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Status of the Global Observing System for Climate

October 2015

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Foreword

This report entitled Status of the Global Observing System for Climate responds to an invitation by the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) at the thirty-third session of the UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) in Cancún, Mexico, in 2010. The conclusions of SBSTA in subsequent years have reinforced the importance ascribed to such a status report. It has recently been completed under the overall guidance of the Global Climate Observing System (GCOS) Steering Committee with contributions from panel members and external experts. It was compiled and coordinated by the lead author, supported by the GCOS Secretariat.

This Status Report performs two functions: It assesses the progress made against the actions set out in the GCOS Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update), while also providing a more generic assessment of the overall adequacy of the global observing system for climate. It makes use of a wide range of supporting GCOS materials published since progress was reported in 2009, many of which have resulted from the outcomes of specialized workshops or working group meetings.

Work on the Status Report was initiated by a scoping meeting held in December 2013 followed by worldwide information collection over the course of a year. The lead author, Adrian Simmons, assisted by the GCOS Secretariat, compiled contributions into initial draft chapters, which were circulated to panel members and associated experts for review and comment. A revised draft was subsequently produced, which included an assessment for each Essential Climate Variable and for each action, as defined by the 2010 Implementation Plan.

A draft version of the full Status Report was submitted for public review from 24 July to 7 September 2015, and was available for open comment on the GCOS website. It was also sent to about 350 institutions and experts, including GCOS sponsors, main World Meteorological Organization (WMO) programmes, GCOS partner institutions, and GCOS panel members and experts, inviting them to comment on it and to redistribute it further as they felt appropriate. The Secretary-General of WMO invited all WMO Members to send their comments to the GCOS Secretariat. The report has thus been subjected to widespread review.

The GCOS review team received some 400 comments from individuals, scientific groups, institutions and national responsible agencies. General comments on the scope and content of the Status Report were overwhelmingly positive, with a few remarks on the need to complement or further justify some aspects. These have been reviewed and addressed in the final version. The comments will also help in the preparation of the next implementation plan in 2016.

The GCOS Steering Committee, at its 23rd meeting in Cape Town, South Africa (29 September to 1 October 2015), approved the Status Report. It has been submitted to the UNFCCC secretariat in October 2015 for consideration by the Parties at the forty-third session of SBSTA, to be held in conjunction with the twenty-first session of the Conference of the Parties, in Paris, France (December 2015).

I would like, on behalf of the GCOS Steering Committee, to congratulate the lead author and to thank him for his Herculean efforts in completing the Status Report. I would also like to thank the chairs of the three GCOS panels and the staff of the GCOS Secretariat for their contributions to the excellent, exhaustive document. I am also grateful to the experts and representatives of partner organizations for their constructive contributions, and look forward to the cooperation of all involved parties in the preparation of the subsequent implementation plan developed in the light of the evidence given in the Status Report.

This Status Report comes at a critical time for the world's understanding and management of climate change. It emphasizes the importance of observations underpinning the science and understanding of climate change and our ability to forecast its likely trajectory. The observations are also critical to inform us of our ability to mitigate the magnitude of climate change and to adapt to changes that cannot be avoided.

Observations are the bedrock on which all other aspects of climate change are founded. The next implementation plan, informed by the Status Report, will set out the further programmes of work needed to improve and extend the observations required for our understanding and management of climate change.

Stephen Briggs, Chairman of the GCOS Steering Committee
Harwell, Oxfordshire, UK
October 2015

Background and outline

Global observation of the Earth's atmosphere, ocean and land is essential for identifying climate variability and change, and for understanding their causes. Observation also provides data that are fundamental for evaluating, refining and initialising the models that predict how the climate system will vary over the months and seasons ahead, and project how climate will change in the longer term under different assumptions concerning greenhouse-gas emissions and other human influences. Long observational records have enabled the Intergovernmental Panel on Climate Change (IPCC) to deliver the message that warming of the climate system is unequivocal.

This report on the *Status of the Global Observing System for Climate* presents an extensive account of how well climate is currently being observed, where progress has been made, and where progress is lacking or deterioration has occurred. It provides a basis for identifying the actions required to reduce gaps in knowledge, to improve monitoring and prediction, to support mitigation, and to help meet increasingly urgent needs for information on impacts, adaptation and vulnerability. It documents improvements in many areas over recent years, but also makes it clear that much remains to be done.

The report has been prepared on behalf of the Steering Committee of the Global Climate Observing System (GCOS). It fulfils the responsibility of the GCOS programme to review and assess the development and implementation of the component parts of the climate observing system, and to report to sponsoring organisations and other participating agencies. It is addressed in the first instance to the sponsors of GCOS: the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization, the United Nations Environment Programme and the International Council of Science. The report is also a response to an invitation from the Subsidiary Body for Scientific and Technological Advice of the United Nations Framework Convention on Climate Change (UNFCCC). The report's review of the progress made in climate observation has a focus on the period since GCOS published its *Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC* in 2003. It assesses in particular the accomplishment of a set of 138 actions formulated in the 2010 update by GCOS of its *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC*. The report lays the foundations on which the GCOS programme is building a new implementation plan for publication in 2016.

Introductory discussion is provided covering the needs for and nature of sustained observation of the climate system, the internationally coordinated arrangements under which observations are made and processed, and the concept of the Essential Climate Variables (ECVs) that provides the organisational framework for this and earlier GCOS reports. The report then systematically reviews overarching and cross-cutting topics. This is followed by reviews of observing networks and the observational status of each ECV. These reviews are provided separately for atmosphere, ocean and land. Discussion is linked in an ordered manner to assessments of the actions from the 2010 Implementation Plan. In doing so the report draws on published material that includes the Fifth IPCC Assessment Report, recent peer-reviewed scientific papers, workshop proceedings and observing-system manuals and guides. It relies on the expert judgement of contributors and the public review process outlined in the foreword. The report analyses data holdings and monitoring information provided by a number of international data centres and presents examples of observational data and derived global data products in the forms of time series and maps.

Several key messages from recent observations and analyses are used in the report to illuminate the discussions for particular variables. Global-mean sea level has continued to rise, and for the first time it has been possible to identify the relative importance of the contributions from thermal expansion, melting ice and the storage of water on land. The deeper ocean has continued to warm despite a slowing of near-surface warming for around ten years prior to 2013. There have been substantial reductions in Arctic sea-ice extent over recent years. There is evidence from new analyses that global-mean surface temperature rose more between 1998 and 2012 than first thought. There is little doubt over the exceptional warmth of the global atmosphere during the current El Niño event.

Interesting and important as such results are, it is not the intention of the report to present a complete picture of what has been learnt from observations or of how much benefit observations bring. More attention is paid to observational uncertainties than to what is known with confidence from observations. This helps guide where emphasis has to be placed in making the required improvements. The immense existing value of past and present investments in the global observing system and the importance of sustaining the operation of well-established components of the system are not dwelt on, but should not be forgotten.

Overall conclusions

The nature, arrangement and extent of observation vary across the atmospheric, oceanic and terrestrial domains. Due to the heritage of many decades of meteorological data collection, atmospheric observation is the best developed, with relatively dense though far from gap-free networks, clear observational standards, largely open data exchange and international data centres covering most if not all variables. It continues to be refined. Ocean observation has developed quickly, with international planning and implementation of observational networks, and new technologies that enable more and better autonomous data collection. Whilst there are still limitations and some issues with established networks, the overall structures are in place for improvement to continue. Terrestrial observations have traditionally been made on smaller scales, with different standards and methods in different countries. They also have a poor history of open data exchange. Space-based observation is now providing global coverage of improving quality for a number of variables, increasingly with open data access, and there is progress in other areas, through global networks for glaciers and permafrost, for example. Standards, methods and data-exchange protocols for key hydrological variables have been developed. An integrated approach to terrestrial observation is still lacking, however.

Most of the **principal findings** that have been drawn from the reviews that have been undertaken variable by variable and action by action fall straightforwardly into two separate groups, one for *in situ* measurement and ground-based remote sensing and one for space-based remote sensing, even though many applications of observations make combined use of both groups of data. It is inevitable in a report such as this one that there are both positive and negative findings, and both need to be acknowledged and taken into account in planning what needs to be undertaken in the future.

For the ***in situ* and other non-space-based components** of the observing system:

- The development and contribution to climate monitoring, understanding and prediction of the Argo network since its floats profiling temperature and salinity were first deployed in the year 2000 has been outstanding. The original goal of 3000 floats was reached in 2007, and the network is now expanding into marginal seas and high latitudes, beginning to host novel sensors that measure biogeochemical variables, and offering the prospect of profiling to greater depths. [5.2.1, 5.4.1, 5.4.2, 5.4.3, 5.4.4, 5.4.5, 5.4.7][1]
- There have been improvements in coverage for a number of longer established *in situ* networks, including the main meteorological networks. The quality of measurements has also shown improvement. [4.2.1, 4.3.4, 4.3.1, 4.4.1, 4.7.5, 5.3.8, 6.3.5]
- Several oceanic and terrestrial networks making *in situ* measurements and networks for ground-based remote-sensing of atmospheric composition have been established or significantly expanded in recent years, although some requirements for forming networks have not been met. [4.6, 5.2, 5.3.10, 5.4.6, 6.2.3, 6.2.4, 6.3.3, 6.3.16]
- Fewer observations have been provided recently by some atmospheric-composition and marine-buoy networks. This has been due to planned closures, inadequate maintenance or unexpected equipment failures. Responses have been effective in limiting some of the shortfalls. Particular issues with tropical moored-buoy networks have prompted a review of the observing system for the tropical Pacific. [4.3.4, 4.7.4, 5.2.3, 5.2.4]
- Surface meteorological measurements from ships have declined in number over the major parts of ocean basins, but have increased near coasts. [4.2.1]
- Some gaps in the coverage of networks over land have been reduced. Local gaps that appear small from a global perspective may nevertheless be critical, especially where populations are at risk or where local changes have global impact. [2.1, 4.2.1, 4.3.1, 4.3.5, 4.7.1, 6.3.1, 6.3.8, 6.3.16]
- Capacity development continues to fall far short of what is needed to fill critical network gaps in a sustainable way, and more generally to ensure that vulnerable developing countries have the local observations needed to adapt to climate change. [3.3, 4.2]
- Automation has increased the temporal frequency of observation and has enabled measurements to be made at additional remote locations, although there are some remaining issues regarding data quality and loss of ancillary information. [4.2, 4.2.1, 4.3.1, 4.3.4, 4.3.6, 4.4.2, 5.2.6, 6.3.5]
- Progress in specifying and establishing reference observing sites and networks has been mixed. It has been good for upper-air measurements. Attaining representative global coverage is a general challenge. [2.4, 4.4.4, 5.2.5, 6.2.3, 6.2.4, 6.3.11]
- There are opportunities to benefit from expanding global near-real-time data exchange and adopting new reporting codes and metadata standards. [3.9, 4.2.1, 4.2.3, 4.4.1, 5.3.3, 6.3.8]
- Recovery of historical data has progressed well in some respects, but is still limited in extent and hampered by restrictive data policies. [3.7, 4.3.2, 4.3.5, 5.3.3, 6.3.5]

[1] The bracketed references to individual sections of the report are intended to be widely illustrative rather than fully comprehensive. Some of the supporting information is given in the reviews of actions from the 2010 Implementation Plan that are provided in Appendix 1 and linked to these sections.

- Generation of data products, for example on surface air temperature, humidity and precipitation, continues to improve. [4.3.1, 4.3.3, 4.3.5]
- Sustaining observing-system activities that are initiated with short-term research funding is a recurrent issue. [3.2, 5.1.3, 6.2.3, 6.3.8, 6.3.16]

For the **space-based component** of the observing system:

- The newer and planned generations of operational meteorological satellite systems offer improved quality and a broader range of measurements. China is becoming established as the provider of a third pillar in the constellation of polar-orbiting systems. [3.4.2, 4.3, 4.5, 5.3, 6.3]
- The European Copernicus programme is placing additional types of observation on an operational basis, with increased coverage and quality of measurement, and accompanying service provision. [3.2, 3.4.3, 3.6, 4.6, 4.7, 5.3, 6.3]
- There have been increases in the numbers of national providers, co-operative international missions and other collaborative arrangements. [3.4.2, 3.4.4]
- There has been very little progress on the continuation of limb sounding and the establishment of a reference mission. [3.4.4, 3.4.7, 4.5.1, 4.5.3, 4.6, 4.7]
- Continuity of measurement is at risk for solar irradiance and for sea-surface temperature at microwave frequencies. [4.5.5, 5.3.1]
- New observational capabilities have been demonstrated, and others are being prepared for demonstration. Future deployment is uncertain for some of the demonstrated capabilities, for example for monitoring cloud and aerosol profiles, sea-ice thickness and soil moisture. [3.4.4, 4.5.2, 4.5.4, 4.7.1, 4.7.2, 4.7.5, 5.3.2, 5.3.5, 6.3.1, 6.3.7, 6.3.16]
- The generation and supply of products derived from space-based observations have progressed well, with increasing attention paid to documenting product quality and uncertainty. [3.4.7, 3.4.8, 3.5, 4.3, 4.5, 4.7, 5.3, 6.3]
- Inter-agency cooperation has been effective in product validation and in starting to develop an architecture for climate monitoring from space and an inventory of products. [3.1, 3.2, 3.4.4, 3.4.7]
- Data access is becoming more open, although there is still progress to be made. Some data remain to be recovered from early missions, and long-term preservation of data, including occasional reprocessing, is not yet fully ensured. [3.4.2, 3.4.3, 3.4.7, 4.5.1, 4.7.4]

Data-centre holdings increase with the passage of time, and are generally distributed by data type. Collections of *in situ* data are held by international data centres for many but by no means all ECVs. Basic satellite data are usually held by the agency that operated the satellite. Derived data products are hosted primarily by the organisations that generate the products. This arrangement is not seen to be problematic, but there are concerns over a set of issues discussed in [3.9, 4.2.3, 4.4.5, 4.6, 5.2, 6.2] or experienced visiting data-centre websites to extract information for this report:

- There are a number of portals and internet search engines that can be used to link to data, but product lists may not be complete and users may be in doubt over what they are missing, and how the observations or products on offer compare.

- Collections of *in situ* data may be some way short of complete and up to date. They depend on submissions or access offered by owners, and thus on owners' data policies and resources, including for recovering data from paper records and obsolete media.
- Data served by a centre may not be in an easy-to-use format, and may lack quality control, merging of data from different sources, duplicate removal, feedback from other users, and so on.
- Data may not be easy to sample, notwithstanding welcome advances in visualisation.

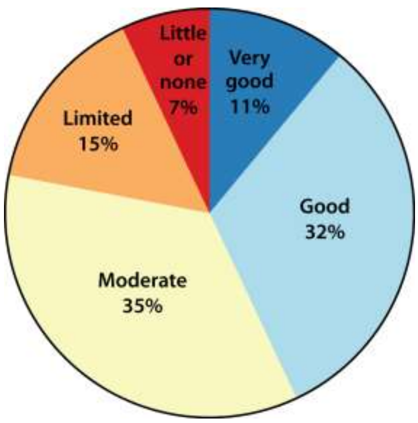
Global reanalysis of comprehensive sets of observations has been sustained, with improving capabilities and better understanding of user requirements and of the deficiencies in current products. The activity is being placed on a firmer footing in Europe through inclusion in operational Copernicus service-provision and in Japan and the USA through the commitment of providers to continue and refresh production. Atmospheric reanalysis for the radiosonde and satellite eras has been supplemented by reanalysis covering the 20th century and more, assimilating only surface atmospheric data but constrained also by observationally based surface and radiative forcings. Reanalysis has become better established for the ocean, the land surface and atmospheric composition. Good progress has also been made on the development of data assimilation systems that couple various elements of the climate system, the atmosphere and ocean in particular. [3.6]

International organisation of observing systems has been strengthened for the atmosphere and ocean, in particular through the development of the WMO Integrated Global Observing System as the framework for the functioning of all WMO observing systems and the revitalisation of the IOC-led Global Ocean Observing System, with guidance provided by a Framework for Ocean Observing. The withdrawal of support for the Global Terrestrial Observing System by its lead sponsor has restricted coordination and standardization for the terrestrial domain, but there has been progress for many individual elements of terrestrial observation. [2.3.3, 3.1, 3.9, 5.1.2, 6.2, 6.3]

Further conclusions concerning overarching and cross-cutting topics, and topics specific to the atmospheric, oceanic and terrestrial domains are presented in chapter 7.

There is **no single metric** or small set of metrics that comprehensively quantifies the current status of the global observing system for climate, how well it meets the broad spectrum of user needs, or how far it has progressed either over many decades or over the past few years. Variations over time of data counts and quality indicators for the better-established ECVs point mainly to a situation that continues to improve, though not entirely. For variables for which observation and international organisation is less well established, progress is indicated in some cases by reporting the establishment of an international network or data centre, or simply by being able to display a global map related to a variable. Statistics on user accesses to web-based information, to observations and data products and to data visualisation tools also serve as metrics, but are often not made evident on data-centre websites.

A general **indication of progress over the past five or so years** is provided by assessing the accomplishment of the actions set out in the 2010 Implementation Plan. Progress has been ranked



Overall progress of actions from the 2010 Plan for each action on a five-category scale. The pie chart on the right shows the distribution by category of all 138 actions. Overall progress is assessed to be moderate to good, with almost twice as many actions falling into the two highest categories than the two lowest ones. 22% of actions have nevertheless been placed in the lowest two categories: progress has been at best limited for almost one action in four. 7% of actions lie in the lowest category, which includes cases where the action called for a network to be improved but performance actually deteriorated. Moreover, some actions relate to incremental steps towards establishment of an adequate component of the overall observing system; good progress on them, though important, is not an end in itself.

To conclude, many countries of the world, developing as well as developed, have improved the contributions that they or their intergovernmental agents make to the global observing system for climate. The system continues to progress and support better the needs of an increasingly wide user community. Aided by the passage of time, the system extends the length of the modern instrumental data record, improving it for recent years by better observations and for earlier years by recovery and better reprocessing and reanalysis of data. Challenged by the passage of time, which makes the response to climate change ever more urgent, the system nevertheless continues to fall short of meeting some essential requirements for observationally based climate information. What needs to be done will be addressed in the forthcoming new implementation plan.

1 Introduction and background

1.1 The context and purpose of this report

Long-term observation of the atmosphere, land and ocean is vital for all countries as economies and societies become increasingly affected by climate variability and change. The various global, regional and national observing networks and systems that together comprise the global observing system for climate provide the data essential for climate analysis, prediction and change-detection. Data records accumulated and preserved over many decades enabled the Intergovernmental Panel on Climate Change (IPCC) to state that warming of the global climate system is unequivocal (IPCC, 2007; 2013).

The expert segment of the third World Climate Conference concluded (WCC-3, 2009) that “networks must be strengthened and sustained in order to monitor climate variability and change, and to evaluate the effectiveness of the policies implemented to mitigate change. Observations are needed to support improvement of climate models, to initialise and enable effective use of model predictions to decades ahead and to guide the use of models for longer-term scenario-based projections. Observations are needed to assess social and economic vulnerabilities and develop the many actions that must be taken to adapt to climate variability and unavoidable change. They must be recognised as essential public goods where the value of global availability of data exceeds any economic or strategic value of withholding national data.”

This report provides an account of the current state of the global observing system for climate and an assessment of the progress that has been made in developing the system over recent years. It has been prepared under the programme of the Global Climate Observing System (GCOS). The report is addressed in the first instance to the sponsors of GCOS: the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU). The report is also a response to an invitation from the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the United Nations Framework Convention on Climate Change (UNFCCC). It covers matters relevant also to the other conventions that entered into force following the 1992 Rio Earth Summit, the Convention on Biological Diversity and the United Nations Convention to Combat Desertification, and to other conventions, protocols and frameworks, most notably the UN-wide Global Framework for Climate Services (GFCS). It may serve more generally as a source of information on the global observation of climate.

The report provides the factual basis on which the GCOS programme is building its new Implementation Plan for the Global Observing System for Climate, for publication in 2016 to succeed the plan published in 2004 and updated in 2010.

1.2 The scope and concept of the global observing system for climate

The glossary of the Fifth Assessment Report (AR5) of the IPCC notes that there are both narrow and wide definitions of climate. Climate in the narrow sense refers to the average weather, or more rigorously to the statistical description in terms of the mean and variability of weather parameters over a period of interest. The classical averaging period is 30 years, as defined by WMO. The parameters are most often surface variables such as temperature, precipitation and wind. Climate in the wider sense is the state, including statistical properties, of the whole climate system. This system is defined in the IPCC glossary to be “the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them.” This report, like the GCOS programme itself, is concerned with climate in the latter, broader sense.

The global observing system for climate is not a single, centrally managed observing system. Rather, it is a composite “system of systems” comprising a set of climate-relevant observing, data-management, product-generation and data-distribution systems. The set includes in particular WMO observing systems that fall within the WMO Integrated Global Observing System (WIGOS), the IOC-led Global Ocean Observing System (GOOS) and the land-surface observing systems that nominally comprise the Global Terrestrial Observing System (GTOS). It also incorporates the climate monitoring undertaken by other programmes concerned with particular components of the climate system or with the impacts of climate change.

This composite observing system is termed the Global Climate Observing System in the sponsors’ memorandum of understanding establishing GCOS. This terminology is barely used in this report so as to distinguish the global observing system for climate from what is termed the GCOS programme, the activities that fall to the GCOS Steering Committee and its working groups, consultants and supporting Secretariat. One charge to the Steering Committee is addressed by this report, namely that to “review and assess the development and implementation of the components of the GCOS, and report to the sponsoring organisations, and to the participating agencies as required”. A second charge is to “identify observational requirements, define design objectives and recommend coordinated actions by sponsoring and participating organisations and agencies, in order to optimize the system's performance and coherence”.

1.3 The cycle of assessment and identification of requirements

In fulfilling its tasks of assessing component observing systems and identifying requirements, the GCOS programme has placed specific emphasis on supporting the UNFCCC, seeking to address what was required for Parties to the Convention to meet their observational commitments and equally have their own needs for global observations met. In 1997 the Conference of the Parties (COP) asked SBSTA, in consultation with the IPCC, to consider and report on the adequacy of the global observing system for climate. The report was in fact prepared and delivered by GCOS in 1998. A Second Adequacy Report was produced by GCOS in 2003, followed this time by an Implementation Plan that identified the actions required to remedy the reported deficiencies in the overall observing system (GCOS, 2003; 2004). Progress on the actions from the 2004 Implementation Plan was assessed after five years and reported in GCOS (2009). Findings were taken into account in preparing an updated Implementation Plan that was published a year later (GCOS, 2010a; referred to hereinafter as IP-10). These documents were to various degrees encouraged, guided or endorsed by SBSTA or the COP itself. The cycle of their production was aligned to enable conclusions of the Third (2001) and Fourth (2007) IPCC Assessment Reports to be taken into account in determining status and needs.

IP-10 was considered by SBSTA at its 33rd Session in late 2010. Among its conclusions, which are reproduced in full in Appendix 3, SBSTA invited the GCOS Secretariat to report on progress made on implementation and encouraged the GCOS programme to review again the adequacy of observing systems. SBSTA also noted the usefulness of regularly updating the plan for implementation. This 2015 Status Report and the 2016 Implementation Plan that is in preparation are the GCOS programme's response to SBSTA. The timing of this response follows previous practice in that it takes into account the latest IPCC Assessment Report, referencing the contributions of Working Group I (The physical science basis; IPCC, 2013) and Working Group II (Impacts, adaptation and vulnerability; IPCC,2014).

No single period is adopted here over which to present the progress made in reaching the current state of climate observation. The time period of relevance differs from one variable to another and from one type of observation to another. Moreover, detailed evidence of progress is more readily available for recent years, reflecting a general improvement in the way observing systems are monitored and monitoring information is reported and retained. This report has some focus on the period since the Second Adequacy Report was prepared in 2002, and especially on the period since 2009 when progress was last reported. The latter is achieved, in particular, through a review of the progress made on each of the 138 actions formulated in IP-10.

Supplementary details to the 2004 and 2010 Implementation Plans related to satellite observations and the requirements for data products based on them were published by the GCOS programme in 2006 and 2011. They were taken into account by the space agencies in their responses to the satellite-specific actions and requirements set out by GCOS, as reported by the Committee on Earth Observation Satellites (CEOS) to SBSTA in 2006 and 2012 respectively. The current status and plans for space-based observation, including the status of product generation and supporting activities, are reviewed extensively in this report, both in general terms and for individual climate variables and IP-10 actions. This covers progress on most of the activities presented in the 2012 CEOS Response and reported in its recent update (CEOS, 2015). The latter provides additional details for many of the satellite-related IP-10 actions that are reviewed in Appendix 1.

1.4 The outline, basis and limits of this report

The following chapter of this report discusses a number of aspects of climate observation. It covers the need for and nature of sustained observation of the climate system, and the internationally coordinated arrangements under which observations are made and processed. It introduces networks and satellite constellations in general, and discusses baseline and reference measurements. It discusses the concept of the Essential Climate Variables (ECVs) that provides an organisational framework for this and earlier GCOS reports, and the framework provided by consideration of the energy, hydrological and carbon cycles. Although primarily intended for scene-setting, it nevertheless notes developments since IP-10 was published.

Chapters 3 to 6, together with Appendices 1 and 2, are the heart of the report, where the bulk of the material related to progress and current status is presented. Chapter 3 discusses cross-cutting and overarching elements, while chapters 4, 5 and 6 focus respectively on the atmospheric, oceanic and terrestrial domains. The ordering of chapter 3 reflects the ordering of the corresponding chapter of IP-10, so as to link most clearly to the reviews of the related IP-10 actions that are provided in Appendix 1. Chapters 4, 5 and 6 provide domain-specific introductions, discussions of networks and other matters that are common to more than one ECV, and accounts for each of the individual ECVs. Links are provided to the reviews of all domain-specific IP-10 actions included in Appendix 1. Appendix 2 is a summary prepared by the UNFCCC Secretariat on systematic observation as reported in recent national communications from Parties to the Convention.

Appendix 3 reproduces the SBSTA conclusions on IP-10 as noted earlier. Appendix 4 summarises how this report was prepared, and Appendix 5 lists the principal contributors. Appendix 6 provides references, Appendix 7 sets out the GCOS Climate Monitoring Principles and Appendix 8 lists acronyms and instruments names, giving corresponding web addresses where relevant.

This report is based largely on published material, including not only the IPCC AR5, but also recent peer-reviewed scientific publications, workshop proceedings, data-centre reports and observing-system manuals and guides. It relies also on the expert judgement of the contributors and the public review process summarised in the foreword. More information is given in Appendix 4. In assembling the report from these various sources, use has also been made of data and information provided by a number of international climate-data centres, for the purpose of preparing figures and tables that quantify the current availability of climate data and how it has changed over time, and that illustrate some of what the data have to show about climate. Use has been made in particular of the data accumulated largely in near-real time by the European Centre for Medium-Range Weather Forecasts, as used both for its forecasting activities out to the seasonal time-scale and for climate reanalysis. This was primarily for reasons of practicality, but it has enabled some informative cross-checking with information available from both data providers and archiving centres. The few instances where near-real-time data receipt is evidently subject to regional practices are noted. In common with earlier GCOS assessment and planning documents, this report for the most part does not consider the various sets of observations made for quite limited durations, such as in field experiments for specific research purposes or in calibration/validation campaigns for satellite missions, important though these can be.

The report does not provide a complete set of references in the manner of IPCC reports, though it does draw heavily on these reports. References are included when they are especially pertinent to the topic in question, or when they report on very recent work. Even then, references are often used simply to illustrate availability or use of observations or a derived data product, and should not be interpreted as implying that a referenced study or product is superior to a study or product that is not referenced. Undertaking product validation and inter-comparison was beyond the scope of what was possible in preparing this report, although the availability and summary findings of such assessments are reported.

The report does not recommend actions in the light of its finding concerning the status of the global observation of climate. Recommendations will be made in the Implementation Plan under development for publication in 2016.

2 Climate Observation

2.1 The need for systematic observation

Systematic observation of the climate system serves many purposes. There are particular needs for observations and derived data products to:

- characterise the state of the global climate system and how it varies;
- monitor the natural and anthropogenic forcing of the climate system;
- enhance the understanding of climate and climate change

- attribute climate events to causes;
- support the modelling and prediction of climate variability and change;
- project climate-change information down to local scales;
- monitor the effectiveness of policies for mitigating climate change;
- assess the impacts of and vulnerability to climate and climate change;
- develop adaptive responses to reduce vulnerability to climate and climate change.

Provision of observations for these purposes is essential for the implementation of climate information services that contribute to sustainable national economic development and public well-being. The climate-sensitive socio-economic sectors for which decision- and policy-making are supported in this way are many, and include agriculture, biological diversity and ecosystem management, coastal and marine protection, energy, financial services, fisheries, forestry, human health, infrastructure for transport, urban settlement and building, tourism and water resource management. Under Articles 4 and 5 of the UNFCCC, Parties to the Convention have agreed to promote and cooperate in systematic observation of the climate system and development of data archives, and to support international efforts to strengthen systematic observation. Many observations also serve other conventions, research programmes and the assessments of the IPCC. Needs include the recovery of historical observations as well as the making of new ones.

Many of the observations that satisfy climate needs also meet other needs, and the primary justification or funding stream for them may relate to these other needs. This is the case in particular for the observations used for forecasting weather, air-quality and sea-state. Here any one observation may be used many times: verifying the forecasts made days, months or seasons previously, initialising the forecast for days, months and seasons ahead, supporting the development or quality assurance of improved models over future years, calibrating the forecasts produced by these models, and characterising climate through repeated use over decades or more ahead as methods of reprocessing and reanalysis are improved.

The observational needs for climate itself have moved beyond those for monitoring and detecting change in averages over months, seasons and years. Access to data with high spatial and temporal resolution, often in near-real time, is required for planning the response to and minimising the impacts of climate change and variability, for monitoring and studying extremes and local impacts, for making seasonal predictions, for attributing recent events, and for general public communication. Monitoring and responding to problems in the observing system also benefits from such access. Moreover, the distinction between short-term forecasting and climate needs are blurred when it comes to adaptation to climate change, as one way of reducing vulnerability to the more-severe weather-related events that may result from climate change is to improve the forecasting of such events at time ranges that are short, but that still allow time for a protective response. This is just one aspect of disaster risk reduction, which more generally requires information based on observations of atmospheric, oceanic and terrestrial variables across a range of timescales.

The different applications of observational data bring with them different requirements for levels of measurement uncertainty, traceability to standards, timeliness of data supply, length and stability of data record, product generation and so on. The requirements for observational coverage may be quite uniform spatially for some purposes, for example for monitoring global trends in temperature or humidity. Requirements may, however, be quite local for other purposes. An example of where observation of local working of the climate system is needed for understanding global impacts is that of the melting of ice-sheet outlet glaciers and its contribution to sea-level rise. Adaptation may require detailed observations for key coastal regions or the regions over land where there is high vulnerability to a particular impact, for example related to disease or agricultural production. Also, the importance of one particular type of observation relative to another may differ from one type of application to another, and can be easier to demonstrate for one application than another. This has to be kept in mind when considering the status of the observation of a particular variable and implications for observing system design and improvement.

2.2 The nature of climate observation

Observation of climate relies on a complementary mix of remote sensing and *in situ* measurement. There are needs for both types of observation, and each has its strengths and weaknesses. Much of the remote sensing is from space, involving passive sensing of the electromagnetic radiation emitted or reflected by the climate system in the spectral range from the ultraviolet (UV) to the microwave (MW), active sensing of the reflection by the climate system of radiation emitted by the satellite, sensing of the occultation of solar and stellar radiation and of GNSS signals, and sensing of local variations in mass of the climate system from variations in the gravitational field experienced by the satellite. In addition to *in situ* measurement of the physical, chemical and biological state of the climate system, there is an increasing need also to gather socioeconomic data for estimating and developing the modelling of anthropogenic impacts on climate, and of the impacts of climate variability and change on human and other life.

Satellites can provide the global or near-global coverage that is needed to describe climate, but their data for the atmosphere are limited in the extent to which near-surface conditions and fine-scale vertical structure in general can be resolved, and in the extent to which information can be provided on wind and below clouds. The information provided from space for ocean and land is largely restricted to the near-surface layer, although important inferences can be drawn on bulk properties from altimetry and gravimetry. *In situ* data are an essential complement, sampling depths and variables that are beyond the view from space, and providing detailed structures and longer historical records. They also serve as anchor points that support the calibration and validation of satellite observations and derived data products. *In situ* data generally have far from uniform geographical coverage, however, and a multiplicity of national institutional arrangements for making the required types of measurement poses challenges related to overall observing-system management, long-term funding and open international data availability.

Observations in general are subject to changes over time in coverage and resolution, and in biases and other error characteristics. Even a generally welcome improvement in coverage may cause a spurious trend or shift in a global data product. This makes monitoring and understanding long-term variability and change a challenge. Addressing this challenge has led to activities directed towards reprocessing data to achieve homogenisation or inter-calibration by adjusting for differences in bias inferred from comparing the data from different types of observation or different instruments. Reprocessing may also be undertaken to benefit from improved knowledge of instrument characteristics or better methods of generating gridded data products from the raw measurements. A modelling framework may also be used to assist in the integration of data of various types and accuracies, using the data assimilation approach established for initialising weather forecasts, in the process known as reanalysis.

2.3 Implementing agencies and international coordination

No single nation or region of the world has the capabilities and resources to develop a complete global climate observing system, not least because *in situ* observations are required over national territories, including airspace and coastal ocean zones. Other major factors are the costs of meeting the increasing requirements for space-based observation and *in situ* observation in international waters that have been made feasible by technological advances. This has been recognized by the establishment and evolution of various arrangements for the international collaboration and coordination that are essential for effective provision of the observations needed to support climate science and services.

2.3.1 National and regional agents for implementation

Whilst many global observing systems and networks are recognised by the name of a coordinating international programme, it is primarily nations that provide climate observations. This includes direct contributions by bodies such as National Meteorological and Hydrological Services (NMHSs), oceanographic institutions and space agencies. Contributions may also be made through formal bi- or multi-lateral collaborations, and through direct support of the international programmes. The latter includes the assuming of particular responsibilities such as operating an international data centre, monitoring the performance of a global observing system or contributing to working groups that develop international practices and standards. Many examples of the specific contributions by nations are given later in this report, though not all can be mentioned. National contributions may be supported from either operational or research funding streams; operational funding often carries some expectation that it will support sustained observation, though in practice both types of funding can suffer from budget cuts and observations may be subject in both cases to constraints that prevent them being made freely available.

A substantial part of the contribution of many European states to the global observing system for climate is through highly developed collaborative arrangements, some of which involve partnerships outside Europe. Intergovernmental agencies, the European Organisation for the Exploitation of Meteorological satellites (EUMETSAT) and the European Space Agency (ESA), and the European Centre for Medium-Range Weather Forecasts (ECMWF), respectively provide space-based observation and environmental monitoring and forecasting. EUMETNET is a grouping of European National Meteorological Services that provides a framework for organising co-operation that currently include programmes for meteorological and marine-surface observation and support for members' activities in climate observation, products and services. Contributions through the European Union have been significantly enhanced by the establishment of an operational programme, Copernicus, providing observations and services covering atmosphere, ocean and land, including climate change. The EU also funds collaborative research projects in areas of climate observation.

Various other regional collaborative arrangements have been established related to climate observation. Some, such as the GOOS Regional Alliances, have been set up as part of wider international coordination. WMO Regional Climate Centres (RCCs) are being instituted to provide operational climate monitoring and data services as part of the regional infrastructure of the GFCS. A number of regional networks of tower sites measuring vertical fluxes of carbon dioxide, water vapour and energy, such as AmeriFlux, AsiaFlux and from European initiatives, are combined with national networks such as those for Australia, Canada, China and Japan, in the FLUXNET "network of regional networks". Regional activities under the GCOS Programme are discussed in Section 3.1.

Observations are also made on a commercial basis, either by an end user with a specific need for local observation for its own use, connected with agriculture for example, or by a commercial provider that sells the data to its customers, who may include a national agency with an observational requirement. Here the licence arrangements for onward data supply determine whether such observations can be regarded as a useful contribution to the global observing system for climate. Publicly funded observations may also not reach the public domain regardless of a country's data policy. This can happen when automatic weather stations are installed to meet the local need of a development project, but the installation does not involve the NMHS of the host country, which might otherwise advise on implementation and operation, and arrange data collection and transmission.

There is also a past and now revitalised tradition in some countries for volunteers to make available their observations of basic climate variables. Volunteers are now also playing a role in digitising the contents of scanned historical data records. The internet has opened up new opportunities for such voluntary contributions.

2.3.2 International arrangements for coordination and assessment

Formal international coordination of weather observation can be dated back to the First International Meteorological Conference in 1853 and the establishment twenty years later of the International Meteorological Organization. Since 1950 it has been undertaken under the auspices of the **WMO**, a specialised agency of the United Nations whose interests today extend to include water, climate and related environmental matters. Coordination of ocean observation falls under the **IOC**, founded in 1960, which works together with WMO on areas of joint interest, in particular through their joint Commission for Oceanography and Marine Meteorology (JCOMM).

Promotion of scientific cooperation in space was established by ICSU in 1958 through formation of the **Committee on Space Research (COSPAR)** at a time when the first artificial Earth-orbiting satellites had been launched by the USSR and USA, and in the light of the successful programme of internationally coordinated observation being undertaken during the International Geophysical Year. Since then, the changing political environment and emergence of additional providers of observations from space has led to new mechanisms for the coordination of activities among the national and intergovernmental agencies that operate space programmes. COSPAR nevertheless continues to fulfil its original role. Indeed, this report draws on a parallel COSPAR-sponsored study of the roadmap to 2025 for observations in support of integrated Earth-system science.

The **Coordination Group for Meteorological Satellites (CGMS)**, formerly the Coordinating Group for Geostationary Satellites) came into being in September 1972, when representatives of Europe, Japan and the USA, and observers from WMO and the Global Atmospheric Research Programme (GARP), met to discuss questions of compatibility among geostationary meteorological satellites. The CGMS promotes coordinated operation and use of data and products from its members' satellite systems, in support of operational weather monitoring and forecasting, and related aspects of climate monitoring.

CEOS was established in 1984 with the broader remit of coordinating international efforts for Earth observation as a whole. Its original focus was on interoperability, common data formats, the intercalibration of instruments, and common validation and inter-comparison of products. CEOS now also provides an established means of communicating with external organisations to respond to requirements for Earth observation. It works jointly with CGMS in developing a strategy, together with the WMO Space Programme, for climate monitoring from space (Dowell *et al.*, 2013), and through a working group on climate.

The **World Climate Research Programme (WCRP)** also plays an important role in climate observation, in addition to its fundamental promotion of research into the functioning, modelling and prediction of climate. It was established in 1980 to follow on from the Global Atmosphere Research Programme, under the sponsorship of WMO, IOC and ICSU. WCRP works with **GCOS** in several ways, including through a set of expert panels on climate observation for atmosphere, ocean and land (AOPC, OOPC and TOPC) and through its Data Advisory Council. Within its component projects it has important initiatives on assessment of observational datasets and their use in evaluating models. It has worked with partners such as the ICSU-sponsored **International Geosphere-Biosphere Programme** (IGBP), which also has observational interests, through their joint membership of the Earth System Science Partnership (ESSP). This is being superseded by arrangements being established with Future Earth, which is absorbing all members of the ESSP other than WCRP.

The co-sponsored programme for **GCOS** itself dates back to 1992 (Houghton *et al*., 2012). Some of its activities have already been introduced; others are discussed later in this report. A review of the programme has recently been completed by a board established by the sponsors (GCOS, 2014a). It characterised GCOS as an active and successful programme serving a broad range of user needs, expressed no doubt that the programme should be continued, and developed a set of eighteen recommendations to the sponsors aimed at ensuring the fitness of the programme for the future.

More recently established, in 2003, and with the broadest remit concerning observation, the **Group on Earth Observations (GEO)** is an *ad hoc* intergovernmental group of around 100 countries that works with participating international organisations to foster new projects and coordinated activities across the full range of Earth observation. GEO is building the Global Earth Observation System of Systems (GEOSS) to provide a framework for integrated observation that supplements the arrangements under which contributing pre-existing systems operate. Its activities over its initial ten years of operation were organised into nine societal benefit areas (SBAs) and cross-cutting initiatives. These SBAs include some, among them weather and climate, for which observation and modelling play a central role, and others such as disasters and health that benefit from observational products. Cross-cutting initiatives include an important emphasis on data sharing. GEO is currently developing a new strategic plan for implementing the GEOSS, to run from 2016 to 2025.

The **Future Earth** initiative launched in 2012 by a multi-partner alliance including ICSU, UNEP, UNESCO and WMO aims to establish a capability to monitor and forecast changes in an Earth system that includes interacting human activities, as part of the provision of the knowledge needed to determine pathways to global sustainability. A further collaboration of UNEP, UNESCO and WMO is the **PROVIA** research programme on climate change vulnerability, impacts and adaptation. It is currently envisaged that neither Future Earth nor PROVIA will establish major new infrastructure for Earth observation or gathering socioeconomic data, but rather that they will work with existing observing systems and coordinating bodies, communicating new data needs as their programmes develop and identify them. Future Earth nevertheless is absorbing projects from pre-existing Earth-system science programmes that include observational components, as noted above in the case of IGBP.

The discussions of individual ECVs and the IP-10 actions associated with them identify some of the subsidiary and other bodies that provide overviews and assessments of climate observations and data products. Not noted explicitly in many cases is the overarching roles of the GCOS and GOOS panels in keeping under review the observation of all ECVs for their respective domains. The GEWEX Data and Assessments Panel, formerly the GEWEX Radiation Panel, of WCRP's core Global Energy and Water Exchanges project coordinates assessments of data products on variables and fluxes related to aerosols, clouds, precipitation, radiation and water vapour. Another core WCRP project, Stratosphere-troposphere Processes And their Role in Climate (SPARC), is also particularly active in assessment.

2.3.3 The principal atmospheric, oceanic and terrestrial observing systems

Several organisational developments related to the principal observing system components for atmosphere, ocean and land have occurred in recent years.

The establishment of **WIGOS** as the framework for the integrated functioning of all WMO observing systems and the contribution of WMO to GOOS, GTOS and the overall global observing system for climate took an important step forward in 2015 with the approval of regulatory material by the Seventeenth World Meteorological Congress, and the decision by the Congress that WIGOS will enter a four-year pre-operational phase at the beginning of 2016. The observing systems that comprise WIGOS are the Global Observing System of the World Weather Watch Programme (WWW/GOS), the observing components of the Global Atmosphere Watch (GAW) Programme, the WMO Hydrological Observing System and the observing component of the Global Cryosphere Watch (GCW). WIGOS encompasses both surface-based networks and space-based observation. The GCOS/WCRP Atmospheric Observation Panel for Climate (AOPC) works in conjunction with WIGOS bodies.

The governance of **GOOS** was revitalized by the 2011 IOC General Assembly. The new GOOS Steering Committee has set up an expanded structure with three expert panels. This includes the Ocean Observations Panel for Climate (OOPC) which GOOS sponsors along with GCOS and WCRP. The other panels cover biogeochemistry (through an expansion of the International Ocean Carbon Coordination Project, IOCCP) and biology and ecosystems. Coastal observations are now a core responsibility of each of the GOOS expert panels, rather than being handled by a separate body.

GTOS differed from the other two main contributing climate observing systems in that it was operated under a secretariat hosted by the Food and Agriculture Organization of the United Nations (FAO), which is not a sponsor of GCOS. The GTOS Secretariat provided substantial support to terrestrial aspects of the GCOS programme during preparation of the Second Adequacy Report and 2004 Implementation Plan. The Sixteenth World Meteorological Congress in fact recommended in 2011 that WMO consult with its fellow sponsors of GCOS to consider the potential pros and cons of adding the FAO as a fifth sponsor of GCOS, given its lead role in GTOS. In practice, however, the support offered to terrestrial aspects of the GCOS programme by the GTOS Secretariat had dwindled over the years, and there has been no support from the FAO or its co-sponsors for a functioning secretariat and steering committee for GTOS since 2011. Amelioration has been provided to a degree by the continued functioning of TOPC as the GCOS/WCRP-sponsored Terrestrial Observation Panel for Climate, and by internationally coordinated activities for terrestrial observation under the ESA-funded GOFC/GOLD (Global Observation for Forest Cover and Land Dynamics) project, the WMO hydrological and cryospheric systems under WIGOS, FLUXNET and several CEOS initiatives. The situation nevertheless remains far from satisfactory; particular consequences are noted later in this report.

2.4 Tiered observing networks and constellations

The GCOS programme has adopted a tiered concept of comprehensive, baseline and reference networks of observing sites, each of which meets a different subset of the needs for climate data discussed in section 2.1.

Comprehensive networks are those that provide data of general quality with the highest spatial and temporal resolution, and the shortest latency of data supply. They are receiving increased attention than hitherto due to the demands for data on extremes, impacts and adaptation, and due to the use of their observations in data-assimilation systems for reanalysis and initialising forecasts. Baseline networks involve a limited number of selected locations that are globally distributed and provide long-term high-quality data records for characterising continental- and global-scale variability and trends. They should have a greater degree of monitoring and management than the comprehensive networks. Reference networks are the sparsest in terms of coverage but make the highest quality observations. These should be metrologically traceable with well-quantified uncertainty, to be used to generate reliable long-term time series and applied for the calibration or validation of other types of observation and derived data products.

These concepts apply also to satellite observing systems. Groups or constellations of satellites making a particular type of measurement may include or be supplemented by a smaller baseline set of instruments providing particularly stable measurements, with the as-yet-unrealised addition of one or more reference missions flying instruments of the highest feasible quality making measurements that are traceable to standards wherever possible.

Although it is in principle desirable to establish and operate networks of all categories for all climate variables, this goal is presently unrealistic. Moreover, the optimal network densities and tiering vary depending on the variable under consideration. Baseline networks are discussed in a number of places in this report. Attention for reference observation has been focussed on the development of the GCOS Reference Upper-air Network (the GRUAN) through involvement of AOPC and its Working Group on the GRUAN in the governance and implementation of this new network, working in conjunction with the Lead Centre provided by Deutscher Wetterdienst (DWD). Establishment of the GRUAN was a key action called for by the GCOS Programme in its 2004 Implementation Plan. Generally though, the notion of a reference set of observations is not used in a very precise way within the climate observation community, and this is reflected in the use of the terminology in this report. A new EU-funded project GAIA-CLIM (Gap Analysis for Integrated Atmospheric ECV Climate Monitoring) aims to advance the definition, documentation and implementation of the tiered approach to characterising observations; it is building in part on CORE-CLIMAX, an earlier EU project that is referenced several times in this report.

IP-10 also discussed ecosystem monitoring sites. Here long-term observations of ecosystem properties, including biodiversity and habitat properties, are made in order to study climate impacts. These measurements need to be made together with observations of the local physical climate and changes in the surrounding environment, such as related to land and water use.

2.5 The Essential Climate Variables

The concept of the ECVs emerged during the first decade of the GCOS programme, and has become well established following the original listing of the ECVs as such by GCOS in its Second Adequacy Report (GCOS, 2003). The concept, its provenance, rationale and uptake, and the challenges and opportunities for its further development are discussed by Bojinski *et al.* (2014).

Figure 1 presents the concept in schematic form. The ECVs are more than a list of variables or groups of related variables for which observations and data products are required to support climate monitoring, forecasting, research, service provision and policy. Aside from relevance, widespread observation of the variable (or of closely-related quantities) must be technically feasible and cost-effective. Knowledge of existing observing capabilities, climate datasets and the level of scientific understanding provides the foundations for selecting the ECVs from a pool of climate-system variables. In addition, guidance is needed to refine observation and the generation of data products, and to facilitate the use of data on the ECVs: user requirements capture the data needs across sectors, climate-focussed principles guide the operation of observing systems and infrastructure, and guidelines for the generation of ECV data records promote good practice by providers and informed application by users, addressing such issues as availability of metadata, provisions for data curation and distribution, and needs for quality assessment and peer review.

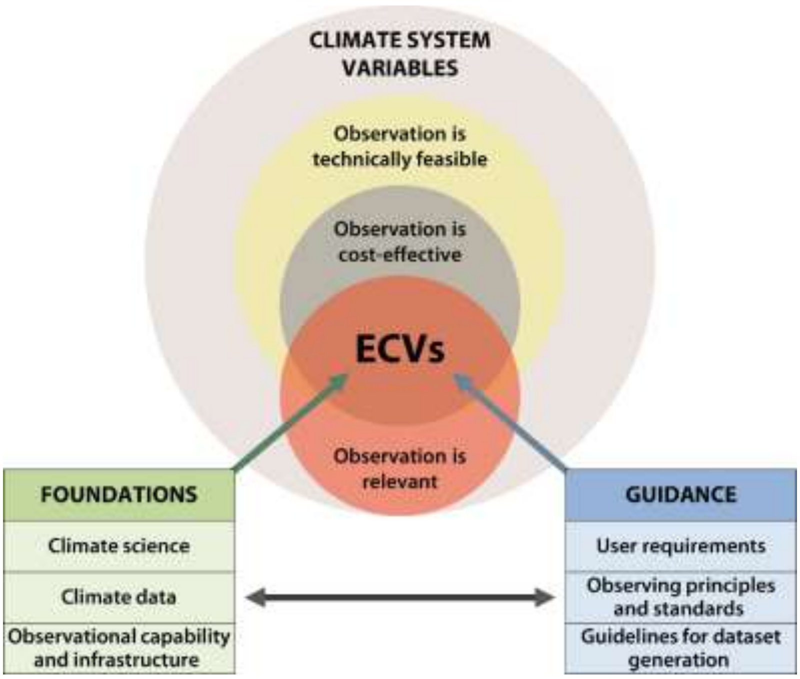


Figure 1: The concept of the Essential Climate Variables. Adapted from Bojinski et al. (2014).

The original list of ECVs provided the organisational basis for the 2004 Implementation Plan and its satellite supplement. A minor revision to the set, including a few changes in terminology, was made in IP-10, which likewise was organised around the ECVs, as reflected in chapters 4 to 6 of this report. The IP-10 list remains current, and is presented in Table 1.

Atmospheric	**Surface:**	**Air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget**
	Upper-air:	**Temperature, wind speed and direction, water vapour, cloud properties, earth radiation budget (including solar irradiance)**
	Composition:	**Carbon dioxide, methane, other long-lived greenhouse gases, ozone and aerosol, supported by their precursors**
Oceanic	**Surface:**	**Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, surface current, ocean colour, carbon dioxide partial pressure, ocean acidity, phytoplankton**
	Sub-surface:	**Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers**
Terrestrial	**River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire disturbance, soil moisture**	

Table 1: The Essential Climate Variables, as defined in IP-10

The first listing of the ECVs was accompanied by development of a status report on them. The report also covered a few other key variables and air-sea fluxes. It included the reasons why observation of each variable was important, the contributing observations including GCOS-designated baseline networks, data management issues, available data products and then-current capabilities, issues and priorities. It was intended to be published as a supplement to the Second Adequacy Report, but exists only as a draft document that is now quite out-of-date. However, the information contained in the present report in the ECV-specific domain sections 4.3, 4.5, 4.7, 5.3, 5.4 and 6.3 provides in essence an update of the unpublished material that was developed alongside the Second Adequacy Report.

2.6 Climate-system cycles

The working of the climate system is commonly studied, characterised and presented in terms of the cycling of water and carbon through the system, and the receipt, transfer and export of energy by the system. The build-up of carbon in the atmosphere, ocean and terrestrial biosphere due to human activities, the consequent accumulation of thermal energy in the system, changes to the distribution of rainfall and the melting of ice are fundamental elements of climate change. Research and monitoring programmes are accordingly often organised around one or other of the cycles.

Each of the current ECVs can be linked directly or indirectly to at least one of the energy, hydrological and carbon cycles. A clear majority can be linked to at least two, and around a third relate to all three cycles, although the degree of relevance varies from ECV to ECV and cycle to cycle. This too makes the GCOS approach of using the domain-based ECVs as an organisational framework a practical one, although as recognised in IP-10 some of the important links between the domains and within the cycles and application areas may thereby be obscured. A similar remark applies if the primary focus of study is the cryosphere rather than one of the cycles. The ECV- and domain-based approach in particular runs the risk that insufficient attention is paid to the key fluxes between the domains.

Other cycles of constituent species also play a part in climate change. In particular, the nitrogen cycle is linked to the carbon cycle through the metabolic needs of organisms for these two elements. Nitrogen is also linked to sulphur through their joint role in aerosol production. Indeed, prior to establishment of the set of ECVs, TOPC developed a plan for climate-related terrestrial observations (GCOS, 1997) that identified a larger set of "key variables", including some related to the cycles of nitrogen and phosphorus. IPCC (2013) expressed confidence that low nitrogen availability will limit carbon storage on land. The limiting role of phosphorus was considered more uncertain, but could become more severe than that of nitrogen on centennial time scales.

3 Overarching and cross-cutting elements

The topics discussed in this chapter follow the ordering of the overarching and cross-cutting topics discussed in the corresponding chapter 3 of IP-10. This is to enable the text to be linked directly to the reviews of the corresponding IP-10 actions (C1 to C23) presented in Appendix 1.

3.1 Planning and reporting

The individual component observing systems for climate and international data centres almost all operate within their own plans, procedures, standards and regulations, coordinated by the agents for implementation as discussed earlier. IP-10 called on all agents for implementation to adjust their activities to respond to the actions identified in the plan. In particular, it formulated Action C1, which invited participating international and intergovernmental organisations to review and update their plans in the light of IP-10, in order to ensure that they better serve the needs of the UNFCCC. Many of the responses from organisations are listed in the review of this action that begins on page 199 of Appendix 1. They are evident in the reports on individual items contained in the subsequent pages of this report, including the reviews of other IP-10 actions.

The needs for global climate observations and products can be addressed only if plans are developed and then implemented in a coordinated manner by national and regional organisations. Climate-observing activities are not commonly coordinated, planned, and integrated across the atmospheric, oceanic and terrestrial domains at the national level, although such activities may be well-coordinated within particular domains, particularly in the case of meteorological observation. The required national coordination mechanisms and plans for systematic observation of the climate system are usually best sustained when national coordinators or committees are designated and assigned responsibility to coordinate planning and implementation of systematic climate observing networks and associated activities across the many organisations and agencies involved with their provision.

All four sponsors of GCOS, and the GCOS programme itself, have advocated for the establishment of GCOS National Coordinators and GCOS National Committees. This led to a growth in the number of

National Coordinators from eleven in October 2006 to 23 in May 2010. IP-10 Action C2 renewed the call, but the number of National Coordinators had increased only to 26 by May 2015. Further discussion is given in the review of the action, starting on page 200. There has likewise been a modest increase in the number of National Focal Points for GCOS and Related Climatological Data designated by WMO Members. National Focal Points have the task to monitor and report on the data availability and quality from surface and upper-air meteorological networks relevant for climate, and are 151 in number in the list published by WMO in September 2015. Regional coordination is provided by a set of nine WMO Commission for Basic Systems (CBS) Lead Centres for GCOS. Meetings of Lead-Centre representatives were held in 2011 and 2013. Reports are available from http://www.wmo.int/pages/prog/gcos.

The GCOS Regional Workshop Programme, completed in 2006, provided a framework for interested nations to work together to identify both national and GCOS network needs in each of the ten regions covered by the Programme. The primary achievement of the programme was development of a set Regional Action Plans (RAPs). However, despite repeated calls by the COP and SBSTA to Parties in a position to do so to support the implementation of the projects contained in the RAPs, GCOS (2009) reported that lack of funding had restricted the number of projects that had been implemented, and that some of the earlier RAPs needed to be brought up to date. IP-10 accordingly formulated Action C3 calling for review of the projects contained in RAPs, and for the RAPs to be updated and revised as necessary. The review of the action starting on page 200 discusses the limited progress achieved since then.

IP-10 recognised that the reporting of activities on systematic climate observation undertaken by Parties to the UNFCCC as part of their National Communications under the Convention had been a valuable contribution to the planning and implementation of the global observing system for climate. Its Action C4, reviewed on page 201, recorded the need for reporting to the UNFCCC on systematic climate observations using current guidelines. The latest communications have provided information helpful for the formulation of this report.

3.2 Towards sustained networks and systems

Important observations of many variables of the climate system are made in the context of research programmes or by space agencies whose primary mission is research and development. This is particularly so in the atmospheric composition, oceanic and terrestrial domains. Once methods are sufficiently mature to guarantee a sustained set of observations to known and useful levels of accuracy and stability, they need to be sustained into the future as an operational observing system. The operational system includes the acquisition, transmission, analysis and archiving of the data housed in an organisation with an appropriate institutional mandate and sustained funding. Often the optimum arrangement is for part if not all of this chain of operations to be funded as part of a research institution's responsibility; in other cases it may involve the transfer of responsibility from an organisation with a research mandate to one with an operational mandate. Such a transfer of responsibility also implies sustained dialogue between the operational entities and the research community so that the operational arm may benefit from or respond to scientific advances. Some success has been achieved in ensuring an orderly process for sustained operation of research-based networks, as called for in IP-10 Action C5, although overall progress on this action as reviewed on page 202 is judged to have been moderate.

The importance of implementation of the GCOS Climate Monitoring Principles (Appendix 7) by those institutions contributing to the operation or sustained networks and systems, especially baseline components, and the support for this by the bodies responsible for coordinating such networks and systems, was restated in IP-10. The plan also recognised the need to characterise the uncertainties associated with every measurement, working towards traceability to SI standards where possible, in collaboration with national metrological institutes. These considerations were embodied in IP-10 Action C6, for which the moderate progress made is reviewed on page 203.

3.3 International support for critical networks

The climate system is global, and the impacts of variability and change can be located far from their source. Monitoring, modelling and prediction all require global data. Filling of gaps in observing networks and making the observations widely available is in the long-term interests of all. Sustaining critical networks can accordingly be viewed as an international responsibility, even if the predominant contribution to many atmospheric and terrestrial networks comes from countries making observations within their own borders.

Despite progress, many countries, especially among the least-developed ones and the small island developing states, still do not have the capabilities or resources to provide the essential *in situ* observations or carry out associated analysis of climate data. One of the technical assistance programmes that helps to address these difficulties is the GCOS Cooperation Mechanism (GCM). The support provided by the Mechanism involves focussed capacity-building and improvement of infrastructure, and in some cases has to include funding of operating expenses associated with making observations using radiosondes. It is evident from much that is presented in this report and others that the requirement for support continues. Although IP-10 called for more contributions by developed countries to the GCOS Cooperation Fund as one means of assisting developing countries to improve their climate observing networks, the review of the corresponding Action, C7, provided on page 204 reports a significant reduction in donations since 2010. It has nevertheless still been possible to undertake a number of projects under the GCM in recent years, as listed in the review.

The GCM is just one of many multinational and bilateral programmes that provide technical assistance. This makes it difficult to assess the overall level of international support for the functioning of critical networks.

3.4 Space-based observation

3.4.1 Introduction

In situ observing networks are largely specific to particular domains or ECVs, although there are links between atmosphere and either ocean or land in the measurement of near-surface variables. These networks are accordingly discussed in chapters 4, 5 and 6 below. In contrast, the measurements made from a particular satellite often relate to all domains, or involve common issues across the domains. This section 3.4 thus discusses general matters related to space-based observation, covering the various topics on which needs were addressed in the broad and multi-faceted IP-10 Action C8. Further discussion specific to particular ECVs is given where appropriate in chapters 4 to 6.

3.4.2 Sustained satellite observing systems for weather and climate

Routine sustained delivery of data from operational polar-orbiting and geostationary satellite systems is fundamental to the provision of services for weather, climate and other environmental aspects. China, the European member states of EUMETSAT, India, Japan, South Korea, Russia and the USA each operate today multi-instrumented meteorological satellites that address a spectrum of needs. Several international agreements cover deployments and data exchange. Established series of satellites deliver data in near-real-time that are vital for numerical weather prediction, but much of the data also make important contributions to the climate data record.

Longstanding cooperation in the operation of geostationary systems has already been noted. This includes instances of the deployment of a backup geostationary satellite of one operator over the region normally covered by another operator, when needed to avoid gaps. Cooperation on polar-orbiting systems has included flying European instruments on US platforms and vice versa. More recently, the USA and Europe have formalised the Joint Polar System (JPS) concept in which responsibilities for the "mid-morning" and "afternoon" sun-synchronous polar orbits are shared. Figure 2 shows the US view of its resulting polar-satellite programme, comprising coverage of the mid-morning orbit by first and second-generation European satellites (Metop and Metop-SG) and of the afternoon orbit by US NOAA satellites, supplemented by coverage of the "early-morning" orbit by satellites of the US Defense Meteorological Satellite Program (DMSP).

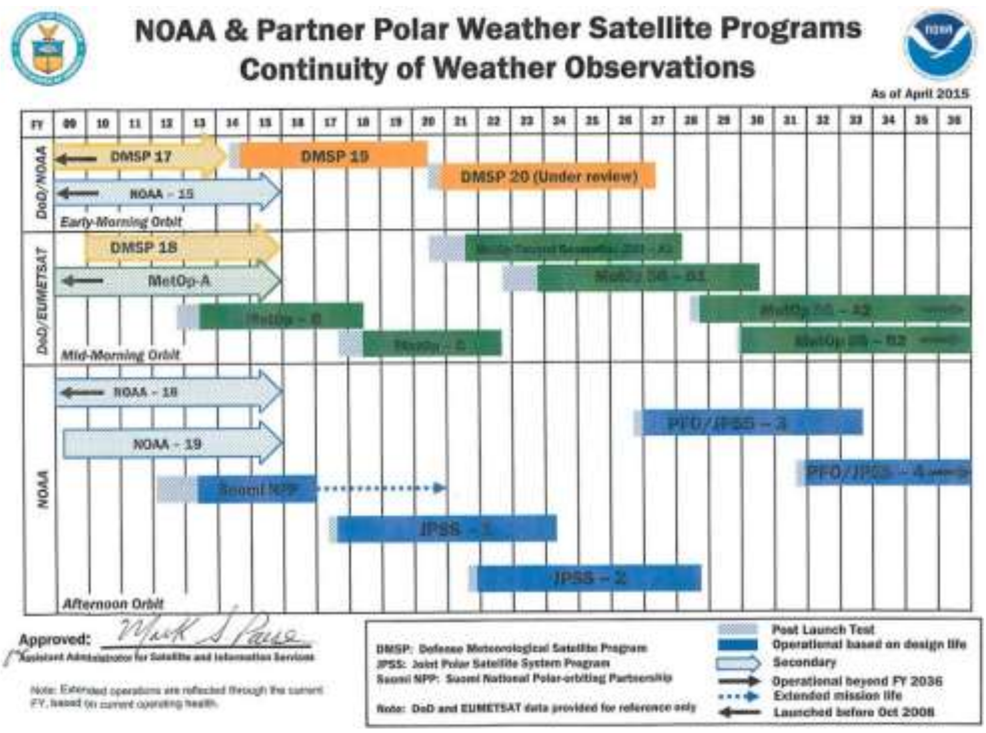


Figure 2 NOAA, EUMETSAT and US Department of Defense (DoD) polar operational satellite programmes as of April 2015. Source: NOAA/NESDIS, downloaded from www.nesdis.noaa.gov/flyout_schedules.html.

Current coverage from polar orbit by European and US satellites is better than is expected for coming years, as long-lived NOAA satellites of the previous generation overlap both with the first of the next-generation NOAA system and with two overlapping European satellites, as indicated in Figure 2. Figure 3 presents examples showing the data distributions from many, though not all, of the instruments (including one flown by NASA) providing temperature and humidity information used by ECMWF in mid-February 2015. Data from MW and infrared (IR) sounders (the AMSU, AIRS, IASI and HIRS instruments; panels (a) to (d) of the figure) give almost complete six-hourly global coverage, and are complemented by clear-sky radiance data from geostationary orbit (panel (e), showing data points from European, Japanese and US systems) and globally well-distributed data from GPS radio occultation (here from European, US and joint Taiwanese-US missions).

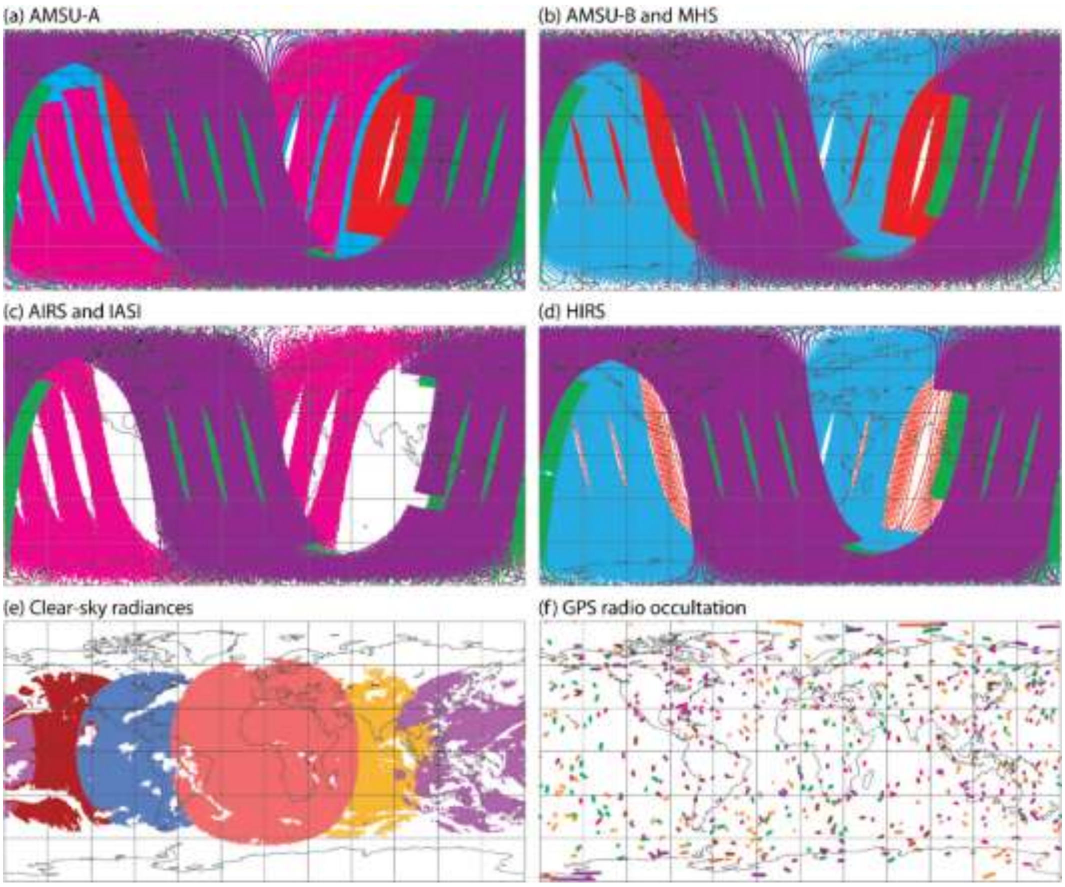


Figure 3: Examples of data coverage by satellite instruments providing data relating to temperature and humidity, based on ECMWF maps of operational data receipt for the six-hour period from 21UTC 17 February to 03UTC 18 February 2015. Colours denote different satellites.[2]

An important contributor to overall capability for coming years will be the series of Chinese FY-3 polar-orbiting meteorological satellites. Here CGMS, with input from the GCOS programme, has played a role through discussion and presentation of the case for complementary coverage of the early-morning orbit by changing the planned deployment of two FY-3 satellites (Eyre and Weston, 2014). FY-3 also provides resilience for other orbits, for which Figure 2 shows a nominal gap in 2017 in the case of the afternoon orbit. A bilateral cooperation agreement between EUMETSAT and the China Meteorological Administration includes arrangements for data and product exchange. ECMWF started operational assimilation of data from the MW humidity sounder on the FY-3B satellite in September 2014.

[2] Figures without an acknowledged source have been prepared especially for this report, using ECMWF facilities.

Generation of operational sea-surface-temperature (SST) products makes use of a variety of satellite data, some from the operational polar-orbiting and geostationary meteorological satellites and others from missions that are nominally for research and development (section 3.4.4). Here too, collaborative arrangements have been established, both through international coordination mechanisms, for example the CEOS “virtual constellation” for SST, and through bi-lateral arrangements, such as that between Japan and the USA for use of all-weather C-band passive MW data from the AMSR2 instrument on JAXA’s GCOM-W1 satellite.

Operational altimeter data are presently delivered by the Ocean Surface Topography Mission/Jason-2, a joint venture between Europe and the USA, a partnership that will be continued by the forthcoming launch of Jason-3. The planned follow-on Jason Continuity of Service mission (Jason-CS) has been designated as Sentinel-6, with launches envisaged in 2020 and 2026. This should ensure continuity of a data record that stretches back more than two decades to the 1992 launch of TOPEX/Poseidon.

3.4.3 The European Copernicus programme

Copernicus is a major European programme for operational Earth observation and associated service delivery that complements and substantially extends the operational programmes discussed above. The launch in April 2014 of Sentinel-1A saw the first spacecraft in orbit out of a series of six so-called Sentinel families (Figure 4) that should all be operational within the next six or so years. It was followed by the launch of Sentinel-2A in June 2015. ESA is responsible for developing the Sentinels on behalf of the European Union; operation will be shared with EUMETSAT, while other institutions provide products and services based on the data from these and complementary satellites. Each Sentinel family is associated with a series of satellites that are expected to be replenished as age or health dictates. Copernicus data and products are free and open to access and use. Berger *et al*. (2012) discuss their potential for addressing some of the challenges associated with advancing Earth-system science.

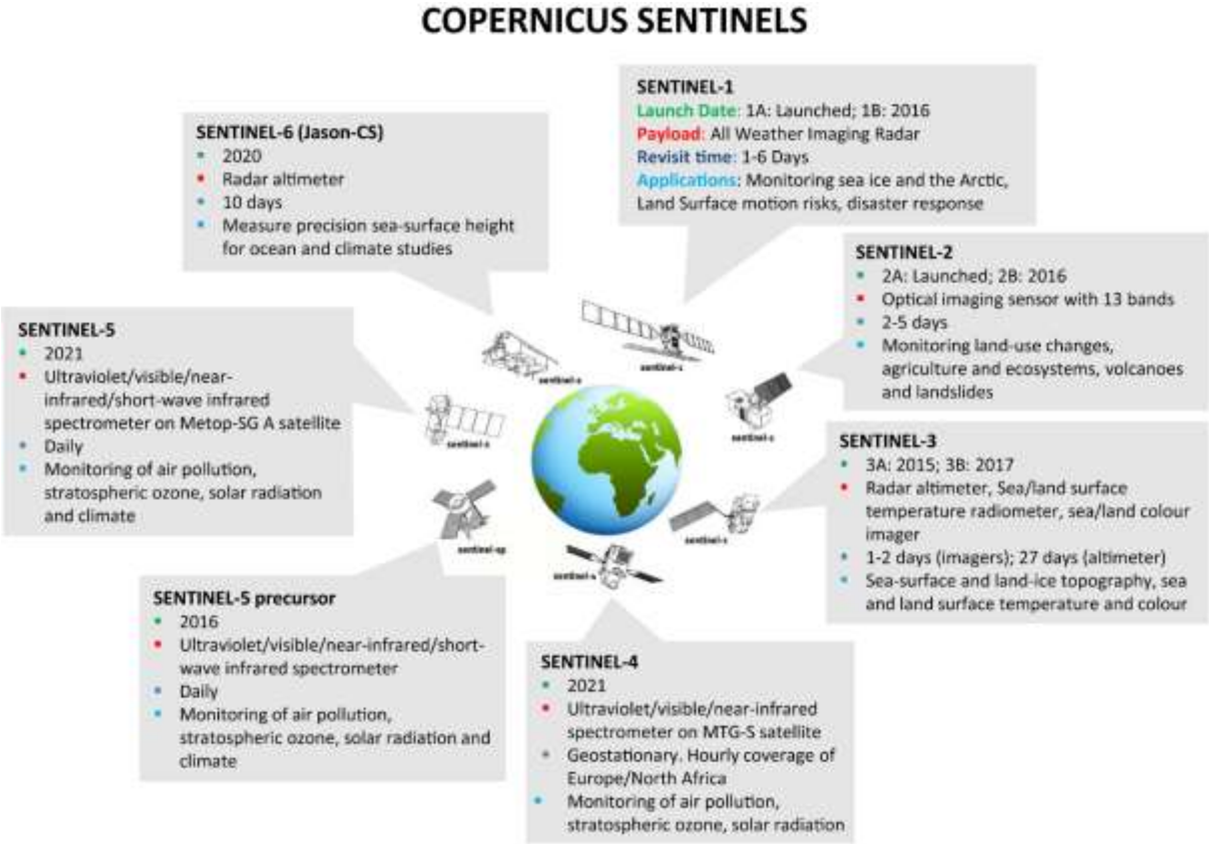


Figure 4 Overview of the satellites of the Copernicus system. Source: ESA.

The Sentinels cover near-term environmental monitoring and forecasting as well as climate. Sentinel-1 will comprise in due course an orbiting pair of C-band Synthetic Aperture Radar (SAR) satellites (1A and 1B) for operational monitoring and disaster response. Sentinel-2A is a complementary optical imaging satellite that will likewise be subsequently joined in orbit by Sentinel-2B. Sentinels 3 to 5 have different goals, using radiometers and spectrometers to measure a wide range of variables from SST to air pollution. Further discussion is given in later sections for individual ECVs. Sentinels 4 and 5 will not be separate satellites; the Sentinel instruments will be deployed instead on operational meteorological geostationary (Meteosat Third Generation) and polar-orbiting (Metop-SG) platforms. A dedicated Sentinel-5 precursor satellite has however been developed for launch in 2016, to minimise the shortfall in key atmospheric composition data resulting from the loss of Envisat in April 2012 and to extend the type of observation provided by the OMI instrument on the EOS Aura satellite and by GOME-2 on Metop. As already noted, Sentinel-6 is the Jason-CS mission.

3.4.4 Missions for research and development, and the challenges of continuity

Beyond the sustained observations provided by operational programmes such as discussed in the preceding two sections, many space agencies operate time-limited missions for short-term measurement of quantities not covered by the operational programmes, for understanding processes and enhancing their modelling, or for development and demonstration of new capabilities. Such missions are increasingly carried out through the cooperative efforts of more than one agency. They sometimes involve either repeated deployment of a particular type of instrument or the deployment of an instrument similar in type to an earlier one, and this may be followed by implementation of the type of measurement within operational programmes. They may thus provide part of a much longer time series of critical measurements, and as such may provide data that are used for climate monitoring or reanalysis, with recalibration as needed. One example is that of data on ocean surface vector wind provided by scatterometers on the ERS-1, ERS-2, QuikSCAT, Metop-A, Metop-B, Oceansat-2 and HY-2A satellites, and by the RapidScat instrument on the International Space Station. Others include the data on aerosol optical depth provided by the MODIS instruments on two EOS satellites and the VIIRS instrument on the Suomi NPP satellite, and on ocean surface-wave height from the radar altimeters on ERS-1, ERS-2, Envisat, Jason-2, Cryosat and SARAL.

Groups of related missions include those measuring soil moisture and ocean surface salinity (SMOS, Aquarius/SAC-D and SMAP), sea-ice thickness (CryoSat and the forthcoming ICESat-2), and clouds, aerosols and radiation (the A-train set comprising CALIPSO, CloudSat and PARASOL, and the forthcoming EarthCARE). Carbon dioxide provides a further example, with column measurements from the SCIAMACHY instrument on Envisat followed by those from the dedicated GOSAT and OCO-2 missions, with continuation to be provided by OCO-3 and GOSAT-2, supplemented by upper tropospheric measurements from hyperspectral IR sounders beginning with AIRS on EOS Aqua and continued by instruments such as IASI on operational meteorological platforms. As noted already for SST, an organisational framework for space agencies to coordinate their related activities for several individual variables or classes of variable is provided by the CEOS virtual constellations.

Several types of challenge have to be faced in seeking to ensure appropriate levels of continuity of key measurements. Although the transfer of some types of observation from a research to an operational basis is generally to be welcomed, there remains a need for intermittent investigative missions, especially for demanding variables such as cloud and aerosol properties. No simple rule exists as to when such missions might be justified, or when transition to routine operation should occur, as this depends on the extent to which data from earlier investigative missions have been exploited to improve models or data analyses, and the extent to which developments in observing technology make potentially useful new types of measurement possible.

The existence of a substantial gap in the provision of a certain type of observation is a particular issue when the use of such data is of demonstrated value for monitoring or prediction, either as input or as routinely used diagnostic data. The prime example is the forthcoming gap in limb-sounding of atmospheric temperature and composition that has been identified for several years by GCOS, the Ozone Research Managers of the Parties to the Vienna Convention for the Protection of the Ozone Layer, WCRP/SPARC and others as needing to be filled or minimised[3]. There is concern also over the continuity of provision of low-frequency MW observations for determining SST. These issues are discussed further in subsequent sections and Appendix 1. Gaps are more justifiable if they are related to new types of observation for which time may be needed to establish the value of the data provided or the robustness of the measurement technology. Examples are the measurements of ocean-surface salinity noted above and the wind measurements expected from ADM-Aeolus. In such cases mission planning needs to be agile so as to minimise gaps for types of observation that have been demonstrated to yield cost-effective benefits. The Architecture for Climate Monitoring from

[3] The 2012 CEOS Response to IP-10 stated: “Agencies need to create plans and allocate funding for additional limb sensors to fly from 2015 to 2025.” The 2015 Update of the CEOS Response notes that “Participants in the CEOS Atmospheric Chemistry Virtual Constellation meeting of 2014 recognize the significance of the looming gap in limb sounding data.”

Space, a joint planning effort by space-agency members of CEOS and CGMS, and by WMO, is expected to systematically address gaps in satellite mission plans and the coordinated generation of climate data records (Dowell *et al.*, 2013).

More generally, CEOS maintains an on-line "Mission, Instruments and Measurements" database (MIMD; database.eohandbook.com), which provides information gathered from its members on their current and future space-based systems, with the future missions categorized as approved, planned, or considered. Other sources of such information include the WMO OSCAR database (www.wmo-sat.info/oscar/satellites) and the Earth Observation Portal provided by ESA (eoportal.org/web/eoportal/satellite-missions). Consulting such databases provides a good overall picture of status, although cross-checking is needed on matters of detail, as these are prone to changes that take time to be registered in the databases. It reveals that the prime meteorological variables and some others are indeed well covered by the planning process, while others are in various degrees of poorer shape.

There are issues of continuity to be addressed even for the operational meteorological and Sentinel satellite systems discussed in sections 3.4.2 and 3.4.3. These include recognised needs to pay more attention now to factors important for climate such as calibration, instrument characterisation, orbital control (Figure 5) and stability, as embodied in the GCOS Climate Monitoring Principles (GCMPs; Appendix 7), than was the case for previous generations of weather satellites. There are also climate-related needs to address questions related to new launches or mission-lifetime extensions in the light of the varying degrees of health of the multiple instruments that are carried by many of these satellites. Change inevitably occurs from one generation of space-borne instrument to the next, but balances have to be struck between reproducing the capabilities of a preceding generation of instrument, so as most closely to preserve long climate records, and improving the capabilities of the new generation of instrument, so as to improve forecasting capability for example.

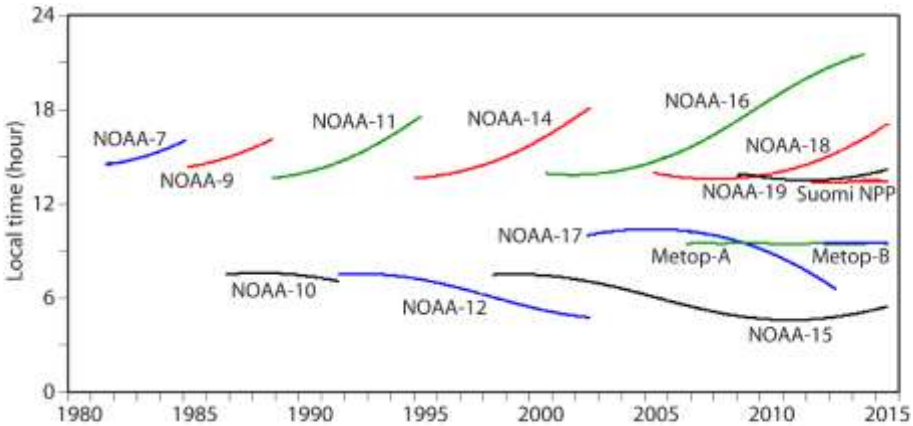


Figure 5: Equatorial crossing times of NOAA and EUMETSAT polar-orbiting meteorological satellites. Orbital drift is absent or very limited for the newer Metop and Suomi NPP systems. Source: NOAA/NESDIS, downloaded from http://www.star.nesdis.noaa.gov, dated 16 July 2015.

3.4.5 Data monitoring

Data from satellites may be affected by changes in the intrinsic performance of instruments, by orbital manoeuvres and drifts, or by occasional exposure to stray light. Users of near-real-time data may be able to take account of planned orbital manoeuvres or predicted stray-light exposure by temporarily suspending their use of data if likely effects cannot be handled well enough by their quality-control systems. In general, however, it is necessary to monitor satellite data on a routine basis to detect changes, in order for agencies to remedy them if possible and for users to decide whether to continue using the data, and if so whether changes are needed in the way data are used.

Space missions are invariably monitored over their operational lifetime by the space agencies responsible for them. The data that missions provide are also monitored by centres that use the data in near-real-time assimilation systems. This typically involves display of quantities such as the means and standard deviations of the differences between the satellite data and equivalent model background and analysis values. Changes over time thus require interpretation, as they can come either from changes in the data assimilation system or from changes in any incoming data, not only the type being monitored. Availability of statistics from different systems helps in the interpretation. A portal linking to the increasing amount of monitoring statistics provided online by a number of weather forecasting centres is provided at https://nwpsaf.eu/monitoring.html by the Satellite Application Facility for Numerical Weather Prediction (NWP SAF) led by the Met Office as an element of the wider EUMETSAT SAF Network. Aside from providing feedback to space-agency providers and information for better immediate use of the data, the near-real-time monitoring helps to identify needs and opportunities for reprocessing prior to future use of data in the generation of specific ECV products and in reanalysis. Reanalysis itself provides feedback on data quality, as discussed below in section 3.6.

Monitoring statistics for the data from a number of *in situ* networks are likewise generated by operational weather prediction and reanalysis systems. They similarly require careful interpretation. Changes in them can provide evidence of changes in assimilated satellite data, as illustrated for example by Simmons *et al*. (2014) in the case of the ERA-Interim reanalysis.

3.4.6 Fundamental forms of climate data records

It is common for climate purposes that data from a succession of instruments of a particular type have to be combined into data records that are used to build products on the ECVs and other variables as discussed further in sections 3.5 and 3.6. A US National Academy of Sciences Report (NRC, 2004) on climate data records defines Fundamental Climate Data Records (FCDRs) as “sensor data (e.g., calibrated radiances, brightness temperatures, radar backscatter) that have been improved and quality controlled over time, together with the ancillary data used to calibrate them.” The Report later makes clear that the FCDR is assumed to have been subject to inter-calibration as well as calibration of the records from individual sensors. It further states “The FCDRs will be the ultimate legacy that the long-term satellite programs leave to the next generation.” The Report also introduces the term “Sensor Data Record” (SDR), stating: “The SDRs are time tagged, geolocated, and calibrated antenna signals, but they will not be created for long-term stability and reliability, and they will therefore not be suitable for climate purposes without reprocessing into FCDRs.”

The term FCDR is used in a few places in IP-10, in other GCOS documents and more widely elsewhere. Its use is retained sparingly in this report, but it has become clear that the FCDR as defined above, even though it is the type of record required by many users, is not the most fundamental form of data record required by some users for climate purposes, and that data do not invariably need to be processed into FCDRs to enable them to be used for climate purposes. The fundamental record that provides the legacy and requires preserving includes the SDR for each of the individual instruments involved in the record. The record must also include as much information as possible to enable future recalibration of the SDRs based on improved knowledge of the instrument.

These considerations apply in particular when products are derived using a forward radiative transfer model to map geophysical variables, such as the background temperature and humidity fields of a reanalysis, into equivalents of a set of SDRs. In such cases, a number of parameters (or metadata) are required for each SDR that enable the radiative transfer model to be tailored to the individual instrument to which the SDR relates. Even for the individual instrument, drifts and shifts in its characteristics over its active in-orbit lifetime may best be catered for by employing a radiative transfer model that accounts for the instrumental changes that occur over that lifetime.

The scene dependence of the differences in measurement between different instruments of the same type means that inter-calibration of data records from a set of satellites in some cases cannot be optimally achieved for climate purposes without knowledge of the very geophysical variables to which the data records relate. Instruments to which this applies include the Stratospheric Sounding Unit (SSU), for which inter-satellite differences and in-orbit changes in modulating cell pressures significantly affect measurements (Kobayashi *et al.*, 2009; Nash and Saunders, 2015), microwave sounders, for which Lu and Bell (2014) present evidence of some significant shifts and drifts relative to nominal pass band centre frequencies, and the High Resolution Infrared Sounder (HIRS), for which the spectral response functions of the many instruments in operation since late 1978 differ appreciably from one to another, with significant errors in some of the functions specified from pre-launch measurement (Shi and Bates, 2011). Revised functions are now available (Saunders *et al.*, 2013). In each case the effect on measurements is lapse-rate dependent, as the vertical profiles of weighting functions change from their nominal forms.

Input from the space agencies and their partners in instrument supply is required to support such work. This is urgent for older instruments because individuals with unique knowledge of them are already retired or about to retire from employment. Recent documentation for the SSU by the Met Office and associated developments of the associated radiative transfer modelling (Nash and Saunders, 2015) provide an example of what can be done.

3.4.7 Inter-calibration of data records

Inter-calibration of SDRs and formation of FCDRs is nevertheless needed for generation of many climate products. This includes through reanalysis, which may use inter-calibrated records either directly for assimilation if forward modelling for a particular type of data has not been developed for individual instruments, or indirectly through assimilation of retrievals for some variables and instruments. Inter-calibration is not an exact, routine process; several different institution provide an FCDR for SSM/I, for example. It may be organised within an agency (see http://ncc.nesdis.noaa.gov/about.php, for example), but is an activity that benefits considerably from international collaboration. It is also an activity for which substantial progress has been made in recent years.

GSICS, the Global Satellite Inter-Calibration System (http://gsics.wmo.int/), is a collaborative international initiative of CGMS and WMO, started in 2005, to harmonize the quality of observations from operational meteorological and environmental satellites, for climate monitoring, weather forecasting and other applications. It is based on a comprehensive calibration strategy that involves monitoring instrument performance, operational inter-calibration of satellite instruments, tying the measurements to absolute references and standards where possible, and recalibration of archived data. As of October 2015, its product catalogue shows 37 entries of which 27 relate to calibration corrections for application to past data.

Calibration of data from space-based observation in general falls under the auspices of the CEOS Working Group on Calibration and Validation (WGCV; http://ceos.org/ourwork/workinggroups/wgcv). It includes a specific activity on quality assurance whose guidelines have been tailored by GSICS to meet its own particular needs. Among other WGCV activities is one on benchmark mission coordination, concerning proposed missions that would provide high-quality reference data that would be used to adjust the calibration of data from other satellites, in particular through comparing measurements where orbits overlap. This is an approach already adopted by GSICS using the most stable current instruments as references. Reference missions are discussed further in the review of IP-10 Action A19 on page 239. The CEOS WGCV also functions through several subgroups. In particular, the work of the Land Product Validation (LPV) Subgroup is referred to in several places in the discussions of specific terrestrial ECVs in chapter 6 and in the reviews of the IP-10 actions associated with them provided in Appendix 1.

3.4.8 Data archives

General discussion on data management and stewardship is given in section 3.9. Whilst for *in situ* observations the key requirement is for the data collected by many different agencies to be accumulated in international data centres relating to individual ECVs or groups of ECVs, satellite data from a particular mission usually cover a substantial geographical area, and data from a particular instrument often does not relate to an individual ECV, or even an ECV specific to the atmospheric, oceanic or terrestrial domain. Basic (so-called “Level-0” and “Level-1”) satellite data also tend to be voluminous, and reprocessing at these levels tends to be carried out by the space agency responsible for the mission, as detailed knowledge of the instruments resides there. The preservation of these data usually also falls to the space agency concerned, although other institutions have held or may continue to hold the responsibility for some older datasets. Use of NOAA VTPR radiance data from the 1970s in reanalysis was only possible because these data had been saved at the US National Center for Atmospheric Research (NCAR), for example. Some scope continues to exist for recovery and rehabilitation of data from early satellite missions, as indicated for temperature sounding data in section 4.5.1, although some potentially usable data may well have been lost, as in the example discussed in section 4.7.4. Recovery of historical *in situ* data is discussed in section 3.7.

Products derived from satellite data are for the most part generated by space agencies or partners with whom they collaborate, rather than by ECV-specific data centres. This is a practical arrangement for datasets that are updated in close to real time or which are subject to reprocessing from time to time, and discovery of such products is facilitated by data portal facilities discussed later, and by use of standard search engines. Examples of products are presented in many of the subsequent ECV-specific sections and the reviews of the related IP-10 actions. In addition, the German national aeronautics and space research centre (DLR) has the wider responsibility of operating the World Data Center for Remote Sensing of the Atmosphere (https://wdc.dlr.de/), under the auspices of both the ICSU World Data System and the WMO GAW (section 4.6).

3.5 Generation of data products

Many users of climate data require analysed products rather than the basic observations. Development and delivery of products for all ECVs is thus vital. Users also express requirements for information on the fitness of products for their purposes. This can be difficult to provide for products that have many and varied uses, when the producers' own resources and knowledge of the applications are limited. Use of the products nevertheless needs to be supported by provision of as much ancillary information as possible, including estimates of uncertainty where practical and the results of any validation carried out against independent data and of comparisons made either with earlier versions of the supplier's product or with independently generated products. Important also in this regard is the assessment of the maturity of products and production systems. Products may be derived by analysis of a single ECV, the focus of this section, or by analysis of a set of ECVs using data assimilation, usually through reanalysis as discussed additionally in the following section.

Data products for specific ECVs are generated either from *in situ* data, satellite data or a combination of the two. In the case of satellite data the product may be a "Level-2" retrieved geophysical variable co-located with the original measurement, for example for use in reanalysis, or a gridded "Level-3" set of values suitable for general use. They may be restricted to a single instrument, or generated by combining data from one or more other instruments, whether flown at the same time or sequentially. Products in general, but especially from *in situ* data, may be generated in the form of indices related to local, regional or global conditions rather than as gridded values. They may also be more freely available than the observations on which they are based. For example, the Global Precipitation Climatology Centre (GPCC) provides free access to monthly gridded precipitation datasets (section 4.3.5) based on analysis of rain-gauge measurements of which some are supplied to it on the condition that the measurements themselves are not released.

Global products may be based on different inputs over land and sea. The gridded "surface temperature" products such as GISTEMP, HadCRUT4 and NOAAGlobalTemp used to provide long-term measures of change in global-mean temperature combine the surface air temperature over land and the surface water temperature of the sea, as discussed further in section 4.3.1. Providers of such products may not make use of satellite data to improve areal coverage over sea if their primary aim is to provide a product that is as consistent as possible for identifying multi-decadal climate change, rather than a product that can more reliably identify shorter-term variations. The GPCP precipitation product (section 4.3.5) combines the GPCC dataset for rainfall over land with satellite-data products that primarily provide complementarity over sea.

Generation of data products also relies on a good underlying archive of the basic observations. For example, the HadISDH surface air humidity product (section 4.3.3) is based on a quality-controlled version of the Integrated Surface Database (ISD; Smith *et al.*, 2011) of NOAA's National Centers for Environmental Information (NCEI), which incorporate the former National Climatic Data Center (NCDC). The ISD provides a sound basis for a product from 1973 onwards, but inadequacies in its holdings of synoptic data prior to 1973 limit the time range of the HadISDH product, as discussed in the review of IP-10 Action A12 beginning on page 229. Another important example is that of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS; Woodruff *et al.*, 2011), which is a vital holding of marine surface data that feeds analyses of both SST and meteorological variables.

Development of data products based on *in situ* observations is generally done by individual institutions, although the global products may depend on separate developments of land and marine components. Collaborative arrangements for satellite products include partnerships between national space agencies and university groups and collaborations such as those between the European space agencies and consortia of national partners involved in the ESA Climate Change Initiative, the EUMETSAT Climate Monitoring SAF and the development of Copernicus services. Wider international collaboration occurs among the space-agencies and other institutions worldwide who cooperate within the SCOPE-CM (Sustained and Coordinated Processing of Environmental Satellite data for Climate Monitoring) network, under which a set of ten product-generation projects are currently being carried out. Taken as a whole, these activities have broadened and strengthened product generation since IP-10.

Many additional examples of ECV products are given in chapters 4, 5 and 6. Further discussion is given in Appendix 1, as IP-10 formulated three actions related to the generation of data products: C9 on achieving adoption of GCOS dataset and product guidelines, and comparison of products, C10 on preparing datasets for analysis and reanalysis, and C11 on establishing sustainable systems for the routine and regular analysis of the ECVs. Moderate to good progress has been made on these actions, as discussed in the reviews of them that begin on page 206.

3.6 Reanalysis

Users of climate data have requirements for the quality, scope, coverage and ease of access and use of products, and for information on the applicability and uncertainties of products. In some instances they may be interested in a particular ECV, but in others they may require consistent information on a set of ECVs. The requirements of a substantial body of users are being increasingly well met by products based on integration of data from a comprehensive mix of *in situ* networks and satellite subsystems, achieved through the process of reanalysis. In this context the term reanalysis is used to describe the use of a fixed data assimilation system to process observations that extend back in time over multiple decades, employing a model of the atmosphere, ocean or coupled climate system to spread information in space and time and between variables, and otherwise to fill gaps in the observational record.

Reanalysis provides a complete coverage in space and time within the constraints of the resolution of the assimilating model and the range of variables whose changes are represented in the model. Use of products from reanalysis to develop links between climatic conditions and socio-economic impacts is viewed as a key approach to develop the relationships needed to interpret the output of climate projection models for the purpose of assessing needs and options for adaptation. This brings with it requirements for higher resolution in space and time of reanalysis products, and associated downscaling approaches to provide local information.

Reanalysis provides datasets for many ECVs, but also makes use of ECV products for those variables that are prescribed in the assimilating model. In turn, reanalysis data provide some of the supplementary input needed to generate several of the ECV products that are based on retrieval of information from remote sensing.

Reanalysis has progressed considerably in recent years. Existing reanalyses have been prolonged, new reanalyses have been completed for atmosphere and ocean, and more refined land-surface products have been developed. Systems that couple atmosphere and ocean, or include much more comprehensive treatments of trace constituents, have begun to be used. Reanalyses have been extended further back in time, into the 19th century in the case of an atmospheric analysis assimilating only surface-pressure data. Provision of reliable information on uncertainties is being helped by the development of ensemble approaches, but remains a challenge. Further details of recent progress and plans are given in the review of IP-10 Action C12, beginning on page 209. This action called for a sustained capacity for global climate reanalysis and for coordination and collaboration to be ensured. There is also an increasing level of activity in regional reanalysis.

Issues of biases and other errors in observations, and limitations and changes in data coverage have to be addressed by producers of reanalyses as they have to by those generating single-ECV data products. The comprehensive reanalyses that assimilate multiple types of data are, however, more susceptible to these issues as the analysis they provide for a particular ECV may be influenced by a greater number of observing-system changes, notwithstanding the benefits that arise in principle from making use of as much observational data on a particular variable as possible, direct or indirect. Improvements over time have meant that newer reanalyses are less prone to such issues, and what is being learnt from the current generation of reanalyses is expected to lead to continuing improvement. This inevitably means that there will be differences between newer and older products from a particular supplier, and differences can also exist among contemporaneous products from suppliers whose assimilation systems are at different stages of development. Continued production of the original NCEP/NCAR reanalysis means that atmospheric reanalyses are now being produced and used from systems whose vintage differs by more than twenty years.

Although differences among several reanalyses do not imply that all provide unreliable results, they do make it necessary to amass evidence to identify the more reliable reanalyses and the degree of reliance that can be placed on them. Assessments that inter-compare the results of several reanalyses without taking such evidence into account may assign an unwarranted low degree of confidence to findings. Including reanalysis products in ECV-specific product assessments such as the GEWEX Radiative Flux Assessment is important, but needs to be carried out for the latest products (section 4.3.6). A comprehensive inter-comparison of reanalyses for the stratosphere is being undertaken by SPARC (Fujiwara and Jackson, 2013). Ten reanalyses of upper-ocean heat-content and other datasets were compared by Xue *et al.* (2012), who showed lower spread among the reanalyses after data from Argo floats became available in the early 2000s. Near-real-time extensions of six ocean reanalyses can be compared at http://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html.

The reanalyses.org website was set up following discussions in 2010 of the WCRP Observations and Assimilation Panel concerning the need to promote informed use of the increasing number of atmospheric reanalyses that were then beginning to become available. The website now provides a substantial amount of material about both atmospheric and oceanic reanalyses, including comparative studies. It also offers a forum for exchanges of experience and views between producers and users.

Joint assimilation of multiple types of observation in a reanalysis provides a basis for estimating biases in the data from particular instruments (section 4.5.1), providing an alternative or complement to the calibration activities of space agencies, such as undertaken for GSICS. Moreover, the closeness of fit of background forecasts and analyses to observations (including those processed passively for monitoring purposes, as well as those assimilated) is an important source of information on other types of observational error, and on the quality of the assimilating model and of the reanalyses themselves. Such feedback data have been saved by producing centres, and have been used to assist radiosonde bias adjustment as discussed in the review of IP-10 Action A18 that starts on page 237. Access to feedback data has in general not been straightforward, however. This is beginning to change, and atmospheric reanalysis centres have discussed increased coordination to enable their products to be compared and diagnosed using feedback data (http://www.coreclimax.eu/?q=Feedback). Contact with users has also been initiated on the topic (Gregow *et al*., 2015). ECMWF has made available feedback from its ERA-20C reanalysis (http://apps.ecmwf.int/datasets/data/era20c-ofa), which assimilated or passively monitored substantial amounts of data from ICOADS. ECMWF is now working with the ICOADS team to enable the information to be included alongside the individual observations in ICOADS.

3.7 Recovery of instrumental data

Generation of data products based on *in situ* instrumental data, whether by direct analysis for individual ECVs or through reanalysis, would be limited to the past forty to fifty years had observational data originally stored on paper or obsolete media not been converted to a modern digital format. This includes the monthly datasets that enabled the IPCC AR5 to discuss aspects of changes in temperature since 1850 or 1880 over land and sea, and changes in precipitation over land since the beginning of the 20th century. These datasets nevertheless exhibit sparse spatial coverage of much the globe in their earlier years, as discussed further in sections 4.3.1 and 4.3.5. Although monthly station averages have often been digitized, daily or sub-daily station and marine data also need to be recovered, as they are important for several purposes, including better understanding of processes, capturing extremes, use in SST analysis and reanalysis, and development of climate services. It is important that as much as practically possible of the considerable amount of early instrumental data on temperature, precipitation and other variables be recovered from paper or other native storage formats. The term data rescue is often used for this activity, as deterioration of the original records may soon cause some data to be lost forever. Here scanning of paper records is the immediate priority, though digitization has to follow in due course if the data are to serve a purpose beyond satisfying occasional historical curiosity.

Data rescue remains resource-limited and fractured in nature, however. Some good efforts are being made nationally and through coordinated European and wider international activities such as the ACRE initiative (Allan et al., 2011), yielding worthwhile enhancements of the databases that underlie the generation of data products. Examples are given in later sections. Large-scale recovery in a coordinated, cost-effective manner nevertheless remains a challenge. Many more data are stored only in their original hard copy than are imaged and stored electronically, and in turn many more data have been imaged than have subsequently been digitised. Although some NMHSs have carried out or are continuing to carry out significant digitization of their data records, and other records have at least been scanned, this is not the case in many NMHSs. Relevant records are in any case often held by other national agencies. IP-10 noted that where resources cannot be found to undertake digitization, scanned copies of the original records should be lodged with international data centres as a precaution against later accidental damage or physical deterioration. This would also facilitate assembly of classes of scanned record suitable for digitization by crowdsourcing, which has proved successful in the case of data from marine voyages (http://www.oldweather.org).

Assessing the quality of the digitised data is an important further aspect of data recovery whose importance is rarely fully realized. It is essential not only to determine that the digitising is a faithful replication of what was measured, but also to assess the long-term homogeneity of the data on an ECV-by-ECV basis. IP-10 identified the need to collect metadata on how observations were made as well as the observations themselves. This can aid in the homogenization of data and in setting parameters for their use in reanalysis. As noted in the preceding section, assimilation of rescued data in a reanalysis is one way in which errors may be detected and biases estimated. This has been demonstrated by the 20th century reanalyses as well as by the more comprehensive atmospheric reanalyses carried out for more-recent decades.

The status of data-rescue activities was summarised by Brunet and Jones (2011), although it is hardly possible to be aware of all ongoing activities around the world. Limited resources often result in only a minimal number of series and/or variables being digitised from a collection of records. The situation can be made worse when projects do not share the digitised series, as this can result in the same data being digitised more than once. Consideration is however beginning to be given to the establishment of a centralised register of projects that would contain details of what is expected to be achieved by each of them. The initial difficulty in setting this up is knowing what has been digitised and whether it is made, or might be made, openly available. For example, much data for the Indian sub-continent up to 1947 was published in printed books that are widely available and have been scanned (as can be seen for example at http://badc.nerc.ac.uk/browse/badc/corral/images/metobs), and at least some of these data appear to have been digitised and used to produce an available gridded daily record of precipitation (Rajeveen *et al*., 2006). It is understood, however, that the digitised station data are not openly available.

The International Surface Temperature Initiative (ISTI; http://www.surfacetemperatures.org/; section 4.3.1) and the International Surface Pressure Databank (ISPD; http://rda.ucar.edu/datasets/ds132.0/; section 4.3.4) are important efforts to build collections of data, but are ECV specific. Separating variables has some advantages as it enables data digitising to have specific deliverables for a funding agency, but keeping all surface synoptic variables measured at a station together for each time step is potentially much more useful in the long run. The case is under consideration for constructing such a dataset, which could be modelled on what ICOADS does for marine surface data, as noted also in the review of IP-10 Action T15. This would address several issues identified for surface atmospheric and terrestrial data in subsequent ECV-specific sections.

Data rescue remains a high priority of the WMO Commission for Climatology (CCl) as well as the GCOS programme. The Commission has plans for better coordination of the rescue and preservation of historical data through its Expert Team on Data Rescue, established for the period 2014-2018. The Team's tasks include arranging the implementation, population and maintenance of an International Data Rescue web portal, operated by the Royal Netherlands Meteorological Institute (KNMI) under the auspices of the GFCS, to summarize key information and provide an analysis of gaps in international data rescue activities. The CCl identifies the inability of some NMHSs to effectively manage and secure their data to be a key risk, and places emphasis on a strategy for widespread national implementation of climate database management systems. The unwillingness of some nations to share historical observational data remains a concern of CCl.

The above discussion provides the review of IP-10 Action C13, which called for the collection, digitization and analysis of historical data records. A second action on this topic, C14, concerning the improvement of holdings in international data centres is discussed a little further on page 211.

3.8 Proxy reconstructions of past climates

The instrumental record for a region of the world will always be limited by the date when the first thermometric or rain-gauge measurement was taken there. Information for earlier times is provided by or potentially available from proxy records for many regions. They include many natural proxies such as trees, corals and ice cores, stretching back to tens of millions of years ago in the case of estimates of CO_2 concentration based on geological evidence. They also include written histories in annals, chronicles, diaries and so on for the more recent past. Proxy evidence is held in a number of archives, in particular at the World Data Center for Paleoclimatology operated by NCEI, which includes the results of reconstructions and modelling (Figure 6). Completeness of reporting is important; archived records do not always hold all the intermediate stages involved in producing the results submitted to data centres.

The activities of the GCOS programme are concerned almost entirely with instrumental observations and the data records associated with them. IP-10 nevertheless recognised that improving the coverage and availability of palaeoclimatological data was important for facilitating analyses that document changes in climate through time, and place the instrumental data record for several ECVs in a longer-term context. The proxy data that relate most closely to the wider thrust of IP-10 are those providing relatively high-frequency evidence on seasonal-to-interannual time scales for the last 2000 years, what has been referred to as the late Holocene. The most recent and spatially-extensive compilation of evidence on a continental basis was published by the PAGES 2K Consortium (2013). The importance of proxy sources inevitably varies from ECV to ECV, being significant for some such as carbon dioxide, surface temperature and precipitation, but provided only through modelling for many others.

Figure 6: Classes of dataset held at the World Data Center for Paleoclimatology. Source: NOAA/NCEI, image from https://www.ncdc.noaa.gov/data-access/paleoclimatology-data.

Three actions were formulated on this topic in IP-10: C15 on research initiatives to acquire high-resolution proxy climate data, C16 on the synthesis of proxy climate and environmental data, and C17 on the preservation of proxy climate and environmental data in archival databases. Their review, which begins on page 211, is based largely on the conclusions of the IPCC AR5 chapter on palaeoclimatological studies (Masson-Delmotte *et al.*, 2013) and on information from the World Data Center website. AR5 records some major progress since AR4, but notes that proxy-based temperature estimates remain scarce for key regions such as Africa, India and parts of the Americas, and that the available syntheses of past precipitation changes are too limited to support regional assessments.

3.9 Data management

The management of data and their associated metadata is an essential component of the global observing system for climate. Fundamental roles are played by international data centres that hold basic archives of *in situ* data, the space agencies and their partners that hold the raw data and products from missions past and present, and the national centres that bear a particular responsibility for the stewardship of data that have yet to be released to the international centres. Real-time monitoring centres, delayed-mode analysis centres and reanalysis centres also play important roles. Important also are information services that aid the discovery and use of archived data. In this regard the Global Observing Systems Information Center (GOSIC; http://www.gosic.org/) provides links to substantial amounts of data and information related to the global observing system for climate and the GCOS programme. It also serves as an entry point to the WMO Information System (WIS) as well as to the GEO Data Portal.

IP-10 noted that data management had for some time been a principal element in some observational programmes, singling out the attention paid to it by the WMO World Weather Watch and WMO CCl, whose continuing advocacy of national climate database management systems has been noted already in section 3.7 and which has established an inter-programme expert team on climate data modernization. Efforts in general needed to be strengthened and extended across the full spectrum of systems contributing to the composite global observing system for climate. Improved data management was highlighted as a priority of the plan. IP-10 identified five main requirements:

- Prompt and regular flow of data to the user community and the international data centres that needed to be in place for each ECV or groups of related ECVs. This was seen to be inadequate for a number of variables and networks, especially in the terrestrial domain. A common and related concern was inadequate support to national data centres, given their key role in assembling records and undertaking quality control.
- Effective access to very large datasets. This was becoming difficult for large satellite and model-based datasets despite advances in technology, especially in developing countries with inadequate information technology infrastructure or technical skills in using complex data. This required the development of derived products or product subsets, and appropriate access mechanisms.
- Facilities and infrastructure to ensure the long-term preservation of data for future use. Once data were in electronic format, they had to be migrated at intervals to newer storage devices, and access software and data formats had to be kept consistent. Consideration had to be given to data stewardship requirements when observing systems were being

planned. Nations responsible for data centres and space agencies needed to support the use of modern information and communication technology as a matter of high priority.

- Monitoring of data streams. This included timely quality control of the observations by the monitoring centres and notification to observing-system operators and managers of both random and systematic errors, so that corrective action could be taken. This would prevent such errors from accumulating in climate records and obviate the need later to make possibly quite uncertain adjustments to, or even deletions of, data from the records.
- Availability of metadata as well as data. International standards and procedures for the storage and exchange of metadata needed to be extended to all variables and implemented for many climate-observing systems. Guidelines needed continuing development to ensure adequate scientific data stewardship.

IP-10 formulated Action C18 on applying standards and procedures for metadata and its storage and exchange, Action C19 on supporting data flow from national to international data centres, Action C20 on ensuring that data policies facilitated the exchange and archiving of all ECV data, and Action C21 on implementing modern distributed data services, with emphasis on building capacity in developing countries and countries with economies in transition. The generally moderate progress made on these particular actions is reviewed beginning on page 213. Data-centre arrangements and related issues are included in the discussions of the status of individual ECVs or of networks linked to groups of ECVs that are given in chapters 4, 5 and 6. Progress has undoubtedly been made, though many of the requirements and issues cited in IP-10 remain to some extent or other.

A report by the Swiss GCOS Office (2015) on the availability of Swiss data submitted to international centres for the atmospheric and terrestrial domains provides both a national view and some more general comment on the complexities, limitations and disparities between the domains and among the ECVs in the arrangements for data centres and the way the centres operate. A recurrent theme of the report's ECV-by-ECV analysis of data centres is an almost complete absence of evident user statistics, which were found for only three of the many data centres that were scrutinised.

3.10 Climate impacts

Aside from the direct ways in which humans bring about environmental change, anthropogenic climate change is likely increasingly to modify environments on large scales, to influence ecosystems, including the range of species, and to have a strong, long-term impact on socio-economic systems and habitats. The challenges of environmental monitoring and responding to changes vary greatly from region to region. Identifying such changes and attributing them to a cause, such as a changing climate, and assessing risks, for example for ecosystems or within urban regions, requires long time series of observations and homogeneous, consistent practices for measuring the systems and variables under consideration. It may require high spatial resolution or collocated time series of climate observations and other environmental parameters, such as nearby changes in land use. Ecological monitoring sites are often located some distance away from sites where meteorological observations are made, and interpolation of information will not always be reliable. IP-10 accordingly identified a growing need for "Essential Ecosystem Records" based on collocated observations of biodiversity and habitat properties, and of physical climate parameters. It formulated Action T4 calling for establishment of a monitoring network for accumulating such records. The very limited progress made on this is reviewed in Appendix 1, on page 283.

IP-10 also identified the need for additional guidance material to help ensure the quality and consistency of observational studies in support of assessments of the impacts of climate variability and change. It noted that much of the information on ecosystems and habitats was limited to phenological data, bringing a need to measure or gather statistics on “impact variables" such as related to health, agricultural yields and habitat properties. Limited availability of studies for many parts of the world meant that there was a need to encourage more long-term impact studies and to ensure that these studies included measurements of basic geophysical climate variables and data on other, mostly socio-economic, factors. Actions C22 and C23 were formulated on these topics; the meagre progress made on them is reviewed starting on page 216.

4 Atmospheric observation

4.1 Introduction

The mean and statistical properties of the near-surface atmosphere define what is commonly termed “climate”, in the narrow sense of the word. The atmosphere’s radiative properties largely govern global temperatures, and its transport properties in conjunction with interactions with the land surface and ocean determine regional climatic conditions. Growth and decay of weather systems and the changes in state of water between vapour, cloud, snow and rain play key roles. Heat, moisture and chemical species are moved around rapidly by winds. Cloud and water vapour feedbacks are major factors in determining the sensitivity of the climate system to forcing factors such as rising levels of greenhouse gases and changes in aerosol distributions. Natural modes of variability of the system on timescales out to a decade and longer involve changes in atmospheric circulation and storm tracks, and in associated patterns of temperature and precipitation. These modes are confounding factors in the identification of anthropogenic climate change.

The status of atmospheric observation presented here follows the usual approach of considering separately the variables that describe surface and upper-air meteorological conditions, and atmospheric composition. Satellite observations have become a fundamental source of information, direct or indirect, on virtually all atmospheric climate variables, but do not extend sufficiently far back in time to give a full historical perspective, and still need to be complemented by *in situ* measurements, especially at lower levels over land. The *in situ* atmospheric observing systems are largely based on the WWW/GOS networks for surface and upper-air observations, and the GAW networks for atmospheric composition, discussed separately in sections 4.2, 4.4 and 4.6 below. Marine networks (section 5.2) also routinely provide substantial amounts of surface air data, and a small amount of upper-air data from ship-based radiosonde ascents. The soundings from fixed Atlantic and Pacific weather ships are an important part of the historical record, predominantly for the pre-satellite period although the last such ship ceased service as recently as the end of 2009. The main elements of satellite observation have already been discussed in general in section 3.4; specific aspects are covered later on a variable-by-variable basis. Many of the contributing networks and systems other than those for atmospheric composition were put in place primarily for weather forecasting, but their importance for climate purposes has become increasingly appreciated, and their operation has been improved accordingly.

4.2 Meteorological surface networks

Meteorological observations at the Earth's surface are vitally important, especially over land, as they characterise the climate of the layer of the atmosphere in which people live, and where many impacts of climate change are likely increasingly to be felt and require action to adapt to them. Climate analysis has traditionally placed emphasis on surface temperature, precipitation and pressure data. Temperature and precipitation have the greatest impact on natural systems and human activities, with pressure providing a perspective on the meteorological systems in which weather is embedded, including their long-term variations. Data on wind speed and direction, water vapour and solar radiation are also important, in part for determining the fluxes between the atmosphere and the underlying land and sea. They have become increasingly important also as emphasis has shifted to the impacts of climate variability and trends. There are also specific needs for such data related to mitigation of climate change, in particular as they support the design and operation of renewable energy systems, including wind and solar farms, and hydroelectric systems.

Lengthy data records are important for characterising low-frequency variations and trends, and for sampling extremes. It is shown later that there are several regions where numerous observing stations provide data covering more than a hundred years in both temperature (Figure 13) and precipitation (Figure 18) databases. Changes over time in station surroundings may need to be taken into account in the analysis of such data records. The Seventeenth World Meteorological Congress in 2015 agreed with a recommendation by the WMO Commission for Instruments and Methods of Observation (CIMO) that support be given for an initiative to identify well-sited long-term observing stations, and to recognise and sustain them as centennial stations.

There is also an increasing requirement for frequent local surface atmospheric data, especially to characterise extremes and more generally to meet needs relating to impacts, vulnerabilities and adaptive responses. The Working Group II contribution to IPCC AR5 notes that standard reporting of climate data for temperature and precipitation by month, season and year obscures changes that shape decision-making (Olsson *et al.*, 2014). Specific applications may require data for specific times of day and periods of the year. The required spatial resolution of observation may also vary considerably. A special case of local measurement is that of the urban environment where an increasing proportion of the world's population resides and where specific impacts and issues of adaptation arise. Although the atmospheric variables on which data are required locally are generally drawn from the basic ECV set, there are needs in places for information on some other weather or air-quality variables, on the frequency and intensity of fog, for example. Observation of some of the weather elements concerned is at risk from increasing use of automation, notwithstanding the other benefits that automation can bring. There may be accompanying local requirements for land-surface or coastal data, some of which may be measured routinely at synoptic stations but not exchanged globally in the way that standard weather data are. Soil moisture is a notable example. Related socioeconomic data may also be required.

IP-10 identified a number of actions to improve the general availability of surface atmospheric observations. The progress made on these actions and the overall status of observation of the surface atmospheric ECVs are assessed here from a global perspective, paying attention to regional variations. The situation regarding local observations is more difficult to assess, as aside from the volume and variety of requirements and limited international data exchange, some needs may be met on a commercial basis and weather stations may be installed as part of a development project where the supporting agency does not consult with the national meteorological service. GCOS (2012a) and GCOS (2013) provide further information and discussion. Assessing the needs for and status of local observation is more a matter for national responsibility, although local trans-boundary issues may require bilateral or regional collaboration. Moreover, the capacities of nations to make the local observations and deliver the required services vary considerably, as highlighted by the report of the high-level taskforce for the GFCS (WMO, 2011; see also the review of IP-10 Action A3 on page 221).

4.2.1 Comprehensive surface networks

The principal sources of surface atmospheric observations over land are the Regional Basic Synoptic Networks (RBSN) and the overlapping Regional Basic Climatological Networks (RBCN) of the WWW/GOS (http://www.wmo.int/pages/prog/www). The locations of stations in these networks and other contributing national networks that transmitted data in near-real time that were received by ECMWF and used in its ERA-Interim reanalysis (Dee *et al*., 2011) are shown in red for the months of October 2002 and October 2014 in Figure 7, for data reported in WMO SYNOP codes. Also shown for October 2014 is the complementary geographical coverage provided by surface data reported in ICAO METAR (aerodrome report) code. Each data message typically includes observations of a number of variables: the SYNOP code allows for information on all surface atmospheric ECVs and observations from the surface of cloud properties, while the METAR code also covers multiple variables (WMO, 2014a). The specific illustrations given in Figure 7 (and Figure 8) are based on the air-temperature element of the two types of report.

Several of the variations in geographical coverage shown in Figure 7 will be seen also in other illustrations in this report. The density of coverage depends on factors such as population distribution, economic activity, conflicts, terrain and scientific need. There are also issues related to data transmission, which is discussed further in the review of IP-10 Action A7 on page 224 for the precipitation element of the report.

Density of coverage increased from 2002 to 2014 for many but not all parts of the world. Overall, the number of SYNOP data received by ECMWF in October 2014 was about 80% higher than the number received in October 2002, counting only one report per hour in the case of stations that report sub-hourly. The increase came both from an increased number of reporting stations and from an increased frequency of reporting: around 30% more SYNOP observation locations are plotted in Figure 7 for 2014 than for 2002. Around 40% of the locations plotted for 2014 did not provide SYNOP data in 2002, but 10% of the locations that provided SYNOP data in 2002 did not do so in 2014. The figure of 10% drops to 8% if METAR data provision for 2014 is taken into account.

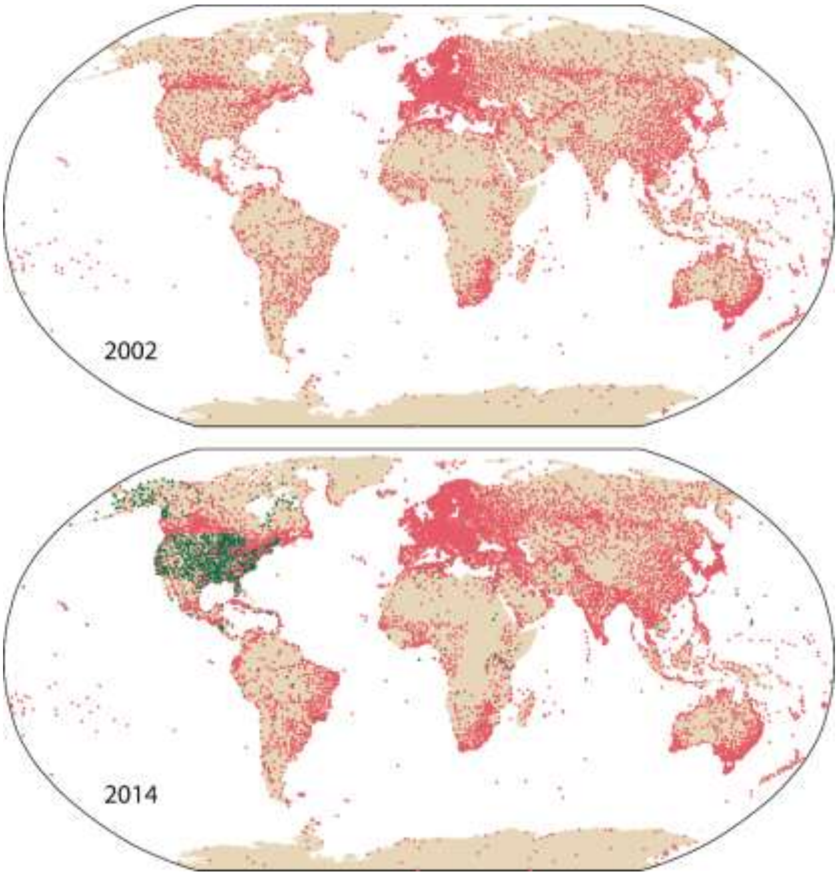


Figure 7: Distribution of surface synoptic data as received operationally by ECMWF and assimilated in ERA-Interim for October 2002 (upper map) and October 2014 (lower map), for data transmitted in WMO SYNOP (red) and METAR (green) codes. SYNOP locations mask nearby or coincident METAR locations. Plots are based on stations reporting dry-bulb temperature, and a symbol is plotted for each 0.5 degree latitude/longitude grid box that contains at least one observation per day on average for the month. METAR data were not assimilated in ERA-Interim for 2002.

Figure 8 shows samples of observation counts for each hour of the day. They are presented both for the data used for ERA-Interim displayed geographically in Figure 7 and for the data collected from many sources that are held in NCEI's ISD. NCEI is a World Data Centre for Meteorology under ICSU's World Data System and a WMO CBS Lead Centre for several GCOS functions. Both datasets show a predominant three-hourly peak in observation numbers, with slightly more data at 12UTC than at any other time. A six-hourly component is more prominent in ECMWF's near-real-time receipt than in the ISD. The ISD holds rather more data, and some future increase would be expected as NCEI accumulates additional data that were not transmitted in close to real time. The difference is little more than 10% at the synoptic hours (00, 03, 06, 09 ... 21UTC) in the example shown, but larger in percentage terms at the intermediate hours (01, 02, 04, 05, 07, 08 … 22, 23UTC). For these hours, ISD shows a larger percentage increase from 2002 to 2014, and METAR data provide a larger supplement to SYNOP data in the case of ECMWF's recent data receipt. There are also considerable national and regional variations in the locations from which hourly data are received in near-real time by ECMWF. Illustration is provided in the review of IP-10 Action A2 given on page 219.

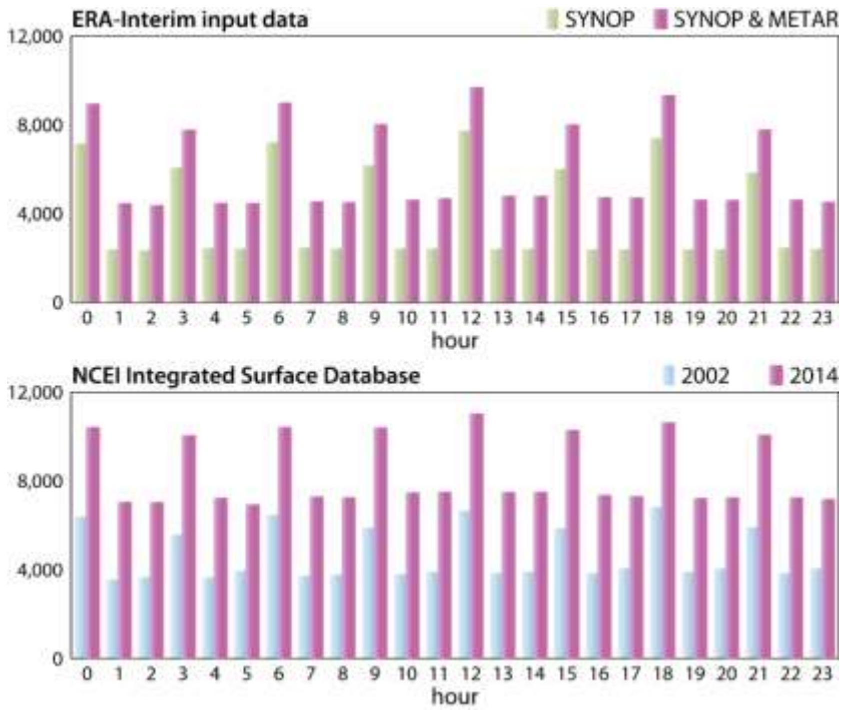


Figure 8: Average counts of surface air temperature observations over land for each hour of the day for October 2014 from ECMWF's operational receipt of data, as processed in ERA-Interim following basic quality-control checks (upper), and for October 2002 and 2014 from the NOAA NCEI Integrated Surface Database after duplicate removal and elimination of sub-hourly data (lower). ERA-Interim counts are shown for SYNOP reports alone, and as supplemented by METAR reports. NCEI data were downloaded from the ISD-Lite data stream on 22 January 2015.

Figure 9 complements Figure 7 by showing in the left-hand panels the geographical distributions of all observations from the network of voluntary observing ships. Some aspects of this network are discussed further in section 5.2.6. Also included in Figure 9 are a small number of locations from which moored buoys and other fixed platforms report in WMO SHIP code. Most are in coastal regions or inland waterways. The observed variable in this case is surface pressure. Coverage is shown for the same sample months of October 2002 and October 2014 as in Figure 7, but January 2015 is also shown because of seasonal variations in ship traffic at high latitudes. There is a more widespread distribution of ships reporting surface atmospheric observations from the Arctic in October 2014 than October 2002; ice conditions in January inhibit such traffic, but traffic to and along the coast of Antarctica can be seen to be established by this month. The ship tracks across the North Atlantic are more concentrated on southern routes in January. Increases in net observational density from 2002 to 2014 are considerable around coasts and for the Atlantic Ocean, but not for the Pacific Ocean.

The larger number of observations in 2014 than 2002 seen in the left-hand panels of Figure 9 comes mainly from more frequent reporting, aided by greater automation, rather than from increases in the number of ships and other reporting platforms: the net count of the data for October 2014 is more than twice that for October 2002, but the increase is reduced to 23% when the count is restricted to observations for 12UTC, for which the corresponding geographical distributions are shown in the right-hand panels of Figure 9. Observations from ships over the interiors of the ocean basins in fact decline at 12UTC from 2002 to 2014; the increase comes from a larger number of reports from coastal regions and inland waterways.

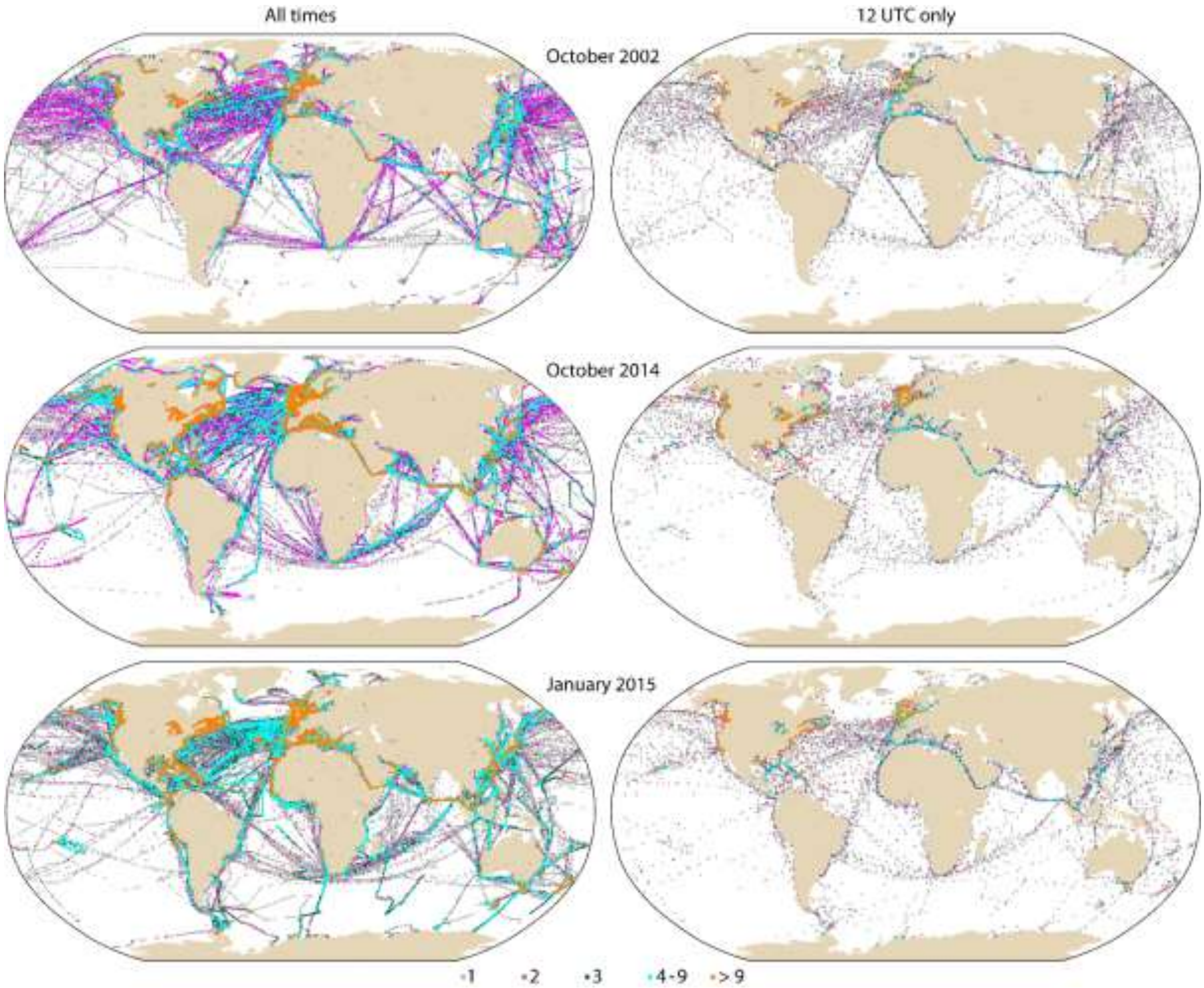


Figure 9: Distribution of surface pressure observations reported in SHIP codes received operationally by ECMWF for October 2002 (top), October 2014 (middle) and January 2015 (bottom). Values are plotted for all observations (left) and for the subset made at 12UTC (right). A symbol is plotted for each 0.5 degree latitude/longitude grid box that contains at least one observation per month. Colour indicates the number of observations per grid box.

Figure 9 also shows a small number of observations over the continents where there are not evident waterways. This could be due to an observation made over land but reported in a ship code, but could be due instead to a misreported ship position. There were generally fewer such instances in 2014 than 2002, and many more (quite evidently associated with misreported positions) in preceding decades. Reduction of such errors is a likely further benefit of increased automation.

Figure 10 illustrates the decline in the number of ship observations over mid-ocean regions since the mid-1980s. Numbers are shown for all marine air temperature observations at the main synoptic hours, as monitored by ERA-Interim, which relied on data received on the GTS for the latter part of the period, and as monitored for ships by ECMWF's more recent reanalysis, ERA-20C, which used ICOADS release 2.5.1 as its source of ship data. Data counts from the two sources are clearly similar. The small differences in the first half of the period show the effect of data recovery, as ICOADS release 2.5.1 provides data additional to the ERA-40 holdings used by ERA-Interim. ERA-40 included data from a release of ICOADS available a little more than ten years earlier. Woodruff *et al.* (2011) report larger increases in observation numbers from data recovery for years before 1980. ICOADS also provides data additional to ERA-Interim's GTS holdings in the second half of the period shown in

Figure 10, by an amount that decreases over time. ERA-20C ran only to the end of 2010, but ERA-Interim shows that the decline in the number of observations over the interiors of the ocean basins continues to the present day when data from only the main synoptic hours are taken into consideration. More-frequent reporting, albeit from fewer platforms, has increased the total number of mid-ocean observations received from ships and moored buoys from a minimum that occurred in 2002.

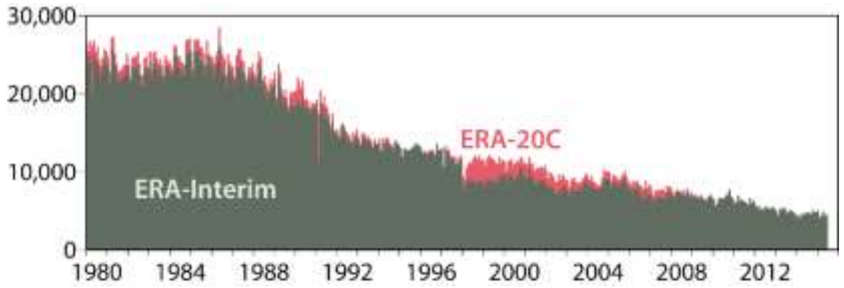


Figure 10: Monthly numbers of air temperature observations from January 1980 to June 2015, based on reports in SHIP code from January 1980 to June 2015 as monitored by ERA-Interim (dark green) and on ship data from ICOADS release 2.5.1 as monitored by ERA-20C (pink), summed over regions of the Atlantic, Pacific and Indian Oceans that are not close to continental coasts. Only observations made at the main synoptic hours of 00, 06, 12 and 18 UTC are included. The regions sampled are (10N-55N; 45W-20W), (0-60S; 30W-0), (5N-60S; 55E-90E), (20N-50N; 140E-170W) and (20S-60S; 180-90W). Inclusion of moored-buoy data reported in SHIP code is minimised by not sampling the tropical Pacific Ocean and counting only observations from the main synoptic hours.

Plots for the total number of used surface-pressure observations are presented in Figure 16 in section 4.3.4. The number of observations of surface pressure reported in SHIP code is generally similar to the corresponding number of air temperature observations for any one month. The number of wind observations is also similar. Observations of dew-point temperature are fewer in number, by 30% or so early in the early 1980s and around 20% in recent years.

4.2.2 Baseline and reference networks

The GCOS Surface Network (GSN) is a baseline network comprising a subset of around 1000 stations chosen mainly to give a fairly uniform spatial coverage from places where there is a good length and quality of data record. A particular product of these stations, additional to their synoptic data, is a monthly CLIMAT message that in principle can include monthly averages, extremes and threshold exceedances for temperature, precipitation and sunshine duration (WMO, 2014a). Transmission, completeness and quality of CLIMAT data are monitored, and coding corrections made where possible, by DWD and the Japan Meteorological Agency (JMA) in their capacities as GSN Monitoring Centres. Production of monthly CLIMAT messages is also expected of the close to 3000 stations that comprise the RBCN; increasing the number of RBCN stations that actually supply such messages has been one subject of recent attention. Another recent initiative has been to develop a message template for reporting daily values within the monthly message; steps are now being taken towards implementation of this additional reporting.

Figure 11 maps almost all the GSN stations and shows their frequency of reporting CLIMATs in 2013. It is based on the data holdings of the designated archive centre, NCEI. Around 70% of stations reported every month in 2013, and some 10% missed only one month. A little under 10% of stations did not report CLIMATs at all, even though many of them send SYNOP messages. The majority of the stations that report in neither format are in Africa. These numbers in fact represent considerable progress since the GCOS programme prepared its Second Report on Adequacy: in 2002 only around 45% of this set of stations (not all of which were then designated as part of the GSN) supplied CLIMAT messages every month, and around 35% provided none. The annual monitoring documents produced since 1999 jointly by DWD and JMA can be accessed either directly from www.dwd.de or via the GOSIC. They record a general increase over time in reporting, with the overall number of messages rising to a completeness of around 90% or better for all regions other than the South-West Pacific (80-85%) and Africa (50-60%). Little if any improvement has been seen in the past few years, however. This is in line with an analysis of NCEI archive statistics presented on page 218 in the review of IP-10 Action A1, which called for improved availability of GSN data. The review of IP-10 Action A2 discusses the provision of CLIMAT messages from non-GSN stations.

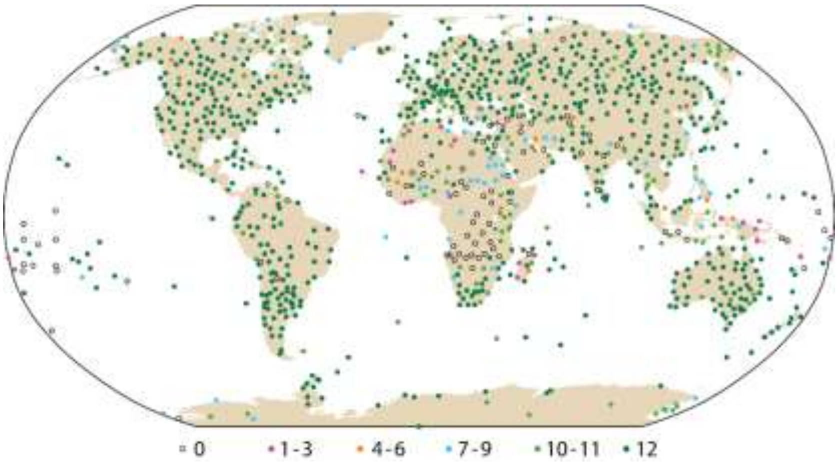


Figure 11: Number of monthly CLIMAT messages for 2013 from each of 1013 (out of 1018) GCOS Surface Network stations for which statistics are reported by NOAA/NCEI, as accessed via http://www.gosic.org/.

A corresponding global surface reference network has not been defined. Reference observation has been established in the USA through implementing a new set of observing sites instrumented to a high standard. The number of sites is now well over one hundred. This US Climate Reference Network began operation in January 2004, and a status report and assessment has been provided (Diamond *et al*., 2013). The case for and practicality of establishing a global network of such sites is being kept under review by the GCOS programme.

4.2.3 Data archives

Several types of dataset provide general holdings of surface atmospheric observations. NCEI's sub-daily ISD has already been mentioned; HadISD provides a subset of ISD for the period from 1973 onwards for stations chosen on the basis of the length of record and reporting frequency, with data additionally subject to a set of quality-control checks (Dunn *et al*., 2012). It is important in such sub-daily datasets that information on all variables be kept together, not only to aid interpretation but also to facilitate conversion between the different variables used for humidity (section 4.3.3).

NCEI also provides a daily Global Historical Climatology Network dataset (GHCN-daily) comprising variables such as maximum and minimum temperature, total daily precipitation, snowfall and snow depth (Menne *et al*., 2012). By April 2014 it comprised more than 2.3 billion daily observations from across the world, with the earliest observation for January 1, 1763. Precipitation data were held for some 92,500 stations, temperature data for some 30,000 stations, and snowfall or snowdepth also for around 30,000 stations. Corresponding GHCN-monthly datasets are provided separately for temperature and precipitation. World Weather Records, available via the GOSIC, include monthly averages of pressure, temperature and precipitation provided by NMHSs, which submit their records under the auspices of WMO. Records have been published decadally by NCEI; those for 2001 to 2010 are still being assembled. Updating will then be moved to an annual basis.

Some regional datasets are available, notably that for daily data provided by the KNMI-led European Climate Assessment and Dataset project (ECA&D; http://www.ecad.eu) from NMHS source archives, which also provides gridded products. Systems that build on ECA&D software are in various stages of establishment for Southeast Asia, Latin America and West Africa (http://www.ecad.eu/icad.php). Many nations also make data and products from their climatological stations directly available. Comparability of such data requires improvement and implementation of guidelines on producing climate datasets with regard to such matters as the definition of the climatological day or how many missing values are acceptable in computing monthly, annual or long-term averages. Such matters fall within the scope of WMO CCl's activity on climate data modernization.

The ISD's holdings of sub-daily data were shown by Smith *et al*. (2011) to be much lower for the years from 1963 to 1972 than for later or immediately earlier years. Much more comprehensive holdings for this period have been accumulated for reanalysis, largely from datasets held at NCAR. Uppala *et al*. (2005; see also review of Action A12 on page 229) quantify this in the case of the input data for ERA-40, which built on earlier developments for the original NCEP/NCAR reanalysis, and were supplied by ECMWF for use in the recent JRA-55 reanalysis (Kobayashi *et al*., 2015). Moreover, the sub-daily data (upper-air as well as surface) used in global or regional reanalyses are beginning to be made openly available by producers of the reanalyses where data policies permit. In the particular case of ECMWF this will be continued through its operation of the Copernicus Climate Change Service. These data may be less complete than are held in source archives, due to decisions on what data to process in each reanalysis, but the datasets carry the advantage of including quality control and other feedback information, specifically background-forecast and analysis departures, accumulated during production.

Reanalysis feedback is just one type of metadata relating to observations that can be helpful in assessing and applying them. Information is needed on the instrumentation used and environment in which the site is located, in particular when changes occur. Initiatives in this regard include the development of a siting classification by CIMO, and development of a Core Metadata Standard for WIGOS.

4.3 Surface variables

4.3.1 Air temperature

Surface air temperature has profound and widespread impacts on human lives and activities, affecting health, agriculture, energy demand and much more. It also has impacts on many natural systems. It is a factor affecting the fluxes of heat, momentum, water vapour and trace species between land and atmosphere and between ocean and atmosphere. Its monitoring provides a key indicator of climate change. Observations of it contribute to estimates of what is commonly known as “global-mean surface temperature” and to a number of indices of extreme conditions.

Surface air temperature is measured over land from the general networks discussed in the preceding section. As indicated there, measurements are made either as values for particular times of the day or as maximum or minimum values for which monthly averages are reported in CLIMAT messages. Marine air temperature is measured from ships and moored buoys, but observations from ships are more challenging to use than observations from land stations because of variable heights of measurement and solar heating of the ship, and their use suffers also from the declining open-ocean data coverage discussed in section 4.2.1. Datasets nevertheless continue to be developed from these data (Kent *et al*., 2013). Estimates with full geographical coverage are available from reanalyses, which generally assimilate more widely available surface pressure and wind observations and infer information also from the SST analyses they use. Anomalies in marine air temperature differ somewhat from anomalies in SST, associated in particular with anomalies in surface wind.

The global-mean surface temperature estimates that are widely used as a measure of global warming (discussed further below) are not based solely on air temperature, however, but instead on a mix of datasets that use surface-air temperature observations over continental land areas, islands and a few fixed marine platforms, and otherwise use observations of SST and the surface temperatures of large inland water bodies. The datasets generally do not provide coverage over and near areas of sea ice, except from a few island stations, and coverage is very limited over the continental ice sheets. Systematic estimates of the relatively large temporal variations in temperature that can occur over these areas are provided by reanalysis; such direct observations as are available currently or in past records from ice mass balance buoys, ships and ice stations are important in this case for evaluation. A recent such study, providing evidence also of both problems and improvement over time in the quality of some types of observation (illustrated later in Figure 78), has been provided for the Arctic by Simmons and Poli (2015). Land-surface temperature data from space-based clear-sky IR measurements (section 6.3.17.1) also contribute, as shown by Fréville et al. (2014) for the data-sparse Antarctic Plateau.

Three well-established and widely used estimates of global-mean surface temperature are those based on gridded products provided by the Met Office in collaboration with the University of East Anglia (current version HadCRUT4, Morice *et al*., 2012), by NASA (GISTEMP, Hansen *et al*., 2010) and by NOAA (MLOST, Vose *et al*., 2012, and its recent replacement NOAAGlobalTemp, Karl *et al*. 2015). Other groups provide estimates that are similarly based on products gridded directly from observations of surface-air temperature and SST; alternatives (based either on SST or on marine air temperature) are provided by reanalysis and by atmospheric models constrained by observations of SST and radiatively active trace species. All present an overall picture of the multi-decadal warming that has been termed unequivocal in the past two IPCC assessment reports. Uncertainties nevertheless remain, both in global averages and in assessing regional and local change for parts of the world where observational coverage is relatively poor and natural variability relatively large. It arises not only because of inadequacies and changes over time in observational coverage, but also because of imperfectly known effects of changes in the way observations are made and changes in the local environments of the measuring stations. Ensembles indicating uncertainty in long-term variations are provided for the HadCRUT4 dataset, and may otherwise be inferred (imperfectly due to common dependences) from the variability among datasets or within the ensembles used in reanalysis and modelling approaches.

Progress continues to be made on these issues. Apart from the general improvements in observational coverage and moves towards better arrangements for metadata noted in the preceding section, it comes from recovery of data and reprocessing of past records, including efforts to adjust for the inhomogeneities in data due to instrumental or siting changes. As an example, Figure 12 compares 30-year-mean temperature deviations from the 1961-1990 norm from HadCRUT4 with the corresponding values from the earlier HadCRUT3 dataset (Brohan *et al*., 2006). HadCRUT4 is chosen rather than NOAAGlobalTemp or GISTEMP as it does not make use of extrapolation or infilling to provide values for grid boxes that do not include observing sites.

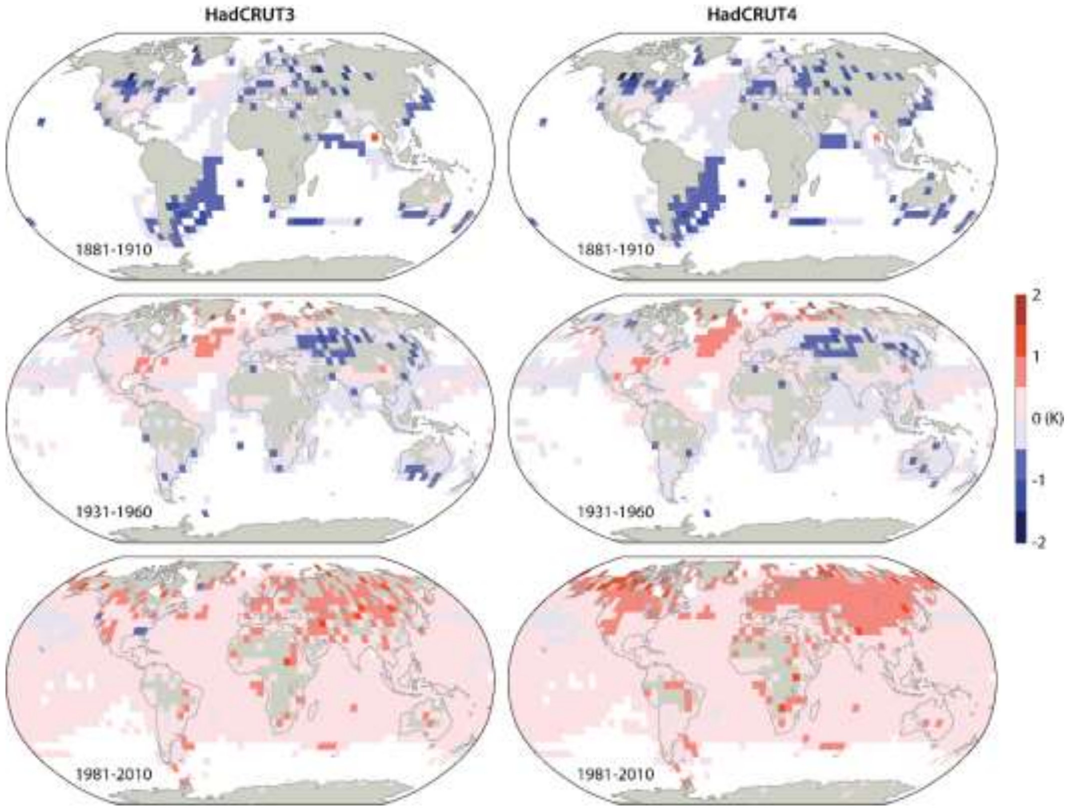


Figure 12: Surface temperature anomalies (K) relative to 1961-1990 from HadCRUT3 (left) and HadCRUT4 (right; median value from version 4.4.0.0). The coloured squares show the $5^O x 5^O$ latitude/longitude grid boxes for which values are provided. Anomalies are shown as averages for three thirty-year periods (1881-1910 (top), 1931-1960 (middle) and 1981-2010 (bottom)). Values are plotted only where no more than 36 months are missing in the thirty-year period.

The maps for both HadCRUT datasets show the much better coverage of the globe provided by the *in situ* observations available for recent decades. HadCRUT4 has better coverage than HadCRUT3, especially over land. Here it is based on the CRUTEM4 dataset, whose improvement over the earlier CRUTEM3 is documented by Jones *et al.* (2012). Improvement is particularly evident at high northern latitudes. CRUTEM4 also differs from CRUTEM3 where there is pre-existing coverage, in part due its use of newly homogenized station data produced by a number of suppliers, NMHSs in particular. The change to CRUTEM4 also reduces differences from the ERA-Interim reanalysis available for the period from 1979. The data gap over South America in earlier years is reduced in recent years due to the improvements in data availability noted earlier, but that over Africa remains substantial. HadCRUT4 still exhibits a data gap over the Arctic Ocean and a much more substantial void over much of Antarctica, the Southern Ocean and the southernmost parts of the Atlantic, Indian and Pacific Oceans.

Evidence presented by Cowtan and Way (2014), Karl *et al*. (2015) and Simmons and Poli (2015) points to warming from 1998 to 2012 that is higher than the central estimate reported by IPCC (2013). Factors involved include sensitivity to analyses of SST and of warm wintertime Arctic temperatures where there has been reduced sea-ice cover in several recent years, as illustrated later in Figure 50 for the month of March. Sub-decadal variability among different analyses remains quite substantial, but there is general agreement among the analyses produced in close to real time that the warmth of the global atmosphere during the current El Niño event is exceptional.

Further progress for temperature over land has been made under the auspices of the ISTI (Thorne *et al*., 2011). A new collection of data is being made with emphasis on ascertaining the provenance of the data and openly documenting the subsequent quality control, data-merging decisions and so on. Strict revision control and versioning are used. An illustration of coverage and length of record is presented in Figure 13. It shows, for example, a much higher density of data over the USA than that of the synoptic data transmitted in near-real time (Figure 7), and higher density more generally. Nevertheless, the regions of less-dense observations and shorter data records are the regions that exhibit poorer coverage in several other illustrations in this report. It should also be noted that not all stations provide records that continue to the present day. The ISTI provides a basis for further work on adjusting for inhomogeneities in data, including from its collection and study of data from parallel measurements made during station-siting or instrumentation changes. It also provides a basis for improved regional estimation of climate variability and trends, and for evaluating and tuning modelling or statistical downscaling approaches to providing information for localities where a historical observational record either does not exist or contains substantial gaps that need to be filled.

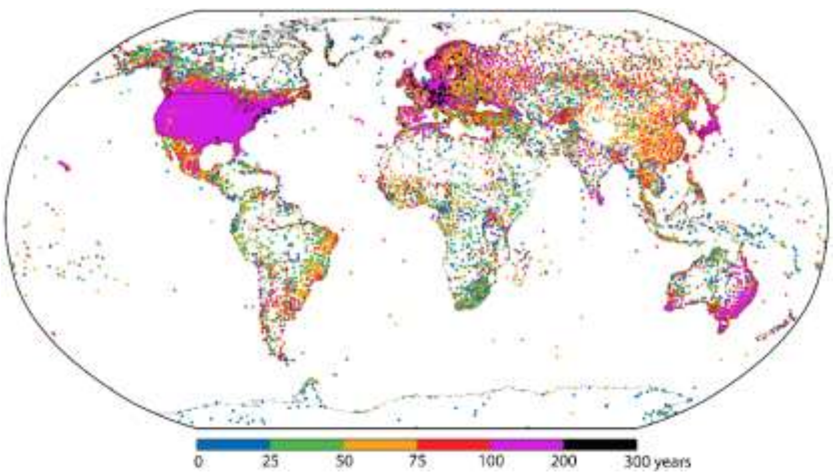


Figure 13: Locations and number of years of data available for more than 32,000 stations for which monthly data are held in the first release of the Global Land Surface Meteorological Databank, organized under the auspices of the International Surface Temperature Initiative. Stations with longer periods of record mask nearby stations with shorter periods of record. Source: Rennie et al. (2014).

Surface air temperature data are used to evaluate 16 out of the 27 core climate-change indices (http://etccdi.pacificclimate.org/list_27_indices.shtml) identified by the Expert Team on Climate

Change Detection and Indices (ETCCDI) established under the auspices of two World Climate Research Programme core projects (Climate and Ocean: Variability, Predictability and Change (CLIVAR) and GEWEX), the WMO CCl and JCOMM. This activity led to the development of data products related to indices of extremes (Alexander *et al*., 2006) with recent improvements in the spatial and temporal coverage of these products, primarily through targeted regional workshops (Donat *et al*., 2013a, b), and in better quantification of uncertainty estimates (Dunn *et al*., 2014).

4.3.2 Wind speed and direction

Surface wind has substantial influence on the exchanges of momentum, heat, moisture and trace species between the atmosphere and the underlying ocean and land. It drives ocean waves, storm surges and sea-ice, and provides a key forcing of the ocean circulation that is responsible for the global transport of important amounts of heat and carbon. It is a sensitive indicator of the state of the global coupled climate system and knowledge of it is important for understanding climate variability and change, and for climate model evaluation. Data on surface wind have direct application to sectors such as transport, construction, energy production, human health, marine safety and emergency management. They are also used in metrics that characterise the strength of tropical cyclones.

Space-borne scatterometer and passive MW imager data (Figure 14), and polarimetric MW data from WindSat, provide valuable sources of information on wind over the oceans, where they are complemented by *in situ* observations that come mainly from voluntary observing ships and buoys. Scatterometers in particular have the potential to provide coverage and a spatial resolution of wind speed and direction that captures important scales of ocean variability and can measure the wind field in the vicinity of tropical cyclones, notwithstanding their limitations for the strongest of winds. Action A-11 in IP-10 called for the required orbital coverage. As discussed in Appendix 1, page 228, data are currently still widely available only from mid-morning orbits, but planning is in place that should result in broader coverage. General issues related to observations from ships and from the array of moored buoys in the tropical Pacific are discussed in Section 4.2.1, Section 5.2 and in the reviews of several of the ocean-domain actions from IP-10, starting on page 257.

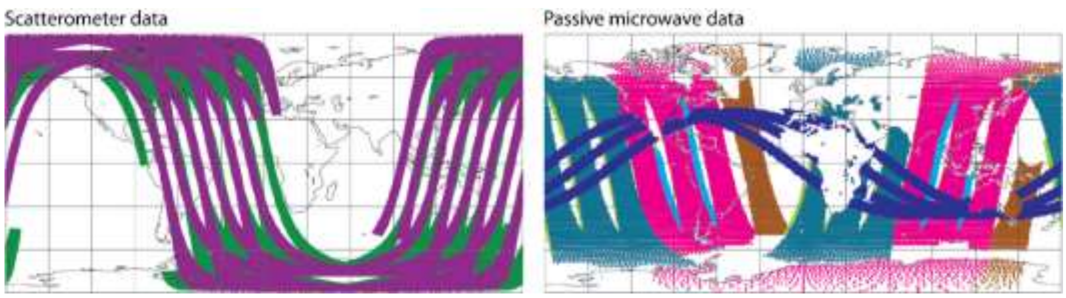


Figure 14: Examples of data coverage by satellite instruments providing data relating to surface wind, based on ECMWF maps of operational data receipt for the six-hour period from 21UTC 29 March to 03UTC 30 March 2015. Colours denote different satellites. Data points are from the scatterometers on the Metop A and B satellites, and from AMSR2, SSM/I, SSMIS and TMI MW imagers. TMI ceased measurement on 8 April 2015. Not shown is the scatterometer data coverage currently provided by the ISS-RapidScat and HY-2A instruments.

Over land the observation of wind speed and direction is accomplished largely through the WWW/GOS surface synoptic meteorological network, although measurements are representative only of quite local conditions for many locations. More broadly representative estimates may be derived from pressure data, and high-frequency pressure data can in particular be useful in stormy situations. Moreover, the higher resolution four-dimensional data assimilation systems now used for reanalysis are capable of making use of hourly data. Action A2 in IP-10 called for increased reporting of hourly data. The general discussion of spatial and temporal resolution, automation and data availability for the surface network given in section 4.2, and the related review of Actions A1 to A5 given on pages 218 to 222 of Appendix 1, apply to surface wind observation in particular.

Methods of observation and spatial sampling of marine winds has varied quite substantially over time. This includes variations in sampling by satellites in recent years, changes over time in the height of anemometer measurements from ships, the change from earlier estimation of winds according to the Beaufort scale from visual observation of sea state, and changes in the number of ships providing data and the routes plied. Here progress in the recovery of data on wind and surface pressure from ships' logs has found application through the recently developed capability for 20th century reanalysis (Compo *et al*., 2011; Poli *et al*., 2013), although the potential of such reanalysis for elucidation of long-term change remains uncertain. Among its list of key observational uncertainties, the IPCC AR5 states: "There is low confidence that any reported long-term (centennial) changes in tropical cyclone characteristics are robust, after accounting for past changes in observing capabilities."

Multi-decadal data products include global datasets from reanalysis, for the recent decades when satellite data provide additional observational constraints as well as for the centennial time range discussed above. These datasets are typically based on assimilating surface wind data only over sea, although other data, notably on surface pressure, constrain the surface wind analyses over land. Berry and Kent (2011) provide a new marine-only dataset from 1973 based on a direct analysis of data from the voluntary observing ships. It includes uncertainty estimates. There are also numerous satellite-based products for ocean winds. Many are linked to individual platforms or instrument types, but Atlas *et al*. (2011) describe a marine dataset based on cross-calibrated satellite data from multiple platforms, drawing also on *in situ* wind data and ECMWF analyses. Assessment of *in situ* data and products tends to be *ad hoc*, with contributions from the series of CLIMAR and MARCDAT workshops. Assessment of satellite data and products is undertaken by the International Ocean Vector Winds Science Team and by the International Winds Working Group of CGMS.

4.3.3 Water vapour

The humidity of air near the surface of the Earth affects the comfort and health of humans, livestock and wildlife, the swarming behaviour of insects and the occurrence of plant disease. Among other impacts are those that stem from the formation of fog. Along with temperature and wind, near-surface water vapour influences the surface fluxes of moisture and thus plays a role in the energy and hydrological cycles.

Several variables relating to water vapour are either measured or used in applications of the data. All can be derived from the actual (or "dry bulb") temperature of the air and the corresponding dew-point temperature, provided also that the atmospheric pressure is known from measurement or from reanalysis. Dew-point temperature is the variable usually reported by observing stations, even if what is directly measured is one of the other variables. Conversion formulae are prescribed in

WMO Technical Regulations. Various methods of measurement are used, and the method generally changes when a change is made from manual to automatic measurement. The CIMO guide (WMO, 2010a) provides further reading on this topic.

Dew-point temperature data are provided by the land and marine surface networks discussed in sections 4.2 and 5.2, and issues of spatial and temporal coverage are as for the other variables provided by these networks. Humidity data are subject to larger uncertainty than those for temperature, due to larger measurement uncertainty and the uncertainties introduced by data conversions. Precision of reporting is a further issue, as shifts in processed products over sea have been linked with the predominant reporting of dew-point temperature only in whole degrees prior to 1982 (Willett *et al*., 2008). Both temperature and dew-point temperature are still today reported only in whole degrees in the METAR code. The main requirement for archived data is for synoptic data (as provided by ISD and HadISD, for example) not daily or monthly summaries, because the various conversions between variables are nonlinear. Action A12 of IP-10 (page 229) concerns the general submission of water vapour data from national networks to the international data centres.

GCOS (2009) reported good progress for this ECV, based on the availability and archiving of data from the synoptic record, the emergence of near-global products based on analysis of the data, and the degree of agreement between these humidity-specific products and reanalyses, as subsequently confirmed by Simmons *et al*. (2010). The humidity-specific products referred to at the time were not continued routinely, although reanalysis was. Now, however, new monthly products for a suite of humidity variables over land, including uncertainty estimates, have been produced based on HadISD data (HadISDH; Willett *et al*., 2014a), and are scheduled to be updated annually. Over sea, the NOCSv2.0 dataset (Berry and Kent, 2011) includes a gridded specific humidity product at 10 m height based on observations from ships. It too comes with uncertainty estimates and is kept up to date.

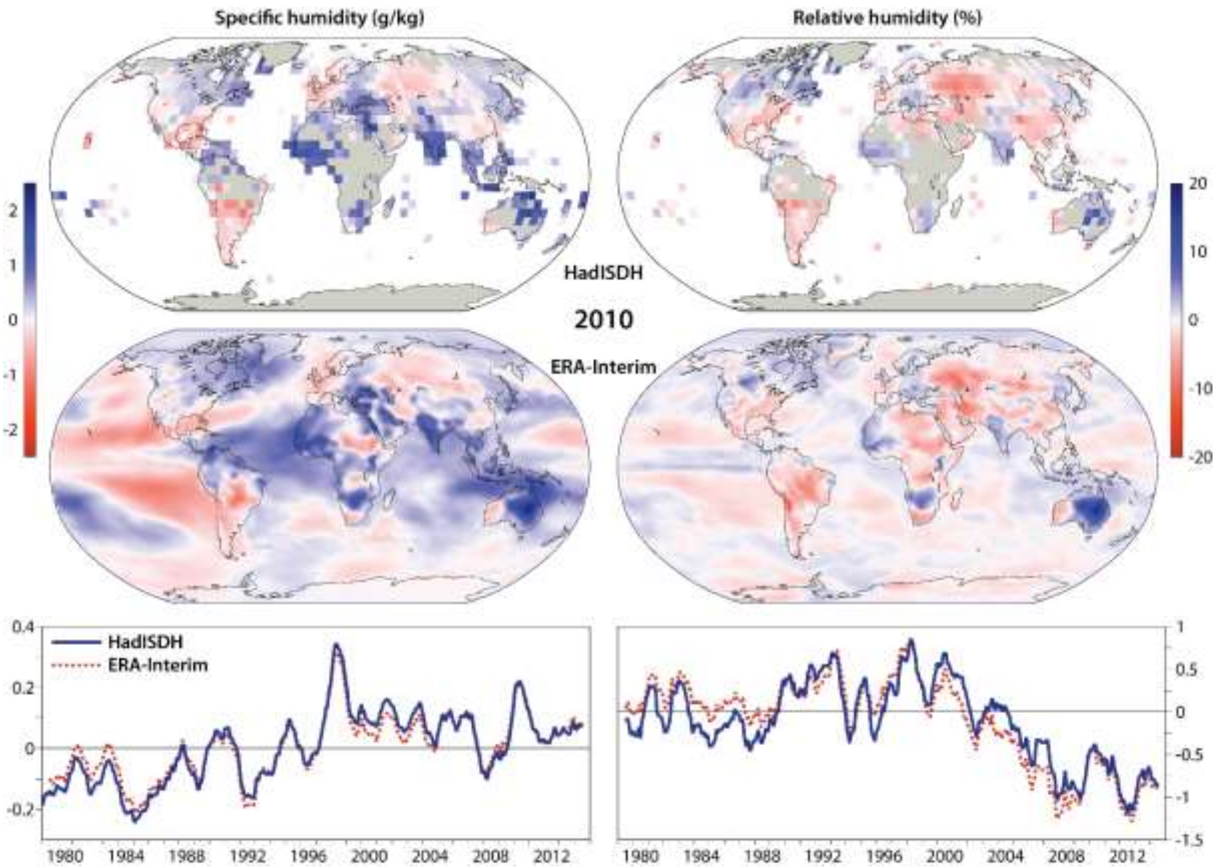


Figure 15: Surface air specific humidity (g/kg; left) and relative humidity (%; right) anomalies relative to 1981-2010 from HadISDH (version 2.0.1) and ERA-Interim, mapped for 2010 and as 12-month running mean time series of land values from 1979 to 2014. Land values are area-averages over the grid squares where HadISDH provides values, weighted by the land-sea mask used by ERA-Interim.

Figure 15 displays examples comparing values of specific and relative humidity from HadISDH and the ERA-Interim reanalysis. ERA-Interim values over land are constrained by the assimilation of the many types of observation that influence its background forecast as well as by its direct analysis of temperature and dew-point data. Its values over sea are strongly influenced by the sea-surface temperature analysis it uses. They show consistency with values over land and from the island stations that contribute to HadISDH. HadISDH provides a coverage of the land masses that reflects the general coverage of surface observations illustrated earlier. Agreement between the two datasets is generally good, more so for specific than relative humidity. A broader set of comparisons is presented and discussed by Willett *et al*. (2014b).

Screen-level observations of temperature and dew point have also been used for some time and with some success in numerical weather prediction and reanalysis systems to provide input data for analyses of soil temperature and humidity (Albergel *et al*., 2012; 2015).

4.3.4 Pressure

Surface pressure is a fundamental meteorological variable for which observations are required for initialising forecasts and for use in reanalysis systems. It is an indicator of circulation patterns: differences between surface pressures at pairs of stations provide traditional indices of the North Atlantic and Southern Oscillations. Other indices are based on zonal-means or principal-component analyses of gridded fields. Surface pressure also provides information on the intensity of weather systems, including tropical cyclones. It has an impact on sea level.

Surface-pressure observations are reported routinely from the synoptic networks for which coverage has been presented in Figure 7. They are complemented by a more sparse set of measurements over sea, mainly from voluntary observing ships and from sensors mounted on some of the drifting and moored buoys. Operational data exchange and quality-control procedures are well established for these types of data. The geographical distribution of drifting buoys equipped with pressure sensors is illustrated in the review of Action A6 of IP-10 given on page 223. It is discussed further there, and later in this section. The corresponding distribution of data from ships has been discussed in section 4.2.1.

Figure 16 illustrates how the numbers of observations of different types have varied over time since 1980. It must be regarded as indicative rather than definitive, as it is based on the data actually used in ECMWF's ERA-Interim reanalysis[4]. It shows a general increase over time in the number of observations, in particular for data reported to be from automatic measurements. This is especially the case for data from ships and the fixed platforms that report in SHIP code, for which the number of manual observations has declined substantially since the 1980s. The number of data reported as from manual observation at land stations has been slightly higher recently than at any time since 1980, although increased frequency of reporting has again to be kept in mind. Observations from drifting buoys increased substantially in the mid-2000s to reach their planned level, as reported in GCOS (2009). Numbers remained steady at this level for a while, but fell quite substantially and disconcertingly in 2011 and 2012. This was because of unexpectedly short buoy lifetimes for reasons explained in section 5.2.3. Problems have now been resolved, and numbers have reached an all-time high.

A particular concern expressed in IP-10 was that surface pressure was not sensed from all drifting buoys. Although IP-10 noted a significant improvement in recent years, it called for surface pressure sensors to be included in the suite of instruments on all buoys. The review of Action A6 (page 223) notes only modest improvement since 2009. There also continues to be a dearth of surface-pressure measurements from drifters located in the tropical and sub-tropical Pacific Ocean. This was noted in GCOS (2009), but has not been remedied.

[4] ERA-Interim did not use data in METAR codes prior to 2004, does not use additional data in a new AUTOMATIC METAR code that would have increased the data count from late 2014, had a slightly higher number of data over land prior to 1995 due to a data-exchange arrangement (Uppala et al., 2005) and otherwise relies predominantly on observations transmitted in near-real time.

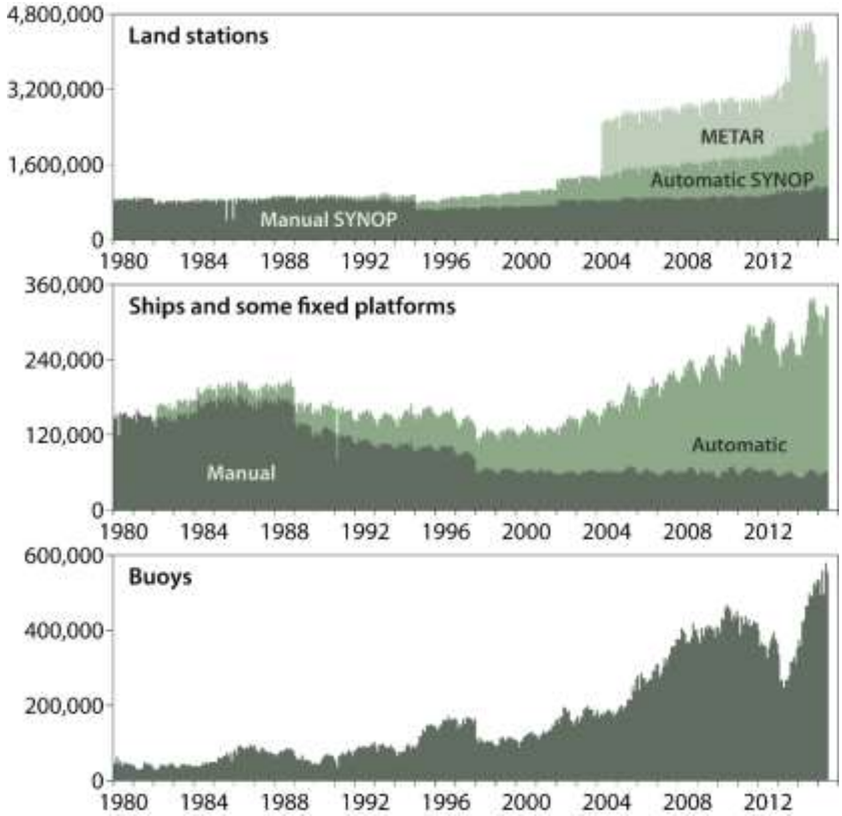


Figure 16: Number of surface-pressure observations from land stations, from ships and fixed platforms that report in SHIP code, and from drifting buoys and those moored buoys that report in BUOY code, assimilated each month in ERA-Interim from January 1980 to June 2015. Shading shows the number of SYNOP and SHIP reports assigned to be manual and automatic, and the number of METAR reports. The surface pressure observations reported in BUOY code are overwhelmingly from ocean drifting buoys.

Surface pressure has not been a variable generally measured from space, but the GOSAT and OCO-2 greenhouse-gas missions in orbit since 2009 and 2014 respectively provide measurements of the amount of oxygen in the atmospheric column, and thus essentially of dry air, as other contributing gases are well-enough mixed. The contribution of column water vapour to surface pressure is only a few hPa, and can be taken to sufficient accuracy from atmospheric data assimilation if not from satellite data, so these satellites provide estimates of surface pressure. It is not yet clear what value this type of observation adds to that provided by high-resolution global data assimilation systems and what the implications are for future measurement from space. Reduction of bias in the retrieval of surface pressure has been one focus of work on estimation of column-averaged dry-air mole fractions of carbon dioxide and methane from GOSAT (Yoshida *et al*., 2013; sections 4.7.1 and 4.7.2).

In addition to the archives for surface atmospheric observations in general that have been noted earlier, the ISPD holds data from the 18th century onwards, extracted from international archives and supplemented by direct contributions. This database has provided input to the 20th century reanalyses referred to in sections 3.6 and 4.3.2. The interest in these reanalyses provides motivation for continued efforts to recover and digitise the contents of paper records of both marine and land measurements of surface pressure. Cram *et al*. (2015) document version 2 of the dataset, illustrating data coverage as a function of year and discussing some of the improvements being made as a result of progress in data recovery and the availability of feedback from use of the data in reanalysis.

4.3.5 Precipitation

Precipitation, either liquid or solid, is perhaps the single most important climate variable directly affecting mankind. Through either its duration, intensity and frequency or its lack of occurrence, it influences the supply of water for personal consumption and use in agriculture, manufacturing industries and power generation, causes risks to life and the functioning of society when associated with floods, landslides and droughts, and affects infrastructure planning, leisure activities and more.

Precipitation is closely related to cloud properties, a number of terrestrial ECVs and to ocean surface salinity. It is indicative of the release of latent heat within the energy cycle as well as being at the heart of the hydrological cycle. Observations are needed for hydrological monitoring, to identify and understand climate variability and change, for understanding, interpreting and attributing particular climate events, for developing and evaluating climate models and for assimilation to constrain reanalyses. This is aside from the importance of these observations for weather prediction. Although classed as a surface ECV, information is needed on the vertical profile of falling hydrometeors, not only within clouds but also below clouds where melting and evaporation can occur.

One of the key uncertainties related to precipitation identified in IPCC AR5 states: "Changes in the water cycle remain less reliably modelled in both their changes and their internal variability, limiting confidence in attribution assessments. Observational uncertainties and the large effect of internal variability on observed precipitation also precludes a more confident assessment of the causes of precipitation changes."

Observation of precipitation is especially challenging, due largely to its intermittency and high spatial variability, but due also to other factors such as the complications from blowing snow. Measurements from gauges remain the principal source of data for climate use over land. Metadata on siting and data on at least wind may be used to correct for characteristic deficiencies in measurement such as undercatch of both rain and snow. Automated systems can provide better time resolution. Ground-based radar provides high spatial and temporal resolution, though with less-complete coverage and limited data exchange. Modern dual-polarization radar is far better in this regard in terms of accuracy and quality control, but the technology is not yet the global standard. IP-10 Action A7, reviewed on page 224, is partly concerned with the submission to international data centres of hourly gauge totals and products derived from radar data; much remains to be done, despite some progress.

Estimates of precipitation from space are made predominantly from passive space-based remote sensing in the spectral range from the visible (VIS) to the MW. The space-based precipitation radar on the TRMM satellite provided an invaluable record of tropical precipitation following launch in 1997 until its operation ceased in April 2015. A precipitation radar currently flies on the GPM Core satellite, covering middle as well as tropical latitudes. Satellite data on precipitation are needed especially over sea and over those land areas where ground-based measurements are either not made or not widely available. Quality control and cross-validation of *in situ* and remotely sensed data remains a key issue.

IP-10 Actions A8, A9 and A10, reviewed starting on page 226, relate to the above topics. Action A8 called for the continuity of satellite products on precipitation to be ensured, for which agencies have provided support for data reprocessing and product generation, including accommodation of new instruments, but which also rests on future continuation of the various types of measurement made from space. The prospects for continuation are assessed to be generally good, with some reservations over the degree of continuity of MW imager data and a specific need to set arrangements in place for continuing precipitation-radar measurements after GPM Core. Action A9 called for deployment of measurement of precipitation on a set of reference moored buoys, to provide data for evaluatiing and refining the products derived from space-based data. Progress is being made, though definition of the required network has yet to be completed. Action A10 called for development and implementation of improved methods for observing precipitation and deriving associated products. Advances here include the deployment of dual polarization ground-based radars, satellite missions that make measurements at MW frequencies sensitive to light rain and snowfall, with future extension to the sub-millimetre wavelength range, and an international programme for intercomparing automatic *in situ* measurements of solid precipitation. They also include initiatives to facilitate and promote the making and submission of measurements by volunteer observers.

Action A7 called generally for precipitation gauge data to be submitted to international centres such as the GPCC (operated by DWD) and NCEI. Figure 17 shows the number of stations from which GPCC holds data for forming its monthly products (Becker *et al*., 2013). The period is from 1901 onwards, and sources of the data are indicated. GPCC relies heavily on data supplied by individual nations, often under the condition that data may be used to generate the gridded products but not resupplied. The openly available data from NCEI's GHCN-monthly archive provide one source, but can be seen to come from far fewer stations than included in total in the GPCC database.

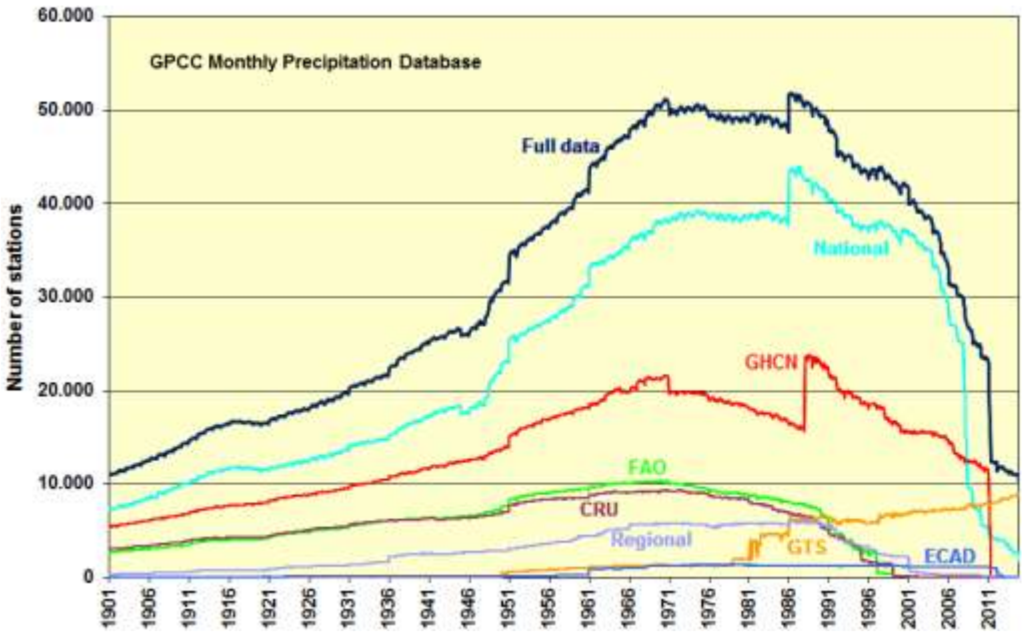


Figure 17: Variation since 1901 in the total number of stations providing data held in the monthly database of the GPCC at DWD as of April 2015 (dark blue line). Also shown are the numbers of stations providing data in each of the sources used by the GPCC. Sources comprise national and regional holdings, and other databases specified in Appendix 8. Further information on the GTS source is presented later, in Figure 80. Figure reproduced with permission of DWD.

Increases in GPCC's holdings have been substantial over the past six years. National data supply over the period has raised the number of stations providing data from about 35000 to 50000 for the years from 1970 to 1985. Data from around 5000 more stations are now in the database for 1951, and around 2000 more station are in the database for 1901. Delays in data acquisition make it difficult to comment on the underlying availability of data for recent years, other than for those obtained from the WMO Global Telecommunications System (GTS), for which discussion is included in the review of Action A7 given in Appendix 1.

Figure 18 shows the geographical distribution of stations in the GPCC database, classified according to the lengths of record held, using the same colouring as in Figure 13 for the ISTI temperature records. As is the case for temperature, the precipitation records span the 20th century for several regions. Many continue up to close to the present day, though some cease in the 1960s or earlier, those providing dense coverage over India, for example. Geographical variations in the density of coverage and lengths of record are generally similar in overall character to those shown for temperature, but are generally larger. There is a particular lack of data over Greenland and Antarctica. More generally, differences reflect not only variations in the density with which observations are made, but also variations in the extent to which individual countries amalgamate, digitise and make available their holdings of precipitation data.

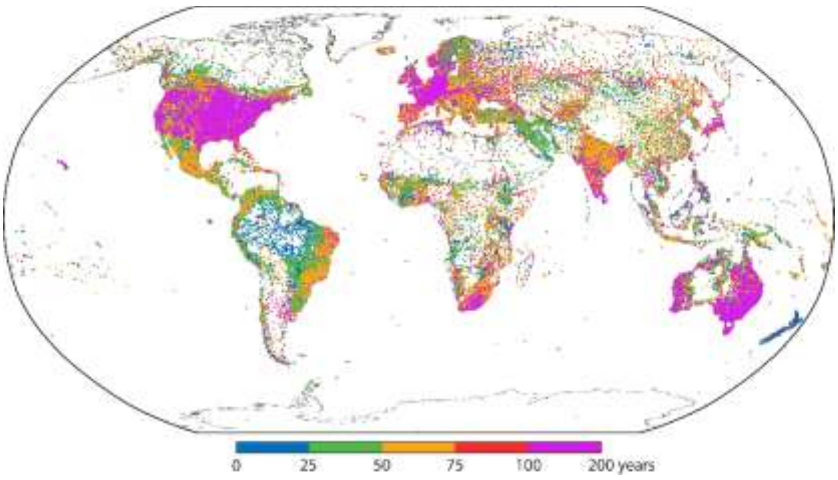


Figure 18: Locations of 75631 stations and lengths of their precipitation records held in the monthly database of the GPCC at DWD. Only stations with records longer than 10 years, covering periods beginning no earlier than 1814, are shown. Figure reproduced with permission of DWD.

The GPCC monthly product based on its full-data record was one of several datasets whose examination led IPCC AR5 to conclude as a key uncertainty: "Confidence in global precipitation change over land is low prior to 1951 and medium afterwards because of data incompleteness." The jump in station numbers in 1951 seen in several curves in Figure 17 is indicative of scope for data recovery for earlier years, although quite how much there is to be gained beyond removal of evident artefacts in data collections is uncertain. Aside from the general issues of data recovery discussed in section 3.7, and of lack of release of data from some countries, recovery of precipitation data has to surmount the obstacles caused by data records that fall under various administrative agencies within individual countries and that lack documentation to support the quality assurance of the records to be recovered.

It was noted in section 4.3.1 that surface air temperature data are used to evaluate 16 out of the 27 core ETCCDI climate-change indices. Precipitation data are used to derive the other 11. The latter all require data on daily precipitation. The indices obtained in the HadEX2 database (Donat *et al*., 2013a) are based on data from 11,600 stations, far fewer than support monthly GPCC products for all but the earliest and latest years. IPCC AR5's key uncertainty: "There is low confidence in an observed global-scale trend in drought or dryness (lack of rainfall), due to lack of direct observations, methodological uncertainties and choice and geographical inconsistencies in the trends" was based in the case of dryness on studies of indices for dry-spell length. Here there is scope for recovery of daily data where needed and more generally for a more widespread open release of such data.

Many different satellite-based and merged satellite-gauge data products exist; the NCAR Climate Data Guide (climatedataguide.ucar.edu) and the CGMS/WMO International Precipitation Working Group (IPWG, http://www.isac.cnr.it/~ipwg/data/datasets.html) provide lists. The GPCP dataset referred to earlier (http://precip.gsfc.nasa.gov/) is one widely used merged product. Combined ground-based radar-gauge products have been produced by several countries; the NOAA NCEP Stage IV product for the contiguous United States is assimilated operationally by ECMWF, for example. A first set of experimental radar climatology products is under development, based on reprocessing. Monthly variations in some reanalysis products have been shown to be in reasonable agreement with gauge-based products, with better agreement for newer reanalyses and newer versions of both types of product, notwithstanding longer-term shifts in reanalyses associated with observing-system changes.

Aside from the interests in precipitation of bodies with general international responsibilities for data reprocessing, product generation and related activities, specific responsibilities fall to the IPWG in the case of satellite measurements and data products. The IPWG undertakes validation and inter-comparison of data products, and has established links with the GEWEX Data Assessment Panel. Notwithstanding the availability of data inventories and guides such as that provided by NCAR, and assessments for specific regions or datasets, an update of the previous comprehensive GEWEX assessment of global data products (WCRP, 2008) is overdue. GEWEX accordingly is preparing to undertake a new activity on precipitation assessment, in which it is planned to issue reports every two years on distinct topics.

4.3.6 Surface radiation budget

Radiation at the Earth's surface is a fundamental component of the surface energy budget that is crucial to many aspects of the working of the climate system, including its energy and hydrological cycles. Systematic ground-based observation is needed for monitoring climate variability and change, and for evaluating products based on satellite data and from reanalyses and model runs. Data are also important for the siting and operation of solar power-generation systems, and for agriculture, health protection and tourism. UV indices and records of sunshine hours support the latter two applications.

Comprehensive observation of the surface radiation budget involves measurement of a number of specific variables: direct normal solar irradiance and exposure, diffuse horizontal solar irradiance and exposure, upwelling solar irradiance and exposure, downwelling IR irradiance and upwelling IR irradiance. The Baseline Surface Radiation Network (BSRN) has operated since 1992 under the auspices of GEWEX. It has established the relevant measurement techniques and has been recognised since 2004 as the GCOS Baseline Network for Surface Radiation. The BSRN provides high-quality measurements of radiation at the surface, but with limited spatial coverage. Its archive has been hosted since 2008 at the World Radiation Monitoring Centre (WRMC; http://bsrn.awi.de) operated by the Alfred Wegener Institute. The Technical Plan for BSRN Data Management was updated recently (König-Langlo *et al*., 2013) and provides information supplementary to that given in this report: on quality control, visualisation and data-handling tools as well as on network characteristics.

Figure 19 shows the locations of stations in the network, including a small number of stations that are known to have been closed but whose data remain useful for some purposes, and a similar number of stations from which observations are planned. This represents an overall improvement on the situation reported in GCOS (2009). The WRMC website in February 2015 shows that data from ten additional stations have since become available, with start dates between March 2009 and December 2014, and that the archive now holds in total more than 8000 monthly records from around 60 stations, starting from 1992 for nine stations. Data-scarce areas remain, however, especially over oceans and for eastern Africa and central Asia. Further discussion of the performance of the BSRN is given in the review of Action A14 of IP-10 on page 232.

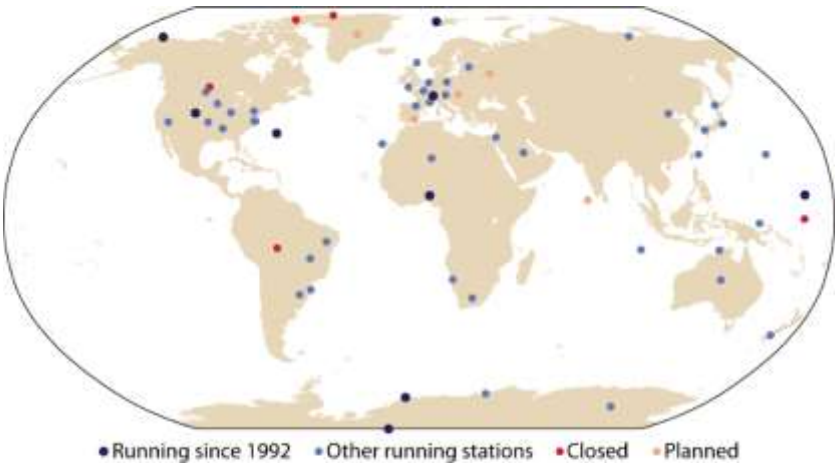


Figure 19: Running, planned and closed BSRN stations. The plotting does not distinguish pairs of nearby US stations in Boulder, Colorado, and near Washington DC. It is based on information from the WRMC, Alfred Wegener Institute, downloaded from http://bsrn.awi.de in February 2015.

The World Radiation Data Centre (WRDC; http://wrdc.mgo.rssi.ru) is hosted by the Voeikov Main Geophysical Observatory of the Russian Federal Service for Hydrometeorology and Environmental Monitoring. It archives and produces quarterly reports on sunshine and surface radiation data from national networks, supplied mostly by NMHSs. Some radiation data, mainly incoming solar, are now transmitted on the GTS in reports provided in either SYNOP code or its replacement BUFR code. Data coverage maps and discussion are provided in the review of Action A13 of IP-10 on page 230. They show a significantly increased number of stations from which data are held, although regular receipt of data, which recently have been subject to quality control by the WRDC, has remained at around 400 stations. The number of users accessing archived data has increased, however. One concern is a reduced number of high-quality solar observations due to automation, although introduction of automatic sunshine-duration meters can bring improvement in observational accuracy for this particular variable. A general lack of long-term records is a further concern. Scope exists for data recovery through digitization of sunshine-recording charts.

Monthly sunshine data are included in some of the monthly CLIMAT reports provided by GSN and RBCN stations. The GSN Monitoring Centre at DWD (GSNMC; http://www.gsnmc.dwd.de) reported in

2010 that the number of RBCN stations providing such data was 787 for January 1985, 946 for January 1995 and 1601 for January 2010. The 2010 figure represents a little over half the total number of stations providing CLIMAT reports. Data coverage tended to mirror that shown for GSN CLIMAT reports in Figure 11, but with a few national exceptions. Most evident was the absence of sunshine data from Brazil for 1985 and 1995 and the USA for 1995 and 2010. Although the GHCN-monthly datasets derived from CLIMAT reports are provided only for temperature and precipitation, the sunshine data are included in the monthly submissions of accumulated GSN data provided to NCEI by the GSNMC, and are available also for January 2000 onwards directly from the GSNMC website, which also provides "quick-look" data for the most recent month or two.

Measurements of surface radiation over sea, mainly of solar fluxes, are made from some of the moored buoys in the networks discussed in section 5.2.4. They are also made during cruises by research vessels.

Surface radiation products have been increasingly derived from satellite data. Examples are the products provided for the period from July 1983 to December 2007 by the NASA/GEWEX Surface Radiation Budget project (http://gewex-srb.larc.nasa.gov/) and the sets of products that span various periods covering from 1983 to the present from the EUMETSAT SAF on Climate Monitoring (CM SAF; http://www.cmsaf.eu) led by DWD. Generation of these products makes use of radiative transfer modelling and ancillary data on several surface and atmospheric variables, which introduces a greater degree of uncertainty into product values than is the case for top-of-the-atmosphere (TOA) fluxes. Assessments, against BSRN data in particular, are reported by data providers, for example by Posselt *et al*. (2012) in the case of the CM SAF, who include results for other products, including some from the ERA-Interim reanalysis. A more independent evaluation (of TOA as well as surface products) has been provided by the GEWEX Radiative Flux Assessment (WCRP, 2012a), although as preparation for this began as long ago as 2004, it is less up-to-date, evaluating the earlier ERA-40 reanalysis rather than ERA-Interim, for example. This assessment noted that although the consensus was not quite as good for the surface as for the TOA due primarily to issues with ancillary data, it was good enough to significantly narrow the spread of estimates provided by current climate models.

Global mean surface downward shortwave and longwave radiative flux estimates were presented in IPCC AR5 with an uncertainty range of 10 Wm^{-2}, based on a study by Wild *et al*. (2013) that combined BSRN and CMIP5 model data. Although Posselt *et al*. (2012) showed that ERA-Interim did not fit BSRN data quite as well as CM SAF products did, the global estimates from ERA-Interim reported by Berrisford *et al*. (2011) are within 1 Wm^{-2} of Wild et al.'s central estimates for the downward and upward longwave fluxes and for the reflected surface solar flux, with a 3 Wm^{-2} difference for the downward surface solar flux.

4.4 Meteorological upper-air networks

Observation of upper-air meteorological variables characterise the atmosphere above the surface of the earth, where dynamic, thermodynamic and constituent-transport processes basic to weather and climate occur. Measurements of temperature, wind, water vapour and cloud are vital for initialising and verifying weather and short-term climate forecasts, for evaluating the characteristics of the models used for longer-term climate projections, and for detecting, understanding and attributing variability and change in the climate system. Data on incoming solar radiation at the top of the atmosphere are fundamental for documenting the external forcing of the climate system and specifying it in models, while data on the outgoing thermal and reflected radiation are important for quantifying the energy budget and evaluating models. Knowledge of the state of the atmosphere is also important for deriving marine and terrestrial information from space-based observation, as well as for the estimation of surface radiation discussed in the preceding section. This includes knowledge of the varying composition of the atmosphere, which is discussed separately in sections 4.6 and 4.7.

Observations from satellites have provided an increasingly important source of upper-air data over more than forty years. Data from radiosondes and commercial aircraft are also important components of the overall observing system. Pilot balloons and ground-based profilers provide supplementary wind information, net water-vapour content is estimated from the delay in receipt of GNSS signals by ground-based receivers, and other forms of ground-based remote sensing also play a role.

General discussion and illustration of the provision of data from satellites is given in section 3.4, and more specific information is given variable by variable in section 4.5. General aspects of the radiosonde and aircraft networks applicable to more than one variable are discussed here.

4.4.1 The comprehensive radiosonde network

Comprehensive, baseline and reference networks are defined for radiosonde measurements. The WMO WWW/GOS provides the comprehensive network. Figure 20 shows the geographical distribution of stations providing data and categorizes the annual number of soundings received, based on data holdings accumulated operationally by ECMWF for the years 2002 and 2014. Small differences in data receipt and archiving may occur between operational centres due to the vagaries of the working of the GTS and data decoding issues, as discussed below for the baseline GCOS network, but these are insignificant from the viewpoint of an overall assessment.

Figure 20 shows notable increases from 2002 to 2014 in the frequency of data provided over Russia, South America and the islands of Southeast Asia and the tropical West Pacific. Coverage has remained poor over much of Africa despite some local improvements in reporting frequency. Of the countries and regions with a decline in reporting, that over Europe is from a particularly high level in 2002. Overall, there is a net increase of 10% from 2002 to 2014 in the number of radiosondes reporting a 500 hPa temperature. Corresponding increases are 13% for dew point and wind. This is accounted for mostly by the overall increase in reporting frequency, although coverage has improved slightly, at least in terms of the evenness of the distribution of observations.

Other improvements can be noted. There were additional increases from 2002 to 2014 in the number of data reported for the stratosphere, with net rises of 20% for temperature and 27% for wind in the number of reports for 30 hPa. There was also an increase in the number of data reported for the significant levels at which additional data are provided by the radiosonde operator to characterise the vertical structure of the ascent more fully. Action A17 of IP-10 called for general improvement of the radiosonde network, and Figure 86 in the review of this action on page 235 shows monthly numbers of radiosonde observations from 1979 to mid-2015. Values for the most recent years prior to 2015 are some 50% higher than in the 1980s and 1990s for the middle troposphere, and about twice as high for the middle stratosphere. Moreover, periodic radiosonde inter-comparison campaigns, reported by Nash *et al*. (2011) in the case of the latest under WMO auspices, studies of the homogeneity of the data record and feedback from data assimilation all point to improvements in data quality as well as quantity, as discussed further in section 4.5.

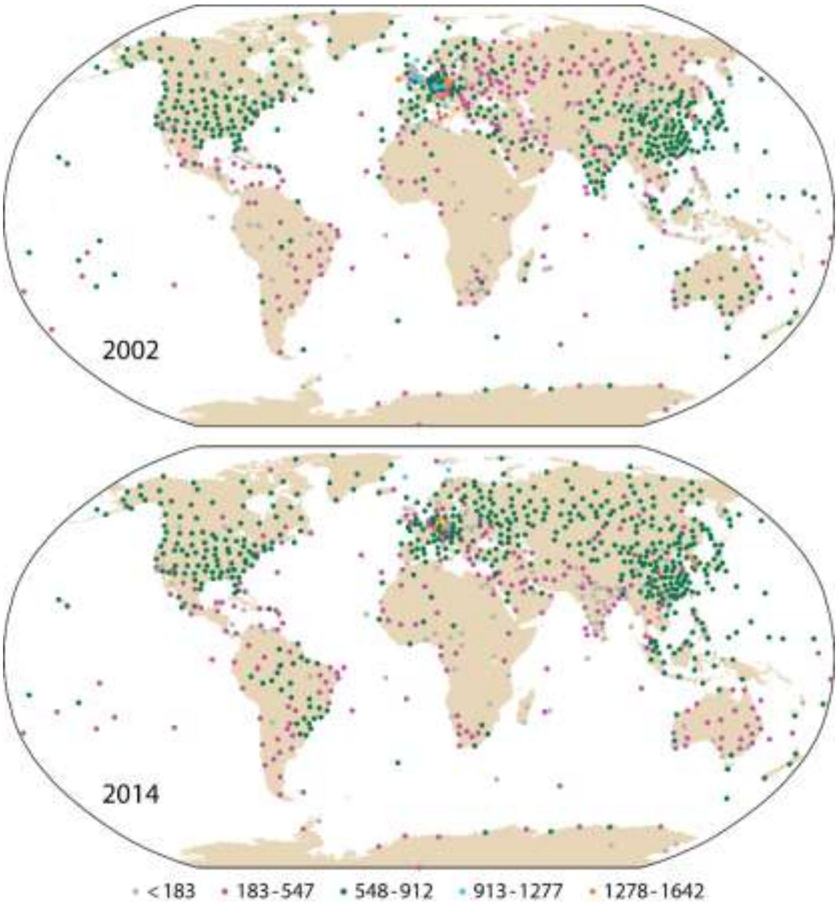


Figure 20: Annual counts of radiosonde reports from fixed land stations received operationally by ECMWF for 2002 and 2014. Plots are based on temperature data received for the 500 hPa level; counts for humidity and winds at this level differ by less than 5% in 2002 and 2% in 2014.

Action A17 of IP-10 specifically called for use of BUFR coding of radiosonde data, to provide high-resolution reports that include the actual time and position of each observational element, a limitation of the long-established alphanumeric TEMP code. Discussion of the transition from TEMP to BUFR coding is included in the review of this action given on page 235. As this transition is currently taking place and far from trouble-free, the results presented in the body of this report are based on the data transmitted in TEMP code.

A few radiosonde ascents are still made from ships, in particular routine automated ones from merchant vessels, but the number received by ECMWF in 2014 was only about 1% of the number of ascents from fixed land stations. Smaller still in overall numbers, but targeted, are the sets of dropsondes occasionally deployed over sea from aircraft, usually in and around severe cyclonic weather systems or where such systems are thought likely to develop. A system to release dropsondes from constant-level balloons (section 4.5.2) has also been developed, and deployed in field experiments (Cohn *et al.*, 2013).

4.4.2 Observations from aircraft

Upper-air data have been provided routinely by measurements made from commercial aircraft since the 1960s. They are a significant observational source for reanalysis systems, in addition to their importance for numerical weather prediction. Introduction of frequent automatic reporting and the expansion of air traffic has resulted in a substantial increase in the amount of data reported and used each day, predominantly for temperature and wind.

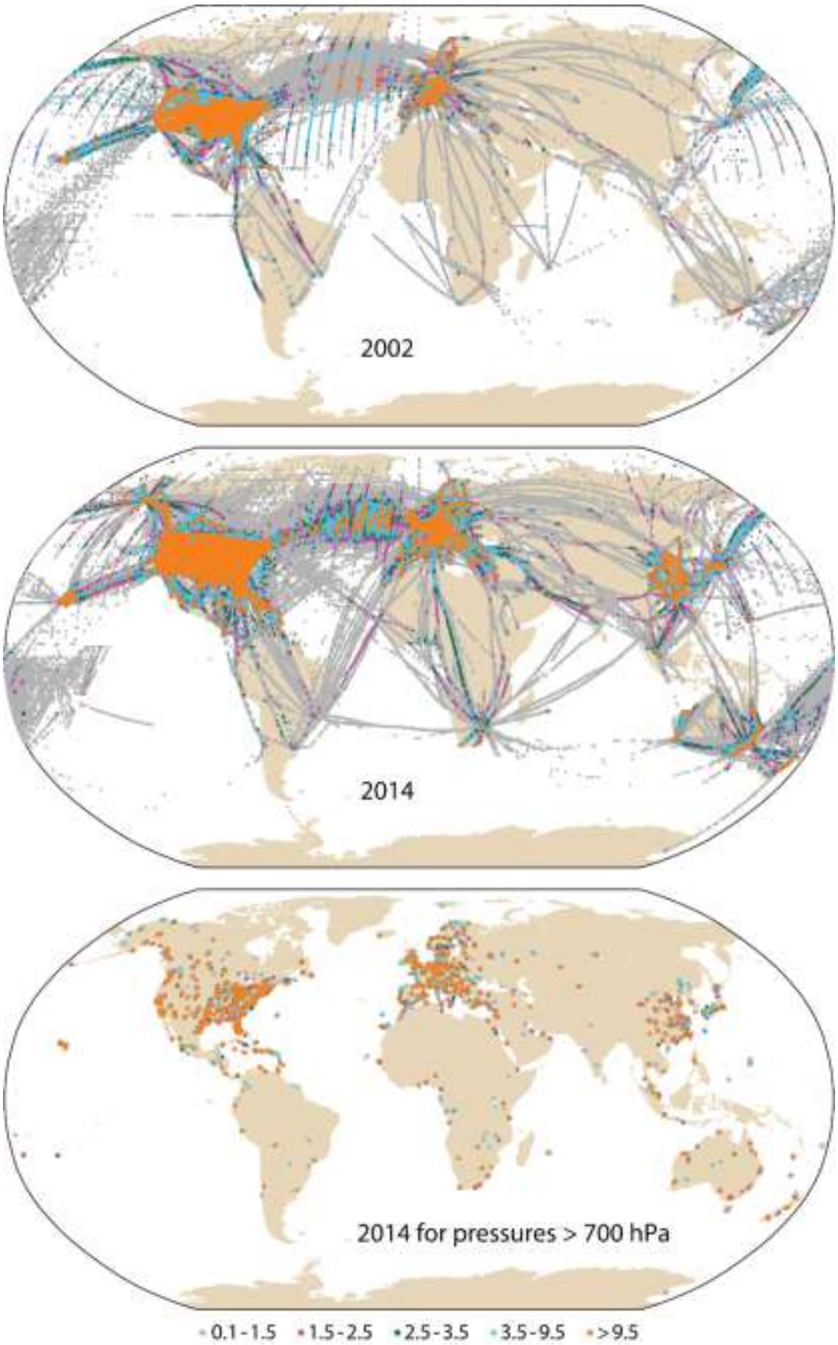


Figure 21: Distribution of aircraft data as received operationally by ECMWF (as ACARS, AIREP and AMDAR reports) for October 2002 (top map) and October 2014 (middle map), and as assimilated operationally for data from pressures greater than 700 hPa (bottom map). Plots are based on the numbers of temperature reports; the corresponding numbers of wind reports are less than 1% smaller. A symbol is plotted for each 0.5 degree latitude/longitude grid box that contains at least three observations per month. Colour indicates the average number of observations per day.

The upper two panels of Figure 21 compare data coverage for October 2002 and October 2014 for the data received routinely by ECMWF. Data distributions clearly depict the major flight routes, though the orientation of a number of observations along lines of longitude is a consequence of some reports being made only every five or ten degrees of longitude. Factors such population distribution, economic activity, conflicts and tourism influence where and how frequently observations are made. Observations currently vary in number by some 30% from weekday to weekend where they are densely located over North America, but show less variability elsewhere. The net increase in observation number from October 2002 to October 2014 is by a factor of more than three. In addition to general increases in the number of flight routes from which data are reported, the change in the number of observations from 2002 to 2014 over eastern China is noteworthy.

The increase in net number of observations has been accompanied by a relatively greater increase in the number of observations provided by aircraft as they either ascend from or descend to airports. The bottom panel of Figure 21 shows the locations and average frequencies of aircraft data assimilated operationally by ECMWF for pressures higher than 700 hPa, for October 2014. The lower tropospheric data from ascending and descending aircraft tend to be provided predominantly for regions that are also well provided for by radiosonde data, although the aircraft data may partly compensate in places for less frequent radiosonde launches, over Australia for example. Data are, however, also provided where there are spatial gaps in radiosonde provision, most notably over southern Africa. Important in this context is the development and gradual implementation of a capability to measure humidity (discussed in section 4.5.3) as well as temperature and wind.

Additional observations are made by aircraft equipped with the TAMDAR system, predominantly over North America on short-haul aircraft that provide relatively more ascent and descent data but less data at high levels than those discussed above. Humidity is included in the set of measured variables. Ongoing assessments of these data are important, as even if they are for a region that already has a relatively high density of other observations, there is a potential for the system to be used in regions where data are more sparse.

4.4.3 Baseline upper-air network

The baseline GCOS Upper-Air Network (GUAN) is a subset of the WWW/GOS radiosonde network chosen to have as uniform a spacing as reasonably possible, taking into account length and quality of historical data records, recent measurement quality and expectations of continuity of operation. The distribution of GUAN stations and indications of the number of 500 hPa temperature and wind reports they provided in 2013 are shown in Figure 22.

Data provision by GUAN stations is monitored by NCEI. Reports dating back to October 2001 can be found at the GOSIC. Figure 22 is nevertheless based on ECMWF’s operational data receipt, as a station-by-station comparison for the year 2013 carried out in preparing this report showed that ECMWF had data from one station on which NCEI did not report and complete data records for the year for two other stations for which NCEI reported data only from July. The latter may be connected with station-list changes that prevented decoding of messages from the two stations, which had caused problems at ECMWF in 2012. This type of problem should be addressed by the move to BUFR encoding, as the BUFR report includes the position of each station with the data, rather than requiring it be found on a station-list. Small discrepancies in data numbers for other stations likely reflect how data flows on the GTS, which was found during preparations for the ERA-40 reanalysis to result in slightly higher data receipt at NCEP than ECMWF (Uppala *et al*., 2005).

Both Figure 22 and NCEI records show two non-reporting GUAN stations for radiosonde temperature. One of them provided (and continues to provide) only wind data from pilot-balloon ascents, while the other suffered equipment failures but resumed sending data in April 2014. Reports in 2013 varied from a near-perfect record of four-times-a-day radiosonde ascents from one station to as few as seven ascents for the whole year from another. Supplementary pilot-balloon ascents provide significant amounts of wind data for stations in Australia, New Zealand and Thailand at times for which radiosonde data are not provided.

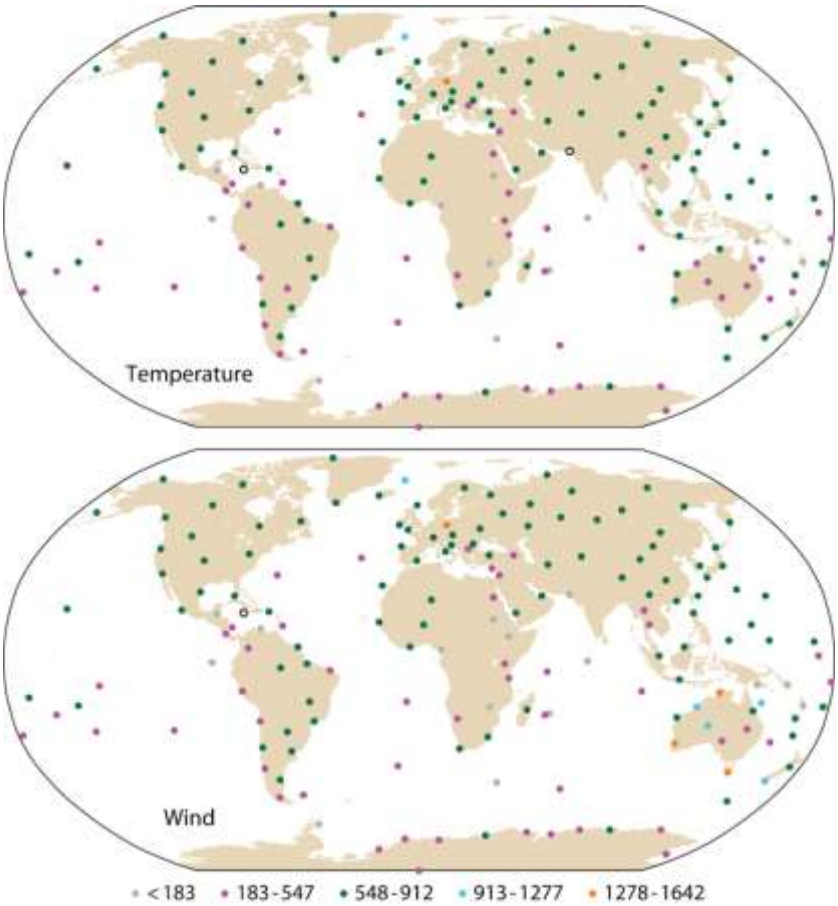


Figure 22: Counts of reports from the 171 stations of the GCOS Upper-Air Network received operationally by ECMWF for 2013. Plots are based on data for temperature (upper map) and wind (lower map) at the 500 hPa level, as reported in either radiosonde (TEMP) or pilot-balloon (PILOT) code; duplicates resulting from a wind observation being reported in both codes are not counted. Open black circles denote the locations of stations that provided no data during the year.

The target observing frequency for GUAN stations is twice per day. A little over 60% of stations achieved this in 2013. This is about the same fraction as for the comprehensive radiosonde network, but indicates a higher launch frequency for GUAN stations than the average for some regions, as the more uniform spacing of the GUAN stations means that a smaller proportion of them are located in countries where twice daily sounding is the norm.

Action A15 of IP-10 called for improved operation of the GUAN. Further discussion of the network is given in the response to this action provided on page 233.

4.4.4 Reference upper-air network

The GCOS Reference Upper-Air Network (GRUAN) developed from a first workshop held in 2005, following an identification of need in the original 2004 Implementation Plan developed by GCOS. With 22 stations located as illustrated in Figure 23, this network has yet to grow to its intended size of around 35 to 40 sites distributed so as to sample regions with differences in topography or climatic regime. The main objectives of the GRUAN are to provide long-term high-quality climate records of vertical profiles of several ECVs measured by radiosonde and other methods, to constrain and calibrate data from more comprehensive global networks, and to provide measurements for process studies to increase understanding of the properties of the atmospheric column. Its initial focus has been on provision of a radiosonde data product that follows key metrological concepts (Dirksen *et al*., 2014). Other products are in development, covering measurements by different types of radiosonde, by frost-point hygrometers and by ground-based remote sensing using lidar, Fourier transform spectroscopy and MW radiometry. Effective working practices, including a site certification process (see Figure 23), and governance and management structures have been put in place.

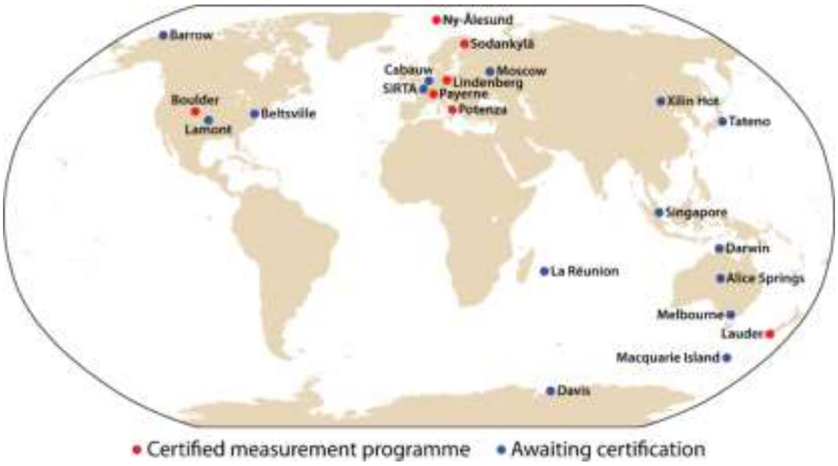


Figure 23: The GCOS Reference Upper Air Network, July 2015. Based on information from http://www.dwd.de/EN/research/international_programme/gruan/home.html.

The Lead Centre for GRUAN is hosted by DWD at its Lindenberg Meteorological Observatory. GRUAN measurements are processed centrally, by the Lead Centre in the case of the initial radiosonde product and by the GeoForschungsZentrum, Potsdam, for the forthcoming GNSS column water vapour product. Products are archived at NCEI and openly available following registration with the Lead Centre.

Bodeker *et al*. (2015) provide an account of the evolution, status and plans for the GRUAN. They also discuss the research that is helping to guide its development and that benefits from its establishment. Further discussion in this report is provided in the review of IP-10 Action A16 presented on page 234.

4.4.5 Data archives

Comprehensive collections of radiosonde data that have been merged from various collections, removing duplicates, are available from NCAR (its Upper Air Database; http://rda.ucar.edu/datasets/) and NCEI (its Integrated Global Radiosonde Archive (IGRA); Durre et al., 2006). NCAR provides separate access to the Comprehensive Historical Upper Air Network (CHUAN; Stickler *et al*., 2010, 2014), a collection of recovered data focussed on the period prior to the 1957-58 International Geophysical Year. NCEI provides access to the RATPAC (Free *et al.*, 2005) subset of data that have been adjusted to reduce inhomogeneities due to changes in instruments and measurement practices. A much more comprehensive collection of adjusted data is available from the University of Vienna (Haimberger *et al*., 2012).

The NCAR archive also holds several datasets containing aircraft data from the 20th century, plus copies of NCEP's operational holdings since then. The datasets have not all been merged into a single one, though some were merged for use in the ERA-40 reanalysis, and were subsequently used in JRA-55. The availability of observational upper-air data and feedback from reanalysis is as discussed in section 4.2.3 for surface data.

4.5 Upper-air variables

4.5.1 Temperature

Temperature is one of the fundamental state variables for which observation is essential for understanding and predicting the behaviour of the atmosphere. It is basic to the energy budget of the climate system as a whole through the temperature-dependence of the longwave radiation of energy from the atmosphere to space. Upper-air observations are of key importance for detecting and attributing climate change in the troposphere and stratosphere. They are needed for the development and evaluation of climate models, and for the initialization of forecasts. They are also needed for characterising the extratropical atmospheric circulation, which is often done using analyses of geopotential height rather than wind. Variations in temperature influence the formation of clouds and precipitation and the rates of chemical reactions, thereby influencing the hydrological and constituent cycles. Data on temperature are also crucial for understanding radiatively important changes in water vapour and cloud in the upper troposphere and lower stratosphere. Temperature affects in particular the formation of polar stratospheric clouds and consequential ozone loss.

Temperatures measured by radiosondes provide the longest available data, and are used both directly to study climate variability and trends, based on datasets such as referenced in section 4.4.5, and as one of the types of data assimilated in numerical prediction and reanalysis systems. Increasing amounts of *in situ* data from aircraft are also used in data assimilation. Top-of-atmosphere MW radiances from the MSU (1978-2006), AMSU-A (from 1998) and other instruments, mostly flown on the operational meteorological polar orbiters, are another key element of the historical climate record, providing a further important input for data assimilation and time series that can be interpreted as deep-layer-mean temperatures. The HIRS IR sounding instruments and predecessor VTPR instruments have provided data since 1972, and the new generation of hyperspectral IR instruments, AIRS and the later IASI and CRIS, have been operational since 2002. The IR SSU provided additional stratospheric data from 1978 to 2006, before being superseded by the newer MW and hyperspectral IR instruments. Use of data from all these IR instruments is well established for reanalysis, notwithstanding some identified issues to be resolved in future production versions. Interpretation of products based only on the radiances is more difficult for the IR instruments because changes in carbon dioxide as well as temperature are involved, and effects of cloud are much more prominent than for the MW instruments.

General discussion of the satellite, radiosonde and aircraft observing systems is given in sections 3.4 and 4.4, and for the related IP-10 Actions reviewed in Appendix 1. A further such Action, A20, which relates to the use of MW and IR radiances, is reviewed on page 239.

All the above types of observation are subject to biases, which have to be adjusted for if the data are to be used effectively, whether in data assimilation or in direct analysis of climate variability and change. Biases in radiosonde data vary in space and time linked to the use of different makes and newer versions of instrument. IP-10 Action A18, reviewed on page 237, concerns the submission of metadata records and radiosonde inter-comparison data to international data centres intended to facilitate adjustment for such biases. Changes in bias may also be inferred from break points in the time series of differences between background fields from reanalyses or operational data assimilation. A reduction in bias as instruments are improved over time is indicated both by this and by the results of successive radiosonde inter-comparisons, as illustrated in the review of Action A18.

Biases in the radiance data from particular satellite instruments can be quite stable in time, but are not invariably so, as measurements may drift because of specific instrument problems or changing solar heating of instruments when orbits drift. There may also be issues linked to the radiative transfer modelling needed to utilise the data, for example due to spectral response functions that are not well known. A number of approaches have been developed to cope, and progress has been generally good in recent years. The basic calibration provided by the GSICS programme has already been discussed in section 3.4.6, as has the role of radiative transfer modelling in addressing some issues.

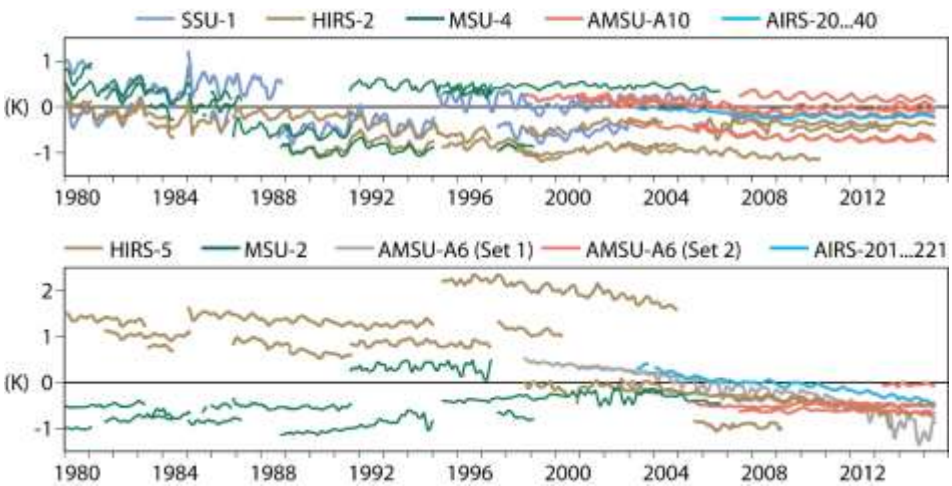


Figure 24: Estimated biases in brightness temperatures (K) from the SSU, HIRS, MSU, AMSU-A and AIRS sounding instruments for channels or groups of channels providing data for the lower to middle stratosphere (top) and middle troposphere (bottom). Each line segment represents the bias for a particular type of instrument (denoted by colour) from a particular satellite. Satellites are TIROS-N, NOAA-6 to NOAA-19, EOS Aqua, Metop-A and Metop-B. Data from channel 6 of AMSU-A are split into two sets to distinguish the drifting biases of the first four instruments flown from the more-stable biases of later instruments. Adapted and extended from Simmons et al. (2014).

Variational methods in which the required bias adjustments for satellite and aircraft data are determined jointly with the atmospheric state itself have proven their value for operational weather forecasting and reanalysis. In this approach, other assimilated data that are unadjusted or externally homogenised, particularly from radiosondes and GNSS RO (see below), provide anchors that inhibit the data assimilation from simply adjusting to a biased model state. Figure 24 presents an example of the bias estimates for selected channels of the sounders from which data were assimilated in ERA-Interim from January 1980 to June 2015. Biases are generally much larger than climate-change signals over the period, but are smaller in amplitude and more stable over time for the latest instruments in orbit. Drifts over time arise because of instrument behaviour in some cases and unaccounted effects of changing carbon-dioxide concentrations in some others. Smaller variations also arise from regime-dependent biases in the assimilating model and changes in anchoring data.

One focus of the development of the GRUAN has been on how the network's measurement programme may best support the calibration of satellite data. Proposals and studies for specific satellite missions dedicated to making high-quality measurements to facilitate calibration of the data from other systems were supported in IP-10, which in Action A19 called for implementation and evaluation of such a mission. Further discussion is given in the review of the action, on page 239.

Another type of satellite data has already proved its worth in this regard, since becoming available in large amounts some nine years ago. GPS (or more generally GNSS) radio occultation (RO) measurements of bending angle relate fairly directly to temperatures in the dry upper troposphere and lower to middle stratosphere. The fundamental measurement of time delay is directly traceable to the SI unit and in theory GNSS RO is therefore well suited to measuring the absolute atmospheric temperature profile. Several subsequent processing steps are required. Some of these have their uncertainties fully quantified, allowing with some development a fully quantified uncertainty budget on measurements and time series. Given their fundamental measurement properties, they provide observations that can be used to calibrate the other types of temperature measurement and provide high vertical fidelity. An inter-comparison of several techniques shows very low structural uncertainty in the records available. More directly, assimilation of GNSS RO data alongside other data gives positive impact in both numerical weather prediction and reanalysis. An outline of current and planned provision for this type of data, and an example of impact on reanalysis, is given in the review of IP-10 Action A21 on page 240.

Layer-mean temperatures in the mesosphere can be derived from the Special Sensor Microwave Imager SSMIS, which has provided data since 2004, and the data may serve to constrain relatively large model errors in this region when assimilated. Temperature profiles derived from MW limb-sounding (the MLS instrument; see review of IP-10 Action A26 on page 245) also fulfil this role; they are assimilated from 2004 onwards in the MERRA-2 reanalysis. Other individual research missions and ground-based remote sensing provide independent data for evaluating reanalyses, as well as data for model evaluation and general enhancement of understanding. Several older satellite-borne instruments such as IRIS, PMR, SCAMS and SSM/T have the potential for recovery to provide input to reanalysis, which also benefits from the recovery of early *in situ* upper-air data discussed in section 3.7.

IPCC AR5 identified the following as a key uncertainty: "There is only medium to low confidence in the rate of change of tropospheric warming and its vertical structure. Estimates of tropospheric warming rates encompass surface temperature warming rate estimates. There is low confidence in the rate and vertical structure of the stratospheric cooling." Improvements in existing types of instrument, in particular lower or more stable biases, better orbital control of satellites and new observations such as from GNSS RO should be noted. They make this IPCC statement a reflection more of the limitations of the past than of the present observing system. Continuation of the traditional MSU data records (as opposed to assimilating the entire MW record in reanalysis) requires that the data from the newer MW instruments be manipulated to produce equivalents of the obsolete MSU measurements, and radiosonde datasets are vulnerable to station closures. Comparisons of time series of temperatures from the latest generation of reanalyses, or of the fits of an individual reanalysis to assimilated observations, generally show better agreement for later years, although issues can arise from quite recent changes to the observing system.

Several alternative data products based on either radiosondes or MSU and MSU-equivalent radiances are available and provision of consistent time series of bending angles from GNSS RO is planned for climate applications. Datasets based on retrievals of temperature from the other types of satellite sounding data are also produced.

A number of international bodies play a role in advising or assessing the quality of temperature observations and data products, whether from individual observation types or from comprehensive reanalysis. This includes WMO CIMO and CBS, and the International TOVS Working Group, for observations and their immediate processing. Brief comparisons of products are made annually in the "State of the Climate" reports published by the American Meteorological Society, as is the case for other ECVs. The stratosphere receives special attention through initiatives of the WCRP SPARC project, which hosts a group on temperature trends as well as the reanalysis inter-comparison project noted earlier. Comparison of temperature analyses is also quite well served by the peer-reviewed scientific literature.

4.5.2 Wind speed and direction

The horizontal components of the atmospheric motion field are, like temperature, fundamental state variables of the system of equations that are commonly solved in the models of atmospheric behaviour used to make forecasts and climate projections. The motion of the atmosphere is also basic to the working of the climate system through transport of water vapour and trace constituents.

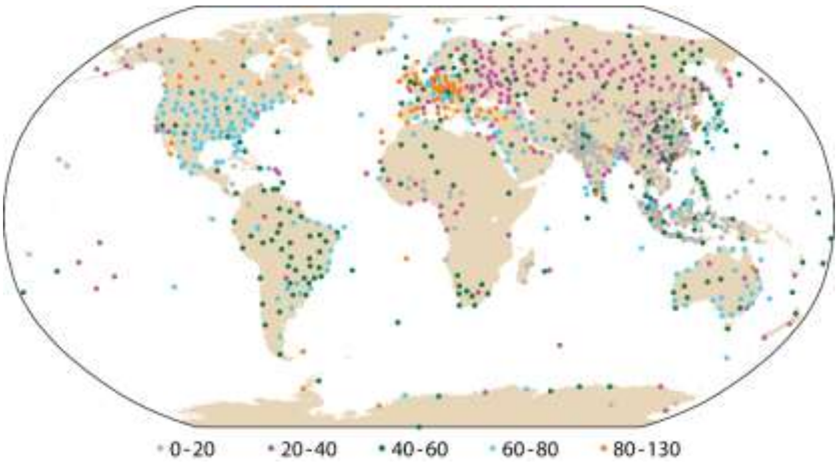


Figure 25: Average number of wind observations per ascent, from radiosonde and pilot-balloon data assimilated operationally by ECMWF in October 2014. At stations where both a TEMP and a PILOT are reported for the same date and time, the radiosonde is given priority, except for stations in WMO Region IV (North America, Central America and the Caribbean), for which the PILOT winds are added to the TEMP winds to form a single ascent, in accord with regional reporting practice.

Observations of wind are made from the radiosonde and aircraft networks discussed in section 4.4. Radiosonde ascents provide data of good vertical extent and resolution, with benefit in recent years from the use of instruments in which wind is determined from GPS-determined location rather than other forms of tracking, as demonstrated by equipment inter-comparisons (Nash *et al.*, 2011). Figure 25 shows quite substantial regional and national differences in the vertical detail provided per ascent, ranging from stations that in October 2014 provided data only at standard pressure levels to a GUAN station that provided on average data at 129 levels. The amount of data provided per ascent has generally increased over time, as documented later for the GUAN subset (Table 6, page 233).

Figure 25 shows winds reported in either PILOT or TEMP codes. Some wind data from radiosonde ascents are reported as a PILOT, but the code is also used for wind data derived from tracking pilot balloons. The latter account for a substantially greater density of observation over South and Southeast Asia, and additional observations for the western part of Africa, than provided by the radiosonde network. Some of the pilot balloons sample only the planetary boundary layer but others reach to around the tropopause. Other regional ground-based observations for the troposphere are made using remote-sensing wind profilers. Data from operational European and Japanese networks and a few sites in North America are currently used routinely at ECMWF, for example. An operational NOAA network over the USA contributed to the data record from 1992 until decommissioned in 2014 for reasons stated to be economic conditions, system obsolescence and the increased availability of data from aircraft and other sources.

Wind data are also derived by tracking clouds and features in the upper tropospheric water-vapour field depicted in successive images from satellites. Data have been provided from imagers on geostationary satellites since the 1970s, and have been derived more recently from polar orbiters, using either near-polar images where orbits overlap frequently or images from two satellites in very similar orbits. Figure 26 presents examples of coverage in a six-hour period; winds from geostationary orbit are also derived from IR and VIS cloud images, and some near-polar water-vapour winds are also available. Line-of-sight winds obtained from space-borne-lidar backscatter with coverage from the planetary boundary layer to the middle stratosphere are awaited from the ADM-Aeolus mission expected to be ready for launch in 2017.

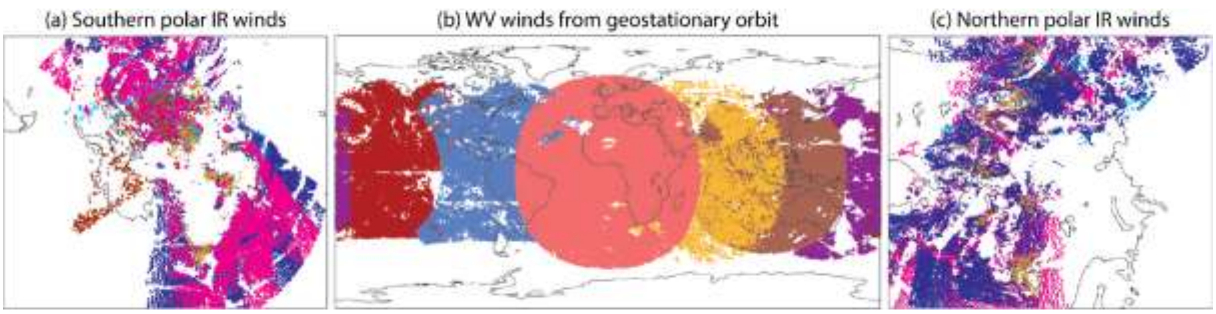


Figure 26: Examples of coverage of winds derived by tracking features in thermal-band IR images from polar-orbiting satellites for (a) the southern polar region and (c) the northern polar region, and (b) in water-vapour-band images from geostationary satellites, based on ECMWF maps of operational data receipt for the six-hour period from 21UTC 1 March to 03UTC 2 March 2015. Colours denote different Chinese, European, Japanese and US satellites.

Global wind data products are provided by data assimilation, either from operational numerical weather prediction or from reanalysis. The multivariate nature of the schemes involved ensures that the generation of wind products draws not only on wind observations but also on temperature observations in the extratropics, consistent with the approximate balance relationships that hold between variables. These products thus benefit from the much more comprehensive observations that satellites provide for the temperature field. Satellite wind data such as shown in Figure 26, which are subject to uncertainty in height assignment and the linkage between cloud-motion and wind, are typically used with quite stringent quality control and thinning. Such use is of demonstrated benefit. This partly reflects improvements over time in methods of deriving winds from images, which have generally been such as to reduce the wind speed biases found in earlier data. IP-10 did not have an action addressed specifically to observation of upper-air wind, but GCOS (2006, 2011a) called for reprocessing of older data. This was already being undertaken by European and Japanese producers, who have since continued this activity. Reprocessing of data from US satellites has also now been carried out, but has yet to be undertaken for data from geostationary orbit prior to the mid-1990s.

Biases in the wind data from radiosondes and pilot balloons have been of less concern than those in radiosonde temperature data, although some instances of confusion between true and magnetic north can be found for wind direction; this can even differ between radiosonde and pilot data from the same station. Problems are more pronounced in older data. Ramella Pralungo and Haimberger (2014) discuss this and provide corresponding homogenising adjustments, noting also that sampling is biased towards clear skies and lower wind speeds over the years prior to around 1960, when visual tracking of balloons was prevalent.

International coordination for space-based wind observation is provided by the CGMS Working Group on Satellite Derived Winds, commonly referred to as the International Winds Working Group.

Observations other than those discussed above, although not present in sufficient numbers or for a sufficient time to form individual climate data records, provide independent data for evaluating reanalysis products if not included in the assimilated data-streams. Examples are the data from sparse rocketsonde profiles, and constant-level balloon datasets such from the EOLE and TWERLE programmes from the 1970s (although TWERLE data were assimilated in ERA-40) and data from the 2010/11 Concordiasi balloon flights. Stratospheric wind data may become available in future from balloons with active level-control being developed in Google's Project Loon. Wind information higher in the stratosphere and in the mesosphere is provided by measurements of Doppler effects using lidar and passive MW radiometry, and from detection of refracted ultrasound.

4.5.3 Water vapour

Water vapour is a key climate variable. It is the predominant gaseous source of IR opacity in the atmosphere, accounting for about 60% of the natural greenhouse effect for clear skies. It also provides a feedback that reinforces tropospheric warming in model projections of climate change. Water vapour condenses to produce clouds, thereby changing radiative properties and releasing latent heat that drives or modifies atmospheric circulation systems. It plays a role in atmospheric chemistry. The presence of water vapour in the lower stratosphere, even though in small amounts, is radiatively significant. Here there is potential for additional climate-change feedbacks through change in the processes that control the entry of water vapour through the cold tropical tropopause, change in the upper stratospheric source due to methane oxidation and change in the transporting Brewer-Dobson circulation. Observations of water vapour are needed to advance scientific understanding, to monitor and attribute climate change, to evaluate models and for use in data assimilation systems to initialise predictions and generate data products through reanalysis. Assimilation of water vapour data may improve wind analyses in regions where advection is the dominant process.

Total column water vapour, in effect the water content of the lower troposphere, is estimated over the oceans from space primarily using data from MW imagers such as AMSR, SSM/I, SSMIS and TMI (Figure 14). Radiosondes provide information for the lower and middle troposphere over land, and their data are increasingly used at the colder temperatures of the upper troposphere as sensors are improved and bias-adjustment approaches developed. GNSS occultation measurements from space also provide information, as humidity influences the refraction of signals in the lower troposphere. Moreover, the delay in reception of GNSS signals measured by ground-based receivers provides estimates of total column water vapour over land; in this case the required progress in international data exchange called for in IP-10 Action A22 is being made, as discussed in the review of this action provided on page 241. Total-column measurements are also provided over land by ground-based upward-viewing MW radiometers and in daylight and clear skies by satellite-borne radiometers operating in the VIS and near-infrared (NIR) spectral ranges. It has already been noted that humidity is measured by the TAMDAR system installed predominantly on aircraft on short-haul routes over North America. Around 10% of AMDAR reports come from longer-haul aircraft equipped with a laser diode system more suited for measurement of upper tropospheric humidity than the capacitive TAMDAR sensor.

Measurement of water vapour in the middle and upper troposphere is well established from space based on the strong absorption lines in the IR and MW spectral range. IR estimates such as from the long series of HIRS instruments or the shorter records from hyperspectral sounders, both in polar orbit, and from geostationary imagers are restricted to areas with no or only low-level clouds, whereas MW estimates from instruments such as SSM/T2, AMSU-B, MHS, ATMS and MWHS are valid in all non-precipitating areas. Clear-air-only sampling results in a global dry bias in estimates based only on IR data, but diagnosis of the ERA-Interim reanalysis indicates only a very small shift when the MW data first become available, around the year 2000. Inter-satellite differences in ERA-Interim's bias estimates are small for AMSU-B, MHS and the newer HIRS instruments.

The small but nevertheless important values of water vapour near the tropopause and in the stratosphere are challenging to measure. Important data records have been accumulated from space-based measurement using limb-sounding and solar occultation. A serious concern for the future is the absence of substantial progress on establishing a long-term programme for such limb measurements, discussed further in the review of IP-10 Action A26 on page 245.

Extreme scarcity of high-quality *in situ* measurements of near-tropopause and stratospheric water vapour was an important reason for advocating the establishment of the GRUAN in GCOS (2004); GRUAN sites are expected to measure at least one high-quality water vapour profile in the upper troposphere and lower stratosphere each month using the best instrumentation possible, typically a balloon-borne frost-point hygrometer. High-quality measurements of water vapour and other constituents are also being made by a small number of specially-equipped commercial aircraft participating in the IAGOS research infrastructure, building on the heritage of the MOZAIC programme.

Biases in observations (illustrated in Figure 27 for radiosondes) and models have been particularly prevalent for water vapour over the years, from the boundary-layer upwards. Changes in data coverage, instrumentation and misinterpretation of the data from particular satellite sounding channels have caused difficulties in creating reliable long-term data products. This has been an issue for reanalysis in particular, as evident in problematic precipitation as well as humidity products. Progress has been made through various approaches to determining and adjusting for observational bias, through careful selection of the data to be used and through improvements in assimilating models and assimilated data on related variables such as temperature. Links between near-surface tropical temperature change and temperature and humidity change in the tropical upper troposphere were for some time difficult to reconcile between observation and modelling, but several recent studies using newer datasets point to a much improved situation.

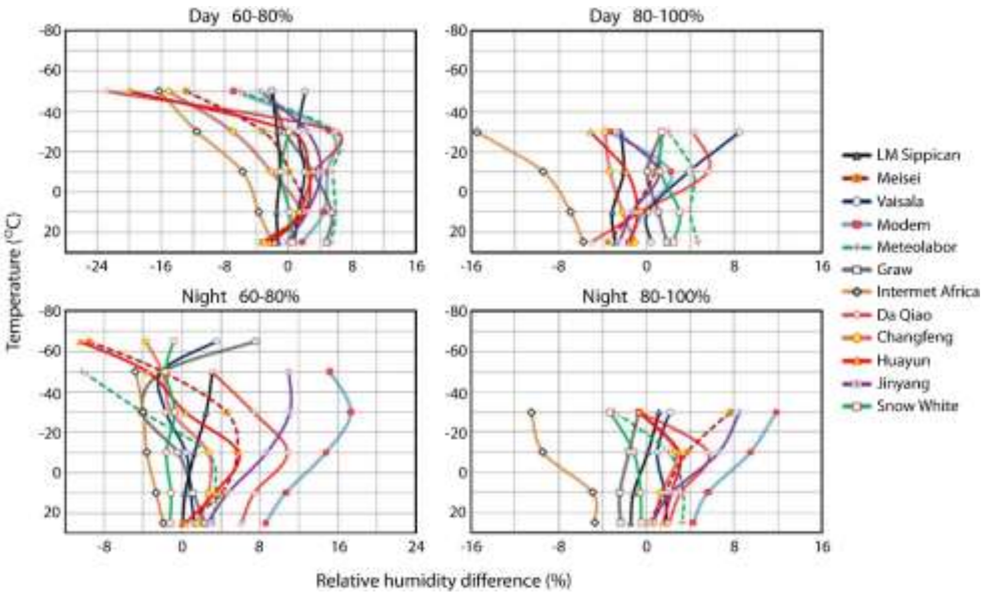


Figure 27: Biases in relative humidity (%) as a function of temperature for instrument types flown in the 2010 WMO inter-comparison of radiosonde systems. Results are shown for 60-80% (left) and 80-100% (right) ranges of relative humidity, for daytime (upper) and night-time (lower) ascents. Source: WMO, reproduced from Nash et al. (2011).

Several alternative FCDRs for the principal types of satellite data exist or are under development. A number of data products on total column water vapour are available based on the data from various instruments. Multi-agency cooperation on sustained generation of upper tropospheric humidity data products is a current SCOPE-CM activity, building on existing products based on data from the IR sensors flown in polar and geostationary orbit, and the MW sensors flown in polar orbit.

Responsible international bodies include, as for temperature, WMO CIMO and CBS, and the International TOVS Working Group, for observations and their immediate processing. Important and timely in the case of water-vapour products is the assessment of them currently being carried out under GEWEX (http://gewex-vap.org/). This assessment began in 2011, and its report is due by the end of 2015. Stratospheric water vapour is the complementary focus of an assessment currently being undertaken by SPARC, as a major update of an earlier activity reported on in 2000.

4.5.4 Cloud Properties

The variable properties of clouds determine their profound effects on radiation and precipitation. They are influenced by and in turn influence the motion of the atmosphere on many scales. They are affected by the presence of aerosols, and modify atmospheric composition in several ways, including the depletion of ozone when they form in the polar stratosphere. The feedback from changes in cloud remains one of the most uncertain aspects of future climate projections and is primarily responsible for the wide range of estimates of climate sensitivity from models. Observations of cloud properties are needed for improved understanding and quantification of both local and larger-scale cloud-related processes, for climate monitoring, for validation and development of numerical models and for their emerging use with these models in data assimilation.

The importance and challenges of observing cloud properties and aerosol interactions is highlighted by the IPCC AR5’s identification of three related key uncertainties, namely that:

- substantial ambiguity and therefore low confidence remains in the observations of global-scale cloud variability and trends;
- the cloud feedback is likely positive but its quantification remains difficult;
- uncertainties in aerosol–cloud interactions and the associated radiative forcing remain large.

Moreover, WCRP has identified clouds, circulation and climate sensitivity as one of its grand challenges.

IP-10 did not specify individual variables that comprise the ECV group “Cloud Properties”, but GCOS (2011a) called in particular for satellite-based data products on cloud amounts, cloud-top temperature and pressure, and optical depth, primarily for cloud effects on radiation, and on the water paths and effective particle radii for liquid and ice, primarily for indication of onset of precipitation. Such products nevertheless may require careful interpretation because of the dependence of data on scene and sensing method. Passive remote sensing, for example, determines in general a ‘radiometric’ height that may lie as much as a few kilometres below the physical cloud-top height. Use of such data for evaluating models or in data assimilation may be based more on use of forward modelling to simulate the measurements than on use of data products, although interpretation or adjoint modelling are still needed to adjust the models or their initial states accordingly.

Observations of cloud from imagers measuring in the VIS to IR range, as well as from IR sounders, have been made for more than 30 years. Cloud liquid-water estimates over the ocean can be retrieved from the measurements made by MW imagers that have provided data over the same period. Important more-recent types of observation have been made measuring multi-angle reflection and polarisation, or radiances in the O_2 absorption band from nadir and limb viewing, and by active methods using lidar and profiling radar. The synergy of these observations, facilitated by the formation flying of several instruments in the A-train, is crucial for improving understanding of clouds. Additional information is provided in the review on page 243 of IP-10 Action A24 on research to improve observations of cloud properties.

Surface-based observations that may be reported in SYNOP messages are the amount, type and base height of clouds, visibility and present and past weather. There is a long history of manual observations of these elements, though with the move to instrumental observation some elements may no longer be measured while others may shift in character. Some of these observations nevertheless find use for the evaluation of model forecasts, reanalyses and satellite data products.

As is the case for other ECVs, satellite data, including products, are generally archived and supplied by the space agencies and their partners involved in either making the measurements or deriving the products. The cloud-related data in SYNOP messages are included in the ISD. A number of collections of surface synoptic data are also held and supplied by NCAR.

The WCRP International Satellite Cloud Climatology Project (ISCCP) has developed a continuous record of IR and VIS radiances, and derived cloud properties, now covering more than 30 years, utilizing both geostationary and polar orbiting satellite data to resolve a 3-hourly diurnal cycle. IP-10 Action A23 called for continuation of such a climate record, including reprocessing; it is reviewed on page 242. Further datasets such as PATMOS-x and CLARA, both based on AVHRR data, have also become available. Hyperspectral sounders are providing what is building up to be long-term additional information, especially on cirrus clouds, day and night.

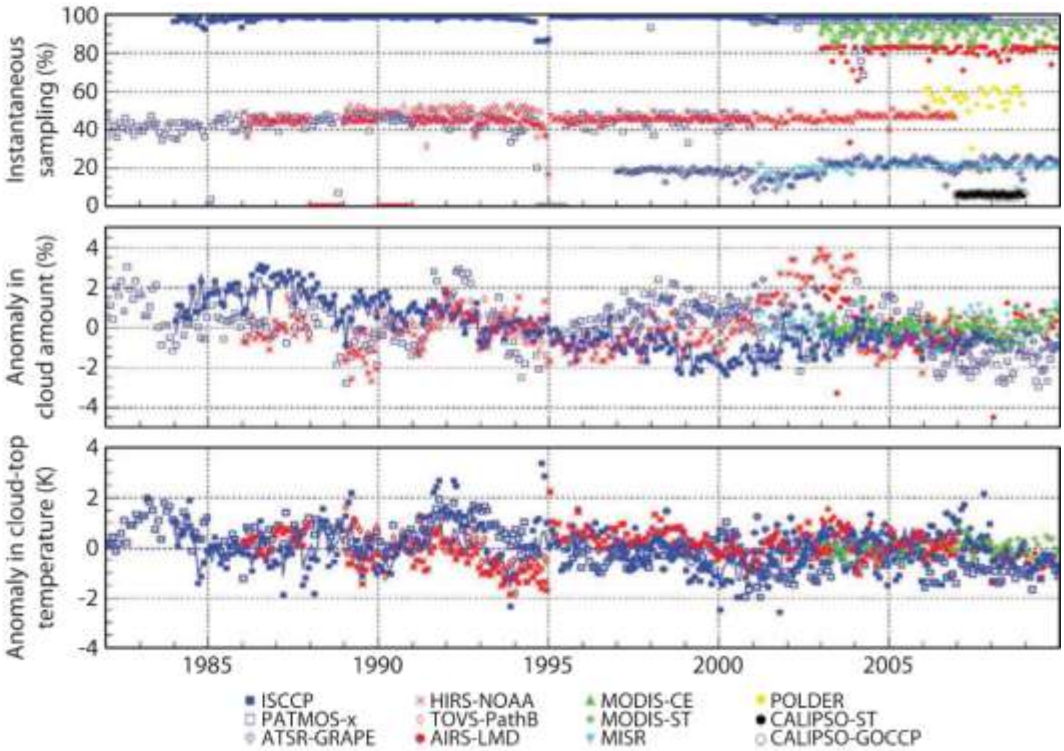


Figure 28: Time series of the monthly-mean instantaneous sampling fraction of the globe (at specific local observation times) of datasets considered in the GEWEX cloud assessment (top), and estimates of the global fractional coverage of cloud (middle) and cloud-top temperature anomalies (bottom). The period covered in the assessment database is shown for each dataset, with local observation time at 1330 LT, apart from ISCCP (1500 LT) and ATSR-GRAPE and MISR (1030 LT). ISCCP anomalies are also shown using all diurnal time statistics (blue line). Source: Stubenrauch et al. (2013).

The GEWEX Cloud Assessment (WCRP, 2012b; Stubenrauch *et al*., 2013) made a coordinated inter-comparison of global monthly gridded cloud products retrieved from measurements by space-borne multispectral imagers, IR sounders and lidar. Extending the providers' self-assessments, the GEWEX assessment has shown how cloud properties are perceived by instruments measuring different parts of the electromagnetic spectrum and how averages and distributions of these properties are affected by instrument choice and some methodological decisions. Although absolute values, especially for high-level clouds, depend on the capability of instruments or retrievals to detect or identify thin cirrus, the relative geographical and seasonal variations in cloud properties agree very well, with a few exceptions such as over deserts and snow-covered regions. Probability density functions of radiative and bulk microphysical properties also agree well, when retrieval filtering or possible biases due to partly cloudy pixels and ice-water misidentification are taken into account. Nevertheless, the study of long-term variations with these datasets requires consideration of many factors, which have to be carefully investigated before attributing any detected trends to climate change. Due to systematic variations of cloud properties with geographical location, time of day and season, any systematic variations in sampling of these distributions can introduce artefacts in the long-term record. Figure 28 shows the periods of availability and sampling of the assessed datasets, and variations over time of their estimates of anomalies in cloud amount and cloud-top temperature.

A database (http://climserv.ipsl.polytechnique.fr/gewexca/) was also established by the GEWEX Cloud Assessment to facilitate further assessments and use of the data products for evaluating models. This database will be updated as reprocessed or extended datasets become available. New versions of at least the ISCCP, MODIS, CALIPSO and AIRS products are expected. The ESA CCI Cloud Project (Hollmann *et al*., 2013) is preparing a new version of its 33-year data product derived from a multi-mission combination of data from AVHRR, MODIS, ATSR-2 and AATSR.

International coordination of activities will also continue under the International Cloud Working Group (ICWG) recently established by CGMS. The series of Cloud Retrieval Evaluation Workshops (CREWs) initiated by EUMETSAT will continue under the auspices of the ICWG. The work of the ICWG includes activities related to the evaluation of cloud retrievals and establishment of best practises. Coordinated evaluation of satellite-based estimates of cloud properties continues within CREW activities focussing on detailed Level-2 data comparisons over limited areas and time periods (e.g. Hamann *et al*., 2014) and within the ESA CCI.

4.5.5 Earth radiation budget

The primary observations related to the Earth's radiation budget are of solar irradiance, the external driver of the climate system, and of the almost compensating reflected solar and emitted longwave radiation that leaves the atmosphere. The observations are made from space, and continuity and stability of measurement are essential for detecting fluctuations and change. Imbalance between incoming and outgoing fluxes is estimated from the increase in heat content of the oceans to be about 0.6 Wm^{-2}, about 0.2% of the input from solar irradiance. This is smaller than the uncertainty of several Wm^{-2} in the measurements of outgoing radiation, which arises largely from uncertainty in absolute calibration. Measuring the variability of fluxes over the globe and over time nevertheless provides insight into the overall behaviour of the climate system, and provides data for the evaluation and improvement of climate models. This includes diurnal variations that can be used to identify biases in the radiation fields of numerical weather prediction models, contributing to the improvements of parameterizations for use in models in general.

Broadband measurements of outgoing radiation have been made since the 1970s. The CERES instrument on NASA's Terra satellite has provided data for more than fifteen years, with instruments also now flying on the Aqua and Suomi NPP platforms, and a final one scheduled for flight on JPSS-1.

Total solar irradiance (TSI) has also been measured since the 1970s. IP-10 noted considerable variation in the absolute values given by different instruments, with the lowest values provided by the latest mission then flying, SORCE. Figure 29 is an update of a figure presented in IP-10 that drew attention to this. It shows good agreement between the data from the SORCE/TIM instrument and subsequent data from the TCTE/TIM and PREMOS instruments. Recalibrated data from ACRIM3 and VIRGO are plotted in this version.

The sunspot number correlates well with TSI variations as shown in Figure 29; agreement with the UV component is even better. No satellite measurements are available from before 1980, but the observations of sunspot number go back to the 17th century and represent a valuable source of information for long term climate analysis.

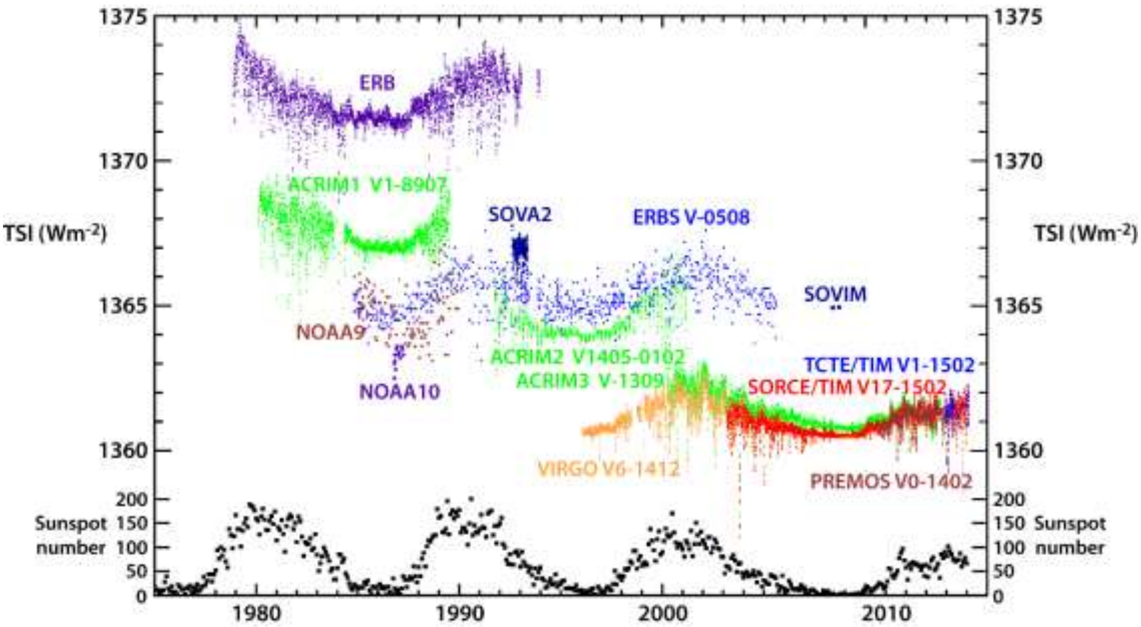


Figure 29: Total solar irradiance from multiple satellite missions and monthly sunspot numbers, from 1975 to 2015. Source: G. Kopp, 11 February 2015, downloaded from http://spot.colorado.edu/~koppg/TSI/.

The importance of variations of solar irradiance in the UV spectral range, which influence distributions of stratospheric ozone and thereby atmospheric temperature and dynamics, has been increasingly appreciated, including from the viewpoint of seasonal forecasting. IPCC (2013) noted that spectrally-resolved measurements during the declining phase of the solar cycle in the 2000s from the SIM instrument on SORCE were rather inconsistent with prior understanding, indicating a need for further validation and uncertainty estimates. Spectrally-resolved measurements of solar irradiances were not identified as a requirement in IP-10, but the need was recognised in GCOS (2011a).

Action A25 of IP-10 called for continued observation of the radiation budget of the Earth. The review of this action on page 244 includes discussion of what currently is, and is not, planned. Continuity has been achieved to date, but is at risk in the case of solar irradiance measurement, especially spectrally resolved measurement.

Data archives include that of NASA for CERES at: http://ceres.larc.nasa.gov and that for the data obtained from geostationary orbit by GERB at http://badc.nerc.ac.uk. The derivation of the flux products provided by these archives requires ancillary data. In the case of GERB they come from the multi-spectral imager (SEVIRI) on the same platform. The need is much more extensive, however, in the case of CERES, for which products are also provided at several levels in the atmosphere and for the Earth's surface (section 4.3.6). This can be seen from the description of how fluxes are computed that is provided at http://ceres.larc.nasa.gov.

The GEWEX Radiative Flux Assessment (WCRP, 2012a; see also section 4.3.6) considered top-of-atmosphere as well as surface fluxes. For the former it concluded that more work is needed on the uncertainties of upwelling short-wave fluxes, including further investigations of instrument calibrations and the effects of poor sampling of the rapid time variations induced by the Earth's rotation and variations in cloud. It also judged that further investigation of the role and quality of ancillary inputs is needed, most notably of data on surface albedo and temperature, and on atmospheric temperature and humidity. A further need is reprocessing of products to address specific identified issues, drawing on understanding of differences between the measurements from the ERBE, CERES, ScaRaB and GERB instruments.

4.6 Networks for atmospheric composition

The atmospheric composition ECVs as originally set out in GCOS (2003) comprised carbon dioxide, methane, ozone, other long-lived greenhouse gases and aerosol properties. The abundances of these gases and of aerosol species are each subject to anthropogenic influences as well as being influenced by variability and change in other variables of the climate system. They in turn influence the state of the climate as a whole through their effect on the radiation budget. Abundances depend on the direct emissions of the species concerned, and also on the emissions of chemically reactive precursor species, particularly in the case of ozone and aerosols. This was recognised in IP-10, which called for measurement and analysis of key precursor species. IPCC AR5 also gave greater emphasis than hitherto to the radiative forcing of climate change due to emitted compounds, illustrated in Figure 30. Some of the other long-lived greenhouse gases are also important because of the part they play in stratospheric ozone depletion. Air quality near the surface of the earth is determined by local concentrations of ozone, aerosols and some of the precursor species.

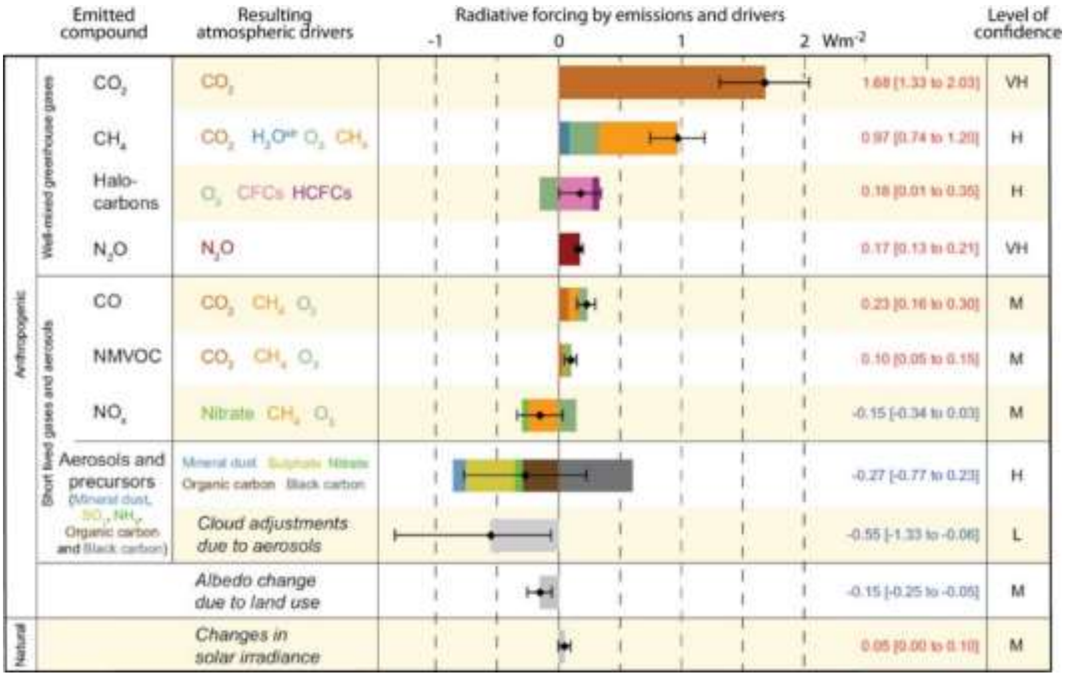


Figure 30: Radiative forcing (Wm^{-2}) of climate change partitioned according to emitted compounds and resulting atmospheric drivers. Source: IPCC (2013; Figure SPM.5).

A substantial set of networks provide *in situ* measurements and ground-based remote sensing of atmospheric composition, general aspects of which are discussed in this section. Space-based remote sensing provides comprehensive coverage for several variables, with varying degrees of capability and maturity. This is discussed ECV by ECV in the following section. Concern has been expressed already in the context of water vapour (section 4.5.3) over absence of substantial progress on IP-10 Action A26 calling for establishment of long-term limb-scanning satellite measurement; this applies also to several composition ECVs and other species whose stratospheric values can be measured in this way.

A network of measurement stations forms the backbone of the GAW Programme of WMO. This network comprises GAW-designated global and regional measurement stations and additional stations from contributing networks. The Global Stations can be seen in Figure 31 to be located in remote, coastal or mountain locations where they sample air that is largely free from influences of local sources. Emphasis is placed on quality assurance. Both the global and the regional stations are operated by their host countries, either by their national meteorological services or by other national scientific organisations. This involves more than 100 countries. Subsets of the GAW stations provide what have been recognised by the GCOS programme as baseline networks for carbon dioxide, methane, nitrous oxide and total ozone, and the majority of the baseline network for ozone profiles. A baseline network has yet to be proposed by GAW for any aerosol properties.

Figure 31: Global GAW Stations, October 2015. Source: WMO.

There are currently 30 GAW Global Stations and more than 400 GAW Regional Stations, supplemented by around 100 stations from the Contributing Networks. The Swiss-supported GAW Station Information System (GAWSIS) provides an interactive map-plotting facility that identifies station locations and provides links to their metadata. It covers the designated GAW stations, stations in the Contributing Networks that are designated as such on the basis of formal agreements with WMO, and stations from other networks with which there is cooperation. The Contributing Networks, as of October 2015, are AD-Net, ALINE, EARLINET, IDAF, IMPROVE, MPLNET, NADP and TCCON (http://www.wmo.int/pages/prog/arep/gaw/GAW_contr_networks.html). Appendix 8 includes network acronyms and links to web pages. Specific discussion is given later for some networks.

The Network for the Detection of Atmospheric Composition Change (NDACC; formerly the Network for the Detection of Stratospheric Change) comprises more than 80 research sites operating under a set of protocols. A protocol also covers arrangements for designated Cooperating Networks; these comprise AERONET, AGAGE, BSRN, GRUAN, HATS, MPLNET, SHADOZ, and TCCON. Site locations are illustrated in Figure 32. They show marked regional variations; absence of stations over the continental land masses of Africa and South and Southeast Asia is striking. It is also evident from comparing Figure 32 with Figure 31 or with station lists for the respective Contributing and Cooperating Networks that single sites may contribute to several networks. This is in part due to multiple agencies operating from the same site. The GCOS baseline ozone profile network includes some ozonesonde stations operating under the auspices of NDACC and SHADOZ that supplement the stations that operate under GAW.

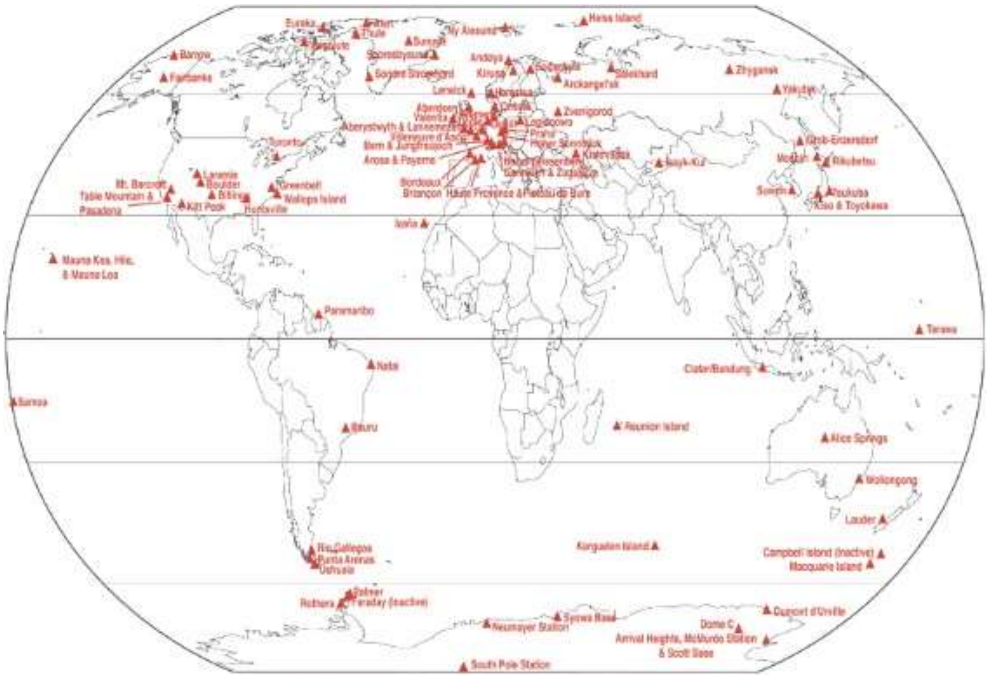


Figure 32: Stations forming the Network for the Detection of Atmospheric Composition Change (NDACC), October 2015. Source: NOAA, downloaded from http://www.ndsc.ncep.noaa.gov/clickmap/.

Surface *in situ* network measurements include cooperative programmes involving approximately weekly sampling of air using flasks whose contents are analysed for the international community by the US NOAA/ESRL, either for a set of greenhouse gases or for halocarbons and other trace species, with additional isotopic measurements made by the University of Colorado. Continuous surface *in situ* measurements from several networks also make important contributions. Ground-based remote sensing provides upper-air abundances of species. Related multi-ECV IP-10 actions are A27 concerning establishment of a network of ground stations using various remote-sensing approaches capable of evaluating satellite sensing of the troposphere, and A28 calling for maintenance and enhancement of the WMO GAW monitoring networks for carbon dioxide and methane. Reviews of these actions begin on page 246 of Appendix 1. Valuable data are also provided by *in situ* airborne sampling of species, involving measurements from a small number of specially equipped commercial airliners participating in the Japanese CONTRAIL and European IAGOS programmes, and measurements from dedicated flights of smaller aircraft. Sonde systems for measuring composition variables additional to ozone are under development.

Observations of surface air quality are made in many countries for monitoring and forecasting atmospheric pollution. Networked activities include those under the European Environment Agency, linking with Copernicus services related to atmospheric composition, and the North American AirNow system. Global network arrangements are not in place. The GAW programme includes an Urban Research Meteorology and Environment project.

Variables related to air quality are impacted by climate change among other factors, and their monitoring and forecasting requires and refines information on the emissions and deposition of chemically reactive species and aerosols. Such information is needed also for climate purposes. Data provided by contributing networks to GAW are available from the network data centres.

Station data on the atmospheric composition ECVs are served by a set of World Data Centres (WDC) that operate under the auspices of GAW. Centres operate for aerosols (the WDCA, hosted by Norway), for greenhouse gases and reactive precursor species (the WDCGG, hosted by Japan) and for ozone and UV radiation (WOUDC, hosted by Canada). A further GAW WDC operates for precipitation chemistry. The archiving arrangements for reactive gases are currently under review. Other sources of station data and related products are the NDACC data centre and suppliers linked to specific networks such as those of AGAGE, NOAA/ESRL and TCCON; a US institution is the host in each of these cases. NOAA/ESRL products include an Annual Greenhouse Gas Index based on combining the concentrations of the so-called long-lived (or well-mixed) greenhouse gases according to their various contributions to the radiative forcing of climate change.

The arrangements for archiving and serving space-based measurements and data products are discussed generally in section 3.4.8. Linked cross-ECV retrieved data-product activities include those of the ESA CCI, which covers four of the composition ECVs, namely carbon dioxide, methane, ozone and aerosol properties, the Copernicus Atmosphere Monitoring Service, which covers these ECVs and the precursor species, and the EUMETSAT SAF Consortium for Atmospheric Composition and UV Radiation. Atmospheric trace gases and aerosols are also two foci of the WDC for Remote Sensing of the Atmosphere.

One objective of observation of some species is to estimate their net surface sources and sinks through a “top-down” approach based on observationally estimated changes in atmospheric abundances and transport modelling. Where sources can be identified as anthropogenic, estimates of emissions from this approach can provide an important check on estimates provided by the “bottom-up” approach based on inventories of the human activities that cause emissions. This brings a need for denser regional *in situ* observation or space-based observation, depending on the species in question, as discussed in the following section for particular ECVs.

Data policies, timeliness, formats and so on are more diverse for composition than for other atmospheric ECVs, reflecting the more diverse character of the observing systems and operating arrangements. Much data comes from research networks with an assigned Principal Investigator (PI) for each contributing member station. Although data are increasingly made more openly available, they may come with various degrees of expectation or obligation on the user to acknowledge or liaise with the PI of a site from which substantial data use has been made, either because special care may be needed in data use or because due acknowledgment is especially important for measurements that are supported by sequences of short-term research grants. Although some observations are made promptly available and utilized either for public communication or in support of monitoring and forecasting activities that operate in close to real time, many are delivered to data centres with delays of several months or more. It is not always made clear in lists or maps of sites that a station is shown because past data are available even though it has ceased operation. Moreover, data from data centres are generally more easily accessible by station rather than by observation time. All this makes overall network monitoring and assessment of current status more difficult for the composition variables.

Scientific Advisory Groups (SAGs) are organised by GAW on a variable by variable basis, largely mirroring its World Data Centre structure, though with separate SAGs for greenhouse and reactive gases. NDACC takes the alternative approach of having working groups on the various types of measurement and on theory and analysis. Biennial WMO/IAEA meetings on Carbon Dioxide, Other Greenhouse Gases and related Measurement Techniques provide a forum for international discussion of topics that include developments of the greenhouse-gas networks, site updates, measurement techniques and calibration, emerging techniques, standards and the integration of observations, data products and policy.

4.7 Composition variables

4.7.1 Carbon dioxide

Carbon dioxide (CO_2) is a naturally occurring greenhouse gas, but one whose abundance has been increased substantially above its pre-industrial value of some 280 ppm by human activities, primarily because of emissions from combustion of fossil fuels, deforestation and other land-use change. These took values to around 340 ppm by the early 1980s. Growth has continued since then, as illustrated in Figure 33, with values exceeding 400 ppm now recorded early in the year over the extratropical northern hemisphere. NOAA/ESRL's global average of values from marine surface stations exceeded 400 ppm in March 2015. Somewhat lower values over the southern hemisphere are a consequence of emissions that are larger in the northern hemisphere. The annual cycle in the northern hemisphere is primarily due to natural biological variations, with carbon dioxide taken up by photosynthesis in the growing season but released throughout the year by respiration. Release by wildfires varies seasonally.

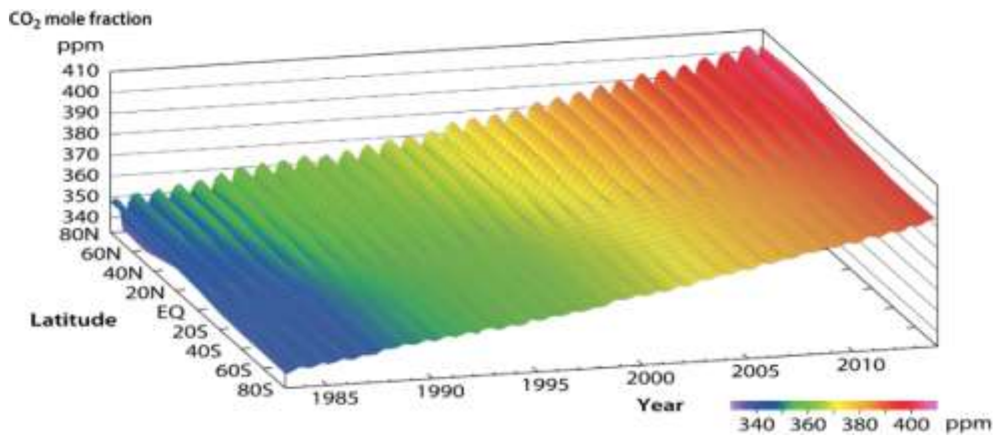


Figure 33: Variation with latitude and time of zonally averaged monthly-mean CO_2 mole fractions, from an analysis of data submitted to the World Data Centre from Greenhouse Gases (WDCGG), Japan Meteorological Agency. The zonally averaged mole fractions were calculated for 20^o latitude bands based on station data shown later in Figure 93. Source: Plate 3.1 of the annual issue of the Data Summary published in March 2015 (WDCGG, 2015).

Figure 30 shows the increase in CO_2 to be the predominant contributor to the radiative forcing of climate change, mostly due to direct emissions of the gas. Estimates of these emissions and of increased uptake of CO_2 by the ocean indicate that around 45% of the amount of CO_2 emitted by human activities has accumulated in the atmosphere, with the remainder taken up by the ocean and by natural terrestrial ecosystems in approximately equal measure. Uncertainties in the regional uptake over land are generally large.

Measurements of CO_2 are required in the first place to monitor the overall rate of accumulation of the gas in the atmosphere, for which careful measurement at a number of well-chosen surface sites is adequate. Denser and more widely located *in situ* sampling or observation from space supported by ground-based remote sensing are needed to improve understanding and monitoring of regional carbon budgets. Isotopic measurements and observations of supplementary atmospheric variables such as the oxygen/nitrogen ratio, carbon monoxide, carbonyl sulphide and long-lived tracer gases (section 4.7.3) also contribute to knowledge of emissions and sinks. Analyses of CO_2 distributions can also improve the extraction of information on temperature and water vapour from the space-based IR sounding data used in numerical weather prediction and reanalysis, and improve specifications in models that do not include an explicit carbon cycle.

Figure 34 presents the locations of fixed stations and ships for which surface data for monthly-mean mole fractions of CO_2 have been submitted to the WDCGG. This includes sites that do not currently report. Many of the sites shown are members of the NOAA/ESRL Cooperative Air Sampling Network. Station coverage for this network can be seen at http://www.esrl.noaa.gov/gmd/ccgg/flask.php. The NOAA network has more sites in the USA than shown in Figure 34, and some additional ones elsewhere, but coverage over Europe is poorer. The network of the European Integrated Carbon Observing System (ICOS) also includes sites additional to those shown in Figure 34. Coverage of the data reported to WDCGG is generally sparse or non-existent over western and central Asia and the interiors of South America, Africa and Australia, a factor causing uncertainty in estimates of regional terrestrial sources and sinks from flux inversions using surface observations. Network maintenance and enhancement is discussed further in the review of IP-10 Action A28 on page 247.

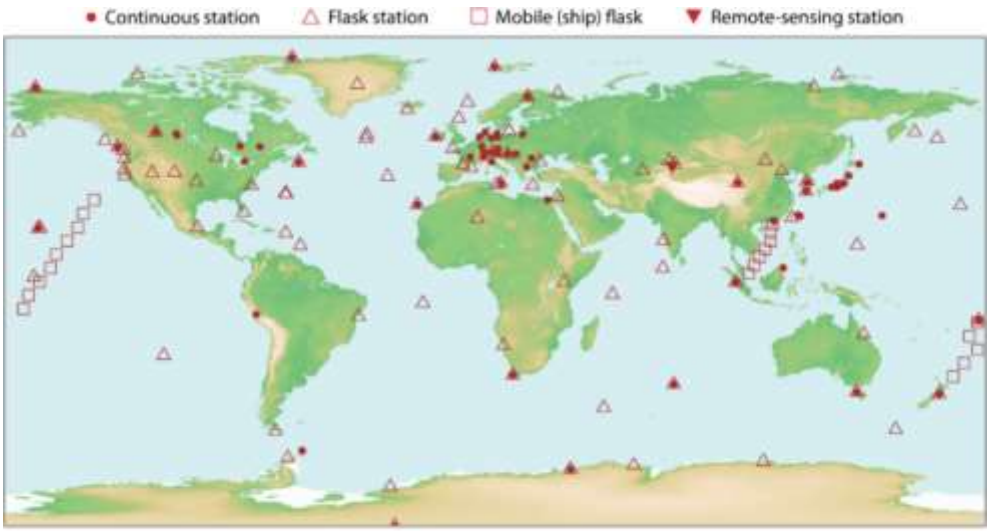


Figure 34: Locations of the stations for which data for monthly mean mole fractions of CO_2 have been submitted to the WDCGG, and types of measurement. Source: WDCGG (2015).

Satellites provide an increasingly important component of the overall observing system for CO_2. Atmospheric column data on CO_2 derived from measuring the spectra of reflected solar radiation have been derived from SCIAMACHY, which provided data for some ten years until 2012. Data of higher precision are provided at present by the dedicated greenhouse-gas missions GOSAT, launched in 2009, and OCO-2, launched in 2014. IP-10 Action A29 called for assessment of space-based data on CO_2 (and methane) and for development of follow-on missions. It is reviewed on page 249. Supplementary information for the middle-to-upper troposphere at tropical and sub-tropical latitudes is provided by high-resolution IR sounders.

Estimation of the net sources and sinks of CO_2 through inversion utilizing surface measurements of gas concentrations dates back to the 1980s. The NOAA/ESRL CarbonTracker facility provides estimates of CO_2 (and methane) fluxes, together with substantial supporting information. There are a number of other regionally based Carbon Trackers, including a European version of CarbonTracker operating as a Wageningen University contribution to ICOS, CarbonTracker-Asia and CarbonTracker-China. A CarbonTracker Australasia is under construction. Flux estimates for CO_2 (together with methane and nitrous oxide) are also among the set of products provided by the Copernicus Atmosphere Monitoring Service. While results broadly agree with bottom-up flux estimates, they nevertheless have considerable uncertainties.

Basu *et al*. (2013) and Maksyutov *et al*. (2013) present first estimates of surface fluxes derived from total-column retrievals of data from GOSAT. Used alone in inversions the GOSAT data give results consistent with but not superior to those from the surface networks, but they have significant impact on flux estimates for the tropics and southern extratropics when used together with the surface data. Using the resulting fluxes in model runs improves the fit in the northern extratropics to column-average data from the TCCON ground-based FTIR network (see review of IP-10 Action A27, page 246), but the presence of biases in the GOSAT retrievals is nevertheless a continuing issue. A recent comparison of CO_2 flux estimates based on GOSAT-based inversions and those from up-scaling from measured eddy covariance fluxes show good agreement in boreal and temperate regions across the Northern Hemisphere but poor agreement in the tropics due to limited eddy flux data for tropical biomes (Kondo *et al*., 2015).

4.7.2 Methane

Methane (CH_4) is the second most significant of the greenhouse gases that have increased in concentration in the atmosphere directly due to human activities, from the viewpoint of the radiative forcing of climate change (Figure 30). Its mole fraction has increased from a pre-industrial level of around 700 ppb to current levels that are around 1900 ppb at high northern latitudes and approach 1800 ppb at the South Pole, as illustrated by measurements at two stations shown in Figure 35.

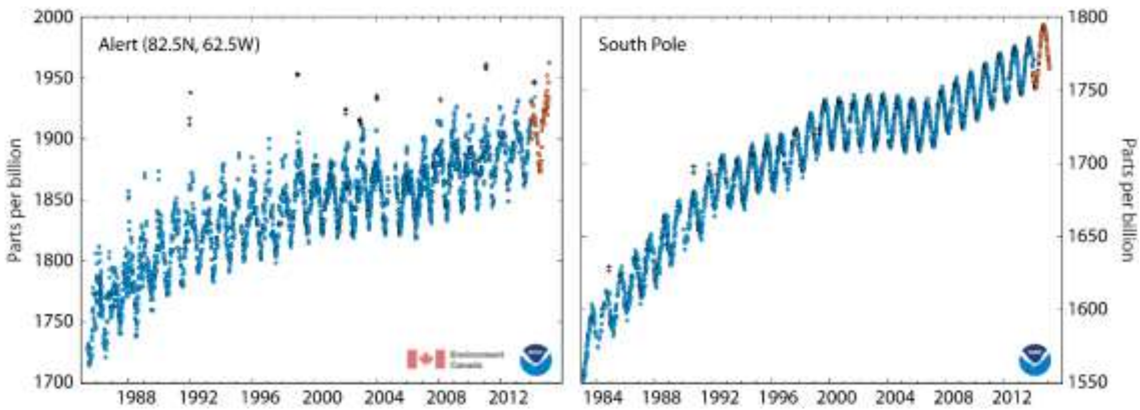


Figure 35: Mole fractions of methane (ppb) measured from flask samples taken at Alert (82.5N, 62.5W) and the South Pole. Blue circles denote data thought to be regionally representative of a remote, well-mixed troposphere. Black crosses denote data not thought to be indicative of background conditions. Data shown in pink are preliminary. All other data have undergone quality assurance and are freely available from NOAA/ESRL/GMD, CDIAC and the WDCGG. Source: NOAA/ESRL, 25 April 2005.

Somewhere between 50 and 65% of the methane emitted into the atmosphere comes from anthropogenic sources such as ruminant livestock, rice cultivation, fossil-fuel use, landfills and biomass burning. Natural sources include wetlands, wildfires and termites, and themselves are affected by climate variability and change. Future emissions of methane (and CO_2) from the melting of permafrost and warming of sub-ocean clathrates may amplify climate change, but are subject to considerable uncertainties.

The atmospheric sink of methane is through oxidation, either in the troposphere where it influences the level of ozone and is influenced by the emissions of other species (Figure 30), or in the upper stratosphere where it is a source of water vapour and affects the concentration of ozone. Methane also plays a key role in the conversion of reactive chlorine to less-reactive HCl in the stratosphere.

The lifetime of methane in the atmosphere is around a decade, much longer than ozone but much shorter than CO_2. The gas is variously described as either short-lived or long-lived; both descriptions can be found in IPCC (2013). The seasonal variation in methane at high southern latitudes, illustrated in Figure 35, is more marked than for CO_2, and is linked to a seasonal variation in oxidation. Methane has less seasonal variation at tropical and subtropical southern latitudes (WDCGG, 2015).

Figure 35 shows considerable fluctuations in the rate of growth of methane over the past three decades. Growth slowed in the 1990s, ceased from 2000 to 2007, and then continued at a steady rate similar overall to that of the 1990s. The same can be seen in plots based on sets of stations within latitude bands included in WDCGG (2015). The reasons for this behaviour were reported by IPCC (2013) as being “still debated”.

Much of the preceding discussion of the observation of CO_2 applies also to methane. In particular, the distribution of stations supplying surface measurements of methane to the WDCGG is similar to that shown for CO_2 in Figure 34. Methane data are reported for slightly fewer stations, but a slightly higher fraction of the data pass the quality-control checks that WDCGG applies before using data in analyses (see review of IP-10 Action A28 on page 247). The TCCON network provides column abundances and some limited profile information for methane, as it does for CO_2 (and indeed for other species including carbon monoxide, nitrous oxide and water vapour). High-resolution IR space-based sounding provides middle-to-upper tropospheric information at tropical and sub-tropical latitudes for methane as well as for CO_2.

Use of satellite data to improve estimates of surface fluxes is better established for methane than CO_2. Estimates of about ten-year duration have been made using retrievals from SCIAMACHY together with measurements of surface values, and compared with those using the surface data alone. Houweling e*t al*. (2014) report one such study, using TCCON and aircraft data to emphasise the importance of bias adjustment of the SCIAMACHY retrievals, and showing that use of the bias-adjusted retrievals implies larger tropical emissions than estimated using surface data alone. Their and other inversions using SCIAMACHY data point to increased emissions from the tropical band as being primarily responsible for the renewed growth in methane concentration around 2007. Comparisons with inversions based on retrievals from the current GOSAT mission (e.g. Alexe *et al*., 2015) show good agreement with those based on bias-adjusted values from SCIAMACHY, the GOSAT data being more precise and less biased, but sparser. The OCO instrument does not sense methane, but several new missions that will do so are under development, as discussed in the review of IP-10 Action A29 on page 249.

4.7.3 Other long-lived greenhouse gases

The ECV “Other long-lived greenhouse gases” refers to a set of gases additional to carbon dioxide and methane that are classified as having atmospheric lifetimes of at least a few years. The term “well-mixed” is also used to characterise them and may be preferred: see Box 8.2 of IPCC (2013) and use of the term in Figure 30. Stratospheric distributions of these species may nevertheless exhibit quite substantial spatial variations, either because of the multi-year time scale of much of the transport and mixing across the region or because of localized photochemical reactions. It is important to measure this set of gases because some already contribute appreciably to the radiative forcing of climate change due to increases in concentration since the pre-industrial era, as illustrated in Figure 30, whilst others are increasing rapidly in concentration and have a strong potential to enhance warming if their emission continues unchecked. Some also have to be monitored because they deplete ozone in the stratosphere. This has to continue for the species that are subject to emission controls under the Montreal Protocol, as their lifetimes are long.

The set of gases include nitrous oxide (N_2O), sulphur hexafluoride (SF_6) and groups of species categorised as chlorofluorocarbon (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs) and perfluorocarbons (PFCs). All have anthropogenic sources and none has a substantial tropospheric sink. Only N_2O has a significant natural source. N_2O, the CFCs and the HCFCs are the species involved in ozone depletion.

N_2O is now the most significant individual greenhouse gas within the set, having exceeded CFC-12 in radiative effect following controls on the latter. It is associated strongly with the nitrogen and carbon cycles and is increasing in the atmosphere mainly from the use of fertilizers. Its atmospheric lifetime is well over 100 years, as stratospheric removal processes are slow. Its mixing ratio in the atmosphere is about 1000 times smaller than that of CO_2, but its global warming potential per unit mass is some 300 times greater over a 100-year time horizon.

The well-mixed nature and general absence of natural sources and sinks means that high-quality measurements from a small network of stations are sufficient for monitoring the tropospheric abundances of this set of gases, although a larger network and isotopic measurements are needed for N_2O to help understand the working of source mechanisms and to distinguish natural sources (which may themselves change as climate changes) from anthropogenic ones. The primary global networks are those of AGAGE and NOAA/ESRL. AGAGE provides data from fewer stations but for a larger number of species, including NF_3, which has been added recently to the list of gases for which reporting is required under the UNFCCC.

Figure 36 presents examples from NOAA/ESRL data for N_2O, SF_6 and several halocarbons. Time series are presented for a set of thirteen stations for which data on the chosen species were openly available for downloading. Not all are from remote locations providing data that are generally free from influences of nearby sources, as can be seen from the spikes in the flask data for HCFC-22 and HFC-134a; variations from stations influenced in this way may in fact be utilised together with other regional data in “top-down” estimation of emissions, as shown for HFC-134a by Hu *et al*. (2015) using data from a set of flask sites and aircraft measurements over the contiguous USA. This included three of the sites used in Figure 36, one of which (Trinidad Head) was responsible for the most prominent spikes seen in the figure.

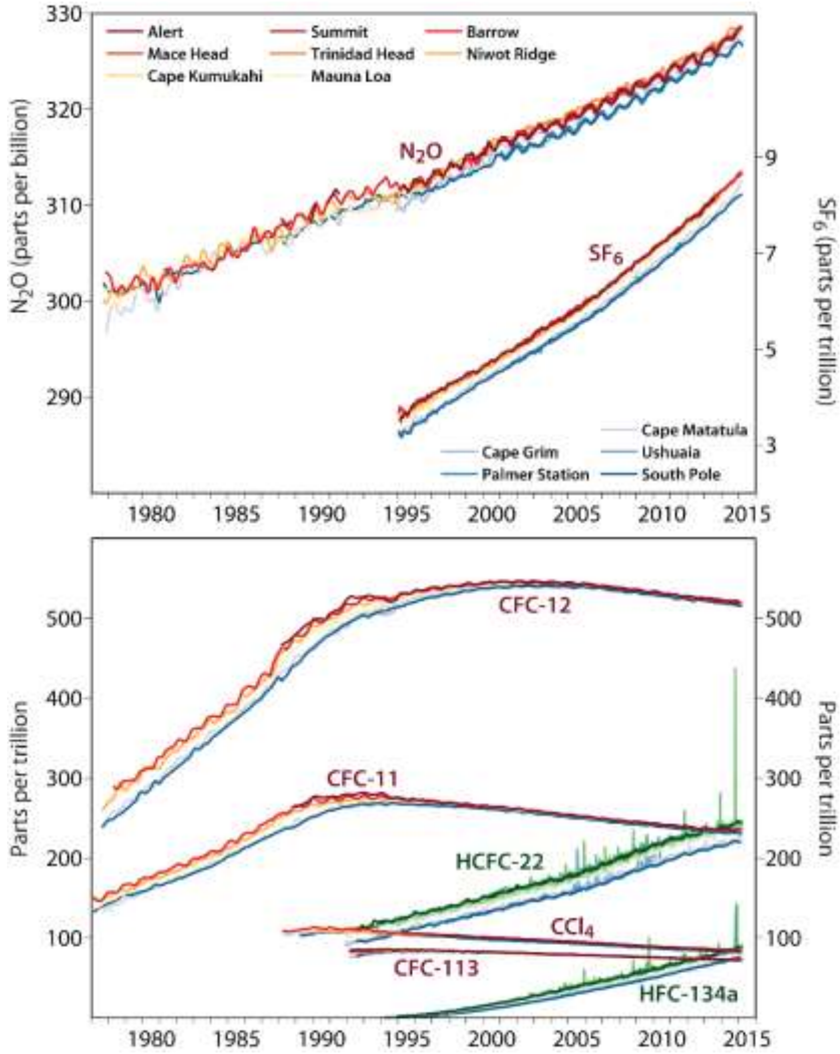


Figure 36: Mole fractions of N_2O (upper panel, left scale; ppb) and SF_6 (upper panel, right scale; ppt) and of six halocarbons (lower panel; ppt) from measurements at a set of thirteen stations in the northern (upper legend) and southern (lower legend) hemispheres. Green colouring is used for the northern hemispheric values of HCFC-22 and HFC-134a, which are plotted using flask data for specific dates. Data for the other variables are monthly values combined from two or more measurement programmes. Data were downloaded from http://www.esrl.noaa.gov/gmd/hats/flask/flasks.html on 17 April 2015.

Generally, however, Figure 36 shows coherent behaviour from station to station, particularly from 1995 onwards following introduction of a new flask system by NOAA. The differences in values between sites in the northern and southern hemispheres seen for species whose concentration grows over time is a clear indication of the predominance of northern-hemisphere sources; the gases concerned are well but not completely mixed globally. N_2O shows a small degree of seasonality. The peaking and subsequent slow decline in concentrations of the CFCs and CCl_4 are evidence of the effectiveness of controls imposed under the Montreal Protocol; HCFC-22 is also a controlled species, but its production and consumption are specified to be phased out completely only from 2030. Plots showing similar results for other stations, and measurements of other variables, can be found at agage.mit.edu/data/agage-data. IP-10 Action A30 (see page 249) called attention to the need to maintain networks for measuring N_2O, SF_6 and the other (halocarbon) species.

Observing the spatial and temporal variability of some of the gases that make up this ECV is important in the stratosphere, not only because some continue to deplete ozone but also because some act as tracers that provide information on the 'age' of stratospheric air, the time since that air was last in the troposphere, a measure of the strength and structure of the Brewer-Dobson circulation. IPCC (2013) expressed low confidence in the existence of long-term changes in several aspects of the global circulation, including the Brewer-Dobson circulation, because of either observational limitations or limited understanding. This was notwithstanding evidence from projections that the circulation is likely to strengthen in a warming climate, with implications for the distributions of ozone and other species.

Ground-based FTIR measurements provide monitoring of N_2O in the stratosphere. Stratospheric data on N_2O (and other species) have also been provided by limb-sounding and occultation measurements from space, such as from ACE-FTS on SCISAT and MLS on Aura. Limited provision for the continuation of limb measurement called for in IP-10 Action 26 is noted in several places in this report. I*n situ* upper-air measurements of N_2O and SF_6 are made from flask samples taken during flights of aircraft in the CONTRAIL fleet.

The annual data summary produced by the WDCGG includes sections on N_2O and on the halocarbons and other halogenated species.

4.7.4 Ozone

Ozone (O_3) is a short-lived greenhouse gas whose changes since the pre-industrial era due to emissions of precursor species contribute to a tropospheric radiative forcing that is larger than that of N_20 but less than that of methane (Figure 30). Ozone is a harmful pollutant when present near the Earth's surface.

Ozone is also the most important radiatively active trace gas in the stratosphere and essentially determines the vertical temperature profile there. Ozone limits the amount of harmful UV radiation reaching the surface. Chemical depletion of stratospheric ozone, and ozone chemistry more generally from the surface to the mesosphere, are influenced by atmospheric temperature, by several of the species covered by the atmospheric composition ECVs and by polar stratospheric clouds. Ozone is influenced by atmospheric dynamics, but in turn influences dynamics via radiative heating. Chemical depletion caused low springtime values of ozone to develop increasingly in the 1980s and 1990s over or near the South Pole (forming the so-called ozone hole). Behaviour over that period and since is also characterised by marked interannual variations, as illustrated in Figure 37.

There are accordingly wide-ranging needs to observe ozone from the ground and from space. It has to be monitored in its guises of greenhouse gas, near-surface pollutant and stratospheric shield against UV radiation. Observation is needed in a climate context to build further scientific understanding, including of links with temperature and circulation and their coupling with chemistry. It is needed to evaluate models and for assimilation in global reanalysis systems. It is needed for provision of services supporting policy relating to emissions of precursor species, production of ozone-depleting substances and protection of health and ecosystems. Observations of ozone also meet shorter-term needs, finding use in air-quality monitoring, in initialising and evaluating air-quality forecasts and in short-term regional reanalysis systems that provide support for policy on air quality. Observations are also needed for monitoring incoming UV radiation at the surface and for initialising a range of global forecasting systems. Ground-based ozone observations are essential for the validation of satellite products and for ensuring consistency of satellite observations in the transition periods between missions.

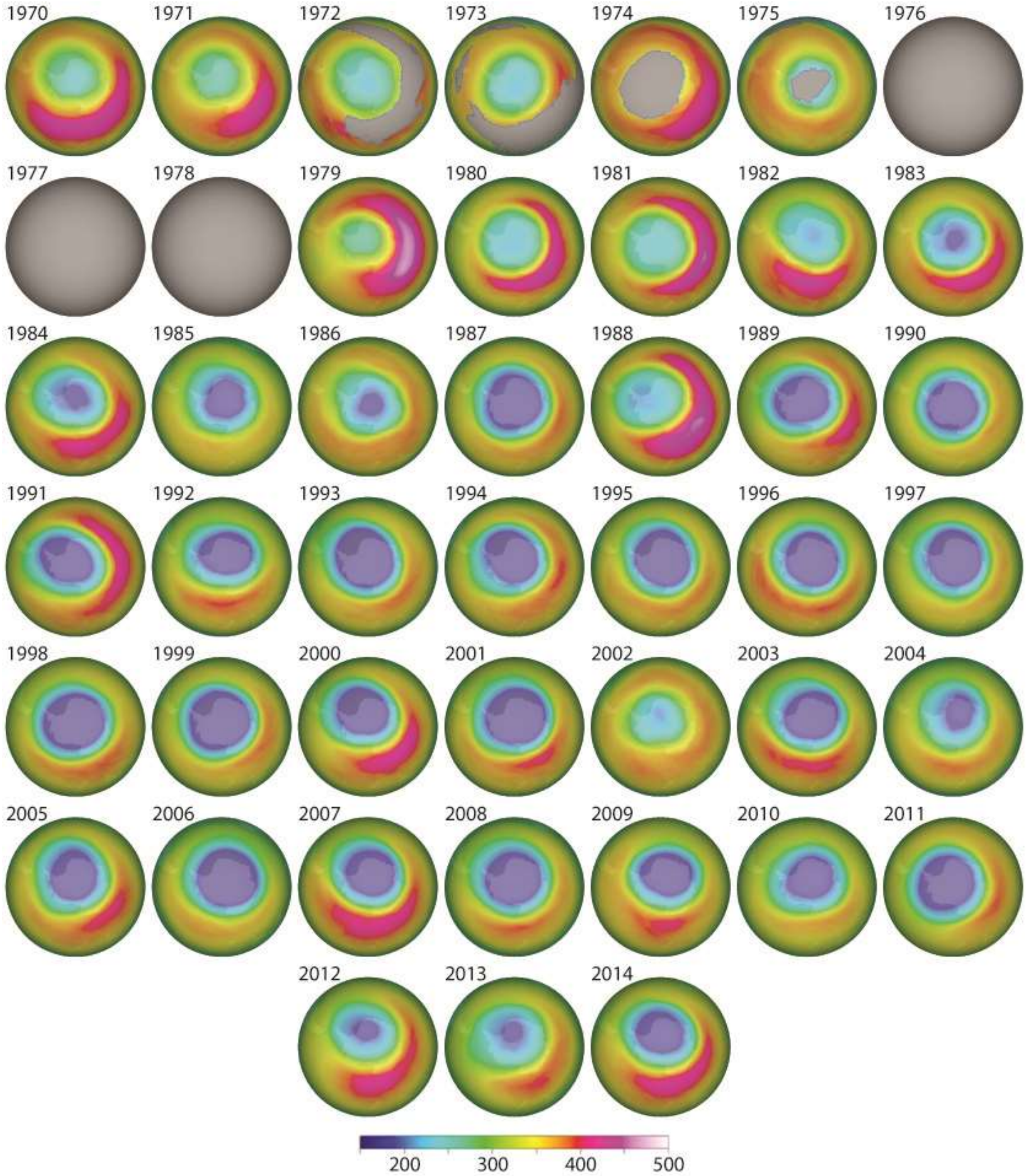


Figure 37: Monthly-mean total-column ozone (Dobson units) for October over the southern hemisphere from 1970 to 2014. Grey shading indicates lack of data. From the KNMI contribution to the pre-operational Copernicus Atmosphere Monitoring Service (van der A et al., 2015). Source: maps downloaded from http://www.temis.nl/protocols/o3hole/o3_history0.php.

The longest data records are from ground-based measurement of total ozone using spectrophotometers, which dates back to the 1920s using Dobson instruments and the 1980s using Brewer instruments. Regular calibrations and inter-comparisons with standard instruments are carried for the Dobson and Brewer sites managed by GAW, which form the designated baseline network for total ozone. Other ground-based measurements of total ozone are provided by filter ozonometers and by FTIR, SAOZ and DOAS instruments. IP-10 Action A31 called inter alia for the quality of the baseline GAW network of Dobson and Brewer instruments to be maintained, and coverage to be improved in the tropics and southern hemisphere. This has not happened: network coverage has in fact declined, as discussed in the review of the action (page 250).

Vertical profiles of ozone have been measured *in situ* by balloon-borne ozonesondes since the 1960s. Stations in the GCOS-designated baseline network are drawn from three networks: GAW, NDACC and SHADOZ. This composite network has also declined; discussion is included in the review of Action A31. Profile information is additionally provided from the Brewer and Dobson spectrometers using the Umkehr method, and from FTIR and lidar instruments. Ozone is one of the trace species for which tropospheric profiles are provided from the ascent and descent paths of the IAGOS fleet of instrumented commercial aircraft.

The total column measurements provide information on ozone trends and data that are used for evaluation or bias adjustment of satellite data products and reanalyses. They were used for bias adjustment in the reanalysis shown in Figure 37, for example. The detailed but more-sparse ozone profile information is important for studies of atmospheric processes, for calculating stratospheric trends, for calculating the radiation balance and for evaluating other data products, including those from operational prediction and reanalysis. High-resolution ozone profiles are especially important in the upper troposphere and lower stratosphere, where ozone changes rapidly in the vertical. Figure 38 compares sample ascents with corresponding profiles based on assimilating satellite data. The first two show the South Pole ozone-hole and a northern high-latitude low-tropopause example; the third is simply one of the latest European soundings received on the GTS at the time of writing.

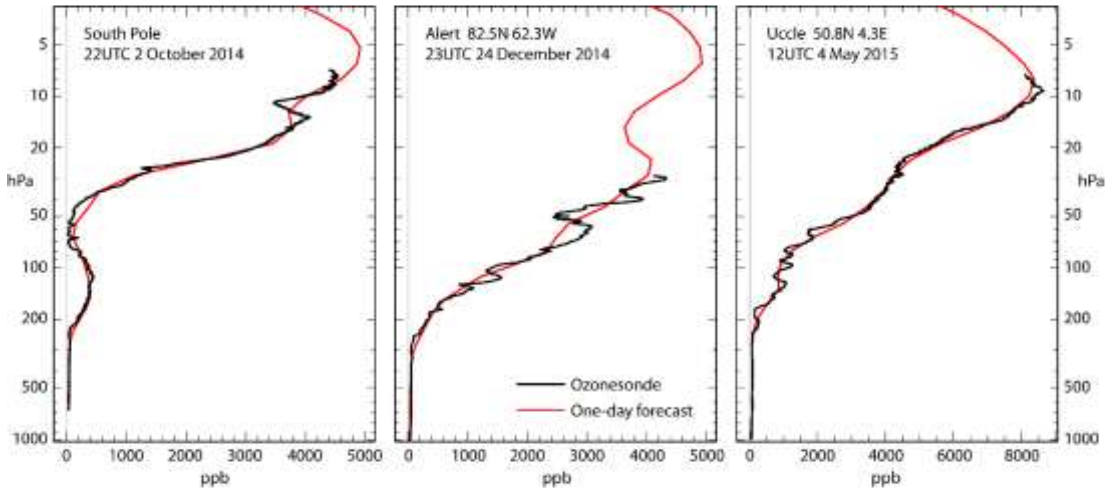


Figure 38: Sample vertical profiles of ozone mixing ratio (ppb) as measured by ozonesondes (black) and from pre-operational Copernicus Atmosphere Monitoring Service short-range (<24 h) forecasts (red) initialised using assimilation of ozone-profile satellite data from MLS (on Aura) and SBUV/2 (on NOAA-19) and total-column ozone satellite data from OMI (on Aura) and GOME-2 (on Metop A and B). See Inness et al. (2015) for further details of the data assimilation system and discussion of tropospheric ozone and precursor species.

Ozone has been measured from space since the 1960s. The multi-sensor reanalysis shown in Figure 37 utilises total-column ozone retrievals from measurements of backscattered solar radiation by UV or UV/VIS spectrometers that range from a BUV instrument on Nimbus-4 in 1970, through TOMS, SBUV, GOME, SCIAMACHY and OMI instruments to GOME-2 on Metop-A and -B. Nadir measurements are also currently made by OMPS. Extensive as this record is, the gap from 1976 to 1978 seen in Figure 37 is not because measurements were not made: a BUV instrument flew on the Atmosphere Explorer-E satellite from late 1975 into 1981, but its radiance data were not preserved in NASA archives for reprocessing (Bhartia *et al.*, 2013).

Several of the instruments listed above deliver vertical-profile information from nadir viewing. Ozone products with higher vertical resolution are provided by limb-viewing of MW and IR emission, solar and stellar occultation and backscattered UV/VIS radiation (including observations undertaken using SCIAMACHY and OMPS as a complement to their nadir viewing). Additional data, though subject to cloud effects, are provided by nadir-viewing IR sounders, notably modern hyperspectral instruments but also the longstanding HIRS instrument, either as instrument-specific products or assimilated in numerical weather prediction and reanalysis systems. The most recent scientific assessment of ozone depletion (WMO, 2014b) provides an almost complete list of the individual satellite instruments concerned. The limited provision for future limb-scanning is discussed in the review of IP-10 Action A26 on page 245.

Most ozone measurements use sunlight and are thus restricted to daytime. Thermal emission and stellar occultation measurements have a particularly important role in measuring ozone at high latitudes during the polar night. A near-full moon can nevertheless provide a sufficient source for ground-based spectrophotometers to provide total-column ozone a few days each month.

Ozone data products are obtained both from retrievals based on individual instruments or groups of instrument, and from data assimilation. Observations of precursor species (discussed in section 4.7.6) help to improve the analysis of tropospheric ozone in comprehensive assimilation systems. IP-10 Action A32 called for continued production and assessment of satellite ozone data records and the reconciliation of residual differences between datasets; it is reviewed on page 252.

Data-centre and advisory arrangements are mainly as already outlined in general for atmospheric composition and satellite data products. Reflecting the different roles played by ozone in the stratosphere, free troposphere and surface, some arrangements for ozone go beyond those nominally dedicated to ozone. Thus the responsibilities of the GAW Scientific Advisory Group for Reactive Gases include tropospheric ozone, and until now the WDCGG has reported on its holdings of surface ozone data.

4.7.5 Aerosol

Atmospheric aerosols are minor constituents of the atmosphere by mass, but a critical component in terms of impacts on climate, and especially climate change. Aerosols influence the global radiation balance directly by scattering and absorbing radiation, and indirectly through influencing cloud reflectivity, cloud cover and cloud lifetime. IPCC (2013) identifies anthropogenic aerosols, including those formed following emissions of precursor species, as the constituents responsible for the greatest uncertainty in the radiative forcing of climate change in the troposphere since the pre-industrial era, as illustrated in Figure 30. AR5 lists this as a key uncertainty “despite a better understanding of some of the relevant atmospheric processes and the availability of global satellite monitoring.”

Tropospheric aerosols are important for other reasons. They can be injurious to health, especially the smaller particles that are estimated to cause around 4 million premature deaths per year (WHO, 2015), and can disrupt air traffic. Long-range transport of dust redistributes mineral nutrients. Whether of natural or anthropogenic origin, the impacts of aerosols may change as climatological conditions such as circulation and rainfall change.

Stratospheric aerosol varies naturally due to episodic volcanic injections of aerosol or its precursor gases (particularly SO_2) and can have large short-term impacts on climate. It is important due to its impact on radiative forcing, warming the lower stratosphere and cooling the troposphere. Its impact on stratospheric chemistry can produce a further impact on climate through change in the distribution of ozone. High values also need to be taken into account in assimilating radiances in reanalysis and in other interpretations of radiance data records, to avoid confusing aerosol and water-vapour signals in the data from some IR channels. Understanding and monitoring the role of stratospheric aerosol in climate is also important as artificial enhancement has been proposed as one of the geoengineering approaches to offsetting tropospheric warming due to increased greenhouse gases, although the artificial aerosol properties may be somewhat different from natural ones.

Observations of aerosols are needed not only because of their direct importance for climate and health, but also because they support applications such as the forecasting of surface air quality, weather and volcanic ash, and services for solar power generation from siting through to yield estimation and monitoring, including effects of deposition of dust as well as changes in insolation. Observations are needed to improve understanding of the role of aerosols in cloud chemistry, in gas-to-particle reactions and in physical cloud and precipitation processes, and related dynamics. They also need to be taken into account in retrieving information from space-based measurements on other ECVs such as trace-gas concentrations and some land and ocean properties, ocean colour for example.

The consolidated ECV table in IP-10 simply refers to this ECV as “aerosol”, whereas the discussion of the ECV itself goes under the title of “aerosol properties”, a more appropriate one given the variety of particles and characteristics involved. GCOS (2011a) noted that various measures of aerosol properties were possible, but focussed on four for products generated from spaced-based data:

- optical depth
- single-scattering albedo
- layer height
- extinction profiles for the troposphere and the lower to middle stratosphere

Taking into account scientific needs, the increasing maturity of aerosol programmes at a number of stations and the improvement of *in situ* instruments for measuring aerosol properties, GAW (2011) recommended a more comprehensive list of variables for long-term measurement at stations in its global network:

- multi-wavelength optical depth
- mass concentration in fine and coarse size fractions
- mass concentration of major chemical components in two size fractions
- light absorption coefficient at various wavelengths
- light scattering and hemispheric backscattering coefficient at various wavelengths
- number concentration

- number size distribution
- cloud condensation nuclei number concentration at various super-saturations
- vertical distribution of aerosol backscattering and extinction
- detailed size fractionated chemical composition
- dependence of aerosol variables on relative humidity, especially aerosol number size distribution and light scattering coefficient.

Despite this recommendation, the GAW website in October 2015 notes that not all GAW stations are able to measure all the aerosol variables recommended above, and that outside Europe and North America there are [only] 15 sites that are categorized as aerosol chemistry sites by GAW. A check on the holdings of the WDCA, made in May 2015, shows data on particle number concentration from 29 GAW stations of which only four were outside Europe and North America. For particle number size distribution, WDCA holds data from 25 GAW stations, all of them European. The GAWSIS shows station numbers of a little over forty for measurement of these two variables, again with the majority over Europe and North America for number concentration and over Europe alone for number size distribution.

Nevertheless, the provision of climate-relevant aerosol data has been substantially improved over the past ten years. In 2014, more than 65 sites worldwide were providing at least one of the three aerosol properties particle size distribution, particle scattering coefficient and particle absorption coefficient. The number of such sites was less than ten prior to 2004. Data quality and traceability has been considerably improved with adoption by the GAW community of standard or inter-comparable protocols and common formats for data and metadata. As borne out by the WDCA holdings, this network expansion has been mainly in North America and Europe; expansion remains to be completed in other regions.

Geographical coverage and station numbers are better for ground-based measurement of aerosol optical depth (AOD), although the majority of observations are again from Europe and North America. AERONET is a federation of sun-photometer networks with standardized operation. Figure 39 shows the locations of sites that in 2002 and 2013 provided AOD data that passed cloud screening and quality assurance. It indicates by colour the number of months for which such data are available. The number of sites increased by a factor of well over two from 2002 to 2013. AERONET data are widely used for bias adjustment or evaluation of global datasets based on satellite measurements and modelling.

Ground-based lidars provide data on several aerosol properties, depending on the type of instrument. Aerosol is also sensed by ground-based MAXDOAS instruments. Brief discussion of networks is given in the review of IP-10 Action A27 on page 246. Attention in recent years has been devoted to exploring the potential for aerosol observation using the low-power ceilometers that are widely deployed in national networks for measuring cloud-base height, including consideration of arrangements for international data exchange and harmonisation of data formats, retrieval algorithms and calibration issues. Also of relevance are the observations of near-surface aerosol properties made by air-quality networks.

Space-based measurement also provides information on a range of aerosol properties. This includes passive measurement in the UV, VIS and IR from geostationary and polar orbit, including limb viewing for the stratosphere exploiting occultation, backscatter and thermal emission. The longest records are for AOD, beginning with data from AVHRR and continuing with data from many instruments, most notably the two MODIS instruments and the combination of ATSR-2 and AATSR, for both of which there are products, from NASA and the ESA CCI respectively. Measurement approaches employing various spectral ranges and resolutions, and various viewing geometries, involving instruments such as GOME-2, IASI, MAESTRO, MISR, OMI and OSIRIS, add to the characterisation of aerosols. Some are planned for continued implementation on future operational platforms.

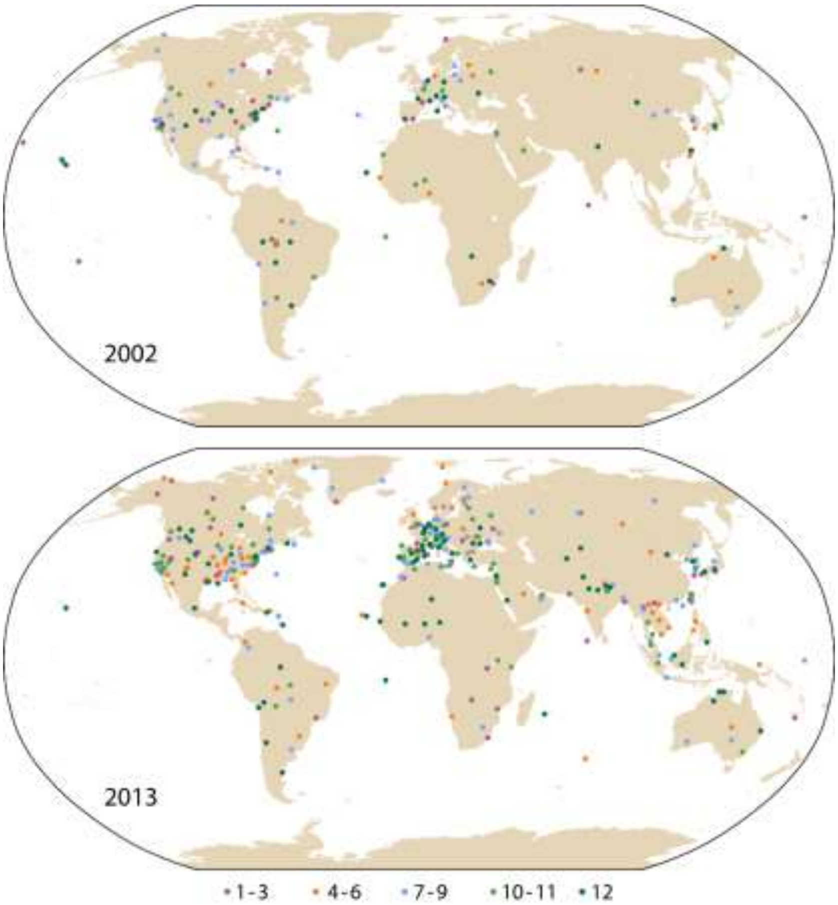


Figure 39: Number of months for which data are available from AERONET sites for 2002 (upper) and 2013 (lower), from information for Level-2 (cloud-screened and quality-assured) data downloaded on 13 May 2015 from http://aeronet.gsfc.nasa.gov/Site_Lists/site_index.html.

In particular, information on particle size, shape and refractive index may be derived from space-based measurements of the polarization of backscattered solar radiation in VIS/NIR spectral bands at multiple viewing angles, and the vertical distribution of aerosols may be sensed using lidar. Polarimetric measurements were made by the PARASOL mission for nine years until late 2013, in tandem for some years with the narrow-swath lidar measurements that have been made since 2006 from the CALIPSO satellite in the "A-train" orbit. An expected resumption of polarimetric measurement from this orbit using a more advanced instrument did not materialise due to the 2011 launch failure of the GLORY mission.

IP-10 Action A33 called for the development and implementation of a strategy for monitoring and analysing aerosol, covering both *in situ* and space-based observation. The review provided on page 254 includes discussion of the planned future provision of space-based observation.

Global data products from the various satellite instruments with aerosol capability are in general available from producing agencies or through consortium arrangements similar to those for other composition variables. The need for reprocessing past observations using improved calibration, cloud screening, surface correction and aerosol microphysical models is ongoing.

The general restriction of aerosol observations to clear-sky conditions and limited capabilities over some types of surface lead to a role for data assimilation to produce complete fields, benefitting from assimilating observations of meteorological and other variables, including fires, that relate to the dynamic sources, transport and deposition of aerosols. NASA/GMAO's MERRA-2 reanalysis includes five species of aerosol, and assimilates AOD data from AVHRR over the oceans from 1979 until the EOS period, when AOD from MODIS, MISR (over bright surfaces) and AERONET are used. MODIS AOD is produced using a retrieval that includes calibration with AERONET data (Buchard *et al*., 2015). In developing the Copernicus Atmosphere Monitoring Service, ECMWF has worked with partners to extend its atmospheric model and associated data assimilation to include greenhouse gases and the aerosols and reactive gases (ozone and the precursor species; see Figure 38) that affect climate forcing and air quality. This system too has been used for reanalysis over the EOS period assimilating MODIS AOD data along with data on precursor species. It is also being used to develop the assimilation of other types of satellite data on aerosol and to develop the linkages between the treatments of aerosols, clouds and reactive gases in modelling and data assimilation.

4.7.6 Precursor species

The importance of observing relatively short-lived gaseous "precursor species" that affect the distributions of ozone and aerosols through chemical interactions was stated in IP-10. Species include nitrogen and sulphur dioxide (NO_2 and SO_2), carbon monoxide (CO) and formaldehyde (HCHO). Estimates of their effect on the radiative forcing of climate change are included in Figure 30. Surface atmospheric concentrations of NO_2 and SO_2 may reach levels that are directly harmful to health and lead to detrimental environmental impacts through acid rain, although emission controls have lowered concentrations over time in many regions. Observations of these species still remain important for air-quality monitoring and forecasting as well as climate. This includes use for assessing emission inventories and modelling, and for determining the injection and subsequent transport of SO_2 from volcanic eruptions and CO from fires.

The species concerned are measured at a number of GAW stations, and the WDCGG has functioned up to now as the data centre for them. CO is one of the species measured from flask samples taken by stations in the NOAA/ESRL Cooperative Air Sampling Network, and the data holdings reported in WDCGG (2015) for this gas are similar to those for CO_2 and CH_4. Much smaller, and declining, numbers are reported for NO_2 and SO_2. WDCGG (2015) shows NO_2 data from just 18 stations for 2012 compared with 34 stations for 2002. The station numbers for SO_2 are 14 for 2012 and 35 for 2002. The reporting stations are almost entirely located in Europe. This is a feature also of the station distributions reported by the GAWSIS for these two pollutants.

Even for Europe, a much greater density of surface observations, albeit not necessarily of the same quality, is available from air-quality monitoring sites. The European Environment Agency's AirBase collection of validated measurements for 2012 comprises values from 1603 stations, 375 of them classified as rural, 402 as suburban and 826 as urban. Their locations can be seen at http://www.eea.europa.eu/themes/air/interactive/no2. This type of data has been used along with ground-based remote sensing (discussed in the review of IP-10 Action A27 on page 246) and data from MOZAIC/IAGOS aircraft for evaluating satellite retrievals. This is needed because of differences among observing systems in their sampling of regions close to sources, where spatial variability can be high.

Observation in the wavelength range from the UV to the thermal IR from nadir-viewing polar-orbiting satellites has provided data on CO, HCHO, NO_2 and SO_2, beginning in the 1990s with values of HCHO and NO_2 from GOME. It continues today with data from instruments such as MOPITT (launched on Terra in late 1999), IASI and TES for CO, volatile organic compounds and ammonia, and OMI and GOME-2 for HCHO, NO_2 and SO_2. Figure 40 presents as an example NO_2 from OMI, showing wintertime values for this gas that are highest in the vicinities of cities where emissions from transport, power generation and other industrial activities are high. The direct emissions are primarily of another precursor, nitric oxide (NO), but this gas reacts with ozone on a timescale of tens of minutes to form NO_2.

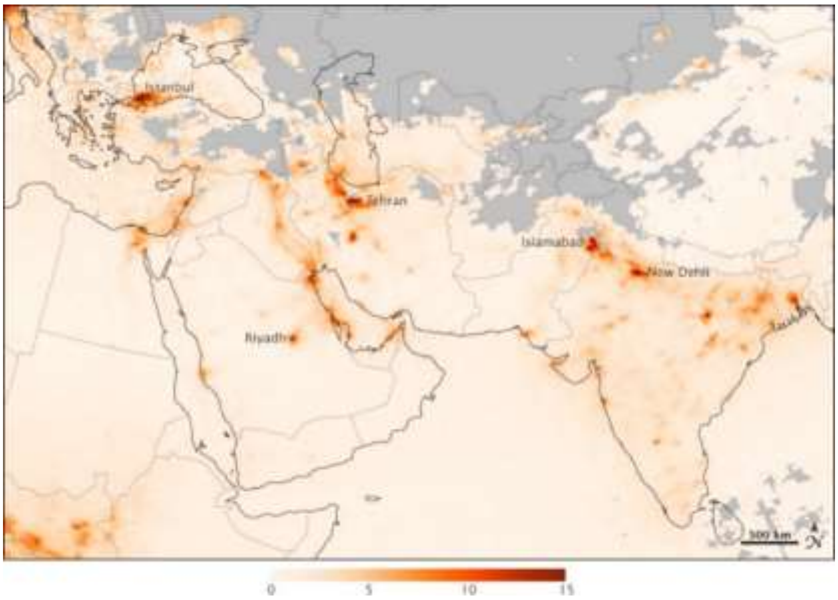


Figure 40: Total column density of nitrogen dioxide (x10^{15} molecules/cm^2) derived from measurements by OMI on the EOS Aura satellite, 1-8 January 2013.
Source: NASA Earth Observatory (http://earthobservatory.nasa.gov).

Space-based sensing capabilities vary from species to species, may degrade over the lifetime of an instrument and generally improve with newer instruments. Planned satellite missions are discussed in the review of IP-10 action A34 on page 255; they offer both refinements of current systems and viewing from geostationary orbit. Profile data from limb viewing (Action A26, page 245) support study of the influence of precursors transported into the upper troposphere and lower stratosphere on the distribution of aerosols, and are combined with data from nadir viewing to characterise the atmospheric column more completely. Lightning is a natural source of nitrogen oxides, and its detection from the coming generation of geostationary meteorological satellites should help quantification and modelling of this source. Ground-based remote sensing is discussed in the review of Action A27 on page 246.

Assimilation of retrieved data continues to develop, including reanalysis over much of the period of instrumental record. Miyazaki *et al*. (2015) report a reanalysis for 2005-2012 that combines limb and nadir data on ozone, NO_2, CO and HNO_3 from the MLS, MOPITT, OMI and TES instruments. Experience in developing the global system for Copernicus is that that CO, NO_2 and O_3 reactive-gas data from instruments to date can be usefully assimilated, along with SO_2 data when signals are strong following volcanic eruptions. The quality of the HCHO data is judged to be sufficient only for them to be used in the form of monthly means to evaluate the HCHO field that evolves over assimilation cycles due to background modelling and the assimilation of data on other variables. The impact of assimilating tropospheric column retrievals of NO_2 is limited due to the short lifetime of NO_2 and other factors, and these data may be better used to adjust emissions rather than initial atmospheric values over each time window of the data assimilation (Inness *et al*., 2015).

5 Oceanic observation

5.1 Introduction

5.1.1 The role of the oceans in the climate system

The oceans play critical roles in the Earth's fundamentally coupled climate system. Advances in our understanding of the role of the oceans in climate are reflected in the prominence of the oceans in IPCC AR5. The oceans are thought to have taken up more than 90% of the excess heat in the climate system. Sea-level rise will have important consequences on many coastal cities and other communities. Sea-ice changes in the Arctic are bringing many changes to the region and its communities. Ocean currents redistribute heat and other properties with major consequences on sea surface temperature in some regions and in turn on regional weather. The oceans hold about fifty times more carbon than the atmosphere, and their sediments thousands of times more, and an estimated 30% or so of the excess carbon in the climate system has been absorbed by the oceans, causing them to become more acidic. Tracking the heat and carbon stored and the exchanges of heat, moisture, momentum and greenhouse gases with the atmosphere are vital for understanding and forecasting the evolution of climate variability and change.

The oceans are a dominant driver of climate variability on timescales beyond a week and up to centuries, the timescales on which a range of critical decisions need to be made in society. The impact of ENSO on large parts of the world is an example; while a coupled ocean-atmosphere mode, it is the ocean which sets the timescales of variability. The oceans have the largest "memory" in the climate system and are the dominant source of predictability for forecasts on seasonal and longer timescales. Ocean-modulated climate variability such as ENSO and the Indian Ocean Dipole also influences monsoons and extreme events such as floods, droughts and hurricane activity and intensity.

Changes in the physical and chemical properties of the ocean have a large impact on ocean health and productivity: the upwelling zones of the oceans provide nutrients that support some of the most biologically productive zones of the planet, and there is growing evidence that oceanic physical and chemical changes strongly control ocean ecosystems. For instance, changes in ocean stratification can influence the availability of nutrients in the photic zone, and also influence the occurrence of de-oxygenated zones, or ‘dead zones’. Ocean acidification also has the potential to have far reaching effects on the health of ocean ecosystems. Warmer waters can cause coral bleaching. Observing changes in the biogeochemical system and in marine ecosystems is critical to projecting their future states, as well as the oceans’ capacity to provide food.

Sea level is a critical variable for low-lying regions, and globally is driven by volume expansion or contraction due to changes in sub-surface temperature and salinity, and by changes in the amount of water held elsewhere, notably in glaciers, ice sheets, artificial continental reservoirs and as groundwater. Long term trends in global sea level need to be considered in the context of regional variability and change driven by modes of climate variability and regional circulation patterns, glacial rebound, water extraction, land use changes and coastal ecosystem degradation.

Sea-ice variability and decline in the Arctic over recent decades involves multiple processes and feedbacks involving both atmospheric forcing and effects of ocean currents and heat storage. Changes in Antarctic sea ice have been smaller; the observed net increase is not well understood, but changes in wind speed and patterns appear to be one factor. Antarctic ice-shelf melting is largely driven by warm ocean currents that melt ice from underneath; this in turn has an impact on ocean properties, deep water formation and the broader ocean circulation.

Ocean information is critical for the delivery of climate services and essential for enabling effective decision-making across the range of climate-sensitive socio-economic sectors.

5.1.2 Observing the Oceans

Following the OceanObs’09 Conference (Hall *et al*., 2010), it was decided that the ocean observing system needed to expand to meet societal needs for observations in support of ocean health and real-time services in addition to climate. The Framework for Ocean Observing (Lindstrom *et al*., 2012) was developed to guide the expansion of sustained ocean observation, focussed on setting requirements for variables, readiness guidelines and a framework for ongoing valuation of the observing system to deliver ocean observations that are fit for purpose.

The role of the oceans in climate and their impacts was highlighted in the IPCC AR5, where the oceans were highly prominent in the contributions of both Working Groups I and II. This prominence is a reflection of the advances in understanding of the role of the oceans in climate, underpinned by progress in implementing systematic and sustained observations of the ocean. GCOS’s recent focus on observational requirements for impacts and adaptation brings a potential for broader connections between the GCOS and GOOS panels, to track the impacts of climate change in coastal systems, ocean health and fisheries.

Attaining and sustaining global coverage is the most significant challenge for the oceanic climate observing system. While high-quality ship-based observations continue to be a central component of the sustained ocean observing system, the further development of autonomous platforms and sensors means that comprehensive and routine observations of the sub-surface ocean are within reach. The international Argo array of profiling floats has revolutionised our understanding of the ocean. Emerging technologies such as gliders, unmanned surface vehicles and new sensors show great promise in providing the required comprehensive observations and reducing reliance on ship time. This challenge will only be met through national commitments to the global implementation and maintenance effort, with international coordination provided by JCOMM and other relevant bodies. JCOMM is encouraging groups coordinating emerging technologies to engage with the JCOMM Observations Coordination Group (OCG).

The development and evolution of the ocean observing system is being coordinated through focussed finite lifetime ‘development’ or ‘redesign’ projects, notably the Tropical Pacific Observing System, TPOS 2020 Project. A Deep Ocean Observing Strategy project is also in the planning stages. These projects are focussed on strengthening and integrating the observing system, capitalising on new technologies to ensure the observing system will meet future requirements.

Reanalysis of the time-varying ocean circulation is necessary to provide dynamically-constrained syntheses of ocean temperature, salinity, current and sea-level observations and to explore the relationships between the physical ocean state with ecosystems and biochemical variability and change. Activities in ocean analysis and data assimilation for reanalysis and forecasting are underway in a number of nations. Enhancement and coordination of the suite of these efforts, needed to meet the specific needs of the UNFCCC, started under the CLIVAR/GODAE umbrella (now GODAE OceanView). Some of the efforts have begun to provide ocean initial conditions for decadal forecasts and emphasis is now on improving the systems and moving them forward into coupled assimilation efforts. Further discussion is given in section 3.6 and in the review of IP-10 Action C12.

5.1.3 Agents for Implementation

Observation of the ocean is coordinated under GOOS. Separate from the work of OOPC and its sibling biogeochemistry and biology panels (section 2.3.3), the JCOMM OCG oversees the technical coordination and implementation of the core observing networks. It covers development of network missions and targets, observing system implementation and performance metrics, piloting, review and inclusion of new technologies, data management, integration and information delivery. The OCG is effectively the implementation-support arm of OOPC, and its membership comprises representatives of the mature ocean observing networks.

Networks that are members of the JCOMM OCG are each coordinated through an international panel or steering team that considers issues such as network targets, national contributions, data management and quality control. The JCOMM *in situ* Observing Platform Support Centre (JCOMMOPS) was established based upon coordination of facilities provided by the Data Buoy Cooperation Panel, the Ship Observations Team and the Argo profiling float programme. JCOMMOPS provides reports of observing system performance, covering funding, national contributions, deployments and servicing status, and near-real-time and delayed-mode data delivery. It is the source of many of the network monitoring plots presented in section 5.2.

As new technologies are scaled up for global implementation, those undertaking coordination are being invited to engage with the JCOMM OCG. For instance, the glider community are now formalising their coordination under a steering team, and are becoming formal members of the OCG. The OCG is also engaging with the IOCCP to strengthen the coordination of the implementation of biogeochemical sensors and observations on existing platforms.

The ten-yearly OceanObs series of conferences has proved to be an invaluable opportunity for the ocean observing community to come together and reframe the vision for the global ocean observing system. Planning for the OceanObs'19 conference is already underway.

Most *in situ* observing activities in the oceans continue to be carried out under research agency support and on research programme time limits. A particular concern is the fragility of the financial arrangements that support most of the present effort; there has been very limited progress in the establishment of national ocean or climate institutions tasked with sustaining a climate-quality ocean observing system. Thus, the primary agents for implementation for *in situ* ocean observation and analyses remain the national and regional research organisations, with their project-time-scale focus and emphasis on PI-driven activities. That said, there are many examples of sustained observing programmes consistently delivering high quality observations largely on research funds and championed by the research community.

IP-10 Action O1 concerned the reporting of national contributions to ocean observation. Action O2 addressed the planning of coastal ocean observation. The reviews of these actions can be found on page 257.

5.2 Networks

A number of oceanic networks provide data on more than one ECV. These networks are discussed in this section. Networks specific to a single ECV are discussed where relevant in the separate accounts given for each ECV in sections 5.3 and 5.4. Space-based observation is discussed in general terms in Section 3.4. IP-10 Action O4, reviewed on page 259, concerned coordination of contributions to CEOS Virtual Constellations for surface ocean ECVs.

IP-10 Action O6 calling for deployment of autonomous *in situ* instruments for biogeochemical and ecosystem variables was aimed at measurements from ships; its review on page 260 concerns the development and deployment of sensors on Argo floats and moorings as well as ships, in view of the progress made in this area. The review of Action O23 (page 271) reports limited progress on the establishment of a network for collocated physical, biological and ecological measurements. Action O29 called for development of autonomous observation of biogeochemical and ecological variables; it receives only brief review on page 274 as further discussion is given in the context of the individual ECVs concerned.

Management of data from these networks and other cross-ECV topics are covered in the reviews provided of a set of IP-10 Actions, O31 to O41, which begin on page 275.

In addition to the networks specified below, data on temperature and salinity are provided by instruments attached to marine mammals, predominantly from the Southern Ocean. These data are used in several analysis systems; a recent study using the Met Office FOAM system is reported by Carse *et al*. (2015). Novel sensors for other variables have been tested by deploying them in this way.

5.2.1 Argo

The broad-scale global array of temperature/salinity profiling floats, known as Argo, has already grown to be a major component of the ocean observing system. Argo is regarded as a standard to which other developing ocean observing systems can aspire. It exemplifies international collaboration and data management as well as offering a new paradigm for data collection.

Deployments began in 2000 and continue today at the rate of about 800 per year. The design of the Argo network is based on experience from the present observing system, on recent knowledge of variability from space-based altimetry, and on the requirements for climate and high-resolution ocean models.

The array currently comprises more than 3900 floats (Figure 41) up from the original target of 3000 reached in 2007. Some 55% are provided by the USA. 30 other countries and the European Union are listed as contributing floats in September 2015, and others provided support for deployment. The array at present provides around 140,000 temperature/salinity profiles and velocity measurements per year, distributed over the global oceans at an average spacing of three degrees. Floats cycle to 2000 m depth every ten days, and the typical lifetime of an individual instrument is four to five years. All data collected by Argo floats are publically available in near-real time via the Global Data Assembly Centres (GDACs) in Brest, France and Monterey, California, after an automated quality-control, and in a delayed-mode, scientifically quality-controlled form via the GDACs within one year of collection.

Figure 41: The global Argo array, including details of national contributions, as of September 2015, when the float count was over 3900. Source: JCOMMOPS.

The original design was to cover from 60^{O}N to 60^{O}S, in open ocean regions (Figure 42). The density and age of floats and other factors are actively monitored to plan proactively and prioritise deployments. Argo is now extending into marginal seas and high latitudes with ice-capable floats; these either have ruggedized antennae for punching through thin ice, or are programmed with ice-avoidance algorithms. Enhancements are also being piloted in the equatorial region and in the near-coastal regions where there are strong boundary currents.

High-latitude sampling was recommended by OceanObs'09, though by then was actually well on its way. Sampling closer to the sea surface has been facilitated by high-bandwidth communications and improved pressure sensors, but sampling through the air-sea interface is still avoided. Sampling in marginal seas is now well established and this also arises naturally as a benefit of high-bandwidth communications

Increased float density in critical areas was also requested by OceanObs'09, though some areas, such as the Kuroshio extension area, were already heavily sampled. Increased density is now available in the equatorial regions and again benefits from the high bandwidth communications. The short surface time eliminates divergence of the floats away from the equator.

A revised target for floats to meet these requirements is currently under discussion.

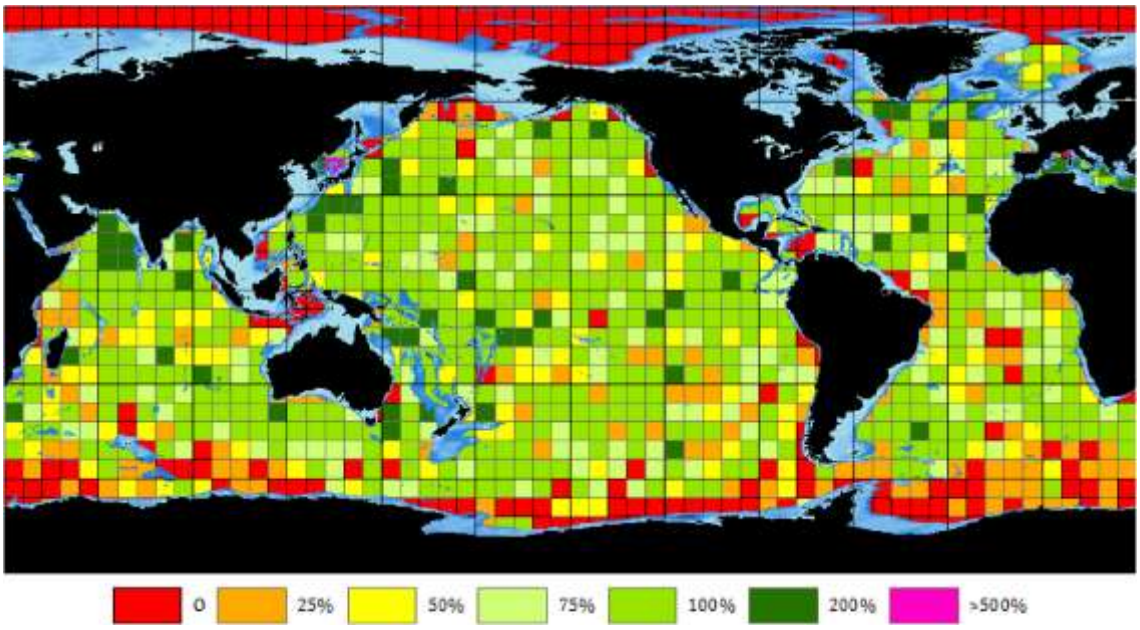


Figure 42: Density of Argo Floats relative to the original mission (60 ^{O}N to 60 ^{O}S), September 2015. A density of 100% corresponds to four floats per 6^{O} grid square. Source: JCOMMOPS.

Argo floats equipped with chemical and bio-optical sensors for measuring oxygen, pH, nitrate, ocean colour and backscatter, are being trialled by a number of national programmes (Figure 43). The JCOMMOPS map for September 2015 shows 280 Argo floats with oxygen sensors, though they were not evenly distributed. Efforts are underway to develop and improve the quality-control procedures for the oxygen data streams before larger scale roll out of these sensors.

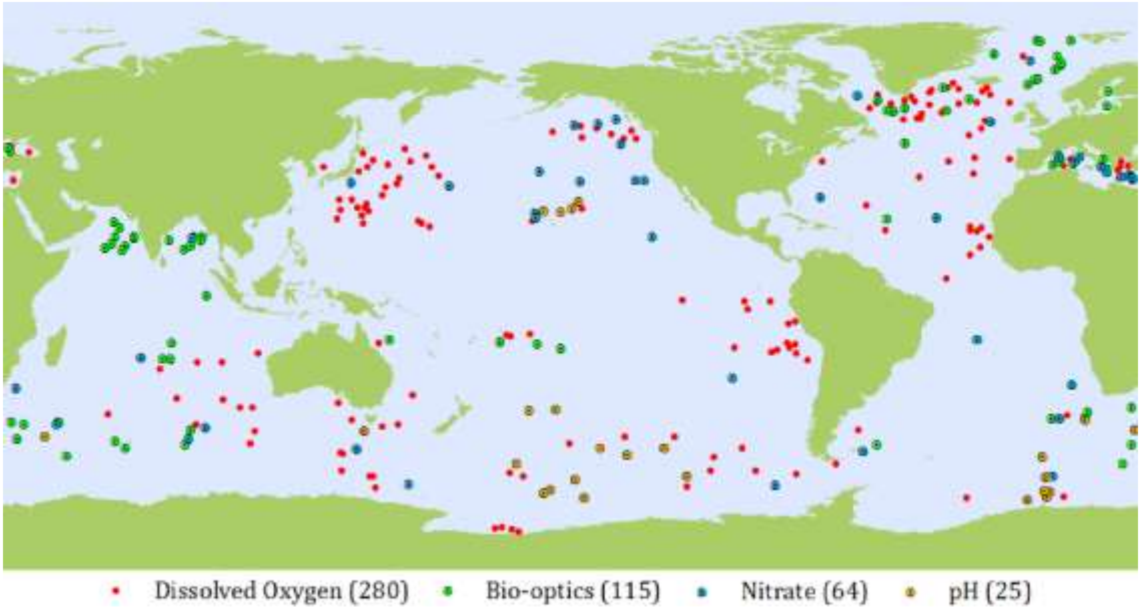


Figure 43: The number and distribution of Argo floats with additional chemical and bio-optical sensors, September 2015. Source: JCOMMOPS.

5.2.2 GO-SHIP repeat hydrography

Global hydrographic surveys have been carried out on about a decadal basis since the 1960s through research programmes such as IIOE, GEOSECS, WOCE/JGOFS, and CLIVAR. In 2009 the Global Ocean Ship-based Hydrographic Program (GO-SHIP) was established as part of GOOS to provide international coordination and scientific oversight of the decadal global ocean survey.

GO-SHIP provides a globally coordinated network of sustained hydrographic sections as part of the global ocean/climate observing system including physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems. GO-SHIP provides approximately decadal resolution of the changes in inventories of heat, freshwater, carbon, oxygen, nutrients and transient tracers, covering the ocean basins from coast to coast and top to bottom, with water column and surface water measurements of the highest required accuracy to detect these changes.

The principal scientific objectives of GO-SHIP are: (1) understanding and documenting the large-scale distributions of ocean-water properties, their changes and the drivers of those changes, and (2) addressing questions such as how what is predominantly natural ocean variability will change in a future in which the ocean is likely to have more dissolved inorganic carbon and have become more acidic and more stratified, and to experience changes in circulation and ventilation processes due to global warming and altered water cycle and sea-ice.

The GO-SHIP Executive Group and Committee of National Representatives provide coordination and oversight of GO-SHIP, and data are freely available through the CLIVAR Carbon Hydrography Data Office (CCHDO) at the Scripps Institute of Oceanography.

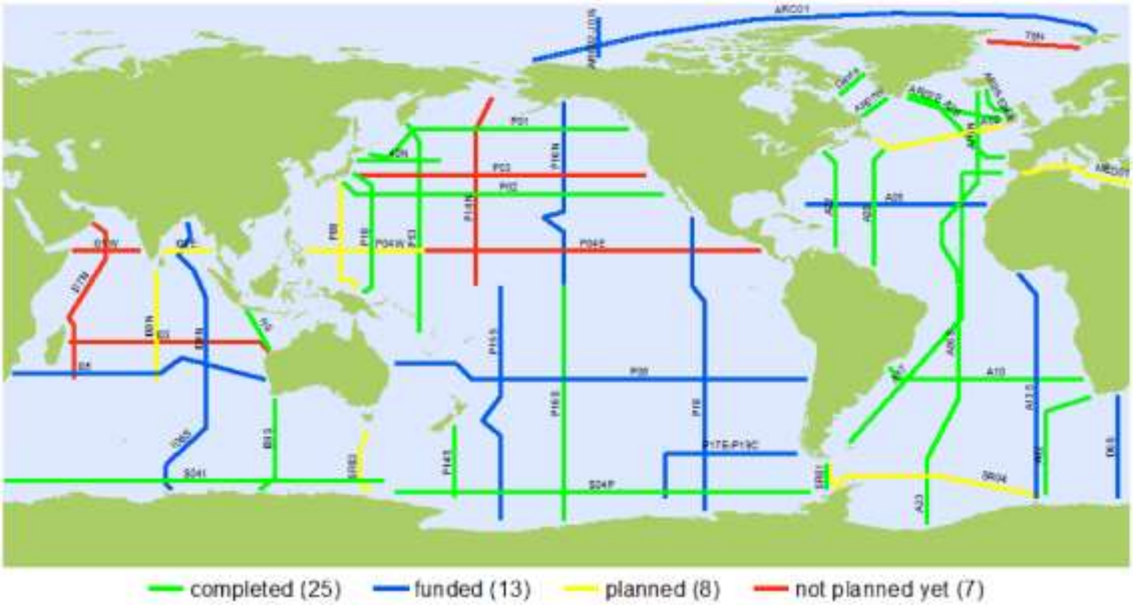


Figure 44: Implementation status against 53-line target of the GO-SHIP 2012-2023 Survey, April 2015. Source: JCOMMOPS.

The 2012-2023 survey is well under way and to date is meeting most targets (Figure 44). A summary of the status of the program to 2014, after three years, is:

- Percentage of the 2012-2023 survey completed: 47%
- Percentage of the 2012-2023 survey completed or funded: 71%
- Percentage of the 2012-2023 survey completed, funded or planned: 87%
- Percentage of the 2012-2023 survey unplanned: 13%

Data have been sent to the appropriate data centres. In particular, bottle and CTD data have been submitted to the designated GO-SHIP repository at the CCHDO (http://cchdo.ucsd.edu/) and Carbon Dioxide Information Analysis Center (CDIAC, http://cdiac.ornl.gov/oceans/).

5.2.3 Drifting buoys

The aim for surface drifting buoys is to maintain a global array of 1,250 satellite-tracked drifters to meet the need for an accurate and globally dense set of *in situ* observations of mixed layer currents, SST and surface (atmospheric) pressure, and to deliver these data to operational (via the GTS) and research users. A small number of drifters also measure winds and salinity. The majority of drifters deployed are standard Surface Velocity Program (SVP) drifters, a little over half of which measure surface pressure.

The present status of the global drifter array is shown in Figure 79, where it relates to IP-10 Action A6 calling for surface-pressure sensors to be deployed on drifters as a matter of routine; see also Action O8. The data from the array support short-term weather prediction and seasonal to inter-annual climate predictions as well as climate research and monitoring. They are also used to validate satellite-derived SSTs and in composite SST products. Recent studies have shown that pressure measurements from drifters have a significant beneficial impact on global numerical weather prediction and that drifters have a high ratio of benefits to costs.

As illustrated earlier in Figure 16 the number of operational drifters fell significantly in 2011 and 2012. This was because drifter lifetimes fell well below the required 450 days. The main causes for this were: (i) faulty battery packs (assembled from poor-quality cells that were not properly secured), (ii) some modems that were not energy-efficient and shortened the drifter lifetime considerably and (iii) a general increase in power consumption of the drifter's electronics. As shown earlier, these issues have since been addressed and the lifetime of drifters has increased; the number of drifters deployed is currently safely above the 1,250 level.

Around 80% of the buoys are provided by the US NOAA Global Drifter Program. The remainder are provided by European countries, individually and through a joint contribution organized through EUMETNET, and by several others.

5.2.4 Moored-buoy networks

The status of the moored buoy arrays is shown in Figure 45. There are around 400 moored systems in operation, with networks operated by many different countries, with the USA providing a little over 50%. It comprises the Tropical Moored Buoy array, various national moored networks and tsunami buoys. The DBCP also maintains close links with the OceanSITES network of reference mooring stations (section 5.2.5).

The tropical array is overseen by the Tropical Moored Buoy Implementation Panel and has the following components:

- The Tropical Atmosphere Ocean / Triangle Trans-Ocean Buoy Network (TAO/TRITON;
- The Prediction and Research Moored Array in the Tropical Atlantic (PIRATA);
- The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA).

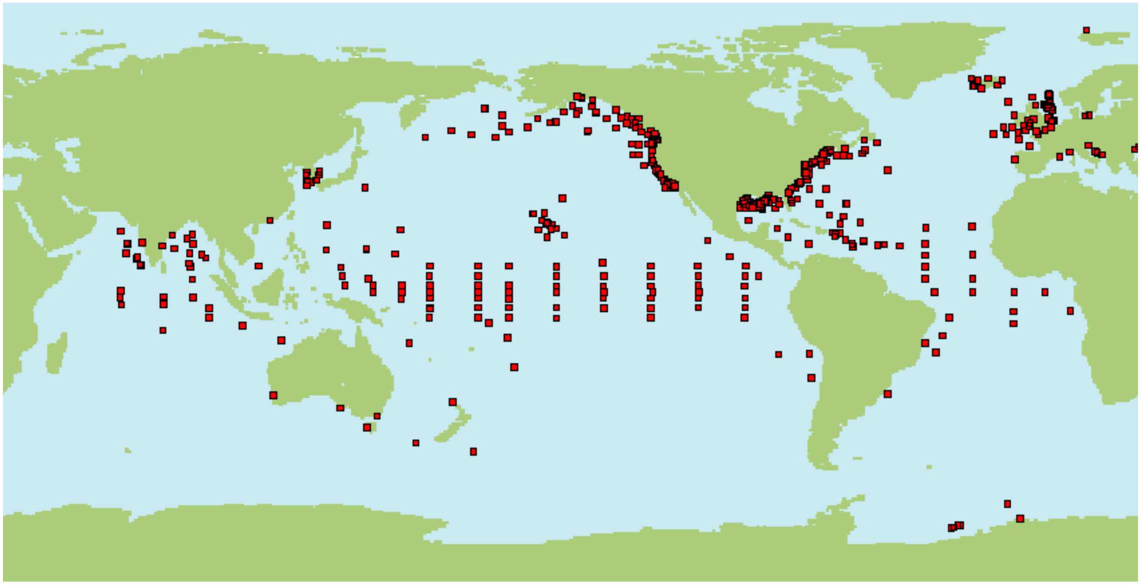


Figure 45: The moored buoy network in April 2015. Some fixed offshore platforms are included. Source: JCOMMOPS.

At its meeting in October 2014, the DBCP noted with concern that the daily average data return for the period from 1 July 2013 to 30 June 2014 was 38% for TAO, 84% for TRITON, 86% for PIRATA and

54% for RAMA. Abnormally low TAO data return was in large part due to buoy vandalism and delays in maintenance cruises, where the average TAO mooring age (time period since deployment) was 16 months as of July 2014, with 42 of 55 TAO moorings having been deployed for more than the design lifetime of 12 months, and one having been deployed for 3 years.

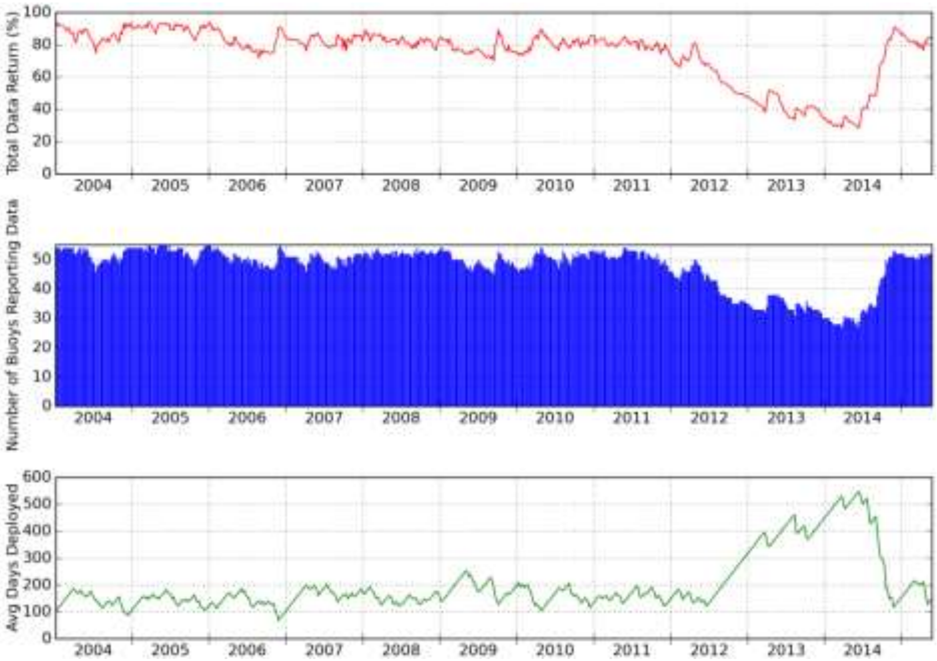


Figure 46: Summary of the data return from the TAO array from January 2004 to May 2015. Upper panel: data return as % of total possible. Middle panel: number of buoys reporting data. Lower panel: average days of deployment. Source: NOAA Pacific Marine Environmental Laboratory.

The decline of the TAO/TRITON array had prompted earlier action. NOAA and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), in collaboration with OOPC, convened a review of the observing system for the Tropical Pacific through a workshop held in January 2014 and associated white papers. Immediate actions to address the deterioration in the observing system were considered along with the activities needed to achieve a more robust and sustainable system. Formulation of the TPOS 2020 project was one outcome. Its aim is to design a modern, sustained Tropical Pacific observing system to support prediction for ocean, weather and climate services and to advance understanding of the physical and biogeochemical variability and predictability of the region. Meanwhile, NOAA has honoured a commitment made at the beginning of the workshop to return the TAO mooring array to 80% by the end of 2014. The decline and restoration of the TAO array is illustrated in Figure 46. Future funding of the array remains uncertain.

Notwithstanding the restoration for now of the TAO array, a staged removal of TRITON moorings has commenced (Figure 47), and there are now only eight out of the original sixteen moorings in place. The array will be down to four moorings by 2017.

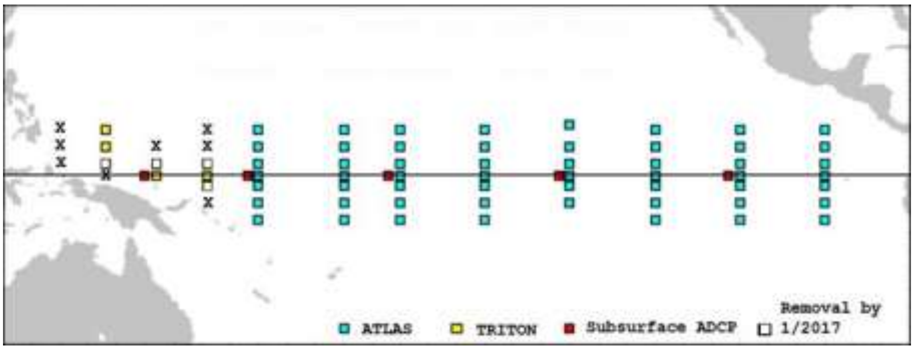


Figure 47: Status of the TAO/TRITON Mooring Array. X marks where TRITON moorings have already been removed. Source: JCOMMOPS.

The primary reasons for data loss in RAMA are a high incidence of vandalism coupled with long mooring deployment periods at some sites. Of 27 surface mooring sites in RAMA implemented by July 2014, five have not been maintained for more than two years due to lack of cruise opportunities. Piracy continues to prevent the full implementation of the array in the western Indian Ocean. The survival rate for ATLAS moorings in RAMA since initial deployments in 2004 is 84%, compared to 90% for TAO (1980 to 2010) and 93% for PIRATA (1997-2014).

To ensure early detection of tsunamis (the vulnerability to which changes as the local average sea-level changes), moored buoys equipped with tsunameters have been installed in regions with a history of generating destructive tsunamis. At present there are approximately 56 moored buoy tsunameter stations. Typically each system consists of an anchored seafloor Bottom Pressure Recorder (BPR) and a companion moored surface buoy for real-time communications. An acoustic link transmits data from the BPR on the seafloor to the surface buoy where the signal is relayed to tsunami warning centres or emergency managers.

An additional important contribution to the overall array of moored buoys are the national networks operated around the coasts of many countries, in particular North America, South America, Western Europe and the Northern Indian Ocean, as shown in Figure 45. Around 90% of these buoys deliver data to the GTS. Capabilities vary from country to country, with most (if not all) buoys measuring meteorological variables and some networks also measuring oceanographic variables. Many of these networks have been in place for 20 years or so and deliver data for weather and ocean-state prediction, as well as providing time-series for marine climate studies, in particular for wave climate.

5.2.5 OceanSITES

OceanSITES is a worldwide system of long-term, deep-water stations (known as ocean reference stations) at which dozens of variables are measured. It is being implemented by an international partnership of researchers. The network, predominantly moorings, provides fixed-point time series of various physical, biogeochemical and atmospheric variables at different locations around the globe, from the atmosphere and sea surface to the sea floor, and include some historical time series. The programme’s objective is to build and maintain a multidisciplinary global network for a broad range of research and operational applications including climate, carbon, and ecosystem variability, and forecasting and ocean state validation. The main focus of the network is to establish indicator trends in the physical and chemical environment. Developments since 2011 include the establishment of the Deep Observing Network (DON) which aims to carry deep-ocean temperature/salinity sensors at existing OceanSITES platforms. Another recent initiative is the

Minimalist OceanSITES Interdisciplinary Network (MOIN). MOIN aims to provide a basic global coverage on how the marine ecosystem functions in relation to physical forcing in the upper ocean and would be a sparse array of moorings with comprehensive multidisciplinary sensor payloads. While the deep ocean temperature/salinity sampling has been successful, limited progress has been made by MOIN due to funding constraints.

All OceanSITES data are publicly available. http://www.oceansites.org provides more information.

IP-10 Action O5 called for completion of a global reference network of 30-40 surface moorings as part of OceanSITES. It is reviewed on page 259.

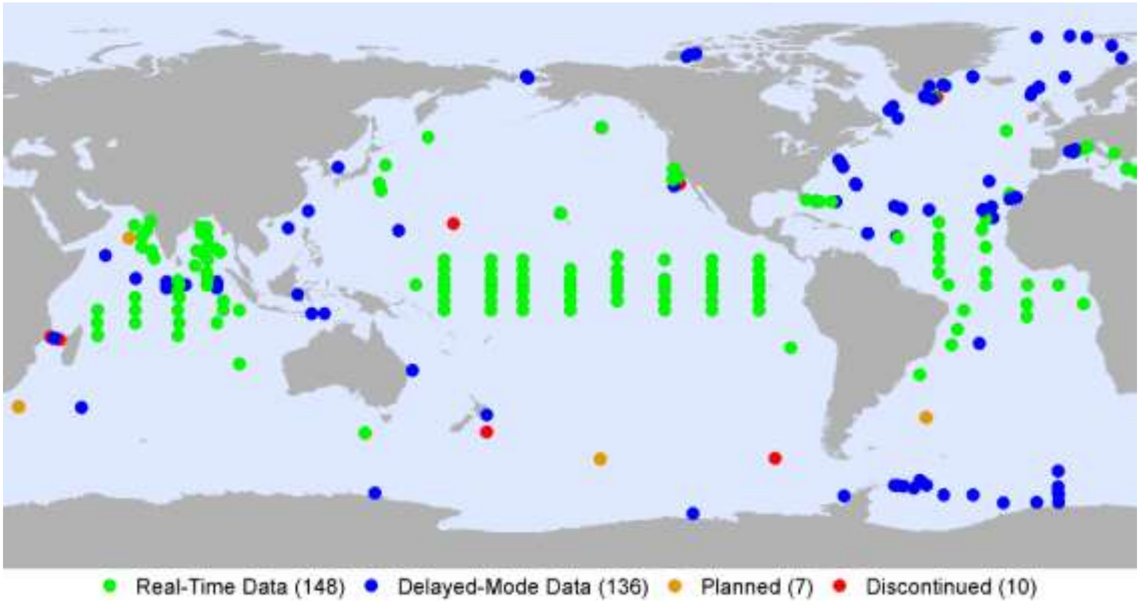


Figure 48: The network of OceanSITES and planned additions, as of September 2014. Source: JCOMMOPS.

5.2.6 Voluntary observing ships

An international fleet of more than 3100 Voluntary Observing Ships (VOS), of which somewhat under a half tend to be active at any one time, currently provide meteorological data which are shared by national meteorological services via the GTS. Figure 96 (in the review of IP-10 Action O3) provides an example of monthly coverage and performance indicators.

These ships, which are primarily recruited from merchant shipping companies, contribute to the international VOS scheme (http://www.jcommops.org/sot/) which is coordinated by a Ship Observations Team (SOT) established under JCOMM. Observations are compiled in electronic logbooks by ship's officers and sent in near-real time to the meteorological services for use in their numerical weather prediction systems (Figure 9). Delayed-mode data are also collected from the ships to supplement climate databases. Ships are recruited to a number of different VOS classes largely depending on the instruments with which they are supplied, but there is an international effort to encourage suitable ships to participate in the VOS Climate (VOSClim) class which aims to produce a higher quality subset of VOS data suitable for climate studies and research. The number of ships that have been upgraded to this VOSClim class is gradually increasing, and now stands at almost 500 ships, accounting for more than one third of the total VOS data supply. There are currently 30 WMO Member States engaged in VOS operations with the majority of observations coming from ships recruited to fleets maintained by the USA, Netherlands, UK, Germany, Canada and France.

Although the overall number of ships recruited to the VOS Scheme has declined over the last two decades the number of observations they supply has, in contrast, grown significantly. Discussion of coverage is given in section 4.2.1. One of the prime reasons for the rise in observations is the increased use of automatic weather stations (AWSs) producing hourly observations. Almost 400 VOS ships are now fitted with AWS systems and this number is expected to rise significantly in the next few years. AWSs report a limited number of measured parameters, however. These are typically pressure, air temperature, humidity, sea temperature, wind speed and wind direction, depending on the type of system used, whereas manually reporting ships provide a wide range of additional visual observations such as cloud cover, height and type, present and past weather, sea state and swell, and icing conditions.

VOS ships are served by a network of international Port Meteorological Officers (PMOs) who visit the ships to provide feedback on their data quality, timeliness and availability. In order to do this effectively comprehensive data quality monitoring tools have been developed by EUMETNET and the UK's Met Office. The PMOs also inspect the ships' meteorological instruments, to ensure they remain within calibration, and provide instruction to officers on the correct observing practices. In addition they collect comprehensive metadata on the ships, and on the location and exposure of their observing instruments. These metadata are stored in an on-line metadata database maintained by E-Surfmar and accessible at: ftp://esurfmar.meteo.fr/pub/Pub47/.

Ship call sign masking still causes problems for some users. This has been discussed by the SOT who are taking further action to address the issues.

The VOS network also underpins the work of many other observing networks, and its ships are routinely used for deployment of Argo floats and drifting buoys. The above discussion provides much of the review of IP-10 Action O3 (page 258) calling for improvement in the number and quality of climate-relevant surface observations from the VOS.

5.2.7 XBT, thermosalinograph and other data from Ships of Opportunity

The JCOMM Ship of Opportunity Programme (SOOP) produces oceanographic sampling from cargo, research and cruise ships, using mainly expendable bathythermographs (XBT), but also expendable conductivity temperature depth profilers (XCTD), acoustic Doppler current profilers (ADCP), thermosalinographs (TSG), and continuous plankton recorders (CPR). Measurements of the partial pressure of carbon dioxide are also made. The XBT measurements are discussed mainly in this section; other types of measurement are discussed in the ECV-specific sections.

The XBT network is based on recommendations from international and regional panels, presented at OceanObs'09. The main mission of the XBT network is the collection of upper ocean temperature profiles, involving repeat sampling at regular intervals along pre-determined routes, called lines or transects. The XBT deployments are designated by their spatial and temporal sampling goals or modes of deployment (Low Density, Frequently Repeated, and High Density or High Resolution) and conducted along repeated, scientifically important transects, on either large or small spatial scales, or at special locations such as boundary currents and chokepoints. These observations are complemented by or complementary to other observational programmes, such as Argo, the surface drifter array, pCO_2 system network and satellite altimetry. Multi-national reviews of the XBT network were carried out at the 1999 and 2009 OceanObs conferences and at four dedicated XBT Science Workshops between 2008 and 2014. Given the advances in the Argo programme, the global XBT network is now focussed on:

- assessment of seasonal and interannual variation of volume of major open ocean currents;
- assessment of boundary current and ocean interior mass and heat transport across basin transects;
- contributing observations for seasonal to multi-decadal variability assessments in upper ocean temperature and heat content;
- initialisation and validation of numerical models.

The accomplishment and maintenance of the recommended transects are dependent on ship traffic, recruitment strategies, budget restraints and scientific and operational needs. The XBT network continues to place more emphasis on the implementation of XBT transects in High Density mode, providing data that are largely used by the scientific community. Around 50 High Density XBT lines are recommended, with around 29 currently fully implemented, occupied four times per year with XBTs deployed every 15-25 km. The XBT lines also provide an important contribution to monitoring the global boundary currents.

The number of XBTs deployed each year has more-or-less halved since the Argo programme began. Approximately 20,000 XBTs are currently deployed annually, of which roughly 17,000 correspond to the XBT network (Figure 49) and are mostly transmitted in near-real time and ingested into operational data bases. The rest of the XBTs, around 3,000, are deployed on research cruises. There are approximately 60 ships participating in the maintenance of the XBT network and 70 ships transmitting TSG data. Data acquisition and transmission into global data bases are crucial for assessing performance.

Observations from the XBT network are almost fully transmitted on the GTS after undergoing automatic quality control. Metadata from XBT observations are critical, particularly for current studies of the XBT fall rate equation. The XBT Science Team met in Beijing in November 2014 to discuss results from these studies and experiments. As a result, the community recommended a unique data set that currently has the lowest bias and errors, and submitted the findings and recommendations for review. NOAA NCEI (formerly the National Oceanographic Data Center) and the French Coriolis centre for *in situ* oceanographic data (http://www.coriolis.eu.org/) are the repositories of all XBT observations and they coordinate the delayed-time data management. The Global Temperature and Salinity Profile Programme currently supports a high-quality delayed-time data processing.

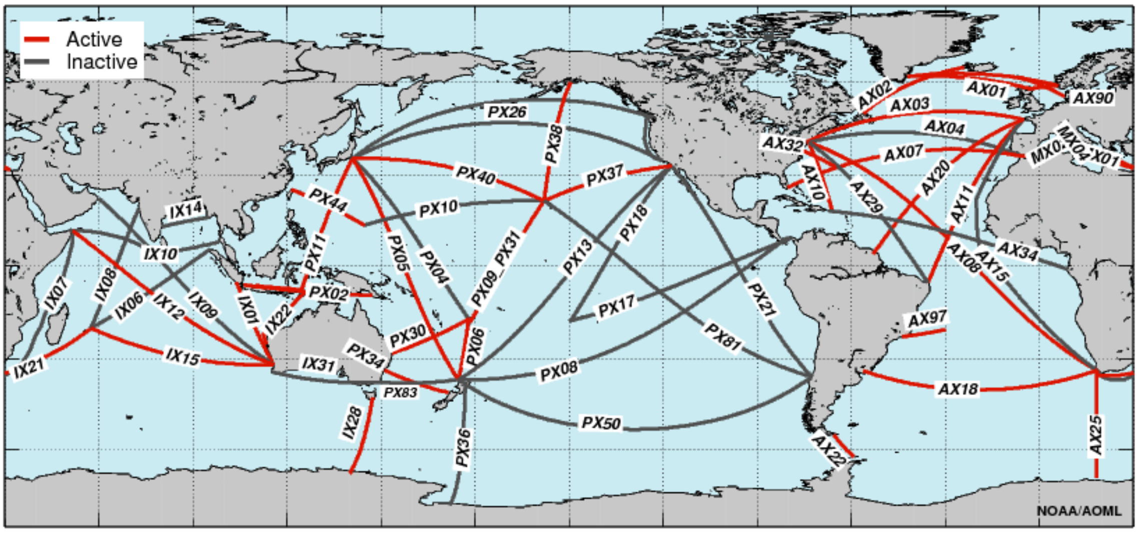


Figure 49: Ship of Opportunity XBT Lines that are currently occupied (red) and unoccupied (black). Source: NOAA/AOML.

5.3 Surface variables

5.3.1 Sea-surface temperature

The large-scale spatial patterns of sea-surface temperature (SST) are related to large-scale weather patterns. SST plays important roles in the exchanges of energy, momentum, moisture and gases between the ocean and atmosphere. The heat and moisture exchanges are a main driver of global weather systems and climate patterns. On 25 to 100 km scales, strong SST gradients can contribute to vertical atmospheric circulations that transfer energy and moisture from the atmospheric boundary-layer to the free atmosphere. On smaller scales, SSTs are used to diagnose adverse conditions for coral reefs. SST has been discussed in section 4.3.1 in the context of global mean surface temperature estimates that are based on surface air temperature over land and SST otherwise. SST is not a good indicator of multi-annual variations in the energy stored in the ocean, however.

The *in situ* observing system for SST feeds the ICOADS database that currently extends back to the late 18th century, with the prospect of further recovered and digitized historical measurements being added. It also feeds near-real-time analysis systems that support forecasting and the extension of reanalyses. The ways measurements have been made, the depths at which they have been made, their biases and the areas covered by them have changed significantly over time. Coverage in most ocean basins has been far from sufficient, as shown already in Figure 12. For the past 30 or more years, however, near-global sampling of SST has become available on a daily to weekly basis due to the advent of IR radiometers on polar-orbiting and geostationary satellites, and more recently of low-frequency MW radiometers on polar-orbiting satellites, and from the measurement made by drifting buoys. Satellite observations play a critical role in filling the spatial gaps in coverage, but do not resolve fully the diurnal cycle which plays a substantial role in increasing energy transfer from the oceans to the atmosphere in the tropics and subtropics. The microwave observations have the considerable advantage of observing through cloud cover, which is very important in winter and spring when large parts of the ocean basin can be covered by cloud. The IR data provided from 1991 to 2012 by the SST-focussed ATSR and AATSR instruments flown respectively on the ERS and Envisat platforms have been have been valuable sources of reference data for calibration schemes. While there have been considerable improvements in SST products, the lack of representation of the diurnal cycle and the challenges of adjusting for observational changes over time and for the differences between one type of observation and another leave scope for further improvement. Furthermore, the various SST products have greater differences near coasts, especially in areas with frequent cloud cover.

IP-10 Action O7, reviewed on page 261 relates to the continued provision of the best possible SST products based on satellite and *in situ* data. Provision of products of improving quality, and with quantified uncertainties, has indeed been achieved. There is nevertheless concern over future provision of MW SST observations, in the absence of confirmation of arrangements for the GCOM-W2 and -W3 missions that are shown in the CEOS MIMD database as still being under consideration for flying the AMSR2 instrument for the 2016-2025 period.

Action O8 relates to *in situ* coverage of SST observations made by drifting buoys and the VOS. General network issues for these types of observation have been covered in section 5.2.

5.3.2 Sea-surface salinity

Salinity is the fraction of water that is comprised of salt and other impurities. Observations of sea surface salinity (SSS) are needed to calculate estimates of oceanic transports of freshwater and other properties on basin to global scales. SSS also provides a good pointer to changes in the water cycle as it is indicates the change in fresh water due to the difference between precipitation and evaporation. Along with coincident SST observations, they allow surface water density to be estimated. *In situ* SSS data also provide important resources for evaluating numerical models, palaeological estimates and satellite observations.

Near-global, broad-scale *in situ* observational coverage of salinity was achieved around 2004. Ocean salinity observations have proven to be an important input for data assimilation, particularly for ocean models that are being used to provide gridded global estimates of ocean circulation. More recently, satellite observations have begun to contribute. Ongoing salinity observations, both surface and sub-surface, are required to further our understanding of the ocean's role in the global water cycle, and to further quantify ocean changes in response to climate change.

Further discussion is provided in the reviews of two IP-10 actions beginning on page 263. Action O11 concerns implementation of a programme for *in situ* observation of sea-surface salinity. O12 concerns investigation of the feasibility of utilizing satellite data for global fields of surface salinity, for which a basis has been provided by the launches of SMOS in 2010 and Aquarius in 2011. The Aquarius mission ended prematurely in June 2015 due to platform failure, but the SMAP mission launched in early 2015 might provide suitable alternative data.

Early gridded products based on Aquarius and SMOS both reveal substantial regional signals in salinity related to precipitation and river outflow. These products highlight the importance of the water cycle and the need to consider river outflow in near-coastal modelling. Several operational models have shown remarkable skill in reproducing the salinities seen in western boundary currents, but many models have serious problems in areas of very strong river outflow.

5.3.3 Sea level

Changes in local sea level are important to coastal communities. These changes can have large impacts on infrastructure and coastal resilience on the time scales from those of tsunamis and storm surges, through the interannual to decadal scales of variability in ocean circulation, out to centuries from sea-level rise in a warming climate. Subsidence of the land may in places have as large an impact as rising seas. For many communities the record of extreme sea-level events is insufficient to assess risk to infrastructure, in part because of inconsistent tide-gauge locations and large uncertainty about changes in the elevation of the land. Global Sea-Level Observing System (GLOSS) stations provide *in situ* calibration and validation data to complement satellite observations, whilst GLOSS data themselves monitor multi-decadal trends in sea-level rise and help reconcile the sea-level signal associated with crustal displacements. Large contributions to uncertainty in GLOSS analyses come from insufficient GLOSS stations and from stations that lack metadata on the position of the tide gauge.

For open-ocean applications, high-accuracy sea-surface height (SSH) data from satellite altimeters resolve significant differences in the rate of sea-level change between ocean basins. Observations from less-precise instruments improve spatial and temporal sampling. SSH is defined differently than sea level: SSH is the topography of the sea surface in geocentric coordinates. It is an indicator of ocean circulation and dynamics at many scales. Satellite measurement of SSH contributes vital information for characterising variability such as associated with ENSO and the North Atlantic Oscillation, and the correlation between SSH variability and underlying sub-surface temperature anomalies can be exploited to derive analyses of variables such as tropical-cyclone heat potential. Data assimilation for basin and mesoscale circulations is acutely reliant on sustained SSH observations. Added value of the assimilation of SSH data is realised when the ocean analyses are used to initialize operational coupled ocean-atmosphere seasonal forecast systems that provide societal benefit, in particular due to their skill at predicting ENSO events.

Global-mean SSH is increasing as a result of ocean volume increase due to thermal expansion and ocean mass increase due to melting glaciers and ice sheets. It is also affected by changes in the amount of liquid water stored on land, particularly in artificial reservoirs and as groundwater. The observing system is adequate for monitoring the evolution of global SSH: IPCC (2013) assessed progress in the estimation of the various contributions to change, and expressed high confidence that the global-mean rise in sea level between 1993 and 2010 was consistent with the individual contributions as estimated from observations, in that the sum of these contributions, 2.8 mm/yr, with an uncertainty range from 2.3 to 3.4 mm/yr, matched sufficiently well the observed rise of 3.2 mm/yr, with uncertainty range from 2.8 to 3.6 mm/yr. The observing system is nevertheless inadequate for resolving changes with smaller spatial and temporal scales, which can be large in magnitude and have substantial impacts on communities. The largest uncertainties in estimates of changes in the thermal energy in the ocean come from uncertainty in the ocean basin volume and from changes in the elevation of tide gauges.

Other societal benefits of sea-level observation include information on storminess from data from the tide-gauge network, and tsunami warnings from a dedicated measurement system.

The coastal tide-gauge network provides a roughly century-long time series of sea level that is supplemented by open-ocean data from altimetry over the last three decades or so. IP-10 Action O9, reviewed on page 262 is concerned with completion of the implementation of the GLOSS network. High-precision altimetry is available for more than two decades, beginning with the 1992 launch of the TOPEX/Poseidon mission. The altimetry constellation requires multiple satellites to maintain sufficient sampling in both time and space: IP-10 Action O10 called for continuous coverage from one high- and two medium-precision altimeters. Recovery of tide-gauge records would be especially useful for the early part of the satellite period, for the purpose of intercalibration with the early space-based data.

5.3.4 Sea state

Waves are generated by ocean surface vector stress and evolve from wind waves to swell when the stress has insufficient magnitude to support the waves. Wave characteristics can also be modified by bathymetry when the depth of the water is sufficiently small compared to the wavelength, or by surface currents, which appear to play a large role in the formation of rogue waves. Sea state is best known for its impacts on marine safety, marine transport and damage to structures. However, waves also affect the growth or decay of sea ice, beach erosion, surface albedo, gas transfer, transport of larvae and contaminants such as oil, and air-sea exchange of energy, moisture and momentum. They thereby play large roles in the global cycles of energy, water and carbon.

Sea state is typically observed from some moored buoys and satellite altimeters, although some wave information can be inferred from coastal radar and specialized drifting buoys. Observations are also provided from some Voluntary Observing Ships and oil platforms. Most moored buoys measuring waves are located in the coastal margins of North America, Europe and Australia (see Figure 45). Wave data are measured by two flux reference buoys (see review of IP-10 Action O16 on page 267). The eddy covariance flux system on two OOI buoys can likely be used to provide the buoy motion for wave calculations. The general lack of this observation adversely impacts estimates of surface stress (and arguably all other surface fluxes) from buoys. The spatial coverage of buoys is far from adequate, except perhaps for coastal applications, where the additional information from radar may help. The temporal sampling for satellite altimeters is also far from adequate. These inadequacies strongly indicate that an alternative approach is needed to gain the information desired from wave observations.

The primary aspects that are measured or retrieved from measurements are the wave height, usually significant wave height (SWH), the average height of the highest 33% of waves, but sometimes maximum wave height, wave period (and hence wavelength) and wave direction (from a much more limited set of platforms). 1-D spectra are measured by most moored buoys, with a limited number of directional wave spectra available from some moored buoys, wave radars and bottom-mounted pressure arrays (in shallow water). Parameters of interest that are not measured by existing systems include crest height (usually parameterized from wave spectra or SWH), wave breaking, whitecapping (derived from some satellite estimates and numerical models), rogue waves (which can be forecast probabilistically by models), and tangentially, Stokes drift (a contribution to surface and sub-surface currents).

The observations from moored buoys are usually derived from wave-induced motions. The bulk of operational wave measurements (those reported through the GTS, for example) are from systems that use an overly simple motion sensor that can result in large errors when the surface winds are strong enough to cause wave breaking. New sensors which measure the full range of motion of the buoys are being increasingly used to alleviate this problem. GPS sensors are also being developed for wave measurement, particularly for drifting buoys.

Other wave measurement systems in varying degrees of use include the wave radars, such as the SAAB Rex and MIROS, extensively used by the oil and gas industry in measurements from platforms. ADCP systems and bottom-mounted pressure sensors, downward looking laser instruments, capacitance wire gauges and wave staffs are also used, usually in a research context rather than for operational measurements. Some measurements are also made using shipboard X-band radar and coastal radar systems. Of these systems, the coastal radars are the closest in readiness for GCOS applications.

In situ data reports are not currently standardized, resulting in impaired utility. Differences in measured waves from different platforms, sensors, processing and moorings have been identified. In particular, a systematic 10% bias has been noted between US and Canadian buoys, the two largest moored buoy networks. Standardized measurements and metadata are essential to ensure consistency between different platforms. Understanding the errors and uncertainties of wave measurements from all systems is the primary focus of the JCOMM-ETWCH Pilot Project on Wave measurement and Test (www.jcomm.info/WET). The WET project also has a primary focus to develop affordable and reliable wave measurements from drifting buoys, in particular from the Global Drifter Program array.

Satellite altimetry measures SWH. Wavelength and wave period can be estimated assuming that the waves are wind-driven, which is often unrealistic. Altimetry provides neither spectral nor directional information. In practice, sampling is too sparse in the open ocean, where wave characteristics change rapidly because of changing weather and swell from distant weather events. Therefore waves are modelled with ocean surface vector stress (or wind converted to stress) and bathymetry being the key input variables. Therefore, the wave observing system mimics the vector wind observing system, with buoys providing comparison data for calibrating winds and waves. Assimilation of the SWH data from satellite altimetry (and also SAR data, see below) into these models is also used.

Information on the 2-D frequency-direction spectral wave energy density is provided by SAR instruments with good accuracy but marginal horizontal/temporal resolution and poor global sampling. Horizontal resolution of 100 km is currently required for use in regional models, with fast delivery of data, within six hours. Real aperture radar capability is expected to be available within five years.

Coastal wave models require different observing methods to those used for the open ocean, due not only to their high resolution but also to limitations of the satellite data close to land. Hence for these models systems such as coastal HF radar are of particular importance. These radars provide information on SWH with limited coverage, good accuracy and acceptable horizontal/temporal resolution. High-resolution observations (up to 100 m resolution) are currently required for data assimilation using coastal models.

Much longer waves such as tsunamis and coastal shelf waves are measured with different systems. Tsunami characteristics are calculated from changes in bottom pressure. Shelf waves are estimated from the coastal part of their signal, which can be seen in tide-gauge observations. These waves are relatively rare, but are more likely to have a strong impact on coastal environments.

5.3.5 Sea ice

Sea ice is most often thought of as a sensitive indicator to changes in the energy absorbed by the ice. It also greatly influences the surface albedo and air/sea exchanges of energy, moisture and carbon. The sea-ice distribution, including polynyas and margins also has an important influence on marine ecosystems. Changes in the distribution of sea ice affect these ecosystems and a number of activities such as shipping, logistic and tourist operations.

Antarctic sea ice extent is remaining steady or increasing slightly, while the total ice mass (estimated from gravity measurements) appears to be decreasing. Recent decline in Arctic summer ice extent, summer ice mass and the type of ice have been suggested as indicators of global change. Changes in Arctic ice have been linked to changes in radiative input due to changing cloud cover, changes in albedo via changes in ice concentration and ice motion due to winds and currents. Smaller changes in Antarctic sea ice may be due to changes in wind speed and patterns. All these mechanisms are related to changes in the overlying atmospheric circulation, which varies considerably on synoptic, seasonal, interannual and decadal scales. The related processes of ice melt, formation, drift and deformation are largely dependent on the energy budget per unit area of ice. Hence the sea-ice system is clearly tied to the energy and water cycles as well as many other ECVs.

The historical record of sea-ice extent is largely pieced together from highly sporadic ship-based observations until 1979, when satellites began to provide sea-ice information. A wide range of technologies and historical data are used to make different sea-ice products. The different satellite technologies have different strengths and weaknesses that appear in products that are based solely on those technologies. For example, freezing-season estimates of sea-ice extent and concentration are effectively determined from the passive MW record, but the melt-season changes are more accurately determined from active microwave observations (typically scatterometers). Neither of these types of observation have the resolution needed to monitor fast ice movement in the Antarctic, nor do they have the capability to determine the thickness of snow resting on the ice. IP-10 Action O20, reviewed on page 269, called for better documentation of the differences and uncertainties in these products. IPCC (2013) noted as a key uncertainty that available data are inadequate to assess the status of change of many characteristics of Antarctic sea ice, such as its thickness. It is likely however that a combination of technologies can be used to greatly improve sea-ice products for the recent record. Action O18 calls for a plan to improve the *in situ* observing system, while Action O19 relates to maintenance of satellite observation programmes. A growing number of organisations are attempting to guide development of the observing system, but a sustainable comprehensive plan still needs to be developed for *in situ* observations.

The sea-ice ECV covers concentration (fraction of the sea covered by ice), extent, area of coverage, motion, deformation, age, thickness, freeboard height of ice above the ocean surface and the timing of ice melt and creation. Other variables are also of interest, but are not considered as sub-variables of this ECV. For example, snow depth on sea ice is also a crucial parameter. Snow influences the accuracy of retrieval of ice thickness for most remote observation methods. Snow contributes to sea-ice mass through snow-ice formation (mainly in the Antarctic) and greatly affects ice growth and melt rates due to its high albedo and thermal insulating properties. Other parameters include melt state and the progression/pattern of seasonal melt and freeze-up, melt-pond distribution and characteristics (mainly in the Arctic, as melt ponds are rare in the Antarctic), lead fraction and ridge size and distribution, the size and distribution of recurrent polynyas, sea-ice production rates in polynyas, floe-size distribution, sea-ice rheology and sea-ice crystal structure and salinity.

An important distinction is between pack ice (sea ice that is in constant motion in response to winds, ocean currents and internal forces) and land-fast or fast ice (stationary sea ice that is held in place in coastal regions by coastal promontories and grounded icebergs, and in sheltered embayments). Although it forms a narrow band along coastal regions, from a few km up to around 200 km wide, fast ice is consolidated, can attain considerable thicknesses, strongly affects coastal processes and erosion, is closely coupled to ice-sheet margins, and its distribution, thickness and seasonality are sensitive indicators of climate variability and change. Fast ice also affects coastal operations and logistics.

The longest time series that discriminates sea ice from open water is from passive MW data. Sea-ice concentration (the fractional coverage of ice), sea-ice extent (total area encompassed by the ice edge above a prescribed threshold, usually 15% concentration), sea-ice area (the product of extent and concentration) and sea-ice drift are obtained from such data. Also derived from the passive MW record, seasonality describes the annual timings of sea-ice advance and retreat and their product, annual ice-season duration. Dating back to 1979, the passive MW dataset provides one of the longest satellite-derived climate records. The decline in Arctic sea-ice cover observed by passive MW sensors is one of the most visible and dramatic indicators of climate change over the past three decades, as illustrated in Figure 50. Sea ice can be discriminated from water in other wavelengths due to its generally higher reflectivity (VIS), lower temperature (IR) and increased backscatter (active MW). However, passive MW is currently considered optimal for long-term, large-scale, and consistent observations because it has all-weather capabilities (independent of solar radiation and little affected by clouds), and a relatively wide swath to obtain daily complete coverage.

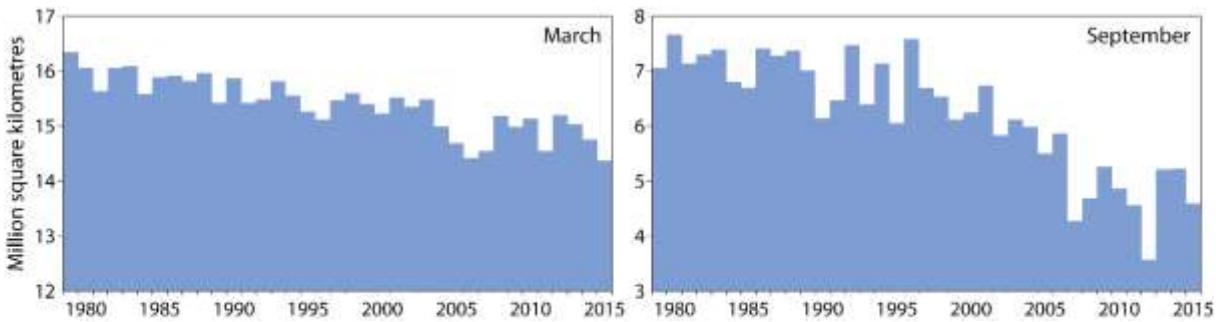


Figure 50: Arctic sea-ice extent for March (left) and September (right) from 1979 to 2015 derived from passive MW satellite data from the SMMR, SSM/I and SSMIS instruments (black). Based on the Sea Ice Index dataset downloaded from the US National Snow and Ice Data Center (http://nsidc.org/data/seaice_index/) on 12 October 2015.

Other space-borne contributions to the ice observing system come from active MW instruments (scatterometers and SARs), VIS imagery and altimeters. The MW sensors have the considerable advantage of being able to penetrate clouds. Scatterometers can be used to measure ice extent and drift while the repeat fine-resolution SAR observations are used to estimate the deformation field. The combination of passive and active MW sensors can be used to track ice motion, including icebergs. This combination can also be used to distinguish first-year ice from the multi-year ice that is prevalent in the Arctic, based on the differences in surface characteristics of these types of ice. Altimeters can measure the freeboard height of the ice surface above the water surface, which can be used to infer the ice thickness. The CryoSat radar altimeter flies in a particularly high-inclination orbit that provides data close to the North Pole. Laser altimetry was used in the former ICESat mission, and is currently being used in airborne campaigns prior to the launch of ICESat-2, scheduled for 2017. The accuracy of these measurements is influenced by snow cover and snow depth. Thin ice up to a thicknesses of about 60 cm can be measured by the SMOS passive MW instrument.

In situ observations of thickness (technically draft – the height above local sea level) can be made with moored and drifting buoys. Ice mass balance buoys also provide crucial point information on the spatio-temporal evolution of the sea ice-snow and its coupling to ocean and atmosphere. Drifting buoys have the added advantage of providing ice drift at the expense of a time series at a fixed location. Ice thickness can also be inferred from Upward Looking Sonar (ULS) from submarines and autonomous underwater vehicles, including fine-scale information on variations in draft.

Active MW coverage is less sensitive to ice age for the C-band than for the Ku-band. Ku-band observations were provided by QSCAT and OSCAT; C-band observations are currently provided by the ASCAT instruments on Metop-A and -B. It has been suggested that coverage from QSCAT combined with ASCAT was effective for tracking the ice edge and ice motion. This has again become feasible with the Sentinel-1 SAR mission now operating in combination with ASCAT.

5.3.6 Surface current

Surface currents span a wide range of space and time scales, from basin-wide motions to mesoscale eddies with scales greater than 100 km, fast narrow currents of the order of 100 km wide, sub-mesoscale features down to the kilometre scale, and finally down to turbulence scales of less than one metre. Large-scale circulations, such as the meridional overturning circulation, have surface components that transport a great deal of energy and consequently allow that energy to be transferred to the atmosphere and greatly impact weather and climate downwind of the air-sea exchanges. On smaller spatial scales, the boundary currents on each side of the ocean basin transport heat, salt and passive tracers, and have a large impact on seaborne commerce and fishing. Motion on these scales also has a large impact on vertical circulation and mixing, and in turn on marine ecosystems and ocean productivity. The equatorial currents and counter currents have a relatively large impact on surface exchanges of energy and moisture. Currents, particularly tidal currents, can also modify storm surge impacts and sea-level changes.

Surface currents are defined here as those motions within the mixed layer: from the top boundary (as measured by HF radar), to 15 m depth (from drogued drifters), to the average within the top 30 m (from gridded syntheses), and at various points in between (from moorings and gliders). Satellite observations based on altimetry can be used to infer the geostrophic portion of surface currents on scales of several hundred kilometres and five to ten days. Currents can be viewed as the sum of geostrophic currents (related to SSH differences), Ekman currents (related to winds), inertial currents (related to winds), tidal currents as well as near-surface currents by driven wind and wave-induced turbulence. HF radars resolve rapid changes, but are limited in spatial coverage to the US coast and a few European locations. Currents are also observed at a few moorings. Drifting buoys (Figure 79) provide global surface currents hourly, at approximately one data point per five degree box. Satellites provide global geostrophic surface currents every five days on a 1/3 degree grid from a constellation of instruments. Drifting buoys and satellite currents are global, and are combined into synthesis products such as from the Ocean Surface Current - Real time (OSCAR) project and from ocean data assimilation. IP-10 Action O17 called for an international centre for ocean surface currents to be established. Several regional centres have been developed (page 267), but a globally recognized centre has yet to be established.

Variability and interaction of currents with winds on the smaller mesoscales and sub-mesoscale are not well captured and are thought likely to play a large and important role in transferring energy from the ocean surface to the deeper ocean. Some of these processes depend on horizontal gradients, which are not resolved with the existing observing system. Furthermore, one outcome of the TPOS 2020 planning process was that the meridional currents associated with equatorial upwelling are not sufficiently accurate to determine the magnitude of this upwelling. The observing system for ocean surface currents is not adequate for determining some key climate processes.

5.3.7 Ocean colour

Ocean colour is measured as the ocean colour radiance (OCR). OCR is the wavelength-dependent solar energy captured by an optical sensor looking down at the sea surface. These water-leaving radiances contain information on the ocean albedo and information on the constituents of the sea water, in particular phytoplankton pigments such as chlorophyll-a. Data analysis is not easy as satellite measurements also include radiation scattered by the atmosphere and ocean surface. The relatively weak OCR signal is some 5-15% of the strength of the incident solar radiation. OCR products are used to assess ocean ecosystem health and productivity, and the role of the oceans in the global carbon cycle, to manage living marine resources, and to quantify the impacts of climate variability and change. OCR products, in particular chlorophyll-a, are also required by the modelling community for the validation of climate models, and for use in data assimilation systems for reanalysis and initialising forecasts.

Knowledge of ocean ecosystem change is inadequate. Satellites provide global coverage of ocean colour, and high-resolution depictions such as illustrated in Figure 51, but the linkage between ocean colour and ecosystem variables, including chlorophyll-a and its distribution with depth, remains limited. Enhanced *in situ* sampling of ocean colour and ecosystem variables is technically feasible, and could help reduce these shortcomings.

Continuous climate-quality OCR measurements have been available for more than a decade. These include data from:

- polar-orbiting global OCR satellite missions, particularly SeaWiFS, MERIS, MODIS-Aqua, OCM-2 on Oceansat-2 and VIIRS (Figure 51), with future measurements to come from OLCI on Sentinel 3A and 3B and SGLI on GCOM-C;
- various bio-optical fixed sites (such as MOBY, BOUSSOLE and AERONET-OC) and mobile surface and sub-surface platforms, for calibration, validation, and product development.

Cross-calibrated measurements from multiple satellites have to be merged to provide an FCDR of top-of-the-atmosphere radiances, primarily in the visible spectrum, from which OCR data products are derived using an atmospheric correction scheme. Accurate calculation of the effect of the atmosphere on the water-leaving radiance reaching the satellite requires additional measurements in the IR. Scientific data products related to marine ecosystems and ocean biogeochemistry are then derived from OCR for near-surface global-ocean water, coastal waters and potentially rivers, lakes and estuaries.

Figure 51: Image from VIIRS collected 29 September 2015 showing fine-scale structure in ocean colour near New Zealand. Source: NASA, downloaded from http://oceancolor.gsfc.nasa.gov/cms/.

The most important OCR data products currently in use are chlorophyll-a concentration (a proxy for phytoplankton biomass), coloured organic matter, particulate organic carbon and suspended sediments. Other products are in development, for instance identifying phytoplankton size classes. The number and usefulness of products can be enhanced through interactions with resource managers such as undertaken in the SAFARI Project, integrated networks for complementary *in situ* sampling and protocol development such as ChloroGIN, and centralized data archive and distribution centres for *in situ* data such as the SeaBASS system.

Key issues or impediments to success related to the development of a coordinated and sustained OCR observing system are:

- continuity of climate-research quality OCR observations and lack of free and timely access to and sharing of OCR data, including Level-0 satellite data;
- lack of developing and sharing of *in situ* databases and derived products of sufficient quality to use for calibrating and validating satellite data products;
- difficulty of sustaining projects for cross-calibrating and merging OCR data across satellite sensors to support global and regional scientific data products;
- the need for continued research and technology development efforts to provide new and improved OCR data streams, algorithms and products, particularly for complex “case-2” waters where optical properties are not dominated by phytoplankton.

To address the issues raised above, GCOS and GOOS supported the plans being developed through participating CEOS space agencies to implement an Ocean Colour Radiometry Virtual Constellation (IP-10 Action O15, reviewed on page 266). The International Ocean Colour Coordinating Group (IOCCG) has provided oversight to ensure that the measurements are implemented in accordance with GCMPs and the requirements outlined by GCOS (2006), as well as to promote associated research. The problems mentioned above are works in progress for the virtual constellation.

Sources of products and supporting information include the ESA CCI ocean-colour project (http://www.esa-oceancolour-cci.org/) and NASA OceanColor Web (http://oceancolor.gsfc.nasa.gov).

5.3.8 Carbon dioxide partial pressure

The surface ocean partial pressure of carbon dioxide, pCO_2, is a critical parameter of the oceanic inorganic carbon system (a) because it largely determines the magnitude and direction of the exchange of CO_2 between the ocean and atmosphere, and (b) because it is a valuable indicator for changes in the upper ocean carbon cycle. It is an oceanic parameter that can be routinely measured autonomously with high accuracy and precision. The first measurements of pCO_2 were initiated in the late 1950s, and the sampling network has grown substantially since then, with the vast majority of observations in recent years. Single investigators drove most efforts in the past, but recently national and international measurement consortia, and international coordination efforts, largely led by IOCCP, have provided a unique approach towards an operational network. The international network of surface pCO_2 observations in its integrated form is developing. The observation network activities includes a multi-ship effort sponsored mainly by the national and EU funding agencies has been operational for nearly two decades. pCO_2 instruments are mostly installed on commercial cargo ships, but measurements on research vessels are increasingly contributing to the network In addition, automated drifting buoys are deployed, largely in campaign mode. This network has provided the basis for estimating the climatological air-sea fluxes of CO_2, and with sophisticated analysis routines the observations are starting to be used to resolve year-to-year variations and to provide basin-wide or global flux estimates at regional resolution. However, physical considerations suggest that there is likely to be considerably more variability on sub-basin scales and shorter time scales than is currently resolved. Therefore, the observation system is considered greatly improved but still inadequate for climate.

This progress has been accomplished in large part to the data and information sharing strategy of IP-10 Action O13 (page 265), in particular through implementing the following activities:

- Global data sharing and archival strategy in the form of the Surface Ocean CO_2 Atlas (SOCAT) first published in 2011 and regularly updated has dramatically changed data quality and data availability for this ECV.
- Objective mapping routines and interpolation techniques including remote-sensing and data assimilation have been thoroughly investigated, and have recently taken a coordinated form in the Surface Ocean CO2 Mapping (SOCOM) inter-comparison project. Auxiliary observations that have proven to be particularly useful are SST, salinity, mixed layer depth, and surface chlorophyll. This ongoing activity aims at creating a portfolio of cross-validated freely available surface ocean interpolated pCO2 data products.

Further information on SOCAT is given in the review of Action O13. An illustration of data coverage is presented in Figure 52.

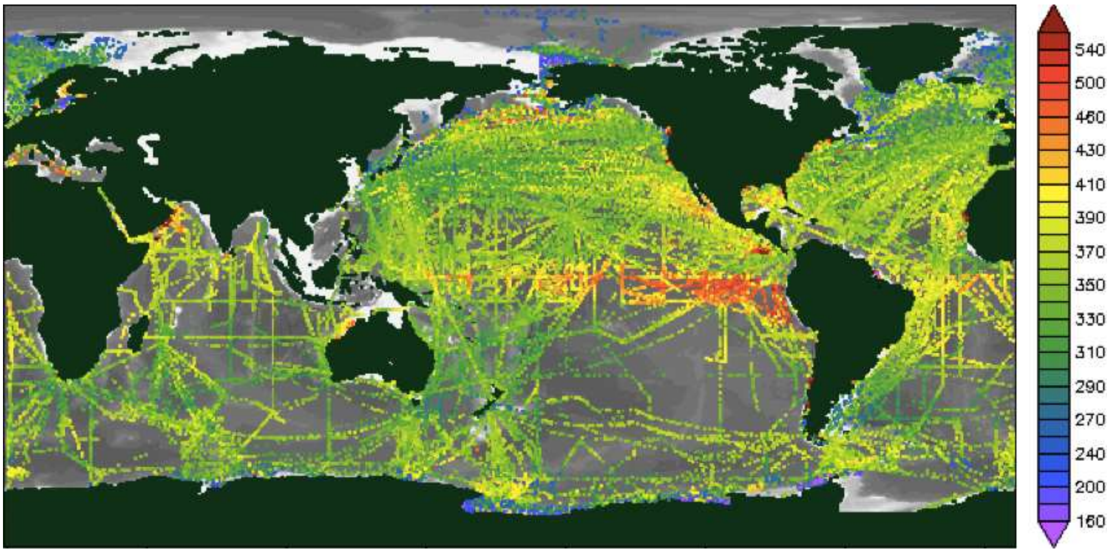


Figure 52: fCO_2 recomputed (µatm) from 2660 cruises between November 1968 and December 2011. Source: SOCAT version 2 database, plotted by the Cruise Data Viewer at http://www.socat.info/.

Issues relating to the development of an integrated and operational network that still need effort and focus are (1) continued technology/automation development for on-board systems including careful calibration, (2) creation of an internationally-agreed implementation strategy to identify the scope and priorities for the sustained system, and (3) sustaining priority trans-basin programmes and development of new programmes according to implementation strategy priorities. World-wide developments are continuing to improve the systems for autonomous measurements on-board ships. The instrument-based systems are currently the only ones producing measurements of sufficiently high quality for climate related research, for example being the only ones to obtain highest quality flags in SOCAT. Hence, several initiatives are continuing on improving the long-term quality of sensor-based systems.

Statistical and numerical studies are being carried out to identify the optimum observational networks. Different techniques that have been applied to observational networks in high-latitude oceans are being applied to other oceans. As these observational networks are parameter-specific, platform-dependent and different for different geographical regions, this activity is ongoing. Once the optimum observational networks are identified, they need to be studied in view of the financial, technical and personnel resources available.

Three areas require particular attention to estimate and understand oceanic CO_2 uptake:

- There remain large regions that are unobserved or under-sampled. In particular, the Southeast Pacific Ocean, and Northeast and Southern Indian Ocean (30˚-50˚S) lack measurements to date. Because commercial ships cannot be used in these regions, alternative platforms such as gliders, drifting buoys and sail drones need investigating.
- Regions experiencing rapid change such as the Arctic and coastal regions require close observation.
- Areas influenced by large-scale climate reorganisation that have a first-order effect on interannual variability of air-sea CO_2 fluxes require continued and expanded monitoring that can be best accomplished with cross-basin transects such as the lines crossing the tropical Pacific, complemented by fixed-point observations on moorings.

5.3.9 Ocean acidity

IP-10 lists ocean acidity twice as an ECV, once as a surface variable and once as a sub-surface variable. The report on ocean acidity provided under the heading of sub-surface variables in section 5.4.6 covers observation of ocean acidity in general, rather than separately for the surface and the sub-surface.

5.3.10 Phytoplankton

Climate variability significantly impacts plankton in the ocean, both the microflora (phytoplankton) and the microfauna (zooplankton), over both short (seasonal to interannual) and long (decadal) time scales. Changes in temperature, salinity, freshwater discharge and loadings of sediments and nutrients, acidification, light, wind forcing and currents impact the abundance, distribution, phenology, diversity, and productivity of these organisms. They are at the base of the marine food web and not fished by humans, though the significant impact of climate on plankton in turn has impacts on the rest of the marine ecosystem including the living marine resources used by humans. This has both ecological and socio-economic implications. Sustained, coordinated effort has to be expended to assess and monitor these changes over time.

Contributing networks and satellite observations include Continuous Plankton Recorder (CPR) surveys, Ocean Colour Radiances observed by satellites, and OceanSITES reference moorings. These are not yet adequate to observe phytoplankton variability for global climate.

Issues to address concerning assessment and monitoring of plankton include the development of standards for species specification and optical characteristics. IP-10 formulated Action O21 to establish a plan for and implement global Continuous Plankton Recorder surveys. In 2011 the Global Alliance of CPR Surveys (GACS) was formed to initiate a more shared and collective global vision. Further discussion is given in the review of this action beginning on page 270. Figure 53 shows current contributing survey programmes. IP-10 Action O22 called for technological development for plankton surveying.

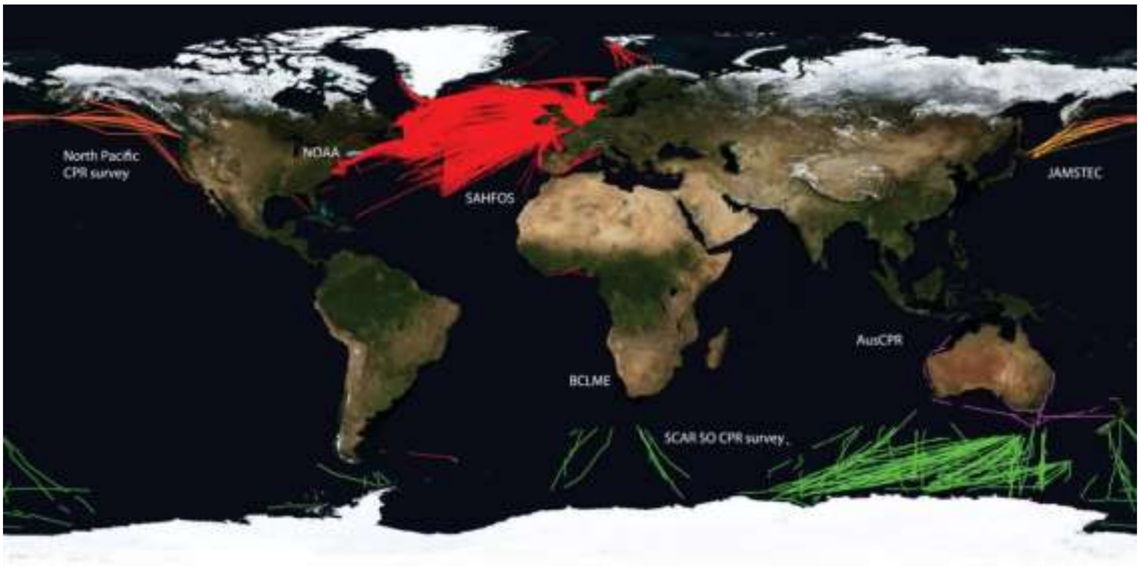


Figure 53: Current CPR survey programmes around the world that contribute to the Global Alliance of Continuous Plankton Recorder Surveys (GACS) network.
Source: http://www.globalcpr.org/maps.aspx.

5.4 Sub-surface variables

5.4.1 Temperature

Sub-surface temperature is a fundamental variable required to monitor variability and change in the physical environment of the ocean, energy flows, climate patterns and sea level, and is essential to the understanding of changes in many other variables in the realms of marine biogeochemistry and biology. Ocean heat content directly derived from sub-surface temperature is of paramount importance in the monitoring of the Earth's climate system and marine environment. Many other physical variables are derived from sub-surface temperature along with sub-surface salinity, including sub-surface density, geostrophic circulation, heat transport and steric sea level. These variables are essential to understanding of variability and change in ocean stratification, circulation patterns (uptake and redistribution of heat and freshwater) and sea level. Heat uptake by the global ocean accounts for more than 90% of the excess heat trapped in the Earth system in the past few decades. This ocean heat uptake helps to mitigate surface warming but in turn increases the global ocean volume through thermal expansion, and thus results in global-mean sea level rise, accounting for about one third of the increase observed over the past few decades. Changes in sub-surface temperature induce changes in mixed-layer depth, thermal/density stratification, mixing rates and currents. All of these physical changes can affect marine biology, not only directly but also indirectly through changes in marine biogeochemistry, such as nutrient and oxygen recycling, uptake of carbon emissions, ocean acidification, and so on.

The Argo network provides broad-scale sub-surface temperature profile data, which can document large-scale variability in the top 2000 m of the ice-free open ocean. In a complementary manner, about 40 repeat XBT lines contribute to sub-surface temperature profile data typically in the upper 760 m of the ocean, and which resolve (along the ship track) mesoscale eddies, fronts, boundary flows to basin-scale upper-ocean circulation variability on a quarterly basis. The XBT network also provides long-term time-series data because part of it has been maintained since the 1980s. IP-10 Action O25, reviewed on page 272, addressed continuity of the XBT time series. The success of this goal is difficult to track because not all of the XBT metadata are shared, but around 25 of these XBT lines have been maintained. OceanSITES reference moorings provide long-term sub-surface temperature time-series data often down to 5000 m at least hourly at fixed locations, with vertical resolution that varies from a few fixed depths to a continuous profile. GO-SHIP CTD observations provide high quality large-scale full-depth decadal snapshots along repeated transects, typically with tens of km spacing along the ship track, which is also essential to calibrate autonomous measurements such as those from Argo floats. IP-10 Action O24 (page 272) was to plan for systematic global full-depth water column sampling for ocean physical and carbon variables in the coming decade and to implementation of that plan. The GO-SHIP observations address this action. Action O27 (page 273) was to complete implementation of the current Tropical Moored Buoy network.

Historical measurements had insufficient spatial/temporal sampling to characterise well the upper ocean. Argo profiling with near-global coverage has contributed to a major improvement in the spatio-temporal variability of ocean heat content estimates in the upper 2000 m. Since the majority of sub-surface temperature data were limited to the upper 700 m or less before the Argo era, IPCC (2013) states: "Below ocean depths of 700 m the sampling in space and time is too sparse to produce annual global ocean temperature and heat content estimates prior to 2005." Such estimates are nevertheless provided by reanalysis systems, as illustrated in the review of IP-10 Action C12 (page 209). IP-10 Action O26 (page 273) was to sustain a network of about 3000 Argo floats; this goal has been achieved. The depth Argo can reach sets the major limitation of our observational capability; IPCC (2013) states: "Observational coverage of the ocean deeper than 2000 m is still extremely limited and hampers more robust estimates of changes in global ocean heat content and carbon content. This also limits the quantification of the contribution of deep ocean warming to sea level rise."

Gridded data sets of global sub-surface temperature are routinely produced at several agencies, ranging from ones purely based observational data to those generated by data assimilation systems. Action O28 (page 274) concerned the assembly of the *in situ* and satellite data into a composite reference reanalysis dataset, and to sustain projects to assimilate the data into models in ocean reanalysis projects. Estimates of global temperature and heat content of the upper ocean based on different data products have been converging as the global Argo array has developed, while the differences are still substantial for climate applications. Estimates before the Argo era diverge considerably. IPCC (2013) states: "Different global estimates of sub-surface ocean temperatures have variations at different times and for different periods, suggesting that sub-decadal variability in the temperature and upper heat content (0 to 700 m) is still poorly characterized in the historical record." The International Quality-controlled Ocean Database (IQuOD) project is under way aimed at significantly improving the quality, consistency and completeness of the historical record.

5.4.2 Salinity

Oceanic observations of sub-surface salinity are required for estimating ocean transports of freshwater and other properties on basin to global scales. Along with coincident sub-surface temperature observations, they are required to calculate *in situ* density and near-surface observations provide an important *in situ* validation for satellite observations of sea surface salinity (SSS). Ongoing sub-surface salinity observations, along with temperature are required to further develop understanding of ocean variability and monitor ongoing ocean property changes in response to climate change. Long-term, high-quality observations are essential to detect and attribute changes in weather patterns, climate modes, planetary heat balance and sea level, as well as to place more rigorous constraints on the likelihood of future warming and sea-level rise projections at global and regional scales. Salinity and temperature observations also provide constraints on air-sea exchanges of fresh water and energy. Coupled systems are being developed for short-term weather forecasting, especially those targeting tropical storms. These, along with ocean reanalysis and forecasting services are dependent on global and near-real-time ocean salinity (and temperature) data streams. Salinity observations have proved to be an important input for ocean data assimilation systems that are being used to provide gridded global estimates of ocean circulation at varying spatial and temporal scales.

Ocean salinity, along with *in situ* temperature observations are measured from the surface to the full-depth of the global ocean and databases store measurements extending to 10,000 m. Sub-surface salinity shares observation networks with sub-surface temperature: Argo for broad-scale observations in the upper 2000 m and GO-SHIP CTD observations for high quality large-scale full-depth decadal snapshots along repeated transects, and OceanSITES reference moorings for long-term time series. Historical sub-surface salinity observations have been recorded since 1772, but *in* *situ* observations are very sparse until the Argo period when near-global, broad-scale salinity observational coverage was achieved around 2005.

The networks for sampling sub-surface salinity are almost identical to those for sub-surface temperature (section 5.3.1); the technical details and the evolution of the system are accordingly not repeated here. The adequacy and actions for temperature also match those for salinity.

5.4.3 Current

Oceanic measurements of sub-surface ocean velocity provide the data needed for estimates of ocean transports of mass, heat, freshwater and other properties on basin to global scales. While the vertical shear of the component of horizontal velocity perpendicular to each station pair of a hydrographic section is straightforward to calculate from geostrophy, determining the absolute velocity field to sufficient accuracy for transport estimates is more problematic. Full-depth direct sub-surface ocean velocity observations can resolve complex velocity structure in the major boundary currents and at the ocean sea floor, and near the equator where synoptic geostrophic calculations are useless. Direct velocity observations are essential for resolving the Ekman-layer contribution to property transports, determining large-scale gyre circulations, estimating ocean mass, heat, freshwater and carbon transports, and providing direct estimates of boundary current transports. Velocity estimates can be used in data assimilation.

The spatial and temporal sampling of horizontal currents, as well as the length of the time series is inadequate for many climate applications. The observing system is extremely inadequate for directly measuring vertical motion. However, dedicated observing systems do measure currents in key locations, providing very valuable constraints on transport and global models.

Boundary and equatorial currents are measured with hourly time resolution by moorings. Shipboard and lowered ADCPs provide sub-surface current data from boundary-current scale to basin scale depending on the horizontal resolutions and tracks of cruises. Argo provides Lagrangian sub-surface current measurements, nominally at 1000 m, and information required to estimate relative geostrophic currents above 2000 m for the global ocean; resulting current products have become available recently. This is one of successes flowing from the achievement of Action O26 to sustain the network of about 3000 Argo profiling floats. Action O27 called for implementation of the Tropical Moored Buoy Network to be completed; as discussed on page 273 and in section 5.2.4, this network has in fact declined. A subset of the tropical mooring have provided direct current observations, as have some coastal moorings. Some dedicated arrays, for example that for the Atlantic meridional overturning circulation, have been set up recently to estimate specific regional transports. Nevertheless the number of direct measurements of sub-surface currents is still inadequate in both in location and duration, as commented by IPCC (2013): “The number of continuous observational time series measuring the strength of climate relevant ocean circulation features (e.g., the meridional overturning circulation) is limited and the existing time series are still too short to assess decadal and longer trends.”

5.4.4 Nutrients

It became clear over the last decade that it is necessary to develop accurate observations of trends in dissolved nutrients in both upper- and deep-ocean waters. Nutrient data are essential biogeochemical information, provide essential links between physical climate variability and ecosystem variability, and give an additional perspective on ocean mixing. Nutrients are not adequately observed, however.

Networks and systems that contribute to the observation of sub-surface nutrients are:

- the repeat survey network;
- the reference station network;
- pilot deployments of bio optical nitrate/phosphate sensors on Argo floats.

The latter two are research and pilot programmes and require additional technological development to attain reliable and accurate autonomous sensors and to deploy observing systems to sample better sub-surface nutrient variability, although significant progress has been made for nitrate sensors in particular. For these observations, it is critical that results from different laboratories can be reliably compared. To get a global consensus for nutrient data, it has been decided that globally accepted certified reference materials (CRMs) will be developed and community-approved requirement to use the CRMs, will be in place. Such reference materials are now commercially available, and the CRMs have been proven to be stable over long time-periods.

The system is not yet adequate because many of the key elements mentioned above are still being developed. It is also likely that spatial and temporal sampling is inadequate.

In 2014, two certified reference materials (CRMs) became available for measurements of nutrients in seawater; a CRM provided by the National Metrology Institute, Japan, and MOOS-3, provided by National Research Council, Canada. Based on that development two major activities were undertaken:

5.4.4.1 International Inter-Calibration Exercises

Several such exercises using the newly developed CRMs have been carried out in recent years, the latest in 2014/15. Results from these first inter-laboratory comparison experiments of currently available CRMs will assess the homogeneity and stability of currently available RMs/CRMs. Currently uncertainties in deep ocean nutrient observations may be responsible for the lack of coherence in the nutrient changes. Sources of inaccuracy include the limited number of observations and the lack of compatibility between measurements from different laboratories at different times. Results of nutrient concentrations from global crossover station analysis have shown discrepancies of up to 10 % for deep nutrient data during the last three decades, and the results of inter-laboratory comparison studies since 2003 showed a similar magnitude of discrepancy among some participant laboratories, although some improvement in the results could be detected.

Analytical discrepancies have been mostly removed from measurements of the CO_2 system after the introduction of “carbon” CRMs and similar improvement is expected from the introduction of nutrients CRMs. Currently available nutrient CRMs are appropriate for the nutrient concentration ranges of nitrate, nitrite, silicate and phosphate found in the Pacific and Atlantic Oceans. Therefore, the opportunity for traceability and comparability of nutrient concentrations throughout most of the global ocean exists and a mechanism to provide reference materials that is traceable to SI through CRMs will be developed. Global availability of the RM traceable to CRM will be made through JAMSTEC, in a similar manner to the carbonate system CRMs from the Scripps Institution of Oceanography, USA.

5.4.4.2 SCOR WG

To promote the use of the new CRMs a SCOR Working Group on Nutrients Standards has been proposed and funded. The primary goal for the Working Group is for nutrient data collected at any place by an individual laboratory and data collected over long time periods by one or more laboratories to be consistent, with certified comparability.

A major challenge for this SCOR WG is to develop a system by which the comparability of data within and between laboratories is better than 1% at full scale of nitrate, phosphate and silicate concentrations. The levels of comparability achieved for the measurement of oceanic salinity and total inorganic carbon are considerably better than 1%. However, both of those parameters are comparatively simple chemically, and exist in the open ocean in much narrower concentration ranges than do the inorganic nutrients.

The mechanisms and protocols established through the SCOR WG for improving the quality of reported oceanic nutrient data will allow the community to detect changes in nutrient levels much more accurately in the future. Improved comparability of reported nutrient concentrations in the water column will also help us to improve estimates of the anthropogenic portion of the observed increase of total carbon in the water column.

Precise mechanisms of a global consensus for reporting nutrient levels are being established, with the goal to properly guarantee comparability of data from different laboratories. This consistency will foster a move toward the comparability of nutrient data using globally accepted CRMs, followed by the recommendation of protocols for their use throughout the marine chemistry community.

5.4.5 Carbon dioxide partial pressure

The oceanic uptake of anthropogenic carbon is a key element of the planetary carbon budget. Over the last 250 years, the ocean has removed about 30% of the CO_2 that has been emitted into the atmosphere as a result of the combined actions of fossil-fuel burning and land-use change. Because the net ocean carbon uptake depends on biological as well as chemical activity, the uptake may change as changes occur in oceanic conditions such as alkalinity currents, temperature, surface winds, and biological activity. At present, the community consensus is that the best strategy for monitoring the long-term interior ocean carbon storage is via a global ocean carbon inventory network that measures both dissolved inorganic carbon and alkalinity. With present technology, a major improvement in our knowledge can be achieved with the agreed full-depth repeat survey programme (GO-SHIP; section 5.2.2), also benefiting from the air-sea exchange of CO_2 information obtained from the surface ocean pCO_2 network. This requires also strong commitments from the participating institutions and nations with fast submission of the data to the data centres in order to facilitate the large-scale synthesis.

The repeat hydrography lines covered by GO-SHIP have largely continued, and is the single most important observing element for interior ocean CO_2. Initial results from the first complete round of repeat survey indicates that the level of variability is higher than originally expected, requiring a reassessment of whether the original plan is adequate to fully characterise the decadal time change of the oceanic inventory of anthropogenic CO_2. In addition, the proposed sampling network was inadequate to determine early responses of the oceanic carbon cycle to global climate change. Results from ocean time-series have proven to be of great value for understanding and documenting temporal trends and variability. However, only a few time-series exists where ocean CO_2 is measured; the situation is particularly serious for measurements in the interior of oceans. Additional time-series need to be initiated in ocean areas currently not monitored. A more rapid repeat cycle for selected ocean survey sections will be needed for assessing the net carbon inventory changes over intervals shorter than 10 years.

One solution to both the above problems is the development of long-lived autonomous sensors for ocean carbon system components that can be deployed on moored or profiling observing elements. These are under development and will significantly increase our global observing capability; particularly promising is the measurement of pH on Argo floats noted in the review of IP-10 Action O6 and below.

5.4.6 Ocean acidity

The scientific and policy needs for coordinated, worldwide information-gathering on ocean acidification and its ecological impacts are now widely recognized. The importance of obtaining such measurements has been endorsed by the UN General Assembly, and by many governmental and non-governmental bodies who have recently assisted the scientific community in developing the Global Ocean Acidification Observing Network (GOA-ON; Figure 54). Three high level goals of GOA-ON aim to provide measurements for management while also delivering scientific knowledge: to improve our understanding of global ocean acidification conditions (Goal 1), to improve our understanding of ecosystem response to ocean acidification (Goal 2), and to acquire and exchange the data and knowledge necessary to optimize the modelling of ocean acidification and its impacts (Goal 3).

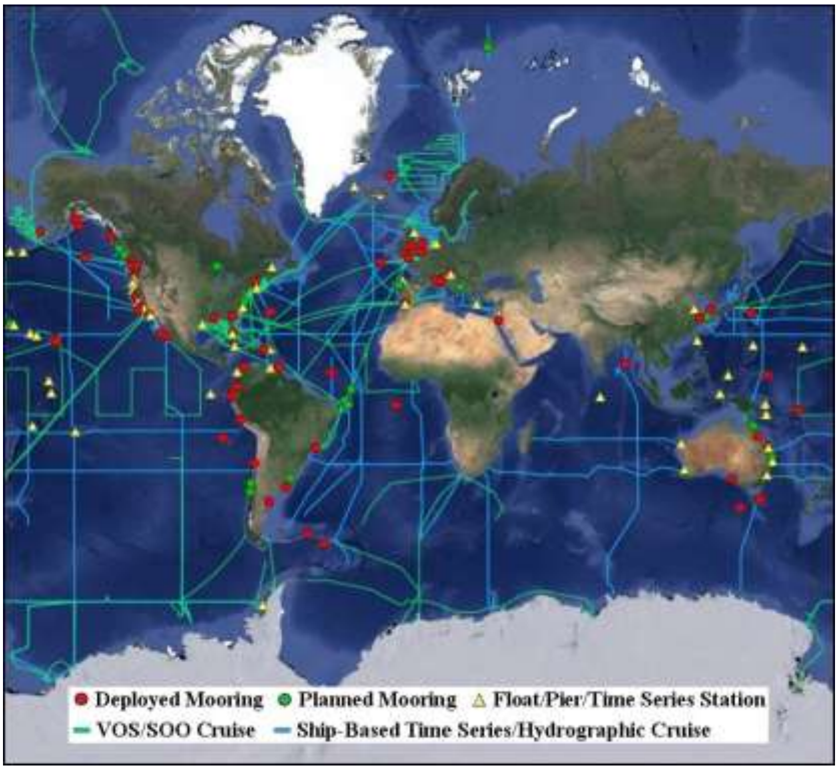


Figure 54: Map of current and planned Global Ocean Acidification Observing Network (GOA-ON) components. Source: http://www.goa-on.org/.

The GOA-ON Requirements and Governance Plan (available from http://www.goa-on.org/) provides broad concepts and key critical details on how to meet these goals. In particular, it defines the Network design strategy, ecosystem and goal-specific variables, spatial and temporal coverage needs, observing-platform-specific recommendations, data quality objectives and requirements, initial GOA-ON products, outcomes and applications, GOA-ON's proposed governance structure and Network support requirements. The effort of GOA-ON to develop the optimal observing system to detect ecosystem impacts of ocean acidification on various types of ecosystem (including tropical, temperate and polar regional seas; warm and cold-water corals; and nearshore, intertidal and estuarine habitats), and in the context of other stressors, has started only recently. Further work will be needed to refine detailed protocols for relevant biological observations on a habitat- or regionally-specific basis.

Future actions of the GOA-ON include facilitating additional measurement efforts in geographical areas of high concern, together with associated capacity-building, strengthening of linkages with experimental and theoretical studies, maintaining and extending communications with the ocean observing community, establishing effective and quality-controlled international data management and data sharing, through distributed data centres, and encouraging the development of synthesis products based on GOA-ON measurements. All this will require that the Network secure the necessary level of support and resources to achieve these actions. The further development of GOA-ON will require the adoption of advanced new technologies that will reliably provide the community with the requisite biogeochemical measures necessary to track ocean acidification synoptically.

Great progress is being made in development of the autonomous sensors technology for pH and pCO_2, and to lesser extent also for measurements of dissolved inorganic carbon and alkalinity. IP-10 Action O14, reviewed on page 266, called for high precision instrumentation, and work in this area is progressing fast, though not complete. The first basin-wide pilot project (Southern Ocean Carbon and Climate Observations and Modeling, SOCCOM) started in 2015 and around 200 autonomous floats capable of measuring pH and other biogeochemical parameters will be released in the rest of 2015 and in 2016. For the first time nearly continuous coverage in time and horizontal and vertical space over the entire basin will be provided via this robotic observing system. Careful calibration procedures for measured parameters (nitrate, pH and oxygen) will be developed, using data from the deep hydrography research cruises planned for the region.

The modelling component of SOCCOM will (amongst other tasks) create assessment tools for the observing system aimed at development of an internationally-agreed implementation strategy to identify priorities for the sustained system for the basin. This strategy might work as a basis for further up-scaling to the global observing system for ocean acidification.

5.4.7 Oxygen

Oxygen is essential for all higher life. Future projections indicate that oceanic oxygen levels will decrease substantially, in part because of ocean warming and increased stratification, a process often referred to as ocean deoxygenation, but also because of increased nutrient loadings in nearshore environments that lead to eutrophication. In a business-as-usual scenario, the ocean is projected to lose nearly 20% of its oxygen. This could have dramatic consequences for marine biogeochemistry and marine life, as the ocean's oxygen minimum zones will expand substantially, and large swaths of ocean will appear that have oxygen levels too low for fast swimming fish to survive, and can potentially reduce the pool of bio-available nitrogen due to reduction of nitrate.

Oxygen is also is an excellent tracer for ocean circulation and ocean biogeochemistry.

Oceanic measurements of oxygen have a long history, and oxygen is the third most-oft-observed water quality after temperature and salinity. The classical method to measure oxygen is the Winkler method, a discrete method that provides highly accurate and precise measurements. Historical data based on the method were collected mostly by research vessels, and accordingly had limited temporal and spatial distribution. Development of autonomous sensors has made substantial progress in recent years and there are now long-term deployments with sufficient accuracy and stability on moorings, gliders and Argo (Figure 43), in line with IP-10 Action O30 (page 275) to deploy a global pilot project of oxygen sensors on profiling floats.

Although a significant number of oxygen sensors are delivering data, the observing networks require development in order to adequately sample sub-surface oxygen variability. In particular the data processing from the autonomous network of Argo floats is not as well developed as for the core Argo project. SCOR Working Group 142 on Quality Control Procedures for Oxygen and Other Biogeochemical Sensors on Floats and Gliders addresses this issue.

5.4.8 Tracers

Ocean tracers are essential for identifying anthropogenic carbon uptake, storage, and transport in the ocean, as well as for understanding multi-year ocean ventilation, long-term mixing and ocean circulation and thereby for providing essential validation information for climate-change models. The repeat network of tracer observations allow for quantification of temporal variability of transport and ventilation.

Ocean tracers are, however, inadequately sampled at present. Current technology for all important tracers requires water samples and subsequent processing of these samples.

GO-SHIP is the primary network contributing to measurement of sub-surface tracers, complemented by intermittent research observations. GO-SHIP's tier-1 data include chlorofluorocarbons (CFC-11 and CFC-12) and SF_6. These tracers are thus regularly measured and reported on. Maintaining the current capacity to observe them should be a priority. New technology will likely make small volume (<10L) sampling for Argon-39 determination feasible within the next decade. Data on Argon-39, with a half-life of 269 years, would fill a large gap for old deep water where the CFCs provide no signal.

IP-10 noted the need for technological development of autonomous sensors. Since then, slow progress has been made on autonomous sampling on moorings, and some tracers are expected to be observable from the reference moorings within the decade. No other progress has been made on development of autonomous sensors for ocean tracers.

6 Terrestrial observation

6.1 Introduction

The terrestrial component of the climate system provides human beings with many resources of vital importance for life, such as water, food, fibre and forest products. At the same time, variability and change in the hydrological and biogeochemical cycles are coupled within the climate system and affect the livelihood of millions of people. The primary way in which the terrestrial domain features in climate variability and change is through changes in water and carbon storage and through feedbacks from changes in land cover and the cryosphere. Precipitation, evapotranspiration, groundwater, soil moisture, lake levels, glaciers and river discharge constitute critical components of the hydrological cycle, with impact on flooding and the availability of water for drinking, agriculture and industry.

Land exhibits a wide variety of natural features, slopes, vegetation and soils that affect water budgets, carbon fluxes and the reflective properties of the surface. It has been estimated that more than half of the Earth's land surface has been modified by humans, with much of the modified area under some form of management. Use of the land changes the characteristics of its surface and thus can induce important local climatic effects, especially through changes in albedo, roughness, soil moisture and evapotranspiration. When large areas are concerned, such as in tropical deforestation, regional and even global climate may be affected. Some land is covered by snow and ice on a seasonal basis, and this land may feature glaciers, permafrost and frozen lakes. Ice sheets cover much of Antarctica and Greenland. Snow- and ice-albedo play an important role in the feedback on climate as it warms or cools, and melting land-based ice contributes to sea-level rise. Sea level also depends on the amount of water held in reservoirs and taken from groundwater. Disturbances to land cover (vegetation change, fire, disease and pests) and soils (notably permafrost and wetlands) have the capacity to alter climate, but also respond to climate in a complex manner through changes in their biogeochemical and physical properties. Precise quantification of the rates of change of several land components is important to determine whether amplification mechanisms through terrestrial processes are operating within the climate system. Increasing significance is being placed on terrestrial data for both fundamental climate understanding and for use in impact and mitigation assessments.

Atmospheric CO_2 and other greenhouse gases are increasing globally while natural terrestrial sources, sinks and stocks, and human interventions in the carbon cycle, including through changes in land cover and use, vary profoundly between regions. Assessments of regional carbon budgets help to identify the processes responsible for controlling larger-scale fluxes. In principle, comparison may be made of "top-down" atmospheric inversion estimates with "bottom-up" observations or estimations of localized carbon fluxes. The basic components of such budgets include measurements of carbon stocks and exchanges with the atmosphere.

Foundations exist for both *in situ* observing networks and space-based observing components for the terrestrial-domain ECVs. They are documented ECV by ECV in section 6.3, after discussion in the following section of several other terrestrial issues for which actions were formulated in IP-10.

6.2 Cross-ECV issues

6.2.1 Standards

Many organisations make terrestrial observations, for a wide range of purposes. As a result, the same variable may be measured by different organisations using different measurement protocols. The resulting lack of homogeneous observations hinders many terrestrial applications and limits the scientific capacity to determine the causes of land-surface changes, and the capacity to monitor the climate-relevant ones. GCOS (2003, 2004) noted the need for an international framework to:

- prepare and issue regulatory and guidance material for making terrestrial observations;
- establish common standards for networks, data management and associated products and services;
- ensure compatibility with standards and initiatives;
- seek hosts for designated international data centres addressing the full range of terrestrial domain ECVs.

Following a request by the UNFCCC regarding the development of such an international framework, the GTOS Secretariat in 2007 proposed three implementation options. These included an option that involved the International Organization for Standardization (ISO). With additional guidance provided by SBSTA, GTOS and partners reached a consensus to proceed with developing a joint UN/ISO-based framework for setting and maintaining standards for terrestrial observations of ECVs. The proposed framework foresaw the establishment of a joint steering group, with specific roles for the participating UN organisations (in defining the requirements for standardization and in providing technical inputs) and for the ISO (in leading the standards development effort). The ISO recognition of WMO as a standards-setting organisation further strengthened the foundation for the proposed framework.

Following an assessment by GTOS of the status of the development of standards for each of the terrestrial ECVs, IP-10 formulated Action T1 calling for continued development and promotion of observational standards and protocols for the terrestrial ECVs. The review of this action given on page 281 notes that there has been progress on this for some individual ECVs, but reports that development of a coordinated cross-ECV approach has been stalled by the failure of FAO to support the GTOS Secretariat and Steering Committee. A further factor has been the questioning by TOPC of the wisdom of the ISO-based approach to standardization that was being adopted, given the lack of maturity and speed of development of the observations of some ECVs.

6.2.2 Exchange of hydrological data

The Global Terrestrial Network for Hydrology (GTN-H) is a joint effort of WMO, GCOS and GTOS with the main objective of linking existing data centres, networks and systems for integrated observations of the global water cycle. It promotes the continued design, implementation and operation of baseline hydrometeorological observation networks. The principal task of the GTN-H is to facilitate access to observations relating to the ECVs within the realm of hydrometeorology. The NMHSs are generally responsible for making the observations required by the different baseline networks, and many other national and international agencies complement the observations of the national services. IP-10 Action T2 called for promotion of the required international exchange of hydrological data and development of integrated products. Moderate progress is indicated in its review, which begins on page 281.

6.2.3 Monitoring at terrestrial reference sites

Many terrestrial ECVs, including FAPAR, LAI, biomass and albedo, are too heterogeneous spatially for global *in situ* measurement to be practical. They are typically measured at a limited number of research sites or retrieved from space-based remote sensing over large areas. Three key requirements for *in situ* measurements at such reference sites in the context of long-term global climate observation were identified in IP-10:

- to ensure that a representative set of biomes are properly and consistently documented over periods of decades or more, monitoring the details of natural vegetation changes and carbon stocks and fluxes;
- to measure key meteorological ECVs to support interpretation of the recorded changes;
- to optimize the joint use of these terrestrial reference sites with a set of sites delivering essential ground data for the validation of satellite-derived products (Action T29) and key ecosystem sites (Action T4).

IP-10 Action T3, reviewed on page 281, called for establishment of the reference network as a subset of sites from the existing FLUXNET and the Long-Term Ecological Research Network (LTER). Only limited progress is reported for this action.

6.2.4 Monitoring terrestrial biodiversity and habitats at key ecosystem sites

Climate change is a driver of wider environmental change, with impacts on habitats, ecosystems and biodiversity. IP-10 called for establishment of “Essential Ecosystem Records” at a set of selected sites, including ones with especially high biodiversity. The sites would undertake systematic, high-quality observation of key parameters of biodiversity and habitat properties. Observations of the local physical climate and changes in surrounding environment, such as land and water use, would also be made at these sites. It was also noted that this would respond to key observing needs of the Convention on Biological Diversity (CBD). Details of the site concept and measurement approach could be developed, for example, by working with the communities coordinated through the GEO Biodiversity Observation Network (GEOBON). The corresponding IP-10 Action, T4, is reviewed on page 283. Although the ecological observing networks that have been established at continental scale are addressing measurement gaps and the challenges of international standardization and harmonization, there has been very little progress on the specific objective of the action.

6.2.5 Evapotranspiration

In addition to information on CO_2 fluxes (discussed below in the review of Action T34), FLUXNET sites provide measurements of evapotranspiration from the land that are an important part of the hydrological cycle, supplementing long-term *in situ* measurements of evaporation from pans. Land-use and climate change induce changes in the amount and distribution of evapotranspiration. IP-10 noted that global products were beginning to be derived from reanalysis and satellite data, and needed independent *in situ* verification. IP-10 Action T5 called for development of an evaporation product that made use of data from existing networks and satellite instruments. It is reviewed on page 284.

6.2.6 Data portal for terrestrial measurement sites

IP-10 concluded that in addition to the data centres associated with each ECV, it would be beneficial to have a central clearing house identifying holders of all the variables. This would facilitate access to multiple variables. It noted that GTOS had made considerable progress in the development of the Terrestrial Ecosystem Monitoring System (TEMS), a web portal for metadata on terrestrial *in situ* measurement sites, including the biogeophysical variables addressed by each site.

IP-10 Action T40 called for revision of the TEMS database to give improved focus on the monitoring of terrestrial ECVs. Lack of a functioning GTOS Secretariat has prevented progress on this; the TEMS database is no longer available.

6.3 Variables

6.3.1 River discharge

River discharge measurements have essential direct applications for water management and related services, including flood protection. They are needed in the longer term to help identify and adapt to some of the most significant potential effects of climate change. The flow of fresh water from rivers into the oceans also needs to be monitored because it reduces ocean salinity, and changes in flow may thereby influence the thermohaline circulation. Data are needed for evaluating the working of the hydrological cycle in climate models and for use in the development and operation of flood-modelling components that are driven by or embedded within climate and shorter-term forecasting models, or will be in coming years.

Although the river discharge ECV as discussed in subsequent paragraphs concerns the rate at which water flows down a river at the point of measurement, there are other aspects of river flow that also need to be measured. This is because rivers play a role in the cycling of carbon, nitrogen and other constituent cycles, and transport suspended sediments that influence the quality and biodiversity of surface waters, riparian environments and the functioning of coastal zones. Rivers are also extensively used in industry, especially for cooling, and this brings an increasing need to monitor the temperature as well as the content of river waters. These additional measurements are needed not only for short-term monitoring but also to appreciate the potential impacts of future changes in river flow, whether from changes in upstream abstraction or changes in climatic inputs.

Monthly observations of river discharge are generally sufficient to estimate continental runoff into the ocean, but daily data are needed to calculate the statistical parameters of river discharge, for example for analyses of the occurrence and impacts of extreme discharges.

IPCC AR5 noted that the most recent and comprehensive analyses of river runoff did not support the AR4 conclusion that global runoff increased during the 20^{th} century. New results also indicated that the AR4 conclusion regarding global increasing trends in droughts since the 1970s are no longer supported. AR5 concluded that confidence is low for an increasing trend in global river discharge during the 20^{th} century and that there continues to be a lack of evidence and thus low confidence regarding the sign of trend in the magnitude and/or frequency of floods on a global scale.

Most countries monitor river discharge, but many are reluctant to release their data. Additional difficulties arise because data are organized in scattered and fragmented ways, with data often managed at sub-national levels, in different sectors and using different archival systems. Even for those data providers that do release their data, delays of a number of years can occur before data are delivered to international data centres such as the Global Runoff Data Centre (GRDC). In addition to the need for better access to existing data, a tendency for observing networks to shrink in some countries, especially the closing of stations with long records, needs to be reversed.

Research and development of interferometric and altimetric approaches to monitoring river water-level and discharge from satellites are being undertaken by the space agencies and partners. A recent such study using Envisat radar altimetry to examine potential for monitoring small Indonesian rivers and lakes is reported by Sulistioadi *et al*. (2015), for example. One goal of the SWOT mission being developed for launch in 2020 is to use a radar interferometer to determine the height (to 10 cm accuracy) and slope (to 1 cm/km) of terrestrial water masses, resolving rivers with widths upward of 100 m and other water bodies with areas upward of 250 m^2. It should enable calculation globally of the rate of water gained or lost in lakes, reservoirs, and wetlands, and the variations in river discharge.

Nevertheless, with current technology *in situ* systems offer the most complete basis for river discharge monitoring. The GRDC has a mandate to collect and redistribute river discharge data from all WMO Members, in accordance with resolution 25 of the thirteenth World Meteorological Congress, which called on Members to provide hydrological data and products with free and unrestricted access to the research and education communities for non-commercial purposes. Despite this, there are still major gaps in the data received by the GRDC, both in terms of the number of rivers monitored and the time it takes for the GRDC to receive the data.

Based on past availability of data, the GRDC has proposed a baseline network of river discharge stations near the mouths of the largest rivers of the world, as ranked by their long-term average annual volume. These stations, a subset of existing gauging stations around the world, collectively form a GCOS Baseline Network, the Global Terrestrial Network for River Discharge (GTN-R). The locations of the stations are shown in Figure 55. Data from them capture about 70% of the global freshwater flux from rivers into the oceans. They have all reported at some time in the past, and most are operating today. This network is now being adjusted in consultation with National Hydrological Services (NHSs), and a total of 281 stations have been confirmed. The status of another 165 stations has not yet been clarified with the 56 NHSs concerned.

The WMO, through its Commission for Hydrology, CHy, has requested that the NHSs responsible for the stations marked in Figure 55 as “not clarified” evaluate the identified gauging stations, determine their operational status and provide the GRDC with this information and all existing data and metadata, including the measurement and data transmission technology used. It has further requested that daily discharge data be submitted to the GRDC within one year of its observation. Important as this is, it is seen as a step towards the ultimate goal of near-real-time receipt from as many stations as possible on all significant rivers. Currently, some stations are able to transmit near real-time data; others need to be upgraded. The status as of March 2015 is that:

- data are provided regularly in near-real-time data to the evolving GTN-R by 16 NHSs, with negotiations ongoing for a further 20 countries;
- unrestricted daily river discharge data from 245 confirmed stations of the GCOS Baseline River Network, from 22 NHSs, are available via the GEOSS Portal.

The material presented above provides a review of IP-10 Action T6 concerning the status of river-gauge measurement and the prompt supply of discharge data.

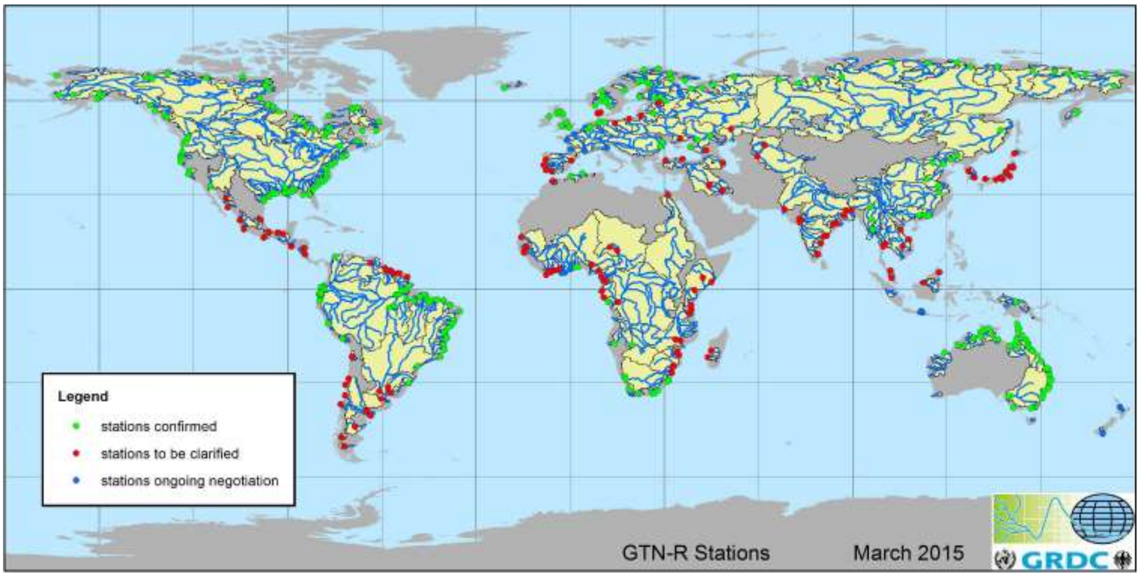


Figure 55: Global Terrestrial Network for River Discharge (GTN-R), a GCOS Baseline Network based on Global Runoff Data Centre priority stations. Source: GRDC (http://www.bafg.de).

The GTN-R, in cooperation with WMO CHy, has been requested to develop mechanisms for transmitting near-real-time river discharge data from the NHSs to the GRDC. Standards for exchanging hydrological data have been under development since 2009 in a joint working group of the OGC (Open Geospatial Consortium) and WMO. The first standard for the exchange of hydrological time series was approved by the OGC in 2011 and the CHy Session in 2012 resolved to commence the process of achieving formal adoption as a WMO standard and registration as a joint WMO/ISO standard. The standard is already widely used by NHSs, promoted by US and EU recommendations. Implementation of these mechanisms will be assessed by the number of priority stations reporting annually with a maximum one-year delay, by the number of near-real-time stations established, by the amount of data transferred or made accessible, and by the number of countries submitting timely data to the GRDC.

Long-term, regular measurements of upstream river discharge on a more detailed spatial scale than GTN-R within countries and catchment areas are necessary to assess potential impacts of climate change on river discharge in terms of river management, water supply, transport and ecosystems. A parallel project to the GTN-R is the WMO CHy “Climate sensitive stations” network, comprising stations with minimum human impact that can be used as reference stations to detect change signals. This relates to IP-10 Action T7 concerning assessment of national needs for river gauges to support impact assessments and adaptation, which is discussed on page 285.

6.3.2 Water use

Data on water extractions and available renewable freshwater provide key information on the availability of freshwater and the amount of water stress in a country. IPCC (2014) reported that for each degree of global warming, approximately 7% of the global population is projected to be exposed to a decrease of renewable water resources of at least 20%. It also reported that climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions. In contrast, water resources are projected to increase at high latitudes. Climate change is also projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment.

	Total withdrawal by sector (%)			Total withdrawal km^3/yr	Freshwater withdrawal km^3/yr
	Municipal	Industrial	Agricultural		
Global	12	19	69	3918	3763
Africa	13	5	82	213	199
Americas	15	34	51	847	843
Asia	9	10	81	2507	2373
Europe	22	57	22	333	332
Oceania	26	15	60	18	17

Table 2: Annual water withdrawal by sector, based on statistics dated around the year 2007. Water withdrawal refers to the water removed from aquifers, lakes and rivers for the sectorial purposes; most is returned to the environment some time later, after use. Total withdrawal includes use of desalinated water, direct use of treated municipal wastewater and direct use of agricultural drainage water. Data from http://www.fao.org/nr/water/aquastat/water_use

The availability of freshwater plays a crucial role in food production and food security. Irrigated land covers about 20% of cropland but contributes about 40% of total food production. Irrigated agriculture accounts for about 70% of all freshwater consumption world-wide and more than 80% in developing countries. Industrial use accounts for a further 20% or so and domestic use a little over 10%. Table 2 provides a breakdown by continent. Future food needs will require intensified production, including increased irrigation of agricultural crops and a likely rise in water consumption that makes production more sensitive to drought. In order to obtain improved quantitative and qualitative information on irrigated land and available water resources, data on their spatial distribution and change over time are essential.

The FAO collects, analyses and disseminates information related to water use through its on-line AQUASTAT database (http://www.fao.org/nr/water/aquastat/main/). The numbers in Table 2 are extracted from a table published in September 2014, although they are based on data that apply for years around 2007; an underlying database can be accessed showing the data available country-by-country, and their date. The IPCC noted in AR5 that relevant socioeconomic data such as on rates of surface water and groundwater withdrawal are limited, even in developed countries. This is discussed further on page 288 of the present report, in the review of IP-10 Action T12 on the archiving and dissemination of information related to irrigation and water resources.

A global product has been provided since 1999, namely the Global Irrigated Area Map. Version 5, dated October 2013, was developed at the University of Bonn in collaboration with the FAO, and is available through AQUASTAT. Figure 56 is taken from the documentation of the product (Siebert *et al*., 2013). It shows irrigated areas and whether surface water or groundwater was used. Finer-resolution products are available for some regional and national areas.

The information note on AQUASTAT (FAO, 2014) recognises that lack of complete time-series for the variables that AQUASTAT holds makes it difficult to determine trends and increase understanding of water in a socio-economic context. Much of the data are of poor quality and often the data are over-interpreted; considerable effort is needed to improve the dataset, but resources are insufficient. The data gaps in AQUASTAT are mainly attributed to lack of information and capacity at national level and lack of resources at all levels. AQUASTAT does perform modelling to supplement country-level data, but the lack of complete time series limits the interpretation possible from its data holdings.

There is a need also for more quality assurance of data submitted to the AQUASTAT database. FAO has developed a new set of guidelines and protocols for national reporting.

Satellite data offer potential for information on use of water for irrigation that is more up to date and better resolved in time. Their application in the estimation of land cover is discussed in section 6.3.10. The classification schemes used may indicate irrigation. This is the case for the ESA CCI 300 m product illustrated in Figure 65, which identifies a class of cropland that is either irrigated or post-flooding. Where irrigation is widespread, further information may come from observations of soil moisture (section 6.3.16) and related diagnostics and products from data assimilation.

The *in situ* information required to complement satellite data, such as the source of irrigation water, the type of irrigation (surface, sprinkler, or micro-irrigation), the timing and frequency of irrigation or the volume of irrigation water used, is generally not available, or available only with considerable time delay in databases such as AQUASTAT.

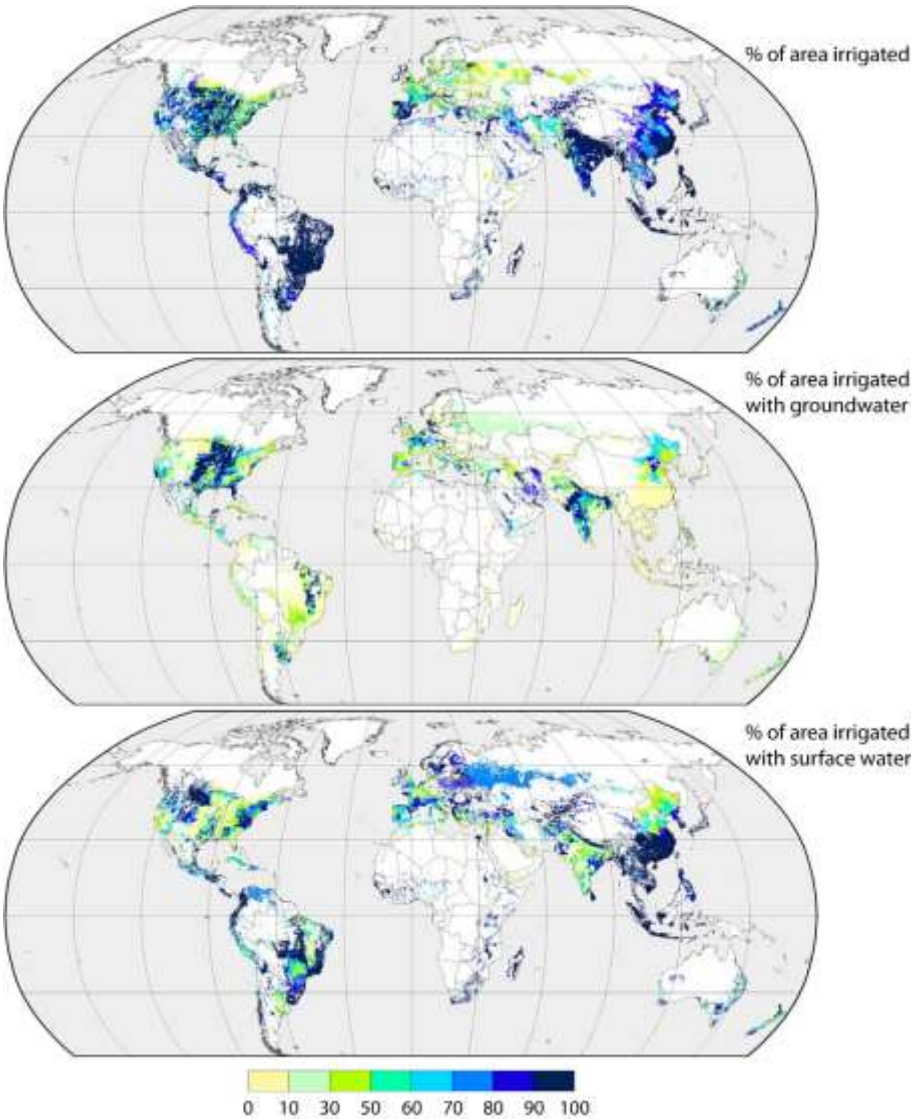


Figure 56: Percentage of area equipped for irrigation that was actually irrigated (top), irrigated by groundwater (middle) and irrigated by surface water (bottom). White areas denote land not equipped for irrigation. Data refer mostly to the period 2000-2008. Source: Siebert et al. (2013).

6.3.3 Groundwater

It is estimated that groundwater accounts for around 30% of the world's total freshwater resources, including those locked in snow and ice, and is by far the largest available reservoir of liquid freshwater. It is today the source of about one third of global water withdrawals. Estimates of the number of people who depend on groundwater supplies for drinking range from 1.5 to 3 billion. Global groundwater abstraction has at least tripled over the past 50 years, much more so in some regions. Use is mainly for agriculture, for which the geographical distribution is shown in Figure 56. The relative increase in groundwater use over recent decades has been larger than that of surface-water use.

Climate change affects groundwater recharge rates through changes in precipitation and evapotranspiration. However, as reported by IPCC (2014), attributing observed groundwater change to climate change is difficult because of land-use change and groundwater abstraction, and the extent to which groundwater abstraction has already been affected by climate change is not known.

Climate change can also affect groundwater through salt-water intrusion in coastal aquifers as sea-level rises. This can be observed by a change in the electrical conductivity of groundwater, but attribution is again complicated by abstraction, as withdrawal of fresh water from the ground may draw more-saline water into the aquifer.

The International Groundwater Resources Assessment Centre (IGRAC) was launched in 2003, and became a UNESCO centre in 2011. In turn, IGRAC has developed the Global Groundwater Monitoring Network (GGMN). The GGMN is a web-based network of networks, set up to improve quality and accessibility of local groundwater data and thus knowledge of the state of groundwater resources. Further information on it is given on page 287, in the review of IP-10 Action T11, which called for establishment of a prototype global network and groundwater monitoring information system.

Data on changes in groundwater can also be derived from space-based measurement. Variations in the amount of water are detectable through variations in the gravitational field measured by the GRACE mission. Ancillary information on changes in snow mass, soil moisture and surface water, which generally requires use of modelling and additional observations, enables the change in groundwater to be inferred. Studies have been made of the depletion of groundwater in northern India (Rodell *et al*., 2009; Tiwari et al., 2009), where Figure 56 shows relatively high use of groundwater for irrigation, and in the Colorado River Basin during a period of drought (Castle *et al*., 2014).

Continuation of space-based gravimetry is discussed on page 293, in the context of IP-10 Action T20 related to space-based monitoring of ice-sheet mass.

6.3.4 Lakes

Information on changes in lake level and area (which are surrogates for changes in lake volume) is required on a monthly basis for climate assessment purposes. Approximately 95% of the volume of water held globally in approximately 4,000,000 lakes is contained in the world's 80 largest lakes, which are recognised within the GCOS/GTOS Global Terrestrial Network for Lakes (GTN-L). GTN-L focusses primarily on two categories of priority lakes: great and mid-size lakes with a natural regime (79 lakes) and great lakes with an artificial water regime (15 lakes).

Satellite-based observations can substantially contribute to the monitoring of lake level and area using appropriate VIS and NIR imager radiances, radar imager radiances, and radar and laser altimetry. This is especially so in remote areas that lack good *in situ* monitoring capability. While satellite imagery (mainly to date from the Landsat series) allows determination of lake shorelines with a resolution of 30 metres (section 6.3.10), current imaging does not provide direct monitoring of the water surface of each lake of the GTN-L every month at high spatial resolution. However, for each lake the link between water height and area may be calculated using four or five selected images taken from low to high water heights, and the relationship then used with height data from satellite altimetry or *in situ* measurement to calculate lake area. This methodology is under development at the Laboratory for Space Studies in Geophysics and Oceanography (Legos) in collaboration with the WMO-recognized International Data Centre on Hydrology of Lakes and Reservoirs (HYDROLARE), hosted by the State Hydrological Institute of the Russian Federation, St. Petersburg.

Observing lake freeze-up and break-up dates provides an important indicator for climate change in boreal and polar regions. Although lake-surface temperature can serve as an indicator for changes in these dates, and for climate change more generally, the most relevant time series for freeze-up and break-up dates come from *in situ* observers. Satellite observations related to the ice-cover, temperature and area of lakes are not considered in this section, as they are as discussed in the accompanying sections for sea-ice, SST and land cover.

Altimetry for large lakes typically has an accuracy ranging from three centimetres to one metre depending on the size and morphology of the lakes. WMO (2006) requires uncertainty in water-level observations from hydrological stations to be one centimetre for lake levels in general and two centimetres under difficult conditions, at the 95% confidence level. Satellite water-level measurements may exceed these limits but still enable the general assessment of seasonal and long-term water-level trends. *In situ* data from ground networks are nevertheless needed to validate the satellite data and support the required improvement in monitoring lakes from space.

Although reservoirs are of undoubted importance in terms of determining terrestrial water storage, fluctuations in the area and level of reservoirs are determined by human activities as well as climate, and reservoirs tend by their nature to be monitored well *in situ*. Space-based altimetry nevertheless provides accessible data on the levels of large reservoirs as well as lakes, and the *in situ* data provide validation of the altimetric data, as illustrated in Figure 57 for the Lake Mead reservoir on the Colorado River in the Southwest USA.

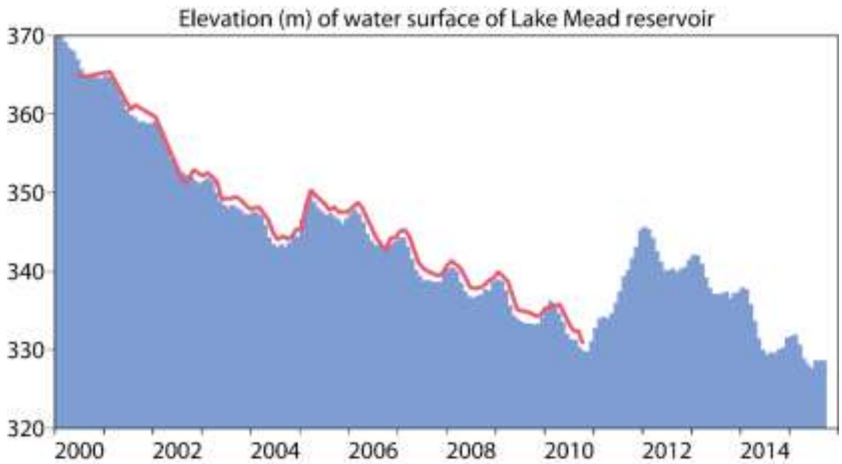


Figure 57: Elevation of the water surface level (metres) of the Lake Mead reservoir from monthly-mean in situ monitoring data (blue) at the Hoover Dam from the US Bureau of Reclamation (http://www.usbr.gov/lc/region/g4000/hourly/mead-elv.html), and from altimetric data (pink) available from the Legos HYDROWEB site (Crétaux et al.*, 2011).*

Sustained long-term observations of the hydrological characteristics of some water bodies extend over many decades or even several centuries. There are observations of ice on Lake Biwa, Japan, that date back to the 15th century; observations of lake levels and outflow for several lakes in Finland, Russia and Switzerland for which data are held by HYDROLARE date from the 19th century. Nevertheless, on a global scale existing monitoring systems are inadequate and datasets from different part of world cannot be readily compared. Long-term information is lacking for some regions.

IP-10 set out three actions, T8, T9 and T10, relating to lakes, all concerned with the delivery of data to HYDROLARE. They are reviewed starting on page 286.

In addition to the data held and accessible from HYDROLARE (http://hydrolare.net/index.php), altimeter data are available from the linked Legos HYDROWEB site (http://ctoh.legos.obs-mip.fr/), the US Department of Agriculture (http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/)) and the ESA River and Lake project (http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main). The Global Lake Temperature Collaboration has compiled a database of summer temperatures and related information for 291 lakes collected *in situ* and/or by satellites for the period 1985–2009. Satellite measurements using AVHRR, ATSR-1, ATSR-2 and AATSR instruments have been collected for 151 lakes (Sharma *et al*., 2015).

6.3.5 Snow cover

Terrestrial snow properties are highly sensitive to changes in temperature and precipitation regimes and are recognised to provide a fundamental indicator of climate variability and change. They also provide a significant feedback effect in a warming climate. Projected loss of seasonal snow extent will strongly affect planetary albedo, soil moisture, growth conditions for vegetation, flood potential and other parameters that influence the surface water and energy balances and have significant societal impacts. Changes in the timing, rate and magnitude of precipitation directly impact the area, extent, depth, water equivalent and wetness of lying snow. These changes will modify land-atmosphere fluxes through changes in latent energy sinks, surface roughness, boundary-layer stability and other processes, in addition to albedo. Snow depth and snow-water equivalent also affect soil temperatures and other characteristics of the ground, including permafrost.

Observations of snow are important not only for understanding and monitoring this role in the climate system. They are also important for initialising and evaluating models covering time scales from weather forecasting (where the presence of lying snow must be represented well to avoid error in near-surface air temperature), through sub-seasonal and seasonal prediction (where initial conditions on snow depth are important, and melting has impacts on soil moisture and the surface energy balance), to long-term climate simulations and projections (where snow/albedo feedbacks must be well represented and changes in snow climatology and the associated hydrology reliably identified). Observational data on snow cover is reasonably trustworthy, but there are large uncertainties in snow-depth products and estimates of regional or hemispheric snow water equivalent.

In situ measurements of snow depth are quite widely included on at least a daily basis in the synoptic reports exchanged on the GTS. Figure 58 presents examples of data coverage, for the Februaries of 2002 and 2015. Features of the map include relatively low data coverage over the USA in both years and better data coverage over Canada and Russia in 2015 than 2002, in regions that can be presumed to be snow-covered. However, several countries that reported zero snow depth in 2002 did not do so in 2015. In marginal regions this makes it difficult to assess whether variations in data coverage are due to lack of snow or lack of measurements. Observations of zero snow depth are important when data are used in assimilation systems as they can act to remove snow that is erroneously present in a background forecast. One of the objectives of the Snow Watch project established under the Global Cryosphere Watch is to promote reporting of zero snow depth as standard practice. The GCW itself is a relatively new programme, established in 2011.

Several factors contribute to the greater number of observations in 2015. Additional coverage over Canada, some European countries and a few other places comes from automatic stations. A number of extra observations come only in the new BUFR code whose use overlaps with the former alphanumeric SYNOP code in February 2015. Data coverage is denser over parts of Europe in 2015 also because conventional coverage has been enhanced by additional national snow reports from several countries. These are provided routinely in near real-time on the GTS under a European initiative. Such networks exist in other nations: for example the US SNOTEL (SNOwpack TELemetry) network also provides near-real-time snow-depth measurements suitable for use in operational data assimilation and reanalysis. Wider international exchange of such data is another objective of Snow Watch.

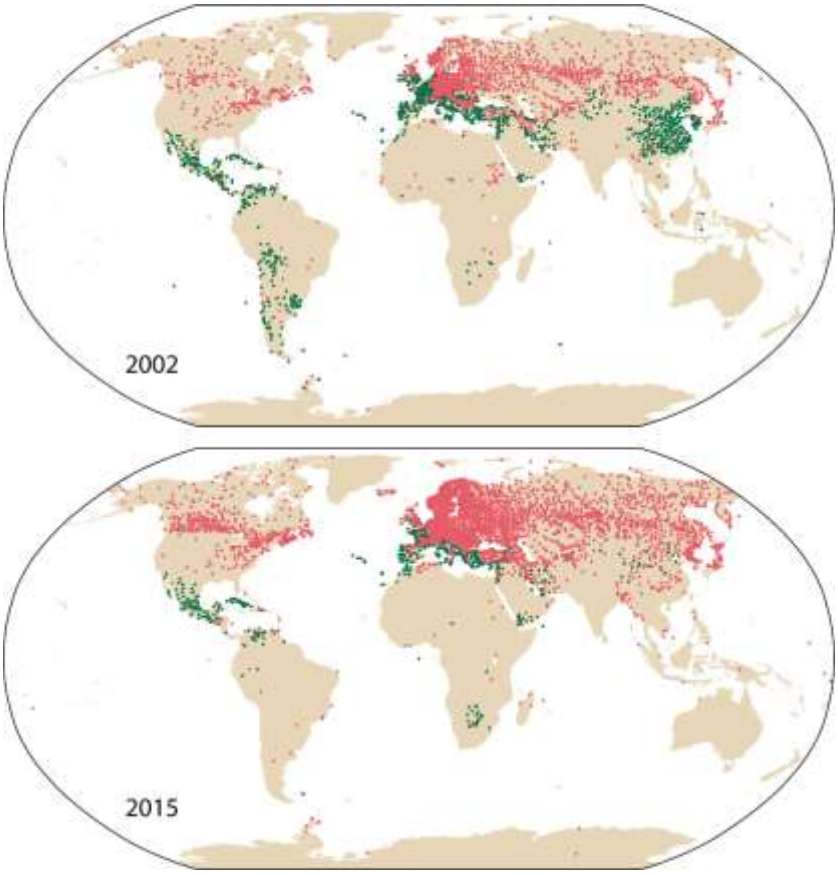


Figure 58: Snow-depth reports received by ECMWF over the GTS in February 2002 (upper) and February 2015 (lower). A red symbol is plotted for each 0.5 degree latitude/longitude grid box that contains at least one observation of positive snow depth during the month in question. A green symbol indicates grid boxes for which there are observations, but all in the month are of zero snow depth. No quality control has been applied.

The need for datasets to examine climate trends and variability, and to support modelling and reanalysis, brings additional requirements for recovery and exchange of historic *in situ* data. The number of observations in standard holdings of synoptic data drops off substantially in earlier years: ERA-40's collection of SYNOP data includes about 2510 snow-depth reports per day for 1978, 500 per day for 1968 and 85 per day in 1958, for February, compared with 2940 reports per day in 2002 and many more today. A number of openly available sources of both snow-depth measurements and surveys of other snow properties have been identified, but there is a lack of readily available historic data for many countries. Further discussion is given on page 289 in the review of IP-10 Action T15.

Space-based observation also plays an important role. Among the products on snow areal extent are a global one from 1999 onwards based on data from the NASA MODIS sensor, and one for the northern hemisphere provided daily since 1997 by the NOAA IMS (Interactive Multisensor Snow and Ice Mapping System). The latter is used in the NSIDC Northern Hemisphere Snow Cover and Sea Ice Extent product, which dates back to the beginning of October 1966, based prior to 1997 on weekly maps produced from visible imagery. The IMS product is also used in snow data assimilation systems for operational weather prediction and reanalysis. In addition, the AMSR instrument provides data on snow-water equivalent, though with limited accuracy over difficult terrain and for deep-snow conditions. Active as well as passive microwave data identify the presence of liquid water (wet snow, or snow wetness). The review of IP-10 Action T16 on page 289 provides further discussion of products and their generation, particularly in the context of integrated analyses.

In situ snow depth reports are included in the archives of synoptic observations discussed in section 4.2.3. In particular, snow depth and snowfall (in addition to precipitation) are core elements of NCEI's GHCN-daily archive. Additional discussion for *in situ* data is given in the review of Action T15. NSIDC is a primary source of data products on snow from space-based and other sources.

Inter-comparison of satellite-derived snow-cover products is the focus of the ESA-funded SnowPEX project being undertaken in coordination with the GCW and the WCRP core project on Climate and Cryosphere (CliC).

6.3.6 Glaciers and ice caps

This ECV was termed "Glaciers and ice caps" in IP-10, but here the term "Glacier" is used more generally, to include ice caps. Glaciers are defined as a perennial mass of ice, and possibly firn and snow, originating on the land surface from the recrystallisation of snow or other forms of solid precipitation and showing evidence of past or present flow. There are several types of glaciers such as glacierets, mountain glaciers, valley glaciers and ice fields, as well as ice caps. Some glacier tongues reach into lakes or the sea and can develop floating ice tongues or ice shelves.

Glacier changes are recognised as independent and natural evidence of climate change, in which high-confidence can be placed. Past, current, and future glacier changes impact on global sea level, the regional water cycle and local hazards.

The Global Terrestrial Network for Glaciers (GTN-G), based on century-long world-wide observations, has developed an integrated, multi-level strategy for global observations. The strategy combines detailed process-oriented *in situ* studies (annual mass-balance measurements) with satellite-based coverage of large glacier ensembles in entire mountain systems (glacier inventories combined with digital elevation models). The GTN-G is a collaboration among the World Glacier Monitoring Service (WGMS), which operates under the auspices of the ICSU World Data System, the IACS of the International Union of Geodesy and Geophysics, UNEP, UNESCO, and WMO, the Global Land Ice Measurement from Space (GLIMS) initiative and NSIDC.

The main variables currently observed in standardized formats are glacier distribution (mainly glacier area, and related length, elevation range and hypsometry, and ideally also mean and maximum glacier thickness) and changes in the mass (Figure 59), volume, area, and length of glaciers. The GTN-G website (http://www.gtn-g.org) provides an overview on and access to all data products.

Glacier inventories derived from satellite remote sensing and digital terrain information need to be repeated at time intervals of a few decades, the typical response time of glaciers to climate change. Current efforts for this activity depend mainly on the processing of data from Landsat radiometers and from ASTER on Terra, following the guidelines provided by GLIMS. An important incentive for the completion of a detailed global glacier inventory comes from the opening of the USGS Landsat archive in 2008/9 and the free availability of global digital elevation models (DEMs) from the Shuttle Radar Topography Mission (SRTM) and ASTER. A DEM is required to derive hydrological divides for separation of contiguous ice masses into glacier entities and subsequently to obtain topographic information such as mean elevation for each glacier entity.

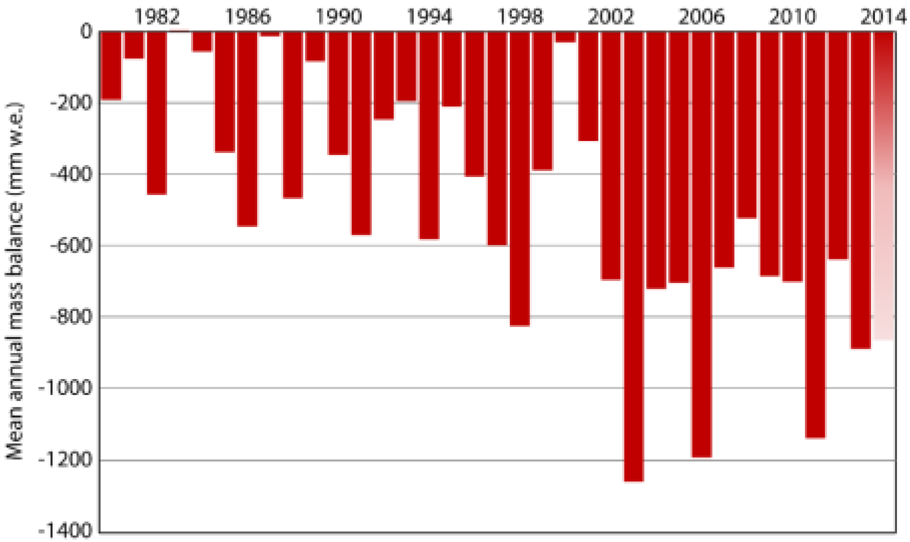


Figure 59: Mean annual glacier mass balance (mm of water equivalent) since 1980, based on 37 glaciers with continuous records, from ten mountain ranges. Data for 2014 are provisional. Source: World Glacier Monitoring Service (http://wgms.ch/mbb/sum13.html).

Changes in the length, area, volume and mass of glaciers are observed using *in situ* and remote sensing methods. Glaciological mass balance data from ablation-stake and snow-pit measurements provide seasonal to annual information on the contribution to runoff. Geodetic methods from *in situ*, airborne and space-borne platforms provide multi-annual to decadal information on volume changes. Based on assumptions on the density of snow, ice and firn, the observed geodetic volume changes can be converted to mass balance and runoff contributions. Glacier volume change and mass balance are a relatively direct reaction to climatic changes. Glacier front variations - from both *in situ* and remotely sensed observations - are an indirect and delayed reaction to climatic changes but allow the observational series to be extended back into the Little Ice Age period.

Progress in recent years is reviewed on page 291 in the context of IP-10 Action T17 calling for glacier observing sites to be maintained, coverage to be improved and QA and inventories to be developed.

Remaining key uncertainties include observational uncertainties (from point readings, interpolation and extrapolation), density conversion uncertainties (from volume change to mass balance), sample uncertainties (related to the representativeness of observation series for entire glacierisations), and uncertainties related to the mass loss contribution from floating ice tongues. For glacier-by-glacier change assessments, current satellite altimetry and gravimetry approaches are subject to severe scale issues, with altimetry providing only point data and gravimetry providing only coarse resolution.

6.3.7 Ice sheets

Our understanding of the timescale of ice sheet response to climate change has changed dramatically over the last decade. Rapid changes in ice-sheet mass have surely contributed to abrupt changes in climate and sea level in the past. The total ice loss from the Greenland and Antarctic ice sheets for the twenty years 1992–2011 (inclusive) has been 4260 ± 1460 Gt, equivalent to 11.7 ± 4.0 mm of sea level. Most of this ice however (3620 Gt) was lost in the second decade of the twenty-year period, and the rate of change has increased steadily with time. Over the years 2007-2011 it was equivalent to 1.2 ± 0.4 mm yr^{-1} of sea level (Figure 60).

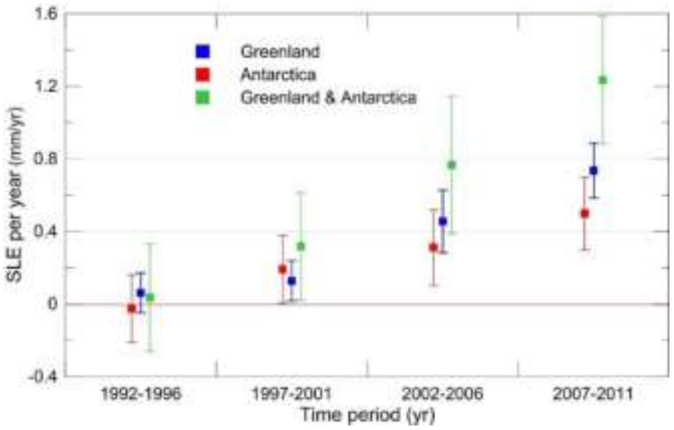


Figure 60: Rate of ice sheet loss in sea level equivalent (SLE) averaged over five-year periods between 1992 and 2011. Source: IPCC (2013; Figure 4.17).

The left-hand panel of Figure 61 shows the cumulative ice-mass loss from the Greenland Ice Sheet over the period 1992-2012 derived from 18 recent studies made by 14 different research groups. This includes the loss from peripheral glaciers. The mass budget method shows the overall partitioning of ice loss from the Greenland Ice Sheet is about 60% to surface mass balance (i.e. runoff) and 40% to discharge from ice flow across the grounding line (IPCC, 2013). However there are significant differences in the relative importance of ice-discharge and surface mass balance in various regions of Greenland. Dynamic losses dominate in southeast, central west and northwest Greenland, whereas in the central north, southwest and northeast sectors, changes in surface mass balance appear to dominate. The average ice-mass change over Greenland from the present assessment has been –121 ± 33 Gt yr^{-1} (a sea level equivalent of 0.33 ±0.09 mm yr^{-1}) over the period 1993 to 2010, and –229 ± 73 Gt yr^{-1} (0.63 ±0.20 mm yr^{-1} sea level equivalent) over the period 2005 to 2010.

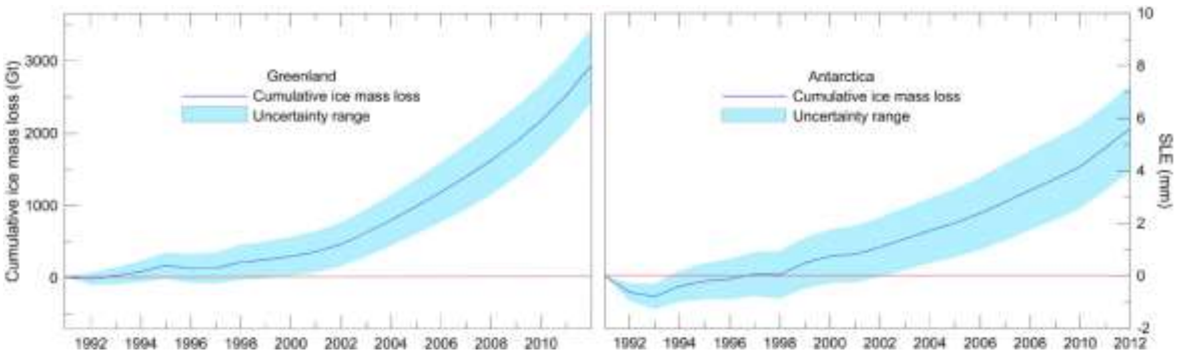


Figure 61: Cumulative ice mass loss over the period 1991 to 2012 and sea level equivalent (SLE) from Greenland (left) derived from the un-weighted annual averages from 18 recent studies, and Antarctica (right), derived from ten studies. Source: IPCC (2013; Figures 4.15 and 4.16).

Observations show that Greenland is thickening at high elevations because of a (predicted) increase in snowfall, but this gain is more than offset by an accelerating mass loss, with a large component from rapidly thinning and accelerating outlet glaciers (Figure 62). Recent observations show a high correlation between periods of heavy surface melting and increases in glacier velocity. A possible cause is rapid meltwater drainage to the base of the glacier, where it enhances basal sliding. An increase in meltwater production in a warmer climate will likely have major consequences on ice-flow rate and mass loss. Recent rapid changes in marginal regions of the Greenland and West Antarctic ice sheets show mainly acceleration and thinning, with some glacier velocities increasing more than twofold. Many of these glacier accelerations closely followed reduction or loss of their floating extensions known as ice shelves.

The right-hand panel of Figure 61 shows the cumulative ice-mass loss from the Antarctic Ice Sheet over the period 1992–2012 derived from recent studies made by 10 different research groups (IPCC, 2013). The average ice mass change over Antarctica from the present assessment has been –97 ± 47 Gt yr^{-1} (a sea level equivalent of 0.27 mm yr^{-1} ±0.13 mm yr^{-1}) over the period 1993 to 2010, and –147 ± 89 Gt yr^{-1} (0.41 ±0.24 mm yr^{-1} sea level equivalent) over the period 2005 to 2010. As for Greenland, these assessments include the peripheral glaciers.

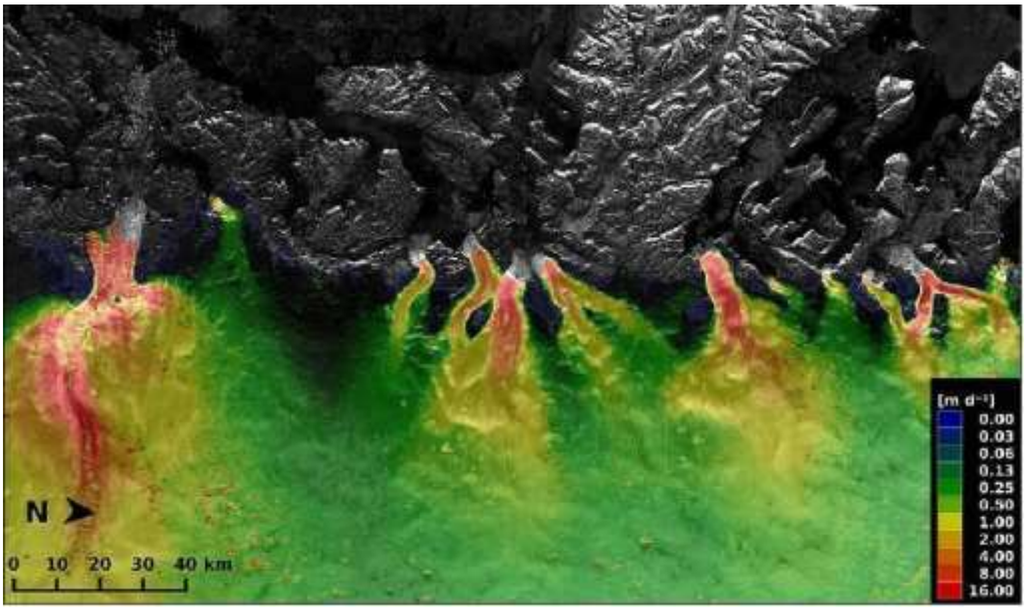


Figure 62: Ice velocities estimated for outlet glaciers along the west coast of Greenland using Sentinel-1A radar scans on 3 and 15 January 2015. Source: Copernicus data (2015), ESA, Enveo, (https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/copernicus-sentinel-1).

Space-based data for estimating changes in ice-sheet mass, and thus corresponding contributions to sea-level change, come from radar and laser altimetry, which measures elevation changes, and from gravimetry. IP-10 Action T20 called for the continuity of such monitoring from space to be ensured; it is reviewed on page 293. In addition, interferometric use of synthetic aperture radar provides data on ice velocity, as illustrated in Figure 62. These data on velocity are used together with data on ice thickness and surface mass balance to provide a further estimate of ice-sheet mass-loss. Shepherd *et* *al*. (2012) describe a set of calculations that reconcile the resulting estimates with those derived from altimetric and gravimetric measurements. Other satellite data of relevance include those that support estimation of surface melt, including the SMMR, SSM/I and SSMIS passive microwave imager data used to construct a multi-decadal record in the NASA MEaSUREs project. Comment on Action T19 concerning research to improve ice sheet models is made on page 292.

In situ measurements, such as of the firn temperature profile and surface climate, are also important for assessing surface mass balance and understanding recent increases in mass loss. Shallow firn cores, notably from traverses of the many areas not covered by manned stations, provide useful information about past decadal variability and trends in ice sheet surface mass balance. IP-10 Action T18, reviewed on page 291, called for continuity of *in situ* ice-sheet measurement and for critical gaps in capability to be filled. Atmospheric reanalysis data and regional climate modelling also are used to estimate the surface mass balance.

Also important is airborne remote sensing. NASA's programme of Ice Bridge campaigns is filling the gap between the space-based ICESat and ICESat-2 laser altimetry missions. It began with measurement over the Antarctic in October/November 2009, and has since flown campaigns each year over both the Arctic and the Antarctic, covering ice sheets and sea ice, using laser altimetry, radar, gravimetry, magnetometry and skin-surface-temperature sensing. The US Center for Remote Sensing of Ice Sheets has also operated airborne lidar and radar measurement campaigns over Antarctica and Greenland, some as part of Ice Bridge.

As is the case for other cryospheric variables, ice-sheet data products are served by NSIDC. In addition, the ice-sheet project of the ESA CCI has recently released a set of products.

6.3.8 Permafrost

The properties of frozen ground react sensitively to climate and environmental change in high-latitude and high-altitude regions. This includes the temperature distribution in the permafrost layer and the depth of the overlying active layer where seasonal freezing and thawing occur. Changes in these quantities have important impacts on terrain stability, coastal erosion, surface and sub-surface water, the carbon cycle and vegetation development. While combined monitoring of meteorological and hydrological variables, soil and vegetation parameters, carbon dioxide and methane fluxes, and the thermal mode of the active layer and permafrost at "reference sites" is the recommended observing approach, most datasets only contain information on temperature and thickness and depth of the frozen and active layers. Standardised *in situ* measurements are essential, as a basis for process understanding and decision-making as well as for calibration and evaluation of climate models.

The Global Terrestrial Network for Permafrost (GTN-P), coordinated by the International Permafrost Association (IPA), forms a GCOS/GTOS baseline network for these variables. The GTN-P Data Management Group at the Arctic Portal (http://www.arcticportal.org/) and the Alfred Wegener Institute, Germany, maintains both borehole temperature and active-layer thickness metadata, and coordinates data management and dissemination. A network of GTN-P National Correspondents (NC) was established in 2013. 22 countries nominated a total of 32 NCs. National numbers of measuring sites are specified in Table 3.

Early in 2015 the GTN-P Database (gtnpdatabase.org; Biskaborn *et al.*, 2015) contained metadata for 1074 boreholes and 274 active-layer monitoring sites, distributed as shown in Figure 63. Measurements are not currently made at some locations, however. GTN-P has also identified new monitoring sites needed to obtain representative coverage in the Europe/Nordic region, within the Russian Federation and within Central Asia (Mongolia, Kazakhstan and China), in the Southern Hemisphere (South America, Antarctica), and in North American mountain ranges and lowlands. A few reference sites have been recommended for development; this would establish a baseline network of Thermal State of Permafrost sites within the International Network of Permafrost Observatories.

Country or region	Number of borehole sites						Number of active-layer measurement sites
	Total	Con-tinuous	Discon-tinuous	Sporadic	Isolated	Other	
Russia	**294**	185	75	2	9	23	**61**
USA (Alaska)	**201**	121	71	3	0	6	**67**
Canada	**194**	57	105	29	3	0	**31**
Mongolia	**91**	45	0	9	37	0	**46**
Antarctica	**72**	1	1	0	0	70	**9**
China	**38**	0	30	7	0	1	**11**
Norway (mainland)	**36**	0	17	16	0	3	**1**
Norway (Svalbard)	**30**	29	0	0	0	1	**7**
Switzerland	**29**	0	17	0	12	0	**2**
Sweden	**19**	2	12	0	5	0	**1**
Greenland	**11**	5	3	1	1	1	**3**
Japan	**10**	0	0	0	7	3	**0**
Italy	**9**	0	7	0	2	0	**0**
Austria	**8**	0	3	0	5	0	**0**
Argentina	**5**	0	0	0	0	5	**0**
Kazakhstan	**5**	0	5	0	0	0	**3**
Iceland	**4**	0	0	0	1	3	**0**
Spain	**3**	0	0	0	0	3	**0**
Germany	**2**	0	0	0	2	0	**0**
Kyrgyzstan	**2**	0	0	0	0	2	**0**
Finland	**1**	0	0	1	0	0	**0**

Table 3: National distributions of GTN-P borehole and active-layer measurement sites. From Biskaborn et al. (2015).

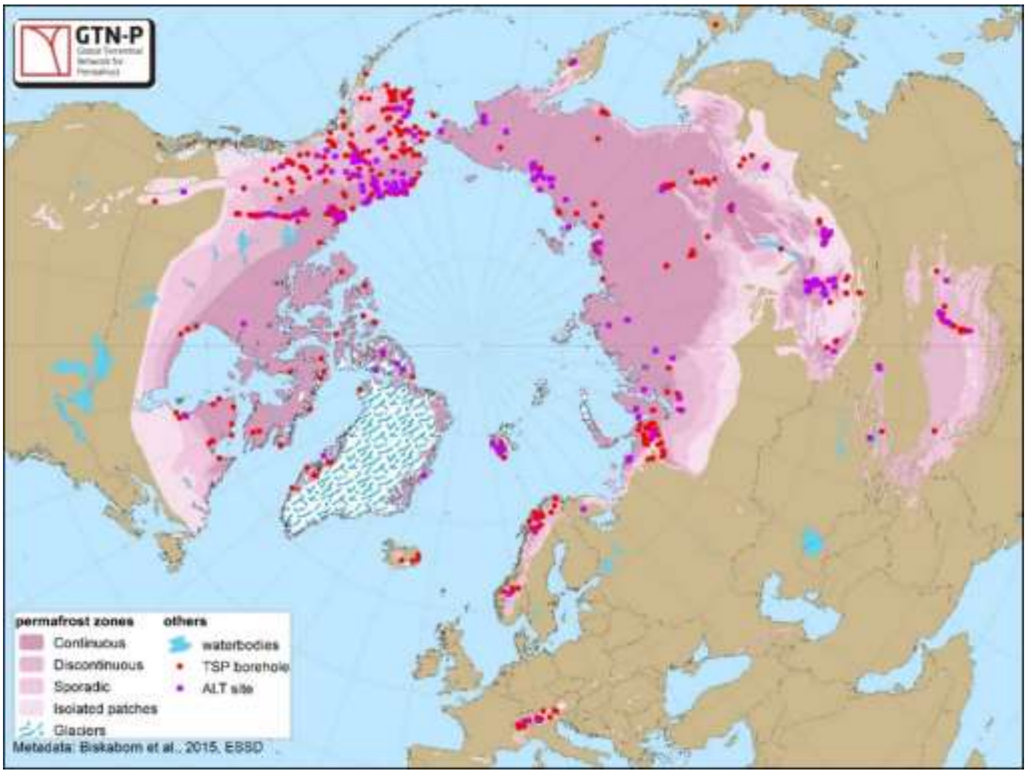


Figure 63: Locations of borehole and active-layer monitoring sites providing data contained in the GTN-P, superimposed on the distribution of permafrost in the northern hemisphere. Source: http://gtnp.arcticportal.org/.

GTN-P *in situ* data acquisition operates on a largely voluntary basis through individual national and regionally-sponsored programmes. Regional projects that have supported or continue to support local networks and observatories include the US Geological Survey Alaskan deep borehole network and the US National Science Foundation-supported CALM and TSP sites in Alaska and Russia, the EU FP7 PAGE21 project, the Russian Academy of Sciences “Evolution of Cryosphere” programme, Canadian transects, the Swiss Permafrost Monitoring Network PERMOS, the alpine PermaNET programme, the Norwegian NORPERM data base and Hovsgol GEF project in Mongolia.

Further discussion is given in Appendix 1, starting on page 293, in the reviews of IP-10 Actions T21, T22 and T23 concerning standards for permafrost observation, national arrangements, the continued operation of networks and the mapping of the seasonal freezing and thawing of soil.

6.3.9 Albedo

The albedo of a land surface is the non-dimensional ratio of the radiation flux reflected by a (typically horizontal) surface in all directions and the incoming irradiance, which is the radiation flux from the upper hemisphere. This is technically known as the bi-hemispherical reflectance factor (BHR), and both fluxes must be relative to the same spectral range. For bare soils and other solid, convex objects, the material interface between the ground and the atmosphere constitutes the reference surface. In the case of vegetation, a reference surface is typically defined at or near the top of the canopy and must be specified explicitly. This “generic” albedo is highly variable in space and time as a result of changes in surface properties (snow deposition and melting, changes in soil moisture and vegetation cover, etc.), as a function of fluctuations in the illumination conditions (solar angular position, atmospheric effects, cloud properties, etc.), and with human activities (e.g. clearing and planting forests, sowing and harvesting crops, burning rangeland, etc.).

Albedo is thus not an intrinsic surface property, but a joint property of the surface and the overlying atmosphere, since the latter's composition (gases, clouds and aerosols) significantly affects the spectral and directional distribution of the irradiance.

Albedo is both a forcing variable affecting the climate and a sensitive indicator of environmental degradation. Given the amount of energy involved in solar radiation fluxes, even a 1% change in land surface albedo generates fluctuations of the order of 3.5 W/m^2 on global and annual averages.

Albedo thus controls the 'supply' side of the surface radiation balance and is required to estimate the net absorption and transmission of solar radiation in the soil-vegetation system. It can be defined spectrally or for spectral bands of finite width with broadband albedos generally referring to the entire 300-3000 nm range (WMO, 2010a) or the two broadband ranges 300-700 and 700-3000 nm. Two simple concepts, corresponding to extreme conditions, have been defined:

- “Black sky albedo”, technically known as the directional hemispherical reflectance factor (DHR), is the reflectance of that surface when the illumination comes from a single direction. Black sky albedo is the albedo in the absence of any atmosphere. It depends on the angular position of the source of light and on surface properties.
- “White sky albedo”, technically known as bi-hemispherical reflectance factor under isotropic illumination (BHR-iso), is the reflectance of that surface when the irradiance is isotropic. The surface albedo under an overcast, homogeneous cloud deck would be a good approximation of white sky albedo. This value depends only on surface properties.

In practice, the actual instantaneous albedo of a land surface is often approximated by a linear combination of the black and white sky albedos, where the weighing factors are the relative proportions of direct and isotropic diffuse radiation, with the clear and cloudy fractions taken as approximate weights. Such a combination is sometimes referred to as the “blue sky albedo”. It depends on the angular position of the main source of illumination for direct radiation, on atmospheric conditions, and on surface properties.

None of these albedo-related quantities are directly measurable from air- or space-borne platforms. Instead, multi-angular reflectance measurements must be interpreted with the help of radiation transfer models to retrieve the desired variables from the actual observations. Significant progress has been made over the last few decades in the development of algorithms to convert directional measurements into flux estimates. The issues of model inversion, as well as angular or spectral integration of directional reflectances into hemispherical values or broad bands, are well-understood, and suites of products (including reflectance anisotropy, black-, white-, and blue-sky albedo estimates) are currently available from various sources to satisfy the diverse needs of a wide range of users. However there is still room for improvement in the presence of snow and ice or in the conversion of measurements from a limited number of spectral bands to broadband values suitable for climate models.

Some albedo measurements (analogous to blue sky values) are acquired *in situ*, for instance, with pyranometers that integrate the incoming radiation reaching the sensor from an entire hemisphere. The coupling of two such instruments back to back to measure simultaneously the irradiance from the sky and the reflectance from the surface is the underlying concept of so-called albedometers. These are deployed to WMO standards (McArthur, 2005; WMO, 2010a) on stationary towers as part of the Baseline Surface Radiation Network (BSRN; section 4.3.6) and additional measurements are now provided by the FLUXNET and ICOS networks. Broadband instruments have been deployed for the most part, although a limited number of spectral measurements now exist. More such measurements would be useful for validating satellite products. The footprint characterised by the *in situ* sensors is driven by the height of the tower above the surface and therefore the applicability of these measurements to satellite derived quantities is governed by the height of the *in situ* instrument above the top of canopy and representativeness of this footprint to the usually larger remotely sensed footprint. While the BSRN tower sites currently provide some of the highest-quality measurements available for radiation at the surface, they are limited in number and the network needs to be expanded and adequately supported to achieve more representative global coverage. Continuous calibration of these *in situ* instruments across the sites is also essential.

Spatial and temporal resolution requirements are highly dependent on the particular application at hand. For climate purposes the global coverage and spatial resolutions provided by most satellite instruments are considered adequate, and a number of space agencies generate albedo products, from both geostationary and polar-orbiting satellites. Noteworthy is a record of more than fifteen years duration available from the MODIS instruments on Terra and Aqua (Figure 64); the current product version is available with 500 m resolution once per eight days, based on overlapping sixteen-day data acquisitions. Although continued and improving provision of imagery from operational meteorological satellites seems assured, as discussed elsewhere in this report, questions remain concerning the accuracy of the products currently available, the existence of systematic biases between them and the stability of products across instruments over prolonged periods of time. Indeed, NASA's VIIRS Land website (http://viirsland.gsfc.nasa.gov/Products/Albedo.html; accessed in July 2015) states that the current VIIRS albedo product provides neither MODIS continuity nor climate-quality records.

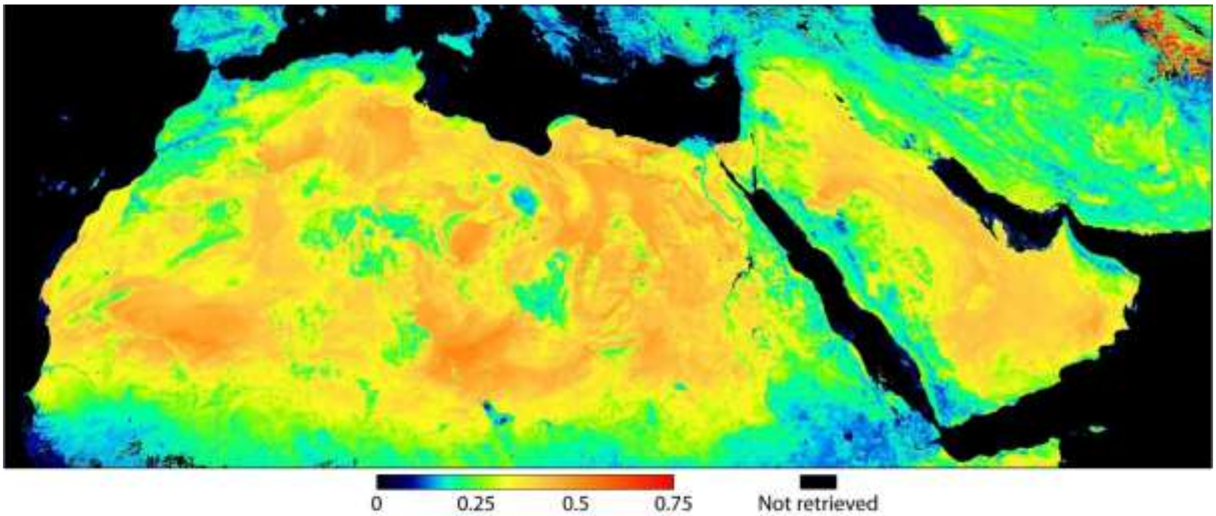


Figure 64: Combined Terra/Aqua MODIS Collection 5 MCD43A3 albedo product based on data acquired between 23 April and 8 May 2015. Source: an 8x3 mosaic of browse tiles downloaded from the online data pool of the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov/data_access/data_pool).

Further discussion is given in Appendix 1, beginning on page 295, in reviews of IP-10 Actions T24 concerning use of *in situ* data for validation of space-based albedo products, and T25 concerning coordinated retrieval of land-surface albedo from a range of past and present sensors.

6.3.10 Land cover (including vegetation type)

Land cover influences climate by modifying water and energy exchanges with the atmosphere and by changing greenhouse gas and aerosol sources and sinks. The amount of carbon in vegetation is roughly similar to the atmosphere; that in soils is significantly larger. Estimates of the contribution of land-use change to the global anthropogenic CO_2 budget reported in IPCC (2013) were based on data on land-cover change, and were highly uncertain, even for the most recent decade. Land-cover distributions are linked to regional climatic conditions, so changes in cover can be due to climate change on a regional scale as well as directly due to human activities.

Many climatically-relevant variables that are difficult to measure at a global scale, such as surface roughness, can be inferred in part from vegetation and land-surface types. Thus, land cover can be a surrogate for other important climate variables. Current climate models operate on resolutions of around 25 to 100 km, but land-cover information at what is termed from an observational viewpoint to be a “moderate” resolution of 250 m to 1 km is needed to describe correctly the spatial heterogeneity of the land surface within model grid cells.

Land-cover, including its change over recent years, is inferred using data from space-based observation. Satellite-borne optical instruments have reached a capability to provide annual global coverage at 10 to 30 m resolution, with improving temporal and spectral characteristics. Continuation of what has been the highest class of observation used to determine land cover over a wide region has been provided to date by Landsat 8, launched in 2013. A significant advance in capability is now being implemented with the launch in June 2015 of Sentinel-2A, the first of pair of satellites that will operate together, each with a relatively wide 290 km swath and 10 m resolution for four of their VIS/IR bands.

The UNFCCC has agreed methodologies for the implementation of Reducing Emissions from Deforestation and Forest Degradation in developing countries (REDD+; UNFCCC, 2010) and relevant space agencies under CEOS have agreed to supply, on a regular basis, the 30 m data necessary for the generation of fine-resolution land-cover maps to support such a methodology. Each country participating in REDD+ will have to implement a National Forest Monitoring System that comprises use of land monitoring from satellite data together with national forest and greenhouse-gas inventories. This will require data with at least 30 m resolution and possibly higher resolution for validation and monitoring hot-spots of change. Forest definitions and methods will be decided at a national level.

It is important in view of considerations such as the above that land-cover classification systems and associated map legends adhere to internationally-agreed standards. Developments include the FAO Land Cover Classification System (Di Gregorio, 2005) and the translations of existing legends prepared subsequently by GOFC-GOLD (Herold *et al*., 2009). A new FAO Land Cover Meta Language (Latham *et al*., 2014) should strengthen the process of harmonisation and translation of legends. Databases must also be accompanied by a description of class-by-class thematic and spatial accuracy.

IP-10 Action T26 called for the production of reliable methods for assessing land-cover map accuracy. It is reviewed on page 296.

IP-10 also called for land-cover products to be produced annually with a resolution in the range from 250 m to 1 km, and five-yearly with a resolution of 10 to 30 m. As can be seen from the products included in the list at http://lpvs.gsfc.nasa.gov/producers2.php?topic=LC provided by the CEOS WGCV LPV focus area on land cover, datasets have been produced at resolutions of between 250 m and 1 km by several institutions, with annual resolution in some cases and for some periods. Products have also begun to appear at 30 m resolution. Figure 65 provides an illustration, showing maps based on two products released in 2014, one with 300 m spatial resolution that resolves a greater number of types of cover, and one with 30 m resolution that evidently captures greater detail, such as related to terrain height, river course and the separation into urban areas, cultivated land and forest. Further discussion is given in the reviews of Actions T27 and T28 that begin on page 297, including illustrations in Figure 101 of decadal changes in land cover.

Lack of compatibility between existing products makes it difficult to use them in combination to monitor climate-induced or direct anthropogenic changes in land cover. The approaches that have been adopted include centralized processing using a single method of image classification, as in the MODLAND, GlobCover and ESA CCI products, and a distributed approach using a network of experts applying regionally specific methods, as used for GLC2000. Using a single source of satellite imager radiances and a uniform classification algorithm has benefits in terms of consistency, but may not yield optimum results for all regions and all land-cover types. Automated land-cover characterisation and land-cover change monitoring remain high on the research agenda.

Systematic global samples of high-resolution satellite imager radiances have also been used to estimate change, for example, by the EC Joint Research Center (TREES-3 and FOREST projects) and in the FAO 2015 Forest Resource Assessment (FAO, 2015). These are based on a sample of 10x10 km Landsat images (30 m resolution) spaced at 1x1 degree intervals (13,689 samples on land, excluding Antarctica). Initiatives such as these will provide much needed capacity-building and offer a framework for acquisition of *in situ* observations to support the satellite image-based monitoring. However, the accuracy of change estimates is low, with only regional estimates of change possible. Some more intensive sampling has been performed for some countries as part of the FRA 2015. The *in situ* networks will also provide information on how land is being used (as opposed to what is covering it). Land use cannot always be inferred from land cover.

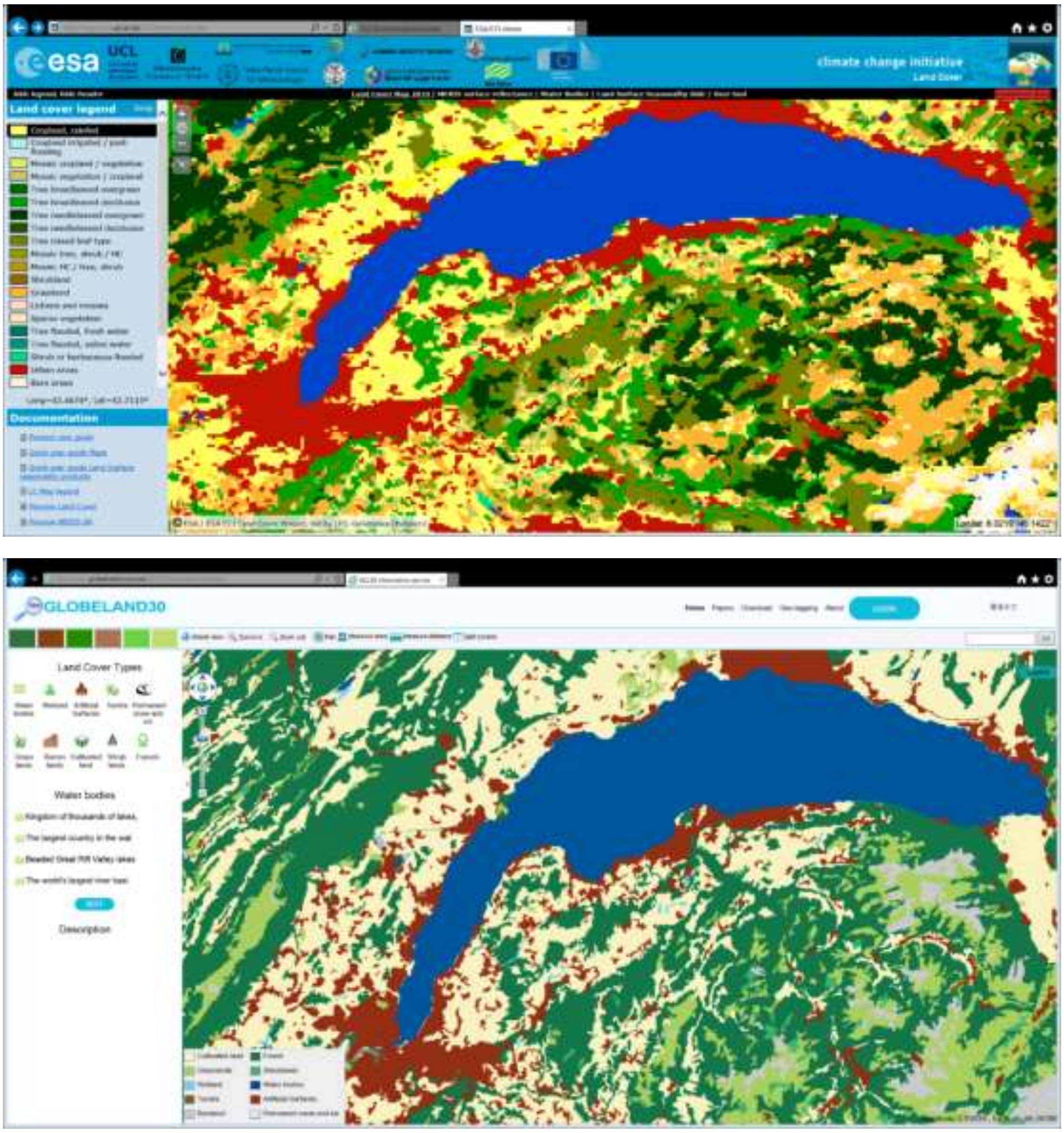


Figure 65: Maps of land cover surrounding Lake Geneva, produced using the data providers' on-line visualisation tools. Upper: The 300 m resolution ESA CCI product for the 2008-2012 epoch based on MERIS and SPOT-Vegetation data, viewed at http://maps.elie.ucl.ac.be/CCI/viewer. Lower: The 30 m resolution NGCC GlobeLand30 product for 2010 based on Landsat data, viewed at http://www.globallandcover.com/GLC30Download/.

6.3.11 Fraction of absorbed photosynthetically active radiation (FAPAR)

Solar radiation in the spectral range from 400 to 700nm, known as Photosynthetically Active Radiation (PAR), provides the energy required by terrestrial vegetation to produce organic materials from mineral components. The part of this PAR that is effectively absorbed by plants is called the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR). It is a non-dimensional quantity varying from zero (over deserts) to up to one (for large, deep, homogeneous canopy layers observed by medium- to low-resolution sensors), although the maximum value is never witnessed in practice because some of the incoming light is always reflected back by the canopy or the underlying ground. FAPAR is related to, but different from, Leaf Area Index (LAI; covered in the following section), which describes the amount of leaf material in the canopy.

FAPAR plays a critical role in assessing the primary productivity of canopies, the associated fixation of atmospheric carbon dioxide, and the energy balance of the surface. As is the case with land surface albedo (section 6.3.9), FAPAR depends on the illumination conditions, i.e. the angular position of the sun with respect to the vegetation layer and the relative contributions of the direct and diffuse irradiances. Both black-sky (assuming only direct radiation) and white-sky (assuming that all the incoming radiation is in the form of isotropic diffuse radiation) FAPAR values may be considered. Models describing the primary productivity of plants and the energy balance of the land surface require either a characterisation of the diurnal evolution of FAPAR or the daily integrated value of FAPAR, depending on the time-step used. Other applications may only require cumulative or aggregated values over longer periods.

For the purpose of environmental applications and carbon cycling, estimating the absorption of radiation by leaves is the primary objective, but other plant elements (trunks, branches, etc.) of the canopy also absorb or scatter radiation. The expression "green FAPAR" is sometimes used to designate the value of FAPAR that is exclusively due to photosynthesizing materials (mostly leaves), i.e. not including scattering and absorption through other processes. FAPAR is difficult to measure directly in the field: *In situ* estimates require the simultaneous measurement of all incoming and outgoing radiation fluxes into and out of the canopy layer, as well as the acquisition of architecture information to account for the absorption by canopy elements other than leaves, especially for complex three-dimensional canopies such as forests. Specific problems such as poorly designed measurement protocols and ubiquitous deficiencies such as failure to account for horizontal fluxes of radiation frequently plague experimental setups. They severely limit the feasibility of effectively comparing FAPAR values derived from space-based instruments with those derived from *in situ* measurements:

- While total PAR irradiance is typically monitored as part of the standard observation protocol at ecological and radiation research sites, such as those in the ICOS, FLUXNET, LTER, and SURFRAD networks, few of these sites generate all the other measurements required to close the radiation budget and derive a reliable estimate of the canopy FAPAR at the scale of the observing space-borne sensors. Ground-based approaches are changing as new technology developments using Wireless Sensor Networks (WSNs) start to emerge. WSNs provide two complementary advantages: large spatial coverage and hyper-temporal sampling of PAR (see the Tropi-dry initiative at http://tropi-dry.eas.ualberta.ca/, for instance).
- A strategy for very detailed sampling (for example at spatial intervals much smaller than the typical sampling distance of space-based sensors and consistent with the size of leaves and gaps in the plant canopy) is required in these field campaigns because FAPAR is highly variable in space and time. Some progress along these lines has been achieved, but this type of approach is not implemented very often.
- Model-based approaches to estimate the accuracy of both *in situ* and space-based products are being developed and initial results are expected to yield a better characterisation of measurement uncertainties.

Information from PAR flux meters or directional PAR meters (such as the Ceptometer) inserted at the bottom of the canopy layer can be used to approximate the hemispherically integrated FAPAR (the latter by sampling over several directions in a short time period). Similarly, interception as derived from devices measuring the directional gap fraction (hemispherical photographs, LAI2000) can be used as proxies but with a lower accuracy. Significant improvements in field measurements are still dearly needed, especially in terms of measuring all relevant radiation fluxes and obtaining more representative spatial sampling statistics to account for the high variability of vegetation. FAPAR is also conditioned by the brightness of both the background and the canopy constituents, such that the accuracy of standard field measurements may decline under snowy conditions.

Global, gridded FAPAR products are routinely generated by Space Agencies and other institutional providers at a typical spatial resolution of 1 km. Renewed efforts to re-process products and re-analyse past data have been made during recent years. Regional products may be available on finer scales of 250-300 m. These remote-sensing products are derived by numerically inverting physically-based radiative transfer models against satellite measurements, typically reflectance observations from a wider spectral region than PAR because NIR and SWIR radiances are needed to account for the contribution of the background. By the same token, observations in the blue spectral band, near the edge of the PAR region, are important to help assess the influence of atmospheric aerosols on the measurements. There is also a clear need for the systematic development of traceability between concept definition, retrieval algorithms and product outcomes to ensure internal consistency, to facilitate the benchmarking of different products, and to establish lacks and gaps that may affect comparisons between space and *in situ* measurements of FAPAR.

The obscuring of the surface by clouds introduces spatial discontinuities in the maps of FAPAR derived from single orbital overpasses. To improve the spatial coverage while maintaining the capability of documenting the phenology of vegetation, individual estimates are composited over standard periods, such as a week, 10 days or a month.

IP-10 Action T29 called for establishment of a network of *in situ* reference sites for calibration and validation of both FAPAR and LAI products; what has been put in place is summarised in the review of the action that is presented on page 299. Action T31 called for operational generation of gridded global products, again for both FAPAR and LAI. It is reviewed on page 301. Figure 66 presents an example for one such pair of products.

6.3.12 Leaf area index (LAI)

The Leaf Area Index (LAI) of a plant canopy or ecosystem, defined as one half the total green leaf area per unit horizontal ground surface area, measures the area of leaf material present in the specified environment. On sloping surfaces, the leaf area should be projected to the underlying ground along the normal to the slope. This dimensionless variable (sometimes expressed in terms of square metres of leaf material per square metre of ground) varies between 0 and values of the order of 10 or so, depending on local conditions. It partly controls important mass and energy exchange processes, such as radiation and rain interception, as well as photosynthesis and respiration, which couple vegetation to the climate system. Hence, LAI appears as a key variable in many models describing vegetation-atmosphere interactions, particularly with respect to the carbon and water cycles.

The meaning and measurement of LAI can be subject to canopy or ecosystem interpretations in the case of plant canopies other than crops, grasses, and broadleaf forests. For example, needles are not as easily accounted for and plant organs other than leaves or needles often contain active pigments and contribute to photosynthesis. Many canopies also exhibit an understory of grasses, shrubs and so on, and/or ground cover such as mosses and lichens that may be included in the live foliage area computation. In all environments, LAI is very sensitive to the spatial scale and resolution of the measuring instrument, as well as to the heterogeneity of the plant canopy and the somewhat arbitrary area of reference. The extreme variability of vegetation over a wide range of spatial scales, from clumps of shoots to clusters of plants, and the often unknown spatial distribution of leaves within the volume, further complicate the estimation and interpretation of this highly scale-dependent variable.

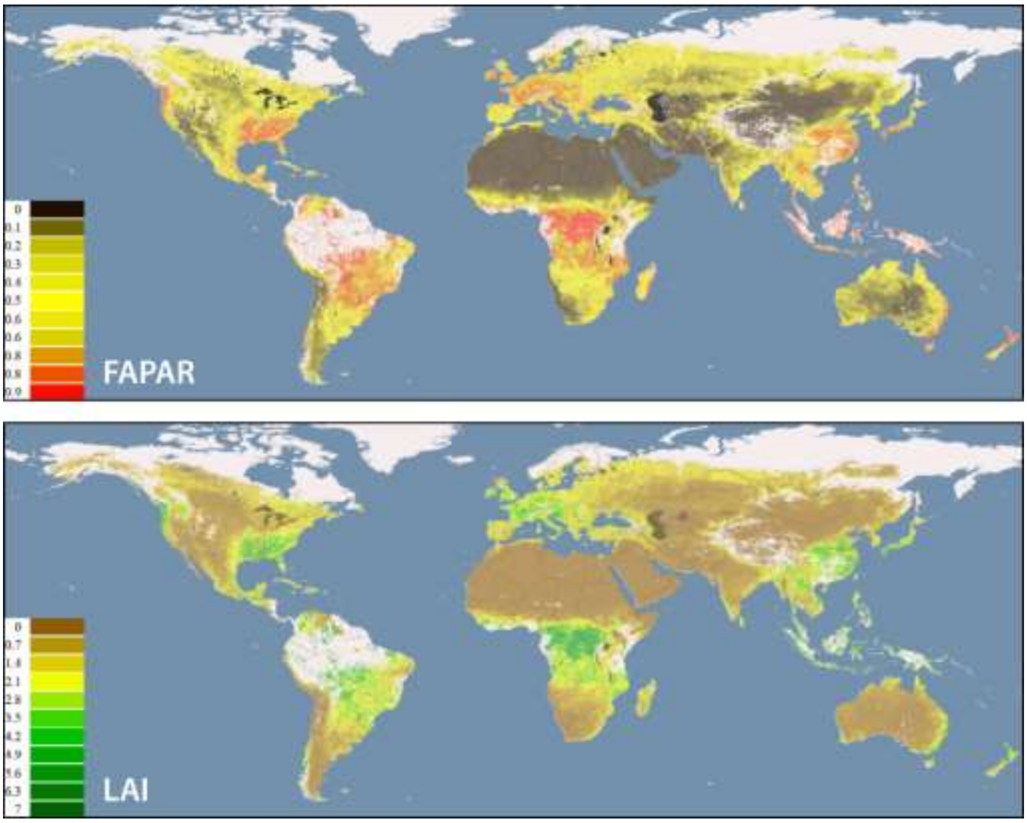


Figure 66: Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) and Leaf Area Index (LAI). Products are based on data from the PROBA-V satellite and dated 3 May 2015. Source: Copernicus Global Land Service, based on quick-look images generated at http://land.copernicus.vgt.vito.be/PDF/portal/Application.html.

Measuring LAI *in situ* entails a variety of methods. Destructive sampling, where all leaves are individually stripped from the plant and measured, often with the help of statistical relations between weight and area, is very labour and time consuming. It can be implemented occasionally on individual plants but is difficult or impossible to deploy over large areas or tall forest trees and this prevents repeated monitoring of the same plants in time. Allometric relations, derived from such individual observations, have been used to estimate the LAI of sets of similar plants. Measurements of light transmittance through the canopy, whether restricted to direct radiation (sun spots) or acquired under largely diffuse irradiance, for example with hemispherical photographs, are subject to somewhat arbitrary thresholds. They are, however, non-destructive, cost-effective, applicable to wide areas and repeatable in time. Since they are sensitive to the presence of plant organs other than leaves, such as branches and trunks, as well as to senescent leaves, the proper interpretation of such measurements requires great attention to the nature of the method, to the particular devices used and their calibration, and to the specific measurement protocol, in particular with regards to spatial sampling. Guidelines on this latter point have been produced by the CEOS WGCV LPV Subgroup, as noted in the review provided on page 300 of IP-10 Action T30 concerning evaluation of LAI products based on satellite data.

Space-based observations provide only indirect measures of LAI, but are nevertheless essential, as *in situ* measurements provide very limited spatial and temporal coverage. LAI is different from FAPAR because it controls the interception of solar radiation in the spectral range relevant for photosynthesis. The retrieval of reliable LAI values from space remains a complex undertaking because it implies sorting out the respective contributions of plant leaves from different layers of vegetation and the underlying ground to the measured radiation flux scattered by the land surface. If the soil reflectance and the canopy structure (specifically the spatial distribution of leaves in the three-dimensional volume sampled by the satellite sensor) can be assumed (or are known from other sources), then the measurements can be directly interpreted in terms of LAI, provided the influence of photosynthetically non-active canopy elements have been accounted for. A better approach is to retrieve jointly the background albedo and the effective LAI, the LAI value that is required by the radiation transfer model to account for the scattered and transmitted fluxes at the spatial resolution of the sensor. Effective LAI is retrieved by assuming a homogeneous canopy structure and can be used to estimate the total transmission through individual canopy layers, which are directly measurable in the field. The relation between LAI and effective LAI should be explored through radiative transfer simulations that account explicitly for the three-dimensional distribution of leaves within the relevant volume.

When the canopy cover is sparse, space-based reflectance measurements are dominated by soil properties, and when the canopy becomes very dense (when the underlying soil or background is no longer contributing to the measurements), the sensitivity of retrieval methods based on reflectance measurements diminishes rapidly. Nonetheless, regular global LAI estimates from space, which requires limited additional resources above those required to produce FAPAR, are currently being produced (see Figure 66 and review of Action T31) at 1 km spatial resolution. As is the case for FAPAR and many other surface properties, the frequent obscuring of the land by clouds necessitates compositing measurements over a week or more in the case of single-satellite products. The feasibility of estimating LAI (and above-ground biomass) from MW sensors and lidar is subject to current research, and such efforts should be pursued.

Unsurprisingly, existing space-based products exhibit biases between themselves as well as substantial differences when compared to field measurements. Difficulties remain with respect to the traceability of methods. Benchmarking retrieval algorithms in round-robin exercises and actual products derived from different satellite instruments are thus essential endeavours to understand and resolve differences and to ensure the accuracy and reliability of products. The absence of a long term, spatially representative network of sites making measurements appropriate for validation purposes remains an obstacle to progress. The initiation of the Sentinel era represents an opportunity to establish improved estimates at both high and medium resolutions supported by *in situ* observations.

6.3.13 Above-ground biomass

Vegetation biomass is a crucial ecological variable for understanding the evolution and potential future changes of the climate system. Photosynthesis withdraws carbon dioxide from the atmosphere and stores carbon in vegetation in an amount comparable to that of atmospheric carbon. Currently biomass is a net sink of carbon with a net flux to the land of 2.6 ± 1.2 Pg C yr^{-1}, partially offset by changes in the amount of biomass due to deforestation and other land cover changes acting as a net source of carbon of 1.1 ± 0.8 Pg C yr^{-1}, taking figures from IPCC (2013). Thus biomass changes provide a net sink of about 1.5 Pg C yr^{-1}, which is equivalent to about 20% of the CO_2 emissions from fossil fuels. Vegetation systems have the potential either to sequester more carbon in the future or to contribute as an even larger source. Depending on the quantity of biomass, vegetation cover can have a direct influence on local, regional and even global climate, particularly on air temperature and water vapour. Therefore, a global assessment of biomass and its dynamics is an essential input to climate models and mitigation and adaptation strategies.

The non-climate applications of biomass information are legion, since forest biomass is a major source of energy and materials across the planet, as well as being related to issues such as biodiversity, water quality and soil erosion.

Only above-ground biomass is measurable with some accuracy at the broad scale, while below-ground biomass stores a large part of total carbon stocks but is rarely measured, as it involves destructive sampling. There can also be significant stores of carbon in dead wood and litter, especially in forests, which can only be measured through *in situ* observations. Below-ground biomass, dead wood and litter are usually estimated in terms of above ground biomass. Many nations have schemes to estimate woody biomass through forest inventories, though traditionally only harvestable wood resources; little is recorded on non-forest biomass, except through agricultural yield statistics. National forest inventories are typically designed to monitor forest stocks and are less accurate at estimating changes. While these estimates typically form one input into the annual reporting[5] on forest resources required by the UNFCCC, additional information is required. The REDD+ initiative is motivating the development of forest inventories across the tropics, and GEO, through its Global Forest Observation Initiative, is helping to provide guidance on the combined use of ground-based and satellite data, as discussed in section 6.3.10. In contrast, research networks remain under threat of reduced resources.

Ground-based inventory is widely used to estimate above-ground biomass; this typically relies on measuring quantities such as tree height and stem diameter at breast height and relating them to above-ground (and indeed below-ground) biomass by allometric equations (e.g. see the FAO's Globallometree database; http://www.globallometree.org/). The IPCC methods for estimating biomass assume that these plot-based measurements are representative of areas with similar vegetation, which can be derived from satellite images or ground-based maps. The IPCC also provides methods for estimating below-ground biomass, dead wood and litter from above-ground biomass estimates. National inventories of biomass differ greatly in definitions, standards and quality, and the detailed information available at national level is normally unavailable internationally. Nonetheless, these form the basis of the country-by-country summary statistics such as are published by the FAO

[5] Annex I parties should report annually but non-annex I parties report every second year. However all countries have to provide annual estimates for each calendar year.

in its five-yearly Global Forest Resource Assessments. Experimental airborne sensors (low-frequency radar and lidar) have demonstrated technologies for estimating biomass distribution and are suitable for satellite implementation that should provide global above-ground biomass information at sub-kilometre resolutions. There are nevertheless limitations to these technologies, of which some are known (for example, reduced sensitivity of radar backscatter at higher levels of biomass) and some still the subject of research. These satellite measurements need *in situ* measurements to relate them to biomass. Further assumptions are needed to estimate carbon from biomass, since the proportion of carbon by weight in dry forest biomass can vary significantly about its typical value of 50%.

Gridded global data are available only in the form of satellite-derived maps, for which several products exist. They are discussed further in the review of IP-10 Action T32 calling for development of demonstration datasets for biomass. Figure 67 presents an example. Most maps are effectively for a single year as they are based on a short lifetime mission (SRTM) or are derived as a single product from a longer time series of measurements such as from ALOS-1, Envisat, ICESat or TanDEM-X.

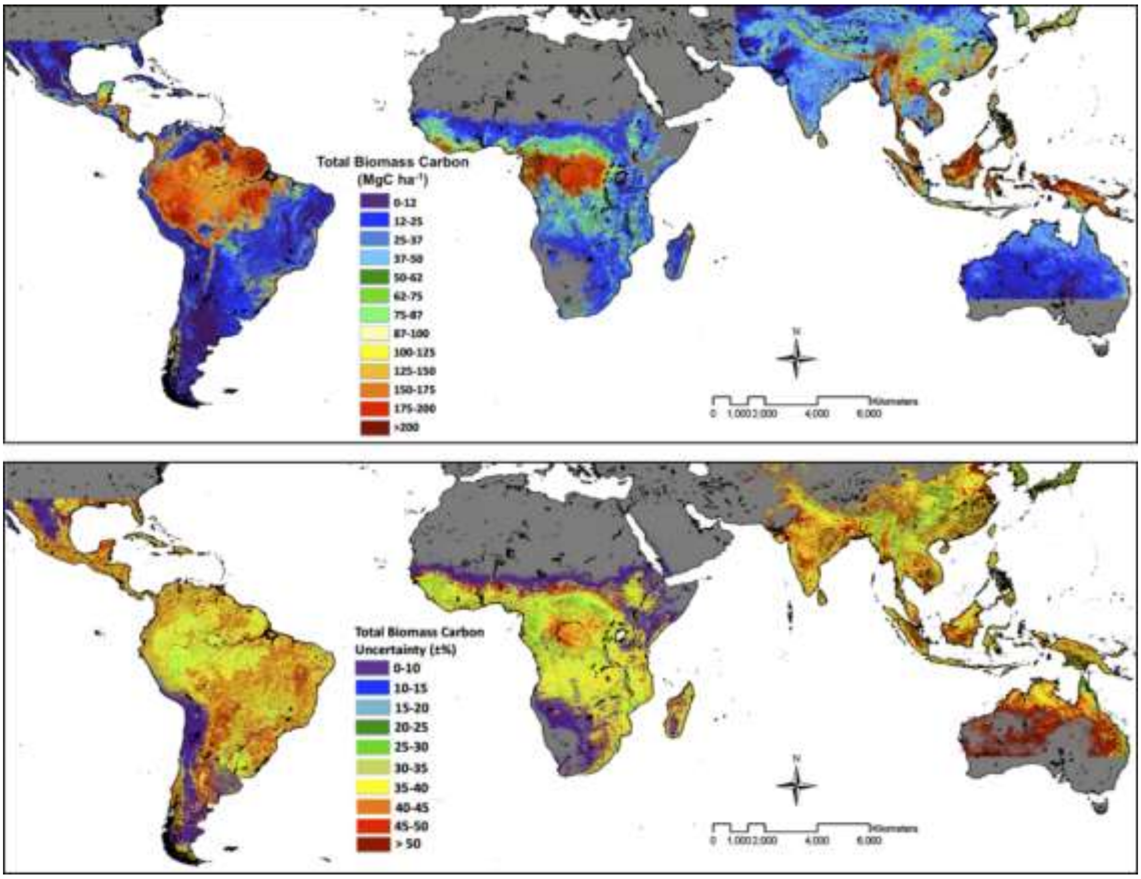


Figure 67: Maps showing an estimate of (upper) forest carbon stock and (lower) its uncertainty. Source: Saatchi et al. (2011).

Cessation of the satellite missions that provided such information has been a concern, but the situation is easing with the recent or imminent launches of the European Sentinel-1 C-band radar satellites and the Japanese ALOS-2 and Argentinian SAOCOM L–band satellites. A further important development has been the selection by ESA of the BIOMASS P-band radar mission dedicated to global forest biomass, though this will not launch before 2020, and the selection by NASA of the Global Ecosystem Dynamics Investigation (GEDI) lidar for deployment on the International Space Station in 2018. GEDI aims to provide the first global, high-resolution observations of the vertical structure of tropical and temperate forests, from which the distribution of above-ground biomass may be estimated.

Annual biomass maps with coverage of all major forest areas on the globe are needed. A spatial scale down to 30 m or better is desirable, but more realistic are estimates at a scale of 500 m to 1 km, though BIOMASS aims to provide measurements at a scale of 200 m. A 20% error is acceptable; this is comparable with the uncertainty in *in situ* measurements in the tropics.

A novel remote-sensing approach that estimates variations in above-ground biomass carbon at lower horizontal resolution from passive MW measurements made over the past two decades has been reported recently by Liu *et al.* (2015). MW emissions are sensitive to water in above-ground vegetation, and the inter-calibrated data record from multiple instruments beginning with SSM/I is translated into a record for above-ground biomass using the spatial map of Saatchi *et al*. (2011; Figure 67). The principal temporal changes identified over the period are losses of biomass due to tropical deforestation, and gains of biomass by extratropical forests and by rain-sensitive tropical savannahs and shrublands.

The FAO acts as the major organiser of global biomass data, but there is no universally recognised data centre. The accuracy of data products is under continual review, but efforts to assign accuracy in the tropics suffer from the small number of *in situ* reference plots and questions over how representative these are. There are nevertheless major efforts underway to reconcile the differences in the published satellite-derived tropical maps and to explain and remove their apparent disagreement with the *in situ* reference data (Mitchard *et al*. 2013, 2014).

6.3.14 Soil carbon

Carbon in soils occurs in organic and inorganic forms. The inorganic carbon is derived from weathered bedrock, is relatively inert and constitutes little to the carbon cycle. Soil organic carbon is derived from plant and other decaying matter and is a significant part of the carbon cycle. About 10% of the atmospheric carbon cycles through soils each year. Soil organic carbon represents the largest terrestrial carbon pool, amounting to about two to three times the net size of the biomass pools. Carbon sinks may be explained by changes in above-ground biomass on seasonal to decadal time scales, but soil organic carbon stocks become significant on longer time scales, and can be a significant source at all time scales after disturbances. Globally, the largest soil organic carbon stocks are located in wetlands and peat lands, most of which are located in boreal and tropical regions. According to the IPCCC AR5, peat lands cover approximately 3 % of the Earth’s land area and are estimated to contain 350 to 550 Gt of carbon, roughly between 20 to 25 % of the world’s soil organic carbon stock. This soil organic carbon is vulnerable to changes in the hydrological cycle as well as to changes in permafrost dynamics in the boreal zone. The total amount of organic carbon stored in soils and its distribution is still highly uncertain, and new estimates of the depths of organic soils are urgently needed.

Changes in soil organic carbon are largely influenced by anthropogenic activities, particularly through the conversion of natural ecosystems to agricultural land or forestry. The soil organic carbon is contained within micro-aggregates, and a part is lost through respiration and erosion after their destruction. Soil organic carbon varies as a function of the texture, bulk density, microbiologic activity, and organic matter contained in the vegetation. Peats are largely comprised of decayed plant material and are over 50% carbon. They can be up to 25m thick. Drainage of organic soils, and the subsequent oxidation of the soil organic carbon, is a large source of CO_2 that can persist for centuries. Destruction of mangroves also allows the carbon stored in the soils to escape. Many authors have proposed quantification of the carbon stored in soils and study of the role of soils as both a source and sink of carbon. Comprehensive measurements of soil organic carbon involve identifying the different soil types and extracting soil samples. Since this is particularly labour-intensive and costly, a composite sampling method is necessary.

Global maps (Figure 68) of soil organic carbon have been produced at a scale of 1x1 km, usually accounting only for carbon to a depth of 1m. These are based on samples combined with soil maps, for example the Harmonised World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC 2012; Hiederer and Köchy, 2011). This combines 9,607 soil profiles with 16,107 soil mapping polygons from four spatially explicit soil databases (see review of IP-10 Action T33 on page 302) to provide a 30x30 arc second (about 1x1 km) spatial raster.

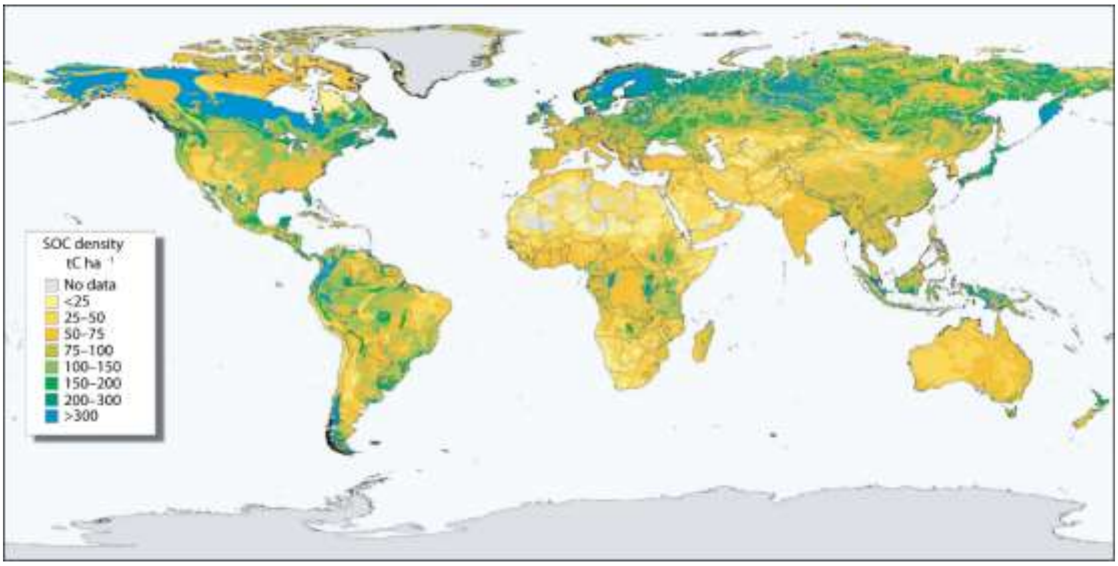


Figure 68: Soil organic carbon (tons of C ha^{-1}) to one-metre depth based on the Harmonized World Soil Database. Source: Scharlemann et al. (2014).

Emissions of carbon from soils are poorly understood. There are two main sources, respiration and changes in stocks due to changes in land use or land cover. Based on a database of measurements, CO_2 emissions from respiration appear to have increased from 1989 to 2008 in line with temperature increases, but it is unclear if this a net increase in CO_2 emissions (loss of soil carbon) or an increase in the rate of carbon cycling. Better measurement of the components of carbon output, particularly distinguishing between output due to increased respiration from plant roots and the immediate root environment and output due to respiration from free-living microbes in the bulk soil, may help. The latest version of the soil respiration database is available on line and has measurements from over 5173 locations (Bond-Lamberty and Thomson, 2014).

Carbon emissions due to change in land use or cover can be estimated by the use either of a bookkeeping approach that tracks carbon stocks in living vegetation, dead plant material, wood products and soils, or of land use change and process-based models of the carbon stocks and fluxes; the bookkeeping approach is the closest to observations (IPCC, 2013). These methods require knowledge of land-use and land-cover changes. The drainage of peat lands is a significant source and can result in fires, the topic of the following section.

6.3.15 Fire disturbance

Fires have impact on several identified radiative forcing agents. While they can be a natural part of many ecosystems they contribute to the build-up of carbon dioxide through deforestation fires, tropical peatland fires, and areas that see an increase in the fire return interval. They also emit methane and are a major source of aerosols, carbon monoxide and oxides of nitrogen, impacting local and regional air quality. Estimates of greenhouse-gas emissions due to fire are essential for realistic modelling of climate and its critical component, the global carbon cycle. Fires caused deliberately for land clearance (agriculture and ranching) or accidentally (lightning strikes and human error) are a major factor in land-cover variability and change, and hence affect fluxes of energy and water to the atmosphere.

Spatially and temporally-resolved trace-gas and aerosol emissions from fires are the main target quantities. These can be inferred using both land-surface and atmospheric measurements (section 4.7), preferably in combination. Fire disturbance data are also needed in the following application domains:

- carbon budget assessments, which need frequent updates of fire emissions and an assessment of the underlying uncertainties;
- dynamic representation of vegetation in climate models, to simulate vegetation birth, growth and death and replacement of species under different soil and climate conditions;
- natural-hazard management, which aims to reduce the impacts of fires on society and natural resources.

Burnt area, as derived from satellites, has been considered to be the primary variable that requires climate-standard continuity, although increasing attention is now being paid to detection of active fires and fire radiative power (FRP). To estimate emissions of trace gases and aerosols, burnt area can be combined with information on 1) available fuel load, 2) the fraction of the fuel load that is also actually combusted (combustion completeness), 3) information about burning efficiency which, in combination with 4) emission coefficients, governs the mapping from burnt biomass to the multiple emitted trace gases and aerosols. Ideally, satellite-derived information on vegetation, such as biomass density and vegetation productivity, is derived in concert with burnt-area measurements to facilitate the conversion from burnt area to emissions. Measurements of burnt area can also be used as a direct input to climate and carbon-cycle models, or, when long time series of data are available, to develop parameterizations for use in climate-driven models for burnt-area simulation. While the same approach can be used for peat fires, the amount of peat consumed by the fire is difficult to measure or estimate. Peat fires usually occur on drained land, as noted in the preceding section, and can be ignited either by fires used to clear the land or naturally. If the fire spreads underground the size and extent of the fire can be difficult to estimate although atmospheric measurements may allow the source strength to be estimated, as discussed in the review of IP-10 Action A34.

Fires are typically patchy and heterogeneous. Active fire detection and FRP information is currently mainly provided using data with 1 km or coarser resolution, capable of reliably discriminating fires down to around 8 MW in FRP. It is likely however that there are more fires burning below this limit than above it, and in some areas such fires may be responsible for the majority of smoke emissions. Examples are the fires associated with agriculture and tropical deforestation. Temporal sampling is also an issue as fire activity has been demonstrated to vary diurnally by an order of magnitude.

GCOS (2011a) identified a target for satellite-based burnt-area products of 250 m spatial resolution from optical remote sensing, ideally on a weekly, 10-day or monthly basis, if possible with day-of-burn information. Currently, an ESA CCI product is available with the MERIS pixel resolution of 333 m, and a MODIS product with 500 m resolution. A set of MODIS active-fire products is available from NASA, and MODIS FRP data are used in the Copernicus Atmosphere Monitoring Service to derive an FRP product (Figure 69) and fire-emission products.

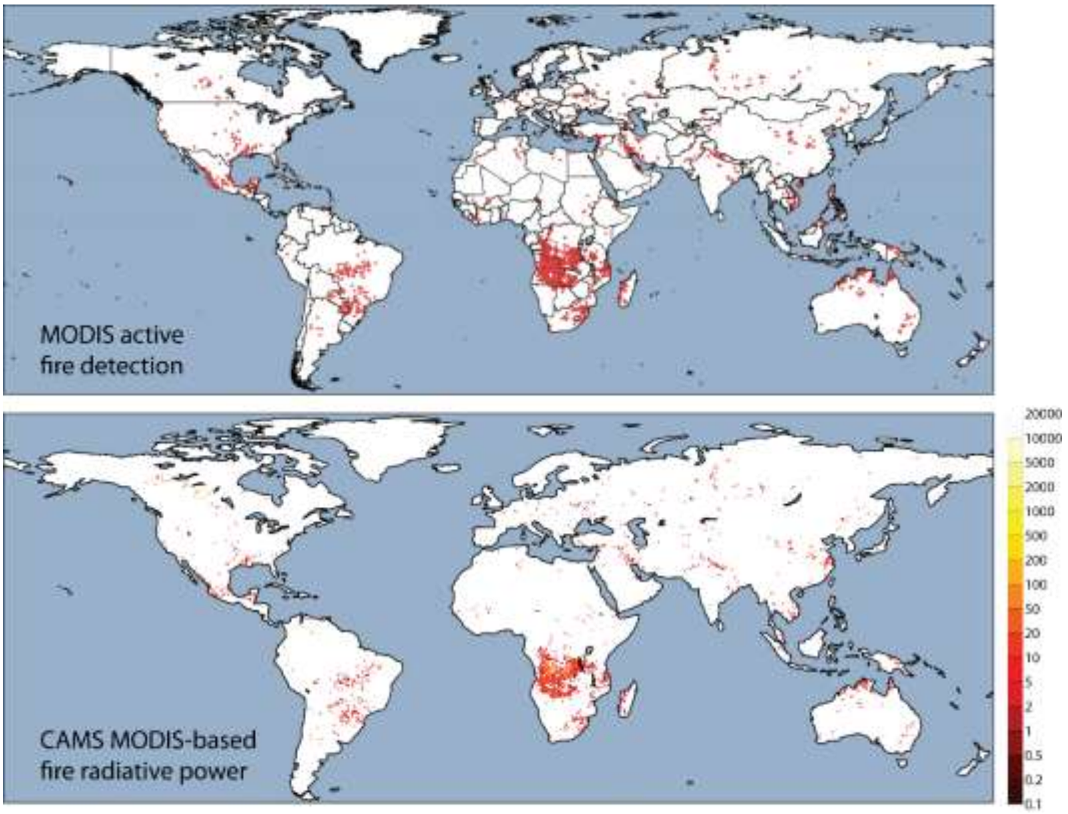


Figure 69: MODIS active-fire detection (upper) and Copernicus Atmosphere Monitoring Service (CAMS) fire radiative power (FRP) areal density (mW/m^2; lower) based on assimilation of MODIS FRP data, for 8 June 2015. Sources: the NASA MODIS product was visualised at https://firms.modaps.eosdis.nasa.gov/firemap/; the CAMS map was downloaded from http://www.copernicus-atmosphere.eu/catalogue.

Active fire detection and FRP measurement from two MODIS instruments provides limited sampling of the diurnal cycle of fires. The imagers on geostationary satellites are increasingly becoming capable of making such measurements, with good temporal sampling but poorer spatial resolution and lack of high-latitude coverage. Merging the information provided from polar and geostationary orbit has proved to be a challenge, as noted in the review of IP-10 Action T39 on page 305.

The CEOS WGCV LPV Subgroup has a focus area on fire products, and as for several other terrestrial ECVs it provides a webpage that links to products and validation information associated with them. Validation of fire products with medium and coarse spatial resolution involves field observations and the use of high spatial resolution imager radiances in collaboration with local fire management organisations and the research community. A fully stratified sampling scheme that adequately represents the nature of fire activity over the globe is under development. The validation protocol for burnt-area products, based on multi-temporal higher spatial resolution reference image radiances, is mature and has been documented (http://lpvs.gsfc.nasa.gov/fire_home.html). The active-fire validation protocol requires simultaneous high spatial resolution airborne or satellite imager radiances, and is in a much earlier stage of development.

A total of five fire-related Actions, T35 to T39, were formulated in IP-10, covering generation of products from the data provided by satellites in polar and geostationary orbit, reprocessing historical satellite data, validation and portal-facilitated data access. Their review begins on page 303.

6.3.16 Soil moisture

Soil moisture is an important variable in land-atmosphere feedbacks at both weather and climate time scales. It plays a major role in determining how the energy flux into the land from incoming radiation is partitioned into fluxes of latent and sensible heat from the land to the atmosphere, and in the allocation of precipitation into runoff, sub-surface flow and infiltration. Soil moisture is intimately involved in the feedback between climate and vegetation, since both local climate and vegetation influence soil moisture through evapotranspiration, while soil moisture is a determinant of the type and condition of vegetation in a region. Changes in soil moisture can accordingly have substantial impact on agricultural productivity, forestry, and ecosystem health.

Information on soil moisture is required to initialise forecasts and to improve process understanding and climate models. It can assist estimation of gas emissions in permafrost regions. It has application in many other important fields, among them the management of water resources, including use for irrigation, crop-yield forecasting, control of water-related diseases, locust monitoring and disaster risk reduction related to droughts, floods and landslides. Indeed, a study across societal benefit areas by GEO (2010) ranked soil moisture second behind precipitation among the variables that were critical priorities for Earth observation from a direct user perspective.

Soil moisture can be highly heterogeneous, varying on small spatial scales along with soil properties and drainage patterns. Satellite measurements integrate over relative large areas, with the presence of vegetation adding complexity to the interpretation. *In situ* measurements are not available widely enough to construct global products, and do not relate easily to the large-scale measurements. Calibration and validation activities need to be carefully chosen and use well-instrumented sites. The need to develop soil-moisture products based on satellite measurements supported by data from *in situ* networks was recognised by GCOS in the 2004 Implementation Plan, but it was not until the 2010 revision of the Plan that feasibility was sufficiently established for soil moisture to be designated an ECV.

In situ soil-moisture data are provided by an increasing number of networks worldwide, and data from freely available collections are being collected, harmonized, quality checked and redistributed by the International Soil Moisture Network (ISMN; see review of IP-10 Action T14 on page 288). There is nevertheless a lack of formal exchange of soil-moisture data among nations, and network coverage is especially poor over Africa and South America. The NASMN database integrates data over North America.

Satellite-based soil-moisture products are available from past and present missions flying active MW scatterometers such as the AMI on ERS-1 and ERS-2, and ASCAT on the Metop series, and from passive MW radiometers such as SMMR, TRMM, AMSR-E, SMOS, WindSat, AMSR2 and SMAP. Although individual satellite data records are too short to be of substantial use for climate applications, active and passive data records have been merged to create a long-term ECV record for soil moisture from November 1978 onwards within the framework of the ESA CCI (http://www.esa-soilmoisture-cci.org/; Dorigo *et al*., 2014). Figure 70 presents an example.

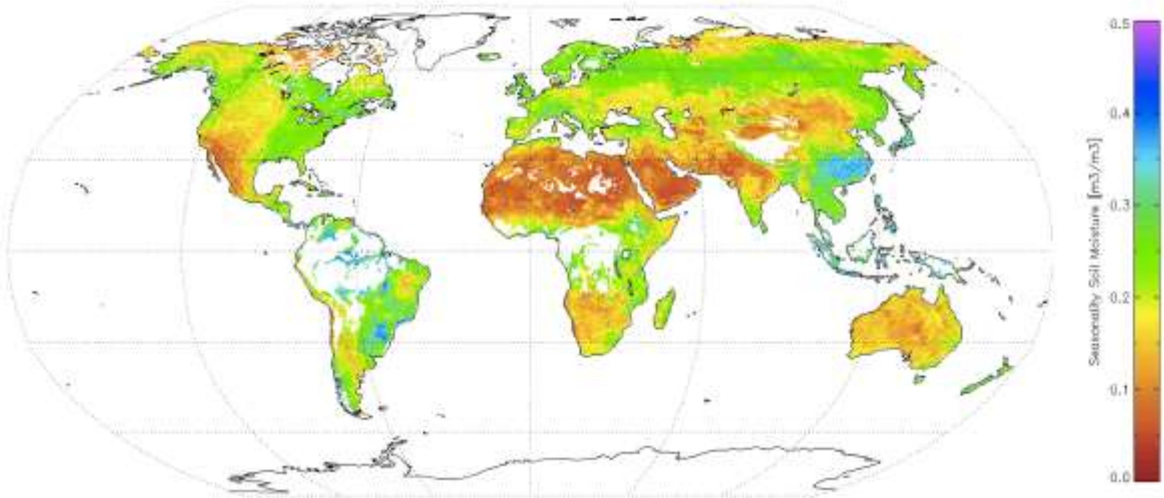


Figure 70: Mean volumetric soil moisture for May derived from combined use of passive and active satellite MW data for 1979-2010. Source: ESA Soil Moisture CCI (http://www.esa-soilmoisture-cci.org/).

Future provision of scatterometer data is discussed in the review of IP-10 Action A11 on page 228. There is no planned dedicated soil-moisture mission to follow on immediately from SMOS and SMAP, although important related data on surface water are expected from the SWOT mission scheduled for launch in 2020.

Data assimilation is used routinely in weather prediction and reanalysis systems to determine soil moisture, including for the root zone that is not reached by space-borne measurement. Screen-level observations of atmospheric temperature and humidity have been used for some time to constrain the modelled soil moisture, while more recently surface soil-moisture data derived from the Metop ASCAT scatterometer have also been assimilated (Dharssi *et al*. 2011; De Rosnay *et al*. 2013). The system developed by ECMWF for its new reanalysis to replace ERA-Interim includes assimilation of data from the ERS AMIs as well as ASCAT. Soil-moisture products are also provided by land surface simulations (Reichle *et al.,* 2011; Balsamo *et al*., 2015) in which land-surface models are driven by atmospheric reanalysis products corrected for bias in precipitation. Albergel *et al*. (2013) compare the quality and trends of these products and the initial version of the CCI product.

Satellite-based data products are served by the space agencies, by Copernicus services and by the national institutions that contribute to production. There is already a large user community for the available products, and a corresponding body of literature dealing with the validation and assessment of these products. Although care has to be exercised, products have been used with success when caveats are clearly identified, masking those areas where the retrieval accuracy is not sufficient for a particular application, for example. As indicated by the land areas shown in white in

Figure 70, retrieval is not possible over densely forested tropical areas and problematic in deserts. International overviews are provided by TOPC, GEWEX and the CEOS WGCV LPV Subgroup.

6.3.17 Additional variables measured from space

6.3.17.1 Land-surface temperature

Land-surface temperature (LST) is determined by the surface energy balance and varies rapidly because of the low thermal inertia of the land surface. LST is a radiative skin temperature that can be inferred from space by measuring the thermal emission, usually at IR wavelengths in cloud-free conditions. There is complexity in interpreting LST due to the sometimes complex structures of land surfaces: the radiative skin temperature may relate to the uppermost vegetation canopy or be a mixture of canopy and ground surface temperatures. All of these surfaces have low heat capacity so their temperatures respond rapidly to variations in incoming solar radiation due to cloud-cover and aerosol variations. Although thermal IR emissivities are generally near unity, with arid soils and rock surfaces the exceptions, the variations of structure can produce significant spatial variations. Variable angular emissivity has also to be taken into account.

LST was not designated an ECV in IP-10 because of the above issues. There has nevertheless been work using LST to fill gaps in the analysis of the surface air temperature ECV based on *in situ* measurements, and to assess the gap filling for this ECV that is provided by reanalyses (section 4.3.1). LST data are also used in determining surface energy and water fluxes, and provide supporting information on surface characteristics, some of which are ECVs. For example, the diurnal variation in LST provides information on vegetation characteristics and soil moisture. Retrieval of LST from MW measurements in cloudy conditions has been investigated and is delivering products of increasing quality. These products are not as well developed as those from IR measurements, but application of the latter requires that clear-sky sampling biases be taken into account. High-accuracy LST time series are now being created for data from both polar and geostationary orbit with associated uncertainty budgets incorporating emissivity and sampling bias effects. The case for designating LST as an ECV is likely to be reconsidered in preparing IP-16.

The CEOS WGCV LPV Subgroup includes a focus area on LST and emissivity. Its web pages (http://lpvs.gsfc.nasa.gov/LST_home.html) provide an account of validation methods and links to IR-based products and validation information, mirroring what has been discussed earlier for several terrestrial ECVs. The International Land Surface Temperature and Emissivity Working Group (ILSTE-WG) works in a complementary fashion as a new international collective unifying LST and emissivity community data providers and users. It promotes and documents best practice on its web-pages at http://ilste-wg.org/.

6.3.17.2 Fluorescence

A new capability for providing data on the photosynthetic activity of vegetation from space-based remote sensing of solar-induced chlorophyll fluorescence has been demonstrated using data from the GOSAT greenhouse-gas mission (Frankenberg *et al*., 2011; Joiner *et al*., 2011), and is expected to be enhanced by the availability of data from OCO-2 and the future GOSAT-2 mission. Such data are important for their use in estimating the uptake of carbon dioxide by vegetation and as an early indicator of vegetation stress due to factors such as high temperature or limited water supply.

7 Conclusions

7.1 General remarks

This report has provided an extensive account of how well climate is currently being observed, where progress has been made, and where progress is lacking or deterioration has occurred. The report has focussed on sustained observing systems, the observational records delivered by them and the developments that are being implemented or planned. Actions to address the findings of the report are being formulated by the GCOS programme in preparing a new Implementation Plan for the overall global observing system for climate, to be published in 2016.

It must be recognised that this report, although extensive, is not fully comprehensive. Its focus has been on the set of Essential Climate Variables and related actions identified in the 2010 update of the Implementation Plan first published by the GCOS programme in 2004. Whilst this has made for an orderly and largely quantitative assessment, the report does not cover in depth the entirety of observational needs, as there are variables that need to be observed even if they have not been designated as ECVs. Observations relating to the cycles of nitrogen and phosphorus have had only fleeting mention, intensive observational field campaigns of limited duration have received little attention and discussion of palaeoclimatological measurements has been far from exhaustive. The 2016 Implementation Plan will set the broad scope of the next cycle of assessment.

It has been noted why particular variables need to be observed, and examples have been presented of how observations have been used and what has been learnt from them. Recent observations have shown that global-mean sea level has continued to rise, and for the first time it has been possible to identify the relative importance of the contributions from thermal expansion, melting ice and the storage of water on land. The deeper ocean has continued to warm despite a slowing of near-surface warming for around ten years prior to 2013. There have been substantial reductions in Arctic sea-ice extent over recent years. There is evidence from new analyses that global-mean surface temperature rose more between 1998 and 2012 than first thought. There is little doubt over the exceptional warmth of the global atmosphere during the current El Niño event.

It has not however been the intention of the report to present to present a complete picture of what has been learnt from observations or of how much benefit observations bring. More attention has been paid to observational uncertainties identified by the IPCC's latest assessment than to what is known with confidence from observations. This helps guide where emphasis has to be placed in making the required improvements, but downplays the immense existing value of past and present investments in the global observing system. Observations have been essential for identifying and understanding climate variability and change. They continue to be so, as future change and its drivers have to be monitored and more-demanding questions on the effectiveness of mitigation and the needs for adaptation have to be answered. Observations are also fundamental for evaluating, refining and initialising the models that predict variations in climate over the seasons ahead, and project how climate will change in the longer term under different assumptions concerning greenhouse-gas emissions and other human influences. Many of the observations also serve other purposes, including weather and air-quality forecasting, disaster risk reduction, water and food security, protection of biodiversity and ecosystems, and sustainable development.

Although the global observing system for climate already meets many requirements, it is still falls some way short of enabling answers to be given to all the questions being asked of climate science and services. The principal findings set out below do not enumerate the benefits of the existing observational record or highlight the vital importance of continuing the record. Rather, they are concerned with identifying those components of the global observing system that have been improved in recent years or are firmly planned to be improved, and those components where improvement is clearly needed.

7.2 Principal findings

Most of the principal findings that have been drawn from the reviews that have been reported variable by variable and action by action fall straightforwardly into two separate groups, one for *in situ* measurement and ground-based remote sensing and one for space-based remote sensing, even though many applications of observations make combined use of both groups of data. It is inevitable in a report such as this one that there are both positive and negative findings, and both need to be acknowledged and taken into account in planning what needs to be undertaken in the future.

For the ***in situ* and other non-space-based components** of the observing system:

- The development and contribution to climate monitoring, understanding and prediction of the Argo network since its floats profiling temperature and salinity were first deployed in the year 2000 has been outstanding. The original goal of 3000 floats was reached in 2007, and the network is now expanding into marginal seas and high latitudes, beginning to host novel sensors that measure biogeochemical variables, and offering the prospect of profiling to greater depths.
- There have been improvements in coverage for a number of longer established *in situ* networks, including the main meteorological networks. The quality of measurements has also shown improvement.
- Several oceanic and terrestrial networks making *in situ* measurements and networks for ground-based remote-sensing of atmospheric composition have been established or significantly expanded in recent years, although some requirements for forming networks have not been met.
- Fewer observations have been provided recently by some atmospheric-composition and marine-buoy networks. This has been due to planned closures, inadequate maintenance or unexpected equipment failures. Responses have been effective in limiting some of the shortfalls. Particular issues with tropical moored-buoy networks have prompted a review of the observing system for the tropical Pacific.
- Surface meteorological measurements from ships have declined in number over the major parts of ocean basins, but have increased near coasts.
- Some gaps in the coverage of networks over land have been reduced. Local gaps that appear small from a global perspective may nevertheless be critical, especially where populations are at risk or where local changes have global impact.
- Capacity development continues to fall far short of what is needed to fill critical network gaps in a sustainable way, and more generally to ensure that vulnerable developing countries have the local observations needed to adapt to climate change.

- Automation has increased the temporal frequency of observation and has enabled measurements to be made at additional remote locations, although there are some remaining issues regarding data quality and loss of ancillary information.
- Progress in specifying and establishing reference observing sites and networks has been mixed. It has been good for upper-air measurements. Attaining representative global coverage is a general challenge.
- There are opportunities to benefit from expanding global near-real-time data exchange and adopting new reporting codes and metadata standards.
- Recovery of historical data has progressed well in some respects, but is still limited in extent and hampered by restrictive data policies.
- Generation of data products, for example on surface air temperature, humidity and precipitation, continues to improve.
- Sustaining observing-system activities that are initiated with short-term research funding is a recurrent issue.

For the **space-based component** of the observing system:

- The newer and planned generations of operational meteorological satellite systems offer improved quality and a broader range of measurements. China is becoming established as the provider of a third pillar in the constellation of polar-orbiting systems.
- The European Copernicus programme is placing additional types of observation on an operational basis, with increased coverage and quality of measurement, and accompanying service provision.
- There have been increases in the numbers of national providers, co-operative international missions and other collaborative arrangements.
- There has been very little progress on the continuation of limb sounding and the establishment of a reference mission.
- Continuity of measurement is at risk for solar irradiance and for sea-surface temperature at microwave frequencies.
- New observational capabilities have been demonstrated, and others are being prepared for demonstration. Future deployment is uncertain for some of the demonstrated capabilities, for example for monitoring cloud and aerosol profiles, sea-ice thickness and soil moisture.
- The generation and supply of products derived from space-based observations have progressed well, with increasing attention paid to documenting product quality and uncertainty.
- Inter-agency cooperation has been effective in product validation and in starting to develop an architecture for climate monitoring from space and an inventory of products.
- Data access is becoming more open, although there is still progress to be made. Some data remain to be recovered from early missions, and long-term preservation of data, including occasional reprocessing, is not yet fully ensured.

Data-centre holdings increase with the passage of time, and are generally distributed by data type. Collections of *in situ* data are held by international data centres for many but by no means all ECVs. Basic satellite data are usually held by the agency that operated the satellite. Derived data products are hosted primarily by the organisations that generate the products. This arrangement is not seen to be problematic, but there are concerns over a set of issues:

- There are a number of portals and internet search engines that can be used to link to data, but product lists may not be complete and users may be in doubt over what they are missing, and how the observations or products on offer compare.
- Collections of *in situ* data may be some way short of complete and up to date. They depend on submissions or access offered by owners, and thus on owners' data policies and resources, including for recovering data from paper records and obsolete media.
- Data served by a centre may not be in an easy-to-use format, and may lack quality control, merging of data from different sources, duplicate removal, feedback from other users, and so on.
- Data may not be easy to sample, notwithstanding welcome advances in visualisation.

Global reanalysis of comprehensive sets of observations has been sustained, with improving capabilities and better understanding of user requirements and of the deficiencies in current products. The activity is being placed on a firmer footing in Europe through inclusion in operational Copernicus service-provision and in Japan and the USA through the commitment of providers to continue and refresh production. Atmospheric reanalysis for the radiosonde and satellite eras has been supplemented by reanalysis covering the 20th century and more, assimilating only surface atmospheric data but constrained also by observationally based surface and radiative forcings. Reanalysis has become better established for the ocean, the land surface and atmospheric composition. Good progress has also been made on the development of data assimilation systems that couple various elements of the climate system, the atmosphere and ocean in particular.

International organisation of observing systems has been strengthened for the atmosphere and ocean, in particular through the development of the WMO Integrated Global Observing System as the framework for the functioning of all WMO observing systems and the revitalisation of the IOC-led Global Ocean Observing System, with guidance provided by a Framework for Ocean Observing. The withdrawal of support for the Global Terrestrial Observing System by its lead sponsor has restricted coordination and standardization for the terrestrial domain, but there has been progress for many individual elements of terrestrial observation.

7.3 Overall progress

There is no single metric or small set of metrics that comprehensively quantifies the current status of the global observing system for climate, how well it meets the broad spectrum of user needs, or how far it has progressed, either over many decades or over the shorter period since GCOS last assessed the adequacy of the system in 2003. Such measures do exist for the ECVs for which observation and monitoring are well established, and examples of the variations over time of data counts and quality indicators have been given for several variables, especially for the atmosphere. They point mainly to a situation that continues to improve, though not entirely. For variables for which observation and international organisation is less well established, progress has been indicated in some cases by reporting the establishment of an international network or data centre, or simply by being able to display a global map related to the variable. Statistics on user accesses to web-based information, to observations and data products and to data visualisation tools also serve as metrics, but are often not made evident on data-centre websites.

7.4 Progress of the actions from the 2010 Implementation Plan

An indication of the progress made over the past five or so years is provided by the assessment of progress made on the set of 138 actions set out in IP-10. Progress is ranked for each action on a five-category scale in Appendix 1. Figure 71 shows the distribution by category of all 138 actions. No attempt has been made to prioritise actions; each receives the same weighting. Other caveats concerning the categorization are expressed in the introduction to Appendix 1.

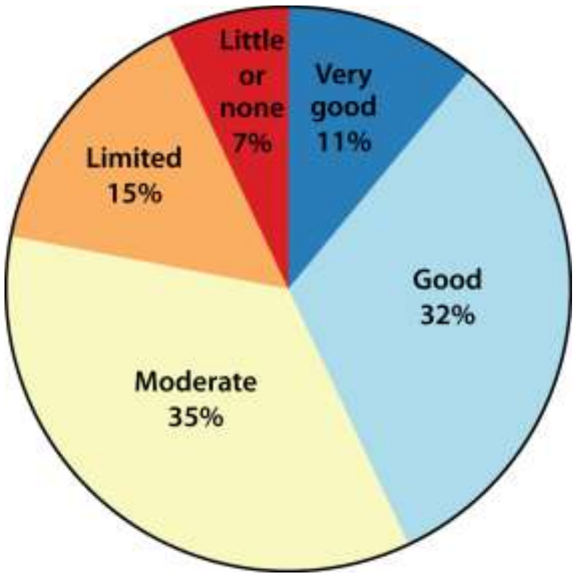


Figure 71: Overall progress of IP-10 actions.

Overall progress on the actions is assessed to be moderate to good. Almost twice as many actions fall into the two highest categories than the two lowest ones. Pleasing though this is, it is no cause for complacency. 22% of actions have been placed in the lowest two categories, similar to what was reported in GCOS (2009) for the progress on actions from the 2004 Implementation Plan. Progress has thus been at best limited for almost one action in four. 7% of actions are placed in the lowest category, which includes cases where the action called for a network to be improved but performance actually deteriorated. Moreover, some actions relate to incremental steps towards establishment of an adequate component of the observing system, and that good progress on them, though important, needs to be followed up by further action to reap the benefit of the progress made to date.

Figure 72 shows the distribution by category separately for the cross-cutting actions and the actions specific to the atmospheric, oceanic and terrestrial domains. Each is broadly similar to the overall picture, and such differences as there are have to be viewed with some caution because of the smaller number of actions on which each pie chart is based. Although comparisons at the level of a few percentage points would not be meaningful, some remarks are nevertheless appropriate.

Four out of the nine actions that have been placed in the lowest category are in the terrestrial domain. A clear factor in this has been the absence of a functioning central GTOS programme, a factor that is also partly responsible for lack of progress on the one cross-cutting action that is in the lowest category. The atmospheric domain has the largest number of actions in the top two categories, as it did in GCOS (2009). Aside from possible domain-bias in what are to some degree subjective judgments, this may reflect the generally well-established nature and integration of observational activities for this domain, through WMO in particular but also CGMS. This facilitates both the setting of achievable actions and the assessment of their accomplishment. The oceanic domain has the highest percentages of actions in both the "limited progress" and the "very good progress" categories. This is partly due to the rankings of actions on cross-ECV data management and reanalysis, and inter-related actions on sensor development, actions of a type less prevalent for the atmospheric and terrestrial domains.

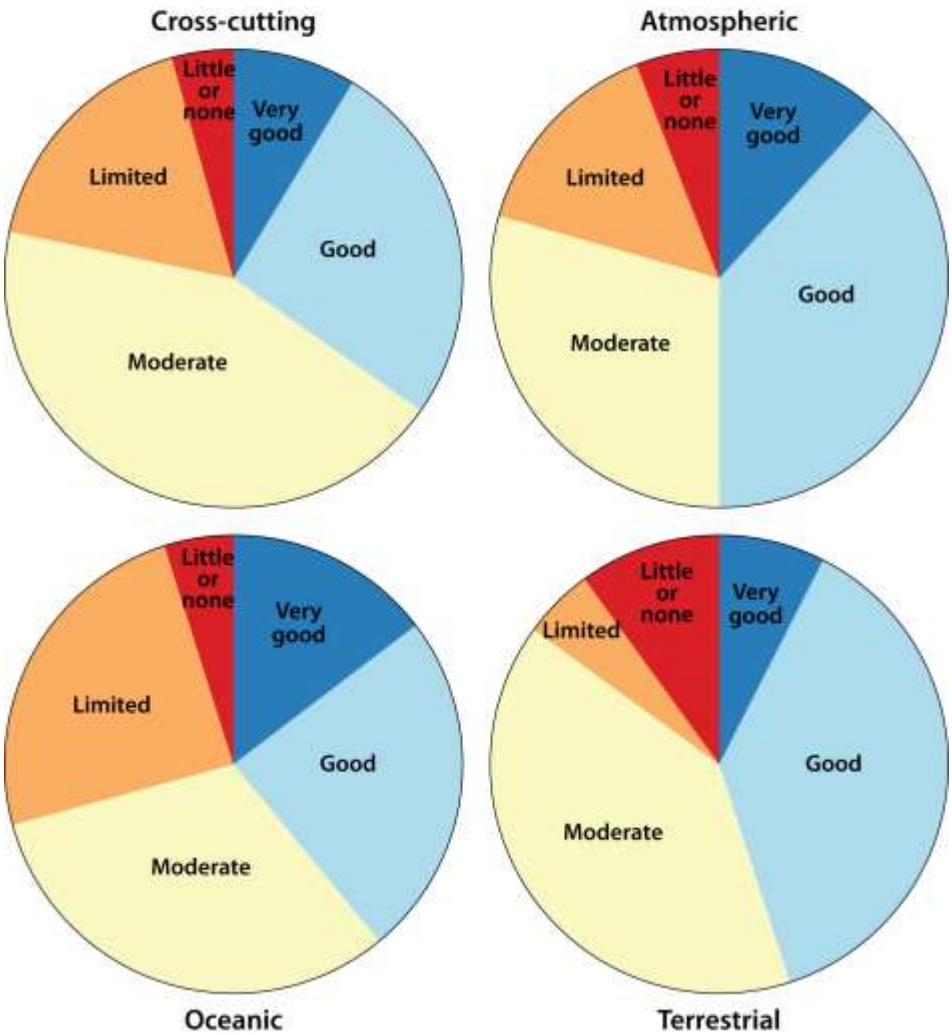


Figure 72: Progress of cross-cutting and domain-specific IP-10 actions.

7.5 Overarching and cross-cutting elements

The main conclusions concerning status and progress on overarching and cross-cutting elements of the global observing system for climate are set out in summary form in section 7.2. Domain-specific comments on some of these topics are given in the following three sections.

The cycle of assessing the performance and required improvements of climate observation undertaken by the GCOS programme has fulfilled a valuable international role in that the successive

2004 and 2010 implementation plans and associated documents, organised within the framework provided by the concept of Essential Climate Variables, have been quite widely reflected in the plans and programmes of the sponsors of GCOS, their subsidiary bodies and other international organisations involved with climate observation. This has been most evident in the case of the space agencies, which have responded both formally to UNFCCC SBSTA and through collective and individual implementary activities. NMHSs and other national agencies have also continued to offer considerable support to the GCOS programme and the component observing systems, through their roles as monitoring, analysis and archive centres and their contributions to international working groups and the like.

Programmatic considerations aside, it is overwhelmingly nations, sometimes via regional cooperation, that provide the observations needed by all. National reports, especially those to the UNFCCC, and other sources of information such as the monitoring results presented in this report provide substantial evidence of increased national attention to meeting the needs for climate observation. This is especially evident for those countries with strong national coordination mechanisms for GCOS. The GCOS programme has sought to promote national and regional coordination, but has not secured the resources needed to pursue this thoroughly. This has also been the case for the follow-up of the Regional Action Plans developed some ten years ago. The Sponsors' Review of the GCOS programme affirmed that there is a continuing need for GCOS involvement in regional assessment of vulnerability and adaptation, anthropogenic influences and mitigation.

There has been a significant recent reduction in the donations to the GCOS trust fund that supports observing-system improvement in developing countries. Although it has still been possible to undertake a number of projects and provide general assistance, efforts are often a case of maintaining capacity rather than increasing it. It is hard to quantify efforts on capacity development in general because of its fragmentary nature, but the persistence of gaps in observing networks make it clear that support for building capacity in those developing countries where the need is strong continues to fall well short of what is required.

The activities undertaken by the GCOS programme relate almost entirely to instrumental observations and the data records associated with them. The 2010 Implementation Plan nevertheless recognised that it was important to improve the coverage and availability of palaeoclimatological data, to enable changes in climate variability through time to be analysed and the instrumental data record for several ECVs to be placed in a longer-term context. IP-10 formulated three actions related to proxy data on climate. Progress on them has been judged to be good.

IP-10 also sought to broaden of scope of the actions on climate observation. When preparing it, biodiversity and habitat properties were originally considered as additional oceanic and terrestrial ECVs, but eventually ruled out. An action (T4) was formulated for the terrestrial domain calling for a monitoring network acquiring "Essential Ecosystem Records", but this has been assessed as showing very little progress. There has also been only limited progress on Action O23 calling for a global network of long-term observation sites to be established covering all major ocean habitats and encouraging collocation of physical, biological and ecological measurement. Better progress has been reported for several other ecosystem-related oceanic actions. IP-10 also formulated actions (C22 and C23) calling for guidelines for undertaking observational studies in support of impact assessments, and encouraging the definition of new impact-related ECVs. There has been little progress up to now on these, although there have been discussions at GCOS workshops on adaptation.

7.6 Atmospheric domain

The well-established nature of meteorological observation, which serves both weather forecasting and climate, and its organisation under the WMO, have made it possible to present a much more comprehensive picture of observational performance and progress for this particular component of the global observing system for climate. The past fifteen years have seen a general growth in the amount and quality of data provided by the *in situ* meteorological observing networks. This follows a period of more mixed performance in the 1990s. There are now fewer regions with poor coverage, but some are persistent, most notably over parts of Africa. Both the spatial density and the temporal frequency of surface observations over land have increased. The amount of data reported per radiosonde ascent has also increased, and there is a potential for provision of more data still, including the actual geographical location and time of each datum, through the move to use of BUFR code for reporting data. Use of BUFR should also bring benefit in the case of surface meteorological data, for example through consistent reporting of data from moored buoys. Full implementation of BUFR is proving a slow process, however.

The number of observations from commercial aircraft continues to rise steeply, by a factor of three over the past five years alone. This includes an increase in the number of reported ascent and descent profiles. Progress is also being made on the implementation of humidity sensors on aircraft. Observations from ships and buoys have continued to rise in number overall, notwithstanding the buoy issues noted in the following section. The number of observations from ships has declined over the Pacific Ocean, however, and it is over much of this ocean that the failure to increase significantly the number of drifting buoys equipped with surface-pressure sensors is most evident. There has been a more general decline in the number of observations received for the main synoptic hours from ships in mid-ocean, but numbers have risen from ships near coasts over the past ten years.

The increasing requirement for local and frequent surface atmospheric data, including systematic international exchange, was recognised in IP-10 actions. Near-real-time exchange of hourly data has increased, including some regional exchange of precipitation data, but there is much scope for improvement. More such data can be obtained from archives, however. Holdings of past data continue to rise in general, and an increasing amount of data on temperature, surface pressure, marine winds and humidity are being used to form data products, either directly for the variable in question or via reanalysis, which in some cases now stretches back over more than a century. Progress has been made in international data collection and data recovery for these variables, but remains restricted by some national data policies. The absence of a single database with a comprehensive collection of the range of surface synoptic data over land is another impeding factor. Monthly station data remain important also; it has been illustrated how precipitation data in this form are transmitted internationally from some stations that do not transmit synoptic data.

The atmospheric domain continues to benefit from progress in the quality and breadth of space-based observation. Hyperspectral IR sounding and GNSS RO have become established types of highly stable data, but there has been improvement more generally in reducing the biases and drifts of sounding data and in increasing orbital stability. This, along with the good progress made on establishing the GCOS Reference Upper Air Network, goes some way to compensating for the limited progress made on establishing a reference satellite mission.

A particular and by now longstanding and much-expressed concern about future provision of space-based observation is the impending loss of limb-emission measurements that have provided much valuable information on temperature, humidity and other constituents, from the upper troposphere to the mesosphere. Another concern is the risk of loss of continuity of measurement of solar irradiance measurement, especially in spectrally resolved form. Follow-on arrangements for high-quality cloud and rainfall observation from space beyond the current CALIPSO, CloudSat and GPM, and future EarthCare, missions are unclear. Observation of upper-air wind from space remains limited, notwithstanding improvements in winds derived from feature-tracking, including welcomed reprocessing. Demonstration of lidar capability by the ADM-Aeolus mission has been delayed, and is awaited with interest.

In situ observation of atmospheric composition remains characterised in general by a multiplicity of networks and issues related to data policies, timeliness of data supply, data formats and data centres. Overall performance has not shown the quite widespread improvements seen for meteorological variables. The general lack of measurements from the main networks for atmospheric composition over large parts of South America, Africa and Asia is striking. This is true also of measurements from the Baseline Surface Radiation Network, an important component of the observing system for the Earth's radiation budget.

Observation of ozone from the GAW network of Dobson and Brewer instruments and from sondes has declined. A baseline network has yet to be proposed by GAW for any aerosol properties, and data-centre holdings for some of the properties of interest are quite limited geographically. AERONET provides an improved near-global coverage of stations measuring aerosol optical depth, though with greatest density of coverage over Europe and North America. There is poor coverage and a decline in the numbers of GAW stations reporting values of NO_2 and SO_2. A global network is not in place for the air-quality measurements made by a large number of environmental agencies, although some regional arrangements are functioning. Aside from the issue of limb scanning, space-based observation for reactive gases and aerosols is in a generally healthy state, with continuity of observations provided by Copernicus missions in particular. Ground-based remote sensing has progressed.

In situ greenhouse-gas measurement appears to have survived a period when budgetary pressures left some mark on the data record, but continuing deficiencies in understanding of quite basic aspects of the budgets of carbon dioxide and methane demonstrate the need for improved observations to determine the emissions and sinks of these gases. Space-based observation of the gases continues to develop, and should lead to a clearer picture of the balance needed in the longer term between observations from the ground and those from space.

Reanalysis is particularly well established for the atmosphere, and continues to improve. It is beginning to complement the traditional products used for monitoring temperature change. Notwithstanding the unequivocal warming observed over multiple decades, reanalysis can help resolve uncertainties that remain in the shorter-term variations in global averages as well as in assessing regional changes. Care nevertheless still has to be exercised in assessing and interpreting its results, especially if a mix of products of different vintages is used. Reanalysis also provides feedback on the quality of the observations it assimilates, and this information is being made more readily available. Improved observational metadata would enable a richer stratification of feedback by observation type; establishment of BUFR encoding and a core WIGOS metadata standard are steps forward in this regard.

7.7 Oceanic domain

Observation of the ocean has progressed substantially through deployment of buoy networks, autonomous sub-surface measurement systems and space-based remote sensing, which complement longer-established and still-essential ship-based programmes. It is now taking place under revised arrangements for scientific guidance and advice, provided by GOOS and its three panels, and under the technical coordination and implementation of JCOMM. Information on implementation, monitoring and data centres is provided for key *in situ* networks by the JCOMM Observing Platform Support Centre. It has been utilised in preparing this report.

Space-based observation of the ocean has been expanded in recent years by the SMOS and Aquarius missions measuring salinity, by the measurements of sea-ice thickness from CryoSat and by the gravimetric measurements of GRACE relating to the distribution of bottom pressure. Generation of products from more-established types of measurement has received increased attention and continues to be improved. Present and firmly planned future missions provide a considerable degree of continuity, but there are concerns over a possible gap in the provision of measurements that sense sea-surface temperature in the microwave, and over absence of planning for future measurement of salinity and of sea ice from a high-inclination orbit such as that of CryoSat.

The success of the Argo programme has already been highlighted in section 7.2. The number of floats has been sustained above its original design level of 3000 for some eight years now. The data have delivered real impact in terms of better analysis and understanding of ocean climate and have enabled new information to be gleaned from the historical data record by viewing it from a new perspective. Technological advances have made it feasible to begin deploying floats in marginal and high-latitude seas, and more than 3900 floats are currently reporting. Several float designs are also being piloted for sampling well below the usual Argo depth limit of 2000 m. A Deep Argo array has the potential to transform understanding of the lower half of the ocean.

Conversely, the performance of the tropical mooring system has deteriorated since GCOS last assessed progress. Between 2011 and the middle of 2014 the data return from the TAO array in the eastern Pacific fell from around 80% to 30% of the maximum possible. Although the return was restored by resumed maintenance in the second half of 2014, a staged removal of moorings from the TRITON array is under way in the western Pacific and the Indian Ocean array has been operating below the 60% level. The increase in Argo observations does not compensate for the loss of information from the moored buoys as the latter provide very different capabilities such as better resolution of temporal variability in the upper ocean and surface meteorological measurements. The surface marine climate data record also suffers from significantly fewer observations from drifting buoys between 2011 and 2013, due to the earlier deployment of a large batch of buoys whose lifetime was shorter than expected.

The last few years have seen rapid development of chemical and bio-optical sensors, with increasing levels of readiness for deployment on Argo floats, gliders and moorings. Currently 7% of floats are equipped with oxygen sensors and a smaller number of floats sense nitrate and pH. Sensors have also been developed for other parameters that can be used to define the marine carbonate system. Bio-optical sensors provide information on chlorophyll-a, particulate organic carbon and dissolved organic material. Progress in recent years has also been made on data collection and support, for example through establishment of the Surface Ocean CO_2 Atlas. Organisation of observing activities has taken place through the International Ocean Carbon Coordination Project and the formation of the Global Ocean Acidification Observing Network and the Global Alliance of Continuous Plankton Recorder Surveys. The considerable progress made in establishing observational capabilities and systems such as these provides a basis for reconsidering the specification of the related ECVs during preparation of the 2016 Implementation Plan.

The sustained ocean observing system remains highly dependent on ships. Their role in taking measurements continues. The current GO-SHIP programme of repeat full-ocean hydrography is proceeding well. Observations of marine meteorological and sea-surface temperatures from Voluntary Observing Ships have increased in number globally, but mid-ocean coverage has declined. Many sub-surface oceanographic observations are still provided by ships of opportunity, although numbers have fallen since the Argo programme began. These ships are, however, being used to deliver observations of an increasing number of ECVs: a comprehensive network of vessels now deliver observations of surface ocean $pC0_2$, for example. Ships are also required to deploy and maintain other components of the ocean observing system and provide infrastructure to support the calibration and validation of data from satellites.

Issues with the TAO/TRITON Array precipitated a review of the overall observing system for the tropical Pacific Ocean and led to the establishment of the TPOS 2020 project. Observing-system projects are also in place for the Atlantic and Southern Oceans, and a general observing strategy for the deep ocean is under development. These projects are in a position to reassess the role of existing technologies and capitalise on new ones, including the Argo developments, gliders and finer-resolution observation from space. It is expected that the projects will also explore new ideas on infrastructure to reduce costs and improve integration of the data provided by the various types of observation.

Insufficient and heterogeneous data management generally creates barriers to full realisation of the value of observations. Some oceanic datasets are managed well, while others need a home. An example of the latter is the data from shipboard and lowered acoustic Doppler current profilers. Near-real-time data supply is not in place for some types of salinity measurement. Data assimilation for near-real-time applications and reanalysis, and an increasing number of research studies require access to multiple data streams, bringing a need for good integration across data-management systems. Some current practices work against developing rich metadata and significantly devalue observations: some buoy locations are now being masked for non-operational users, even in delayed mode, and similarly some Voluntary Observing Ship identifiers (such as the call sign) are being deleted from near-real-time records. Data rescue has become very limited, and is in need of revitalisation.

Several other issues that should be taken into account in formulating the 2016 Implementation Plan have been identified in preparing this report. Actions will be required where feasible to address the sampling inadequacies for specific ECVs noted in chapter 5. The current categorisation of ECVs into surface and sub-surface variables is open to review, given the variations that can occur close to the physical surface, the types of measurement that can be made and the requirements for information on fluxes across the air-sea interface. Surface vector stress has been argued from an oceanic viewpoint to be a more appropriate interfacial variable than atmospheric surface wind. Recent improvement in the technology for long-term deployment of eddy-covariance sensors may be drawn on. The three ocean panels are each developing a focus on improving observation of coastal zones, where there are particular needs associated with impacts and adaptation. This should be reflected in coordinated planning that takes interfaces with related elements of terrestrial observation into account.

7.8 Terrestrial domain

There has long been a much lower level of international coordination and data exchange for the terrestrial component of the observing system, and this disparity has recently increased. While arrangements for the atmospheric and oceanic domains have continued to develop, those for the terrestrial domain have deteriorated due to withdrawal of support by the FAO for a functioning secretariat and steering committee for GTOS. Although GOFC-GOLD, WMO and CEOS have continued to be active in several important areas, and GCOS has maintained an overview through TOPC, other GTOS activities have ceased. It is not easy at this stage to assess the extent to which the lack of an overall organisational framework for terrestrial observation is damaging progress, but specific actions set out in the 2010 Implementation Plan that called for the involvement of GTOS in development and promotion of standards and in developing ecosystem monitoring have failed to progress as envisaged. Overall leadership of terrestrial observation is lacking. Furthermore, without clarification on the future of GTOS by its sponsors it is difficult for other arrangements to be established.

The monitoring of individual terrestrial ECVs has nevertheless advanced considerably. This is most evident for space-based observation, where new missions enhancing data on variables such as ice sheets, land cover and soil moisture have been launched over the last five years, complementing the continued supply of data from established missions, in particular from the long-lived MODIS instruments on NASA Earth Observing System platforms. A new capability to observe the photosynthetic activity of vegetation by sensing chlorophyll fluorescence has also been demonstrated. Future missions for above-ground biomass and surface water are in preparation. Additional and improved data products include ones on land cover at as fine as 30 m resolution, soil moisture over more than 30 years, ice-sheet mass balance, albedo and fires. The CEOS Land Product Validation Subgroup has been effective in coordinating standardised inter-comparison of space-based datasets and comparisons with *in situ* or other suitable reference data. Improved digital elevation models based on data from satellites find application in monitoring glaciers, in addition to being used to improve the representation of orographic effects in climate models.

Ground measurement is the primary method of monitoring some variables, soil carbon and permafrost for example, as well as being needed for calibration and validation of many space-based data products. Lack of an integrated framework for network monitoring, the inherent nature of the measurements in several cases and restricted data exchange make it difficult to quantify changes in the number of *in situ* observations being made for some variables. The snow data exchanged on the GTS are one exception; here there has been an increase in the density of coverage of exchanged snow-depth data, though coverage remains sparse in places and more-widespread reporting of the absence of lying snow is required. Snow is a variable for which there has been some progress on data rescue, though much remains to be done.

Data archiving and access vary considerably among the terrestrial ECVs. Many cryospheric datasets are stored and supplied by the US National Snow and Ice Data Center, and arrangements for space-based data and derived products are generally as for the other domains. New international network arrangements that bring together data from a number of mainly national or sub-national measurement networks for groundwater and soil moisture have been set up over the past few years. Another recent development is a new management system for data from the Global Terrestrial Network for Permafrost. Long-term funding arrangements are lacking in some cases. Such arrangements are important if data centres are to take on the responsibility for preservation and supply of data collected on a short-term project basis.

Even when network arrangements and data centres are in place, data holdings may be far from complete, spatially and over time. This is the case for the Global Terrestrial Network for River Discharge and the associated Global Run-off Data Centre, for example. Although most countries monitor river discharge, many are reluctant to share data and such data as are made available to the GRDC may be supplied only after a delay of a number of years. GRDC's data holdings show large regional differences in both density of coverage and availability of recent data. There has been a move to near-real-time data supply by a number of countries, but overall progress has been slow.

The water use ECV differs from other ECVs in that the data on it has come up to now from the garnering of statistics from multiple sources, relating primarily to irrigation, rather than from direct observation. It has not seen much recent attention by the GCOS programme, although the FAO's AQUASTAT programme continues to develop data gathering and service provision. Water stress, the difference between water use and freshwater availability, is an extremely important parameter measuring one impact of climate change that is predicted to increase for large populations. However the ECV as currently interpreted inadequately monitors water use and does not address the difference between use and availability, and hence water stress. This ECV is a candidate for reconsideration in preparing the 2016 Implementation Plan, taking into account improved capabilities for monitoring crops and soils from space.

Appendix 1 Progress by Action in the 2010 Implementation Plan

The 2010 version of the Implementation Plan developed by the GCOS programme, IP-10, identified a total of 138 actions. The context of each action was provided in IP-10, and in general can be appreciated from the cross-cutting and ECV-specific discussions in chapters 3 to 6 of this report, where all actions are referenced.

Some of the IP-10 actions were of an overarching or cross-cutting nature, while others were related primarily to the atmospheric, oceanic or terrestrial domains. Some were specific and time-limited; others were more general and open-ended. Some were easily verifiable, but others were not, either because of their general nature or because their evaluation would have required dedicated surveys that were beyond what was possible in practice in preparing this report.

The actions are set out verbatim in the coloured boxes in this Appendix, and each is followed by a review of the progress made on that action. Actions have been colour-coded according to an assessment of the degree of success achieved, following a similar approach adopted in the assessment published in 2009 of the actions from the original 2004 version of the Implementation Plan. Deciding on a ranking has been relatively easy in cases where an action has been plainly accomplished or where progress has clearly not been made. Generally, however, the ranking is subjective in nature, and open to discussion in particular cases. It also has to be recognised that some actions were more challenging to achieve than others, as reflected in part in the cost implications attached to each. The assessment nevertheless provides overall indications of progress.

The colour-coding is as follows:

Category A: Action completed, perhaps exceeding reasonable expectations. Very good progress on ongoing tasks.

Category B: Action largely completed according to expectation. Good progress on ongoing tasks.

Category C: Moderate progress overall, although progress may be good for some part of the action.

Category D: Limited progress overall, although progress may be moderate or good for some part of the action.

Category E: Very little or no progress, or deterioration rather than progress.

Overarching and cross-cutting actions

C1: Review and update international plans to ensure they better serve UNFCCC needs

Action: Participating international and intergovernmental organizations are invited to review and update their plans in light of this document in order to ensure they better serve the needs of the UNFCCC.

Who: International and intergovernmental organizations.

Time-Frame: Inclusion in plans by 2011 and continuing updates as appropriate.

Performance Indicator: Actions incorporated in plans.

Annual Cost Implications: <1M US$ (10% in non-Annex-I Parties).

There have been a quite considerable number of positive responses from international and intergovernmental organisations to IP-10. These include:

- the formal response to the UNFCCC by CEOS, prepared in coordination with CGMS and other stakeholders, which sets out specific activities and responsibilities for each of the IP-10 actions that relate to space-based observation;
- the WIGOS Implementation Plan for the Evolution of Global Observing Systems, which draws heavily on IP-10 and includes actions to emphasize and propagate the requirements identified by GCOS;
- the GFCS Implementation Plan, which recognises the essential basis provided by the IP-10 for the observation and monitoring component of the Framework, while recognising that IP-10 alone does not encompass the full observational needs of climate services;
- the EU Copernicus initiative, which includes provision of services supplying ECV data products;
- the GEO Work Plan for 2012-2015, which supports the undertaking of the specific actions contained in IP-10;
- the development by CEOS, CGMS and the WMO Space programme of a Strategy Towards an Architecture for Climate Monitoring from Space and an inventory of ECV data records;
- the ESA Climate Change Initiative, which is structured around a set of ECVs and took GCOS requirements as the starting point for its own review of user requirements;
- the EUMETSAT Strategy, which for climate monitoring involves responding to requirements for climate data records expressed by GCOS;
- the Framework for Ocean Observing, which built on the concept of Essential Climate Variables to develop the concept of a set of Essential Ocean Variables and provides alignment for the GOOS programme.

Although many specific activities in terrestrial observation relate to IP-10, the lack of support for a functioning GTOS Secretariat and Steering Committee discussed in the response to IP-10 Action T1 on page 281 has meant there has been an absence of overarching planning for the terrestrial domain that draws on IP-10.

C2: Develop national coordination and plans

Action: Designate national coordinators and/or committees, achieve national coordination, and produce national plans for contributions to the global observing system for climate in the context of this Plan.

Who: Parties, through the national representatives to GCOS Sponsor Organizations and designated GCOS National Coordinators.

Time-Frame: Urgent and ongoing.

Performance Indicator: Number of GCOS National Coordinators and/or national coordination committees in place.

Annual Cost Implications: 1-10M US$ (70% in non-Annex-I Parties).

It was noted in section 3.1 that 26 countries had designated National Coordinators (NCs) by May 2015, a modest increase over the number of 23 NCs in place five years earlier.

The national coordination that exists in some countries is evident in various ways. Examples include the provision of promotional material such as the video prepared on the Swiss national programme available from http://www.meteoswiss.admin.ch and the inventory report on German Climate Observing Systems available from http://www.gcos.de. Other national coordinating and support activities can be found from national websites such as those for the UK (http://www.ukeof.org.uk) and the USA (http://www.gosic.org/gcos/USGCOS.html), or in the reporting under UNFCCC guidelines discussed below in the review of Action C4.

The GCOS Secretariat was unsuccessful in its application to ICSU in 2012 for funding of a workshop for NCs and interested parties which would have allowed an exchange experience and formulation of a strategy for improving the functioning and numbers of NCs.

The Seventeenth World Meteorological Congress in 2015 restated the urge to WMO Members to establish GCOS National Committees and identify GCOS National Coordinators in order to facilitate coordinated national action on observing systems for climate, taking into account the joint international sponsorship of GCOS and the evolving international arrangements for GEOSS and GFCS.

C3: Review the projects contained in RAPs and update and revise the RAPs as necessary

Action: Review the projects contained in RAPs for consistency with this Plan and update and revise the RAPs as necessary.

Who: Regional organizations and associations in cooperation with the GCOS Secretariat and the bodies responsible for the component observing systems.

Time-Frame: 2011.

Performance Indicator: Implementation strategy meetings held and number of RAP projects implemented.

Annual Cost Implications: 1-10M US$ (90% in non-Annex-I Parties).

Limited availability of Secretariat support and funding for the required meetings has restricted progress on this action. Explicit review of the RAP projects and development of updated plans has been carried out only for South America. The GCOS Secretariat and the International Research Center on El Niño (CIIFEN), with the financial support of the Swiss Government through MeteoSwiss, the Spanish Government through the Spanish Climate Change Office (OECC), and the Spanish Meteorology Agency (AEMET), designed and organized a Regional Workshop that was held in Ecuador in March 2012 (GCOS, 2012a). As part of the preparation for the workshop, an evaluation of the status and implementation of the eleven projects contained in the 2004 GCOS RAP for South

America was undertaken (GCOS, 2012b). One general conclusion was that while none of the projects had been implemented as an identified direct result of being included in the RAP, national efforts driven by several institutions, circumstances, and initiatives had made progress on several of the topics covered by the projects, and thereby had contributed to the overall GCOS Programme. The workshop itself identified recommended actions for three sectors: risk management, agriculture and food security, and water resources. It also developed recommendations concerning coordination and follow-up, resource mobilization, data management, surface and upper-air meteorological networks, hydrological networks, UV radiation monitoring, ocean observations, training and capacity building, and climate services and the demonstration of socio-economic development.

Regional workshops on climate observation have been held under auspices other than GCOS. Two examples are a WMO workshop on Climate Monitoring including the Implementation of a Climate Watch System in RA I with focus on eastern and southern Africa (WCDMP, 2013) and a GFCS Observation Workshop for Central Asia held in Kyrgyzstan in September 2015 organized in the framework of the Swiss Capacity Building and Twinning for Climate Observing Systems (CATCOS) project.

C4: Report to the UNFCCC on systematic climate observations

Action: Report to the UNFCCC on systematic climate observations using current guidelines.
Who: Parties with the UNFCCC.
Time-Frame: Conforming with UNFCCC guidelines.
Performance Indicator: Number of Parties reporting within specified timeframes.
Annual Cost Implications: 1-10M US$ (70% in non-Annex-I Parties).

This action is achieved in part because all Annex-1 countries submitted their sixth national communications to the UNFCCC in either 2013 or 2014, and communications have also been submitted by a number of non-Annex-1 countries over the past three years. Reports can be found at http://unfccc.int/national_reports/items/1408.php. However, the extent to which guidelines for reporting on systematic observation have been followed in detail has been variable. A few countries have produced separate reports available from the GCOS website that provide considerably more information, following the guidelines, than in their sixth communications. The separate report from Japan lists responses to several IP-10 actions, for example.

A summary of the sixth national communications prepared by the UNFCCC Secretariat is reproduced in Appendix 2, starting on page 306. Although the quantitative information provided by some countries in their communications has not been used in this report because corresponding information is not provided for many countries, the reports have nevertheless provided some useful inputs on particular matters. This includes some explanatory information on budgetary constraints. Overall, the picture given in the summary contained in Appendix 2 is in tune with what is presented in this report from the viewpoint of the overall status of ground-based observing networks and satellite systems.

C5: Ensure process for sustained operation of research-based networks and systems

Action: Ensure an orderly process for sustained operation of research-based networks and systems for ECVs.

Who: All organizations operating networks contributing to GCOS.

Time-Frame: Continuous.

Performance Indicator: Number of sustained networks and systems.

Annual Cost Implications: Covered in domains.

Progress on this action has been mixed. The discussions of satellite systems given in section 3.4 provide examples of orderly transitions for several types of instrument and observation. They include both an expansion of the type of observation made from operational meteorological satellites and the establishment of the operational Sentinel satellites of the Copernicus programme. In both cases the new operational capabilities replace or expand types of measurement previously provided from research platforms. The same transition from research to operations can be seen in the arrangements for the provision of products. However, despite these considerable successes no way has been found for the sustained operation of atmospheric limb sounding called for in IP-10, and there is uncertainty over how new observational capabilities will be sustained once they have been demonstrated by current and planned research missions to have a potential role to play in climate monitoring. Here the development of processes such as the CEOS virtual constellations and the strategy towards an architecture for climate monitoring from space are steps that should contribute to sustainable future operations.

An example of an orderly sustaining of operation of *in situ* measurement is that of the Argo network to which some 30 countries contribute floats, with funding provided by a mix of research and operational agencies (http://www.argo.ucsd.edu/Organisation.html). Other countries have provided important assistance with deployments. Argo has been sustained since reaching its design target of 3000 floats in 2007 and is now being expanded towards more than 4000 floats including coverage of marginal seas and measurement of a wider range of variables, as discussed in chapter 5. Orderly processes for the operation of the GRUAN have been established as discussed in section 4.4.4 and the review of Action A16. The TPOS 2020 Project is an orderly process working towards a sustainable Tropical Pacific Observing System, but grew out of a disorderly though subsequently reversed decline in the state of the tropical mooring network in the eastern Pacific. The EU Infrastructure supporting atmospheric observing programs such as ICOS or IAGOS in the long-term has considerably improved sustainability of some ECV observation in Europe. Other elements of the observing system remain funded by a series of research grants that are especially exposed to non-renewal in case of budgetary difficulties, although long-term observing programmes and databases have also not been immune from the effects of funding cuts or redistributions.

C6: Ensure all climate observing activities adhere to the GCMPs

Action: Ensure all climate observing activities adhere to the GCMPs.

Who: Parties and agencies operating observing programmes, including calibration undertaken in collaboration with national metrology institutes.

Time-Frame: Continuous, urgent.

Performance Indicator: Extent to which GCMPs are applied.

Annual Cost Implications: Covered in domains. See C8 for satellite component.

The GCOS Climate Monitoring Principles, the GCMPs, comprising the original ten basic principles and an additional ten related to observations from space, are set out in full in Appendix 7 on page 338. It is important that climate observing activities seek to adhere to them. Action C6 is a broad action that comprises elements that are addressed in many places in the body of this report and in many of the reviews of IP-10 Actions contained in this Appendix. In general the set of additional principles related to space-based observation have been followed to a greater or lesser extent. It is less easy to be specific as to the degree of adherence to the original basic principles, though the persistence of data-poor regions in *in situ* networks and shortfalls in data numbers for several types of observation are evidence of a continuing need for better observance of some principles.

There has been growing collaboration with national metrological institutes. A workshop held jointly by WMO and the International Bureau of Weights and Measures has drawn up sets of recommendations relating to coordination of metrological services for the meteorological community, the development of guidelines and operating procedures, research and development, and inter-community knowledge transfer (WMO, 2010b). Metrological considerations play an important role in defining GRUAN activities, in the cal/val of satellite data and in the measurement of trace gases in the atmosphere. The GCOS programme was represented at a meeting of representatives of national metrological institutes held at the UK National Physical Laboratory (NPL) in February 2013 to define the existing and emerging metrology challenges associated with Low Carbon and Climate Science. A conference was hosted by NPL in May 2015, bringing together representatives from international research organizations, to investigate and prioritise the role that metrology should play in supporting the robust measurement of ECVs, reported at http://www.npl.co.uk/news/npl-hosts-metrology-for-climate-meeting. Continuing European collaboration in Metrology for Earth observation and climate is reported at http://www.meteoc.org/index.html.

C7: Support implementation in developing countries

Action: Support the implementation of the global observing system for climate in developing countries and countries with economies in transition through membership in the GCOS Cooperation Mechanism (GCM) and contributions to the GCOS Cooperation Fund.

Who: Parties (Annex-I), through their participation in multinational and bilateral technical cooperation programmes, and the GCM.

Time-Frame: Immediately and continuous.

Performance Indicator: Resources dedicated to climate observing system projects in developing countries and countries with economies in transition; number of Parties contributing to the GCM.

Annual Cost Implications: Covered in the domains.

The GCM was established to identify and make the most effective use of resources available for improving climate observing systems in developing countries, particularly to enable them to collect, exchange, and utilize data on a continuing basis in pursuance of the UNFCCC. Since 2005, the GCM has received and distributed over 3 million USD in support of the GCOS networks, primarily in the atmospheric domain: the GCOS Surface Network (GSN) and GCOS Upper-Air Network (GUAN). A list of the GCM projects undertaken since 2010 is given in Table 4.

There has nevertheless been a significant reduction in the donations to the GCOS trust fund since 2010. Many of the GCOS sponsors have limited resources available to support International projects and in some cases are choosing a bi-lateral strategy direct with the recipient countries, or supporting new initiatives such as the GFCS. Thus the GCM has limited funds to support new projects, whether arising from requests by countries and or from identification of key gaps by monitoring. This has resulted in an expanding list of candidate projects. The success of the GCM is also dependent on the role of the GCOS Implementation Manager, a position that initially was supported part-time by the USA, but more recently has been filled through a full-time secondment supported by the UK.

Date	Beneficiary	Donor and funding	Nature of support
2010	Cook Islands	Japan 100k USD	Renovations for the Pukapuka and the Penrhyn GSN stations
2011	Angola	Netherlands 50k USD	Support and new instrumentation for the surface climate observations network
2011	Tanzania	Switzerland 100k USD	Provision of upper-air equipment, Radiosondes and Balloons for the operations of the Dar Es Salam GUAN station, one sounding per day
2011	Sudan	Switzerland and Japan 100k USD	Provision of upper-air equipment, radiosondes and balloons for the operations of the Khartoum GUAN station, one sounding per day
2011 (Jun)	Madagascar	Netherlands 310k USD	Upgrade of 11 GSN stations
2011 (Dec)	Democratic Republic of Congo	Netherlands 125k USD	Supply, installation and training for 2 AWS systems at GSN stations, including communication link to HQ
2012 (Apr)	Armenia	Japan 50k USD	Provision of balloons and radiosondes for the operations of the Yerevan GUAN station, one sounding per day

2012 (May)	Zambia	Netherlands 69k USD	Supply, installation and training for telecommunication equipment
2011-2012	Cook Islands	Japan 100k USD	Provision of balloons and radiosondes for the operations of the Rarotonga GUAN station, one sounding per day
2012 (Dec)	Maldives	UK 77k USD	Provision of balloons and radiosondes for the operations of the Gan GUAN station, one sounding per day
2013 (Apr)	Ecuador	GCM funds 5k USD	Replacement power supply unit for the hydrogen generator system at the San Cristobal GUAN station
2013-2015	Armenia	Japan 125k USD	Provision of balloons and radiosondes for the operations of the Yerevan GUAN station, one sounding per day
2014-2015	Africa – RA 1	Greece 33k USD	Contract with consultant based in Zimbabwe to work on projects in the Region, scoping visits to priority countries and data/network issues
2015 (Feb)	Zimbabwe	Germany 22k USD	Repair, service and local staff training for the hydrogen generator system at the Harare GUAN station
2015 (Mar)	Maldives	UK 25k USD	Repair, service and local staff training for the hydrogen generator system at the Gan GUAN station
2015 (In planning)	Maldives	Japan 25k USD	Provision of balloons and radiosondes for the operations of the Gan GUAN station
2015 (In planning)	Armenia	Japan 50k USD	Provision of balloons and radiosondes for the operations of the Yerevan GUAN station, one sounding per day

Table 4: Projects undertaken through the GCM with implementation from 2010 to 2015

C8: Ensure continuity and over-lap of key satellite sensors, and related data processing

Action: Ensure continuity and over-lap of key satellite sensors; recording and archiving of all satellite metadata; maintaining appropriate data formats for all archived data; providing data service systems that ensure accessibility; undertaking reprocessing of all data relevant to climate for inclusion in integrated climate analyses and reanalyses, undertaking sustained generation of satellite-based ECV products.

Who: Space agencies and satellite data reprocessing centres.

Time-Frame: Continuing, of high priority.

Performance Indicator: Continuity and consistency of data records.

Annual Cost Implications: Covered in the domains.

The substantial progress made on this multi-faceted action is covered by the discussion given in section 3.4, supplemented by the many references to the space-based component of the overall observing system that are made in discussing the status of observation of individual ECVs in chapters 4, 5 and 6. Not all that is needed has been achieved, however.

C9: Achieve adoption of GCOS dataset and product guidelines, and comparison of products

Action: Achieve adoption of the GCOS dataset and product guidelines; critical comparison of datasets/products and advice on product generation for all ECVs by the climate community.

Who: Parties' national agencies, working with key international coordination bodies, such as CEOS, GEO, IGBP, and IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA), and coordinated through GCOS and WCRP.

Time-Frame: Wide adoption by 2011 and ongoing.

Performance Indicator: Level of adoption of guidelines; number of datasets stating adoption of guidelines; number of ECVs for which routine intercomparison arrangements are in place.

Annual Cost Implications: 1-10M US$ (20% in non-Annex-I Parties).

The GCOS dataset and product guidelines were published in 2010 in updated form (GCOS, 2010b). The first step in promotion of their adoption was a workshop on evaluation of global climate-related datasets held with WCRP one year later (GCOS, 2011b). Products for eight ECVs derived from space-based data were evaluated against the guidelines, and an inventory structure that built on the guidelines was developed for characterising datasets. A prototype inventory (http://ecv-inventory.com) has since been established under CEOS, CGMS and the WMO Space Programme, with entries based on answers to a questionnaire to space agencies concerning their products. Further resources need to be devoted to develop the inventory for use; this remains on the agenda of the CEOS-CGMS Joint Working Group on Climate. Extension to add products based on in *situ* data has been considered, but further action has still to be taken.

One of the published GCOS guidelines is "Application of a quantitative maturity index if possible". This rather general wording reflected the emerging state of the formal assessment of the maturity of data records at the time, reported subsequently by Bates and Privette (2012). Considerable progress since then has been made on system maturity assessment by the Copernicus preparatory project CORE-CLIMAX, as reported by Schulz (2015).

Providing inventory entries does not of itself guarantee that guidelines have been followed, but the completeness of entries for a particular product and comparison with those for alternative products should prompt good practice. Much of the product generation and provision of products by or in partnership with space agencies does largely follow GCOS guidelines and principles, but there is progress that remains to be made. For example, strict version identification is problematic even for some of the main global surface temperature datasets, as the values a user downloads can change according to the month of download due to incorporation of late arriving data, even in the absence of a more major change of input such as the move to a different source of SST analysis for GISTEMP in January 2013. Although a time stamp in the dataset name or header information does provide for unique identification, users commonly fail to report the versions of the datasets they use to obtain their published results. The IPCC's Fifth Assessment Report contains many examples of this.

C10: Prepare datasets for analysis and reanalysis

Action: Prepare the atmospheric, oceanic, terrestrial and cryospheric datasets and metadata, including historic data records, for climate analyses and reanalyses.

Who: Parties with Data Centres (e.g., WDCs), working together with technical commissions and the scientific community, especially the joint WOAP/AOPC Working Group on Observational Datasets for Reanalysis and the ACRE collaborative initiative.

Time-Frame: Now and ongoing.

Performance Indicator: New or improved datasets available for analysis or reanalysis.

Annual Cost Implications: Covered in domains.

AOPC and the now-defunct WCRP Observations and Assimilation Panel (WOAP) set up their joint Working Group on Observational Data Sets for Reanalysis in 2007, but the Group failed to make substantial progress and has now been disbanded. There have, however, been numerous successful activities that have enhanced the datasets used in analysis and reanalysis. They include recovery of radiosonde data, the combination of this type of data from several sources and the refinement of data homogenization as detailed in section 4.4.5. There has been continued enhancement of the ICOADS collection of surface marine data and of the ISPD collection of surface pressure data. Feedback on quality issues with some of these data has been provided by their use in reanalysis. Collections of monthly land-station data for use in long-term direct analyses of temperature anomalies and calculations of global-mean surface temperature have also been enhanced, as illustrated in section 4.3.1, moves have been made towards more prompt reporting of such data, and there has been progress in accounting for biases in the formation of corresponding analyses of sea-surface temperature. Action to improve data on lying snow is discussed in the review of Action T15. The situation is also quite healthy with regard to past satellite data, for which there has been a continuation of reprocessing efforts, including now for data from US geostationary platforms as well as those from Europe and Japan (section 4.5.2). For ocean reanalysis, collections of temperature and salinity profile data have been enhanced, and sea-level anomaly data from satellite altimetry are being utilised from the early 1990s onwards.

Progress still has to be made on combining collections of surface synoptic data, particularly prior to 1973, as discussed in sections 3.5 and 3.7 and in the review of Action A12. Notwithstanding progress on particular collections of data for ocean reanalysis, the production of a combined reference dataset remains to be achieved, as discussed in the review of Action O28.

Reanalysis also requires input data on atmospheric composition and surface emissions, to extents that depend on the how comprehensive a model is used in the data assimilation. Here the work undertaken in the CMIPs to prepare input for climate-model simulations provides much of what is needed. Reanalysis also makes use of other datasets; atmospheric reanalysis benefits from datasets on terrestrial ECVs related to albedo and vegetation, for example. Non-ECV data such as on terrain height and bathymetry are also needed from time to time as models are refined. Such requirements apply also for the models used for climate simulation, prediction and projection. This is a further application for Digital Elevation Models, discussed in section 6.3.6 in the context of glacier monitoring.

C11: Establish sustainable systems for the routine and regular analysis of the ECVs

Action: Establish sustainable systems for the routine and regular analysis of the ECVs, as appropriate and feasible, including measures of uncertainty.

Who: Parties sponsoring internationally-designated analysis activities, with guidance from WCRP, IGBP and IPCC.

Time-Frame: Now and ongoing

Performance Indicator: Quality and range of analyses of the ECVs.

Annual Cost Implications: Covered in domains.

Generation of data products is being carried out routinely for an increasing number of ECVs, with occasional upgrades of production systems and reprocessing. This is the case for both single-ECV products and for the products derived from reanalysis. The status of the latter is covered in the following review of Action C12. Production is for the most part carried out by agencies with operational mandates, or by agencies that are not strongly dependent on short-term research funding, though the funding for generating products based on satellite data may be tied to the funding of particular missions.

Examples for *in situ* data include the sustained monthly production of datasets on surface air temperature over land and sea surface temperature that are combined and used to estimate global-mean surface temperature (section 4.3.1), and on precipitation such as the GPCC monitoring product (section 4.3.5). The recently introduced routine production of the HadISDH family of monthly surface air humidity products (section 4.3.3) currently occurs on an annual basis.

Development of a number space-based data products for the ECVs is carried out on a project basis, but the engagement of operational agencies in some of these projects offers a route to sustained generation for products demonstrated to be of merit. Alternatively, another institution may take over the generation of a mature product to ensure it is sustained, as happened in the move of responsibility for ISCCP to NCEI (Action A23) and is envisaged to occur as Copernicus services become fully operational.

Increasing attention is being paid to providing estimates or indicators of uncertainty. Measures of uncertainty are provided, for example, for a number of the latest versions of *in situ* data products made available by the Met Office Hadley Centre, and for the new products of the ESA CCI. Assimilation of wind data derived from imagery from geostationary satellites has long benefitted from the availability of data providers' quality flags in making decisions on data use. The type of information provided can vary substantially from product to product; it may relate, for example, to uncertainty in either the instantaneous state of the ECV or its multi-decadal variability. Estimation of uncertainty remains a challenge.

C12: Establish a sustained capacity for global climate reanalysis and ensure coordination

Action: Establish a sustained capacity for global climate reanalysis and ensure coordination and collaboration among reanalysis centres.

Who: National and international agencies.

Time-Frame: Continue ongoing activity but with climate trends better addressed by 2014, and expansion into coupled reanalysis by 2016.

Performance Indicator: Reanalysis centres endowed with long-term and coordinated programmes; cyclical flow of products of improving quality and widening range.

Annual Cost Implications: 10-30M (Mainly Annex-I Parties)

Global reanalysis activities for atmosphere and ocean have been sustained by the principal producing centres since IP-10, both through extension of existing production streams and through new products. The newer reanalyses tend to be produced using systems with higher horizontal, vertical and temporal resolution as well as other refinements of the assimilating model and observational analysis that enable them to assimilate new types of observation whose use was precluded or sub-optimal in earlier reanalyses.

Comprehensive global atmospheric analyses that are currently running are ECMWF's ERA-Interim (Dee *et al.*, 2011), JMA's JRA-55 (Kobayashi *et al.*, 2015; replacing JRA-25 (Onogi *et al.* 2007) in January 2014), NASA/GMAO's MERRA (Rienecker *et al.*, 2011; soon to be superseded by MERRA-2) and NOAA/NCEP's CFSR (Saha *et al.*, 2010). Unlike other centres, NOAA/NCEP continue also to extend earlier products: their original NCEP/NCAR and NCEP/DOE reanalyses. JRA-55 runs from 1958 onwards, the other newer products from 1979. JRA-55 is accompanied by a version that does not include the assimilation of satellite data (JRA-55C; Kobayashi *et al.*, 2014) and an AMIP-type integration, which is a run of the assimilating model in which the only use of observations is implicit in prescribed sea-surface temperatures and other boundary and forcing fields. Reanalyses have also been run over the 20th century and more, by NOAA/CIRES assimilating only surface-pressure observations (Compo *et al.*, 2011; latest version V2c from 1851 onwards) and by ECMWF assimilating marine surface wind as well as surface pressure observations (Poli *et al.*, 2013). Each have accompanying AMIP-type integrations.

Reanalysis has become important also for the oceans, for purposes such as monitoring, forecast calibration and understanding the role of the ocean in the climate system, addressing for example the key issue for climate variability and change of the extent to which heating of the oceans is distributed between upper and deeper layers (Balmaseda *et al.*, 2013; Figure 73). Although ocean reanalysis lacks the very large user base that exists for atmospheric reanalysis, the list of current ocean reanalyses provided at https://reanalyses.org/ is longer than that for global atmospheric reanalyses. The six ocean reanalyses referred to in section 3.6 that are currently being extended in near-real time and compared at http://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html are from Australian, European, Japanese and US institutions.

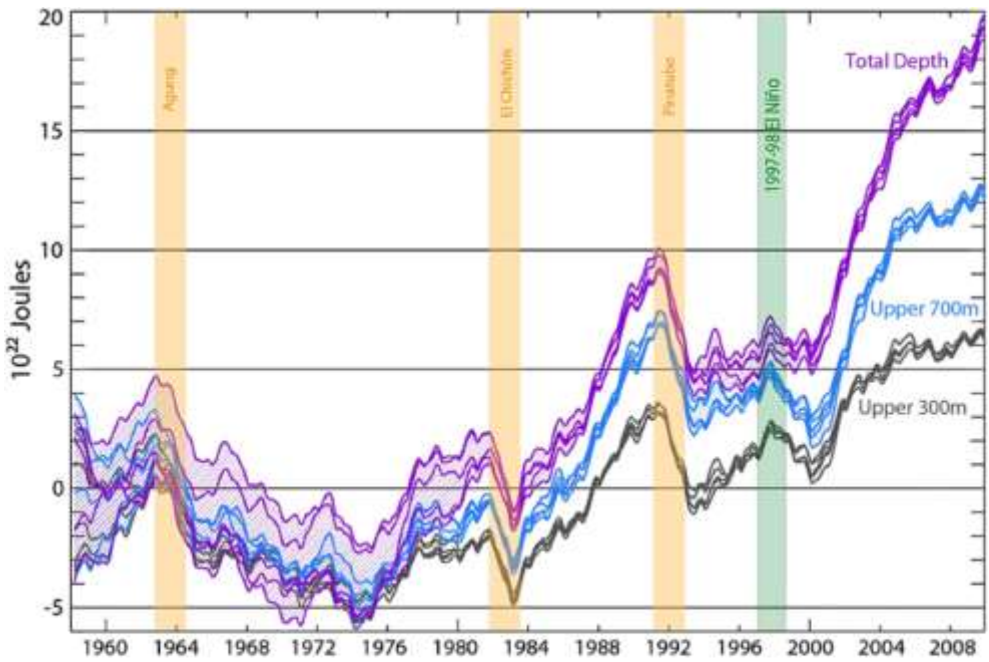


Figure 73: Heat content of the upper 300 m (grey), the upper 700 m (blue) and the total depth (violet) of the ocean from the five ensemble members of the ORAS4 reanalysis. The time series show twelve-month running mean anomalies with respect to the 1958–1965 base period. The vertical coloured bars indicate two-year intervals following major volcanic eruptions and the 1997–98 El Niño event. Differences in the spread among ensemble members indicate lower uncertainty in the results for recent years and upper layers. Source: Balmaseda et al. (2013).

The CFSR is a coupled atmosphere-ocean reanalysis, with coupling occurring through the background forecasts of the data assimilation system, with sea surface temperature prescribed for the atmospheric model from a separately produced analysis to which the upper level of the ocean model was relaxed as part of the ocean analysis. MERRA-2 includes aerosol species, while a separate shorter reanalysis for greenhouse and reactive gases as well as aerosols has been undertaken by ECMWF and partners in preparation for Copernicus (section 4.7).

Future European production of global reanalyses will be sustained under Copernicus. ECMWF will soon begin production of ERA5, an atmospheric reanalysis that will replace ERA-Interim, and ORAS5, a replacement for its ocean reanalysis ORAS4. Coupled atmosphere-ocean reanalysis is another activity being undertaken in preparation for Copernicus. A new Japanese reanalysis, JRA-3Q, is being planned with the aim of starting production in FY2018.

Coordination and collaboration have continued at many levels, ranging from the Fourth WCRP International Conference on Reanalysis held in 2012, through workshops held under various auspices to bi-lateral institutional cooperation, EU projects and informal contacts between members of what is still a relatively small group of producers. The WCRP Data Advisory Council and WOAP before it, the WCRP/CLIVAR Global Synthesis and Observations Panel, and AOPC have overseen activities. Inter-comparison of ocean reanalyses is discussed in the review of Action O39.

C13: Collect, digitize and analyse historical data records

Action: Collect, digitize and analyse the historical atmospheric, oceanic and terrestrial data records from the beginning of instrumental observations in a region and submit to International Data Centres.

Who: Parties, working through the WMO Commission on Climatology (CCl), the WMO Commission for Hydrology (CHy), other appropriate coordinating bodies (e.g., the GTOS Secretariat), the appropriate national agencies, and designated International Data Centres.

Time-Frame: Continuing.

Performance Indicator: Data receipt at designated International Data Centres.

Annual Cost Implications: 10-30M US$ (60% in non-Annex-I Parties).

The review of this action item is covered by the discussion given in section 3.7.

C14: Improve data holdings in international data centres

Action: Improving data holdings in International Data Centres (IDCs).

Who: IDCs to send details of their data possessions to each of the Parties. The Parties to respond back to the IDCs about the quality and quantity of the data and ensure that the IDCs hold all available data.

Time-Frame: Complete by 2014.

Performance Indicator: Percentage of responses from Parties.

Annual Cost Implications: 10-30M US$ (60% in non-Annex-I Parties).

Progress is marked as moderate as data holdings in international data centres have continued to improve, as documented in domain-specific chapters of this report and in associated reviews of IP-10 actions where relevant. IP-10 proposed a specific dialogue for this action, however. A systematic survey of international data centres has not been undertaken to ascertain the precise status of their contacts with national data holders, but feedback from centres that are proactive in requesting data submissions indicates a mixed response, ranging from the setting up of arrangements for automatic updating of data holdings to blunt rebuffal.

C15: Undertake research initiatives to acquire high-resolution proxy climate data

Action: Undertake research initiatives to acquire high-resolution proxy climate data by extending spatial coverage into new regions, extending temporal coverage back in time and exploiting new sources.

Who: Parties' national research programmes in cooperation with WCRP and IGBP.

Time-Frame: Continuing.

Performance Indicator: Reports in scientific literature.

Annual Cost Implications: 10-30M US$ (60% in non-Annex-I Parties).

Chapter 5 of the Working Group I contribution to IPCC AR5 (Masson-Delmotte *et al.*, 2013) identified major progress since AR4 in the acquisition of new and more precise information from palaeoclimatological data acquisitions, the synthesis of regional information and new simulations carried out using the same models as used for the reported climate projections. Ice-core records of the concentrations of the well-mixed greenhouse gases have been extended back from 650 to 800 thousand years ago, and the temporal resolution of records has been increased. There has been further development of geological proxies that extend CO_2 estimates back much further in time, though with lower confidence. New records of past depositions of mineral-dust aerosols have been obtained from deep-sea sediments as well as ice cores. A variety of other recent data acquisitions has provided to a more comprehensive view of the dynamics of monsoon systems on various time scales. New results from high-resolution coral records indicate that the El Niño-Southern Oscillation (ENSO) system has been highly variable throughout the past 7000 years, and geological data together with ice-sheet-model simulations suggest that the West Antarctic ice sheet is very sensitive to sub-surface warming of the Southern Ocean, implying with medium confidence a retreat of the West Antarctic ice sheet if atmospheric CO_2 concentrations stay within or above the 350 to 450 ppm range for several millennia.

C16: Improve synthesis of proxy climate and environmental data

Action: Improve synthesis of proxy climate and proxy environmental data on multi-decadal to millennial time scales, including better chronologies for existing records, particularly from the Tropics, Asia, the Southern Hemisphere and the Southern Ocean.

Who: Parties' national research programmes in cooperation with WCRP and IGBP.

Time-Frame: Continuing.

Performance Indicator: Reports in scientific literature.

Annual Cost Implications: 10-30M US$ (80% in non-Annex-I Parties).

A "2k Network" of participants in the IGBP core project PAGES, which also has a scientific partnership with WCRP, focusses its research effort on the past one to two thousand years. The network comprises nine regional groups covering all continents, the oceans and the Arctic. In 2013 it published reconstructions of continental-scale temperature variability over the last two millennia for seven regions; the oceans and Africa were not included. A long-term cooling trend up to the late 19th century was the most coherent feature. Temperature variability showed distinct regional patterns at multi-decadal to centennial scales, and there was no globally synchronous multi-decadal warm or cold intervals that define a worldwide Medieval Warm Period or Little Ice Age. The records on which these reconstructions were built have been archived at the World Data Center for Paleoclimatology.

IPCC AR5 concluded that the period 1983–2012 was very likely the warmest 30-year period of the last 800 years for the northern hemisphere, and likely the warmest 30-year period of the last 1400 years. This statement was supported by comparison of instrumental temperatures with reconstructions, and was consistent with AR4.

AR5 also reported on new surface temperature reconstructions for periods further in the past. Multi-millennial cooling trends extended over the past 5000 years. Reconstructions and simulations of the warmest millennia of the last interglacial period (129,000 to 116,000 years ago) showed with medium confidence that global mean annual surface temperatures were never more than 2K higher than immediately pre-industrial values. Reconstructions and simulations for several periods showed polar amplification, a stronger response at high latitudes than in global averages to changes in atmospheric greenhouse-gas concentrations.

C17: Preserve proxy climate and environmental data in archival databases

Action: Preserve proxy climate and proxy environmental data (both the original measurements as well as the final reconstructions) in archival databases.

Who: World Data Centre for Paleoclimatology in cooperation with national research programmes.

Time-Frame: Continuing.

Performance Indicator: Completeness of archival databases and availability of data to the research community through International Data Centres.

Annual Cost Implications: 1-10M US$ (30% in non-Annex-I Parties).

Out of the 21030 data records held by the World Data Centre for Paleoclimatology at the end of 2014 (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets), 1080 had been acquired that year. Acquisitions, including reconstructions, in immediately preceding years were 540 in 2013, 369 in 2012 and 319 in 2011. 450 were acquired for the period from 5 March 2010 to the end of that year. Figure 74 shows the locations of data records.

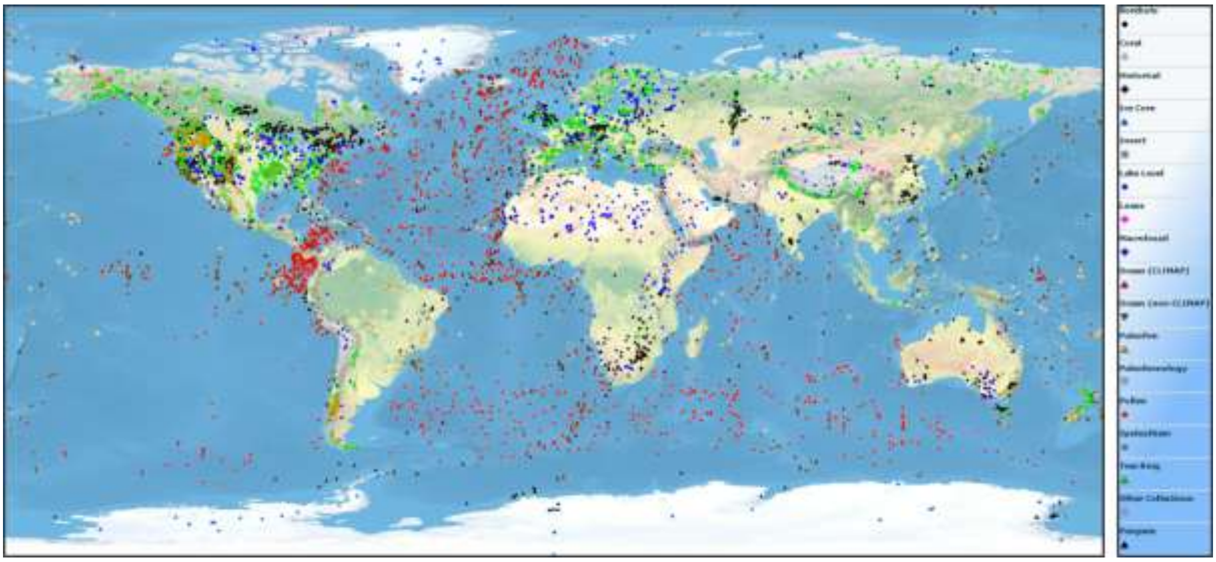


Figure 74: locations of data records (excluding reconstructions) held at the World Data Centre for Paleoclimatology. Source: NOAA, map generated at http://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=paleo&theme=paleo.

C18: Apply standards and procedures for metadata and its storage and exchange

Action: Apply standards and procedures for metadata and its storage and exchange.

Who: Operators of GCOS related systems, including data centres.

Time-Frame: Initial implementation of the operational WIS and GEOSS systems is occurring in 2010, implementations will be ongoing thereafter.

Performance Indicator: Number of ECV related datasets accessible through standard mechanisms.

Annual Cost Implications: <1M US$ (20 k US$ per data centre) (10% in non-Annex-I Parties).

The Seventeenth World Meteorological Congress approved the WIGOS Core Metadata Standard in May, 2015. The standard is intended to cover all the needs of WMO programmes, including those related to climate. It is evidently too soon to expect this general standard to have been applied. Lack of progress on overall standards for terrestrial observation is discussed in section 6.2.1 and in the review of the corresponding IP-10 Action T1.

Notwithstanding the limited pace or lack of progress on general standards, the discussions of domain-specific ECVs and the related IP-10 actions provide several instances of progress with regard to standards and metadata. Action A18, for example, discusses how the move to use BUFR rather than alphanumeric code to represent data for transmission provides the opportunity for operators of observing sites to provide much more metadata within the transmitted records of individual radiosonde ascents. However, the move to BUFR encoding has not been without problems (Action A17), and it is too early to assess the improvement in transmission of metadata that has resulted.

C19: Support data flow from national to international data centres

Action: Ensure national data centres are supported to enable timely, efficient and quality-controlled flow of all ECV data to International Data Centres (other than the very large satellite datasets that are usually managed by the responsible space agency). Ensure timely flow of feedback from monitoring centres to observing network operators.

Who: Parties with coordination by appropriate technical commissions and international programmes.

Time-Frame: Continuing, of high priority.

Performance Indicator: Data receipt at centres and archives.

Annual Cost Implications: 10-30M US$ (70% in non-Annex-I Parties).

It is difficult to assess in general how well national data centres are supported with resources to enable transfer of data to international data centres, or how restricted they are in what they can deliver to such centres by the national data policies imposed upon them. There are examples of good practice and increases in the holdings of international data centres, but the overall situation is unclear. Further discussion relating to the assessment of the situation regarding data policy is given in the following review of Action C20.

A system of WMO CBS monitoring centres is in place for synoptic meteorological data. A list of the nine centres that fulfil this role showing the variables for which they are responsible can be found at https://www.wmo.int/pages/prog/www/DPS/Monitoring-home/mon-leadcentre.htm. Centres report routinely at six-monthly intervals, but may make statistics available online in near-real-time. The monthly CLIMAT reports that are transmitted on the GTS are scrutinised by the GSN Monitoring Centres operated by DWD and JMA, who provide feedback both to data providers through a set of CBS Lead Centres for GCOS (http://www.wmo.int/pages/prog/gcos/index.php?name=CBSLeadCentres) and to AOPC through annual reports. Further discussion is given in section 4.2.2.

Statistics on data holdings, including recent data receipts, are provided by a number of the international data centres; examples are presented in several places elsewhere in this report. Some others provide annual reports, again as illustrated in this report. Monitoring of satellite data is discussed in section 3.4.5.

C20: Ensure that data policies facilitate the exchange and archiving of all ECV data

Action: Ensure that data policies facilitate the exchange and archiving of all ECV data.

Who: Parties and international agencies, appropriate technical commissions, and international programmes.

Time-Frame: Continuing, of high priority.

Performance Indicator: Number of countries adhering to data policies favouring free and open exchange of ECV data.

Annual Cost Implications: 1-10M US$ (70% in non-Annex-I Parties).

Several countries have adopted more-open data policies since IP-10 was published. The data policy for Copernicus is an open one, and many data products generated under other auspices are freely available. Nevertheless, much climate-relevant data remains restricted by national data policies, and even when not restricted in this way, data may not be transmitted promptly to international data centres or centres producing products in close to real time, as illustrated elsewhere in this report.

A complete picture of national data policies is not readily available. In agreeing a resolution on the WMO policy on the international exchange of climate data and products to support the implementation of the GFCS, the Seventeenth World Meteorological Congress in 2015 requested the Secretary General of WMO to undertake a global survey and analysis of WMO Members' various data policies and models of service provision, identifying successful strategies and best practices.

C21: Implement modern distributed data services

Action: Implement modern distributed data services, drawing on the experiences of the WIS as it develops, with emphasis on building capacity in developing countries and countries with economies in transition, both to enable these countries to benefit from the large volumes of data available world-wide and to enable these countries to more readily provide their data to the rest of the world.

Who: Parties' national services and space agencies for implementation in general, and Parties through their support of multinational and bilateral technical cooperation programmes, and the GCM.

Time-Frame: Continuing, with particular focus on the 2011-2014 time period.

Performance Indicator: Volumes of data transmitted and received by countries and agencies.

Annual Cost Implications: 30-100M US$ (90% in non-Annex-I Parties).

The main activity related to this action has been the implementation of the WMO Information System itself (Figure 75). The fundamental structure of the WIS is now in place, with fifteen Global Information System Centres (GISCs) either operational or close to being so. A total of 374 centres had been registered as of 4 June 2015, comprising Data Collection or Production Centres (DCPCs) and National Centres (NCs) as well as the GISCs. Regional Implementation Plans and supporting structures have been established. Actual implementation remains to be achieved in many countries, however.

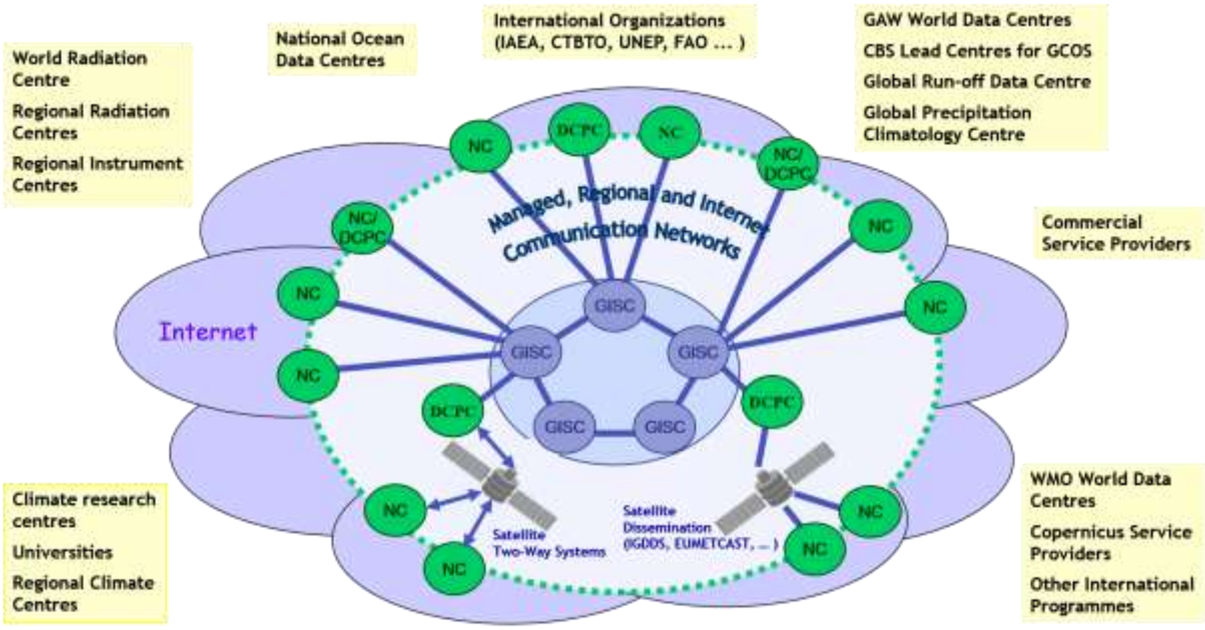


Figure 75: Structure of the WMO Information System (WIS). Communication with the external institutions shown in the yellow boxes is through real-time push and on-demand pull mechanisms. Source: WMO.

C22: Develop guidelines for observations and data exchange to support impact assessments

Action: Develop and publish guidelines for undertaking observational studies in support of impact assessments and to ensure that data policies facilitate the exchange and archiving of all impact-relevant observational data.

Who: IPCC TGICA, GTOS and IGBP.

Time-Frame: 2011.

Performance Indicator: Guideline published.

Annual Cost Implications: <1M US$ (10% in non-Annex-I Parties).

There has been an apparent lack of activity on this subject by the bodies envisaged to be involved. The IPCC Task Group on Data and Scenario Support (TGICA), in its report to the 40th Session of the IPCC held in October 2014, listed seven items of technical guidance and factsheets for which documents were in different stages of development. None related explicitly to guidelines for observational studies in support of impact assessments. GTOS lacks a functioning secretariat and steering committee (see also review of action T1). IGBP has published a report dated May 2012 entitled “The Merton Initiative: Towards a Global Observing System for the Human Environment” but its stated requirements are very general, much more so than those of IP-10. The IGBP will close at the end of 2015, and it is not evident that Future Earth, which will absorb ongoing IGBP projects, will engage in the type of observational support called for in this action.

C23: Promote recognition of need for guidelines and definition of new impact-related ECVs

Action: Encourage recognition by scientific funding bodies of the need to consider guidelines for the conduct of observational impact studies, and encourage the definition of new impact-related ECVs.

Who: Parties and ICSU

Time-Frame: 2011 (Achieve improved recognition).

Performance Indicator: Availability of supporting data; proposals for new ECVs.

Annual Cost Implications: 1-10M US$ (50% in non-Annex-I Parties).

The absence of progress in developing guidelines reported with regard to Action C22 inhibits recognition by funding bodies of the need to consider such guidelines. Funding bodies have, however, been receptive to the general concept of the ECVs, and definition of new impact-related ECVs is one way that progress may be instigated.

Efforts have been made towards defining impact-related ECVs, or at least recognising impact-related variables as being essential to observe in other frameworks. The vehicle for defining new ECVs is the Implementation Plan to succeed IP-10 that GCOS is developing for publication in 2016, for which this Status Report is a foundational document. In preparation, the GCOS programme has held two workshops (GCOS 2013, 2015) related to adaptation. The workshops reviewed the adequacy for adaptation of the ECVs, or at least of the adequacy of the specifications for their observation, and identified several areas that could benefit from reconsidering or broadening of the ECVs or development of sector-specific climate variables to complement the ECVs.

Two such sector-specific developments, for which input was provided by the GCOS programme, are relevant in this context. One is the introduction of Essential Ocean Variables (EOVs) in the Framework for Ocean Observing (Lindstrom *et al*., 2012). The other is the introduction of Essential Biodiversity Variables (Pereira *et al*., 2013) discussed further in the review of Action T4. In both cases there is scope for inclusion of variables related to impacts and adaptation that are in addition to those that fall in the set of ECVs, and which in due course could be recognised as additional ECVs.

Atmospheric actions

A1: Improve the availability of near real-time and historical GSN data

Action: Improve the availability of near real-time and historical GSN data.

Who: National Meteorological Services, in coordination/cooperation with WMO CBS, and with advice from the AOPC.

Time-Frame: Continuous for monitoring GSN performance and receipt of data at Archive Centre.

Performance Indicator: Data archive statistics at WDC Asheville and National Communications to UNFCCC.

Annual Cost Implications: 10-30M US$ (70% in non-Annex-I Parties).

The general character of the GCOS Surface Network, the GSN, is discussed in section 4.2.2. The number of stations designated to be part of the GSN rose from 987 in 2001 to 1017 in 2014, but some of the original stations no longer operate. NCEI statistics from http://gosic.org of data held in its Monthly Climatic Data for the World archive show CLIMAT reports from 2001 onwards for 803 of the stations in the 2014 list. For these stations, Table 5 shows the overall annual completeness of NCEI's holdings of CLIMAT data, and the corresponding completeness of holdings for each WMO region. Although completeness of CLIMAT records rose substantially in earlier years, it has been steady or declined a little over the past five years, despite an increase in reporting of synoptic data by these stations over this period. The exception is Antarctica, where reporting of CLIMATs rose to a completeness level of 98% in 2014.

	All stations	Region I Africa	Region II Asia	Region III S America	Region IV N America C America Caribbean	Region V SW Pacific	Region VI Europe	Antarctica
Stations	803	135	212	84	114	133	102	23
2001	69	46	69	75	87	73	74	52
2002	73	51	72	81	90	73	82	51
2003	74	51	73	81	92	75	83	60
2004	75	48	79	70	94	77	88	50
2005	78	54	86	76	95	75	88	57
2006	81	52	91	82	95	76	92	63
2007	83	56	91	84	97	82	93	72
2008	85	59	93	84	97	82	97	78
2009	88	64	93	90	97	85	98	86
2010	87	62	92	95	95	85	98	89
2011	85	56	92	92	97	83	96	89
2012	85	60	91	94	97	80	94	85
2013	86	60	92	96	98	78	93	92
2014	85	59	91	91	96	84	91	98

Table 5: Number of monthly CLIMAT messages per year expressed as a percentage of the maximum possible number, accumulated from 803 current GSN stations for which NCEI presents archive statistics back to 2001. Accumulations for the stations within each WMO region are also shown.

A2: Obtain further progress in the systematic international exchange of surface data

Action: Obtain further progress in the systematic international exchange of both hourly SYNOP reports and monthly CLIMAT reports from the WWW/GOS RBSN.

Who: National Meteorological Services, in cooperation/coordination with WMO CBS, WMO CCl, WMO RAs, and WMO WWW.

Time-Frame: Continuous, with significant improvement in receipt of RBSN synoptic and CLIMAT data by 2014.

Performance Indicator: Data archive statistics at WDC Asheville.

Annual Cost Implications: 1-10M US$ (60% in non-Annex-I Parties).

Progress in the exchange of hourly SYNOP reports and related data is discussed and illustrated in sections 4.2 and 4.3 of this report, and additional information is given in the review of Action A12 concerning the exchange of water-vapour data (page 229).

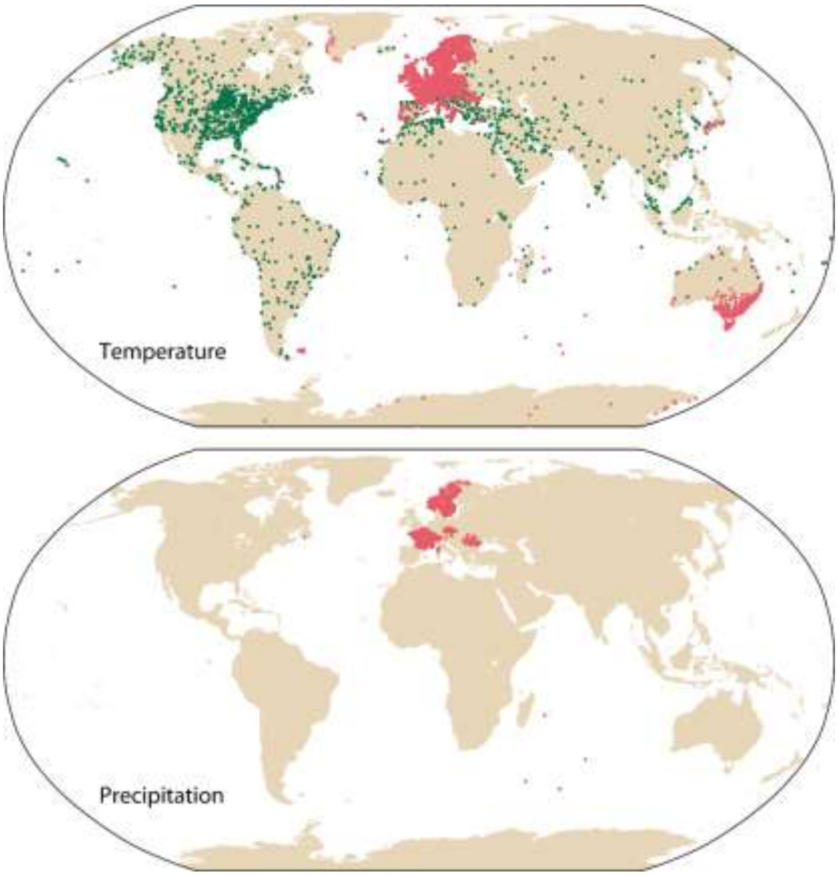


Figure 76: Distribution of surface synoptic data as received operationally by ECMWF in SYNOP (red) or METAR (green) code on the GTS for the intermediate hours of 01, 02, 04, 05, 07, 08, 10, 11, 13, 14, 16, 17, 19, 20, 22 and 23UTC in October 2014. Plots are based on stations reporting dry bulb temperature (upper) and precipitation over the past hour (lower). A symbol is plotted for each 0.5 degree latitude/longitude grid box that contains at least 90% of the maximum possible data from a single station for the month. SYNOP locations mask nearby or coincident METAR locations.

One further aspect of the international exchange of hourly SYNOP reports concerns the national and regional variations in the sources of data that can be received from the GTS. This is illustrated in Figure 76 for ECMWF's receipts of reports for temperature and hourly accumulation of precipitation. There is substantial coverage of hourly temperature data in SYNOP reports from much of Europe, but also from Japan, Australia, Greenland, Antarctica and isolated stations with territorial links with

European countries. Broader international coverage is provided by METAR reports. Hourly precipitation data come in SYNOP reports from a smaller set of European countries and from five overseas French territories: four islands in the southern Indian Ocean and St Pierre and Miquelon south of Newfoundland. Whilst in some cases lack of coverage may be due to the hourly observations not being made, they are known to be made in other cases. For the latter, lack of data supply is likely due to national or regional policies for exchange of hourly data on the GTS, although there could also be some issues in the routing of messages within the GTS.

Figure 77, like Table 5 above, is based on NCEI statistics from http://gosic.org of CLIMAT data held in its Monthly Climatic Data for the World archive. It shows monthly counts of CLIMAT records from the WWW/GOS stations as a whole and from the subset of stations that forms the GSN. Both current and formerly active GSN stations are included in this case. Counts are separated by WMO Region. They show marked regional variations in the proportion of CLIMAT data provided by non-GSN stations, with Europe providing the highest proportion, despite a decline over recent years in the number of CLIMATs provided by both its GSN and its non-GSN stations. Overall, there has been a slight increase in the proportion of data provided by non-GSN stations from around 65% or lower in earlier years to above 68% in the later months of 2014. Supporting efforts of the WMO Commission for Climatology include the promotion of climate database management systems to automate the generation of CLIMAT messages by NMHSs.

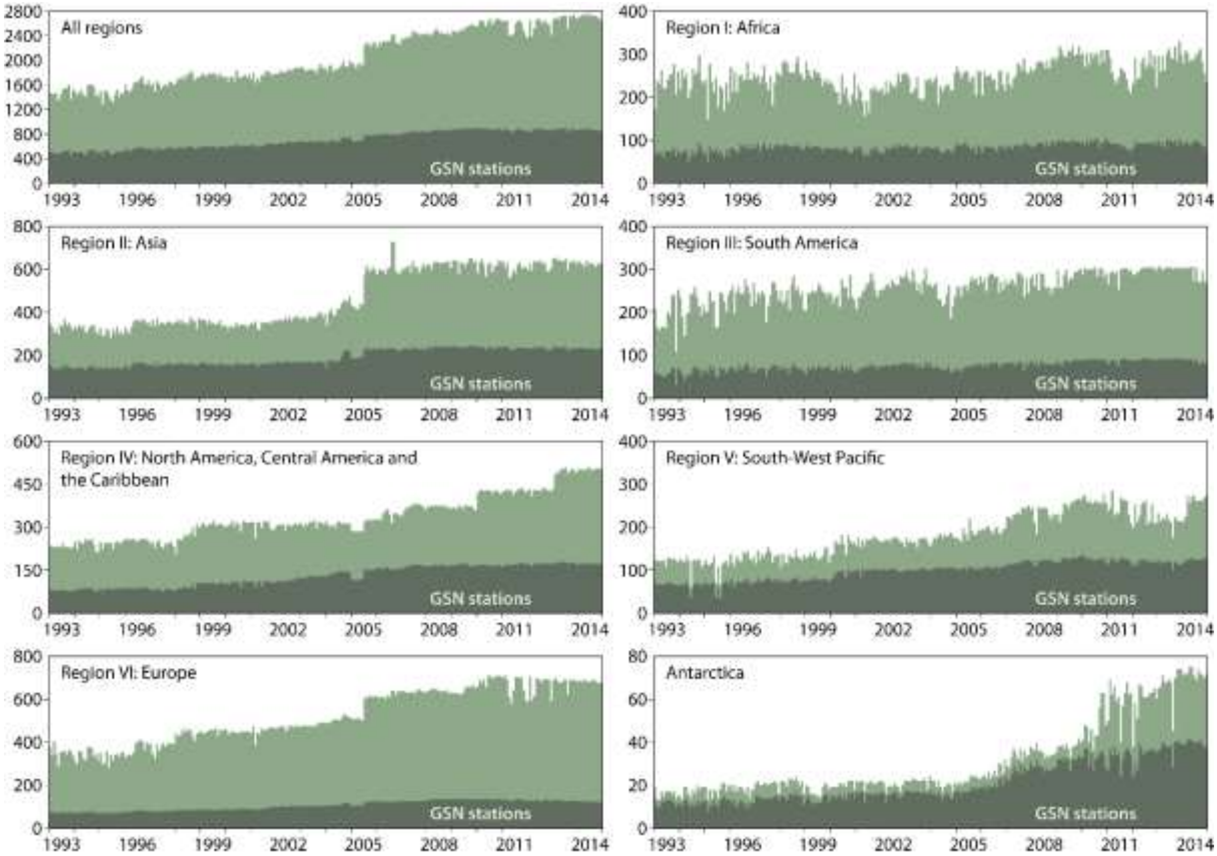


Figure 77: Number of CLIMAT records archived monthly by NCEI, from all stations and the GSN subset, summed over all WMO regions and for each region separately. Numbers are shown from 1993 to 2014. 1993 is the first year for which numbers are subsequently sustained.

A3: Sustain operation of surface stations addressing national and sub-national needs

Action: Ensure sustained operation of surface meteorological stations addressing national and sub-national needs, and implement additional stations where necessary; and exchange hourly SYNOP reports and monthly CLIMAT reports from all stations internationally.

Who: National Meteorological Services, in cooperation/coordination with WMO CBS, WMO CCl, WMO RAs, and WMO WWW.

Time-Frame: Full operation of all stations globally by 2015.

Performance Indicator: Data archive statistics at WDC Asheville.

Annual Cost Implications: 100-300M US$ (90% in non-Annex-I Parties).

Increased exchange of hourly SYNOP reports and monthly CLIMAT reports is discussed and illustrated in sections 4.2 and 4.3 of this report, and further information is given in the reviews of Action A2 above and A12 below. It may be inferred that the documented continuity and increases in geographical coverage and higher frequency of observation serve to meet some national and sub-national needs as well as international needs. Other data from surface meteorological stations that are made for national or sub-national purposes, including some made privately for commercial purposes, are not available internationally, because of either data policies or telecommunication issues. This makes it difficult to assess fully the extent to which progress has been made. Nevertheless, some of the persistent gaps in data coverage in maps such as presented in Figure 7 and Figure 11, the information provided in National Communications submitted by non-Annex-I Parties to the UNFCCC, and analysis such as presented in section 4.3 of the Report of the High-level Taskforce for the GFCS (WMO, 2011) all point to a continuing need for resourcing and implementation.

A4: Apply the GCMPs to all climate-relevant measurements from surface networks

Action: Apply the GCMPs to all measurements relevant for climate from surface networks.

Who: National Meteorological Services, in coordination with WMO CBS, WMO CCl, WMO RAs, and GCOS Secretariat.

Time-Frame: Continuous.

Performance Indicator: Quality and homogeneity of data and metadata submitted to International Data Centres.

Annual Cost Implications: 10-30M US$ (70% in non-Annex-I Parties).

This action is sub-component of the cross-cutting Action C6. As in the case of C6, it is an important action, but a broad one whose success or otherwise is difficult to assess in general. Other actions reviewed here and discussions in the body of the text relate to specific principles. The Technical Commissions of WMO continue to emphasize the importance of the GCMPs in their planning and guidance documents, and to foster actions that contribute towards implementation of specific principles.

A5: Implement guidelines for changing to automatic surface observation

Action: Implement guidelines and procedures for the transition from manual to automatic surface observing stations. Conduct expert review of the impact of increasing use of automatic stations on the surface climate data record.

Who: Parties operating GSN stations for implementation. WMO CCl, in cooperation with the WMO CIMO, WMO CBS for review.

Time-Frame: Ongoing for implementation. Review by 2014.

Performance Indicator: Implementation noted in National Communication.

Annual Cost Implications: 1-10M US$ (60% in non-Annex-I Parties).

This action was formulated following the publication in 2008 of guidelines and procedures by a WMO CBS Expert Team, as reported in GCOS (2009). Since then guidelines have also been published by WMO CCl and WMO CIMO.

Although there has been some progress in this general area, including improved instrumentation, application of quality-control procedures and within-country network monitoring, problems remain. The 2014 session of CIMO noted "ongoing difficulties being experienced by Members in operating automatic observing systems" and "requested its Management Group to develop a plan to revive the series of International Conferences on Experiences with Automatic Weather Stations in Operational Use within National Weather Services (ICEAWS), to be conducted in all Regions, in order to provide a forum for knowledge transfer between Members on the subject." This session of CIMO also recalled an earlier decision that "the CIMO Guide should include a chapter related to measurements and observations in Polar Regions, including measurements from automatic weather stations and agreed that this task would become one of the priorities of CIMO in the next intersessional period [2014-2018]."

Availability of metadata is key general requirement to enable observations from different instruments to be characterised and used in an optimal way. In the case of synoptic surface observations, data may be separated according to whether they are identified as coming from automatic or manual stations, and can be assessed against independent estimates provided by a reanalysis system. Figure 78 presents an example, comparing the fits of (unassimilated) surface air temperature observations to the ERA-Interim variational analysis, for data identified as coming from manual and automatic land stations located in the high Arctic, for each of the last three decades. It shows little bias in the fits of the data from manual stations to ERA-Interim, whereas the data from the automatic stations are biased warm compared with the reanalysis, though the bias decreases over time. Standard deviations of the fits also decrease over time, for both sets of observations. When reanalysis temperatures are very low, the automatic stations report temperatures with a large spread that are generally higher than reanalysis values; such a feature is not seen for the manual stations for the latest decade. Something of it can be seen for these stations for the earlier two decades, although this may be because some of the early reports from automatic stations were not identified as such. Possible effects of overall differences in the siting of manual and automatic stations also need to be kept in mind.

Expansion of this approach would be facilitated by improved availability of reanalysis feedback and metadata on instrumentation and siting.

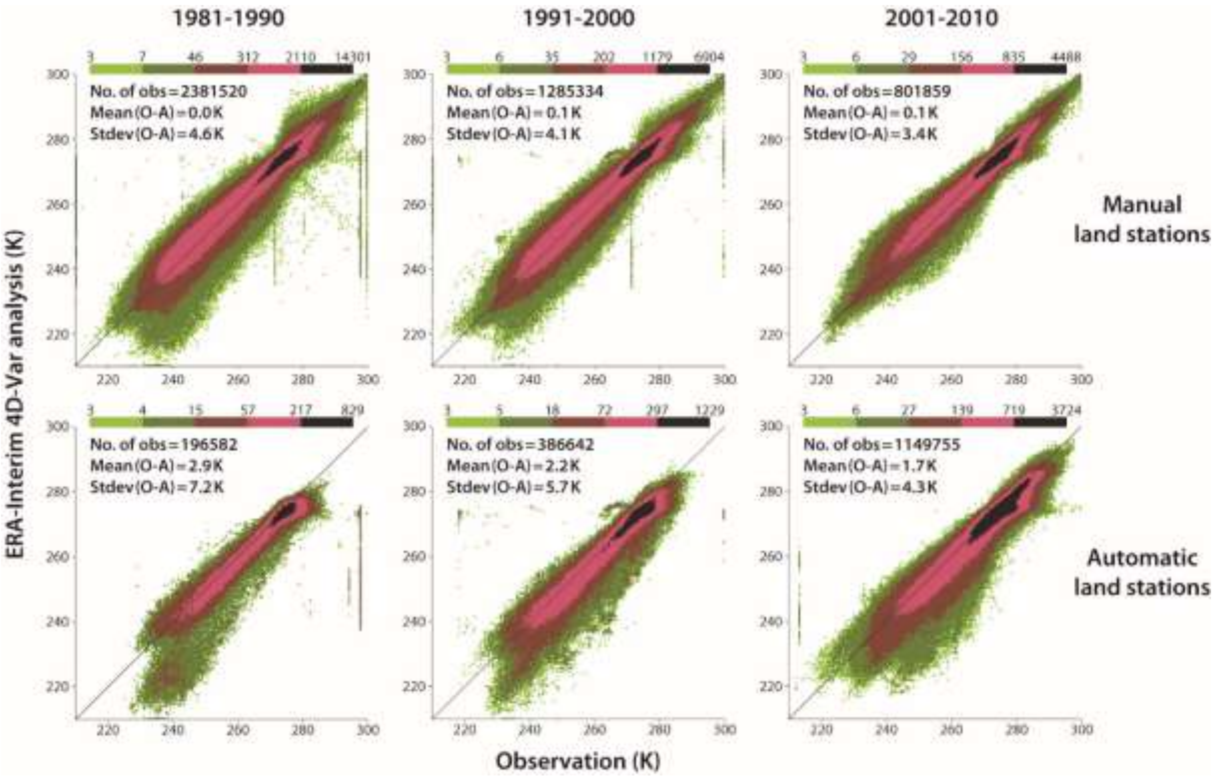


Figure 78: Scatter plots of ERA-Interim 4D-Var analysis and observed values of surface air temperature for observations located at latitudes north of 70^{O}N from 1981 to 1990 (left), 1991-2000 (middle) and 2001-2010 (right), for reports identified as from manual land stations (upper) and automatic land stations (lower). Colour shading indicates the density range of points within each 0.5 K square into which values have been binned; ranges are shown in the legend for each individual plot. Means and standard deviations of the differences between observations and analyses (O-A) are also shown. Values are obtained from the 4D-Var ERA-Interim data assimilation, which monitors but does not assimilate these types of observation. See also Simmons and Poli (2015).

A6: Incorporate atmospheric pressure sensors on drifting buoys routinely

Action: Seek cooperation from organizations operating drifting buoy programmes to incorporate atmospheric pressure sensors as a matter of routine.

Who: Parties deploying drifting buoys and buoy-operating organizations, coordinated through JCOMM, with advice from OOPC and AOPC.

Time-Frame: Complete by 2014.

Performance Indicator: Percentage of buoys with sea-level pressure (SLP) sensors.

Annual Cost Implications: <1M US$ (Mainly by Annex-I Parties).

GCOS (2009) reported that the percentage of drifting buoys equipped with atmospheric pressure sensors increased from around 30% in early 2003 to 50% in early 2009. Over this period the total number of buoys increased by around 20%. Specifically, 549 out of 1122 buoys (49%) had pressure sensors on 23 February 2009. Figure 79 shows the situation on 6 July 2015: 756 out of 1402 buoys, or about 54%, had pressure sensors. The net increase in surface-pressure measurements from drifting buoys received routinely by ECMWF is shown in Figure 16.

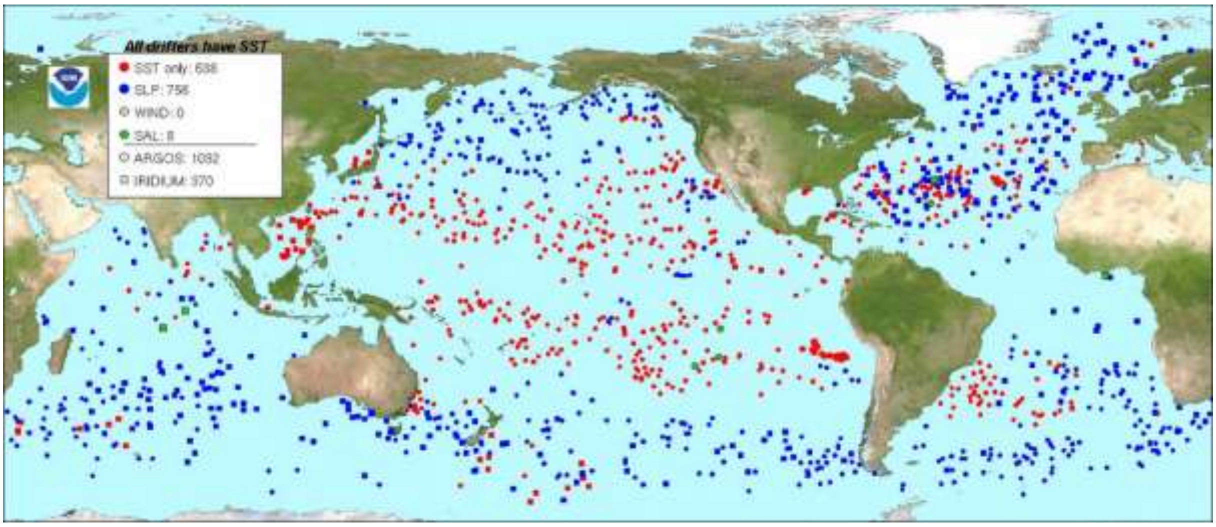


Figure 79 Distribution of 1402 drifting buoys on 6 July 2015, showing those equipped with surface-pressure, wind and salinity sensors, in addition to sensors for sea-surface temperature. Source: NOAA/AOML, downloaded from http://www.aoml.noaa.gov/phod/graphics/dacdata/.

The increase from 49 to 54% in the proportion of buoys fitted with atmospheric pressure sensors is only a modest one considering the relatively low cost of Action A6. Furthermore, the geographical distribution shown in Figure 79 reveals a dearth of buoys with pressure sensors in the tropical and sub-tropical Pacific, extending well beyond the equatorial region where surface-pressure data are of lower value. On top of this, the temporary drop-off in overall buoy numbers from 2011 to 2013 illustrated in Figure 16 has to be noted.

A7: Submit all precipitation data from national networks to international data centres

Action: Submit all precipitation data, including hourly totals where possible and radar-derived precipitation products, from national networks to the International Data Centres.

Who: National Meteorological Services, with coordination through the WMO CCl.

Time-Frame: Continuous.

Performance Indicator: Percentage of nations providing all precipitation data to the International Data Centres. Percentage of stations for which hourly data available.

Annual Cost Implications: 1-10M US$ (60% in non-Annex-I Parties).

Discussion of submission of precipitation data to the GPCC is given in section 4.3.5. Figure 80 and Figure 81 provide more detail in the case of data received by GPCC in close to real time from the GTS. Figure 80 shows an increase over time in the number of stations from which data are received in this way, particularly in the case of precipitation data received in SYNOP messages, which may report precipitation accumulated over the past one, three, six, twelve or 24 hours. The growth until 2011 in the number of stations providing monthly precipitation values in CLIMAT messages as reported here based on GPCC data receipts is very similar to that shown in Figure 77 based on the CLIMAT data holdings of NCEI.

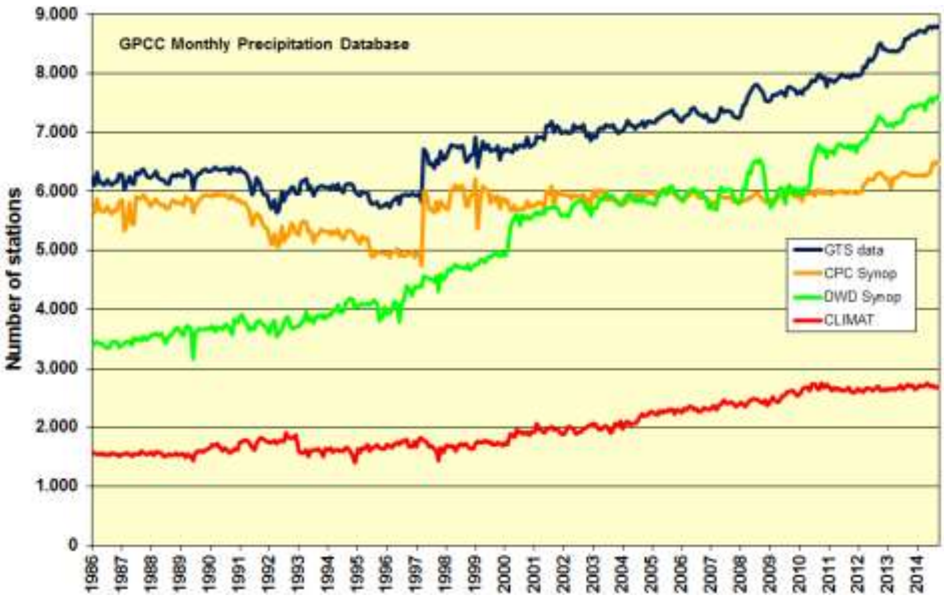


Figure 80: Variation since 1986 in the number of stations providing precipitation data via the WMO Global Telecommunications System (GTS) as accumulated in the monthly database of the GPCC at DWD (dark blue line), in the number of stations providing synoptic data on the GTS, as received directly by DWD (green) and as received by NOAA's Climate Prediction Center (CPC) and forwarded to DWD (orange), and in the number of stations providing monthly precipitation totals in CLIMAT messages (red). Figure reproduced with permission of DWD.

Figure 81 shows the geographical distribution of the stations from which GPCC received precipitation data via the GTS in October 2014 and used them in its Monitoring Product. It shows generally good global coverage of land areas, with variations in data coverage quite similar to that shown in Figure 7 for ECMWF's receipt of SYNOP temperature reports. Although gaps in coverage are largely the same, a better coverage of precipitation data over north-eastern Africa is evident. This is due to the additional coverage provided by CLIMAT reports from stations from which little or no data are received in SYNOP reports; the locations of those stations that report as part of the GSN can be seen in Figure 11. The CLIMAT data also contribute to better coverage elsewhere, notably over the USA, which transmits a relatively low density of SYNOP reports to Europe on the GTS, as is evident in Figure 7 for temperature and Figure 58 for snow depth.

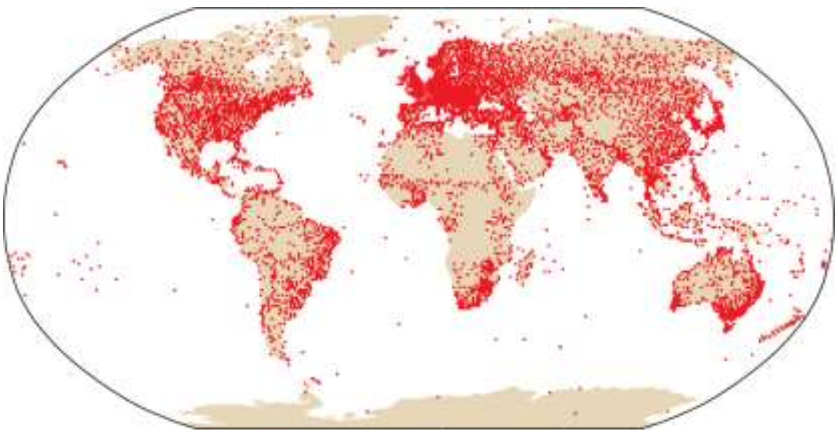


Figure 81: Distribution of the 5511 one degree latitude/longitude grid boxes that contain at least one station contributing GTS data used to produce the GPCC precipitation monitoring product with this resolution for October 2014. A total of 8798 stations contributed data.

Some progress has been made with respect to data with high temporal and spatial resolution, though much more remains to be achieved. Action A7 called for increased submission of hourly precipitation measurements to international data centres, where possible. ECMWF's GTS receipt of hourly data in October 2014 is shown in Figure 76 as part of the review of Action A2. Hourly precipitation data are included in the SYNOP reports from very few countries, although national datasets with hourly resolution are produced by other countries. With regard to surface radar data, NCEI has undertaken the reprocessing of data from the US NEXRAD network, and DWD has started reprocessing German radar data. The GEWEX Data Assessment Panel plans to revive an organised activity on the reprocessing of surface radar data, in particular to address the requirements of WCRP's Grand Challenge on Extremes. A Workshop on Radar Data Exchange, held in April 2013 under the auspices of WMO CBS, addressed harmonization of radar reflectivity formats and the gathering of requirements, including those of climate applications.

A8: Ensure continuity of satellite precipitation products

Action: Ensure continuity of satellite precipitation products.

Who: Space agencies.

Time-Frame: Continuous.

Performance Indicator: Long-term homogeneous satellite-based global precipitation products.

Annual Cost Implications: 10-30M US$ (for generation of climate products, assuming missions funded for other operational purposes) (Mainly by Annex-I Parties).

Production of datasets, including those merging satellite and rain-gauge data, and the homogeneity of what is produced have largely been maintained due to the commitments of agencies to support data reprocessing, including intercalibration, and to extend product generation to include data from new types of instrument. Extension of data records appears assured for the future due to the continuity of provision of VIS/IR data from the ring of operational geostationary satellites and of passive MW sounding data from operational polar orbiters. A more diverse set of platforms currently provides or are planned to provide passive MW imaging; long-term continuity is not as fully assured for this type of measurement. A more-than-seventeen-year data record from the TRMM precipitation radar came to an end in April 2015. A period of overlap exists between the tropical measurements provided by TRMM and the measurements provided by the precipitation radar on the GPM Core satellite launched in May 2014, which covers middle as well as tropical latitudes. Arrangements for long-term continuity of precipitation-radar measurements from space are not yet in place.

A9: Equip all reference moored buoys with precipitation-measuring instruments

Action: Equip all buoys in the Ocean Reference Mooring Network with precipitation-measuring instruments.

Who: Parties deploying moorings, in cooperation with JCOMM and OOPC.

Time-Frame: Complete by 2014.

Performance Indicator: Number of instruments deployed and data submitted to International Data Centres.

Annual Cost Implications: <1M US$ (Mainly by Annex-I Parties).

Action O5 of IP-10 called for completion of the definition of a Surface Reference Mooring Network as part of the OceanSITES Reference Mooring Network. As noted in the review of the action given on page 259, the Surface Reference Mooring Network (referred to in Action A9 as the Ocean Reference

Mooring Network) has yet to be fully established. Rainfall measurements are, however, already made from a number of buoys in the OceanSITES network, particularly in the Tropics. All surface moorings in the RAMA (Indian Ocean), PIRATA (tropical Atlantic Ocean) and TRITON (tropical western Pacific Ocean) arrays have rain gauges, and this is true of four of the TAO (tropical eastern Pacific Ocean) moorings also. The buoys deployed by the Woods Hole Oceanographic Institution in both the Tropics and middle latitudes, and by Météo-France in the Mediterranean, also measure precipitation. Such measurements are not made by the buoys deployed by Canada, Ireland and the United Kingdom. The JCOMM DBCP Task Team on Moored Buoys is working on an improved metadata collection system that should make such information readily accessible in the future.

A10: Improve methods for observing precipitation and deriving global products

Action: Develop and implement improved methods for observing precipitation and deriving global precipitation products that take into account advances in technology and fulfil GCOS requirements.

Who: Parties' national research programmes through WCRP, in cooperation with GCOS.

Time-Frame: Continuous.

Performance Indicator: Implemented methods; improved (in resolution, accuracy, time/space coverage) analyses of global precipitation.

Annual Cost Implications: 10-30M US$ (40% in non-Annex-I Parties).

Improved observations of precipitation from space are being made or are expected from new and planned missions. The GPM Core precipitation radar is more sensitive than the TRMM radar to light rain and snowfall and provides information on drop-size distribution. The accompanying MW imager includes high-frequency channels likewise providing information on light rain and snowfall. The GPM Core provides a basis for calibrating the data from precipitation-sensitive sensors on a constellation of other satellites. Two instruments under development for Metop-SG are the MWI microwave imager, which like GPM Core includes channels for light-rain and snowfall measurement, and the ICI instrument that will sense at higher frequencies still and provide data on hydrometeor profiles. Precipitation estimates from geostationary orbit will benefit from the higher spatial and temporal resolution and additional spectral bands of the next generation of operational imagers, the first of which to reach orbit is on the Japanese Himawari-8 satellite launched in October 2014.

Enhancement of ground-based observation includes the recent and ongoing introduction of dual-polarization radars that provide information on the type of precipitation and can distinguish precipitation from other airborne objects, including some such as dust and flying debris from tornadoes that are important in a weather forecasting context. Measurements of the attenuation of the MW signals used in commercial communication links has been demonstrated to have potential for providing additional data on rainfall over land, particularly where links are dense in urban areas. The WMO Solid Precipitation Intercomparison Experiment has been established to evaluate the performance of automatic sensors used to measure solid precipitation. Rain-gauge measurement by a large body of volunteers is by no means new – more than three thousand volunteers were active in the British Isles in the 19th century – but has been revitalised recently. The establishment of the CoCoRaHS network in North America, from which data have been included by NCEI in its GHCN-daily database since 2010, is a notable example. Further initiatives are underway in other regions, under the auspices of CCl and WIGOS.

There are many activities generating precipitation products, although most focus on near-real-time datasets. Fulfilment of GCOS requirements or guidelines is not systematically assessed, although information for some datasets is included in the inventory being developed by the CEOS/CGMS Working Group on Climate (see review of response to Action C9). Further discussion of products and their assessment is given in section 4.3.5.

A11: Ensure availability of wind products from AM- and PM-satellite scatterometers

Action: Ensure continuous generation of wind-related products from AM and PM satellite scatterometers or equivalent observations.

Who: Space agencies.

Time-Frame: Continuous.

Performance Indicator: Long-term satellite observations of surface winds every six hours.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

Data have been provided routinely from the mid-morning orbit by the European ASCAT instrument on Metop-A since soon after launch in October 2006. Data from 2007 to 2013 have been reprocessed using a calibration that was introduced for operational data in 2014. Metop-B has delivered data from a similar orbit since September 2012. Continuity of coverage from this orbit is expected from the ASCAT on Metop-C, due for launch later this decade, and then by the SCA instrument on Metop-SG.

Data from the Indian OSCAT scatterometer on OceanSat-2, launched into a noon orbit in September 2009, was utilised in operational numerical weather prediction prior to failure of the instrument in February, 2014. ScatSat-1 is planned as a gap-filling scatterometer mission from 2015, to be followed by a further scatterometer flight on OceanSat-3. Noon orbits are planned for these two new missions.

The Chinese HY-2A oceanographic satellite, the first in a series of four, currently provides data from a scatterometer in early-morning orbit. The WindRAD scatterometer on the future Chinese FY-3E and FY-3G meteorological satellites will enhance coverage of the early-morning orbit. It is unique among in-flight and planned instruments in offering both C- and Ku-band measurements, with two polarizations.

RapidScat, derived from the US SeaWinds instrument that operated on QuikScat from 1999 to 2009, is deployed in a non-sun-synchronous orbit on the International Space Station. The mission helps patch gaps in coverage, but is planned to operate for only a two-year period.

A12: Submit water vapour data to the International Data Centres

Action: Submit water vapour data from national networks to the International Data Centres.

Who: National Meteorological Services, through WMO CBS and International Data Centres, with input from AOPC.

Time-Frame: Continuing.

Performance Indicator: Data availability in analysis centres and archive, and scientific reports on the use of these data.

Annual Cost Implications: <1M US$ (60% in non-Annex-I Parties).

Increased submission of data relating to water vapour has occurred as part of the general increase in availability of data from synoptic networks discussed in sections 4.2 and 4.3. Specifically, for the sample months of October 2002 and October 2014 for which data locations and counts were shown in Figure 7 and Figure 8 respectively, the number of pairs of dry-bulb and dew-point temperature observations increased by 74% from 2002 to 2014 in the case of ISD (taking the hourly sampling provided by ISD-lite). The corresponding increase was by 80% in the case of data received operationally by ECMWF in SYNOP code. The percentage of observations of temperature that are accompanied by an observation of dew-point data has decreased a little, from 96% in October 2002 to 92% in October 2014 in the case of ISD, but increased slightly, from 97% to 98%, in the case of SYNOP data held by ECMWF.

Willett *et al*. (2014a) report on the use of water vapour data to construct the gridded HadISDH products, and discuss seasonal and interannual variability and trends over the period 1973-2013. Figure 82 shows the variation over time in the number of stations from which data are used in their analysis for specific and relative humidity, after quality control and homogenization. Numbers increase from 1973 until around 1990, and then remain steady until falling after 2005. Most of the fall is accounted for by reduced use of data from US stations, although these station nevertheless provided some 20% of the total count of a little over 3000 stations used monthly in 2013. ECMWF's six-hourly operational analysis of 2 m relative humidity currently uses data from some 9000 stations.

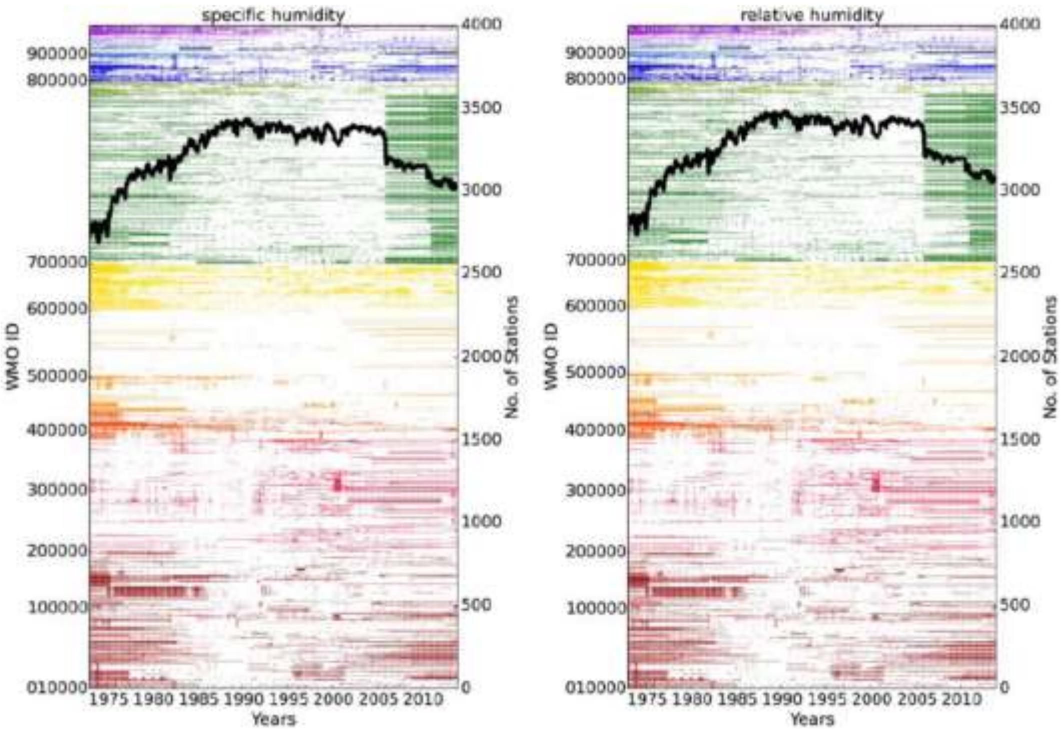


Figure 82: Number of stations (black lines; right-hand scale) from which data are selected for use to construct gridded products for specific (left) and relative (right) humidity, as a function of year. Also shown in colour are missing station months as a function of WMO ID (left scale). The colour coding denotes different geographical regions. Source: Willett et al. (2014a).

Low holdings of data in ISD prior to 1973 determined the starting year for HadISDH. Larger amounts of humidity data were assimilated in the ERA-40 reanalysis from September 1957 onwards. 94% of stations reporting dry-bulb temperature also reported dew-point temperature in October 1972, and on average more than 4850 stations per day reported both values at 12UTC. Some 200 fewer stations reported for 00UTC. For October 1957, 93% of reports of dry-bulb temperature included dew point temperature, with data available on average from a little under 3000 stations each day at 12UTC. The ERA-40 data holdings were amassed some fifteen years ago, largely from NCAR's holdings in the case of pre-1979 data; some of the national data gaps prior to 1967 noted by Uppala *et al*. (2005) may now be able to be filled due to data recovery efforts.

A13: Submit surface radiation data to the WRDC and expand radiometer deployments

Action: Submit surface radiation data with quality indicators from national networks to the World Radiation Data Centre (WRDC), and expand deployment of net radiometers at WWW/GOS surface synoptic stations.

Who: National Meteorological Services and others, in collaboration with the WRDC.

Time-Frame: Ongoing.

Performance Indicator: Data availability in WRDC.

Annual Cost Implications: 1-10M US$ (70% in non-Annex-I Parties).

Figure 83 shows the locations of the 1590 stations for which the World Radiation Data Centre held archive data for some period since January 1964, as of March 2014. This represents a significant increase on the figure of 1118 reported in GCOS (2009). Some data are held for most countries, with the largest exception occurring for several in South America. Coverage is densest for Western Europe.

The locations of stations reporting for the period from January 2013 to August 2014 (as of September 2014) are shown in Figure 84. The count of 395 stations is similar to the number of about 400 stations quoted in GCOS (2009). The volume of data received annually by the WRDC increased substantially between 2000 and 2001, but has remained quite steady since then, apart from a large increase in 2010 when Australia supplied a large amount of its archived data. Annual data accesses by users increased in number by a factor of about five from 2001 to 2009, after which they have been quite steady.

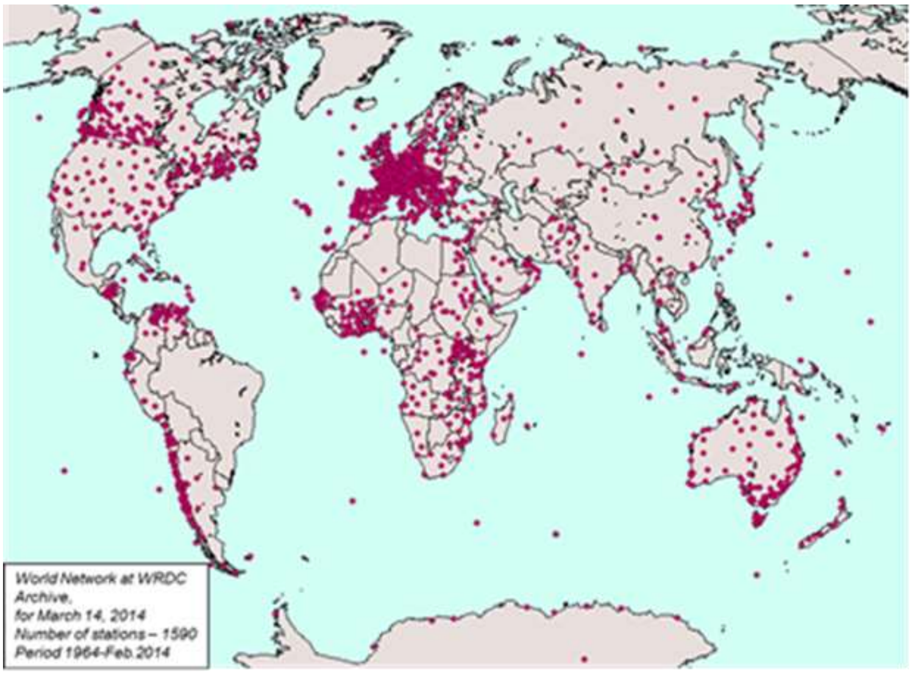


Figure 83: Distribution of the 1590 stations for which data were held by the World Radiation Data Centre for some part of the period from January 1964 to February 2014 as of 14 March 2014. Source: World Radiation Data Centre.

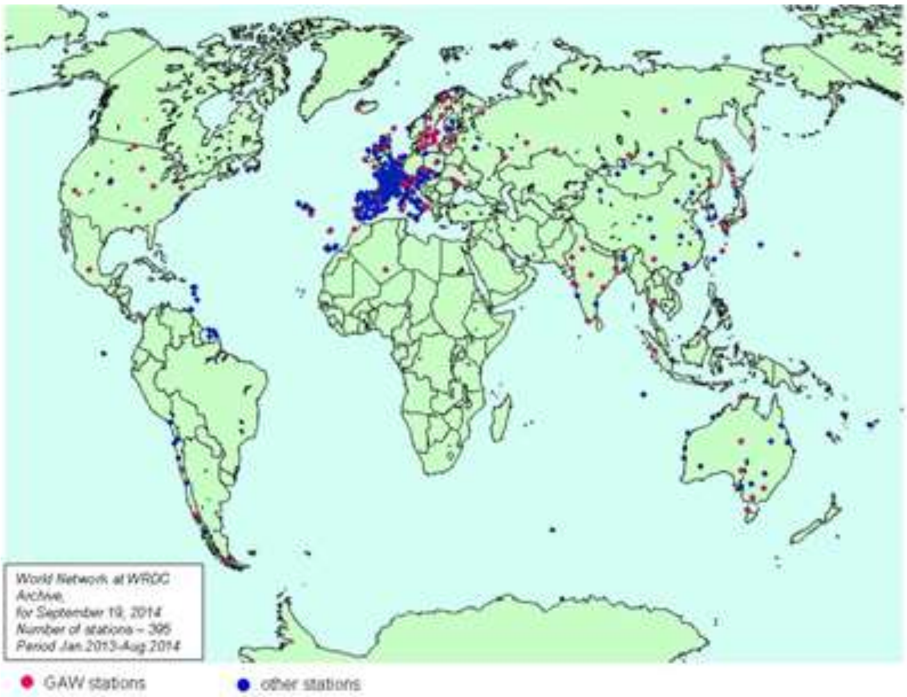


Figure 84: Distribution of the 395 stations for which data were held by the World Radiation Data Centre for some part of the period from January 2013 to August 2014 as of 19 September 2014. Source: World Radiation Data Centre.

A14: Ensure continued long-term operation of the BSRN and expand the network

Action: Ensure continued long-term operation of the BSRN and expand the network to obtain globally more representative coverage. Establish formal analysis infrastructure.

Who: Parties' national services and research programmes operating BSRN sites in cooperation with AOPC and the WCRP GEWEX Radiation Panel.

Time-Frame: Ongoing (network operation and extension); by 2012 (analysis infrastructure).

Performance Indicator: The number of BSRN stations regularly submitting data to International Data Centres; analysis infrastructure in place.

Annual Cost Implications: 1-10M US$ (20% in non-Annex-I Parties).

A coverage map and indication of a continuing increase in overall station numbers, despite some closures due to budgetary pressures, is discussed in section 4.3.6. Concerning data delivery, around a third of the stations provide values within six months of measurement time, but as of February 2015 twelve stations had delivered no data from 2010 onwards. The status of some of these stations is unknown. Not all stations follow the recommended BSRN quality-control checks, but an overall increase of data quality is clear from consistency checks of the measurements provided, which are presented at http://bsrn.awi.de/en/products/quality-code/comparisons.html in terms of annual station-by-station scatter plots for each year for which data are held.

Although network operation is subject to routine analysis such as reported above, a formal analysis of the BSRN data to estimate global fields would be problematic due to limitations in data coverage. Discussion is given in section 4.3.6 of the use of BSRN data together with model data to provide global estimates, and of the use of the BSRN data to evaluate global products derived from satellite data and reanalysis.

A15: Improve operation of the GUAN

Action: Improve operation of the GUAN, including infrastructure and data management.

Who: Parties operating GUAN stations, in cooperation with GCOS Secretariat and WMO CBS.

Time-Frame: Ongoing.

Performance Indicator: Percentage of data archived in WDC Asheville.

Annual Cost Implications: 10-30M US$ (80% in non-Annex-I Parties).

The general character of the GCOS Upper-Air Network, the GUAN, is discussed in section 4.4.3. The number of stations designated to be part of the GUAN rose from 150 in 2002 to 171 in 2014, but some of the original 150 no longer operate. NCEI's monitoring statistics accessible from http://gosic.org are available for 127 stations for each month from 2002 to 2014. Table 6 presents some annual averages. These statistics include not only radiosonde ascents, but also pilot-balloon ascents that provide only wind information.

Year	Ascents per day	Ascents per day at		Temperature data per ascent	Humidity data per ascent	Wind data per ascent	Percentage of ascents reaching at least	
		00UTC	12UTC				50 hPa	10 hPa
2002	1.65	0.66	0.68	33.4	26.5	45.0	74	28
2003	1.80	0.73	0.75	33.2	26.4	45.3	74	29
2004	1.75	0.74	0.74	35.0	27.8	47.6	77	31
2005	1.73	0.76	0.71	35.1	27.9	47.8	75	31
2006	1.71	0.74	0.70	36.6	29.5	50.2	75	35
2007	1.74	0.77	0.71	37.3	30.7	50.8	77	37
2008	1.69	0.75	0.69	38.4	31.8	52.6	78	38
2009	1.70	0.75	0.71	38.5	31.7	52.7	78	35
2010	1.74	0.75	0.72	41.5	34.5	55.4	79	37
2011	1.73	0.75	0.73	43.5	36.6	55.9	78	36
2012	1.70	0.75	0.73	44.1	37.1	56.7	77	35
2013	1.69	0.74	0.72	46.3	39.1	60.1	78	34
2014	1.69	0.74	0.73	46.4	40.0	60.3	78	37

Table 6: Average annual performance statistics of 127 GUAN stations for which NCEI presents monitoring results for each year from 2002 to 2014

Table 6 shows a small overall fall in the average number of ascents per day from each station since 2003. This is however accounted for mainly by a reduction in the relatively small number of stations that provide either a radiosonde or a pilot-balloon ascent four times a day. The number of ascents provided for 00UTC and 12UTC has changed little since 2003.

What has changed, and this is the case for the radiosonde network as a whole, is the number of temperature, humidity and wind values provided per ascent, with a proportionately larger increase for humidity than temperature, and for temperature than wind. A small factor is an increase in the average height reached by each ascent that took place early in the period, but the main reason is an increase in the reporting of data for significant levels. Improved performance of humidity sensors and the software that processes the raw measurements may have resulted in humidity data being reported for a larger part of the ascent.

The GCOS guide to the GUAN (and GSN) was updated in 2010 (GCOS, 2010c). As noted in the guide, there are no formal requirements on the accuracy of GUAN measurements beyond those expected of the WWW/GOS network as a whole (WMO, 2010a), although best practices for stations are set out (WMO, 2013). GCOS also held a workshop in 2014 to review, *inter alia*, the GUAN. The meeting (GCOS, 2014b) debated and reaffirmed the value of having a baseline radiosonde network. It concluded that although data coverage was important for the GUAN, attention should also be paid to data quality. It was proposed that GUAN data be actively monitored for quality and adherence, and that certification or designation be applied to sites that meet GUAN requirements.

A16: Continue implementation of the GCOS Reference Upper-Air Network

Action: Continue implementation of the GCOS Reference Upper-Air Network of high-quality radiosondes and other supporting observations, including operational requirements and data management, archiving and analysis.

Who: National Meteorological Services and research agencies, in cooperation with AOPC, WMO CBS, and the Lead Centre for GRUAN.

Time-Frame: Implementation largely complete by 2013.

Performance Indicator: Number of sites contributing reference-quality data for archive and analysis.

Annual Cost Implications: 30-100M US$ (20% in non-Annex-I Parties).

General discussion of the GRUAN and a map showing site locations are provided in section 4.4.4. Substantial progress has been made with implementation, though it is far from complete. The first product, for the Vaisala RS92 radiosonde, has been defined (Dirksen *et al*., 2014). All but three of the fifteen stations in the network in February 2015 made ascents and provided product data in 2014, though with varying frequencies and quality assessments (Figure 85).

Definitions of products for other types of radiosonde and the other measurement techniques employed by sites, noted in section 4.4.4, are under development. The established working practices include a gradual process of site certification. A Manual and a Guide for the GRUAN have been published jointly by GCOS and WIGOS. Material from these documents is expected to be incorporated into the WMO Manual on the Global Observing System and the corresponding WMO Guide.

Despite good progress on operational matters and associated science, progress has been modest in expanding the network to its target of 35 to 40 sites. GCOS (2009) reported on the selection of an initial set of 14 sites. This was increased by one soon afterwards. By February 2015 a further three sites had been added since, but three other sites, all in the Tropical West Pacific, could not be continued due to closure of activities by the US ARM programme. One of these sites, Darwin, has since announced its intention to join the network under the Australian Bureau of Meteorology, and a further six sites (four of them also under the Bureau of Meteorology) have likewise announced their intention to join. All are included in the network map shown in Figure 23. This marks an important step forward for the GRUAN, although there remains an absence of stations in mainland Africa and South America.

Network design and expansion criteria were developed at a workshop in 2012.

Figure 85: Quality assessment of data from Vaisala RS-92 radiosonde ascents made by 12 GRUAN stations in 2014. Results for one station are shown separately for manual and automatic launches. Coloured vertical lines represent ascents, with colour indicating the quality flag. Green denotes data that have been processed, passed all quality checks and archived at NCEI as GRUAN measurements. Yellow denotes data that have been processed but failed one or more of the strict GRUAN quality checks. Red denotes ascents that could not be processed or for which it is known that operational procedures were not followed completely. Source: DWD, adapted from a plot generated online at http://www.dwd.de/gruan.

A17: Improve the WWW/GOS radiosonde network, including use of BUFR coding

Action: Improve implementation of the WWW/GOS radiosonde network compatible with the GCMPs and provide data in full compliance with the BUFR coding convention.

Who: National Meteorological Services, in cooperation with WMO CBS and WMO RAs.

Time-Frame: Continuing.

Performance Indicator: Percentage of real-time upper-air data received in BUFR code with no quality problems.

Annual Cost Implications: 10-30M US$ (60% in non-Annex-I Parties).

Aspects of the improvement of the performance of the WWW/GOS radiosonde network are discussed in section 4.4.1, where Figure 20 compares geographical coverage and frequency of reporting for 2002 and 2014. Figure 86 presents monthly global observation counts of radiosonde temperature observations for mid-tropospheric and mid-stratospheric layers, from January 1979 to June 2015. Counts for other layers are reported by Simmons *et al*. (2014) for years up to 2012. The figure shows a generally improving situation over time, with a dip in the 1990s following dissolution of the Union of Soviet Socialist Republics, and a steeper increase between 2005 and 2010. The rise is larger in relative terms for the stratospheric layer. The annual variation that is more pronounced for the tropospheric layer, and becomes larger over time, is mainly due to variation in the amount of data reported at significant levels within the layer.

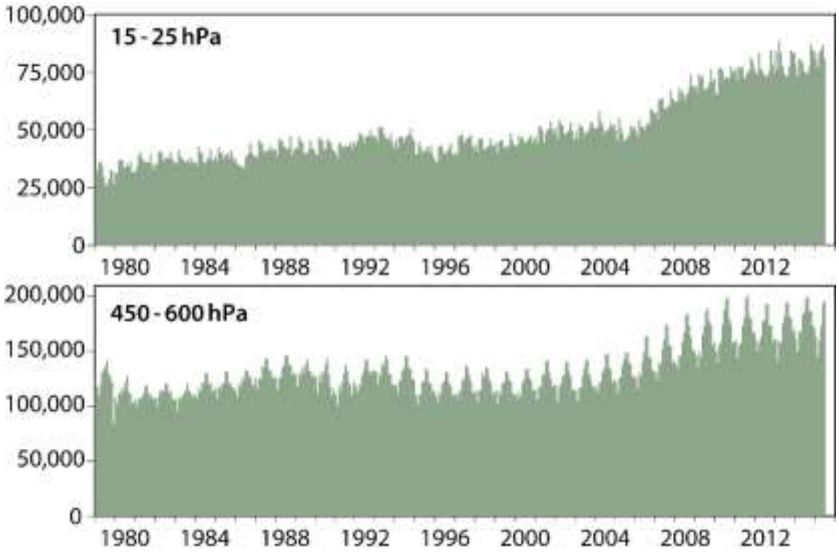


Figure 86: Number of radiosonde observations of temperature for the layers 15-25 hPa (upper) and 450-600 hPa (lower) from land stations assimilated each month in ERA-Interim from January 1979 to June 2015.

Although Figure 20 shows a quite uniform frequency of ascent over the extratropical northern hemisphere, much more variability is seen when it comes to the amount of data reported for each ascent. This has been noted already for wind data in section 4.5.2, and is illustrated in Figure 87 for temperature reports sampled for the month of October 2014. Some variation can occur depending on terrain height, which may explain why yields over much of the western USA are lower than over the east of the country, and prevailing weather can have an effect through its influence on the presence of significant levels. It is nevertheless evident from Figure 87 that there are regional and national differences in the detail to which ascents have been reported in the alphanumeric code used hitherto. Changes in vertical resolution over time have been shown in Table 6 in the case of GUAN stations.

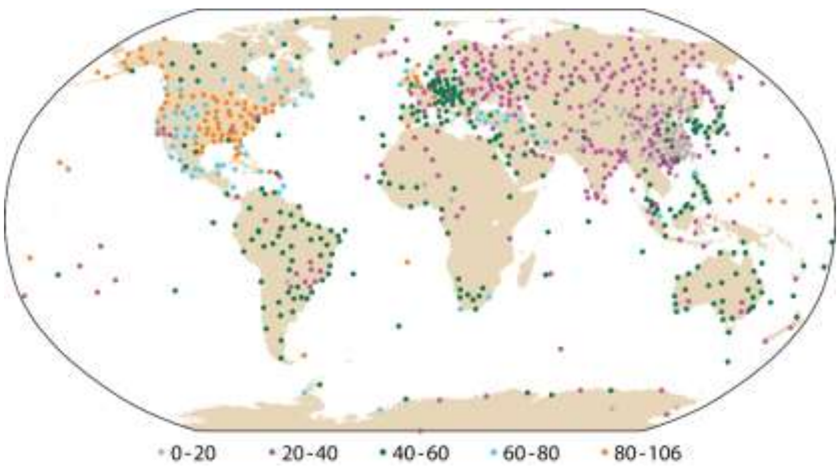


Figure 87: Average number of temperature observations per radiosonde ascent received operationally by ECMWF in October 2014.

Progress on the provision of data in full compliance with the BUFR coding standard has been slow, and where action has been taken, implementation has fallen short of what is required. WMO CBS agreed in 2010 that November 2014 was the deadline beyond which radiosonde data should be distributed only in BUFR format, with continued exchange of data in alphanumeric code only by bilateral agreement. By November 2014, however, only a small number of NMHSs were providing full BUFR data in the intended way, reporting ascents at high vertical resolution with the actual time and position specified for each observational element. Many NMHSs were instead simply sending messages in BUFR format but with essentially the same information content as in the former TEMP alphanumeric code, which brought no real progress. Progress since then has been gradual. In August 2015, only about 10% of radiosonde stations, mostly in Europe, were providing high resolution BUFR reports. A further 10% or so were providing native BUFR reports but at low resolution. Around 50% of stations were providing BUFR-reformatted TEMP reports. Work was continuing in order to resolve problems in some of these BUFR reports. In the meantime, many but not all stations continue to report their data in TEMP as well as BUFR code. Care will be needed when building an archival radiosonde data record for the transition period. This applies also to other types of data for which there have been issues during the change to BUFR encoding.

A18: Submit metadata records and radiosonde inter-comparison data to centres

Action: Submit metadata records and inter-comparisons for radiosonde observations to International Data Centres.

Who: National Meteorological Services, in cooperation with WMO CBS, WMO CIMO, and AOPC.

Time-Frame: Ongoing.

Performance Indicator: Percentage of sites giving metadata to WDC Asheville.

Annual Cost Implications: <1M US$ (50% in non-Annex-I Parties).

Progress on the Action as stated has been minimal, although some additional metadata and data have been received by NCEI. However, the move to BUFR encoding of radiosonde data provides operators with the opportunity to report much more metadata with the ascent itself, which if implemented fully should substantially reduce the need for separate metadata supply in the future. In addition, a Task Team on established by the WMO Inter-Commission Coordination Group on WIGOS has developed a the WIGOS Core Metadata Standard recently approved by the Seventeenth World Meteorological Congress as noted in the context of Action C18.

The 2010 WMO radiosonde inter-comparison was documented in depth by Nash *et al*. (2011). All raw data that had been made especially available by manufacturers and used in analysis included in the report had to be destroyed at the end of the inter-comparison, but processed data are available through WMO CIMO. Comparing the results of successive inter-comparison campaigns provides measures of overall improvements in instrumentation over time. Figure 88 provides an example.

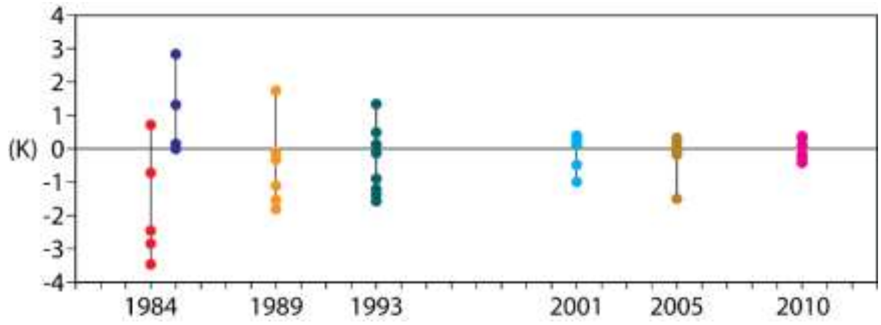


Figure 88: Spread of radiosonde measurements of 10 hPa night-time temperatures relative to a control measurement, as recorded in successive WMO radiosonde inter-comparisons. The choice of control varied from campaign to campaign. Source: Philipona et al. (2014), adapted from Jeannet et al, (2008).

Another indication of improvement in data quality comes from reduction over time in the magnitude of the bias adjustments made to the data by homogenization methods. Figure 89 shows this for one approach in which changes in instrument or operating practice are inferred from changes in the time series of differences between the data and background forecasts from reanalysis. The adjustments are predominantly one-signed, corresponding to a removal of overall warm bias that is larger in the data from older instruments. As such they reduce an overestimation of stratospheric cooling that results from use of the raw data. If the adjustments themselves are unbiased, remaining undetected changes would be expected to result in a residual overestimation of stratospheric cooling (and underestimation of tropospheric warming).

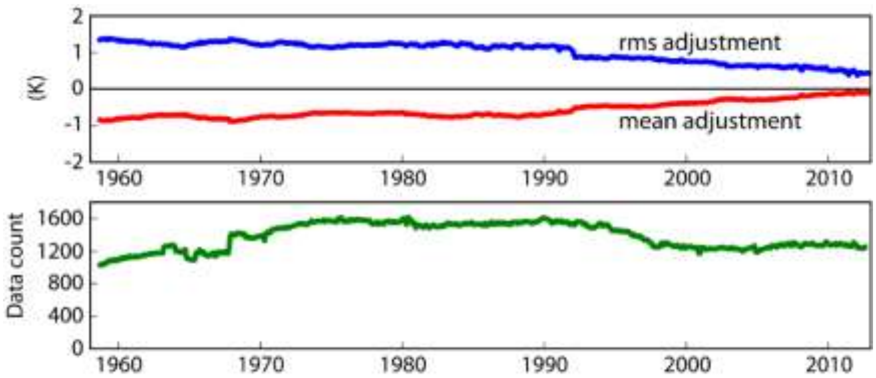


Figure 89: Variation over time in the root-mean-square and mean bias adjustments for temperature (K) derived by the RAOBCORE method (Haimberger et al., 2012) for 100 hPa radiosonde observations north of 30^{O}N (Upper panel, based on use of ERA-40 background up to 1978 and ERA-Interim background from 1979). The number of adjusted observations is shown in the lower panel. Source: L. Haimberger, University of Vienna.

A19: Implement and evaluate a satellite climate calibration mission

Action: Implement and evaluate a satellite climate calibration mission, e.g., CLARREO.

Who: Space agencies (e.g., NOAA, NASA, etc).

Time-Frame: Ongoing.

Performance Indicator: Improved quality of satellite radiance data for climate monitoring.

Annual Cost Implications: 100-300M US$ (Mainly by Annex-I Parties).

Little direct progress has been made on the implementation of a satellite climate calibration mission, although studies continue. The situation concerning CLARREO is clearly set out on the NASA web pages relating to the instrument, which in June 2015 stated: "Due to NASA budget considerations, CLARREO remains in an extended pre-Phase A with a launch readiness date of no earlier than 2023. NASA continues to fund efforts to refine the mission design and to examine alternative platforms, such as the International Space Station, focussing on lower cost implementation while achieving a majority of the CLARREO science objectives." Studies are also being undertaken related to a complementary mission TRUTHS that has been proposed by the UK's National Physical laboratory. Additional comment is provided in the review of Action A25.

Partial mitigation of this situation is emerging from the demonstrated stability of data provided by hyperspectral sounders and GNSS occultation, and from the establishment of the GRUAN. A workshop has explored the potential role in calibration of such good-quality observations, and identified a set of actions required to make further progress (WMO, 2014c).

A20: Continue derivation of MSU-like data; establish FCDRs from high-resolution IR data

Action: Ensure the continued derivation of MSU-like radiance data, and establish FCDRs from the high-resolution IR sounders, following the GCMPs.

Who: Space agencies.

Time-Frame: Continuing.

Performance Indicator: Quality and quantity of data; availability of data and products.

Annual Cost Implications: 1-10M US$ (for generation of datasets, assuming missions, including overlap and launch-on-failure policies, are funded for other operational purposes) (Mainly by Annex-I Parties).

Supply of MW sounding data has continued routinely from operational meteorological polar-orbiting satellite systems. The Chinese (FY-3), European (Metop and Metop-SG) and US (Suomi NPP and JPSS) systems discussed in section 3.4.2 are expected to continue to provide such data for coming decades.

Time series based originally on data from the MSU instruments operated from 1978 to 2006 have been used for nearly two decades to estimate layer-average temperature trends. They are being continued using data from the successor AMSU-A instruments and development is in progress to include data from the ATMS instrument now deployed on the first of the latest generation of NOAA polar orbiters. This continuation is not seamless, however. For the transition from MSU to AMSU there was a change in channels. Many more channels are available from AMSU, but none is directly equivalent to any MSU channel: the data from them relate to slightly different layers of the atmosphere. ATMS fields of view for different channels are mapped differently on the surface to those from AMSU. On the other hand, the good orbital control of newer platforms (Figure 5) and lower biases of newer instruments (Figure 24) contribute to more reliable time series. There is also good experience of drawing on the multi-instrumental microwave data record in reanalysis.

Work is in progress to construct FCDRs from the AIRS, IASI and CrIS hyperspectral IR sounders.

A21: Ensure the continuity of the constellation of GNSS RO satellites

Action: Ensure the continuity of the constellation of GNSS RO satellites.

Who: Space agencies.

Time-Frame: Ongoing; replacement for current COSMIC constellation needs to be approved urgently to avoid or minimise a data gap.

Performance Indicator: Volume of data available and percentage of data exchanged.

Annual Cost Implications: 10-30M US$ (Mainly by Annex-I Parties).

The amount of GNSS RO data used routinely by ECMWF in numerical weather prediction and reanalysis has varied since data from the COSMIC network of receivers first became available around the end of 2006 (Figure 90), but in broad terms has remained stable. Loss of data from COSMIC receivers as the network has aged has been compensated by availability of data from the high-yielding Metop-A platform and more recently Metop-B. Data of this type from the GRACE mission are also used, while those from receivers on the TerraSAR-X and TanDEM-X satellites are under consideration for use. A receiver is also deployed on the current FY-3C satellite, and receivers are planned to be flown on subsequent satellites in this series.

Approval for the replacement of the COSMIC constellation current at the time IP-10 was published took some time, but a set of six COSMIC-2 receivers is scheduled to be launched into low-inclination orbits in 2016, with deployment of a further six such receivers into high-inclination expected in 2018.

The top panel of Figure 90 shows monthly counts of the RO data assimilated by ERA-Interim for the tropical belt, and is complemented by illustrations of a particularly significant impact on reanalyses of assimilating data in significant numbers from 2007. The middle panel compares tropical-mean 100 hPa (near-tropopause) temperatures from ERA-Interim and JRA-55, both of which assimilated RO data, and from MERRA, which did not. Prior to assimilation of significant amounts of RO data, tropical tropopause temperatures were significantly lower in ERA-Interim than in either JRA-55 or MERRA. The middle panel shows how the ERA-Interim and JRA-55 curves come together once RO data are assimilated, with the JRA-55 curve separating from that for MERRA. The indication from the RO data is that ERA-Interim is indeed biased cold prior to 2007, but that both JRA-55 (prior to 2007) and MERRA are biased warm. The bottom panel shows corresponding fits of the ERA-Interim background forecasts and analyses to radiosonde temperatures near the tropical tropopause. It confirms the cold bias of ERA-Interim prior to 2007, and shows how ERA-Interim fits the radiosonde data are better once significant amounts of RO data are also assimilated.

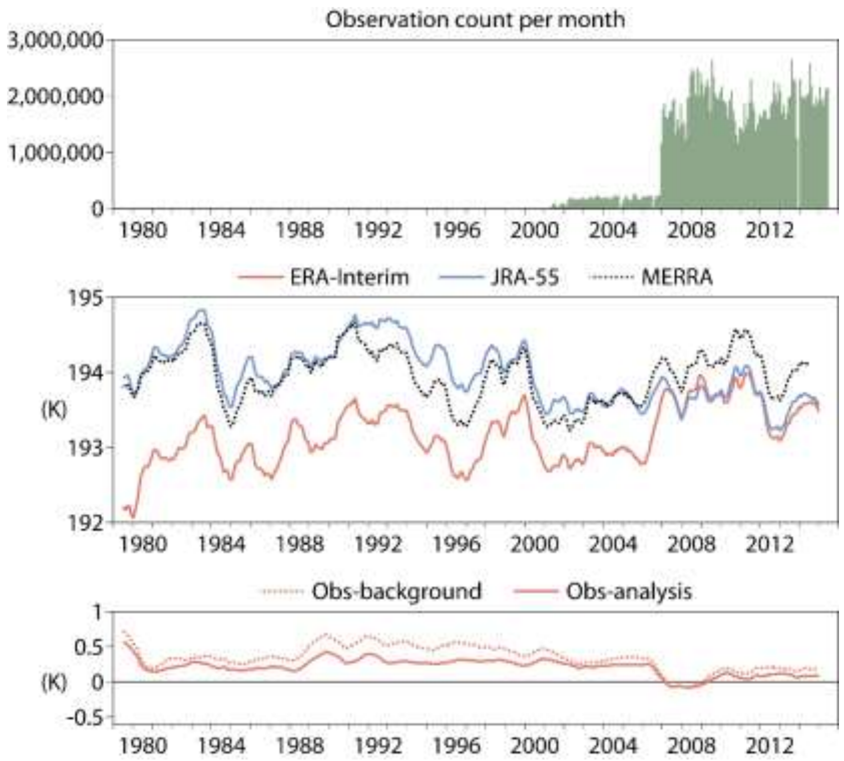


Figure 90: Monthly counts of GNSS radio occultation data for the tropical belt assimilated by ERA-Interim (top), and twelve month running averages of tropical-mean 100 hPa temperature from ERA-Interim, JRA-55 and MERRA (middle) and of the mean analysis and background fits of ERA-Interim to tropical radiosonde temperatures reported for the layer from 85 to 125 hPa (bottom). A technical issue caused no radio occultation data to be assimilated for the last few weeks of 2013. Adapted and updated from Simmons et al. (2014).

A22: Implement global exchange of data from ground-based GPS receivers

Action: Finalise standard and implement exchange of data globally from the networks of ground-based GPS receivers.

Who: WMO CIMO and WMO CBS, in cooperation with national agencies.

Time-Frame: Finalisation of standard urgent, implementation by 2012.

Performance Indicator: Number of sites providing data.

Annual Cost Implications: <1M US$ (20% in non-Annex-I Parties).

Good progress has been made on implementing the exchange of data related to the vertically integrated water-vapour content of the atmosphere obtained from ground-based GPS receivers. Figure 91 shows an example of the locations of data routinely available in Europe, comprising dense coverage for the continent itself and recently available US data with good coverage. Data are received from a number of other sites located in all continents, but coverage is sparse, indicating the scope for further progress.

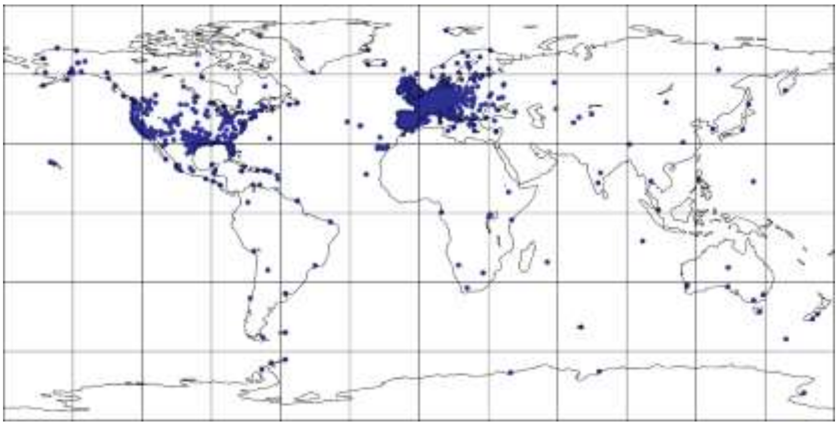


Figure 91: Example of coverage of data from ground-based GPS receivers, from ECMWF map of operational data receipt for the six-hour period from 21UTC 17 February to 03UTC 18 February 2015.

A23: Continue climate record of visible and infrared radiances, including reprocessing

Action: Continue the climate data record of visible and infrared radiances, e.g., from the International Satellite Cloud Climatology Project, and include additional data streams as they become available; pursue reprocessing as a continuous activity taking into account lessons learnt from preceding research.

Who: Space agencies, for processing.

Time-Frame: Continuous.

Performance Indicator: Long-term availability of global homogeneous data at high frequency.

Annual Cost Implications: 10-30M US$ (for generation of datasets and products) (Mainly by Annex-I Parties).

The ISCCP data record is being continued. Responsibilities have been transferred from NASA GISS to NOAA NCEI. The gridded record (GridSat-B1) of ISCCP B1 brightness temperatures (Figure 92) is at Version 2 and updated quarterly. A new “H-series” of higher-resolution products, extending the period of product record from 1983-2009 to 1980-2013 has been developed for release in 2015. Multi-agency contributions to sustained production are made through one of the Phase-2 projects of SCOPE-CM. Additional activities are being carried out under GSICS and the ESA CCI Cloud Project.

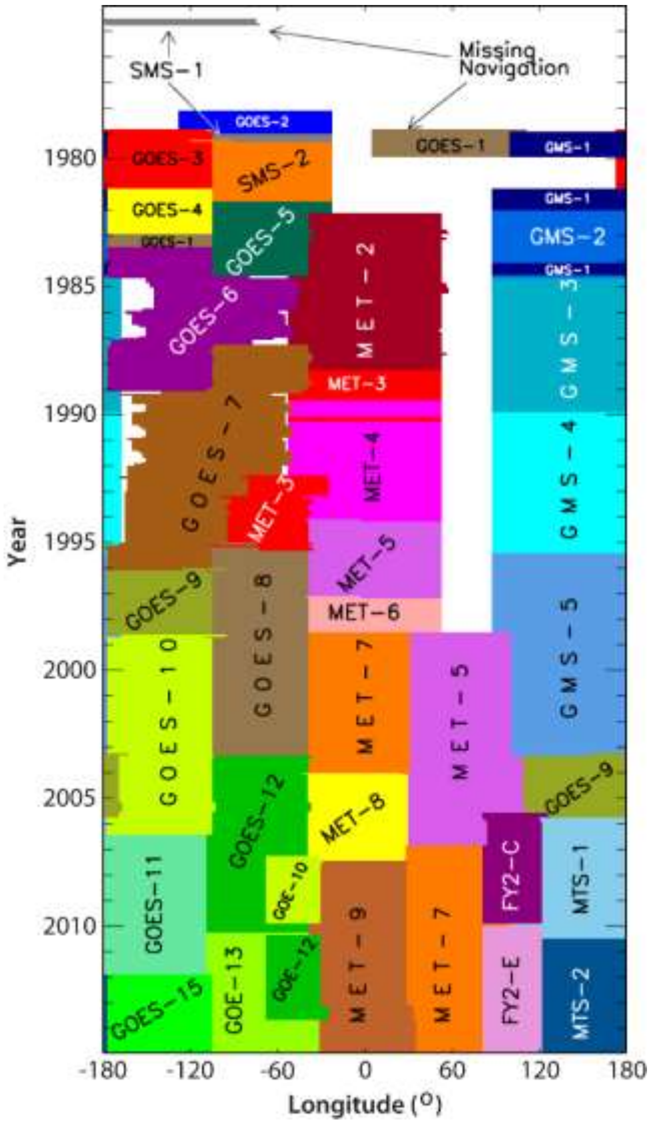


Figure 92: "Geostationary Quilt" showing the time series of geostationary satellite coverage at the equator used, or planned for use, in ISCPP B1 data records. Source: NOAA/NCEI (http://www.NCEI.noaa.gov/isccp; see also Knapp et al., 2011).

A24: Research to improve observations of cloud properties

Action: Research to improve observations of the three-dimensional spatial and temporal distribution of cloud properties.

Who: Parties' national research and space agencies, in cooperation with the WCRP.

Time-Frame: Continuous.

Performance Indicator: New cloud products.

Annual Cost Implications: 30-100M US$ (Mainly by Annex-I Parties).

The period since publication of IP-10 has seen continuation of the complementary observations of cloud (and aerosol and radiative) properties from four A-Train (section 3.4.4) satellites: Aqua, carrying a MODIS imaging spectroradiometer, launched in 2002, Parasol, launched in 2004 and ceasing measurement in 2013, and CALIPSO and CloudSat, both launched in 2006. Parasol provided multi-angular and polarimetric measurements, CALIPSO provides lidar and passive VIS/IR measurements and CloudSat provides measurements deeper into clouds using a profiling radar. This has led for the first time to a climatology of vertical cloud extent and layering, with identification of cloud types. It has enabled a substantial body of research involving the application of these observations, and data products that were included in the GEWEX cloud assessment (Figure 28).

New provision of lidar and radar observations will come from a single platform: the EarthCare satellite. The CATS cloud-aerosol lidar flown on the International Space Station since early 2015 is aimed both as a potential gap-filler, should CALIPSO cease measurement prior to the launch of EarthCare, and as a demonstrator of its laser technology. Operational continuation of MODIS-type imagery is assured on operational meteorological polar systems, and the 3MI instrument due to be flown on Metop-SG builds on the heritage of the POLDER instrument on Parasol. Another development is measurement in additional MW channels that provide information on ice clouds, including channels in the 118GHz oxygen band from the MWHS-2 instrument currently flying on FY-3C, and in the high-frequency bands to be sensed by the ICI instrument to be flown on Metop-SG. Capability for lightning detection is included in the coming generation of geostationary meteorological satellites, with launches scheduled from 2016 onwards.

Research also continues using aircraft measurements, sondes providing radiometric measurements and video of hydrometeors, and various forms of ground-based remote sensing.

A25: Ensure continuation of Earth Radiation Budget observations

Action: Ensure continuation of Earth Radiation Budget observations, with at least one dedicated satellite mission operating at any one time.

Who: Space agencies.

Time-Frame: Ongoing.

Performance Indicator: Long-term data availability at archives.

Annual Cost Implications: 30-100M US$ (Mainly by Annex-I Parties).

As indicated in section 4.5.5, observations of outgoing radiation have continued since 2010 from the CERES instruments on Terra and Aqua, and have been made from Suomi NPP following its launch in 2011. A final CERES instrument is scheduled to fly on JPSS-1. Radiation-budget measurements will also be made from JPSS-2, but with a change of instrument. Measurements are also being made by and are planned from the ERM instruments flown on the operational Chinese FY-3 polar orbiters, with an instrument upgrade from ERM-1 to ERM-2 planned for future satellites in the series. Several operational issues affect the provision of data from the GERB instruments in geostationary orbit on MSG platforms. The final such instrument is on MSG-4, which was launched into orbital storage in July 2015.

Figure 29 shows a continuation of data on total solar irradiance until early 2015. SORCE, launched in 2003, continues to provide data but has to operate (following a short complete break) in a hybrid mode in which instruments are switched on only when the satellite is sunlit. Continued operation is important because of the loss of the total solar irradiance measurements expected from another TIM instrument due to the launch failure of the GLORY mission in 2011. The TSI Calibration Transfer Experiment (TCTE), which was launched in 2013 as a replacement for GLORY’s TSI measurement component, is currently providing some needed continuity and redundancy in the TSI measurements. A TSIS dual-instrument package measuring both total and spectrally resolved irradiance, with heritage from the SORCE instruments, is scheduled to fly on the International Space Station from

2017. Total (but not spectrally resolved) solar irradiance is also part of the suite of quantities measured by FY-3 satellites. As with FY-3's ERM instruments, improved versions of the instruments measuring total irradiance are being implemented on later satellites in the series. The continuation of sunspot-number observations and the corresponding calibration with solar irradiance measurements will provide insight in the long-term variability of TSI, and especially its UV component (which correlates even better than TSI with sunspot number), extending back well beyond the period where it could be measured directly from satellite.

There are also initiatives to investigate use of small satellites for measuring the radiation budget. Examples are the forthcoming RAVAN and SIMBA cubesat missions, both of which are designed to measure outgoing reflected and emitted radiation, with SIMBA also measuring total solar irradiance.

The proposed CLARREO and TRUTHS missions (see review of Action A19) have important potential contributions to make both directly through well-calibrated measurements and indirectly through facilitating inter-calibration of the data from other platforms. This would be for outgoing radiation in the case of CLARREO, with SI-traceability for the IR component. TRUTHS offers the additional prospect of high-quality measurement of total and spectrally resolved solar irradiance, and SI-traceability for the reflected solar component.

A26: Establish long-term limb-scanning satellite measurement

Action: Establish long-term limb-scanning satellite measurement of profiles of water vapour, ozone and other important species from the UT/LS up to 50 km.

Who: Space agencies, in conjunction with WMO GAW.

Time-Frame: Ongoing, with urgency in initial planning to minimize data gap.

Performance Indicator: Continuity of UT/LS and upper stratospheric data records.

Annual Cost Implications: 100-300M US$ (including mission costs) (Mainly by Annex-I Parties).

There has been only limited progress towards establishing long-term limb scanning. Without change, a gap in comprehensive limb-emission measurement will begin when the MLS instrument on Aura ceases to function. Limb-scattering measurement in the UV/VIS parts of the spectrum provides data on ozone and some other species, but is restricted to sunlit regions. Such data are currently delivered by the OMPS instrument on NOAA's Suomi NPP satellite, and are scheduled from JPSS-2 but not JPSS-1, so a gap in OMPS data provision will occur unless the NPP instrument functions for more than ten years (Figure 2). The UV/VIS OMS-limb instrument scheduled to fly on FY-3E from 2017 and then on FY-3G offers an alternative source of such data. Also, SAGE-III on the International Space Station should provide data based on solar occultation from 2016.

MW limb sounding after MLS/Aura is referred to in the CEOS timeline only for the Global Atmospheric Chemistry Mission under consideration by NASA for launch in 2030. The proposed PREMIER mission could have helped fill the gap but was not selected by ESA as its 7th Earth Explorer mission. Studies are being undertaken for a proposed SMILES-2 instrument, building on the experience of six months of operation of SMILES on the International Space Station in 2009/10.

A27: Establish a network of ground stations for validating satellite remote sensing

Action: Establish a network of ground stations (MAXDOAS, lidar, FTIR) capable of validating satellite remote sensing of the troposphere.

Who: Space agencies, working with existing networks and environmental protection agencies.

Time-Frame: Urgent.

Performance Indicator: Availability of comprehensive validation reports and near real-time monitoring based on the data from the network.

Annual Cost Implications: 10-30M US$ (30% in non-Annex-I Parties).

The preamble to this Action in IP-10 identified the need for an enhanced set of ground-based remote-sensing measurements for validation of satellite observations and data products on atmospheric composition, as well as a concerted programme of *in situ* observations, exploiting the contribution that can be made from the GRUAN. Progress and current status of the GRUAN is discussed in section 4.4.4 and in the review of IP-10 Action A16, and its role in satellite calibration and validation is noted in the review of IP-10 Action A19. It includes programmes for ground-based remote sensing using lidar and FTIR approaches, but also MW radiometry. The overall objective of the GAIA-CLIM project (section 2.4) is to establish a sound methodology for characterising space-based data by ground-based measurement; the project can be seen as a contribution towards full achievement of this action.

Separate network arrangements exist for FTIR, lidar and MAXDOAS ground-based remote sensing, although in practice a number of observing sites or locations, among them GRUAN sites, host more than one of type of instrument, and also *in situ* surface measurement. The status of this action is placed in category B on the basis of the expansion of the TCCON FTIR and MAXDOAS networks. The status of the overall lidar network for aerosols is unclear.

The Total Carbon Column Observing Network (TCCON) is based on ground-based Fourier transform spectrometers that measure NIR solar spectra. Examples of use of data from this FTIR network are given in sections 4.7.1 and 4.7.2 in the context of satellite-based observations of CO_2 and CH_4 and the use of these and *in situ* observations to estimate surface source and sinks. TCCON was initiated in 2004, and its website in May 2015 listed 26 sites as either making or having made observations, of which 10 were identified as joining the network in 2010 or later. Other constituents measured include N_2O, CO and H_2O.

The implementation plan for the GAW Aerosol Lidar Observation Network (GALION; GAW, 2007) noted that advanced aerosol lidar systems were still relatively complex, expensive, and delicate instruments requiring substantial efforts for operation and maintenance, although substantial progress had been made towards increased reliability and automated operation. It was accordingly not feasible to implement a global aerosol lidar network by installing a homogeneous set of systems at a number of stations selected for optimal coverage. GALION was thus established as a network of networks, making use of existing systems at established stations, of the experienced operators of these systems, and of existing network structures, noting that contributing networks would need to meet GAW requirements for consistency of data across the network, ensured quality and enhanced data distribution.

Networks that contribute to the GALION include the global MPLNET and NDACC networks and regional networks for East Asia (AD-Net), Europe (EARLINET) and South America (ALINE). The 2007 implementation plan identified a total of 101 stations that were either established or expected to be established soon so as to comprise the GALION. The GAWSIS in May 2015 identified 77 registered GALION stations, but this includes stations for which no lidar data are listed available. The current status of this network is hard to discern.

The MAXDOAS (Multi-AXis Differential Optical Absorption Spectroscopy) technique utilizes multiple viewing directions in addition to the zenith to detect absorbers of scattered sunlight in the lowest few kilometres of the atmosphere, using radiative transfer modelling to retrieve the vertical distribution of aerosol and a number of tropospheric gaseous species, including nitrogen dioxide, formaldehyde and sulphur dioxide. It is a relatively new approach, appearing only around the time GCOS published its Second Adequacy Report. Expanding the number of stations equipped with MAXDOAS instruments has been one focus of NDACC. Its tabulation of UV/VIS network status as of October 2013 (http://ndacc-uvvis-wg.aeronomie.be/instruments.php; accessed 5 August 2015) listed a total 27 operating stations of which seven deployed MAXDOAS instruments. Eight of a further nine listed candidate stations were expected also use this type of instrument.

A28: Maintain and enhance the WMO GAW CO_2 and CH_4 monitoring networks

Action: Maintain and enhance the WMO GAW Global Atmospheric CO_2 and CH_4 Monitoring Networks as major contributions to the GCOS Comprehensive Networks for CO_2 and CH_4.

Who: Parties' national services, research agencies, and space agencies, under the guidance of WMO GAW and its Scientific Advisory Group for Greenhouse Gases, in cooperation with the AOPC.

Time-Frame: Ongoing.

Performance Indicator: Dataflow to archive and analyses centres.

Annual Cost Implications: 10-30M US$ (50% in non-Annex-I Parties).

Operation of the surface monitoring networks for CO_2 and CH_4 has been in essence maintained but not significantly enhanced, as judged by data delivery to the GAW WDCGG and the current data holdings of NOAA/ESRL. Budgetary pressures have however caused some suspension of measurement over part of the period since IP-10 was published.

Figure 93 shows the records of monthly-mean CO_2 data reported by the WDCGG, based on data submitted to it from the sites shown earlier in Figure 34. Monthly means were calculated from hourly or other submitted mole fractions for stations for which monthly means were not submitted. A number of records are short or intermittent, and a few others have values that are evidently outliers. Many give consistent values, however, showing overall growth over time, the seasonal cycle in the northern hemisphere and the lag in values in the southern hemisphere. Values from 124 stations, about 65% of those reporting data, were selected by WDCGG to produce the synthesis presented in Figure 33. The situation for CH_4 is largely similar, with data reported for slightly fewer stations, but with 70% passing quality control. Data from 121 stations were used to produce the corresponding plots for CH_4 presented in WDCGG (2015).

It can be seen in Figure 93 that data from a number of stations have not been reported for recent years. This is balanced to some extent by data from stations that have reported only recently. Overall, about half of the stations providing data chosen by WDCGG for analysis provided complete reports for 2013. The corresponding WDCGG data summary published in 2009 shows that eight more stations provided complete CO_2 data records that were selected for analysis for the year 2007. The situation is similar for CH_4. However, in both cases the shortfall in 2013 is more than accounted for by an absence of shipboard measurements made along the track between New Zealand and the western coast of the USA that can be seen in Figure 34. This measurement programme was suspended in 2012 for budgetary reasons, but resumed at the beginning of 2015 due to a recovery in funding. The period of suspension can be seen by visualising data records at http://www.esrl.noaa.gov/gmd/dv/iadv/.

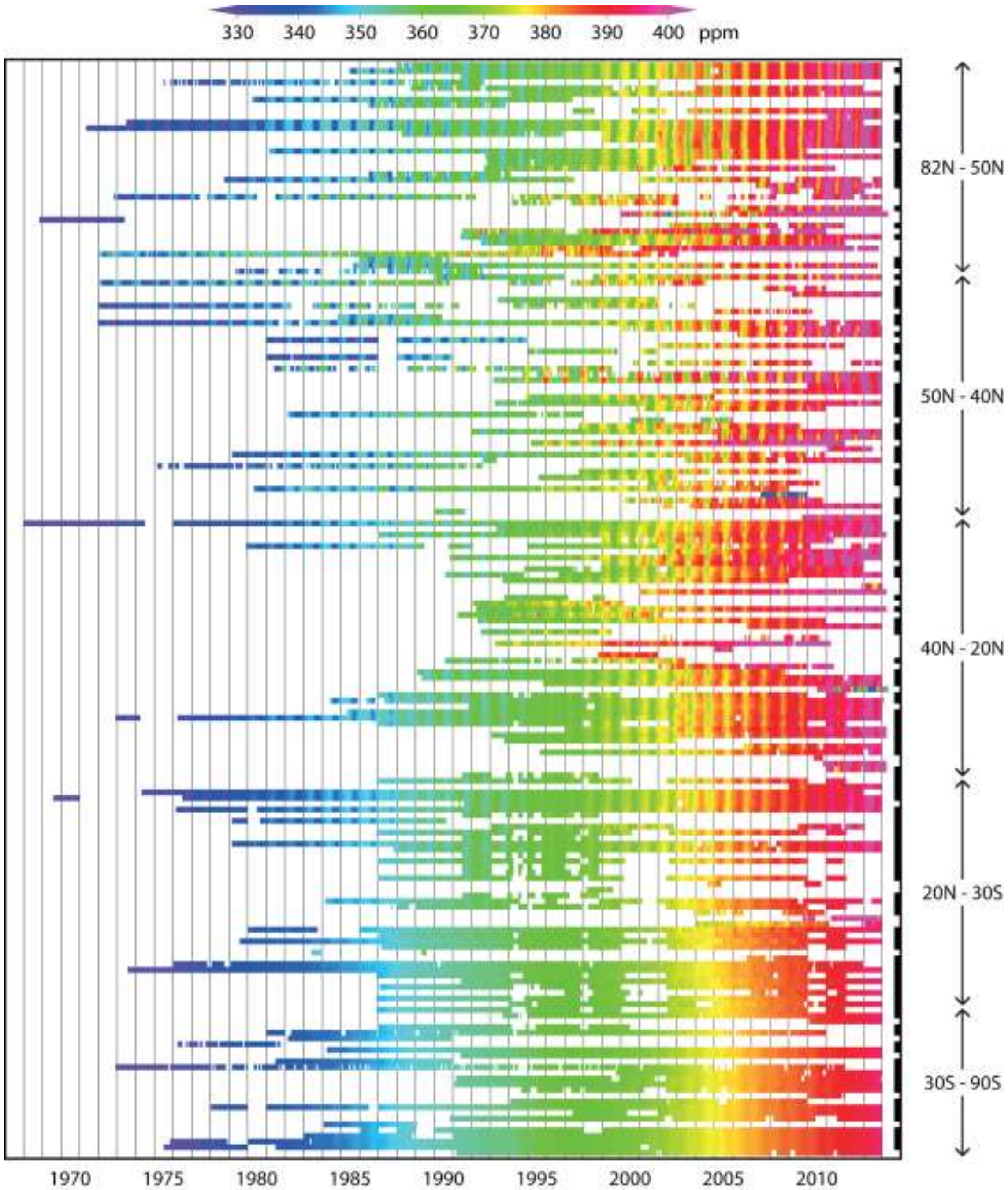


Figure 93: Monthly-mean mole fractions from data reported to the World Data Centre for Greenhouse Gases (WDCGG). Each coloured horizontal bar represents data from a particular type of measurement for a particular station. Stations are ordered from north to south. Source: WDCGG, adapted from Plate 3.1 of WDCGG (2015), based on data reported by July 2014. The black bar to the right of many of the coloured bars denotes data used in the analysis shown in Figure 33.

A29: Assess space-based measurements of CO_2 and CH_4, and develop follow-ons

Action: Assess the value of the data provided by current space-based measurements of CO_2 and CH_4, and develop and implement proposals for follow-on missions accordingly.

Who: Parties' research institutions and space agencies.

Time-Frame: Urgent, to minimise data gap following GOSAT.

Performance Indicator: Assessment and proposal documents; approval of consequent missions.

Annual Cost Implications: 1-10M US$ initially, increasing with implementation (10% in non-Annex-I Parties).

Data from SCIAMACHY, which operated from 2002 to 2012, and GOSAT, launched in 2002, supplemented by the more-limited data from IR sounding, have provided the basis to date for assessments of the value of space-based measurements of CO_2 and CH_4, summarised in sections 4.7.1 and 4.7.2. In addition, first results are also becoming available from OCO-2, launched in 2014 following the 2009 launch failure of the original OCO. OCO-2 provides CO_2 data of higher precision, can track glint so as to provide ocean coverage at higher latitudes, and can be operated so as to target specific ground sites, in particular where FTIR data (Action A27) are available for validation. Although OCO-2 can identify higher values of CO_2 over industrial and city sites, its swath is only of the order of 10 km at nadir. Work to refine data retrievals for all instruments continues, in particular under the Japanese and US national programmes of the operators of the instruments now in orbit, and under the European Copernicus and CCI initiatives.

Prospects for continued and then improved measurements appear to be good. An OCO-3 instrument is being built using the OCO-2 flight spare to operate from the International Space Station following a late-2016 launch. Also scheduled for launch in 2016 is the Chinese Tansat instrument, similarly focussed on CO_2 measurement. GOSAT-2 is being developed for launch in 2018 with the prospect of providing significantly better precision for both CO_2 and CH_4. It will include a pointing system to autonomously find and point to cloud-free areas for observation, which is expected to increase substantially the amount of data available for analysis. It will also provide measurements of carbon monoxide and improved aerosol imaging for estimation of fine particulate matter and black carbon.

There are additional missions under development. Instruments for CH_4 that build on the capabilities of SCHIAMACHY will fly on the Sentinel-5 precursor mission planned for launch in 2016 and on Metop-SG as Sentinel-5. CH_4 is the focus of a Franco-German lidar mission, MERLIN, which is expected to be launched around the end of this decade. ASCENDS is a CO_2 lidar mission recommended to NASA in 2007. It is shown in the 2015 update of the CEOS MIMD to be under consideration for operation in the 2022-2026 timeframe.

A30: Maintain networks for halocarbon and N_2O and SF_6 measurements

Action: Maintain networks for halocarbon and N_2O and SF_6 measurements.

Who: Parties' national research agencies and national services, through WMO GAW.

Time-Frame: Ongoing.

Performance Indicator: Data flow to archive and analyses centres.

Annual Cost Implications: 1-10M US$ (20% in non-Annex-I Parties).

The networks for these gases have been discussed in section 4.7.3, where Figure 36 presents time series of data for several species from stations in the NOAA/ESRL Halogen and Trace Species (HATS) network. These plots and corresponding ones for the AGAGE network demonstrate that the two small networks of stations have been maintained, and measurements have for the most part been continued for the individual species. An exception is SF_6 from the HATS network, for which data continue to be available from six stations making continuous measurements using gas chromatographs but are no longer available from flask measurements due to equipment degradation at a time of financial austerity. Alternative measurements of SF_6 have, however, been made using different equipment for the larger set of flask samples collected from the NOAA/ESRL Cooperative Air Sampling Network used for CO_2 and CH_4 measurement.

A31: Maintain the quality of the baseline ozone networks, and improve coverage

Action: Maintain the quality of the GCOS Global Baseline (Profile and Total) Ozone Networks coordinated by the WMO GAW and seek to increase coverage in the Tropics and Southern Hemisphere. Improve timeliness of provision of data to users and promote adoption of a single code standard.

Who: Parties' national research agencies and services, through WMO GAW and partners, in consultation with AOPC.

Time-Frame: Ongoing.

Performance Indicator: Network coverage and operating statistics.

Annual Cost Implications: 1-10M US$ (50% in non-Annex-I Parties).

In 2007, the GCOS programme designated the set of GAW stations operating Dobson and/or Brewer spectrophotometers as a baseline network for total ozone. Although nominally comprising 132 stations, almost-complete monthly records from 117 stations are revealed by a search for 2007 of data held in the World Ozone and Ultraviolet Radiation Data Centre (WOUDC). Holdings comprised 1354 records in total. Monthly-means varied from 128 Dobson units at Belgrano (77.9S) under the ozone hole in September to 564 Dobson units at Alert (82.5N) under a low tropopause in February. The corresponding baseline ozone profile network was designated as comprising the stations making measurements with ozonesondes from the GAW and cooperating NDACC and SHADOZ networks. A data search shows WOUDC to be holding 2606 ascents from 61 stations for 2007, an average of about one sounding every 8.5 days. ECMWF accumulates ascents from sources including the WOUDC, the NDACC and SHADOZ data centres, and the GTS, for the purposes of evaluating its data-assimilation products: it holds 3139 ascents from 71 stations for 2007.

Figure 94 shows data holdings for each year from 1989 onwards for the two baseline networks. For each, data numbers rise in the years up to around 2000 and then fluctuate about a steady level until around 2008. IP-10 called for maintenance or improvement of the networks, but WOUDC holdings have fallen year-on-year since 2008 for both the column and the profile measurements. Some of this is undoubtedly due to time lags between measurement and submission to data centre, as illustrated by the greater amount of additional data that ECMWF holds for the latest years. It is known, however, that measurement has ceased at a number of stations over the past few years.

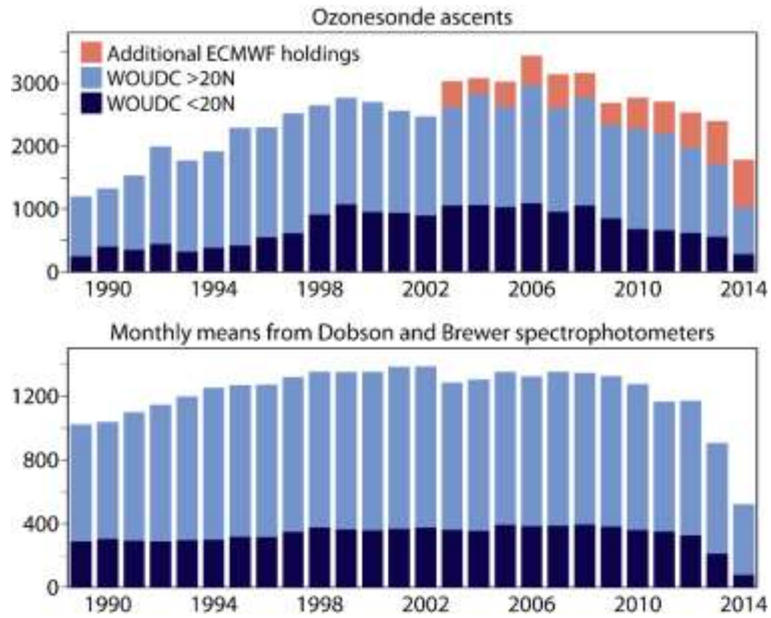


Figure 94: Annual counts of ozonesonde ascents (upper) and of monthly spectrophotometer records (lower), based on a data search of the WOUDC on 8 May 2015 (blue bars), and additional ozonesonde data accumulated by ECMWF from 2003 onwards, mainly from the NDACC and SHADOZ networks and from soundings made promptly available on the GTS (pink bars). Light and dark blue bars denote WOUDC holdings from stations respectively north and south of 20^{O}N.

The proportion of ozonesonde ascents held by WOUDC that come from the tropics and southern hemisphere rises from the early 1990s to reach a maximum of just over 40% in 2003, but subsequently declines to about 30%. The corresponding proportion for total column ozone records is steadier, and in fact largest in 2011 at just over 30%.

The distribution of stations in 2002 and 2012 for which WOUDC reports holdings is shown in Figure 95. Widespread areas with little or no coverage are evident, particularly for profile data. Coverage is most dense over Europe, as in many maps in this report. This becomes more pronounced still when the frequency of ozonesonde launches is examined. Based on the enhanced holdings of ECMWF from the beginning of 2003 to early May 2015, three stations average more than two ascents per week: Payerne, Uccle and Hohenpeissenberg, all in Europe. Of the twelve stations averaging better than once per week, five are in Europe, four in Antarctica and three in North America. WOUDC reports that it holds no data for two of these twelve stations (Boulder and the South Pole) for the period in question.

IP-10 Action A31 also called for adoption of a common code standard for ozone data to be promoted. It is hard to discern progress on this topic.

It should be noted that the status of action A31 is also of concern for operational weather and air-quality prediction.

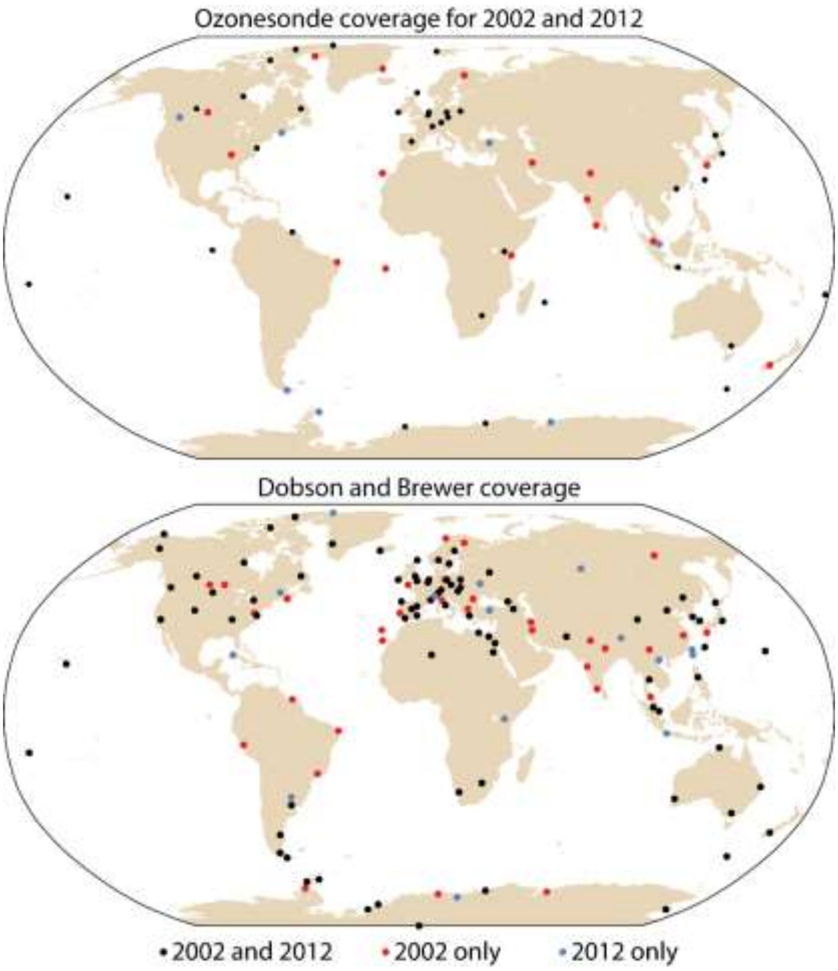


Figure 95: Locations of stations in 2002 and 2012 from WOUDC holdings for ozonesonde (upper) and Dobson or Brewer spectrophotometer data. Red denotes stations that did not provide data in 2012, and blue denotes stations that did not provide data in 2002. Based on a data search of the WOUDC made on 8 May 2015.

A32: Continue production and assess satellite ozone data records

Action: Continue production of satellite ozone data records (column, tropospheric ozone and ozone profiles) suitable for studies of interannual variability and trend analysis. Reconcile residual differences between ozone datasets produced by different satellite systems.

Who: Space agencies.

Time-Frame: Ongoing.

Performance Indicator: Statistics on availability and quality of data.

Annual Cost Implications: 10-30M US$ (Mainly by Annex-I Parties).

Production of satellite data records for ozone has been continued, mainly by the agencies responsible for the missions or individual instruments concerned, or by consortia established by or linked with such agencies, as is the case for several other ECVs. For ozone this includes use of data assimilation to generate products based on the data provided by multiple instruments. The illustrations in section 4.7.4 comprise an example of a reanalysis focussed on the multi-decadal variation of stratospheric ozone, and an example of the use of ozonesonde data to help evaluate a more comprehensive assimilation product that provides ozone fields along with a suite of other composition and meteorological variables aimed *inter alia* at providing data that may be used for understanding individual events and the variability from year to year. The quality of each type of product in turn depends on the quality of the retrieved (Level-2) data that are assimilated, and differences between the datasets from different satellite systems are reconciled by quality-control decisions that limit the use of data and by bias adjustment approaches that use ground-based measurements either to adjust the input data or as independent data for evaluating outputs.

Assessment of approaches and evaluation of satellite-based data products through comparisons with other such products and with *in situ* measurements and ground-based remote sensing has become well established in general. Two examples are provided by the investigation by Ziemke *et al*. (2014) of three approaches to mapping both tropospheric and stratospheric ozone based on NASA data products derived from the OMI and MLS instruments on Aura, and by the evaluation of retrieved profiles from MIPAS by Laeng *et al*. (2014). The latter work was undertaken partly under the ESA CCI, which established a round-robin approach for assessing competing product-generation algorithms. Another development is the provision of facilities for on-line display of comparisons of satellite products with validating data such as from ground stations or aircraft ascents and descents. Examples are provided by the validation site of the EUMETSAT SAF for Atmospheric Composition and UV Radiation, or validation accessible from the online product-portfolio pages of the Copernicus Atmosphere Monitoring Service.

Although much of the capability and space-based data on ozone relate to the stratosphere, products with limited vertical resolution have been derived for the troposphere from individual instruments such as GOME-2 and IASI, and from the combination of OMI and MLS data. Tropospheric ozone products from data assimilation may benefit indirectly from prior incorporation of data on precursor species. An activity to produce a first Tropospheric Ozone Assessment Report (TOAR) has been initiated, and is planned to include consideration of present and future satellite systems and the more general matter of design of the future global programme of observation.

Measurements of total ozone over the sunlit face of the Earth are beginning to be made by the joint NOAA/NASA mission DSCOVR, which in June 2015 reached L1 orbit, at the neutral gravity point between the Earth and sun approximately one million miles from Earth.

Future product generation requires both continued funding for the product generation itself, from the measurements made by past missions as well as new ones, and continued funding of the missions that provide the fundamental space-based measurements and the networks that provide data for calibration and validation. Nadir measurements are catered for in the established plans for operational missions, which now include Sentinel-5 and its precursor under Copernicus. Developments in measurement from geostationary orbit are discussed in the review of Action A34.

Concerns regarding the limited provision for limb scanning are recorded in the review of Action 26 and at several other places in this report. Decline in baseline networks providing supporting data is discussed in the preceding review of Action A31.

A33: Develop and implement a strategy for monitoring and analysing aerosol

Action: Develop and implement a coordinated strategy to monitor and analyse the distribution of aerosols and aerosol properties. The strategy should address the definition of a GCOS baseline network or networks for *in situ* measurements, assess the needs and capabilities for operational and research satellite missions for the next two decades, and propose arrangements for coordinated mission planning.

Who: Parties' national services, research agencies and space agencies, with guidance from AOPC and in cooperation with WMO GAW and AERONET.

Time-Frame: Ongoing, with definition of baseline *in situ* components and satellite strategy by 2011.

Performance Indicator: Designation of GCOS baseline network(s). Strategy document, followed by implementation of strategy.

Annual Cost Implications: 10-30M US$ (20% in non-Annex-I Parties).

Progress on Action A33 as regards the strategy for surface networks has been slow. A meeting was held in April 2009 to develop recommendations for a composite surface-based aerosol network, but was published only after some three and a half years as GAW (2012). The report recognised the substantial potential for improving the integration of observations across the various networks measuring aerosol properties, and the further need to develop cost-efficient monitoring capacity in regions with inadequate observational coverage. It identified the steps needed to implement a "network of networks" approach for Europe and in the wider international context. There is, however, little evidence of further development and implementation. In particular, a baseline network for ground-based measurement has yet to be proposed for GCOS designation. This is notwithstanding progress within networks (section 4.7.5), and the use in practice of data from AERONET as a baseline for aerosol optical depth at 500nm wavelength. The WDCA does not provide AERONET data: the disparity in number (sampled in May 2015) between the several hundreds of stations for which AERONET provides cloud-screened and quality assured AOD data for 2013 (Figure 39) and the eight GAW stations for which the WDCA provides AOD data for the same year is striking.

Action A33 also called for the needs and capabilities for operational and research satellite missions for the next two decades to be assessed, and for arrangements to be made for coordinated mission planning. Whilst this has not been done as part of a coordinated strategy that also addresses the needs for ground-based and airborne measurement, extensive provision is being made for the long-term measurement of aerosol properties with a degree of international coordination of mission planning.

VIS/IR imagers providing MODIS-type aerosol products are flying or planned for the operational Chinese, European and US polar-orbiting operational meteorological satellites, for which coordination of orbital coverage is discussed in section 3.4.2. The instrument complement of Europe's Metop-SG will also include 3MI, a multi-viewing, multi-channel, multi-polarization imager dedicated to aerosol measurement, and the improved spectral and radiometric characteristics of its IASI-NG sounder should provide further benefit. Prior to Metop-SG, JAXA's GCOM-C will provide polarimetric measurements with forward and backward views at red and NIR wavelengths. The operational Sentinel-3 and Sentinel-5 satellites (and the Sentinel-5 precursor) will also provide continuation of capabilities from polar orbit. Aerosol information will also be a by-product of planned wind and greenhouse-gas missions.

In addition to continuation of availability of aerosol information from general-purpose VIS/IR imaging from geostationary orbit, AOD and some information on speciation is expected to be provided by

UV/VIS or UV/VIS/NIR instruments that sample more-limited regions from this orbit. The CEOS Atmospheric Composition Constellation is playing a coordinating role for aspects of these missions. The infrared sounder to be flown on the next generation of Meteosat is expected to provide additional information on volcanic ash. Further discussion of measurement from geostationary orbit is given in the following review of Action A34.

The EarthCare satellite will follow CALIPSO and CloudSat, providing from one platform both lidar measurement of aerosol and radar cloud-profiling, with a multi spectral imager for cross-track data on aerosols and clouds. The need to augment future operational aerosol monitoring from space by such research missions is likely to continue. Given also the expansion of operational capabilities and the requirement for complementary ground-based observation, the need for a strategy for coordinated global aerosol measurement appears to remain.

A34: Ensure continuity of space-based products for the precursor species

Action: Ensure continuity of products based on space-based measurement of the precursors (NO_2, SO_2, HCHO and CO in particular) of ozone and aerosols and derive consistent emission databases, seeking to improve temporal and spatial resolution.

Who: Space agencies, in collaboration with national environmental agencies and meteorological services.

Time-Frame: Requirement has to be taken into account now in mission planning, to avoid a gap in the 2020 timeframe.

Performance Indicator: Availability of the necessary measurements, appropriate plans for future missions, and derived emission data bases.

Annual Cost Implications: 10-30M US$ (10% in non-Annex-I Parties).

Continuity of missions to date is discussed in section 4.7.6, and the associated product generation has continued. This has included refinement of retrievals and reprocessing of data records. Considering for example MOPITT, the instrument that has been operating the longest, a fifth version of CO retrievals was introduced in 2011, and version 6 has subsequently been developed and implemented (Deeter *et al*., 2014), providing a data record that now extends beyond fifteen years.

Prospects for continuity of production and improvement of products, including spatial and temporal resolution, are generally good, apart from the concerns over limb viewing discussed in the context of Action A26. In orbit, but not discussed in section 4.7.6 is the nadir-viewing OMPS instrument on the Suomi NPP satellite, to be followed by similar instruments on subsequent JPSS satellites. NO_2 and SO_2 products from this instrument are being developed (Yang *et al*., 2014). Beyond the instruments already in orbit and similar ones that will fly on successor satellites such as Metop-C, the TROPOMI instrument on the Sentinel-5 precursor builds on the heritage of SCIAMACHY and OMI, offering a much smaller 7 km^2 footprint, better signal-to-noise characteristics and data products for each of main precursor species (Veefkind *et al*., 2014). It will be followed by the Sentinel-5 instruments with similar specification that will fly on the Metop-SG series. Improved sensing of CO and SO_2 will also come from the next generation of IASI instruments on this series of satellites (Crevoisier *et al*., 2014). Data on precursors may also come from the OMS-nadir instrument planned for future FY-3 satellites.

Additional regional information will be provided by novel deployments of instruments on geostationary platforms. As noted in the discussions of Actions A32 and A33, each of the systems under development also measure ozone and aerosol. Products will be provided hourly during daylight.

Sentinel-4 is a UV/VIS/NIR instrument scheduled to fly on two successive Meteosat Third Generation platforms providing products over Europe and North Africa with 8 km resolution over a nominal period of 15.5 years. Data on CO will be derived from a sounder flying on the same satellite.

The GEMS and TEMPO instruments will operate in the UV/VIS spectral range, providing data respectively over the Korean Peninsula and neighbouring parts of the Asia-Pacific region and over much of North America. GEMS will provide 5 km resolution and has a design lifetime of at least ten years. TEMPO has finer 2 x 4.5 km resolution, and is expected to launch first, on a commercial platform around the end of 2017, though with only a two-year design life. Subsequent options are under consideration (http://geo-cape.larc.nasa.gov/; May 2015).

Action A34 also called for derivation of consistent emission databases. The atmospheric lifetime of CO is sufficiently long for observations to be used in flux inversion schemes to refine estimates of emissions in a way similar to that done for CO_2 and CH_4. One such study is that of Hooghiemstra *et al*. (2012), who utilised both surface measurements of CO from selected sites from the NOAA/ESRL Cooperative Air Sampling Network and MOPITT data to adjust emissions over South America, using independent flask and IASI data for validating the improved simulation that results from using the adjusted emissions. In a broader approach, Fortems-Cheiney *et al*. (2012 adjusted estimates of atmospheric production of HCHO by oxidation of non-methane volatile organic compounds (NMVOCs), the surface emissions of CO and CH_4, and OH concentrations within the same inversion, including use of OMI HCHO and MOPITT CO data. The revised estimate of the production of HCHO in turn implied a revised estimate of the biogenic emissions of NMVOCs.

Satellite products have been shown to have potential for adjusting the spatial distributions provided by emission inventories for shorter-lived species. The potential also to infer revised emissions within data assimilation cycles is noted in section 4.7.6. Use of products in the estimation of natural emissions has been demonstrated in case studies of wildfires (e.g. Huijnen *et al*., 2012) and volcanic eruptions (e.g. Flemming and Inness, 2013).

Oceanic actions

O1: Analyse the ocean section of national reports on systematic observation for climate

Action: Analyse the ocean section of national reports on systematic observation for climate to the UNFCCC, and encourage non-Annex-I Parties to contribute reports.

Who: IOC and I-GOOS JCOMM, in consultation with GOOS.

Time-Frame: Conforming to UNFCCC guidelines.

Performance Indicators: Number of Parties providing reports on their ocean observing activities.

Annual Cost Implications: <1M US$ (10% in non-Annex-I Parties).

The general situation regarding national reporting under the UNFCCC is covered in the review of Action C4 and Appendix 2. Forty-three Annex-1 countries and the European Union provided the UNFCCC with communications in 2013 or 2014 on their climate related activities. A spot check revealed that around 75% of these countries contributed to observation of the ocean. However, perhaps another 10% of the nations contributed to ocean analysis, and perhaps 15% of the reporting nations contributed to local efforts for which it was difficult to assess if the observations represented sustained efforts. The synthesis by the UNFCCC Secretariat reproduced in Appendix 2 summarises how Parties saw that progress in systematic oceanic observation included generally enhanced observation of the oceanic ECVs, with advances in the monitoring of polar regions, the carbonate system in particular.

The number of reports received in the same period from non-Annex-1 countries that are not landlocked is quite limited. However, national-level contributions to sustained observations are generally reported through the JCOMM Observations Coordination Group. For example, of the 30 nations contributing Argo floats active in June 2015 (section 5.2.1), 13 were not Annex-1 Parties to the UNFCCC. This was true of three out of 12 countries providing drifting buoys and three out of 16 countries plus the EU providing moored buoys. An overwhelming number of platforms is nevertheless provided by Annex-1 Parties, the USA in particular (section 5.2).

O2: Establish prioritized plans that address the needs to monitor the coastal regions

Action: Establish prioritized national and regional plans that address the needs to monitor the coastal regions and support adaptation and understanding of vulnerabilities.

Who: All coastal Parties, in consultation with PICO and OOPC.

Time-Frame: Continuing.

Performance Indicator: Publications by regions (e.g., GRAs) and nations of their plans for coastal climate observing systems, and reporting their progress against performance measures established by technical advisory bodies, including PICO and OOPC.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

The GOOS Panel for Integrated Coastal Observations (PICO) developed a plan for implementation of coastal observations, published as GOOS (2012a). It included consideration of regional coastal ocean observing systems. The Plan was discussed by the 5th GOOS Regional Alliances Forum in 2011. PICO was dissolved that year, however. GOOS decided that coastal observations instead should be considered as an integrated component of the Global Ocean Observing System and therefore charged the three GOOS expert panels to consider coastal observation requirements as part of their mandate. OOPC has moved its interests towards the coast. The next focus area for OOPC will be an evaluation of the observing system for boundary currents and shelf interactions. OOPC is also considering ECV requirements specifically for coastal zones. The Biogeochemistry Panel has a focus on the role of coastal oceans in carbon cycling and storage, and initial analyses by the Biology and Ecosystems panel suggest a strong initial focus on coastal ecosystems, including mangroves, sea grasses and coral reefs.

O3: Improve number and quality of climate-relevant surface observations from the VOS

Action: Improve number and quality of climate-relevant marine surface observations from the VOS. Improve metadata acquisition and management for as many VOS as possible through VOSClim, together with improved measurement systems.

Who: National meteorological agencies and climate services, with the commercial shipping companies.

Time-Frame: Continuous.

Performance Indicator: Increased quantity and quality of VOS reports.

Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

Discussions and illustrations of the status of climate-relevant marine surface observations from the VOS are provided in sections 4.3.4 and 5.2.6. The target number for VOSCLIM ships in VOS is that they should comprise at least 25% of VOS. In January 2015, VOSCLIM ships represented 28% of the VOS fleet (Figure 96).

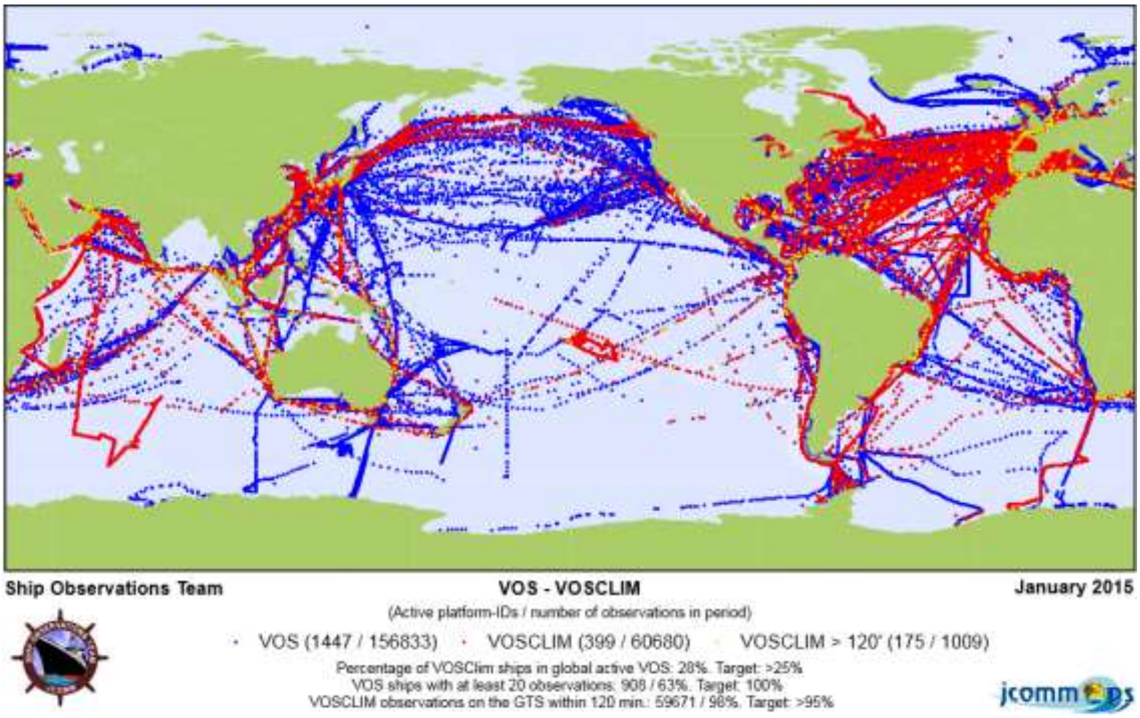


Figure 96: Distributions of VOS and VOSCLIM platforms in January 2015, and key performance indicators for the month. Source: JCOMMOPS.

O4: Ensure coordination of contributions to CEOS Virtual Constellations for surface ECVs

Action: Ensure coordination of contributions to CEOS Virtual Constellations for each ocean surface ECV, in relation to *in situ* ocean observing systems.

Who: Space agencies, in consultation with CEOS Virtual Constellation teams, JCOMM, and GCOS.

Time-Frame: Continuous.

Performance Indicators: Annually updated charts on adequacy of commitments to space-based ocean observing system from CEOS.

Annual Cost Implications: <1M US$ (Mainly by Annex-I Parties and implementation cost covered in Actions below).

CEOS is actively pursuing the virtual constellations. It added a Sea Surface Temperature Virtual Constellation in late 2011. An update of the CEO process paper on the virtual constellations was completed in 2013, and adequacy is routinely evaluated. Recommendations have progressed beyond numbers to address other issues such as coverage. Recent status reports on the four constellations related to ocean surface ECVs, namely those related to vector wind, colour, topography and temperature, can be found in presentations to the 30th session of the CEOS Strategic Implementation Team, available from http://ceos.org/meetings/sit-30/.

O5: Complete global reference network of 30-40 surface moorings as part of OceanSITES

Action: Complete and maintain a globally-distributed network of 30-40 surface moorings as part of the OceanSITES Reference Mooring Network.

Who: Parties' national services and ocean research agencies responding to the OceanSITES plan.

Time-Frame: Network complete by 2014.

Performance Indicator: Moorings operational and reporting to archives.

Annual Cost Implications: 30-100M US$ (10% in non-Annex-I Parties).

The intent under the OceanSITES plan is to have a broadly spaced, global array of surface moorings. These moorings would be well instrumented with the aim of collecting quality-controlled surface and ocean data of well-documented accuracies. In this way they will serve as "Reference Moorings" and provide "Reference Time Series" to support validation of model fields, anchor model and blended products, and serve as foci for process studies and other observations. The mooring line should carry a multidisciplinary set of ocean instruments extending down from the upper ocean. The surface moorings should carry a set of surface meteorological and oceanic sensors (wind speed and direction, air temperature and humidity, incoming shortwave and longwave radiation, barometric pressure, rain rate, sea surface temperature and salinity, and near-surface ocean current) to enable the air-sea heat flux, freshwater flux and horizontal momentum flux to be calculated. The plan does not list measurement of sea state, despite its influence on these fluxes.

The plan takes the perspective that there are a number of broad regions of the world ocean, such as the equatorial Pacific, the trade wind regions of each basin, the central gyre regions and others. It also takes the perspective that there are a number of "critical" regions where large signals are to be found and/or where the goals of improving understanding of the ocean and the coupled ocean-atmosphere system and of improving models would be much better addressed by the availability of quality time series from a surface mooring. Together, these characteristic and critical sites are the ones where OceanSITES advocates a sustained surface mooring should be established; and, across the globe, OceanSITES suggests this would require 30-40 moorings.

The IP-10 goal of completing such a network was not met by 2014, but good progress is being made. The tropical region is covered by TAO-Triton, PIRATA and RAMA in the Pacific, Atlantic and Indian Oceans respectively. International cooperation and planning on the path forward for the Pacific ENSO observing system was initiated by the TPOS workshop in January 2014. Discussions of expansions to PIRATA have occurred in the context of CLIVAR. From the perspective of this action item, focus is on the surface moorings with complete instrumentation and the capability to collect air-sea flux time series, and these moorings are a subset of the TAO-TRITON, PIRATA and RAMA moored arrays. The density of sampling with such moorings is close to being at the level envisioned by OceanSITES.

The extratropical and high-latitude oceans are not, however, at the sampling density planned by OceanSITES. The Kuroshio region is one of the few critical regions with instruments. New initiatives and renewed effort are making progress on installations at high latitudes. The Australian IMOS surface mooring at 46°S, south of Tasmania, has been redeployed. JAMSTEC has tested a surface mooring close to the Antarctic. The US National Science Foundation Ocean Observatories Initiative (OOI) deployed surface moorings in the Irminger Sea, in the Argentine Basic and in the Southern Ocean west of Tierra del Fuego between September 2014 and March 2015. Joint US and Indian efforts have extended moored arrays northward from the RAMA equatorial array, including into the northern Bay of Bengal.

Availability of ship-time and the costs associated with these surface moorings, which are serviced once a year, continue to present challenges to the completion of the OceanSITES Reference Mooring Network. Damage from fishing gear and vandalism, and biofouling also remain challenges. OceanSITES is an action group of DBCP, which provides a forum for cooperation and discussion of such challenges. Its future activities include work to place the data from these reference moorings in the hands of users and to demonstrate the scientific and societal values of reference time series from these moorings. Collaborations with activities such as the CLIVARGSOP/GODAE reanalyses and workshops are being sought.

O6: Deploy autonomous *in situ* instruments for biogeochemical and ecosystem variables

Action: Develop and deploy a ship-based reference network of robust autonomous *in situ* instrumentation for biogeochemical and ecosystem variables.

Who: Parties' national ocean research agencies, supported by the IGBP and IOCCG.

Time-Frame: Plan published and pilot project deployed by 2014.

Performance Indicator: Pilot project implemented; progress towards global coverage with consistent measurements.

Annual Cost Implications: 10-30M US$ (10% in non-Annex-I Parties).

Carbonate sensors have been further developed since IP-10 was developed. A number of Argo floats are equipped with highly precise low-power consuming pH sensors. Developments of autonomous systems for underway ship measurements of dissolved inorganic carbon, alkalinity, pH and pCO_2 have progressed, with a number of systems available on the open market. Concept studies of interior ocean pCO_2 measurements on floats have been conducted, and pCO_2 instrumentation is regularly (but infrequently) being deployed on moorings. The community is taking stock on best practices in sensor deployment and data reporting, as the development of sensors is progressing. Pilot projects with biogeochemical sensors on Argo are in progress, particularly in the Southern Ocean.

O7: Continue provision of SST fields based on mix of IR and MW satellite and *in situ* data

Action: Continue the provision of best possible SST fields based on a continuous coverage-mix of polar orbiting IR and geostationary IR measurements, combined with passive microwave coverage, and appropriate linkage with the comprehensive *in situ* networks noted in O8.

Who: Space agencies, coordinated through CEOS, CGMS, and WMO Space Programme.

Time-Frame: Continuing.

Performance Indicator: Agreement of plans for maintaining a CEOS Virtual Constellation for SST.

Annual Cost Implications: 1-10M US$ (for generation of datasets) (Mainly by Annex-I Parties).

The provision of SST fields has been continued, as called for by this action. A variety of products using *in situ* or satellite data, or combinations of the two, have been refined, developed or planned since IP-10 was published, in particular by the Met Office Hadley Centre, NOAA NCEI and the ESA CCI. A notably comprehensive mix of observations is used in the OSTIA analysis produced operationally by the Met Office (http://podaac.jpl.nasa.gov/dataset/UKMO-L4HRfnd-GLOB-OSTIA). Nevertheless, although the progress on this action is marked as good overall, there is serious concern over the future provision of SST information from space-based MW data.

There are plans for continued SST observation from polar orbiting IR and geostationary IR missions, as well as for continued *in situ* observation. The deployment of the SLSTR instrument on Sentinel-3, due for first launch in late 2015, will resume high-quality IR measurement of the type provided from 1991 to 2012 by the ATSR and AATSR instruments. The Global High Resolution Sea Surface Temperature (GHRSST) programme (to which the OSTIA analysis contributes) provides a successful forum for maximizing the advantages of collocated *in situ* and satellite data for intercalibration. However, as discussed also in section 5.3.1 there are currently no firm plans for continuing MW SST coverage past the existing satellites. MW observations provide relatively coarse resolution, with poor coverage along coastlines due to land contaminations. They have, however, the considerable advantage over IR instruments of being able to observe through cloud cover. The quality of SST products will diminish, particularly in high-latitude winters, if MW SST data are not available. There are already concerns of a 0.3K bias between MW and IR SSTs during high-latitude winters in areas of common cloud cover.

O8: Sustain drifting-buoy coverage; enhance VOS effort for improved ocean temperature

Action: Sustain global coverage of the drifting buoy array (total array of 1250 drifting buoys equipped with ocean temperature sensors), obtain global coverage of atmospheric pressure sensors on the drifting buoys, and obtain improved ocean temperature from an enhanced VOS effort.

Who: Parties' national services and research programmes through JCOMM, Data Buoy Cooperation Panel, and the Ship Observations Team.

Time-Frame: Continuing (sustain drifting buoy array and enhance VOS by 2014).

Performance Indicator: Data submitted to analysis centres and archives.

Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

As discussed in 5.2.3, drifting buoy numbers were not sustained at the planned level throughout the period, although the problems experienced in 2011 and 2012 have now been remedied. The review of Action A6 shows only limited progress in equipping buoys with atmospheric pressure sensors, with a continuing lack of pressure measurements over much of the Pacific Ocean.

The number of SST observations provided by the VOS increased up to at least 2012, as can be seen in Figure 97, which is based on delayed-mode data collection. As near-real-time data receipt of atmospheric observations from the VOS was higher in 2014 than 2012, as illustrated in Figure 16, it is likely that the number of SST observations was high for this year also, as the proportion of reports including SST measurements did not vary much over earlier years.

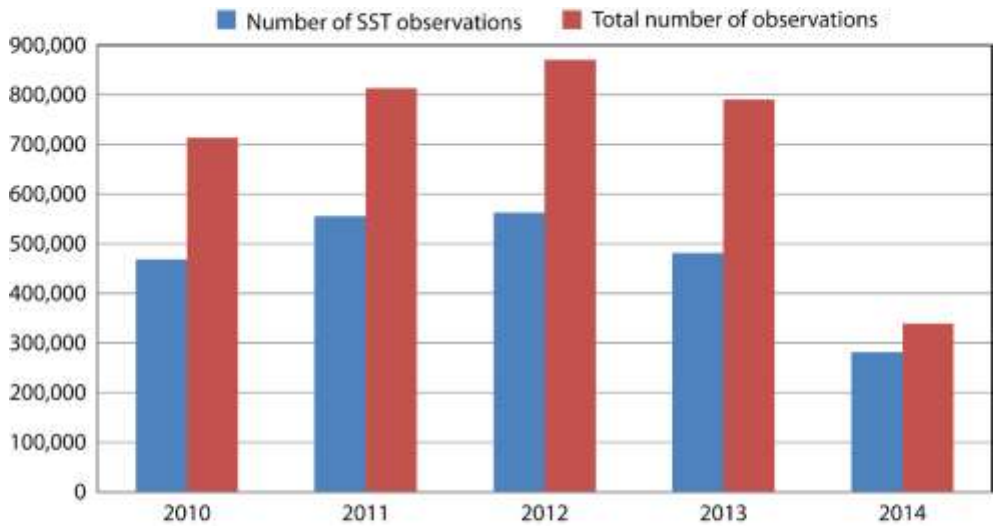


Figure 97: Total number of VOS observations, and the number that included SST, from delayed-mode data collection for the years 2010 to 2014. Souce: Global Collecting Centre operated by DWD, based on data received up to June 2015.

O9: Implement the GLOSS tide-gauge network, manage data and build capacity

Action: Implement the GLOSS Core Network of about 300 tide gauges, with geocentrically-located high-accuracy gauges; ensure continuous acquisition, real-time exchange and archiving of high-frequency data; put all regional and local tide gauge measurements within the same global geodetic reference system; ensure historical sea-level records are recovered and exchanged; include sea-level objectives in the capacity-building programmes of GOOS, JCOMM, WMO, other related bodies, and the GCOS system improvement programme.

Who: Parties' national agencies, coordinated through GLOSS of JCOMM.

Time-Frame: Complete by 2014.

Performance Indicator: Data availability at International Data Centres, global coverage, number of capacity-building projects.

Annual Cost Implications: 1-10M US$ (70% in non-Annex-I Parties).

Although considerable progress has been made over the past decade toward the implementation of the GLOSS Core Network (GCN), the IP-10 goal of complete implementation of the GCN by 2014 has not been met. Between 80-90% of GCN stations currently report in near-real time or fast-delivery mode, with monthly quality checking, and over 50% of stations include a vertical land motion component. The GLOSS Implementation Plan was updated in 2012 with specific recommendations for maintaining and expanding the GCN (GOOS, 2012b).

The chief reason for incomplete implementation is the lack of dedicated, sustained funding for sea-level monitoring in many of the contributing countries and the lack of any substantial centralized resources that GLOSS could use to assist where necessary. GLOSS serves an important advisory role, provides technical and scientific training courses, and handles data assembly, distribution and archiving, but the programme would be strengthened considerably by additional resources to assist nations in need with GCN operation and maintenance. GLOSS has a wide outreach to countries, with more than 70 contributing observations to GLOSS data centres, and is well positioned to coordinate resources for maximum impact across the GCN.

The highest priority growth area for the GCN, particularly in support of satellite altimetry, is the expansion of direct vertical land motion measurements at tide-gauge locations. GLOSS continues to advocate for the installation of continuous GNSS (cGNSS) stations near GCN stations, and for precise levelling between tide-gauge sensors, tide-gauge benchmarks and cGNSS stations. A new GLOSS manual is under development with updated information on levelling and links to material concerning the establishment of cGNSS capabilities. At stations where cGNSS is not yet possible then efforts can be made to determine the ellipsoidal heights of tide-gauge benchmarks via campaign GNSS measurements. GLOSS is working with various geodetic and land survey agencies via GGOS to address these needs for GCN stations.

O10: Ensure continuous coverage from one high- and two medium-precision altimeters

Action: Ensure continuous coverage from one higher-precision, medium-inclination altimeter and two medium-precision, higher-inclination altimeters.

Who: Space agencies, with coordination through the CEOS Constellation for Ocean Surface Topography, CGMS, and the WMO Space Programme.

Time-Frame: Continuous.

Performance Indicator: Satellites operating, and provision of data to analysis centres.

Annual Cost Implications: 30-100M US$ (Mainly by Annex-I Parties).

Jason-2 continues to operate and is approaching its seventh year in orbit; its design life was 5 years. Jason-3 was expected to be launched in summer of 2015, but is on hold due to an earlier launch failure. It too has a design life of 5 years. As noted in section 3.4, the planned follow-on Jason Continuity of Service mission (Jason-CS) has been designated as Sentinel-6, with launches envisaged in 2020 and 2026. Some elements of funding for this mission remain to be secured. AltiKa and CryoSat are both providing higher inclination altimeter observations, used to improve spatial and temporal coverage.

O11: Implement a programme for *in situ* observation of sea-surface salinity

Action: Implement a programme to observe sea-surface salinity to include Argo profiling floats, surface drifting buoys, SOOP ships, tropical moorings, reference moorings, and research ships.

Who: Parties' national services and ocean research programmes, through IODE and JCOMM, in collaboration with CLIVAR.

Time-Frame: By 2014.

Performance Indicator: Data availability at International Data Centres.

Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

Near-surface salinity is now often measured on Argo profiling floats, tropical moorings, reference moorings and research ships. The shallowest depths measured by Argo and tropical moorings are typically five and one metre respectively, although some ship-based measurements can be shallower.

If salinity is measured on drifting buoys and the Ship of Opportunity Programme (SOOP), the data do not enter the operational data stream because there is no single programme to work with and archive these data. Individual programs exist for Argo, tropical moorings and some research and voluntary observing ships through the GOSUD programme. The accuracy of observations archived in the National Buoy Data Center (NBDC) observations is a potential issue because there is a lack of information on bias.

Incomplete arrangements for near-real-time supply of salinity data is a concern as it limits the amount of data used in the assimilation systems for operational seasonal forecasting. The types of data for which there is not near-real-time supply are used in reanalysis systems, however (Action O28).

O12: Investigate feasibility of utilizing satellite data for global fields of surface salinity

Action: Research programmes should investigate the feasibility of utilizing satellite data to help resolve global fields of SSS.

Who: Space agencies, in collaboration with the ocean research community.

Time-Frame: Feasibility studies complete by 2014.

Performance Indicator: Reports in literature and to OOPC.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

Satellite observations from SMOS and Aquarius (prior to platform failure in June 2015) have provided SSS data over the global ocean since 2010 and 2011 respectively, and research has already provided ample evidence of their utility. The observations are significantly contributing to the understanding of SSS variations on various spatial and temporal scales, especially those inadequately resolved by the near-global Argo array, namely spatial scales less than a few hundred kilometres, on synoptic to intraseasonal time scales. Moreover, satellites provide coverage of SSS in regions that are currently poorly sampled by *in situ* systems, such as marginal seas, which is critical to research on the linkages of regional water cycles with the ocean. Examples for the applications of satellite SSS data include studies of river plumes, marginal-sea salinity variations, open-ocean salinity fronts, Gulf Stream eddies, tropical instability waves, Rossby waves, and the relationships between SSS and climate modes such as the Madden-Julian Oscillation, Indian Ocean Dipole and ENSO. Satellite SSS and SST data together provide global estimates of surface density to facilitate studies of the formation of water masses at the ocean surface. Satellite SSS products are being assimilating into ocean models to improve ocean state estimation and initialize seasonal-to-interannual prediction. Satellite SSS data have also been used with SST and ocean-colour measurements to study total alkalinity and ocean acidity on the global scale. The quality of satellite SSS products is better in the tropics and subtropics than in high-latitude oceans because of the reduced sensitivity of the L-band salinity sensor to salinity in cold-water regimes. The recent loss of the Aquarius satellite mission has adversely affected ocean salinity research, especially in many marginal seas where Aquarius data have demonstrated their value in studying the linkages between regional water cycles and ocean circulation.

O13: Develop an internationally-agreed strategy for measuring surface pCO_2

Action: Develop and implement an internationally-agreed strategy for measuring surface pCO_2.
Who: IOCCP, in consultation with OOPC; implementation through national services and research programmes.
Time-Frame: Implementation strategy for end-2010; full implementation by 2014.
Performance Indicator: Flow of data into internationally-agreed data archives.
Annual Cost Implications: 1-10M US$ (Mainly Annex-I Parties).

Single investigators drove most efforts for measuring surface pCO_2 in the past, but recently national and international measurement consortia, and international coordination efforts largely led by IOCCP have provided a unique approach towards an operational network. The international network of surface pCO_2 observations in its integrated form is in the early stages of development. Global data sharing and archival strategy in a form of the Surface Ocean CO_2 Atlas (SOCAT) first published in 2011 has dramatically changed data quality and data availability for this ECV. The Ocean Thematic Centre (OTC) of the Integrated Carbon Observing System (ICOS) is currently under consideration, and if accepted it will provide sustained operational funding to EU investigators.

Objective mapping routines and interpolation techniques including remote sensing and data assimilation have been thoroughly investigated, and have recently taken a coordinated form in the Surface Ocean CO_2 Mapping (SOCOM) inter-comparison project. Auxiliary observations that have proven to be particularly useful are sea-surface temperature, salinity, mixed layer depth and surface chlorophyll. This ongoing activity aims at creating a portfolio of cross-validated freely available surface ocean interpolated pCO_2 data products.

The Surface Ocean CO_2 Atlas (SOCAT, (http://www.socat.info/) was initiated by the International Ocean Carbon Coordination Project, SOLAS and IMBER in April 2007 (IOCCP, 2007). The first public release of SOCAT (version 1.5) took place on 14 September 2011, followed by the release of version 2 in June 2013.

SOCAT version 1.5 had 6.3 million surface water measurements of the fugacity of CO_2 from 1851 voyages in the global oceans, including the Arctic Ocean and coastal seas, between 1968 and 2007. All surface water fCO2 observations in SOCAT have been put in a uniform format, recalculated and rigorously quality controlled using fully documented methods (Pfeil *et al.*, 2012). In addition, a mean monthly fCO2 gridded product on a 1˚ by 1˚ grid has been constructed from this data set (Sabine *et al.*, 2012).

Version 2 of SOCAT was released in June 2013 (Bakker *et al.*, 2014) as an update of the previous release with more data (10.1 million surface water fCO_2 values) and extended data coverage (from 1968–2007 to 1957–2011). The quality control criteria, while similar in both versions, have been applied more strictly in version 2. The SOCAT website has links to quality control comments, metadata, individual data set files, and synthesis and gridded data products.

SOCAT version 2 strongly improves data access for global carbon scientists. Potential applications include constraints on the global carbon budget, studies of seasonal, inter-annual and decadal variability of oceanic CO_2 fluxes at meso-, regional- and global scales, and of the processes driving this variability. SOCAT will aid network design to determine the optimal fCO_2 data coverage required for accurate quantification of the oceanic CO_2 sink, its variation and trends. Using the fCO_2 data and algorithms to determine the gas transfer velocity, monthly, basin-wide maps of CO_2 air-sea fluxes are created using statistical techniques, neural networks, modelling and data assimilation for constraining global carbon budgets and the terrestrial and oceanic sinks. SOCAT data provide initialisation and validation fields for ocean carbon cycle models.

Version 3 of SCOCAT was released in September 2015.

O14: Develop instrumentation for the autonomous measurement of DIC, Alk, or pH

Action: Develop instrumentation for the autonomous measurement of either DIC, Alk, or pH with high accuracy and precision.

Who: Parties' national research programmes, coordinated through IOCCP.

Time-Frame: Strategy: 2010; technology: 2012; pilot project: 2014.

Performance Indicator: Development of instrumentation and strategy, demonstration in pilot project.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

Carbonate sensors have been further developed since IP-10 was published. A number of Argo floats are equipped with highly precise low-power-consuming pH sensors. Developments of autonomous systems for underway measurements of dissolved inorganic carbon (DIC), alkalinity (Alk), pH and pCO_2 have progressed, with a number of systems available on the open market. Concept studies of interior ocean pCO_2 measurements on floats have been conducted, and pCO_2 instrumentation is regularly (but infrequently) being deployed on moorings. The community is taking stock on best practices in sensor deployment and data reporting, as the development of sensors is progressing. Pilot projects with biogeochemical sensors on Argo are in progress, particularly in the Southern Ocean.

The Global Ocean Acidification Observing Network (GOA-ON) currently has network activities that include a small number of mooring sites and a few underway systems, where either pH or DIC is regularly measured. Coordination of these activities has been recently significantly strengthened through establishment of the GOA-ON. Great progress is being made in development of the autonomous sensors technology for pH, DIC and alkalinity measurements. The first basin-wide pilot project (Southern Ocean Carbon and Climate Observations and Modeling, SOCCOM) started in the Southern Ocean in 2015 and around 200 autonomous floats capable of measuring pH and other biogeochemical parameters will be released throughout 2015-2016.

O15: Implement continuity of ocean colour radiance data through a virtual constellation

Action: Implement continuity of ocean colour radiance datasets through the plan for an Ocean Colour Radiometry Virtual Constellation.

Who: CEOS space agencies, in consultation with IOCCG and GEO.

Time-Frame: Implement plan as accepted by CEOS agencies in 2009.

Performance Indicator: Global coverage with consistent sensors operating according to the GCMPs; flow of data into agreed archives.

Annual Cost Implications: 30-100M US$ (10% in non-Annex-I Parties).

Table 7 shows progress and plans of a set of tasks related to this action, as reported in March 2015. Task VC-1 is complete and a list of the relevant data sets for the OCR-VC can be found on the IOCCG website at http://www.ioccg.org/data/sensors.html. For VC-6, the vision and plan for an essential OCR-Virtual Constellation space segment (from polar and geostationary orbit) is scheduled to be defined for the next decade by the end of 2016 for CEOS. IOCCG has recently updated the listing, specifications and details of current and planned ocean-colour sensors, as documented at:

- current Sensors - http://www.ioccg.org/sensors/current.html
- planned Sensors - http://www.ioccg.org/sensors/scheduled.html

VC-1	List of relevant datasets from VCs	Q4 2014
VC-6	Vision and plan for an essential OCR Virtual Constellation space segment (Polar and GEO)	Q4 2016
VC-7	Catalogue of cal/val infrastructure and activities	Q2 2015
VC-8	Action plan for GEO Blue Carbon components	Q1 2015
VC-9	Implementation of the International Network for Sensor Intercomparison and Uncertainty Assessment for Ocean Colour Radiometry (INSITU-OCR)	Q1 2015
VC-10	Recommend the creation of a GEO Water Quality Community of Practice	Q2 2015

Table 7: Timetable for progress on the Ocean Colour Radiometry Virtual Constellation reported to the CEOS Strategic Implementation Team in March, 2015

O16: Implement wave measurement as part of the Surface Reference Mooring Network

Action: Implement a wave measurement component as part of the Surface Reference Mooring Network.

Who: Parties operating moorings, coordinated through the JCOMM Expert Team on Waves and Surges.

Time-Frame: Deployed by 2014.

Performance Indicator: Sea state measurement in the International Data Centres.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

Spectral wave measurements are now being made by two of the Surface Reference Mooring Network buoys and wave data can be inferred from two others. While other data from the Stratus and 55S, 95W buoys that are making the direct measurements are held by the designated Global Data Assembly Centres, the NOAA National Data Buoy Center and the IFREMER Coriolis centre, the wave data are not included in the data records. Based on the performance indicator, this action has clearly been unsuccessful, although the action is awarded a status of low progress given that some measurements are being taken. It has yet to be clarified where the wave data are being stored.

O17: Establish an international group to assemble data, and analyse surface currents

Action: Establish an international group to assemble surface drifting buoy motion data, ship drift current estimates, current estimates based on wind stress and surface topography fields; prepare an integrated analysis of the surface current field.

Who: OOPC will work with JCOMM and WCRP.

Time-Frame: 2014.

Performance Indicator: Number of global current fields available routinely.

Annual Cost Implications: <1M US$ (10% in non-Annex-I Parties).

Currently there are several national and regional groups working on surface currents, but there is no international group (beyond the EU) assembling observations into an integrated current field. Both NASA and ESA support projects (OSCAR and Globcurrent) to examine currents. There are also many ocean modelling communities (ECMWF, HYCOM, ROMS and others) that synthesise observations to produce surface-current products as part of more comprehensive analyses and reanalyses.

O18: Plan, establish and sustain systematic *in situ* observation in the Arctic and Antarctic

Action: Plan, establish and sustain systematic *in situ* observations from sea-ice buoys, visual surveys (SOOP and Aircraft), and ULS in the Arctic and Antarctic.

Who: Arctic Party research agencies, supported by the Arctic Council; Party research agencies, supported by CLIVAR Southern Ocean Panel; JCOMM, working with CliC and OOPC.

Time-Frame: Internationally-agreed plans published by end 2010, implementation build-up through 2014.

Performance Indicators: Publication of internationally-agreed plans, establishment of agreements/frameworks for coordination of sustained Arctic and Southern ocean observations, implementation according to plan.

Annual Cost Implications: Plan and agreement of frameworks: <1M US$; Implementation: 10-30M US$ (Mainly Annex-I Parties).

It is not easy to find a comprehensive summary of progress, status overview or approved plans for sustained *in situ* observations from websites such as those of CliC, IAOOS, Arctic ECRA and the Arctic Council/AMAP. There are, however, a growing number of infrastructure initiatives. One is the Norwegian Svalbard Integrated Earth Observing System (SIOS) project that would contribute to establish in the crucial area of the Svalbard Archipelago and surroundings an important node in the "Sustaining Arctic Observing Networks" process co-sponsored by the Arctic Council and the International Arctic Science Committee. SIOS is still subject to approval and funding, however. The EU Horizon 2020 framework programme has a call for proposals for submission in 2016 concerned with development of an integrated Arctic observing system.

The Arctic Science Summit Week (ASSW) is the annual gathering of the international organisations engaged in supporting and facilitating Arctic research. The purpose of the summit is to provide opportunities for coordination, collaboration and cooperation in all areas of Arctic science. The summit attracts scientists, students, policy makers and other professionals from all over the world. The 2015 meeting took place from 23-30 April in Toyama, Japan; its final report is not yet published.

CliC has a working group on Antarctic Sea Ice Processes and Climate (ASPeCt), which has a key objective of improving understanding of the Antarctic sea ice zone through focussed and ongoing field programmes, remote sensing and numerical modelling. The WCRP/SCAR International Programme for Antarctic Buoys (IPAB) maintains a network of drifting buoys in the Southern Ocean. IPAB works in close collaboration with ASPeCt, in particular over sea ice. More than 50 buoys were deployed in the Weddell Sea from June to August 2013 and January to March 2014. Buoys were of various types, and contributed by several institutions. Ten buoys were also deployed in the Ross Sea sector in February 2014. Data acquisition and analysis software for bridge-based observations of near-ship sea ice has been developed at the Australian Antarctic Division. It is designed to process data on both Arctic and Antarctic sea ice.

O19: Ensure sustained satellite-based (microwave, SAR, visible and IR) sea-ice products

Action: Ensure sustained satellite-based (microwave, SAR, visible and IR) sea-ice products.

Who: Parties' national services, research programmes and space agencies, coordinated through the WMO Space Programme and Global Cryosphere Watch, CGMS, and CEOS; National services for *in situ* systems, coordinated through WCRP CliC and JCOMM.

Time-Frame: Continuing.

Performance Indicator: Sea-ice data in International Data Centres.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

Satellite-based estimates of sea-ice extent, motion and other characteristics continue to be made and provided as gridded products through several centres. The long-term passive MW record currently continued by the SSMIS instrument on DMSP platforms (Figure 2) is expected be extended by data from instruments on the operational Chinese (FY-3) and European (Metop-SG) polar orbiters.

Continuity of European active MW sensing (scatterometer, SAR and altimeter) is secured into the mid-2020s and beyond from operational Metop and Sentinel platforms, with contributions expected also from NASA's ICESat-2 and Chinese missions. Funding for other instruments from the United States, Japan, and India is uncertain, but mission plans are under development. The European contributions will be sufficient for many applications related to sea ice. There is concern nevertheless at the loss of coverage near the North Pole once observations from CryoSat's high-inclination orbit cease.

O20: Document global sea-ice product uncertainty and plan improvements to products

Action: Document the status of global sea-ice analysis and reanalysis product uncertainty (via a quantitative summary comparison of sea-ice products) and to prepare a plan to improve the products.

Who: Parties' national agencies, supported by WCRP CliC and JCOMM Expert Team on Sea Ice (ETSI).

Time-Frame: By end of 2011.

Performance Indicators: Peer-reviewed articles on state of sea-ice analysis uncertainty; Publication of internationally-agreed strategy to reduce uncertainty.

Annual Cost Implications: <1M US$ (Mainly Annex-I Parties).

Extensive analyses and inter-comparisons of passive MW sea ice retrieval algorithms show close agreement on the strength of the negative trend in Arctic sea-ice area and extent (Ivanova *et al.*, 2014). However, they are individually biased from the mean varying from 0.481 to 0.559 million km^2 in area and 0.216 to 0.335 million km^2 in extent during the period 1979–2012. In comparison they vary from 0.359 to 0.422 million km^2 in area and 0.167 to 0.208 million km^2 in extent for the period 1992–2012.

A subset of the CMIP5 simulations have been used to investigate the Arctic sea-ice decline and ice export for the period 1957-2005 (Langehaug *et al.*, 2013). Both SAR observations and NCEP reanalysis data were used for inter-comparison and validation. In particular it was found that the different CMIP5 ensemble members do not reproduce the same positive long-term trend for the sea ice export as revealed in the NCEP data. Within the Copernicus Marine Service there are extensive plans for reanalyses of the changes and variability of high-latitude seas and the Arctic Ocean.

O21: Establish plan for and implement global Continuous Plankton Recorder surveys

Action: Establish plan for, and implement, global Continuous Plankton Recorder surveys.

Who: Parties' national research agencies, working with SCOR and GOOS/OOPC.

Time-Frame: Internationally-agreed plans published by end 2010; implementation build-up through 2014.

Performance Indicators: Publication of internationally-agreed plans; establishment of agreements/frameworks for coordination of sustained global Continuous Plankton Recorder surveys; implementation according to plan.

Annual Cost Implications: 10-30M US$ (Mainly by Annex-I Parties).

The Continuous Plankton Recorder (CPR) survey in the North Atlantic is recognised as the longest sustained and geographically most extensive marine biological survey in the world. It has operated since 1931. The dataset comprises a uniquely large record of marine biodiversity covering around 1000 taxa over multi-decadal periods. While the North Atlantic is the longest running CPR survey there are a number of large independent surveys operating around the world, for example the Southern Ocean CPR survey. The establishment of a global network of CPR surveys with a centralised database has been a collective long-term goal. In 2011 the Global Alliance of CPR Surveys (GACS) was formed to initiate a more shared and collective global vision. As well as traditionally providing phytoplankton and biological data, most CPR tows also record a number of physical variables and chlorophyll along their tracks.

The key aim of the GACS is to understand changes in plankton biodiversity and key planktonic indicators at ocean basin scales through a global network of CPR surveys. The initial vision was to unify all the data collected by various CPR surveys around the world into a centralised global database, thus enabling scientists to monitor and understand global plankton changes. GACS has a number of specific aims which include:

- development of a global CPR database (established in 2011);
- production of a regular global marine status report (first published in 2011);
- ensuring common standards and methodologies are maintained;
- providing an interface for plankton biodiversity with other global ocean observation programmes;
- setting up and maintaining a website for publicity and data access;
- facilitating new surveys and developing capacity building procedures;
- facilitating secondments of CPR scientists between GACS institutions.

GACS brings together the expertise of approximately 60 plankton specialists, scientists, technicians and administrators from 14 laboratories around the world, which tow a common and consistent sampling tool, the CPR, from about 50 vessels. Working together, pooling data and resources, was considered essential in order to understand the effects of environmental changes on plankton biodiversity at a global level. Numerous local and regional monitoring and observational programmes have been established in the past, but to date there has been lack of a holistic perspective on plankton biodiversity in response to global events such as climate warming and ocean acidification. GACS will provide that perspective using CPR data, a well-recognised and standardised methodology. It will also allow changes and events at a local or regional level to be assessed in a world-wide context.

Ten regional surveys have currently joined GACS, with the most recent surveys being Australia, New Zealand and South Africa. Regional surveys are also being developed, with GACS support, by France, Brazil, Japan, Cyprus, India and South Korea. The global database has been developed, as well as the website www.globalcpr.org. GACS has established links or formal affiliations with a number of key international stakeholders including SCOR, GCOS, GEOBON, SCAR, GOOS, SOOS, POGO and PICES. At present, there are large areas of the world's oceans, notably the sub-tropical and tropical regions of the Atlantic, Pacific and Indian Oceans where there are no regular CPR surveys or plankton monitoring in general. GACS aims to improve coverage in those areas and hence has the specific aims mentioned above of facilitating new surveys and capacity building. The current performance indicators of GACs include a biannual Global Marine Ecological Status Report which summarises ecological indicators and operational developments. The ecological indicators employed by GACs are closely aligned with developing EOVs (Essential Ocean Variables) and EBVs (Essential Biodiversity Variables) as well as the ECVs.

O22: Develop technology for underway plankton survey capabilities

Action: Develop technology for underway plankton survey capabilities.

Who: Parties' national research agencies, working with SCOR and GOOS/OOPC.

Time-Frame: Continuous.

Performance Indicators: Successful pilot deployment of new technologies.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

The SeaFlow flow-cytometer for continuous observations of phytoplankton was presented at conferences in 2011. Whilst this seems to have been successfully deployed in a trial, little progress has been visible since that deployment.

O23: Establish network for collocated physical, biological and ecological measurements

Action: Establish a global network of long-term observation sites covering all major ocean habitats and encourage collocation of physical, biological and ecological measurements.

Who: Parties' national research and operational agencies, supported by GOOS/PICO, OOPC, GRAs, and other partners.

Time-Frame: 2014.

Performance Indicators: Reporting on implementation status of network.

Annual Cost Implications: 30-100M US$ (50% in non-Annex-I Parties).

OceanSITES has been working to flesh out and get traction on a proposed global sparse array of time series moorings with comprehensive multidisciplinary sensor payloads, called MOIN. OceanSITES put a higher initial priority on raising funds for its deep ocean temperature and salinity sampling, however. Although it has been successful at getting a pool of instruments to implement that, it has not made as much progress on getting financial support for MOIN.

The Ocean Observatories Initiative (see also Action O5) is supporting the fielding of quite a wide suite of multidisciplinary sensors that is providing valuable experience of the viability of long-term moored deployments of such sensors. This will guide which sensors to deploy more widely. FixO3 and EMSO and other efforts are pushing the sensor envelope further as well. Satellites also contribute to surface coverage of physical and ocean colour data.

O24: Develop full-depth water-column sampling for physical and carbon variables

Action: Development of a plan for systematic global full-depth water column sampling for ocean physical and carbon variables in the coming decade; implementation of that plan.

Who: National research programmes supported by the GO-SHIP project and IOCCP.

Time-Frame: Continuing.

Performance Indicator: Published internationally-agreed plan from the GO-SHIP process, implementation tracked via data submitted to archives. Percentage coverage of the sections.

Annual Cost Implications: 10-30M US$ (Mainly by Annex-I Parties).

General progress of the GO-SHIP repeat hydrography is presented in section 5.2.2.

The GO-SHIP Committee has defined the hydrographic sections along which a specified set of physical and carbon variables should be measured as internationally agreed Reference Sections (http://www.go-ship.org/RefSecs/goship_ref_secs.html). The GO-SHIP Committee Executive Group has separated physical and carbon variables into three levels of different importance and timelines for submission of data to CCHDO (http://www.go-ship.org/DatReq.html). Level-1 data are of highest priority and should be collected at least once per decade along all Reference Sections. Level-2 data are highly desirable as augmentation and addition and should be collected as possible. The information on planned and recent GO-SHIP cruises is available at the GO-SHIP website (http://www.go-ship.org/CruisePlans.html; see also Figure 44) to facilitate cruise planning by national research programmes. Development of the decadal sampling plan is not completed but evolving with the support by the GO-SHIP process as described above. Implementation can be tracked at the CCHDO website, while percentage coverage of the desired global sampling is not obvious.

The GO-SHIP level-1 data are: any two of dissolved inorganic carbon (DIC), total alkalinity and pH; CTD pressure, temperature, salinity (calculated); CTD oxygen (sensor); bottle salinity; nutrients by standard auto analyzer (NO_3/NO_2, PO_4, SiO_3); dissolved oxygen; chlorofluorocarbons (CFC-11, -12, -113) and SF_6; surface underway system data on temperature, salinity and pCO_2; shipboard and lowered ADCP; underway navigation and bathymetry data; and meteorological data.

The level-2 data are: discrete pCO_2; 14C by AMS; CCl_4 ; ∂13C of DIC; DIC; dissolved organic nitrogen; Fe/trace metals; CTD transmissometer data; surface underway system data on pCO_2, nutrients, O_2, Chl-Pod vertically resolved temperatures and skin temperature.

Particular discussion in the case of measurement of carbon dioxide partial pressure, including evidence of the need to reassess the plan, is given in section 5.4.5.

O25: Sustain the ship-of-opportunity XBT/XCTD transoceanic network

Action: Sustain the Ship-of-Opportunity XBT/XCTD transoceanic network of about 40 sections.

Who: Parties' national agencies, coordinated through the Ship Observations Team of JCOMM.

Time-Frame: Continuing.

Performance Indicator: Data submitted to archive. Percentage coverage of the sections.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

A subset of some 25 lines are ongoing. However, there are challenges securing ships on regular routes. While the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) provides the information (http://www.aoml.noaa.gov/phod/goos/xbtscience/reportsumm.php) on annual XBT deployment and transects by month, these statistics are unlikely to be complete. This is because some XBT agencies send operational metadata only to AOML, some agencies send these data only to JCOMMOPS and some do not share their data at all. An international yearly SOOP survey analysing the global performance, coordinated by JCOMMOPS and based on metadata sent to JCOMMOPS by all operators, could thus not be produced for a couple of years, as no repository currently comprises all data. Following a SOT decision in April 2015, AOML will now send all metadata they have on a regular basis to JCOMMOPS, where they will be merged with all other available data. An *ad hoc* task team with members from all countries deploying XBTs will help the setting up of an appropriate collection procedure and format, and the production of the yearly SOOP survey will be resumed as soon as possible.

O26: Sustain the network of about 3000 Argo global profiling floats

Action: Sustain the network of about 3000 Argo global profiling floats, reseeding the network with replacement floats to fill gaps, and maintain density (about 800 per year).

Who: Parties participating in the Argo Project and in cooperation with the Observations Coordination Group of JCOMM.

Time-Frame: Continuous.

Performance Indicator: Number of reporting floats. Percentage of network deployed.

Annual Cost Implications: 30-100M US$ (10% in non-Annex-I Parties).

Sustaining the Argo array has been successfully achieved, with over 3900 floats as of September 2015, and Argo coverage extending into marginal seas and the high-latitude oceans (using ice-capable floats with ruggedized antennae or ice avoidance algorithms). Deployments are targeted where gaps open up in the array, and in regions where floats are ageing. Future development of Argo observations are being discussed in the context of a range of 'future Argo enhancements' which include regional enhancements (with revised coverage targets in the marginal seas, equatorial region and boundary currents), as well as biogeochemical and deep pilot projects. Further discussion is given in section 5.2.1.

O27: Complete implementation of the current Tropical Moored Buoy Network

Action: Complete implementation of the current Tropical Moored Buoy, a total network of about 120 moorings.

Who: Parties national agencies, coordinated through the Tropical Mooring Panel of JCOMM.

Time-Frame: Array complete by 2011.

Performance Indicator: Data acquisition at International Data Centres.

Annual Cost Implications: 30-100M US$ (20% in non-Annex-I Parties).

The decline of the Tropical Moored Buoy networks is documented in section 5.2.4. The remedial maintenance of the TAO array in the second half of 2014 and establishment of the TPOS2020 project are acknowledged as important, but the net reduction from 79% of the planned array reported in GCOS (2009) to 66% in December 2014 causes this action to be placed in the lowest category.

A new concern is that TAO buoy location data (to the nearest 0.1 degree) are being transmitted only through the GTS. The locations are masked in data archives, which hold only the ‘design’ rather than 'actual' locations. The move is part of plans to counter vandalism. This situation needs further investigation to determine if the locations will be unmasked after some period.

O28: Develop a composite reference reanalysis dataset and ocean reanalysis projects

Action: Develop projects designed to assemble the *in situ* and satellite data into a composite reference reanalysis dataset, and to sustain projects to assimilate the data into models in ocean reanalysis projects.

Who: Parties' national ocean research programmes and space supported by WCRP.

Time-Frame: Continuous.

Performance Indicator: Project for data assembly launched, availability and scientific use of ocean reanalysis products.

Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

A single, composite reference dataset for ocean reanalysis has not been assembled, but there has been progress in the generation, reprocessing and gathering together of the disparate component datasets needed to undertake ocean reanalysis. For example, Good *et al*. (2013) describe the development of the EN4 dataset of temperature and salinity profiles. Data were assembled from a number of databases, and duplicate removal, bias adjustments and quality control were applied. The earlier EN3 database was used in ECMWF's latest ORAP5 reanalysis (Xuo *et al*., 2015); EN4 will be used in ECMWF's forthcoming ORAS5 reanalysis. ORAP5 also made use of an altimetry data from AVISO, a bottom-pressure climatology from GRACE gravimetric measurements, SST and sea-ice data from OSTIA, additional SST data from NOAA, and surface forcing data from ERA-Interim.

CLIVAR/GSOP is leading an internationally-coordinated effort for coordinated quality-control of global sub-surface ocean climate observations, the International Quality-Controlled Ocean Database (IQuOD) effort (http://www.iquod.org). The main goal of the IQuOD initiative is to produce and freely distribute the highest quality, complete and consistent historical sub-surface ocean temperature global database, along with metadata and assigned uncertainties, and some downstream added-value products. Future, plans include extension of a similar effort to other sub-surface ocean variables, such as salinity, oxygen and nutrients. The project structure and work plan have been developed with exchanging scientific and technical information among participating institutions and agencies through several meetings organized so far. Several institutions have contributed in terms of data sharing and project development, but general funding for this activity has yet to be secured.

O29: Develop autonomous observation of biogeochemical and ecological variables

Action: Work with research programmes to develop autonomous capability for biogeochemical and ecological variables, for deployment on OceanSITES and in other pilot project reference sites.

Who: Parties' national ocean research programmes, in cooperation with the Integrated Marine Biogeochemistry and Ecosystem Research, Surface Ocean – Lower Atmosphere Study, and Land-Oceans Interactions in the Coastal Zone of IGBP.

Time-Frame: Continuing.

Performance Indicators: Systems available for measuring pCO_2, ocean acidity, oxygen, nutrients, phytoplankton, marine biodiversity, habitats, with other ecosystem parameters available for use in reference network applications.

Annual Cost Implications: 1-10M US$ (50% in non-Annex-I Parties).

There has been rapid progress in the development and testing of bio-optical sensors, which are routinely part of the payload for ocean gliders, are used on some OceanSITES moorings and are being tested on some Argo floats. Oxygen, pH and bio optical sensors are being piloted on Argo floats; there were 279 Bio-Argo floats in the Argo array at the end of June 2015. The GOOS Biogeochemistry Panel is involved in testing and evaluating these sensors, and also held a summer school in 2015 focussed on their use. http://www.ioccp.org/index.php/instruments-and-sensors provides further details of bio-geochemical sensors.

O30: Deploy a global pilot project of oxygen sensors on profiling floats

Action: Deploy a global pilot project of oxygen sensors on profiling floats.
Who: Parties, in cooperation with the Argo Project and the Observations Coordination Group of JCOMM.
Time-Frame: Continuous.
Performance Indicator: Number of floats reporting oxygen.
Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

Argo statistics for September 2015 show 280 active floats equipped with oxygen sensors (Figure 43). No specific target for the total number or density of oxygen floats has been developed, and routine quality-control processes require additional attention and resources. The SCOR Working Group was funded to work on developing data quality control procedures for Argo floats with oxygen sensors. Plans for the future deployment and coordination of floats with oxygen sensors are being discussed in the context of a range of 'future Argo enhancements' which include high-latitude, regional, biogeochemical and deep-observing pilot projects. The SOCCOM project (see Action O14) includes floats with these sensors.

O31: Monitoring the implementation of the IOC Data Policy

Action: Monitoring the implementation of the IOC Data Policy.
Who: JCOMM.
Time-Frame: Continuous.
Performance Indicator: Reports by JCOMM and IODE to the IOC.
Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

Assessment of this action is based on a JCOMM Data Management Programme Area report on data systems relevant to JCOMM activities. In nearly all cases data from the ocean observing systems are being provided in a timely fashion, free, and unrestricted for international exchange, fulfilling the IOC Data Policy; however, many data portal services are in need of improvement and some data assets need formalised connections to the suite of JCOMM-monitored observing systems. One example of the need for improvement is provided by TSG data, which are collected from many SOT ships, but the collection is not brought together anywhere. ADCP data also lack coordination that would increase their access and value in SOT-SOOP. Ocean glider data are becoming important but do not yet have a coordinating hub. Increasing the impact of the OceanSITES programme on research could be achieved by including the observations into readily accessible global collections that maintain source-record tracking, such as the WOD and ICOADS.

The EU-funded Ocean Data Interoperability Platform (ODIP) is a project that started in 2012 with the aim of contributing to the removal of barriers hindering the effective sharing of data across scientific domains and international boundaries. ODIP includes the major organisations engaged in ocean data management in EU, US, and Australia. ODIP is also supported by the IODE.

O32: Develop and implement comprehensive ocean data management procedures

Action: Develop and implement comprehensive ocean data management procedures, building on the experience of the JCOMM Pilot Project for WIGOS.

Who: IODE and JCOMM.

Time-Frame: 2012.

Performance Indicator: Improved standards and accessibility of ocean data; Report of the 4th session of JCOMM.

Annual Cost Implications: 1-10M US$ (20% in non-Annex-I Parties).

This action identifies the agents for implementation for data topics. JCOMM is establishing a Task Team for Integrated Marine Meteorological and Oceanographic Services within WIS (TT-MOWIS). The goal is to provide interoperability with the WIS of the operational marine meteorological and ocean forecasting systems. JCOMM Expert Team on Marine Climatology (ETMC) is also working on the implementation of the Marine Climate Data System (MCDS), as discussed in the review of Action O38.

O33: Undertake a project to develop an international standard for ocean metadata

Action: Undertake a project to develop an international standard for ocean metadata.

Who: IODE and JCOMM in collaboration with WMO CBS and ISO.

Time-Frame: Standard developed by 2011.

Performance Indicator: Publication of standard for an agreed initial set of the ECVs. Plan to progress to further ECV.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

The ODIP will at least partially address this issue through the goal of data interoperability. Work undertaken by JCOMM-IODE Expert Team on Data Management Protocols (ETDMP) has resulted in limited success. There are several ship-related projects such as R2R, Value Added ICOADS (IVAD) and IQuOD that are seeking to standardize and improve the availability of metadata. WIGOS will also consider third-party data sources in its work plan, and JCOMM is establishing a Task Team for Integrated Marine Meteorological and Oceanographic Services within WIS (TT-MOWIS) as noted for Action O32. Funding for these efforts is poor to non-existent for historical data.

O34: Apply innovations to develop ocean data exchange and use

Action: Undertake a project to apply the innovations emerging from the WMO Information System, and innovations such as OPeNDAP to develop an ocean data transport system for data exchange between centres and for open use by the ocean community generally.

Who: JCOMM.

Time-Frame: Report by 2012.

Performance Indicator: Report published.

Annual Cost Implications: <1M US$ (10% in non-Annex-I Parties).

ODIP and other groups are setting standards. NetCDF is usually the standard for data storage. However, there are other formats for satellite data, and some sub-surface ship data are stored in Excel files. OPenDAP is one standard for transporting data over the net. The community is moving increasingly to Web data services. As noted for Actions O32 and O33 JCOMM is establishing the TT-MOWIS. Movement to storage formats that are relatively easy to access over the web (e.g. netCDF) is highly desired. Progress is nevertheless slower than expected in IP-10, which envisaged a project report by 2012.

O35: Plan and implement a system of data and analysis centres for each ocean ECV

Action: Plan and implement a system of regional, specialized and global data and analysis centres for each ocean ECV.

Who: Parties' national services under guidance from IODE and JCOMM.

Time-Frame: Plan finished by 2012, implementation following.

Performance Indicator: Plan published; access to data streams by ECV

Annual Cost Implications: 10-30M US$ (30% in non-Annex-I Parties).

Little or no progress has been made on this action. A view has been expressed that the action was premature or inadvisable; this should be reconsidered in the formulation of the 2016 Implementation Plan by the GCOS programme.

O36: Support data rescue projects

Action: Support data rescue projects.

Who: Parties' national services with coordination by IODE through its GODAR project.

Time-Frame: Continuing.

Performance Indicator: Datasets in archive.

Annual Cost Implications: 1-10M US$ (30% in non-Annex-I Parties).

JCOMM's work on the implementation of the Marine Climate Data System is discussed in the review of Action O38. Progress on data rescue through this route has been very limited because it has taken until now for the first of the Centres for Marine Meteorological and Oceanographic Climate Data to be established. Another issues is that the Global Oceanographic Data Archaeology and Rescue project has been discontinued. In summary, data rescue efforts needs rescuing. Efforts such as IQuOD and IVAD, which restore metadata to the data record are also a critically important part of making good use of the historical data.

O37: Develop telecommunications, two-way for dynamic control of observation

Action: Develop enhanced and more cost-effective telecommunication capabilities, including two-way communications for dynamic control of systems, instruments and sensors.

Who: Parties, coordinated through JCOMM.

Time-Frame: Continuing.

Performance Indicator: Capacity to communicate data from ocean instrumentation to ocean data centres.

Annual Cost Implications: 1-10M US$ (50% in non-Annex-I Parties).

There have been several successes in improving telecommunications, such as Iridium and Argos 2, 3 and 4. Establishment of a SATCOM forum of users of satellite data telecommunication systems is progressing well under WMO CBS leadership. A workshop and an *ad hoc* forum have been held, and implementation was requested by the Seventeenth World Meteorological Congress in June 2015.

Sensor observations from many research vessels are delivered in near-real time. This timeliness has allowed for rapid identification of issues with data. Consequently, rapid communication with ship technicians often results in the problems being resolved with little loss of high-quality data.

O38: Develop plans and coordinate work on data assembly and analyses

Action: Develop plans for, and coordinate work on, data assembly and analyses.

Who: JCOMM and IODE, in collaboration with CLIVAR, CliC, WOAP, GODAE, and other relevant research and data management activities.

Time-Frame: 2013.

Performance Indicator: Number of ocean climatologies and integrated datasets available.

Annual Cost Implications: <1M US$ (Mainly by Annex-I Parties).

WCRP data management issues are discussed by its Data Advisory Council (WDAC). CLIVAR has a Data Policy (http://www.clivar.org/resources/data/data-policy) and endorsed projects need to follow it. Synthesis of ocean data (analysis of the ocean) is coordinated through the Global Synthesis and Observations Panel Ocean Reanalysis Intercomparison Project, as discussed in the review of Action O39.

WCRP is currently developing a WDAC Flux Task Team to address flux issues across its programme. WDAC also promotes the obs4MIPs and ana4MIPs initiatives, which make data products available for use in model evaluation. A number of ocean products are candidates for near-term publication under these initiatives.

The JCOMM Expert Team on Marine Climatology is also working on the implementation of the Marine Climate Data System (MCDS), its data flow and the integration of products through Centres for Marine Meteorological and Oceanographic Climate Data (CMOCs). Establishment of the first CMOC was approved by the Seventeenth World Meteorological Congress. It will be located at the National Marine Data and Information Service of the Chinese State Oceanic Administration. This work is a JCOMM-IODE Cooperation, where IODE NODCs, and IODE GDACs have a role to play. It is also one of JCOMM's contribution to the GFCS.

Many ECVs are also associated with international science teams or groups (such as the satellite constellation science teams), and these teams or groups often produce multiple synthesis products. These products are often optimized for specific applications, and can have quite different strengths and weaknesses. The intention is that the CMOCs will work with these groups and to compare the products.

O39: Develop plans and pilot projects for global products based on data assimilation

Action: Develop plans and pilot projects for the production of global products based on data assimilation into models. All possible ECVs.

Who: Parties’ national services and ocean research agencies, through CLIVAR, the CLIVAR Global Synthesis and Observations Panel, and GODAE.

Time-Frame: 2013.

Performance Indicator: Number of global oceanic climate analysis centres.

Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

The situation concerning international coordination of the generation of products by data assimilation and of the inter-comparison of products is reported here. The undertaking of reanalysis projects was called for in IP-10 Action O40. Global products are also generated by operational forecasting activities.

GODAE OceanView (GOV) fosters and coordinates the development of new ocean monitoring, modelling and assimilation systems for ocean forecasting on a global and regional scale both for operational and for research applications with the goal of improved accuracy and utility of ocean analysis and forecasting products. It provides international coordination and leadership in the testing of the next generation of ocean analysis and forecasting systems, covering bio-geochemical and eco-systems as well as physical oceanography, and extending from the open ocean into shelf seas and coastal waters. Contributors to this effort are the GOV national and regional operational ocean forecasting centres (https://www.godae-oceanview.org/science/ocean-forecasting-systems/) and specific science task teams. GOV promotes access to data and information products and enhanced uptake of ocean analysis and forecasting products with governments, the public and private sectors, for example the provision of products to the European Copernicus Marine Service.

The Ocean Reanalysis Intercomparison Project (ORA-IP), started in 2006 and several workshops have been organised in order to evaluate products and discuss ways forward, under the original framework set out in http://www.clivar.org/sites/default/files/documents/GSOP_global_intercomp_V2_1.pdf. In 2011, a joint workshop with GOV set stronger collaborations between CLIVAR/GSOP and GOV, in addition to the development of a new phase of the ORA-IP project. A joint GOV CLIVAR/GSOP workshop on inter-comparison of reanalyses was held in 2013 (https://www.godae-oceanview.org/outreach/meetings-workshops). ORA-IP currently relies on individual ocean synthesis groups to provide the diagnostic outputs (such as heat content distribution) to individual volunteers to analyse the ensemble results. A central repository for ocean synthesis products that have a standard format (CF compliant, for example) has been identified as desirable, but has not been resourced. The Integrated Climate Data Center at the University of Hamburg has a prototype Ocean Synthesis Directory. This also requires individual groups to prepare their output in standard format and share it freely with the community. Some groups are constrained in doing this by the policy of their sponsor or institution.

O40: Undertake pilot projects of reanalysis of ocean data

Action: Undertake pilot projects of reanalysis of ocean data.
Who: Parties’ national research programmes, coordinated through OOPC and WCRP.
Time-Frame: 2010.
Performance Indicator: Number of global ocean reanalyses available.
Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

Ocean reanalysis has progressed beyond the stage of pilot projects. Progress is discussed in section 3.6 and the review of Action C12.

O41: Promote research and development in support of the global observing system

Action: Promote and facilitate research and development (new improved technologies in particular), in support of the global ocean observing system for climate.

Who: Parties' national ocean research programmes and space agencies, in cooperation with GOOS, GCOS, and WCRP.

Time-Frame: Continuing.

Performance Indicator: More cost-effective and efficient methods and networks; strong research efforts related to the observing system; number of additional ECVs feasible for sustained observation; improved utility of ocean climate products.

Annual Cost Implications: 30-100M US$ (10% in non-Annex-I Parties).

The envisaged promotion and facilitation is ongoing, in the context of the Framework for Ocean Observing. Emerging observation platforms include gliders, unmanned surface vehicles such as wavegliders, profiling moorings, biogeochemical sensors and new satellite missions. OOPC's evaluations of the observing system have a strong focus on the role of new technologies to fill gaps, lower costs or expand range of variables measured. The JCOMM OCG are also reaching out to emerging observing networks to engage them in technical coordination activities focussed on standards and best practices, capitalising on the synergies between the networks.

Space-based observation of ocean salinity is one example of success, although the observations are of substantially lower accuracy for very cold water. Several new concepts are in development for satellite observations of surface vector currents, involving Doppler scatterometers and the Wavemill MW interferometric SAR. The Deep Ocean Observing Strategy (DOOS) is a GOOS project that is in the early stages of development; it has the goal of improving observation from below 2000 m depth to near the sea floor. Pilot Argo floats are being tested up to 4000 and 6000 m depth, and a future network is a likely key component of the DOOS.

Terrestrial actions

T1: Develop and promote observational standards and protocols for the terrestrial ECVs

Action: Ensure the development of observational standards and protocols for the each of the terrestrial ECVs; promote adoption of standards on a national level.

Who: GTOS, in conjunction with the sponsors of the UN/ISO terrestrial framework (WMO, FAO, ICSU, UNEP, and UNESCO).

Time-Frame: Develop a work plan for the development of standards by 2010; UN/ISO framework implemented by 2012; national-level adoption of standards by 2014

Performance Indicator: Number of terrestrial ECVs with international standards; uptake of standards by Parties (percentage of terrestrial ECV observations following standards).

Annual Cost Implications: <1M US$, increasing to 1-10M US$ (Mainly by Annex-I Parties).

While there has been good progress in developing standards and protocols for several individual ECVs, as discussed in places in section 6.3 and in the reviews of other IP-10 actions, there has not been the coordinated progress envisaged for this action. This is largely because of the absence of support from the FAO for a functioning secretariat and steering committee for GTOS for the past three or more years. This resulted in a lack of leadership and hence progress on this and several other actions. The intentions of the FAO and its fellow sponsors for the future of GTOS remain to be clarified.

GTOS published in 2008 and 2009 a series of documents recording existing standards and practices for terrestrial ECVs. This was considered by TOPC to be a very valuable contribution. These documents, and their hosting GTOS website, are now in urgent need of updating.

The approach to developing standards also became a matter of discussion. As noted in section 6.2.1, GTOS was working with ISO to produce measurement standards for each ECV. However, members of TOPC had a number of serious reservations about this approach, at least at the current state of development of terrestrial observations, when it was discussed at the 13th and 14th sessions of the panel. Arguments are set out in the reports of the sessions (http://www.wmo.int/pages/prog/gcos/). Further debate was cut short when the GTOS Secretariat ceased to function.

T2: Promote exchange of hydrological data and development of integrated products

Action: Achieve national recognition of the need to exchange hydrological data of all networks encompassed by GTN-H, in particular the GCOS/GTOS baseline networks, and facilitate the development of integrated hydrological products to demonstrate the value of these coordinated and sustained global hydrological networks.

Who: GTN-H Coordinator, WMO, GCOS, GTOS, in consultation with GTN-H Partners.

Time-Frame: Continuing; 2011 (demonstration products).

Performance Indicator: Number of datasets available in International Data Centres; Number of available demonstration products.

Annual Cost Implications: <1M US$ (Mainly by Annex-I Parties).

Progress has been achieved insofar as the nations represented at the Seventeenth World Meteorological Congress agreed in 2015 a resolution on the international exchange of climate data and products to support the implementation of the GFCS. Annex 1 of the resolution explicitly identifies*, inter alia*, climate relevant satellite data and products and climate relevant cryospheric data, in particular snow cover, snow depth and glacial monitoring, as necessary to enable society to manage better the risks and opportunities arising from climate variability and change for all nations, especially for those who are most vulnerable to climate-related hazards. These data should be made accessible among Members on a free and unrestricted basis. The Congress also resolved that the climate data and products covered by Resolution 40 (Cg-XII) and the GFCS relevant data and products subsumed under Resolution 25 (Cg-XIII) relating to hydrological data will continue to be governed respectively by these two resolutions.

The GTN-H encompasses networks for nine ECVs: precipitation, water vapour, river discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, and soil moisture. With regard to cryospheric variables, the affiliated network of networks is GTN-G. The availability of data for these variables and issues of inadequate observational coverage and data exchange are discussed in sections 4.3 and 6.3, and in the reviews of specific IP-10 actions related to them given in this Appendix. Discussion includes where possible the availability of data products based on some degree of integration.

The GTN-H in principal also includes evapotranspiration, for which discussion is given below in the review of IP-10 Action T5. GTN-H is also affiliated with GNIP (the Global Network of Isotopes in Precipitation) of the IAEA and WMO.

T3: Develop a global terrestrial reference network of monitoring sites

Action: Development of a subset of current LTER and FLUXNET sites into a global terrestrial reference network for monitoring sites with sustained funding perspective, and collocated measurements of meteorological ECVs; seek linkage with Actions T4 and T29 as appropriate.

Who: Parties' national services and research agencies, FLUXNET organizations, NEON, and ICOS, in association with CEOS WGCV, CGMS-GSICS, and GTOS (TCO and TOPC).

Time-frame: Implementation started by 2011, completed by 2014.

Performance Indicator: Plan for the development and application of standardised protocols for the measurements of fluxes and state variables.

Annual Cost Implications: 30-100M US$ (40% in non-Annex-I Parties).

Although FLUXNET and LTER continue to function, there has been little progress towards establishment of a subset of reference sites as a global network.

The issues to be addressed in establishing such a network were discussed and reported by TOPC in 2011. The most important issue was to secure long-term funding for a selected set of sites to make the full suite of observations following a common protocol or set of standards. Some progress was reported to be being made through Ameriflux, ICOS, NEON and some other continental flux networks. The second, related issue was the lack of a well-funded international data centre to hold the database. Data centres operated regionally, sometimes on the basis of short term and limited funding with no institutional arrangement in place for keeping the data for the longer term. The third issue was that of limited public availability of data. Considerable progress in harmonisation of a subset of data had been achieved, but access to these data was not easy for the outside community. Aside from efforts to open up databases, progress was foreseen to be made by following the GRUAN model, which would involve selecting a small number of stations and defining the list of requirements to provide a specific basis to put forward for national and international funding. Commitments would also be needed to support a management structure and data centre.

Following lack of progress of a joint proposal by TOPC and GTOS in 2012 for ESA support for a network of ecosystem reference sites for cal/val of related satellite data and products, the 2013 TOPC session gave support to a proposal from the CEOS WGCV LPV Subgroup for a new attempt to promote such a network to CEOS as a whole.

T4: Initiate a monitoring network acquiring "Essential Ecosystem Records"

Action: Initiate an ecosystem monitoring network acquiring "Essential Ecosystem Records" (see section 3.8), by exploiting collocation opportunities with the global terrestrial reference network (Action T3) and the network of validation sites (T29).

Who: Parties' national services and research agencies, GTOS (Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD)), TOPC, GEOBON, in association with the UNCBD.

Time-frame: Network concept and observation approach by 2011; Implementation by 2014.

Performance Indicator: Availability of essential ecosystem records, including proper documentation, from all designated sites in the network.

Annual Cost Implications: 30-100M US$ (50% in non-Annex-I Parties).

Very little progress has been possible on Action T4 due to lack of progress on the related Action T3 and the inactive state of the GTOS Secretariat and Steering Committee (Action T1). Of some relevance is the development by the Group on Earth Observations Biodiversity Observation Network (GEOBON) of a system of Essential Biodiversity Variables (EBVs; Pereira *et al*., 2013, and Figure 98) building on the ECV concept. The Convention on Biological Diversity (CBD) has invited GEOBON to continue its work on the identification of EBVs and the development of associated data sets to support the meeting of their Ad Hoc Technical Expert Group on Indicators for the Strategic Plan for Biodiversity 2011-2020. Although these EBVs are not yet linked to a global reference network of monitoring sites, they provide a basis for monitoring programmes worldwide.

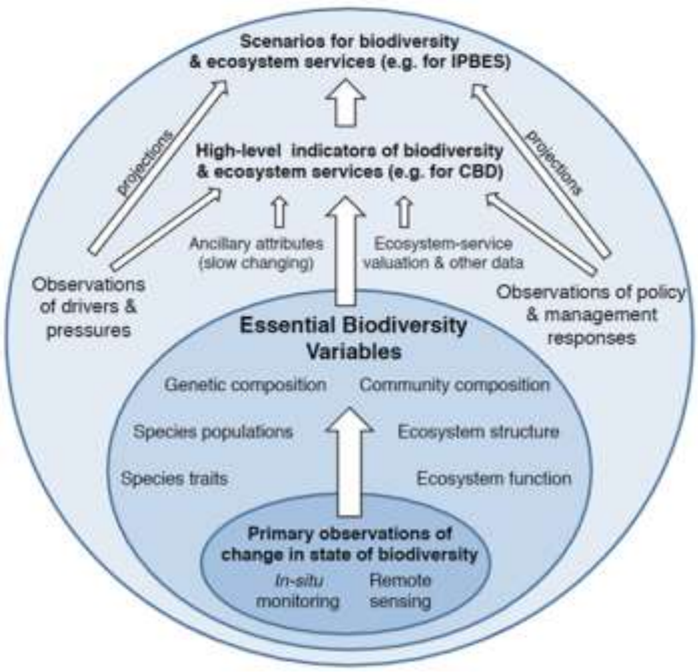


Figure 98: The concept of Essential Biodiversity variables. Source: Pereira et al. *(2013).*

T5: Develop an evaporation product from existing network and satellite observations

Action: Develop an experimental evaporation product from existing networks and satellite observations.

Who: Parties, national services, research groups through GTN-H, IGWCO, TOPC, GEWEX Land Flux Panel and WCRP CliC.

Time frame: 2013-2015.

Performance indicator: Availability of a validated global satellite product of total evaporation.

Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

A product-evaluation activity has been undertaken in the framework of the GEWEX LandFlux initiative. As noted at http://www.iac.ethz.ch/groups/seneviratne/research/LandFlux-EVAL, the following types of dataset were considered:

- remote-sensing products;
- land-surface modelling products;
- reanalyses (ERA, JRA, MERRA, NCEP);
- diagnostic estimates from the atmospheric water balance;
- products derived from flux measurements.

One outcome of the activity was a set of monthly benchmark products based on synthesis of the various individual datasets that were available for the periods 1989-1995 and 1989-2005 (Mueller *et al*., 2013). Results confirmed earlier findings of an increase in evapotranspiration from 1989 to 1997 and a decrease thereafter, notwithstanding uncertainties in absolute values. Improved data on input variables, especially precipitation, as well as better parameterizations of evapotranspiration were identified as being needed in order to reduce uncertainties.

T6: Determine status of river gauges and ensure prompt supply of discharge data

Action: Confirm locations of GTN-R sites, determine operational status of gauges at all GTN-R sites, and ensure that the GRDC receive daily river discharge data from all priority reference sites within one year of their observation (including measurement and data transmission technology used).

Who: National Hydrological Services, through WMO CHy in cooperation with TOPC, GTOS and the GRDC.

Time-Frame: 2011.

Performance Indicator: Reports to WMO CHy on the completeness of the GTN-R record held in the GRDC including the number of stations and nations submitting data to the GRDC, National Communication to UNFCCC.

Annual Cost Implications: 1-10M US$ (60% in non-Annex-I Parties).

Development of the GTN-R is proceeding, but progress is slow due to limited resources and the reluctance of many national hydrological services to contribute to the GTN-R by verifying the station selection and providing river discharge data in a timely fashion. The status of this action is otherwise fully covered by the material presented in section 6.3.1

T7: Assess national needs for river gauges to support impact assessments and adaptation

Action: Assess national needs for river gauges in support of impact assessments and adaptation, and consider the adequacy of those networks.

Who: National Hydrological Services, in collaboration with WMO CHy and TOPC.

Time-Frame: 2014.

Performance Indicator: National needs identified; options for implementation explored.

Annual Cost Implication: 10-30M US$ (80% in non-Annex-I Parties).

GCOS has held workshops on the adaption needs of nations in general as they relate to the definition and observation of the ECVs, which have restated the need in general for measurements of river discharge. It is not within the remit of GCOS itself to assess the needs of specific nations, other than within the context of support offered under the GCM (Action C7, page 204).

Sampling the sixth national communications of Annex-1 Parties to the UNFCCC confirms the importance attached nationally to river discharge. Several Parties report details of their measurement programmes, some noting near-real-time reporting. The reports also indicate the importance attached to river temperature and water quality, and river ice in some cases. No special concern regarding the status of the measurement of river discharge was discerned from the reports examined, and none is mentioned in the summary of reporting on systematic observation prepared by the UNFCCC Secretariat, which is reproduced in Appendix 2.

The national communications of non-Annex-1 countries place considerable importance on matters relating to rivers. It is difficult to assess the overall situation with regard to flow measurement, but from sampling some of the more recent reports, the Philippines and Sierra Leone are two countries that refer to establishment of more river-gauge stations as one of their capacity-building needs. Tajikistan records the support of Switzerland in renovating 30 priority gauging stations and meteorological stations in river formation catchment areas. Concerning capacity-development needs it states that staffing is the most acute problem and that there is limited expertise in the introduction and application of automatic weather and gauging stations, as well as their integration into the regular network of observations. Moldova reports on installations of automatic river monitoring systems over the past ten years. Lesotho discusses measurement of sediment flow in rivers as an indicator of soil loss within catchments.

Internationally, as discussed in section 6.3.1 the WMO CHy "Climate sensitive stations" network was set up to comprise stations that provide reference data in which signals from climate variability and change are unaffected by significant direct changes due to human activity within the river basin. Such data are needed to assess potential impacts of climate change on river discharge in terms of river management, water supply, transport and ecosystems. Figure 99 shows the locations of the 1198 such stations for which the GRDC reported data holdings in May 2015. Geographical coverage can be seen to be highly variable. Data are held for fewer than half of the 2476 stations in 26 countries that were reported to CHy in 2008 as having been identified as potential contributors.

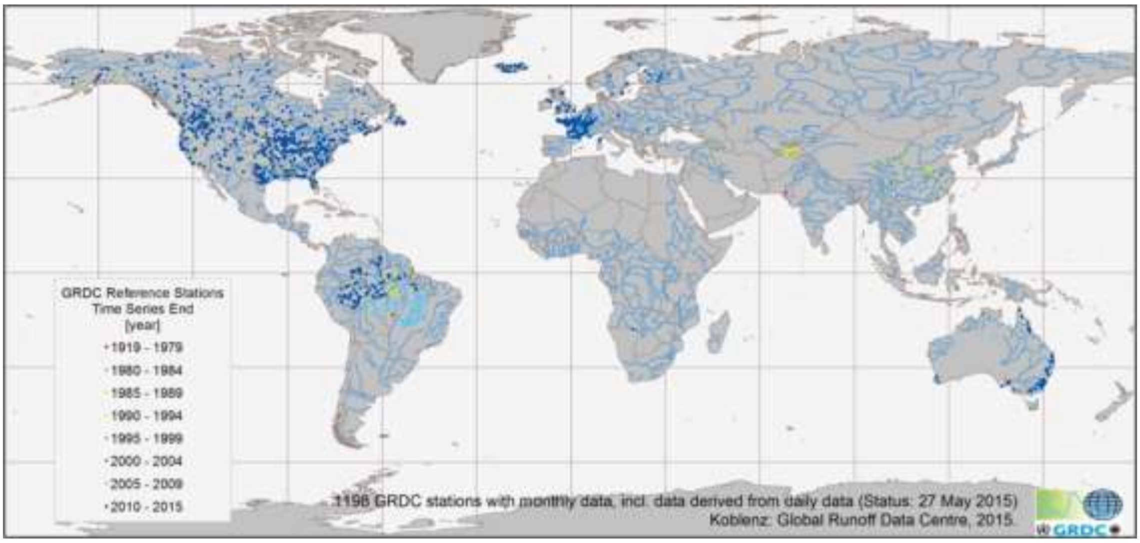


Figure 99: Locations and dates of end of monthly time series of river-discharge data from 1198 stations designated by nations to be "climate sensitive". Source: Global Runoff Data Centre.

T8: Submit current lake level and area data to the international data centre

Action: Submit weekly/monthly lake level/area data to the International Data Centre; submit weekly/monthly altimeter-derived lake levels by space agencies to HYDROLARE.

Who: National Hydrological Services through WMO CHy, and other institutions and agencies providing and holding data; space agencies; HYDROLARE.

Time-Frame: 90% coverage of available data from GTN-L by 2012.

Performance Indicator: Completeness of database.

Annual Cost Implications: 1-10M US$ (40% in non-Annex-I Parties).

HYDROLARE is a relatively new international data centre, having started operation only at the beginning of 2009. Its initial data holdings comprised lake data from Russia and countries of the former Soviet Union. By the end of 2013 it had received additional *in situ* lake data from 14 countries out of the 38 who were invited to submit data.

The Legos HYDROWEB database (section 6.3.4) contains water levels for some 150 lakes and reservoirs derived from satellite altimetry (Figure 57). This includes around 60% of the lakes in the GTN-L priority list. Data from 60 lakes and reservoirs were provided by Legos to HYDROLARE in 2013, comprising data from lakes in the priority list and others for which *in situ* data are in the HYDROLARE database. These data were based on altimetry from TOPEX/Poseidon, GFO, Jason-1, Jason-2 and Envisat, and run to the end of 2011. The next stage of this work is to update time series using more recent altimetric data, including from the Saral/Altika mission launched in 2013.

T9: Submit historical lake level and area data to the international data centre

Action: Submit weekly/monthly lake level and area data measured during the 19th and 20th centuries for the GTN-L lakes to HYDROLARE.

Who: National Hydrological Services and other agencies providing and holding data, in cooperation with WMO CHy and HYDROLARE.

Time-Frame: Completion of archive by 2012.

Performance Indicator: Completeness of database.

Annual Cost Implications: <1M US$ (40% in non-Annex-I Parties).

Currently the HYDROLARE database contains mean monthly *in situ* water-level data, and *in situ* data on the water level on the first day of the month, for 19 out of 79 lakes included in GTN-L list of priority lakes.

Data submitted to HYDROLARE in 2013 included Finnish and Swiss data running from the beginning of observation until 2012. The submissions include some time series going back into the 19th century. HYDROLARE holds monthly mean data and data for the first of each month for much of the 20th century for the North American Great Lakes, with data from some stations reaching back to 1860.

The delivery of historic data is nevertheless an ongoing issue, although emphasis has been placed in the first instance on establishing a reporting system for current data.

T10: Submit surface and sub-surface water temperature, freeze and break-up lake data

Action: Submit weekly surface and sub-surface water temperature, date of freeze-up and date of break-up of lakes in GTN-L to HYDROLARE.

Who: National Hydrological Services and other institutions and agencies holding and providing data; space agencies.

Time-frame: Continuous.

Performance Indicator: Completeness of database

Annual Cost Implications: <1M US$ (40% in non-Annex-I Parties).

There has been moderate progress on this action as currently the HYDROLARE database contains decadal and mean monthly *in situ* water temperature data and maximum ice-cover thickness data for 14 out of the 79 lakes included in GTN-L priority list.

T11: Establish prototype global network and groundwater monitoring information system

Action: Establish prototype GTN-GW and a Global Groundwater Monitoring Information System (GGMS) as a web-portal for all GTN-GW datasets; deliver readily available data and products to the information system.

Who: IGRAC, in cooperation with TOPC.

Time-Frame: 2014.

Performance Indicator: Reports to WMO CHy on the completeness of the GTN-GW record held in the GGMS, including the number of records in, and nations submitting data to, the GGMS; web-based delivery of products to the community.

Annual Cost Implications: 1-10M US$ (40% in non-Annex-I Parties).

The Global Groundwater Monitoring Network (GGMN) uses aggregated information from existing networks making local measurements, in order to represent regional changes of groundwater resources at a scale relevant for global assessment. Data collection and data upload to the GGMN system have taken place and agreements have been signed with national focal points to formalize their role and contribution to the network. New functionalities to analyse groundwater data have been added to the GGMN web-portal.

IGRAC has introduced the GGMN in around 25 countries. It has organized regional groundwater monitoring workshops in Kenya (June 2012), Zambia (November 2012), Uruguay (December 2013) and China (March 2014).

T12: Archive and disseminate information related to irrigation and water resources

Action: Archive and disseminate information related to irrigation and water resources through the FAO AQUASTAT database and other means; assure adequate quality control for all products.

Who: FAO, in collaboration with UN Statistics Division.

Time-Frame: Continuous.

Performance Indicator: Information contained in the AQUASTAT database.

Annual Cost Implications: <1M US$ (Mainly by Annex-I Parties).

The discussion and illustrations provided from AQUASTAT in section 6.3.2 demonstrate a continuation and updating of activities. Nevertheless, the current database contains national statistics that are prone to relate to a mix of past years and be incomplete. To take three examples from the "Irrigation areas sheets" available on the AQUASTAT website as of 30 May 2015:

- values for Australia are dated 2013 for the area actually irrigated and 2006 for the area equipped for irrigation and the technology used (surface, sprinkler and localised); the water source (surface, ground, mixed, waste and agricultural drainage) is not specified;
- values for Brazil are dated 2010 for the area equipped for irrigation, 2006 for the area actually irrigated and 1998 for the water sources;
- values for China are dated 2006 apart from those for use of wastewater, which are dated 1998.

The AQUASAT website also reports ongoing activities:

- a further update of the global map of irrigation areas is in its final stages;
- an update of data for twenty countries in the Americas is in progress.

T13: Develop a record of globally-gridded near-surface soil moisture from satellites

Action: Develop a record of validated globally-gridded near-surface soil moisture from satellites.

Who: Parties' national services and research programmes, through GEWEX and TOPC in collaboration with space agencies.

Time frame: 2014.

Performance indicator Availability of globally validated soil moisture products from the early satellites until now.

Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

The data product now available through the ESA CCI programme illustrated in Figure 70 was originally developed in ESA's WACMOS project. It runs from November 1978 onwards. Data for the first part of the period are based solely on passive microwave data, beginning with those from the SMMR instrument on Nimbus 7. Active microwave (scatterometer) data are used in addition, beginning with those from the AMI on ERS-1, from 1991. Version 2.0 of the product, released in 2014, covers the period to the end of 2013. Development continues in Phase 2 of the CCI (2015-2017), with the goal of providing a framework for operational production.

It was noted in section 6.3.16 that shorter data records are available for individual satellite instruments (see, for example, http://disc.sci.gsfc.nasa.gov/giovanni), and that the scatterometer data from ERS-1 onwards are being assimilated in ECMWF's latest comprehensive reanalysis.

T14: Develop a Global Terrestrial Network for Soil Moisture (GTN-SM)

Action: Develop Global Terrestrial Network for Soil Moisture (GTN-SM).

Who: Parties' national services and research programmes, through IGWCO, GEWEX and TOPC in collaboration with space agencies.

Time frame: 2014.

Performance indicator: Fully functional GTN-SM with a set of *in situ* observations (possibly collocated with reference network, cf. T3), with standard measurement protocol and data quality and archiving procedures.

Annual Cost Implications: 1-10M US$ (40% in non-Annex-I Parties).

The International Soil Moisture Network has been established (http://ismn.geo.tuwien.ac.at/) and functions as the GTN-SM. It comprises a set of around 50 networks from 20 or so countries, and includes both important collections of past data (Robock *et al.*, 2000) and data from operational networks such as the US Climate Reference Network (Bell *et al.*, 2013). Applications include the evaluation of data products derived either directly from satellite measurements or by land-surface reanalysis (e.g. Albergel *et al.*, 2013; Paulik *et al.*, 2014). Harmonization of data has been achieved, but there is an apparent absence of standards and lack of formal exchange of soil-moisture data among nations, notwithstanding the inclusion of this variable within established regulatory and guidance material (WMO, 2010a; 2013). Network coverage is especially poor over Africa and South America.

Transition of the International Soil Moisture Network to an operational data service has yet to be achieved.

T15: Strengthen snow-cover and snowfall observing sites and recover historical data

Action: Strengthen and maintain existing snow-cover and snowfall observing sites; ensure that sites exchange snow data internationally; establish global monitoring of that data on the GTS; and recover historical data.

Who: National Meteorological and Hydrological Services and research agencies, in cooperation with WMO GCW and WCRP and with advice from TOPC, AOPC, and the GTN-H.

Time-Frame: Continuing; receipt of 90% of snow measurements in International Data Centres.

Performance Indicator: Data submission to national centres such as the National Snow and Ice Data Center (USA) and World Data Services.

Annual Cost Implications: 1-10M US$ (20% in non-Annex-I Parties).

The situation concerning *in situ* measurements and international exchange of data on snow depth is discussed in section 6.3.5. Monitoring of GTS data is provided by the operational centres that process the data alongside other synoptic data for weather forecasting. Observation of snowfall is included within earlier discussion of precipitation, in section 4.3.5 and in the review of Actions A7 to A10.

A 2014 workshop (http://www.coreclimax.eu/?q=Snow) held by the Copernicus preparatory project CORE-CLIMAX discussed the status of historical *in situ* snow data, and how to advance towards global archives. It identified more than twenty available large historical *in situ* snow datasets. The open availability of a new 212-station historical snow dataset from China was welcomed, but it was noted that there were significant gaps in the publically available historical snow data records over wide areas, including most of Western Europe and parts of Asia. The importance of rescue of historical snow data was stressed.

Regarding the international archiving of historical *in situ* snow-cover data, the workshop recommended separate management of two groups of historical snow data:

- for point-wise measurements from stations, support was given to the emerging concept of a comprehensive archive of *in situ* surface data over land, which could be modelled on the ICOADS for the marine surface; this would encompass all meteorological and related environmental variables measured at land stations, including snow depth, along with a characterisation of the measurement site and equipment changes;
- for transect-based measurements of multiple properties of snow (snow courses or snow surveys), the establishment of a dedicated global archive was recommended, as was a specific proposal by the Finnish Meteorological Institute to establish a prototype archive that could also collect near-real-time snow-course data.

T16: Obtain integrated analyses of snow cover over both hemispheres

Action: Obtain integrated analyses of snow cover over both hemispheres.

Who: Space agencies and research agencies in cooperation with WMO GCW and CliC, with advice from TOPC, AOPC and IACS

Time-Frame: Continuous.

Performance Indicator: Availability of snow-cover products for both hemispheres.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

Of the satellite products referred to in section 6.3.5, the NOAA IMS and the longer term NSIDC product derived in part from it are multi-sensor, as is the near-real-time SSM/I-SSMIS EASE-Grid Daily Global Ice Concentration and Snow Extent product provided by NSIDC. Snow cover refers here to whether or not the surface is covered by snow, as distinct from the equivalent liquid water content or the depth of the snow. Global snow-cover and snow-water-equivalent products are available from the ESA GlobSnow project (www.globsnow.info), based respectively of data from the ERS-2 ATSR-2 and Envisat AATSR sensors, and from the SMMR, SSM/I and SSMIS instruments. As is the case for other ECVs, refinements to retrieval algorithms and the generation of multi-sensor products continue as validation is undertaken. Examples include work to exploit the capability of km-resolution AVHRR data back to 1985 and to take advantage of extensive oversampling of multi-sensor footprints to enhance gridding resolution for passive MW data.

Data assimilation provides an approach to integrating information from *In situ* snow-depth measurements and snow-cover estimates from satellite data. This is established for operational weather prediction, and is an area in which significant improvements have been made in recent years (e.g. de Rosnay *et al*., 2014). The ECMWF system, for example, combines *in situ* observations of snow depth with the NOAA IMS snow cover data.

T17: Maintain glacier observing sites, improve coverage and develop QA and inventories

Action: Maintain current glacier observing sites and add additional sites and infrastructure in data-sparse regions, including South America, Africa, the Himalayas, and New Zealand; attribute quality levels to long-term mass balance measurements; complete satellite-based glacier inventories in key areas.

Who: Parties' national services and agencies coordinated by GTN-G partners, WGMS, GLIMS, and NSIDC.

Time-Frame: Continuing, new sites by 2015.

Performance Indicator: Completeness of database held at NSIDC from WGMS and GLIMS.

Annual Cost Implications: 10-30M US$ (80% in non-Annex-I Parties).

There are several capacity building and twinning programmes active in the Andes and in Asia aimed at extending the *in situ* mass-balance networks. There has also been some progress in extending the volume-change dataset: thanks to air- and space-borne sensors, geodetic volume changes can potentially be observed at thousands of glaciers at decadal intervals. However, tapping this potential requires additional resources for both the data centres and the investigators.

There has also been some advance in enhancing the current dataset on glacier-front variations, based mainly on *in situ* measurements, with remotely sensed observations. Progress has also been made by compiling data from literature reviews and by integrating a few long time series of glacier-front variations from reconstructions.

There has been good progress in compiling a globally complete, high quality glacier inventory (Pfeffer *et al*., 2014). However, there are considerably more regional and national glacier inventories produced than are actively compiled and loaded into the international database.

Finally, there has been little progress in improving the funding situation for international glacier data centres and services as well as for long-term glacier monitoring programmes.

T18: Ensure continuity of *in situ* ice sheet measurements and fill critical gaps

Action: Ensure continuity of *in situ* ice sheet measurements and fill critical measurement gaps.

Who: Parties, working with WCRP CliC, IACS, and SCAR.

Time-Frame: Ongoing.

Performance Indicator: Integrated assessment of ice sheet change supported by verifying observations.

Annual Cost Implications: 10-30M US$ (Mainly by Annex-I Parties).

IPCC (2013) notes the following: "Since AR4 satellite, airborne and *in situ* observations have greatly improved our ability to identify and quantify change in the vast polar ice sheets of Antarctica and Greenland. As a direct consequence, our understanding of the underlying drivers of ice-sheet change is also much improved". *In situ* measurements for ice sheet mass balance assessments are crucial to verify the mass balance models and for the interpretation of satellite data. These measurements include, but are not limited to: snow accumulation, surface melt, air temperatures, surface wind speed, surface radiation balance, turbulent energy fluxes, surface properties such as snow wetness and albedo, snow and firn density and compression, ice velocity, to name just a few. All these *in situ* measurements are used for process understanding and model parameterization and verification of model output over the entire ice-sheet surface.

The two ice sheets, Greenland and Antarctica, are very large and cannot be adequately sampled with *in situ* measurements. Hence, the measurements that are made in different climatic regions of the ice sheets have to be sustained for the long-term so that geographical variability over time can be captured effectively. Snow accumulation is a key variable of the mass balance and small changes have a large impact on the balance. Such changes are not well captured by *in situ* observations, however. They also cannot be observed directly from space. A combination of repeat aircraft and satellite laser/altimeter measurements, with snow compaction modelling based on *in situ* measurements is a possible basis for estimating snow accumulation on ice sheets.

T19: Carry out research to improve ice sheet models, for assessing future sea level rise

Action: Research into ice sheet model improvement to assess future sea level rise.

Who: WCRP CliC sea level cross-cut, IACS, and SCAR.

Time-Frame: International initiative to asses sea level rise within 5+ years

Performance Indicator: Reduction of sea level rise uncertainty in future climate prediction from ice sheet contributions to within 20% of thermal expansion of the ocean.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

IPCC (2013) notes the following. “Since the publication of the AR4, there has been substantial progress in understanding the relevant processes as well as in developing new ice sheet models that are capable of simulating them.” It also notes that the substantial progress in modelling is “particularly for Greenland” and that when calibrated appropriately, the improved models “can reproduce the observed rapid changes in ice sheet outflow for individual glacier systems (e.g., Pine Island Glacier in Antarctica; medium confidence). However, models of ice sheet response to global warming and particularly ice sheet–ocean interactions are incomplete and the omission of ice sheet models, especially of dynamics, from the model budget of the past means that they have not been as critically evaluated as other contributions.”

As regards assessment of global-mean sea level (GMSL) rise, IPCC (2013) writes: “the evidence now available gives a clearer account of observed GMSL change than in previous IPCC assessments, in two respects. First, reasonable agreement can be demonstrated throughout the period since 1900 between GMSL rise as observed and as calculated from the sum of contributions. From 1993, all contributions can be estimated from observations; for earlier periods, a combination of models and observations is needed. Second, when both models and observations are available, they are consistent within uncertainties. These two advances give confidence in the 21st century sea level projections. The ice-sheet contributions have the potential to increase substantially due to rapid dynamical change *[cross-references]* but have been relatively small up to the present *[cross-references]*. Therefore, the closure of the sea level budget to date does not test the reliability of ice-sheet models in projecting future rapid dynamical change; we have only medium confidence in these models, on the basis of theoretical and empirical understanding of the relevant processes and observations of changes up to the present.”

T20: Ensure continuity of altimetric and gravimetric satellite ice-sheet monitoring

Action: Ensure continuity of laser, altimetry, and gravity satellite missions adequate to monitor ice masses over decadal timeframes.

Who: Space agencies, in cooperation with WCRP CliC and TOPC.

Time-Frame: New sensors to be launched: 10-30 years.

Performance Indicator: Appropriate follow-on missions agreed.

Annual Cost Implications: 30-100M US$ (Mainly by Annex-I Parties).

The radar altimeter on Envisat provided data for the first part of the period since IP-10 was published. A surface-elevation-change product comprising five-yearly running means for 1999-2012 based on data from Envisat and the earlier ERS-2 satellite is among those recently released by the ESA CCI. The principal more recent source of altimetry for determining ice-sheet elevation has been ESA's CryoSat, launched in April 2010. The increased sampling it offers and resultant capability to map changes over a three-year period are reported for Antarctica by McMillan *et al*. (2014). The CEOS MIMD lists Canada's RADARSAT-2, India's RISAT-1 and Japan's ALOS-2 as other current radar missions providing data on ice-sheet topography. A number of forthcoming missions of this type are also listed, of which three multi-satellite missions have approved status. In order of first launch they are Sentinel-3, Argentina's SAOCOM-1 and RADARSAT C. The joint US/Indian mission NISAR will also provide data on ice sheets. None of these missions is planned for an orbit with the particularly high inclination that enables CryoSat to provide Antarctic ice-sheet data to within only a little over 200 km of the South Pole.

NASA's ICESat laser altimeter ceased providing data in 2009. ICESat-2 is scheduled to provide further laser altimetry from space following launch in 2017. As noted in section 6.3.7, the aircraft-based Ice Bridge campaigns are providing data in the interim.

The joint US-German gravimetric mission GRACE uses radar to measure small gravity-induced variations in the distance between its twin satellites, which orbit around 220 km apart. GRACE is now in its fourteenth year of operation, and no longer observes continuously due to battery limitations. The follow-on mission scheduled from 2017 is designed to evaluate a highly desirable increase in spatial resolution through use of laser interferometry to measure the separation of its two component satellites, in addition to continuing the data record based on radar ranging provided by GRACE. A GRACE-II mission is listed in the CEOS MIMD as under consideration for a 2030 launch.

T21: Refine standards for permafrost observation and establish national data centres

Action: Refine and implement international observing standards and practices for permafrost and combine with environmental variable measurements; establish national data centres.

Who: Parties' national services/research institutions and International Permafrost Association.

Time-Frame: Complete by 2010.

Performance Indicator: Implemented guidelines and establishment of national centres.

Annual Cost Implications: <1M US$ (10% in non-Annex-I Parties).

The Strategy and Implementation Plan developed for GTN-P (GTN-P, 2012) under the auspices of the International Permafrost Association summarises existing measurement methods, protocols and standards, including the requirement for metadata on observing sites for which an existing ISO standard provides a basis. A GTN-P database (http://gtnp.arcticportal.org/) has been developed by the EU FP7 PAGE21 project; it is compliant with the ISO standard. It provides a basis for standardised reporting, a thesaurus on terms used in permafrost studies, tutorials and promotion of comprehensive reporting of metadata. Biskaborn *et al*. (2015) give further detail. Longer-term funding for the operation and continued development of the database is not yet secured.

As noted in section 6.3.8, a network of GTN-P National Correspondents (NCs) has been established. The GTN-P Strategy identifies the NCs as having the responsibilities for fostering the implementation of the Strategy within their countries and for stimulating and coordinating the collection of data and reporting by individual investigators, to enable the emergence of an operational framework for handling permafrost data in the country and ensure data are fed into the GTN-P information system. Figure 100 is an example of a data plot generated from the Swiss national PERMOS network cited as an example in the GTN-P Strategy.

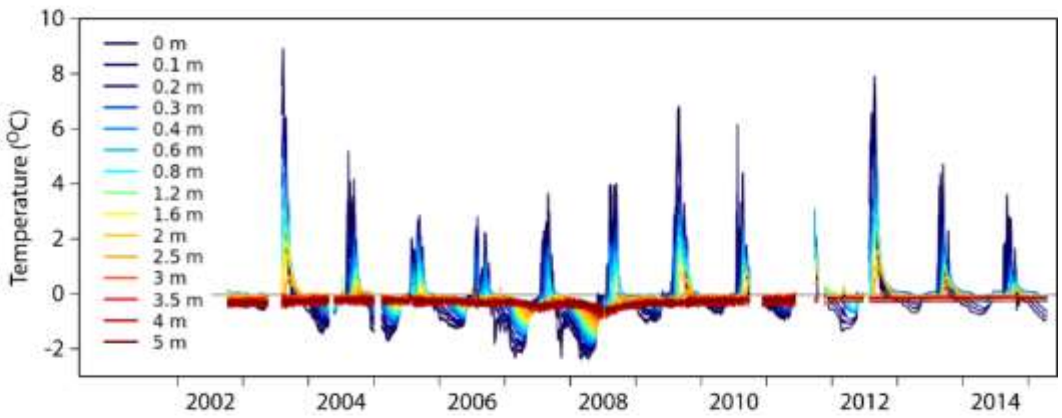


Figure 100: Temperature variation over time at depths indicated by colour from Schilthorn borehole SCH_5200 from the Permafrost Monitoring Switzerland (PERMOS) network. Source: plot generated at http://shinypermos.geo.uzh.ch/app/BoreholeDataBrowser/.

T22: Sustain and improve borehole and active-layer permafrost networks

Action: Ensure continuity of the existing GTN-P borehole and active layer networks, upgrade existing sites, and build "reference sites."

Who: Parties' national services/research institutions and International Permafrost Association. IGOS Cryosphere Theme team and WMO GCW to ensure continuity and associated Earth observation-derived variables.

Time-Frame: Continuing.

Performance Indicator: Number of sustained sites; completeness of database.

Annual Cost Implications: 10-30M US$ (20% in non-Annex-I Parties).

Two components of the GTN-P, the international networks for the Thermal State of the Permafrost (TSP) and Circumpolar Active Layer Monitoring (CALM), are the major providers of data. It is noted in section 6.3.8 that the GTN-P Database included metadata for 1074 boreholes and 274 active-layer monitoring sites early in 2015, a rise on the corresponding figures of 1059 and 239 reported in May 2014. It is not easy to discern in how many places measurements are not currently being made, but the summary table available from the CALM website (http://www.gwu.edu/~calm/data/north.html) includes end-of-season thaw-depth data for 2014 from a quite considerable proportion of sites, and current data can be found elsewhere for other sites, such as illustrated in Figure 100.

It is also noted in section 6.3.8 that GTN-P has also identified new monitoring sites needed to obtain representative coverage in several regions, and has recommended a few reference sites for development.

T23: Implement operational mapping of seasonal soil freeze/thaw

Action: Implement operational mapping of seasonal soil freeze/thaw through an international initiative for monitoring seasonally-frozen ground in non-permafrost regions.

Who: Parties, space agencies, national services, and NSIDC, with guidance from International Permafrost Association, the IGOS Cryosphere Theme team, and WMO GCW.

Time-Frame: Complete by 2013.

Performance Indicator: Number and quality of mapping products published.

Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

The IPCC AR5 records a reduction in the thickness of seasonally-frozen soil over the period 1930-2000 based on a study by Frauenfeld and Zhang (2011) of soil-temperature data for Kazakhstan and Russia. There have been more recent national studies, and a data set of Northern Hemisphere Seasonal and Intermittent Frozen Ground Areas for 1901-2001 is available from NISDC. Soil-temperature data are not exchanged internationally on a routine basis, however, and operational mapping of seasonal freezing and thawing has not been implemented.

The NASA MEASUREs project has produced freeze/thaw datasets based on combining SMMR, SSM-I and SSMIS data, and on AMSR-E data (https://nsidc.org/data/nsidc-0477/). Inter-calibration of the data records from AMSR-E and AMSR2, using overlapping measurements from the FY-3B MWRI, are reported by Du *et al.* (2014).

Numerical weather prediction and reanalysis systems provide routine global estimates of soil temperatures in a small number of layers reaching down several metres. There is very little published literature on the quality of products, particularly for frozen ground, but Albergel *et al*. (2015) report an assessment of the ECMWF NWP system, using European and US measurements for 2012. The latter include data from high-elevation sites from the SNOTEL network. Examples are presented showing good agreement of near-surface soil temperatures where ground is correctly detected as frozen, but significant biases for spells in spring and autumn associated with mismatches between the height of the ground-surface of the assimilating model and the height of the observing station. The capabilities of the current generation of higher-resolution reanalyses for detecting longer-term changes over time remain to be assessed.

T24: Develop *in situ* cal/val of space-based albedo products

Action: Obtain, archive and make available *in situ* calibration/validation measurements and collocated albedo products from all space agencies generating such products; promote benchmarking activities to assess the quality and reliability of albedo products.

Who: Space agencies in cooperation with CEOS WGCV.

Time-Frame: Full benchmarking/intercomparison by 2012.

Performance Indicator: Publication of inter-comparison/validation reports.

Annual Cost Implications: 1-10M US$ (20% in non-Annex-I Parties).

As reported in section 6.3.9, the tower sites of the BSRN network currently provide some of the highest-quality measurements available for validating albedo products from space-based observation, but they are few in number. Additional measurements are provided by the FLUXNET and ICOS networks. Examples of use of BSRN and FLUXNET data in the validation of the MODIS product illustrated in Figure 64 are reported respectively by Wang *et al*. (2014) and Cescatti *et al*. (2012). Information on the ICOS network of ecosystem sites can be found at http://www.europe-fluxdata.eu/icos.

The CEOS WGCV LPV Subgroup includes a focus area on validation of surface radiation and albedo products. A list of products is provided at http://lpvs.gsfc.nasa.gov/producers2.php?topic=SurfaceRad. Links to validation information are included.

T25: Implement coordinated retrieval of land surface albedo from satellite sensors

Action: Implement globally coordinated and linked data processing to retrieve land surface albedo from a range of sensors on a daily and global basis using both archived and current Earth Observation systems.

Who: Space agencies, through the CGMS and WMO Space Programme.

Time-Frame: Reprocess archived data by 2012, then generate continuously.

Performance Indicator: Completeness of archive.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties)

Progress on this action has been made within the inter-agency SCOPE-CM initiative. The set of pilot activities undertaken in the first phase of the initiative included a project for generating a land-surface albedo product from the constellation of geostationary satellites (Lattanzio *et al*., 2013). First collaborative activities in fact had begun in 2008, but were expanded in 2011 when the algorithm applied to data from European and Japanese satellites was implemented also for the data from US platforms. Data covering the period 2000-2003 were produced by all three participating agencies. The project continues in the second phase of SCOPE-CM, in which the aim of the agencies is to process data from all but the earliest of their satellites depicted in the "geostationary quilt" shown in Figure 92. Moreover, a new pilot project has been established in the second phase, with the aim of deriving a roadmap for estimating surface albedo by combining data from several different instruments flown in polar orbit. The method is to be demonstrated using AVHRR and MODIS images.

ESA's GlobAlbedo project (http://www.globalbedo.org/) earlier developed a dataset for the period 1998-2011 based on data from MERIS on Envisat and two SPOT-Vegetation satellites.

T26: Produce reliable methods for assessing land-cover map accuracy

Action: Produce reliable accepted methods for land-cover map accuracy assessment.

Who: CEOS WGCV, in collaboration with GOFC-GOLD and GLCN.

Time-Frame: By 2010 then continuously.

Performance Indicator: Protocol availability.

Annual Cost Implications: <1M US$ (10% in non-Annex-I Parties).

The CEOS WGCV LPV Subgroup has focus area on land cover, whose activities are closely coordinated with the land cover team of GOFC-GOLD and its related project office funded by ESA. It cites, at http://lpvs.gsfc.nasa.gov/LC_home.html, two key references for validation of land-cover datasets:

- Strahler *et al*. (2006) on recommendations for evaluation and accuracy assessment; and

- Olofsson *et al.* (2014) on good practices for assessing accuracy and estimating area of land-cover change.

It further refers to the review by Tsendbazar *et al*. (2015) of existing land cover reference data sets and their suitability as function of the user community, and notes that with increasing resolution of future land cover products, the existing reference data sets will need further development.

T27: Generate annual products documenting global land-cover characteristics

Action: Generate annual products documenting global land-cover characteristics and dynamics at resolutions between 250m and 1km, according to internationally-agreed standards and accompanied by statistical descriptions of their accuracy.

Who: Parties' national services, research institutes and space agencies in collaboration with GLCN and GOFC-GOLD research partners and the GEO Forest Carbon Tracking task team.

Time-Frame: By 2011, then continuously.

Performance Indicator: Dataset availability.

Annual Cost Implications: 1-10M US$ (20% in non-Annex-I Parties).

The CEOS WGCV LPV Subgroup focus area on land cover provides a list of products, including links to validation information, at http://lpvs.gsfc.nasa.gov/producers2.php?topic=LC. It can be seen there that some datasets have been produced at resolutions of between 250 m and 1 km by several institutions, with annual resolution in some cases and for some periods. A NASA MODIS product (http://landval.gsfc.nasa.gov/MODIS/ProductStatus.php?ProductID=MOD12) is available with 500 m spatial resolution annually from 2001 to 2012, validated to Stage 2. The LPV Subgroup defines this stage as follows: "Product accuracy is estimated over a significant set of locations and time periods by comparison with reference in situ or other suitable reference data. Spatial and temporal consistency of the product and consistency with similar products has been evaluated over globally representative locations and time periods. Results are published in the peer-reviewed literature."

Temporal variations may not be well captured, however. In particular, the ESA CCI Land Cover project delivered in 2014 its first set of global land cover products, at 300 m spatial resolution for three epochs centred on the years 2010 (2008-2012), 2005 (2003-2007) and 2000 (1998-2002), based on data from MERIS and SPOT-Vegetation. As illustrated earlier in Figure 65, the product distinguishes 22 classes of cover. However, land-cover changes were identified only at 1 km resolution and applied to only a limited number of classes. In particular, visualisation of the products for the different epochs does not show the substantial change in distribution of urban areas for China illustrated in Figure 101. Nor does it show as extensive a reduction in forested land for the Amazon as illustrated in the same figure.

T28: Generate five-yearly higher resolution maps documenting global land cover

Action: Generate maps documenting global land cover based on continuous 10-30m land surface imagery every 5 years, according to internationally-agreed standards and accompanied by statistical descriptions of their accuracy.

Who: Space agencies, in cooperation with GCOS, GTOS, GOFC-GOLD, GLCN, and other members of CEOS.

Time-Frame: First by 2012, then continuously.

Performance Indicator: Availability of operational plans, funding mechanisms, eventually maps.

Annual Cost Implications: 10-30M US$ (20% in non-Annex-I Parties).

The free availability since January 2009 of all data from Landsat has enabled significant progress to be made in the generation of products with 30 m spatial resolution, though not yet with five-year temporal resolution or with as extensive a classification of surface types as achieved at lower resolution.

A first 30 m dataset was reported by Gong *et al*. (2013), based on Landsat images that were distributed in time with peaks around 2000 and 2010. Forest loss and gain, as well as extent, were documented by Hansen *et al*. (2013) in products for the period from 2000 to 2012 at 30 m spatial resolution. Loss was allocated annually. In 2014, the GlobeLand30 dataset (illustrated already in Figure 65) was released (Chen *et al*., 2015). It provides a classification of land cover into ten types at 30 m resolution, for the years 2000 and 2010. A 30-year global dataset describing both seasonal and longer-term variations in surface water at 30 m resolution has been derived recently from Landsat (5, 7 and 8) imagery by the European Commission Joint Research Centre, Ispra, and the Google Earth Engine team.

Figure 101 presents examples from the GlobeLand30 dataset for 2000 and 2010. The left-hand panels show substantial growth between these years in the amount of land covered by the city of Beijing and neighbouring cities and towns, and considerable coastal development. The right-hand panels show loss of Amazonian forest cover over the period; the corresponding loss of forest cover derived by Hansen *et al*. (2013) is viewable at full resolution at http://earthenginepartners.appspot.com/science-2013-global-forest for comparison. Validation statistics are presented in each of the referenced scientific papers. Chen *et al*. (2015) note that an international validation of GlobeLand30 will be organized with the support of the United Nations initiative on Global Geospatial Information Management and GEO over the next two years.

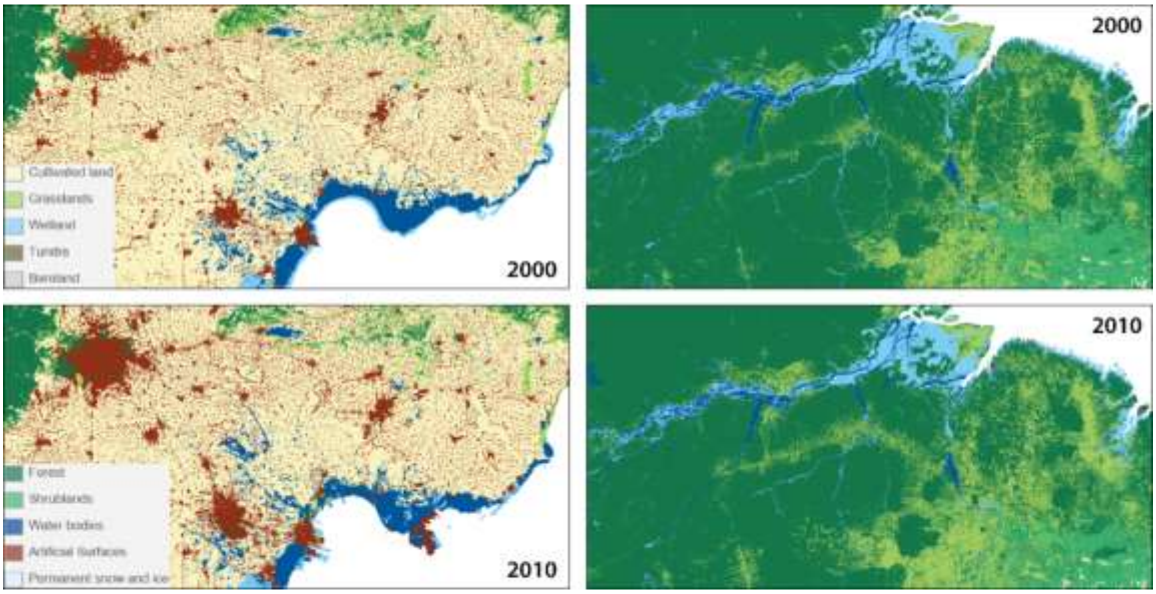


Figure 101: Land-cover maps for the vicinity of Beijing and south-eastwards to the coast, and for the Amazon and southwards. Source: 30 m resolution NGCC GlobeLand30 product for 2000 (upper) and 2010 (lower), viewed at http://www.globallandcover.com/GLC30Download/.

T29: Establish a cal/val network of *in situ* reference sites for FAPAR and LAI

Action: Establish a calibration/validation network of *in situ* reference sites for FAPAR and LAI and conduct systematic, comprehensive evaluation campaigns to understand and resolve differences between the products and increase their accuracy.

Who: Parties' national and regional research centres, in cooperation with space agencies coordinated by CEOS WGCV, GCOS and GTOS.

Time-Frame: Network operational by 2012.

Performance Indicator: Data available to analysis centres.

Annual Cost Implications: 1-10M US$ (40% in non-Annex-I Parties).

The CEOS WGCV has established a network of "BELMANIP2" calibration/validation sites. It is an updated version of the BELMANIP1 network (Baret *et al*., 2006), which was built using sites from existing experimental networks (such as FLUXNET, AERONET, VALERI and BigFoot) completed with selected sites from the GLC2000 land-cover map. To be independent from ground experiment measurements and to better represent the variability of vegetation types and climatological conditions at the Earth's surface, BELMANIP2 was built using the GlobCover vegetation land-cover map derived from MERIS images in 2009. The site selection was performed for each ten-degree band of latitude by keeping the same proportion of biome types within the selected sites as within the whole band of latitude. Attention was paid so that the sites were homogeneous over a 10x10 km² area, almost flat and with a minimum proportion of urban area and permanent water bodies. The original BELMANIP2 dataset included 420 sites. The updated BELMANIP2.1 dataset complements BELMANIP2 by adding 25 sites corresponding to bare soil areas (deserts) and tropical forests. In addition, the ImagineS (http://fp7-imagines.eu/) project has set-up a network of 17 cropland and grassland sites to collect ground measurements for product validation.

The Belmanip 2 and ImagineS collections of LAI and FAPAR data are campaign-based and have uneven temporal sampling and no secured continuity. For FAPAR, a concept is currently being developed and first wireless sensor networks implemented with calibrated radiation sensors, a prerequisite to develop continuous fiducial reference data sets. The CEOS WGCY LPV Subgroup is coordinating data acquisition for LAI and FAPAR with existing networks through protocol review, but this work is under development only. Apart from traceability of *in situ* measurements, spatial sampling and representativeness need to be tested for existing network sites.

T30: Evaluate LAI satellite products and benchmark them against *in situ* measurements

Action: Evaluate the various LAI satellite products and benchmark them against *in situ* measurements to arrive at an agreed operational product.

Who: Parties' national and regional research centres, in cooperation with space agencies and CEOS WGCV, GCOS/TOPC, and GTOS.

Time-Frame: Benchmark by 2012.

Performance Indicator: Agreement on operational product.

Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

The LAI Version 1 product of the Copernicus Land Monitoring Services, discussed further in the following review of Action T31, has been validated following the guidelines proposed by the CEOS WGCV LPV Subgroup. It comprises

- an inter-comparison with existing global products at global and regional scales using the BELMANIP2 network of sites to perform the statistical analysis;
- a direct comparison with ground –based reference maps.

Camacho *et al*. (2013) report on the validation of initial products for FAPAR as well as LAI.

The LPV Subgroup includes a focus area on biophysical products, and (as noted for other ECVs and corresponding focus areas) it provides a webpage listing products with specific links to documents on validation procedures (http://lpvs.gsfc.nasa.gov/producers2.php?topic=LAI). As of May 2015, the current Copernicus and NASA MODIS LAI products are both ranked as validated at Stage 2.

The limitations to reaching a higher validation stage noted by the LPV Subgroup include an insufficient number of global LAI products to generate an unbiased ensemble (product inter-comparison studies), and the limited number of validation sites and associated spatial and temporal gaps of *in situ* reference data coverage (direct validation). However, as noted in its good practices document, available at http://lpvs.gsfc.nasa.gov/LAI_home.html, progress has been made towards standardized spatial sampling schemes and *in situ* measurement techniques. A number of recommendations have been identified associated with the good practices document, which will be regularly monitored for progress.

T31: Operationalize the generation of gridded global products for FAPAR and LAI

Action: Operationalize the generation of FAPAR and LAI products as gridded global products at spatial resolution of 2km or better over time periods as long as possible.

Who: Space agencies, coordinated through CEOS WGCV, with advice from GCOS and GTOS.

Time-Frame: 2012.

Performance Indicator: One or more countries or operational data providers accept the charge of generating, maintaining, and distributing global FAPAR products.

Annual Cost Implications: 10-30M US$ (10% in non-Annex-I Parties).

The global Copernicus (http://land.copernicus.eu/global/products/lai) and NASA MODIS products (http://modis.gsfc.nasa.gov/data/dataprod/mod15.php) for LAI noted in the above review of Action T30 are accompanied by products for FAPAR. Each is generated routinely at 1 km spatial resolution in close to real time, with a time lag that mainly reflects the accumulation period needed to attain sufficient coverage. These periods are twelve days for the Copernicus products, eight days for a single MODIS instrument and four days for the combined MODIS product based on data from the Terra and Aqua satellites. As of May 2015, the Copernicus product based on data from the SPOT-Vegetation satellites is classed as operational, and products based on data from the PROBA-V satellite and from a combination of SPOT and PROBA data have demonstration or development status. Data extend back to late 1998 in the case of the Copernicus product from the SPOT-Vegetation satellites and early 2000 in the case of MODIS Terra. There are also MERIS FAPAR products at 1.2 km and 0.5^{O} resolution for the period 2002-2012.

FAPAR and LAI are also variables for which products are provided routinely by the NOAA Climate Data Record Program (http://www.ncdc.noaa.gov/cdr/operationalcdrs.html) based on AVHRR data and by the EUMETSAT Land SAF (http://landsaf.meteo.pt) for the domain viewed by the SEVIRI instrument on the geostationary Meteosat Second Generation platform.

As is the case for LAI, links to products and validation are provided by the CEOS WGCV LPV Subgroup (http://lpvs.gsfc.nasa.gov/Fpar_home.html).

T32: Develop demonstration datasets for above-ground biomass

Action: Develop demonstration datasets of above ground biomass across all biomes.

Who: Parties, space agencies, national institutes, research organizations, FAO in association with GTOS, TOPC, and the GOFC-GOLD Biomass Working Group.

Time frame: 2012.

Performance Indicator: Availability of global gridded estimates of above ground biomass and associated carbon content.

Annual Cost Implications: 1-10M US$ (20% in non-Annex-I Parties).

There are very extensive *in situ* datasets in the temperate and boreal zones, developed nationally, principally for the information needs of commercial forestry. However, this information is normally not available in a spatially explicit form. *In situ* networks in the Tropics are much less extensive and well developed, but these are being developed in several countries, partly due to the stimulus provided by UN-REDD and the REDD+ initiative. There are also important ecological networks, notably RAINFOR in the Amazon and Afritron in Africa, and the network organised by the Smithsonian Center for Tropical Forest Science.

Biomass products derived from space-based observation do not suffer the restrictions on *in situ* data and several continental scale maps of biomass have been produced in recent years. The carbon stock of forests north of 30°N as of 2010 have been derived (Thurner *et al.*, 2013) using long time series of C-band Envisat satellite radar data (Santoro *et al.*, 2011). Two biomass maps of the coterminous USA have been produced under the auspices of the North American Carbon Program: (i) that described in Kellndorfer *et al.* (2012) is for the year 2000 at 30 m resolution and is based on a combination of USDA Forest Service Forest Inventory and Analysis data with high-resolution InSAR data acquired from the 2000 SRTM and optical remote sensing data acquired from the Landsat ETM+ sensor; (ii) a map for year 2005 has been derived using a combination of ALOS PALSAR, Landsat, ICESat forest height, and SRTM data (Saatchi, personal communication). Two pan-tropical biomass maps (Saatchi *et al*., 2011; Baccini *et al*. 2012) at grid scales of 1 km and 500 m respectively have been derived, both of which rely heavily on the archive of forest height estimates derived from the Geoscience Laser Altimeter System on ICESat before its failure in 2009 (Lefsky, 2010). There are significant regional differences between these two tropical maps, although when aggregated to country- or biome-scale these disagreements tend to decrease (Mitchard *et al*., 2013). In addition, these maps do not exhibit the main northeast to southwest gradient of decreasing biomass across Amazonia inferred from *in situ* data (Mitchard *et al*., 2014). Current work is seeking to resolve these discrepancies.

T33: Develop a database of soil carbon measurements and global products

Action: Develop a global database of soil carbon measurements and techniques for extrapolation to global gridded products of soil carbon.

Who: Parties, national institutes, research organisations, and FAO, in association with GTOS and TOPC.

Time frame 2012-2014.

Performance Indicator: Completeness of database and availability of prototype soil carbon maps.

Annual Cost Implications: 1-10M US$ (10% in non-Annex-I Parties).

The Harmonised World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) combining 9,607 soil profiles has been assembled by IIASA and FAO from data from a wide range of sources including:

- ISRIC-World Soil Information, (International Soil Reference and Information Centre);
- the ICSU World Data Centre for Soils (WDC-Soils);
- the European Soil Bureau Network; and
- the Institute of Soil Science, Chinese Academy of Sciences.

Soil carbon maps have been produced from these data, as illustrated earlier in Figure 68.

T34: Develop globally gridded estimates of terrestrial carbon fluxes

Action: Develop globally gridded estimates of terrestrial carbon flux from *in situ* observations and satellite products and assimilation/inversions models.

Who: Reanalysis centres and research organisations, in association with national institutes, space agencies, and FAO/GTOS (TCO and TOPC).

Time Frame: 2014-2019.

Performance indicator: Availability of data assimilation systems and global time series of maps of various terrestrial components of carbon exchange (e.g., GPP, NEP, and NBP).

Annual Cost Implications: 10-30M US$ (Mainly by Annex-I Parties).

Global estimates of carbon fluxes have been produced by several groups. Peylin *et al.* (2013) compared CO_2 fluxes from eleven datasets, several of which covered periods of more than twenty years. Further discussion for CO_2 is given in section 4.7.1. Fluxes of methane are discussed in section 4.7.2.

T35: Reanalyse the historical satellite data on fire disturbance

Action: Reanalyse the historical fire disturbance satellite data (1982 to present).

Who: Space agencies, working with research groups coordinated by GOFC-GOLD.

Time-Frame: By 2012.

Performance Indicator: Establishment of a consistent dataset, including the globally available 1km AVHRR data record.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

There was originally some interest in reanalysing the earliest satellite data on fire disturbance, as expressed for example at several of the annual sessions of TOPC. Several institutions sought to determine suitable datasets and made some slow progress. However, interest has become focussed on looking forward with more reliable sensors and better quality data sets.

Version 4 of the Global Fire Emissions Database (GFED4; http://www.globalfiredata.org/) provides a monthly burnt-area product from mid-1995 onwards, based on the ATSR family of sensors, the VIRS instrument on TRMM and the MODIS instruments on the Terra and Aqua satellites. MODIS active-fire products are available from 2000 onwards (http://modis-fire.umd.edu/pages/ActiveFire.php).

T36: Continue generating fire products from low-orbit satellites

Action: Continue generation of consistent burnt area, active fire, and FRP products from low orbit satellites, including version intercomparisons to allow un-biased, long-term record development.

Who: Space agencies, in collaboration with GOFC-GOLD.

Time-Frame: Continuous.

Performance Indicator: Availability of data.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

Generation of fire products from instruments flown in polar orbit has been continued. Product listings can be found through the links discussed in the review of Action T38. Burnt-area, active-fire detection and fire-radiative-power products are all available based on data from the MODIS instruments. Fire-detection and fire-risk products are also generated from AVHRR data. The ESA CCI has developed a burnt-area product by combining spectral information from MERIS and thermal information from the MODIS active fires product. Earlier work had investigated possible use of ATSR, AATSR and SPOT-Vegetation data. Continued production and further development is being undertaken by the space agencies and their partners, with contributions also from Copernicus services and GOFC-GOLD.

Operational continuity is expected to be provided by products from VIIRS on the Suomi NPP and JPSS platforms, from future imagers on other operational polar meteorological platforms and from the SLSTR instrument on Sentinel-3.

T37: Develop and apply a validation protocol for fire disturbance data

Action: Develop and apply validation protocol to fire disturbance data.

Who: Space agencies and research organizations.

Time-Frame: By 2012.

Performance Indicator: Publication of accuracy statistics.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties

The CEOS WGCV LPV Subgroup published best practice guideline for burnt-area products in 2009. The ESA CCI Fire Project published the validation plan for its products in 2011. The plan and standardised validation reports are available at https://geogra.uah.es/fire_cci/content/documents. The LPV Subgroup was also engaged in the process (see also the following Action). A peer-reviewed paper on the validation data set and methodology has been published by the CCI team (Padilla *et al.*, 2014).

The fire-related activities carried out by the Copernicus Atmosphere Monitoring Service (http://www.copernicus-atmosphere.eu/) focus on provision of data on emissions by fires, based on use of Fire Radiative Power data from satellites. Validation accordingly makes use of comparisons of data assimilation and forecast products with ground-based AERONET and *in situ* PM10 measurements (Kaiser *et al.*, 2012) in regions where aerosols (section 4.7.5) are dominated by smoke, and with data on the emitted reactive-gas species (section 4.7.6). Validation reports on service products are published quarterly, and include identification of occasional near-real-time service issues such as temporary misinterpretation of lava on Iceland as wildfire emissions in early September 2014. This should enable such issues to be avoided when data are used later in reanalyses.

T38: Make fire products available through links from a single international data portal

Action: Make gridded burnt area, active fire, and FRP products available through links from a single International Data Portal.

Who: Coordinated through GOFC-GOLD.

Time-Frame: Continuous.

Performance Indicator: Continued operation of the GFMC and the development of the Data Portal.

Annual Cost Implications: <1M US$ (Mainly by Annex-I Parties).

As noted in the body of this report, the GOSIC portal (http://gosic.org/gcos) provides links to data products for individual ECVs. This includes the fire disturbance ECV, for which links include ones to the European products of the Copernicus Atmosphere Monitoring Service and Global Land Service, the ESA CCI and the EUMETSAT Land SAF, and to the NASA/USGS MODIS products. Links are either direct, or go through the product list, with separately linked validation information, that is provided by the CEOS WGCV LPV Subgroup focus area on fire (http://lpvs.gsfc.nasa.gov/producers2.php?topic=fire). Product links are also provided by the GOFC-GOLD Fire Monitoring and Mapping Implementation Team (http://gofc-fire.umd.edu/resources/DataPrvdrRscs/).

T39: Develop set of fire products from the set of operational geostationary satellites

Action: Develop set of active fire and FRP products from the global suite of operational geostationary satellites.

Who: Through operators of geostationary systems, via CGMS, GSICS, and GOFC-GOLD.

Time-Frame: Continuous.

Performance Indicator: Availability of products.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

Products have been developed from the GOES (http://www.ospo.noaa.gov/Products/land/fire.html; http://www.copernicus-atmosphere.eu/catalogue/) and Meteosat (http://landsaf.meteo.pt/) series of geostationary satellites. They supplement those from polar orbit (Action T36) by providing better resolution of the diurnal cycle. Progress is marked only as moderate, however, as there are issues still to be addressed in combining the products from geostationary orbit with the established products from polar orbit. These issues arise from differences in viewing angle and spatial resolution. Kaiser *et al*. (2014) provide a recent discussion in the context of the fire data assimilation system established for the Copernicus Atmosphere Monitoring Service. A significant improvement in data from geostationary orbit is expected from GOES-R series of satellites, the first of which is due for launch in 2016.

T40: Revise the Terrestrial Ecosystems Monitoring Sites (TEMS) database

Action: Revision of TEMS with improved focus on the monitoring of terrestrial ECVs.

Who: Parties' national services and research programmes contributing to TEMS, in cooperation with GTOS, GOSIC, and GCMD, and in consultation with the GCOS Secretariat.

Time-Frame: By 2012.

Performance Indicator: Improvement of site coverage measuring terrestrial ECVs.

Annual Cost Implications: 1-10M US$ (Mainly by Annex-I Parties).

Lack of a functioning GTOS Secretariat has prevented any progress on this (see review of Action T1).

Appendix 2 National communications to the UNFCCC on systematic observation

The following reproduces verbatim an extract on systematic observation from a compilation and synthesis of the sixth national communications and first biennial reports from Parties included in Annex I to the UN Framework Convention on Climate Change (FCCC/SBI/2014/INF.20/Add.2, paras 55-64), prepared by the UNFCCC Secretariat.

Most Parties are involved in maintaining the operations of the global observing systems, especially within the framework of the Global Climate Observing System (GCOS), and all Parties provided information on systematic observation in their NC6s. The degree to which Parties adhered to the "Revised UNFCCC reporting guidelines on global climate change observing systems" and the provision of detailed technical reports on systematic observation in conjunction with the NC6s varied among Parties. Only a few Parties provided such detailed technical reports, either as a separate report or as an annex to their NC6, namely Denmark, Germany, Greece, New Zealand and United Kingdom. Finland referred to its report provided to the GCOS secretariat; and Austria and Switzerland reported on providing such reports through their national GCOS offices. Australia referred to an annex for the provision of data regarding atmospheric, ocean and terrestrial essential climate variables (ECVs).

Parties took various approaches in providing the required information on programmes, networks and/or systems that they are operating to provide observations of atmospheric, oceanic and terrestrial ECVs, as well as on their contributions to GCOS and other global observation systems, including the Global Terrestrial Observing System and the Global Ocean Observing System. Several Parties provided detailed information on their national contributions to observations of ECVs through networks specified in the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC, and a few Parties specified actions taken in response to the recommendations contained in that plan and the new requirements identified in the 2010 update of the plan.

Several Parties highlighted their participation in the activities of the Committee on Earth Observation Satellites and their contributions and provision of support to the Global Earth Observation System of Systems of the Group on Earth Observations.

When reporting on their observation networks, programmes and systems contributing to GCOS and the observation of ECVs in the long term, many Parties highlighted several advances made in improving the availability of climate data. Several Parties reported on the development of new infrastructure for global observation systems and services, including through enhanced international cooperation, and their efforts to organize access to multiple sources of data from Earth observation satellites and in-situ platforms, aimed at providing reliable and up-to-date information to support both adaptation and mitigation. Improvements in linking adaptation and observations were also highlighted in the context of the development and implementation of the various components of the GFCS.

While sustaining the operation of their in-situ observation and monitoring networks, many Parties reported on their participation in the space-based observations of ECVs. Major initiatives highlighted include the Copernicus programme (former Global Monitoring for Environment and Security programme) and its Climate Change service. They also include the activities of the European Organisation for the Exploitation of Meteorological Satellites; and the European Space Agency (ESA), including the ESA Climate Change Initiative for global monitoring of ECVs.

Further significant efforts to improve global climate observations necessary to identify the causes, status and impacts of climate change reported by Parties with space agencies include: the development and operation of the Greenhouse Gases Observing Satellite by Japan, contributing to strengthening the observation and monitoring of region-by-region absorption and GHG emissions; and the support provided by the United States through the National Aeronautics and Space Administration (NASA) and NOAA to a number of major satellite missions that provide sustained global observations of the land surface, oceans, atmosphere, ice sheets and biosphere. In addition, some Parties that are not satellite operators reported on the production and provision of global products using data acquired from satellite observations of the atmospheric, oceanic and terrestrial domains.

Areas where Parties saw progress in relation to systematic observation include: enhanced observations of the global carbon cycle, including sinks and sources of CO_2; enhanced observations of oceanic ECVs and the cryosphere; advances in monitoring various parameters in the polar regions, including new climate-relevant infrastructure, such as polar buoys; the development of a new service for the long-term systematic satellite monitoring of the cryosphere; and the provision of palaeoclimatological data, for example to support studies on the correlation between changes in temperature and changes in atmospheric CO_2 levels in the past. Permafrost monitoring is another area where advances have been made in recent years, but at the same time there are potential challenges reported with regard to securing the long-term continuity of maintaining permafrost monitoring, as one Party reported that monitoring continues to rely on short-term funding projects. Another key area reported is the monitoring of the carbonate system in the Arctic seas to support research on the causes of, and trends in, ocean acidification in the Arctic.

Growing demands for monitoring were highlighted, for example with regard to vegetation, soil conditions and biological diversity.

Several Parties reported on activities for digitising and rescuing historical data sets, including in developing countries, and making available climate observation data through international data centres, as well as their commitment to endorsing the data-sharing policies of the World Meteorological Organization. Many Parties are making historical climate and weather data and other climate data sets freely available to all users, for example on the Internet. As regards reporting on capacity-building in developing countries with regard to climate observations, several Parties reported such activities. Several Parties highlighted regional efforts to enhance climate observations, data sharing and related capacity-building. Some Parties also highlighted their contribution to the GCOS Cooperation Mechanism to enhance the quality of climate-related observations, in particular in developing countries.

Problems reported with regard to the sustained provision of climate observations include the suspension of some observation activities owing to budgetary constraints. For example, Portugal reported on suspending activities within Global Atmospheric Watch and some other monitoring programmes contributing observations of ECVs since mid-2010. Some Parties also reported on the need for the modernization of their observation networks.

Appendix 3 Extract from the conclusions of the 33rd Session of UNFCCC SBSTA

The following is a verbatim extract of paragraphs related to IP-10 from the Report of the UNFCCC Subsidiary Body for Scientific and Technological Advice on its thirty-third session, held in Cancún from 30 November to 4 December 2010. Footnotes are not reproduced. The full Report is available at http://unfccc.int/meetings/cancun_nov_2010/session/6330/php/view/reports.php.

39. The SBSTA welcomed the Update of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (hereinafter referred to as the 2010 updated GCOS implementation plan), submitted by the secretariat of GCOS and prepared under the guidance of the GCOS Steering Committee.

40. The SBSTA noted the sound assessment of requirements for climate-related observations that this plan provides and its enhanced focus on adaptation, in particular the identification of needs for improving land and coastal networks for observations relevant to vulnerability assessments and adaptation, with specific emphasis on developing countries.

41. The SBSTA urged Parties to work towards full implementation of the 2010 updated GCOS implementation plan and to consider, within the context of their national capabilities, what actions they can take at the national, regional and international levels to contribute to the implementation of the plan.

42. The SBSTA further encouraged Parties to increase consideration of GCOS-related implementation in relevant national and regional activities, such as those undertaken by regional centres and national meteorological and hydrological, terrestrial and oceanographic services and those undertaken in the context of adaptation. In this regard, the SBSTA encouraged Parties and relevant organizations to increase coordination of relevant activities and to build upon and enhance existing national and regional centres with the aim of facilitating implementation of the GCOS regional action plans and strengthening observation networks.

43. The SBSTA further noted the importance of historical observations as the basis for analysis and reanalysis and encouraged Parties and relevant organizations to increase their data rescue and digitization of historical observations and to establish and strengthen international coordination initiatives for these activities.

44. The SBSTA encouraged Parties, when providing information related to systematic observation in their detailed technical reports on systematic observations provided in conjunction with their national communications and in line with relevant reporting guidelines to take into consideration the new requirements identified in the 2010 updated GCOS implementation plan, in particular the new essential climate variables (ECVs). The SBSTA noted that any future revision of relevant UNFCCC reporting guidelines, in particular those on global climate change observing systems, should take into account the new elements identified in that plan.

45. The SBSTA invited the GCOS secretariat to report on progress made in the implementation of the 2010 updated GCOS implementation plan on a regular basis, at subsequent sessions of the SBSTA, as appropriate. In this regard it encouraged the GCOS to review, in broad consultation with relevant partners, the adequacy of observing systems for climate, such as by updating the

Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC. It noted the usefulness of updating the GCOS implementation plan on a regular basis, so as to take into consideration developments under the Convention and their related observational needs. The SBSTA agreed to consider, at its thirty-fifth session, issues related to the timing of GCOS contributions to the SBSTA.

Appendix 4 Production of this report

A scoping meeting for this report was held in December 2013. This was followed by a period of information collection and the drafting of tables with information about the ECVs by members of the GCOS panels and invited experts. For each ECV, table entries summarised the definition, the status of observation, relevant networks and satellite datasets as well as data storage, access and data centres, if any.

The Lead Author assisted by the GCOS Secretariat compiled these contributions into initial draft chapters of this report, which were circulated to panel members and associated experts for review and comment. A revised draft was subsequently produced. It contained an assessment for each ECV and for each action as defined by the GCOS Implementation Plan published in 2010. The Lead Author added introductory background and conclusions, and some supplementary information.

This draft was then circulated for public review for 6 weeks from 24 July to 7 September 2015. The draft was circulated to a wide range of invited experts, to WMO Members and to relevant WMO Technical Commissions and the appropriate WMO Expert Teams, to the representatives of the sponsoring organisations of GCOS and others from the wider community. The report was also made available on the internet for review to anyone who wished to participate.

Around 400 comments were received by the Secretariat. They were addressed in a new version prepared by the Lead Author, assisted by the GCOS Secretariat, who consulted with panel members where necessary.

The document was approved by the GCOS Steering Committee, subject to minor amendments and copy-editing, at its twenty-third meeting in Cape Town, 29 September to 1 October 2015.

Appendix 5 lists contributors. The list includes members of the GCOS Steering Committee and its panels as well as experts invited to panel meetings and others who provided substantive input into the document.

This report builds on a wide range of information to review the current status of the global observing system for climate and assess the outcomes of the actions identified in GCOS Implementation Plan published in 2010 (IP-10) . The information consulted includes:

- Earlier GCOS Reports, in particular:
  - The last assessment of progress, the Progress Report on the Implementation of the Global Observing System for Climate in support of the UNFCCC 2004-2008 , August 2009, GCOS-129;
  - IP-10, the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update), August 2010, GCOS-138;
  - The so-called “satellite supplement”, Systematic Observation Requirements for Satellite-based Products for Climate - Supplemental details to the satellite-based component of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC - 2011 Update, December 2011, GCOS-154.

- The scoping meeting for the status report, Scoping Meeting for the Assessment of the Adequacy of the Global Observing System for Climate, Geneva, Switzerland, 12-13 December 2013, GCOS-178;
- A number of GCOS Workshops including:
    - GCOS Workshop on Observations for Adaptation to Climate Variability and Change, Offenbach, Germany, 26–28 February 2013, GCOS-166;
    - Workshop on the review of the GCOS Surface Network (GSN), GCOS Upper-Air Network (GUAN), and related atmospheric networks, Ispra, Italy, 7-8 April 2014, GCOS-182;
    - Report of the joint GCOS/GOFC-GOLD Workshop on Observations for Climate Change Mitigation, Geneva, Switzerland, 5-7 May 2014, GCOS-185;
    - GCOS Workshop on Enhancing Observation to Support Preparedness and Adaption in a Changing Climate - Learning from the IPCC 5th Assessment Report (WG II). Held in collaboration with the IPCC and UNFCCC, Bonn, Germany, 10-12 February 2015, GCOS-191;
- The annual meetings of the GCOS panels – the Atmospheric Observation Panel for Climate (AOPC), the Ocean Observations Panel for Climate (OOPC) and the Terrestrial Observation Panel for Climate (TOPC) - where the status of the global observing system was discussed;
- The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013; 2014) which has, amongst other things, assessed key uncertainties that result from deficiencies in observation;
- The workshop held by the World Climate Research Programme (WCRP), co-sponsored by the IPCC, with support from Swiss government, "IPCC AR5 (WG I): lessons learnt for climate change research and WCRP", 8-10 September 2014, Bern, Switzerland
- The WCRP Open Science Conference (24-28 October 2011, Denver, CO, USA) , and SPARC Data Requirements Workshop;
- The Climate Symposium 2014, 13-17 October 2014, in Darmstadt, Germany;
- National communications to the UNFCCC on systematic observation;
- A draft COSPAR report on Observation and Integrated Earth-system Science: A roadmap for 2016-2025;
- Planning documents of the GCOS sponsors;
- CEOS/CGMS/WMO initiatives concerning the architecture for climate monitoring from space, as inventory of ECV datasets and mission databases;
- Other assessments of requirements such as those of GEO and the ESA Climate Change Initiative.

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Appendix 7 GCOS Climate Monitoring Principles

Effective monitoring systems for climate should adhere to the following principles[6]:

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.
2. A suitable period of overlap for new and old observing systems should be required.
3. The results of calibration, validation and data homogeneity assessments, and assessments of algorithm changes, should be treated with the same care as data.
4. A capacity to routinely assess the quality and homogeneity of data on extreme events, including high-resolution data and related descriptive information, should be ensured.
5. Consideration of environmental climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional and global observing priorities.
6. Uninterrupted station operations and observing systems should be maintained.
7. A high priority should be given to additional observations in data-poor regions and regions sensitive to change.
8. Long-term requirements should be specified to network designers, operators and instrument engineers at the outset of new system design and implementation.
9. The carefully-planned conversion of research observing systems to long-term operations should be promoted.
10. Data management systems that facilitate access, use and interpretation should be included as essential elements of climate monitoring systems.

Furthermore, satellite systems for monitoring climate need to:

(a) Take steps to make radiance calibration, calibration-monitoring and satellite-to-satellite cross-calibration of the full operational constellation a part of the operational satellite system; and

(b) Take steps to sample the Earth system in such a way that climate-relevant (diurnal, seasonal, and long-term interannual) changes can be resolved.

[6] The ten basic principles were adopted by the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) through decision 5/CP.5 at COP 5 in November 1999. The complete set of principles was adopted by the World Meteorological Congress through Resolution 9 (Cg-XIV) in May 2003; agreed by the Committee on Earth Observation Satellites (CEOS) at its 17th Plenary in November 2003; and adopted by COP through decision 11/CP.9 at COP 9 in December 2003.

Thus satellite systems for climate monitoring should adhere to the following specific principles:

11. Constant sampling within the diurnal cycle (minimizing the effects of orbital decay and orbit drift) should be maintained.

12. A suitable period of overlap for new and old satellite systems should be ensured for a period adequate to determine inter-satellite biases and maintain the homogeneity and consistency of time-series observations.

13. Continuity of satellite measurements (i.e., elimination of gaps in the long-term record) through appropriate launch and orbital strategies should be ensured.

14. Rigorous pre-launch instrument characterization and calibration, including radiance confirmation against an international radiance scale provided by a national metrology institute, should be ensured.

15. On-board calibration adequate for climate system observations should be ensured and associated instrument characteristics monitored.

16. Operational production of priority climate products should be sustained and peer-reviewed new products should be introduced as appropriate.

17. Data systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained.

18. Use of functioning baseline instruments that meet the calibration and stability requirements stated above should be maintained for as long as possible, even when these exist on de-commissioned satellites.

19. Complementary *in situ* baseline observations for satellite measurements should be maintained through appropriate activities and cooperation.

20. Random errors and time-dependent biases in satellite observations and derived products should be identified.

Appendix 8 Acronyms, abbreviations and names

AATSR	Advanced Along Track Scanning Radiometer http://www.leos.le.ac.uk/AATSR/
ACARS	Aircraft Communications Addressing and Reporting System
ACE-FTS	Atmospheric Chemistry Experiment - Fourier Transform Spectrometer http://www.ace.uwaterloo.ca/instruments_acefts.html
ACRE	Atmospheric Circulation Reconstructions over the Earth
ACRIM	Active Cavity Radiometer Irradiance Monitoring Satellite (NASA Earth Observing System Programme) http://www.acrim.com/
ADCP	Acoustic Doppler Current Profiler
AD-Net	Asian dust and aerosol lidar observation network
ADM/AEOLUS	Atmospheric Dynamic Mission (ESA) http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/ADM-Aeolus
AERONET	Federation of networks of sun photometers http://aeronet.gsfc.nasa.gov/
AGAGE	Advanced Global Atmospheric Gases Experiment https://agage.mit.edu/
AGU	American Geophysical Union http://sites.agu.org/
AIREP	Aircraft Report (for meteorological observations)
AIRS	Atmospheric Infra-Red Sounder (NASA) http://airs.jpl.nasa.gov/
ALINE	Latin American Lidar Network http://lalinet.org/
ALOS	Advanced Land Observing Satellite http://global.jaxa.jp/projects/sat/alos/
AMDAR	Aircraft Meteorological Data Relay
AMERIFLUX	Network of sites making surface flux measurements over North and South America http://ameriflux.lbl.gov/
AMI	Advanced Microwave Instrument, a scatterometer flown on ERS-1 and ERS-2
AMIP	Atmospheric Model Intercomparison Project http://www-pcmdi.llnl.gov/projects/amip/
AMS	American Meteorological Society https://www2.ametsoc.org/ams/
AMSR-E, 2	Advanced Microwave Scanning Radiometer (JAXA) http://sharaku.eorc.jaxa.jp/AMSR/
AMSU	Advanced Microwave Sounding Unit http://www.remss.com/missions/amsu
AOML	Atlantic Oceanographic and Meteorological Laboratory (NOAA) http://www.aoml.noaa.gov/
AOPC	Atmospheric Observation Panel for Climate (GCOS) http://www.wmo.ch/pages/prog/gcos/index.php?name=AOPC
API	Application Program Interface
AQUASTAT	FAO's global water information system http://www.fao.org/nr/water/aquastat/main/index.stm
AR4 and AR5	Assessment Reports 4 and 5 (IPCC)
ARM	Atmospheric Radiation Measurement climate research facility https://www.arm.gov/
ASAR	Advanced Synthetic Aperture Radar (ESA) https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat/instruments/asar

ASCAT	Advanced Scatterometer (EUMETSAT) http://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Metop/MetopDesign/ASCAT/index.html
ASCENDS	Active Sensing of CO2 Emissions over Nights, Days and Seasons (LIDAR mission proposed to NASA)
AsiaFlux	Network of sites making surface flux measurements over Asia http://www.asiaflux.net/
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer (NASA) https://asterweb.jpl.nasa.gov/
ATLAS	Autonomous Temperature Line Acquisition System (ocean moorings)
ATMS	Advanced Technology Microwave Sounder (NASA) http://npp.gsfc.nasa.gov/atms.html
ATSR	Along Track Scanning Radiometer (ESA)
ATSR-GRAPE	Global Cloud and Aerosol Dataset Produced from ATSR data
AVHRR	Advanced Very High Resolution Radiometer (NOAA) http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data (satellite altimetry data set) http://www.aviso.altimetry.fr/en/home.html
AWS	Automatic Weather Station
BELMANIP	Benchmark Land Multisite Analysis and Intercomparison of Products (CEOS)
BIOMASS	Selected future ESA Earth Explorer Mission
BOUSSOLE	Buoy for the Acquisition of Long-term Time Series http://www.obs-vlfr.fr/Boussole/html/home/home.php
BSRN	Baseline Surface Radiation Monitoring Network http://www.knmi.nl/bsrn/
BUFR	Binary Universal Form for the Representation of meteorological data
BUV	Backscatter Ultraviolet Spectrometer
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (NASA/CNES) http://www.nasa.gov/mission_pages/calipso/spacecraft/index.html
CAMS	Copernicus Atmosphere Monitoring Service
CarbonTracker	Tool that tracks time dependent emissions and uptake of atmospheric CO_2 and CH_4, natural and man-made http://www.esrl.noaa.gov/gmd/ccgg/data-products.html
CarbonTracker Europe	A European version of the tool, for CO_2 http://www.carbontracker.eu/index.html
CATS	Cloud-Aerosol Transport System (Lidar instrument on International Space Station)
CBS	WMO Commission for Basic Systems
CCHDO	CLIVAR Carbon Hydrography Data Office (Scripps Institute for Oceanography)
CCI	Climate Change Initiative of ESA http://ionia1.esrin.esa.int
CCl	Commission for Climatology of WMO http://www.wmo.int/pages/prog/wcp/ccl/index_en.php
CDIAC	Carbon Dioxide Information Analysis Center http://cdiac.ornl.gov/oceans/
CEOS	Committee on Earth Observation Satellites http://www.ceos.org
CEOS MIMD	CEOS Missions, Instruments and Measurements database http://database.eohandbook.com/
CERES	Clouds and the Earth's Radiant Energy System (NASA) http://ceres.larc.nasa.gov/
CFC	Chloro Fluoro Carbons

CFSR	Climate Forecast System Reanalysis (NOAA/NCEP) http://cfs.ncep.noaa.gov/cfsr/
CGMS	Coordination Group for Meteorological Satellites http://www.cgms-info.org
CGMS-GSICS	CGMS Global Space-based Inter-Calibration System http://gsics.wmo.int/
CHy	WMO Commission for Hydrology http://www.wmo.int/pages/prog/hwrp/chy/
CIMO	WMO Commission for Instruments and Methods of Observations https://www.wmo.int/pages/prog/www/CIMO/AboutCIMO.html
CIRES	Cooperative Institute for Research In Environmental Sciences http://cires.colorado.edu/about/noaa/
CLARA	CLoud, Albedo and RAdiation dataset (EUMETSAT)
CLIMAR	JCOMM workshop series on Advances in Marine Climatology
CLIVAR	Climate and Ocean: Variability, Predictability and Change, a WCRP core project http://www.clivar.org/
CLIVAR/GSOP	CLIVAR Global Synthesis and Observations Panel
ChloroGIN	The Chlorophyll Global Integrated Network
CLARREO	Climate Absolute Radiance and Refractivity Observatory (proposed NASA mission)
CM-SAF	Satellite Application Facility on Climate Monitoring http://www.cmsaf.eu/EN/Home/home_node.html
CMCC	Euro-Mediterranean Center on Climate Change http://www.cmcc.it/
CMIP	Coupled Model Intercomparison Project (WCRP) http://cmip-pcmdi.llnl.gov/
CMOC	Centres for Marine Meteorological and Oceanographic Climate Data
CNES	Centre National d'Etudes Spatiales https://cnes.fr/
CO2	Carbon Dioxide
CONTRAIL	Comprehensive Observation Network for TRace gases by AIrLiner http://www.cger.nies.go.jp/contrail/contrail.html
COP	Conference of the Parties (to UNFCCC)
Copernicus	European Earth observation programme (previously GMES) http://www.copernicus.eu/
CORE-CLIMAX	COordinating Earth observation data validation for RE-analysis for CLIMAte ServiceS (EU funded project)
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate http://www.cosmic.ucar.edu/
COSPAR	Committee on Space Research (ICSU) http://www.icsu.org/what-we-do/interdisciplinary-bodies/cospar/
CPR	Continuous Plankton Recorder
CREWs	Cloud Retrieval Evaluation Workshops
CRIS	Cross-track Infrared Sounder (NASA) http://npp.gsfc.nasa.gov/cris.html
CRM	Certified Reference Materials (for nutrients and minerals in water)
CRU	Climatic Research Unit of the University of East Anglia http://www.cru.uea.ac.uk/
CRUTEM	Temperature data sets developed by Climatic Research Unit
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia's national science agency) http://www.csiro.au/
CTD	Conductivity Temperature Depth profiler
DAAC	Distributed Active Archive Center (NASA)
DBCP	Data Buoy Cooperation Panel http://www.jcommops.org/dbcp/

DEM	Digital Elevation Model
DMPA	Data Management Programme Area
DMSP	Defense Meteorological Satellite Program
DOAS	Differential Optical Absorption Spectroscopy
DOOS	Deep Ocean Observing Strategy
DSCOVR	Deep Space Climate Observatory http://www.nesdis.noaa.gov/DSCOVR/
DWD	Deutscher Wetterdienst http://www.dwd.de/
EARLINET	European Aerosol Research Lidar Network http://www.earlinet.org/
EBV	Essential Biodiversity Variables
ECMWF	European Centre for Medium-Range Weather Forecasts http://www.ecmwf.int
ECRA	European Climate Research Alliance http://www.ecra-climate.eu/
ECV	Essential Climate Variable
EMSO	European Multidisciplinary Seafloor and water column Observatory http://www.emso-eu.org/
EN3 and EN4	UK Met Office subsurface ocean temperature and salinity data sets http://www.metoffice.gov.uk/hadobs/en3/ http://www.metoffice.gov.uk/hadobs/en4/
ENSO	El Niño Southern Oscillation
Envisat	Environmental Satellite (ESA) http://www.esa.int/Our_Activities/Observing_the_Earth/Envisat
EOLE	Southern Hemisphere Balloon Observations experiment (CNES 1971-1972)
EOV	Essential Ocean Variable
ERA	European (or ECMWF) ReAnalysis http://www.ecmwf.int/en/research/climate-reanalysis
ERA-CLIM	European Reanalysis of the Global Climate System http://www.era-clim.eu/
ERBE	Earth Radiation Budget Experiment http://www.nasa.gov/centers/langley/news/factsheets/ERBE.html
ERM-1 and 2	Earth Radiation Measurement instruments on board Chinese satellites http://www.wmo-sat.info/oscar/instruments/view/132
ERS-1, -2	European Remote Sensing satellites (ESA)
ESA	European Space Agency http://www.esa.int
ESSP	Earth System Science Partnership
ETCCDI	CCl/CLIVAR/JCOMM Expert Team (ET) on Climate Change Detection and Indices http://www.clivar.org/panels-and-working-groups/etccdi/etccdi.php
ETH	Swiss Federal Institute of Technology in Zurich https://www.ethz.ch/en.html
ETM or ETM+	Landsat Enhanced Thematic Mapper (Plus) https://lta.cr.usgs.gov/LETMP
EU	European Union
EUMETNET	grouping of 31 European National Meteorological Services http://www.eumetnet.eu/
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites http://www.eumetsat.int
FAO	Food and Agricultural Organization of the United Nations http://www.fao.int
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FCDR	Fundamental Climate Data Record

FCOVER	Fraction of Vegetation Cover
FLUXNET	Flux and Energy Exchange Network http://fluxnet.ornl.gov/introduction
FOAM	Met Office Forecast Ocean Assimilation Model
FP7	European Union Research Framework Programme (2007-2013) http://ec.europa.eu/research/fp7/index_en.cfm
FRP	Fire Radiative Power
FTIR	Fourier Transform Infrared Spectrometry
FY	Feng-Yun Chinese satellite series
GACS	Global Alliance of Continuous Plankton Recorder Surveys http://www.globalcpr.org/
GALION	GAW Aerosol Lidar Observation Network
GAW	Global Atmosphere Watch programme of WMO focused on atmospheric composition http://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html
GAWSIS	GAW Station Information System, developed and operated by Switzerland http://gaw.empa.ch/gawsis/
GCM	GCOS Cooperation Mechanism
GCMD	Global Change Master Directory http://gcmd.nasa.gov/
GCMP	GCOS Climate Monitoring Principles
GCN	GLOSS (Global Sea Level Observing System) Core Network
GCOM	Global Change Observation Mission (Japan) https://directory.eoportal.org/web/eoportal/satellite-missions/g/gcom
GCOM-C	Global Change Observation Mission – Climate http://global.jaxa.jp/projects/sat/gcom_c/
GCOM-W	Global Change Observation Mission for Water http://global.jaxa.jp/projects/sat/gcom_w/
GCOS	Global Climate Observing System http://www.wmo.int/pages/prog/gcos/
GCW	Global Cryosphere Watch http://globalcryospherewatch.org/
GDAC	Global Data Assembly Centres (Argo data)
GEDI	Global Ecosystem Dynamics Investigation (NASA lidar system) http://science.nasa.gov/missions/gedi/
GEF	Global Environment Facility https://www.thegef.org/gef/whatisgef
GEMS	Geostationary Environment Monitoring Spectrometer http://www.ballaerospace.com/page.jsp?page=319
GEO	Group on Earth Observations https://www.earthobservations.org/index.php
GEOBON	GEO Biodiversity Observation Network http://geobon.org/
GEOSECS	Geochemical Ocean Sections Study http://odv.awi.de/en/data/ocean/geosecs/
GEOSS	Global Earth Observation System of Systems
	GEOSS data portal: http://www.geoportal.org/web/guest/geo_home_stp
GERB	Geostationary Earth Radiation Budget instrument (Meteosat) https://www.google.ch/search?hl=&q=gerb&gws_rd=ssl#q=gerb+instrument
GEWEX	Global Energy and Water Exchanges project of WCRP http://www.gewex.org
GFCS	Global Framework for Climate Services http://gfcs.wmo.int/
GFMC	Global Fire Monitoring Center http://www.fire.uni-freiburg.de/

GFO	Geosat Follow On mission http://www.altimetry.info/html/missions/gfo/welcome_en.html
GGIS	Global Groundwater Information System http://www.un-igrac.org/publications/104
GGMN	Global Groundwater Monitoring Network http://www.un-igrac.org/publications/281
GGOS	Global Geodetic Observing System http://www.ggos.org/
GHCN	Global Historical Climatology Network https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/global-historical-climatology-network-ghcn
GHG	Greenhouse Gases
GISC	Global Information System Centre (WMO)
GISS	Goddard Institute for Space Studies (NASA) http://www.giss.nasa.gov/
GISTEMP	GISS Surface Temperature Analysis
GLC2000	Global Land Cover database for the year 2000 (EU)
GLCN	Global Land Cover Network (FAO) http://www.glcn.org/index_en.jsp
GLIMS	Global Land Ice Measurements from Space http://www.glims.org/
GLODAP	GLobal Ocean Data Analysis Project http://cdiac.ornl.gov/oceans/glodap/
GLOSS	Global Sea Level Observing System http://www.gloss-sealevel.org/
GMES	Global Monitoring for Environment and Security (EU), now Copernicus
GMI	Global Modeling Initiative (NASA) http://gmi.gsfc.nasa.gov/
GMSL	Global Mean Sea Level
GNIP	Global Network of Isotopes in Precipitation (IAEA)
GNSS	Global Navigation Satellite System http://egnos-portal.gsa.europa.eu/discover-egnos/about-egnos/what-gnss
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program http://www.go-ship.org/
GOA-ON	Global Ocean Acidification Observing Network http://goa-on.org/
GODAE	Global Ocean Data Assimilation Experiment https://www.godae.org/
GODAR	Global Oceanographic Data Archaeology and Rescue (NOAA) https://www.nodc.noaa.gov/General/NODC-dataexch/NODC-godar.html
GOES	Geostationary Operational Environmental Satellite (NOAA) http://www.goes.noaa.gov/
GOFC-GOLD	Global Observations of Forest and Land Cover Dynamics http://www.fao.org/gtos/gofc-gold/
GOME	Global Ozone Monitoring Experiment (EUMETSAT) http://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Metop/MetopDesign/GOME2/index.html
GOOS	Global Ocean Observing System http://www.ioc-goos.org/
GOSAT	Greenhouse gases Observing SATellite (Japan) http://www.gosat.nies.go.jp/
GOSIC	Global Observing Systems Information Center http://www.gosic.org/
GOSUD	Global Ocean Surface Underway Data http://www.gosud.org/
GPCC	Global Precipitation Climatology Centre http://www.dwd.de/bvbw/appmanager/bvbw/dwdwwwDesktop?_nfpb=true&_windowLabel=T12404818261141645314319&_urlType=action&switchLang=en&_pageLabel=_dwdwww_klima_umwelt_datenzentren_wzn

GPCP	Global Precipitation Climatology Project http://precip.gsfc.nasa.gov/
GPM	Global Precipitation Measurement (NASA) http://www.nasa.gov/mission_pages/GPM/main/index.html
GPP	Gross Primary Production
GPS	Global Positioning System http://www.gps.gov/
GRACE	Gravity Recovery and Climate Experiment (NASA) http://www.csr.utexas.edu/grace/
GRDC	Global Runoff Data Centre, Federal Institute of Hydrology, Koblenz, Germany http://www.bafg.de/GRDC
GRUAN	GCOS Reference Upper Air Network https://www.wmo.int/pages/prog/gcos/index.php?name=GRUAN
GSICS	Global Space-based Inter-calibration System http://gsics.wmo.int/
GSN	GCOS Surface Network http://www.gosic.org/content/gcos-surface-network-gsn-program-overview
GSNMC	GCOS Surface Network Monitoring Centre http://www.dwd.de/bvbw/appmanager/bvbw/dwdwwwDesktop/?_nfpb=true&switchLang=en&_pageLabel=_dwdwww_klima_umwelt_datenzentren_gsnmc
GTN	Global Terrestrial Network
GTN-G	Global Terrestrial Network for Glaciers http://www.gtn-g.org/
GTN-GW	Global Terrestrial Network – Ground water ftp://ftp.fao.org/docrep/fao/011/i0197e/i0197e07.pdf
GTN-H	Global Terrestrial Network – Hydrology http://gtn-h.unh.edu/
GTN-L	Global Terrestrial Network Lakes
GTN-P	Global Terrestrial Network for Permafrost http://gtnp.arcticportal.org/
GTN-R	Global Terrestrial Network for River Discharge http://www.bafg.de/GRDC/EN/04_spcldtbss/44_GTNR/gtnr_node.html
GTN-SM	Global Terrestrial Network for Soil Moisture http://www.gosic.org/content/gcos-terrestrial-ecv-soil-moisture
GTOS	Global Terrestrial Observing System http://www.fao.org/gtos/
GTS	Global Telecommunication System (WMO) http://www.wmo.ch/pages/prog/www/TEM/GTS/index_en.html
GUAN	GCOS Upper-Air Network
HATS	Halocarbons and other Trace Species Group of NOAA/CMDL
HadCRUT4	Hadley Centre Climate Research Unit temperature data set http://www.metoffice.gov.uk/hadobs/hadcrut4/
HCFC	Hydrochlorofluorocarbon
HCHO	Formaldehyde
HFC	Hydrofluorocarbon
HIRS	High-resolution Infrared Radiation Sounder (EUMETSAT)
Horizon 2020	EU Framework Programme for Research and Innovation http://ec.europa.eu/programmes/horizon2020/
HY-2	Ocean observation/monitoring satellite series (China) https://directory.eoportal.org/web/eoportal/satellite-missions/h/hy-2a
HYCOM	HYbrid Coordinate Ocean Model https://hycom.org/
HYDROLARE	Hydrology data base on lakes and reservoirs http://hydrolare.net/

HYDROWEB	Hydrology data base (LEGOS) http://ctoh.legos.obs-mip.fr/products/hydroweb
IACS	International Association of Cryospheric Sciences http://www.cryosphericsciences.org/
IAEA	International Atomic Energy Agency https://www.iaea.org/
IAGOS	In-service Aircraft for a Global Observing System http://www.iagos.org/
IAOOS	Ice, Atmosphere, Arctic Ocean Observing System http://www.polarprediction.net/fileadmin/user_upload/redakteur/Home/YOPP/Yopp_Summit_Presentation/Session_8_13_IAOOS.pdf
IASI	Infrared Atmospheric Sounding Interferometer (EUMETSAT) http://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Metop/MetopDesign/IASI/index.html
IASI-NG	IASI New Generation (CNES) ftp://ftp.legos.obs-mip.fr/pub/tmp3m/IGARSS2014/pdfs/0001373.pdf
ICAO	International Civil Aviation Organization
ICES	International Council for the Exploration of the Sea http://www.ices.dk/Pages/default.aspx
ICESat	Ice, Clouds, and Land Elevation Satellite (NASA) http://icesat.gsfc.nasa.gov/
ICOADS	International Comprehensive Ocean-Atmosphere Data Set (NOAA) http://icoads.noaa.gov/
ICOS	Integrated Carbon Observation System (EU) https://www.icos-ri.eu/
ICSU	International Council for Science http://www.icsu.org/
ICWG	International Cloud Working Group http://www.wmo.int/pages/prog/sat/meetings/documents/IPET-SUP-1_INF_03-03_ICWG-Update.pdf
IDAF	IGAC DEBITS AFRICA (atmospheric Chemistry Network in Africa) http://idaf.sedoo.fr/spip.php?rubrique3
IDC	International Data Centre
IEEE	Institute of Electrical and Electronics Engineers https://www.ieee.org/index.html
IFREMER	'Institut Français de Recherche pour l'Exploitation de la Mer http://wwz.ifremer.fr/
IGBP	International Geosphere-Biosphere Programme http://www.igbp.net/
IGOS	Integrated Global Observing Strategy http://www.fao.org/gtos/igos/
IGRAC	International Groundwater Resources Assessment Centre http://www.un-igrac.org/
IGWCO	Integrated Global Water Cycle Observations (GEO) https://www.earthobservations.org/wa_igwco.shtml
IIASA	International Institute for Applied Systems Analysis http://www.iiasa.ac.at/
IIOE	International Indian Ocean Expedition http://global-oceans.org/site/2nd-international-indian-ocean-expedition
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research http://www.imber.info/
IMOS	Integrated Marine Observing System (Australia) http://www.imos.org.au/
IMPROVE	Interagency Monitoring of Protected Visual Environments http://vista.cira.colostate.edu/improve/
IMS	Interactive Multisensor Snow and Ice Mapping System (NOAA) http://www.natice.noaa.gov/ims/

IR	Infrared
IOC	Intergovernmental Oceanographic Commission of UNESCO http://ioc-unesco.org/
IOCCG	International Ocean Colour Coordinating Group http://www.ioccg.org/
IOCCP	International Ocean Carbon. Coordination Project http://www.ioccp.org/
IODE	International Oceanographic Data and Information Exchange (IOC) http://www.iode.org/
IPCC	Intergovernmental Panel on Climate Change http://www.ipcc.ch/
IPWG	International Precipitation Working Group (CGMS) http://www.isac.cnr.it/~ipwg/
IQuod	International Quality-Controlled Ocean Database http://www.iquod.org/
IRIS	Interface Region Imaging Spectrograph (NASA) http://www.nasa.gov/mission_pages/iris/spacecraft/index.html
ISCCP	International Satellite Cloud Climatology Project http://isccp.giss.nasa.gov/
ISD	Integrated Surface Database (NOAA) https://www.ncdc.noaa.gov/isd
ISMN	International Soil Moisture Network http://ismn.geo.tuwien.ac.at
ISO	International Organization for Standardization http://www.iso.org/iso/home.html
ISPD	International Surface Pressure Databank https://reanalyses.org/observations/international-surface-pressure-databank
ISPRS	International Society for Photogrammetry and Remote Sensing http://www.isprs.org/
ISRO	Indian Space Research Organisation http://www.isro.gov.in/
ISS	International Space Station http://www.nasa.gov/mission_pages/station/main/index.html
ISS-Rapidscat	International Space Station Rapid Scat- terometer http://www.jpl.nasa.gov/missions/iss-rapidscat/
ISTI	International Surface Temperature Initiative http://www.surfacetemperatures.org/
ISTI-POST	ISTI- Parallel Observations Science Team
JAMSTEC	Japan Agency for Marine-Earth Science and Technology http://www.jamstec.go.jp/e/
JAXA	Japan Aerospace Exploration Agency http://global.jaxa.jp/
JCOMM	Joint Commission on Oceanography and Marine Meteorology http://www.jcomm.info/
JCOMM-IODE	JCOMM International Oceanographic Data and Information Exchange http://www.iode.org/index.php?option=com_content&view=article&id=96&Itemid=123
JCOMMOPS	JCOMM in situ Observations Programme Support Centre http://www.jcommops.org/new/
JMA	Japan Meteorological Agency http://www.jma.go.jp/jma/indexe.html
JPSS	Joint Polar Satellite System (NOAA) http://www.jpss.noaa.gov/
JRA	Japanese Reanalysis projects http://jra.kishou.go.jp/JRA-55/index_en.html
KNMI	Royal Netherlands Meteorological Institute http://www.knmi.nl/index_en.html
LAI	Leaf Area Index
LPV	Land Product Validation
LST	Land-surface temperature
LTER	Long-Term Ecological Research Network http://www.lternet.edu/

MAESTRO	Measurement of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation (Canada) http://www.ace.uwaterloo.ca/instruments_maestro.html
MACC	Monitoring Atmospheric Composition and Climate (Copernicus) https://www.gmes-atmosphere.eu/
MARCDAT	Workshop on Advances in the Use of Historical Marine Climate Data
MAXDOAS	Multi Axis Differential Optical Absorption Spectroscopy
MERIS	Medium Resolution Imaging Spectrometer on Envisat https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat/instruments/meris
MERRA	Modern Era Retrospective-Analysis for Research and Applications (NASA) http://gmao.gsfc.nasa.gov/merra/
METAR	Meteorological Terminal Aviation Routine Weather Report
Metop	European polar orbiting meteorological satellite series (EUMETSAT)
MHS	Microwave Humidity Sounder (NOAA/EUMETSAT) http://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Metop/MetopDesign/MHS/index.html
MIPAS	Michaelson Interferometer for Passive Atmospheric Sounding (on ENVISAT, ESA) https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat/instruments/mipas
MISR	Multi-angle Imaging SpectroRadiometer (NASA) https://www-misr.jpl.nasa.gov/
MLOST	Merged Land–Ocean Surface Temperature Analysis (NOAA) https://www.ncdc.noaa.gov/data-access/marineocean-data/mlost
MLS	Microwave Limb Sounder https://mls.jpl.nasa.gov/index-eos-mls.php
MOBY	Marine Optical Buoy Program https://moby.mlml.calstate.edu/
MODIS	Moderate Resolution Imaging Spectroradiometer (NASA) http://modis.gsfc.nasa.gov/
MOIN	Minimalist OceanSITES Interdisciplinary Network
MOPITT	Measurements Of Pollution In The Troposphere (NASA instrument) https://www2.acom.ucar.edu/mopitt
MOZAIC	Measurements of OZone, water vapour, carbon monoxide and nitrogen oxides by in-service AIrbus aircraft http://www.iagos.fr/web/rubrique2.html
MPLNET	Micro Pulse Lidar Network (NOAA) http://www.ndsc.ncep.noaa.gov/coop/mplnet/
MSG	Meteosat Second Generation http://www.esa.int/Our_Activities/Observing_the_Earth/Meteosat_Second_Generation
MSU	Microwave Sounding Unit (NOAA) http://www.remss.com/missions/amsu
MWHS	Micro-Wave Humidity Sounder (on polar orbiting FY Chinese satellites) http://database.eohandbook.com/database/instrumentsummary.aspx?instrumentID=669
MWRI	Microwave Radiation Imager on FY-3 satellites
NADP	National Atmospheric Deposition Program http://nadp.sws.uiuc.edu/nadp/
NASA	National Aeronautics and Space Administration http://www.nasa.gov/
NASA/GMAO	NASA Global Modeling and Assimilation Office http://gmao.gsfc.nasa.gov/
NASMD	North American Soil Moisture Database http://soilmoisture.tamu.edu
NCAR	National Centre for Atmospheric Research https://ncar.ucar.edu/

NCDC	National Climatic Data Center http://www.ncdc.noaa.gov/
NCEI	NOAA's National Centers for Environmental Information http://www.ncdc.noaa.gov
NCEP	National Centers for Environmental Prediction http://www.ncep.noaa.gov/
NC6	Sixth national communication (under the UNFCCC)
NDACC	Network for the Detection of Atmospheric Composition Change http://www.ndsc.ncep.noaa.gov/
NEON	National Ecological Observatory Network http://www.neoninc.org/
NESDIS	National Environmental Satellite, Data, and Information Service http://www.nesdis.noaa.gov/
NEXRAD	Next Generation Weather Radar https://www.ncdc.noaa.gov/data-access/radar-data/nexrad
NGCC	National Geomatics Center of China http://ngcc.sbsm.gov.cn/article/en
NHS	National Hydrological Service
NIR	Near Infra-Red
NISAR	NASA-ISRO SAR Mission http://nisar.jpl.nasa.gov/
NMHs	National Meteorological and Hydrological Services
NMVOC	Non-methane volatile organic compound
NOAA	US National Oceanographic and Atmospheric Administration http://www.noaa.gov
NOAAGlobalTemp	NOAA merged Global land-sea Temperature analysis https://www.ncdc.noaa.gov/data-access/marineocean-data/noaa-global-surface-temperature-noaaglobaltemp
NOCS	National Oceanography Centre Southampton http://noc.ac.uk/southampton
NODC	National Oceanographic Data Center (NOAA) https://www.nodc.noaa.gov/
NPL	National Physical Laboratory (UK) http://www.npl.co.uk/
NSIDC	National Snow and Ice Data Center http://nsidc.org/
NWP	Numerical Weather Prediction
OceanSITES	Ocean Sustained Interdisciplinary Time series Environment observation System http://oceansites.jcommops.org/
OCG	Observations Coordination Group (JCOMM)
OCM	Ocean Colour Monitor on Oceansat-1 and 2 (India)
OCO	Orbiting Carbon Observatory (NASA) http://oco.jpl.nasa.gov/
OCR	Ocean Colour Radiance
OCR-VC	Ocean. Colour Radiance. Virtual Constellation (CEOS)
ODIP	Ocean Data Interoperability Platform http://www.odip.org/
OGC	Open Geospatial Consortium www.opengeospatial.org
OLCI	Ocean and Land Colour Imager on Sentinel 3
OMI	Ozone Monitoring Instrument http://www.nasa.gov/mission_pages/aura/spacecraft/omi.html
OMPS	Ozone Mapping & Profiler Suite (NASA) http://npp.gsfc.nasa.gov/omps.html
OMS	Ozone Mapping Spectrometer (China)
OOI	Ocean Observatories Initiative http://oceanobservatories.org/
OOPC	Ocean Observations Panel for Climate https://www.wmo.int/pages/prog/gcos/index.php?name=OOPC

ORA-IP	Ocean Reanalysis Intercomparison Project http://www.researchgate.net/publication/266374001_The_Ocean_Reanalyses_Intercomparison_Project_(ORA-IP)
ORAP	Ocean Research Advisory Panel http://www.nopp.org/about-nopp/nopp-committees/orap/
ORAS	Ocean Reanalysis System (ECMWF) http://www.ecmwf.int/en/research/climate-reanalysis/ocean-reanalysis
ORNL	Oak Ridge National Laboratory https://www.ornl.gov/
OSCAR	Observing Systems Capability Analysis and Review Tool (WMO) http://www.wmo-sat.info/oscar/
OSCAT	Oceansat-2 Scatterometer (India) https://data.gov.in/keywords/oscat
OSIRIS	Optical Spectrograph and InfraRed Imaging System (Canada) http://osirus.usask.ca/?q=node/1
OSTIA	Operational Sea Surface Temperature and Sea Ice Analysis (UK Met Office) http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html
PAGE21	Changing Permafrost in the Arctic and its Global Effects in the 21st Century (EU) http://www.page21.eu/
PAGES	Past Global Changes, an IGBP project http://www.pages-igbp.org/about/general-overview
PALSAR	Phased Array type L-band Synthetic Aperture Radar (Japan) http://www.eorc.jaxa.jp/ALOS/en/about/palsar.htm
PAR	Photosynthetically Active Radiation
PARASOL	Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (CNES) https://directory.eoportal.org/web/eoportal/satellite-missions/p/parasol
PERMOS	Swiss Permafrost Monitoring Network http://www.permos.ch/
PICES	North Pacific Marine Science Organization https://www.pices.int/
PICO	Panel for Integrated Coastal Observations (GOOS)
PIRATA	Prediction and Research Moored Array in the Atlantic http://www.pmel.noaa.gov/pirata/
PM10	Particulate Matter up to 10 micrometers in size
PMEL	Pacific Marine Environmental Laboratory (NOAA) http://www.pmel.noaa.gov/
PMR	Pressure Modulator Radiometer (NOAA) http://www.wmo-sat.info/oscar/instruments/view/401
POGO	Partnership for Observation of the Global Oceans http://www.ocean-partners.org/
POLDER	Polarization and Directionality of the Earth's Reflectances (CNES) https://polder-mission.cnes.fr/en/POLDER/GP_instrument.htm
PREMOS	Satellite Experiment to Monitor the Solar Irradiance at Selected Wavelengths (CNES) https://picard.cnes.fr/en/PICARD/GP_instruments.htm
PROBA	PRoject for OnBoard Autonomy (ESA) http://www.esa.int/Our_Activities/Space_Engineering_Technology/Proba_Missions
PROVIA	Global Programme of Research on Vulnerability, Impacts and Adaptation http://www.unep.org/provia/
QuickSCAT	Earth observation satellite carrying the SeaWinds scatterometer (NASA) http://www.remss.com/missions/qscat
R2R	Rolling Deck to Repository program (USA) http://www.rvdata.us/

RADARSAT	Canadian Remote Sensing satellite http://www.asc-csa.gc.ca/eng/satellites/radarsat/
RAMA	Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction http://www.pmel.noaa.gov/tao/rama/
RAP	Regional Action Plan (GCOS)
RATPAC	Radiosonde Atmospheric Temperature Products for Assessing Climate https://www.ncdc.noaa.gov/data-access/weather-balloon/radiosonde-atmospheric-temperature-products-accessing-climate
RBCN	Regional Basic Climatological Network http://www.wmo.ch/pages/prog/www/ois/rbsn-rbcn/rbsn-rbcn-home.htm
RBSN	Regional Basic Synoptic Network http://www.wmo.ch/pages/prog/www/ois/rbsn-rbcn/rbsn-rbcn-home.htm
REDD	Reducing emissions from deforestation and forest degradation (UNFCCC) http://www.un-redd.org/
ROMS	Regional Ocean Modeling System https://www.myroms.org/
SAF	Satellite Application Facility (EUMETSAT) http://www.eumetsat.int/website/home/Satellites/GroundSegment/Safs/index.html
SAFARI	Societal Applications in Fisheries & Aquaculture using Remotely-Sensed Imagery http://www.oceanobs09.net/proceedings/cwp/Forget-OceanObs09.cwp.30.pdf
SAG	Scientific Advisory Group
SAGE III	Stratospheric Aerosol and Gas Experiment (NASA) http://sage.nasa.gov/SAGE3ISS/
SAOCOM	SAR Observation & Communications Satellite (Argentina) http://space.skyrocket.de/doc_sdat/saocom-1.htm
SAOZ	Système D'Analyse par Observations Zénithales http://saoz.obs.uvsq.fr/
SAR	Synthetic Aperture Radar http://www.radartutorial.eu/20.airborne/ab07.en.html
SARAL	Satellite with ARgos and ALtiKa (France-India) https://en.wikipedia.org/wiki/SARAL
SBA	Societal Benefit Area (GEO)
SBSTA	Subsidiary Body for Scientific and Technological Advice (UNFCCC) http://unfccc.int/bodies/body/6399.php
SBUV	Solar Backscatter Ultraviolet Instrument (NOAA) http://www.ozonelayer.noaa.gov/action/sbuv2.htm
SCAMS	Scanning Microwave Spectrometer (NASA) http://www.wmo-sat.info/oscar/instruments/view/468
SCAR	Scientific Committee on Antarctic research http://www.scar.org/
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY www.sciamachy.org/
SCOPE-CM	Sustained and Coordinated Processing of Environmental Satellite data for Climate Monitoring http://www.scope-cm.org/
SCOR	Scientific Committee on Oceanic Research http://www.scor-int.org/
SDR	Sensor Data Record
SeaBASS	SeaWiFS Bio-Optical Archive and Storage System http://oceancolor.gsfc.nasa.gov
SeaWIFS	Sea-Viewing Wide Field-of-View Sensor (NASA) http://oceancolor.gsfc.nasa.gov/SeaWiFS/

SEVIRI	Spinning Enhanced Visible and InfraRed Imager (EUMETSAT) http://www.esa.int/esapub/bulletin/bullet111/chapter4_bul111.pdf
SF6	sodium hexafluoride
SGLI	Second Generation Global Imager on GCOM-C (Japan) http://www.ioccg.org/sensors/sgli.html
SHADOZ	Southern Hemisphere ADditional OZonesondes http://croc.gsfc.nasa.gov/shadoz/
SIOS	Svalbard Integrated Earth Observing System http://www.sios-svalbard.org/servlet/Satellite?c=Page&pagename=sios/Hovedsidemal&cid=1234130481072
SLSTR	Sea and Land Surface Temperature Radiometer (ESA-EU) https://sentinel.esa.int/web/sentinel/sentinel-3-slstr-wiki/-/wiki/Sentinel%20Three%20SLSTR/Instrument
SMAP	Soil Moisture Active Passive (NASA) http://smap.jpl.nasa.gov/mission/description/
SMILES	Superconducting Submillimeter-Wave Limb-Emission Sounder (NASA) http://www.nasa.gov/mission_pages/station/research/experiments/638.html
SMMR	Scanning Multichannel Microwave Radiometer (NASA) http://nsidc.org/data/docs/daac/smmr_instrument.gd.html
SMOS	Soil Moisture and Ocean Salinity (ESA) http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/SMOS
SNOTEL	SNOwpack TELemetry network http://www.wcc.nrcs.usda.gov/snow/
SnowPEX	Intercomparison and evaluation of satellite-based snow-cover products http://calvalportal.ceos.org/projects/snowpex
SOCAT	Surface Ocean CO2 Atlas http://www.socat.info/
SOCCOM	Southern Ocean Carbon and Climate Observations and Modeling project soccom.princeton.edu/
SOCOM	Surface Ocean CO_2 Mapping inter-comparison project
SOLAS	Surface Ocean - Lower Atmosphere Study project http://www.solas-int.org/
SOOP	Ship Of Opportunity Programme https://www.wmo.int/pages/prog/amp/mmop/JCOMM/OPA/SOT/soop.html
SOOS	Southern Ocean Observing System http://www.soos.aq/
SORCE	Solar Radiation and Climate Experiment (NASA) http://science.nasa.gov/missions/sorce/
SOT	Ship Observations Team (JCOMM)
SPARC	Stratosphere-troposphere Processes And their Role in Climate (WCRP) http://www.sparc-climate.org/
SPOT	Satellite Pour l'Observation de la Terre (CNES) https://en.wikipedia.org/wiki/SPOT_(satellite)
SPOT-Vegetation	Instrument on board SPOT satellites http://www.spot-vegetation.com/
SRTM	Shuttle Radar Topography Mission (NASA) http://www2.jpl.nasa.gov/srtm/
SSH	sea-surface height
SSM/I	Special Sensor Microwave Image (DMSP satellites) http://www.remss.com/missions/ssmi
SSMIS	Special Sensor Microwave Imager Sounder (DMSP satellites) https://nsidc.org/data/docs/daac/ssmis_instrument/

SSM/T-2	Special Sensor Microwave/Temperature Profiler (NASA) http://www.wmo-sat.info/oscar/instruments/view/535
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SUOMI-NPP	Suomi National Polar-orbiting Partnership (NASA) http://www.nasa.gov/mission_pages/NPP/main/index.html
SURFRAD	Surface Radiation Budget Network http://www.esrl.noaa.gov/gmd/grad/surfrad/
SWH	Significant Wave Height
SWIR	Short-Wave InfraRed
SWOT	Surface Water and Ocean Topography mission (NASA/CNES) https://swot.jpl.nasa.gov/mission/
SYNOP	Surface Synoptic Observation https://en.wikipedia.org/wiki/SYNOP
TAMDAR	Tropospheric Airborne Meteorological Data Reporting https://en.wikipedia.org/wiki/TAMDAR
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurement (German satellite)
TAO	Tropical Atmosphere Ocean project http://www.pmel.noaa.gov/tao/
TAO/TRITON	Triangle Trans-Ocean Buoy Network (Japan/USA) https://www.sprep.org/pi-goos/the-tao-triton-array
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurement (Germany)
TCCON	Total Carbon Column Observing Network http://www.tccon.caltech.edu/
TCTE	Total Solar Irradiance Calibration Transfer Experiment (NASA) http://npp.gsfc.nasa.gov/tcte.html
TEMIS	Tropospheric Emission Monitoring Internet Service http://www.temis.nl/index.php
TES	Tropospheric Emission Spectrometer (NASA) http://tes.jpl.nasa.gov/
TIM	Total Irradiance Monitoring instrument http://earthobservatory.nasa.gov/Features/SORCE/sorce_07.php
TIROS-N	Last of the TIROS (Television Infrared Observation Satellite) NOAA satellite series http://science.nasa.gov/missions/tiros/
TMI	TRMM Microwave Imager (NASA) http://pmm.nasa.gov/trmm/tmi
TOA	Top Of Atmosphere
TOAR	Tropospheric Ozone Assessment Report, initiated by the International Global Atmospheric Chemistry (IGAC) Project http://www.igacproject.org/TOAR
TOMS	Total Ozone Mapping Spectrometer (NASA) http://science.nasa.gov/missions/toms/
TOPC	Terrestrial Observation Panel for Climate (GCOS) http://www.wmo.int/pages/prog/gcos/?name=TOPC
TOPEX/Poseidon	Topography Experiment/Poseidon (CNES/NASA) https://sealevel.jpl.nasa.gov/missions/topex/
TOVS	TIROS Operational Vertical Sounder (NOAA) http://www.ozonelayer.noaa.gov/action/tovs.htm
TPOS	Tropical Pacific Observing System
TPOS 2020	TPOS for 2020 http://tpos2020.org/
TRMM	Tropical Rainfall Measuring Mission http://trmm.gsfc.nasa.gov/
TROPOMI	TROPOspheric Monitoring Instrument (ESA/EU) http://www.tropomi.eu/
TRUTHS	Traceable Radiometry Underpinning Terrestrial- and Helio- Studies (UK) http://www.npl.co.uk/truths

TSG	Thermosalinograph
TSI	Total Solar Irradiance
TSIS	Total and Spectral Solar Irradiance Sensor http://lasp.colorado.edu/home/missions-projects/quick-facts-tsis/
TSP	Thermal State of the Permafrost network (GTN-P)
TT-Mowis	Cross-cutting Task Team for Integrated Marine Meteorological and Oceanographic Services within WIS (JCOMM) http://www.jcomm.info/index.php?option=com_oe&task=viewGroupRecord&groupID=318
TWERLE	Tropical Wind, Energy Conversion, and Reference Level Experiment (NASA/NCAR) http://stratocat.com.ar/stratopedia/5.htm
ULS	Upward Looking Sonar (on submarines)
UN	United Nations
UNCBD	United Nations Convention on Biological Diversity https://www.cbd.int/
UNEP	United Nations Environment Programme http://www.unep.org/
UNESCO	United Nations Educational, Scientific and Cultural Organization http://en.unesco.org/
UNFCCC	United Nations Framework Convention on Climate Change http://unfccc.int/2860.php
USD	United States Dollar
USDA	United States Department of Agriculture http://www.usda.gov/wps/portal/usda/usdahome
USGS	United States Geological Survey http://www.usgs.gov/
UT/LS	Upper Troposphere/Lower Stratosphere
UTC	Coordinated Universal Time
UV	UltraViolet
VALERI	VAlidation of Land European Remote sensing Instruments network http://w3.avignon.inra.fr/valeri/
VIIRS	Visible Infrared Imaging Radiometer Suite NASA/NOAA) http://npp.gsfc.nasa.gov/viirs.html
VIRGO	Variability of Solar Irradiance and Gravity Oscillations http://www.ias.fr/virgo/
VIRS	Visible and Infrared Scanner (NASA) http://trmm.gsfc.nasa.gov/overview_dir/virs.html
VIS	VISible
VOC	Volatile Organic Compound https://en.wikipedia.org/wiki/Volatile_organic_compound
VOS	Voluntary Observing Ship
VOSClim	Voluntary Observing Ship Climate http://www.vos.noaa.gov/vosclim.shtml
VTPR	Vertical Temperature Profile Radiometer (NOAA) https://www.ncdc.noaa.gov/oa/rsad/vtpr.html
WACMOS	Water Cycle Observation Multi-mission Strategy http://due.esrin.esa.int/stse/projects/stse_project.php?id=105
WCRP	World Climate Research Programme http://www.wcrp-climate.org
WDAC	WCRP Data Advisory Council
WDC	World Data Centre http://www.wmo.int/pages/prog/wcp/wcdmp/GCDS_5.php

WDCA	World Data Centre for Aerosols (Norway) http://www.gaw-wdca.org/
WDCGG	World Data Centre for Greenhouse Gases (Japan) http://ds.data.jma.go.jp/gmd/wdcgg/
WET	Wave measurement Evaluation and Test project http://www.jcomm.info/index.php?option=com_content&view=article&id=62
WGCV	CEOS Working Group on Calibration & Validation http://ceos.org/ourwork/workinggroups/wgcv/
WGMS	World Glacier Monitoring Service http://wgms.ch/
WIGOS	WMO Integrated Global Observing System http://www.wmo.int/pages/prog/www/wigos/index_en.html
WIS	WMO Information System http://www.wmo.int/pages/prog/www/WIS/
WMO	World Meteorological Organization http://www.wmo.int
WOAP	WCRP Observation and Assimilation Panel http://www.wcrp-climate.org/WOAP.shtml
WOCE	World Ocean Circulation Experiment https://www.nodc.noaa.gov/woce/
WOD	World Ocean Database https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html
WOUDC	World Ozone and Ultraviolet Radiation Data Centre (Canada) http://woudc.org/
WRDC	World Radiation Data Centre (Russia) http://wrdc.mgo.rssi.ru/
WRMC	World Radiation Monitoring Center (BSRN) http://www.bsrn.awi.de/
WSN	Wireless Sensor Networks http://www.ni.com/white-paper/7142/en/
XBT	Expendable BathyThermograph https://en.wikipedia.org/wiki/Bathythermograph#Expendable_bathythermograph