Science plan

French Arctic Initiative 2015-2020

Science plan 2015-2020 of the French Arctic Initiative

FRENCH ARCTIC INITIATIVE

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Introduction

■ Scientific context

In 2004, the Arctic Climate Impact Assessment, requested by the Arctic Council, already reported major impacts of climate change on the Arctic environment: greater increases in air and ocean temperatures compared to other regions, melting glaciers and pack ice, thawing permafrost, changes in ocean circulation and atmospheric dynamics. In addition to the pressure on the environment caused by climate change, we now see rapidly growing economic activity that is potentially polluting (exploitation of natural resources, tourism) the Arctic. All of these changes that can disrupt ecosystems affect, in turn, the health, culture, social organisation and infrastructure of local populations. This troubling situation requires urgent action to control and mitigate impacts through governance that is currently being put in place, for the more harmonious development of a region that also presents real opportunities for humanity. In this context, the scientific community is at the forefront providing answers for stakeholders but also faces a severe lack of understanding of the most fundamental processes that govern the functioning of the Arctic, a region where the rigorous climate makes accessibility difficult. In 2007-2008, the 4th International Polar Year gave fresh impetus to scientific research in the Arctic. Post-IPY, several nations are now developing national programs and coordinating the continuation and expansion of research efforts in the Arctic. Several international programs are therefore emerging, including under the auspices of the Arctic Council and the International Arctic Science Committee (IASC).

In this context, France declared in 2009, through the Minister of Higher Education and Research, its intention to establish a national Arctic research program. The CNRS, mandated to implement this initiative, launched reflection and consultation activities in 2012 that would lead to the creation, in partnership with several other research organizations, of the French Arctic Initiative. This document is a summary of this work. It describes the major scientific objectives that France is willing and able to tackle in the Arctic, in collaboration with its international partners.

■ Current strengths

Since the expeditions of Jean-Baptiste Charcot, Paul-Émile Victor and Jean Malaurie to Greenland, the French scientific community has been continuously present in different Arctic regions. It now has about 500 scientists who dedicate all or part of their research to the Arctic.

• Overview of French research

France currently has the ninth highest number, worldwide, of scientific publications on the Arctic (2010-2014), coming behind countries with which it actively collaborates: the United States, Canada, Norway, United Kingdom, Germany, Russia, Sweden and China. The National Centre for Scientific Research (CNRS) is involved in 71% of these publications, usually in partnership with French universities and other research organizations, including the Atomic Energy and Alternative Energies Commission *(Commissariat à l'énergie atomique et aux énergies alternatives, CEA)*, *Météo-France* and the Geological and Mining Research Bureau *(Bureau de Recherches Géologiques et Minières,* BRGM*)*. The themes in which the French community is particularly active concern the ocean, climate, sea ice, ecology and anthropology (Fig. 1). Remote sensing and modelling together with in-situ observations and analysis approaches are particularly apparent in these research activities.

The leading laboratories in the French scientific community working in the Arctic include the following, amongst others: the Laboratory for Glaciology and Environmental Geophysics *(Laboratoire de Glaciologie et Géophysique de l'Environnement,* LGGE, Grenoble), the Laboratory for Climate and Environmental Sciences *(Laboratoire des Sciences du Climat et de l'Environnement*, LSCE, Gif-sur-Yvette), the Laboratory for Atmosphere, Environment and Satellite Observations *(Laboratoire Atmosphères, Milieux*, *Observations Spatiales*, LATMOS, Paris), the Laboratory for Oceanography and Climate: Experiments and Numerical Approaches *(Laboratoire d'Océanographie et du Climat - Expérimentations et Approches Numériques*, LOCEAN, Paris), the laboratory for Oceanic and Continental Environments and Paleoenvironments *(Environnements et Paléoenvironnements Océaniques et Continentaux*, EPOC, Bordeaux), the European University Institute for the Sea *(Institut Universitaire Européen de la Mer*, IUEM, Brest), the Dynamic Meteorology Laboratory *(Laboratoire de Météorologie Dynamique*, LMD, Paris), the Laboratory for Geophysical Studies and Satellite Oceanography *(Laboratoire d'Études en Géophysique et Océanographie Spatiales*, LEGOS, Toulouse) and the Centre for Functional Ecology and Evolution *(Centre d'Ecologie Fonctionnelle et Evolutive*, CEFE, Montpellier). These laboratories conduct climate, atmosphere, ice, ocean and ecosystem studies. In Earth sciences, there is the Paris Institute for Global Physics *(Institut de Physique du Globe de Paris*, IPGP, Paris), Environmental Geosciences

Toulouse *(Géosciences Environnement Toulouse*, GET) and the Magmas and Volcanoes Laboratory *(Laboratoire Magmas et Volcans*, LMV, Clermont-Ferrand). For the humanities and social sciences, there is the laboratory for Theory and Models for Urban and Regional Planning *(laboratoire Théoriser et Modéliser pour Aménager*, THEMA, Besançon), which analyses the contemporary changes in Arctic landscapes, the National Institute for Eastern Languages and Civilizations *(Institut National des Langues et Civilisations Orientales*, INALCO) studying current developments within Arctic and sub-Arctic indigenous communities (especially in ethno-linguistic, socioeconomic and geopolitical areas) and the research laboratory for Cultures, Environments, Arctic, Representations, Climate *(Cultures, Environnements, Arctique, Représentations, Climat*, CEARC, UVSQ) specializing in Arctic studies in the humanities and social sciences (circumpolar ethno-history, Arctic anthropology, Arctic societies and climate change). Finally, the Takuvik laboratory *('Unité Mixte Internationale'* of CNRS and Université Laval, Canada), established in 2011, now plays an important role in French research on Arctic ecosystems and geosystems.

In recent years, several large-scale projects led by French researchers have been supported at the national level. The French National Research Agency *(Agence Nationale de la Recherche*, ANR), for example, funded the BRISK, MALINA and POLARCAT projects that included significant international partnerships. The Investments for the Future program (Investissement d'Avenir) also supported innovative equipment projects for the Arctic (e.g. IAOOS, NAOS). Finally, major international projects funded by the European Commission have been, or are being, led by French researchers (e.g. DAMOCLES, ACCESS).

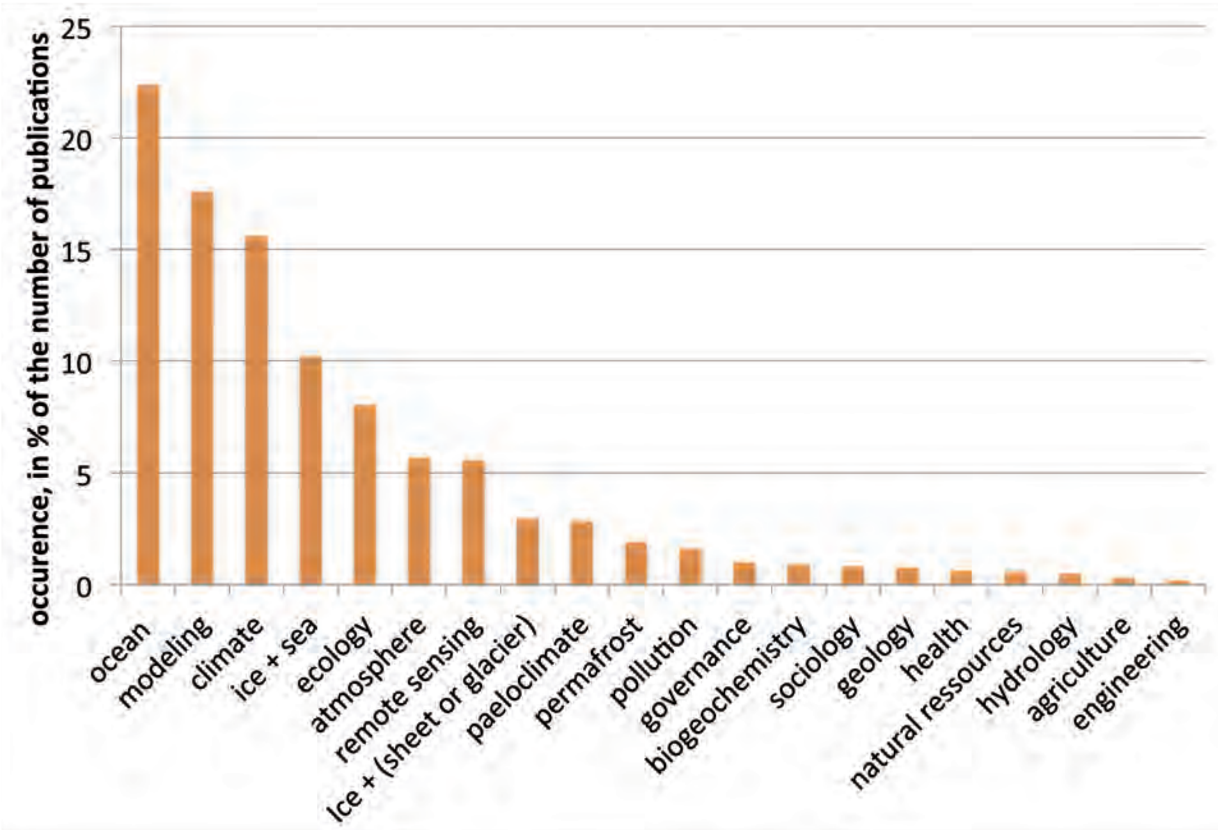


Figure 1: Occurrence of publications by the French community by theme (not mutually exclusive) from 2010 to 2014. Statistics obtained from ISI Web of Science on July 3, 2014, using the following keywords (arctic and): ocean (or sea), modeling (or modelling), climate, ice + sea, ecology (or ecosystem), atmosphere, remote sensing, ice + sheet or glacier, paleoclimate (or past climate), permafrost, governance (or law or political or sustainable development), biogeochemistry, sociology (or anthropology or archeology or ethnology or culture or religion), geology (or geodynamics or geophysics or geochemistry), health (or medecine or clinical), natural ressources (or mine or oil), hydrology, agriculture (or agronomy), engineering.

• Resources and infrastructure

The Paul Émile Victor French Polar Institute *(Institut polaire français Paul Émile Victor*, IPEV) is an organisation *(Groupement d'Intérêt Public*, GIP) that can offer resources and expertise. Its role is to provide a legal framework and the human, logistical, technical and financial resources necessary for the development of French polar research. One of the strengths of the agency is the scientific base in Spitsbergen (Franco-German AWIPEV station) that IPEV developed in collaboration with the Alfred Wegener Institute (AWI) to study ecology, internal geophysics, atmospheric sciences, glaciology and oceanography. Its budget for the Arctic (1.3 M€/year) currently supports 23 projects. The Institute, recently renewed for 12 years, confirmed its commitment to developing the national scientific community's activities in the Arctic.

National observational resources of note include airborne, in situ and satellite instrumented platforms. Airborne instruments such as the radar-lidar (RALI) and microphysical instruments developed by the Laboratory of Physical Meteorology *(Laboratoire de Météorologie Physique*, LAMP, Clermont-Ferrand) for the study of clouds and aerosols are an example of strengths in France's array of instruments. The French community has access to 3 aircraft and stratospheric balloons measuring pollutant transport, aerosols and ozone as well as the transport of air masses. The community heavily relies on satellite observations to study sea ice and ice-covered surfaces, clouds, ocean circulation, and marine primary production. Data from various satellites (e.g. MODIS, SMOS, MeTOP) are exploited for Arctic research.

The technical division of INSU develops in situ resources; over several years, autonomous measurements have been made in the atmosphere, ocean and ice (e.g. Equipex IAOOS and NAOS for ARGO floats in the Arctic, CLIMCOR for climate and core archives). Unmanned underwater vehicles are also launched under the ice (ACOBAR, ACCESS projects).

The French community leads or participates in observatories conducive to the development of activities in a regional context (e.g. SIOS – Svalbard Integrated Artic Observing System, development of the Yakutia site in Siberia). Observation networks covering local spatial scales (e.g. OHMI Nunavik - International Human-Environment Observatory in Nunavik, *Observatoire Hommes-Milieux International Nunavik*) and larger scales, such as the Sustaining Arctic Observing Networks (SAON), that reinforce observations across the Arctic, facilitating partnerships and synergies between existing observational activities and data management, sharing and synthesis of data and information. The measurements taken in the Arctic by SNO NDACC-France for the study of the loss of polar ozone should also be mentioned.

In France, there are bases, centres and data centres dedicated to the atmosphere (ICARE), ocean (CORIOLIS), soils (SMOS) and remote sensing (CERSAT) giving access to satellite data as well as observation services.

As mentioned above, French research stands out in the areas of climate, oceans and ice, which is reflected in the projects developed by the national community's experts in climate modelling. In recent years, the modelling community has made many significant advances:

- Troposphere-stratosphere dynamic coupling and chemistry-climate interactions in the Arctic (e.g. ESMs of IPSL and CNRM, LMDz-REPROBUS) implemented in the models developed at GIEC, at OMM and in international projects (e.g. POLARCAT)
- Coupled biogeochemistry and physical studies of the ocean-sea ice system forced by atmospheric data (e.g. NEMO-LIM)
- Coupled atmosphere-ice-ocean models (e.g. CMIP5) and the interaction of pack ice with the atmosphere and ocean (e.g. GRISLI-MAR)
- Land surface processes and their interaction with the atmosphere and ocean (e.g. Orchidee)
- Arctic regional-scale forecasts (e.g. Mercator Océan). These forecasts are climatic but also evaluate the ice extent and its impact on atmospheric circulation (e.g. MIMOSA).

French research includes the development of strongly transdisciplinary and cross-sectoral centres, projects, activities and groups. The following is a nonexhaustive list:

- The French-Siberian Centre *(Centre Franco-Sibérien)*, created in 2013, is a centre for training and research for the study of the environment, climate, continental biosphere and society.
- The European projects ACCESS (Arctic Climate Change, Economy and Society) and ARTISTICC of the Belmont Forum (Adaptation Research a Transdisciplinary Community and Policy Centred Approach) studying marine ecosystems and societies in a context of climate change, and biomonitoring of coastal water quality in the Arctic, respectively.
- The project ANR CLASSIQUE *(CLimat, Agriculture et Société SIbérienne – QUelle Evolution ?*, Climate, Agriculture and Siberian Society – What Evolution?) involves 6 laboratories. This project aims to understand the impacts of climate change on the Siberian environment and society and the feedbacks

in an innovative attempt to link the natural sciences with the humanities and social sciences.

- ANR BRISK (Linking the Scientific Knowledge on Arctic Change to That of Aboriginal Peoples: Vulnerability and Adaptation of Societies and the Environment) involves 7 laboratories. It develops cutting edge interdisciplinary and transdisciplinary methodologies to establish synergies between science and indigenous knowledge on climate and global change in the Arctic.

- The GDR 'Polar Mutations' *(Mutations Polaires, 3062)*, established on January 1, 2007, comprises about 60 researchers from InSHS, InEE and INSU of CNRS. Its program is based on two main research areas involving the social sciences (the program *'Avativut - ce qui nous environne'*) and environmental science (current effects of climate change).

■ International programmatic context

In recent years, many French initiatives have been developed in the Arctic through various non-coordinated activities in response to local initiatives financed by, amongst others, the IPEV and CNRS. The Arctic Initiative is an initiative to coordinate and structure the French community to unite these dispersed efforts and, consequently, to improve the understanding and visibility of the French community internationally. At the European level, a few calls for projects have led to the development of pluridisciplinary projects but again they were activities limited to a particular theme carried out in the Arctic.

New, more coordinated initiatives have emerged recently and have been the subject of international calls for projects: for example, the NSF ArcSEES programme which was open to national and international partnerships as part of a transdisciplinary approach. On the European side, the European Commission has supported initiatives supported by national funding agencies. This is the case of JPI Climate, which launched a call for proposals on two themes including one on the Siberian permafrost and boreal forests, an opportunity to develop the existing cooperation with Russia. Although not selected by ANR's administrative council, this second theme is a priority of the French Arctic Initiative.

The Belmont Forum recently launched a call for proposals for a CRA (Cooperative Research Action) on the Arctic led by the US NSF and open to researchers from all countries with a deadline of July 31, 2014. The ANR and CNRS are partners for this call: ANR for funding particular activities and CNRS, in kind, representing the Arctic Initiative. Finally, CNRS and IPEV are members of the European Polar Board (EPB), which includes the major players in polar research and logistics, and consequently the Arctic. The EPB decided to respond, with the support of all its members, to the 'BG15' call for proposals that opened in 2013 for the coordination of polar scientific research of the European Horizon 2020 program with regard to the strengthening of relationships between Europe, the United States and Canada. Both IPEV and CNRS are stakeholders in the joint European response that was submitted under the coordination of the German Alfred Wegener Institute (June 26, 2014) and which provides a platform for exchanges between researchers as well as a programmatic and consulting tool for the European Commission for polar scientific activities, and therefore the Arctic. The new Future Earth program that is currently being put in place should also, in the coming years, direct a part of its activities towards the Arctic.

Other programmatic activities are being developed showing once again that there are real scientific directions regarding the Arctic that should be strengthened as they arise in the coming years and to which the French community should be prepared to contribute.

■ Purpose of this document

This document is a summary of the major research themes that the French scientific community will implement in the Arctic in the coming years. These themes reflect both the state of the art and the strengths of the French community, and therefore, the research that this community is willing and able to continue in the Arctic.

The Arctic Initiative's prospective activity that led to the preparation of this document was complementary to the reflection already carried out in the disciplinary communities (e.g. ocean-atmosphere in 2010 and 2011) and institutes (e.g. InEE and IPEV in 2012: http://www.cnrs.fr/fr/pdf/inee/inee-prospective-recherches-polaires/). It aimed to extend the discussions to all disciplines and to the entire national scientific community interested in scientific issues regarding the Arctic in the following: space science, environmental science, humanities, social science and health science. We invited all French scientists studying the Arctic to participate and those wishing to become involved in scientific research on Arctic issues.

This prospective activity was also directed at researchers with cutting edge expertise but not necessarily focused on a particular environment, which could also contribute to the development of more innovative research in the Arctic.

To facilitate interdisciplinary discussions, this prospective activity was organised into 9 themes concerning major Arctic research topics and resources to be shared:

- Permafrost
- Biodiversity and Ecosystems
- Climate: atmosphere-ice-ocean
- Geodynamics and natural resources
- Human activities and their impacts
- Governance and geopolitics
- Arctic societies and knowledge systems
- Observations
- Modelling

The prospective activity was carried out in 4 steps:

1 - On March 6, 2013, an online forum was launched on the Arctic Initiative website (www.chantier-arctique.fr) to collect suggestions for research areas to develop in the coming years. 285 people participated in the forum with a total of 344 contributions. The compilation of contributions on May 3, 2013, was a document of 273 pages.

2 - From June 3 to 5, 2013, a national conference was organised at the Collège de France in partnership with the Chair of Climate and Ocean Evolution (Chaire sur l'évolution du climat et de l'océan, Édouard Bard). During these 3 days, the 446 registered participants were able to hear international experts from different fields of Arctic research, and they presented their research in the form of short oral presentations or posters. This conference brought together, for the first time, a significant part of the French scientific community from all disciplines interested in the Arctic.

3 - On June 6, 2013, a day for the prospective was held at the Oceanographic Institute (Institut Océanographique) to synthesize the information gathered through the online forum and to continue the activity in various forms (plenary discussions, meetings in thematic subgroups, series of presentations by the community regarding scientific questions).

4 - Afterwards, the Arctic Initiative's Scientific Committee (SC) synthesized all of the information generated by the activities described above and produced a summary stating main research objectives.

For efficiency, the Arctic Initiative SC produced its science plan document by setting as an objective to provide the scientific basis of calls for proposals for coming years. This summary is also intended to inform the Arctic Initiative's Steering Committee of the major issues that the French community can address. Our foreign partners also want to know France's priorities in Arctic research and the level of resources in place (expertise, research groups, activities, infrastructure, etc.). The MAE (Ministry of Foreign Affairs) recently decided to write a French roadmap for the Arctic, which will also include the scientific priorities of the French community.

The core of the prospective document consists of a total of 10 major research objectives, defined on the basis of the information gathered, and aimed at stimulating interaction among the disciplines. Only a highly interdisciplinary approach can achieve these objectives. These 10 objectives are presented in the following sections in order of the most specific to the most integrative. The inter-disciplinarity, which is always present, covers a diverse and growing range. The prospective document also includes an inventory of current strengths and a series of recommendations aimed at enhancing and developing observations and modelling resources.

Major scientific issues

Arctic and global atmospheric variability: amplification, couplings and impacts

Scientific objective

Identifying connections between Arctic variability and global climate as well as understanding the underlying atmospheric mechanisms such as transport, surface-troposphere-stratosphere couplings and teleconnections. Clarifying the impact of the Arctic cryosphere on global atmospheric variability and, conversely, the impact of dynamic anomalies in the lower latitudes on the modes of atmospheric variability in the Arctic.

Improving our understanding of the mechanisms responsible for polar amplification and identifying the major feedbacks. Assessing the current warming in the Arctic and the ability of climate models to represent it, in the light of past climates, identifying its impacts on human activities and measuring how indigenous peoples perceive them. Predicting what Arctic warming will be during the next century.

Context

Regional changes in the Arctic induce atmospheric changes on a larger scale. This relationship often involves an atmospheric response to land or marine cryosphere anomalies by a sequence of complex mechanisms. An underlying issue in the Arctic is to identify new predictors for climate of the northern hemisphere at the seasonal to interannual scale.

Conversely, the atmospheric (troposphere and stratosphere) variability across the Northern Hemisphere influences the Arctic through numerous atmospheric couplings and remote connections. The latter seem, for example, to exercise a control over the occurrence of extreme events such as cold-air outbreaks. Furthermore atmospheric transport of pollutants (anthropogenic or natural) emitted at midlatitudes allows them to exert a remote control on the radiation balance and, more generally, the Arctic climate. This control can also be exerted indirectly via transport towards the Arctic of heat and moisture anomalies generated in midlatitudes.

Both the strong impact of the Arctic on the Earth climate and the great vulnerability of the Arctic to global change are well recognized. Progress on these issues requires conducting studies on fundamental processes of atmosphere dynamics and chemistry which are specific to the Arctic. These involve complex interactions between the surface and the troposphere (especially via the snow and sea ice covers), exchanges through the tropopause and the dynamical coupling with the stratosphere, which all need to be better understood. In the Arctic, these interactions include links between sea ice, the wave activity and the intensity of the stratospheric vortex, as well as between the stratospheric annular mode, the tropospheric dynamics and the surface conditions, of which our understanding is still incomplete.

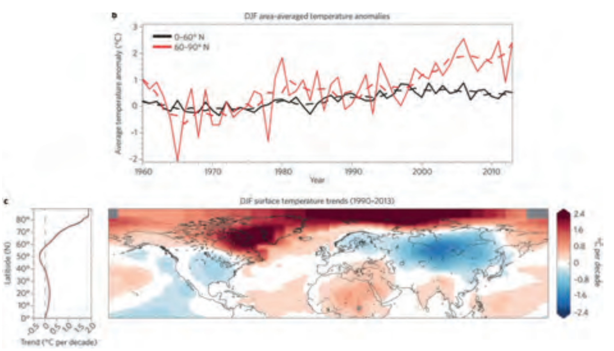


Figure 1.1: (top) Area-average surface temperature anomalies (°C) from 0° to 60° N (solid black line) and 60° to 90° N (solid red line) along with five-year smoothing (dashed black and red lines, respectively) and (bottom) winter temperature linear trends over the most recent period from 1990 shown as spatial distribution (right) and zonal averages (°C par 10 ans). Data from the NASA/GISS temperature analysis (http://data.giss.nasa.gov/gistemp). After Cohen et al.*, 2014.*

Recent years have seen the increasingly indisputable emergence of the role of atmospheric chemistry (troposphere and stratosphere) and interactions between chemistry, physics and atmosphere dynamics in the climate variability. This recognition has been accompanied by the development of increasingly comprehensive chemistry-climate models (including heterogeneous aerosols and chemistry) and chemistry-transport models, and the development of dedicated instrumentation (spectrometers, lidar and radar implemented from ground networks, and airborne, balloon and satellite missions). These tools are particularly useful in the Arctic where a major issue is monitoring the evolution in the concentration of stratospheric ozone and understanding chemistry-climate interactions that constrain it, to anticipate this evolution in the context of climate change (stratospheric cooling and increased humidity, increased natural and anthropogenic emissions).

Since the late 19th century, the northern regions of the globe (north of 60°N) have warmed about 2 times faster than the rest of the Earth and this amplification is expected to grow over the next century. The particularly rapid increase in Arctic air temperature, known as polar amplification, has been attributed to internal positive feedbacks in the Arctic climate system that intensify the response to anthropogenic forcing. It has also been identified in past climate changes (glacial climate, geological climates such as high CO_2 worlds, IPCC AR5). Polar amplification thus suggests the existence of regional characteristics that should be analysed to better understand the Arctic climate system as a whole as well as its variability, but also to anticipate changes. The analysis of past climates, relying in particular on the reconstruction of key climate variables and the mechanisms involved, should help to understand current climate changes in the context of the internal variability of the climate system and its response to natural and anthropogenic forcing. It also allows testing the ability of climate models to represent the magnitude and mechanisms of past changes that were more intense (warm geological periods) or more rapid (glacial instabilities) than those recently observed.

A research challenge will be to identify and prioritize the important feedbacks leading to the polar amplification mechanism. These feedbacks arise from numerous, complex couplings between the different physical (including, in particular, the cryosphere), chemical and biological components of the climate system, possibly involving nonlinearities that could lead to tipping points. The seasonality of Arctic warming, more pronounced in the fall, suggests a major role of sea ice which has become increasingly seasonal, but other components such as the snow cover, the water vapour content and other trace/aerosol species, clouds, greenhouse gas emissions and changes in atmospheric circulation have also been identified as possible candidates. For longer time scales, changes in the vegetation distribution and feedbacks related to thawing permafrost could also play a role.

Polar amplification leads to an exacerbation of the impacts of climate change in the Arctic. Quantifying these impacts is a prerequisite to assist in the adaptation of local populations, and more generally the living environment, to changes in the physical environment, but also for harmonious and effective management of this region facing a rapid opening to economic exploitation. The current Arctic warming is creating new prospects for economic development. Since the early 20th century, it has allowed the revival of subsistence farming and pastoral activities in Greenland. These practices are the cause of many environmental changes on time scales ranging from decades to millennia depending on the location, with impacts which are still hard to assess. This assessment requires a better understanding of the current state of ecosystems, a comparison of these states/conditions with the former conditions (retro-observation) and the study of the interactions between climatic forcing and anthropogenic forcing. This will ultimately help local management policies to minimise impacts related to these local activities. This area of research addresses the changes in land use and their impacts.

■ Detailed description of the objective and approach

• Arctic variability and Northern Hemisphere climate

Recent studies suggest links between the variability of Arctic sea ice and the midlatitud climate variability. The strongly negative phases of the NAO observed in the winters of 2010 and 2013 and which caused snowy, cold weather events in western Europe could be due to abnormal arctic sea ice retreat in late summer leading to the development of a warm-Arctic cold-Siberia anomaly via mechanisms that remain unclear. Winter sea ice anomalies in the Barents Sea could explain the warm temperature anomalies in northern Europe. Controversies and uncertainties still remain as to the actual impacts of the arctic sea ice and snow covers, and the underlying mechanisms. The studies that led to these conclusions were often based on a single model with results difficult to generalise because of the highly nonlinear nature of the response of the atmosphere, or were based on series of observations that were too short to ascertain the robustness of the suggested link.

Atmospheric variability in low and middle latitudes of the

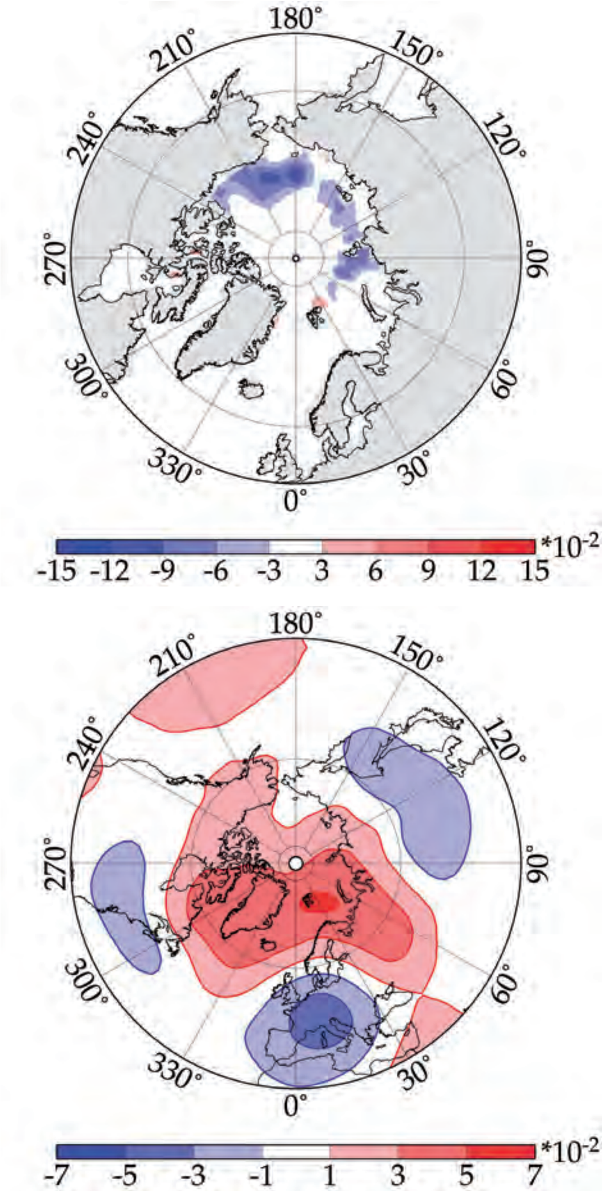


Figure 1.2: First pair of coupled patterns (obtained by the MCA) of HadISST1 sea ice concentration in August/September with ERA-Interim 500 hPa geopotential height fields in winter (DJF) 1989-2010: (top) sea ice concentration anomaly and (bottom) corresponding 500 hPa geopotential height anomalies. Reduced sea ice cover in the Beaufort and East Siberian seas in late summer would be associated with a pressure anomaly pattern resembling the NAO- in the following winter. After Jaiser et al.*, 2012.*

Northern Hemisphere could reciprocally have an impact on the Arctic variability. For example, studies show a relationship between the snow cover over the Eurasian continent and the Arctic Oscillation (AO) index since the late 1970s. The proposed mechanism involves, in particular, the stratosphere and the polar vortex. However, it has not been established whether these relationships are robust throughout the 20th century and further studies are needed. The study of large-scale atmospheric conditions should also help to address issues concerning the frequency of occurrence and the distribution of devastating polar storms, known as polar lows, and their sensitivity to climate change. In the North Atlantic, these storms seem particularly sensitive to weather regimes that define favourable conditions for their development. It is important to assess the importance of this large-scale preconditioning with regards to regional scale processes responding to changes in surface conditions. The decrease in sea ice extent, by allowing extra energy storage in the ocean which will be eventually returned to the atmosphere, could induce dynamical changes in the atmosphere favouring the occurrence of such storms in areas or at time periods where they were not frequent. The analysis of past changes and future trends in the occurrence of extreme events should be strengthened, requiring an improved capability to forecast weather systems and their feedbacks with the climate system, an activity that should be integrated in the international effort undertaken as part of the IPI (International Polar Initiative).

To improve our understanding of the links between the Arctic and Northern Hemisphere climate variability, initiatives to improve observational data sets and to complement direct observations with reconstructions or reanalyses should be encouraged. It is important to maintain efforts around the development of reconstructions validated by in situ observations. Reconstructions of variables such as the sea ice extent or the continental hydrology should be carried out in a way similar to the recent reconstruction of the Eurasian snow cover extent. Moreover, carrying out reanalyses requires having datasets for the entire assimilation period and therefore recovering old observations ('data rescue').

A better understanding of the mechanisms involved in the relationship between the Arctic variability and the midlatitudes of the Northern Hemisphere must also rely on efficient coupled ocean-ice-atmosphere models (AOGCM) that best represent the spatiotemporal characteristics of the climate system. The use of large sets of past and future simulations carried out as part of the successive CMIP inter-comparisons is however limited by biases (on the averages and trends) compared to observations. One reason is certainly the lack of a sufficiently detailed representation of some components of the system (the stratosphere and its chemistry, aerosols-cloud feedbacks, sea ice, snow cover, boundary layer, etc.) for which modelling efforts should be continued. Limited area models in which priority is given to the representation of processes which are specific to polar regions should be strengthened. AOGCMs are useful tools for another promising research area, which is seasonal forecasting. The effort in this case must be focused on the construction of realistic initial states based on reconstructions or reanalyses, for ensemble simulations of a

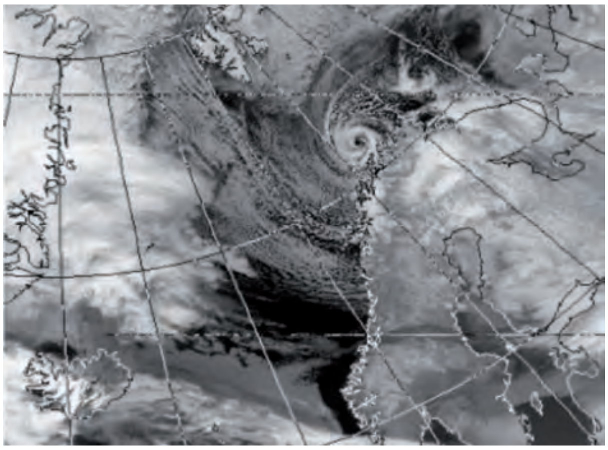


Figure 1.3: Infrared satellite image showing a cold-air outbreak (represented by cloud streets) leading to formation of a polar low (http://www.sat.dundee.ac.uk/freeimages.htm)

few months, in order to maximize the chances of reproducing the mechanisms of variability actually observed.

• Impact of aerosols and trace species on Arctic climate

Studies suggest that, in addition to CO_2 and methane, short-lived species (tropospheric ozone, aerosols) could contribute significantly to arctic warming but there is uncertainty as to the actual importance of their contribution, partly because of our partial knowledge of the emissions and the proportion of non-local sources (the extra-polar latitudes where there is particularly high anthropogenic pressure) compared to local sources (including the reemission and/or the transformation by the snow cover). These uncertainties are particularly high for emissions from, for example, fires and flaring of fossil fuels, which produce large amounts of traces species such as ozone precursors and black carbon. With regard to biomass burning, new technologies for chemical measurements in ice cores from Greenland should allow reconstructions of the last millennium historical period and their comparison with current measurements. Uncertainties on tropospheric ozone sources include their latitudinal distribution, the contribution of anthropogenic emissions relative to that of fires, photochemical ozone production during pollutant transport and the role of the nitrogen species reservoir (including snow). New local sources of ozone precursors and aerosols such as emissions from increasing shipping activities, may also become important in the future. The mechanisms of aerosol loss, in particular by wet deposition for the black carbon, are still little observed which limits their validation in models.

High altitudes (upper troposphere and stratosphere) aerosols also play an important role in stratospheric chemistry, such as the destruction of ozone by sulphur aerosols from volcanic eruptions, or in the Earth radiation budget. Monitoring the concentrations of these aerosols, identifying their origin (local or non local) and their nature, and understanding how they interact with the Arctic atmosphere dynamics (including the polar vortex and troposphere-stratosphere exchanges) are important challenges for understanding climate variability in the Arctic.

Responding to the problems above requires approaches combining modelling and observations: ground stations, ocean buoys, satellite observations (CALIPSO-CloudSat, EarthCare, IASI, GOSAT), airborne measurements, balloons for vertical distributions of tropospheric properties and ice coring in Greenland. Regarding satellite observations, it is necessary to undertake studies dedicated to estimating variables at very high latitudes. Field observations must rely on developments in autonomous instrumentation (microlidar, unmanned aircraft) and new airborne sensors.

• The stratosphere and its couplings with the upper atmosphere, the troposphere and the surface

The dynamics of the arctic stratosphere, its interactions with the troposphere, the role of the polar vortex in chemistry-climate interactions and transport processes are key research themes to better understand the physical (temperature, humidity, distribution and variability/persistence of the polar vortex) and chemical (aerosols, halocarbons, polar stratospheric clouds) environment of the stratosphere and to monitor its evolution in the context of climate change.

In particular, the evolution of stratospheric ozone in the Arctic depends not only on the evolution of the halogen load but also on the climate evolution. Analyses of the measurements acquired by dedicated networks (NDACC), from space or through the implementation of specific airborne campaigns and balloons must be conducted in parallel: spectrometer measurements of total column ozone, nitrogen oxides and the halogen load at global and regional scales to better understand the processes of ozone destruction, monitoring of the vertical distribution of ozone and stratospheric particles (polar stratospheric clouds and aerosols) and trends in stratospheric temperature using satellite observations and lidar measurements, measurements of microphysical properties of polar stratospheric clouds and stratospheric aerosols using counters to clarify the role of non-sulphur aerosols, found in abundance in the polar vortex, in the destruction of ozone. Furthermore, the effects of solar variability, especially the variability in the UV flux and precipitation of solar particles, on stratospheric photochemistry and dynamics should be clarified. The same applies to the response of stratospheric chemistry to the evolution of the greenhouse gas concentrations (carbon dioxide, methane) and the Earth radiation budget in the Arctic region. These observations should help to validate and improve models (chemistry-climate, chemistry -transport and dynamics) which, in turn, help to identify the underlying mechanisms.

Sudden Stratospheric Warmings (SSW), which are striking examples of the stratosphere-troposphere-surface dynamical coupling, influence the evolution of the winter polar vortex in the Northern Hemisphere stratosphere. They are essential not only for the evolution of the stratosphere and the destruction of ozone but also for their impact on the lowest

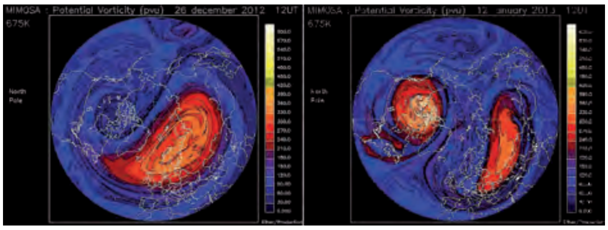


Figure 1.4: Distributions of potential vorticity of the Northern Hemisphere stratosphere (at 675 K or 20 hPa) during winter 2012-2013 as simulated by the MIMOSA model. The distributions show the evolution of the polar vortex leading to a sudden stratospheric warming of high amplitude early January 2013. Note the displacement of the vortex on December 26, 2012 (left) followed by the vortex break-up on January 12, 2013 (right). After Angot, 2013.

layers of the atmosphere. Characterizing the state of the troposphere before, during and after SSW is a priority. The role of tropospheric blocking regimes in the generation of SSWs as well as the impact of SSWs on Cold Air Outbreaks must be better understood. Even though the SSWs are roughly understood, their occurrence is random and unpredictable. The increase in their frequency during the last decade remains to be confirmed and chemistry-climate models simulate highly variable occurrences in future climate projections. More generally, we must improve our understanding of the dynamics of the polar vortex, the occurrence of specific events such as FrIACs (intrusions of tropical air in the polar regions), as well as the chemical composition of the lower polar stratosphere in relation to the transport of reactive species from midlatitudes.

The study of the upper atmosphere in the Arctic relates to auroral physics and couplings between the magnetosphere, the ionosphere and the atmosphere. The processes underlying these interactions are still poorly understood, including what causes the ion escape in the daytime polar ionosphere, the phase shift between electron heating and ionospheric ion heating under the influence of geomagnetic pulsations, the polarisation of aurora red radiation, and the triggering of instabilities in the polar magnetic cusp.

• Arctic warming and its amplification: mechanisms and couplings

With regards to the Arctic radiation budget, the processes controlling the surface albedo must be better understood and quantified. Aerosol deposits on ice and snow, such as black carbon from fossil fuel combustion, natural changes in the sea ice surface related to surface melting (early disappearance of the snow cover, increase in melt ponds) and increasing open water area can cause substantial reductions in the surface albedo amplifying surface warming. Observations from space provide relatively short time series of albedo and these estimates should be validated by field measurements. More generally, the role of interactions between the atmosphere and the surface should be better understood and evaluated. Dynamic processes (transport, deposition) controlling the distribution of deposits on snow and ice need to be clarified and evaluated with regards to the distribution of emissions. Feedbacks between atmospheric dynamics, clouds, aerosols and trace species (e.g. ozone) probably also have a strong impact on the radiative balance (shortwave and longwave) in the Arctic. For example, the decrease in Arctic summer clouds leads to increased ice melt and possibly warms the ocean. The mechanisms controlling the distribution of clouds and aerosols as well as the sequence of associated feedbacks onto the surface need to be studied in more detail, in particular to improve their representation that is still too imperfect in climate models. Cloud physics need to be better understood, especially mixed-phase clouds which are frequently observed in the Arctic and have a strong impact on the radiation budget, as well as the interactions of these clouds with temperature (water/ice partition in clouds, for example) and aerosols. The presence of liquid water in clouds could amplify the surface energy balance. The properties of these clouds are difficult to observe from space which requires field observations. The contribution of tropospheric ozone to Arctic warming must be better quantified.

Recent studies suggest that a substantial part of the Arctic warming amplification could be the result of changes in atmospheric circulation influencing the meridional heat transport towards the Arctic or the regional redistribution of air masses. It is important to determine the importance of these large-scale mechanisms with regard to arctic feedbacks. Studies should be conducted to explore the impact of tropospheric warming on the patterns of large-scale and Arctic atmosphere variability, especially via the intensification and shifting of the mid-latitude depression trajectories, changes in

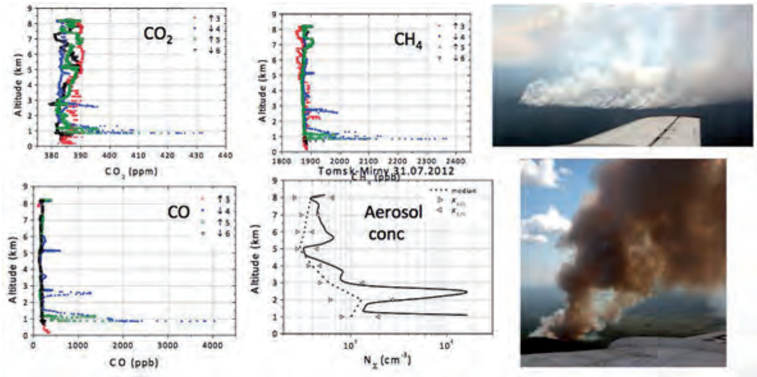


Figure 1.5: Data collected during the YAK July 2012 summer campaign showing highly elevated concentrations of CO, CH_4, CO_2 and aerosols close to Siberian boreal fires. After Paris et al.*, 2013.*

the meridional heat and moisture transports to the Arctic and polar vortex shrinking/expansion.

It is also essential to identify the part of these changes which is due to the internal variability of the climate system (NAO, ENSO). The positive NAO trend over the past decades, responsible for stronger winter warming north of 40°N, could be linked to the Atlantic Multidecadal Oscillation (AMO). These hypotheses can be explored using sufficiently long coupled simulations or ensemble simulations. They can also be tested using palaeoclimatic data that provide information on the atmospheric variability in the absence of anthropogenic pressure. Improvements in model physics are needed to improve the representation of the internal variability, which is currently underestimated in model simulations, and to account for climate feedbacks associated with temperature and humidity variations. Model evaluations can be supported by simulations of specific past periods such as the last millennium, the beginning of the Holocene or the last interglacial, used as benchmark tests.

A current challenge is to determine the importance of local natural emissions of greenhouse gases (carbon dioxide, methane) as a result of arctic warming with respect to quantities transported and emitted elsewhere. Changes in soils, with the gradual thawing of permafrost and the dissociation of ocean methane hydrates, result in increasing local emissions which may trigger positive climate feedbacks. Past climates (Palaeocene-Eocene, perhaps the last interglacial) include examples of such feedbacks. Concerning marine sources, we need to assess the ability of current warming to penetrate the ocean margin underground and destabilize the hydrates, and the potential for these underwater gas sources to actually contribute to emissions to the atmosphere. Analyses of organic assemblages and markers and associated environmental parameters (temperature, salinity, terrigenous inputs, water mass ventilation) to characterize past episodes of clathrate destabilisation can help understand the current variability. These analyses should allow a synthesis of observations to be established in order to characterize rare, episodic events against detectable trends. Concerning the permafrost, better understanding of the physico-chemistry and the biological processes in the active layer that control exchanges with the atmosphere and vegetation is needed, relying on observational networks and data inversions in order to distinguish what is locally emitted from what is transported.

Reconstructions show that polar amplification also existed in past climates that were very different from the current climate (in terms of both atmospheric temperature and carbon dioxide concentration) and that it has contributed to major past changes in response to atmospheric greenhouse gas concentration variations (high CO_2 worlds, low CO_2 worlds), at different time scales. The mechanisms underlying the past climate equilibriums can be analysed from palaeoclimatic reconstructions and/or climate simulations and aid in the interpretation of current observations and climate projections. In addition, the Greenland ice archives are of great value and should soon allow the study of major climatic periods and transitions such as the last interglacial and the glacial inception. When external climate forcings are well known (e.g. distribution of solar energy as a result of Earth orbital parameters), it is possible to use palaeoclimatic data to test climate feedbacks in models (e.g. past inter-glacial periods). Combining simulations of past and future climates using the same models, with accurate reconstructions of past climates, provide the opportunity to constrain certain aspects of projections. The goal is to combine data from ice cores with paleoceanographic and continental data to build the regional structure of changes (amplitude, spatial distribution, rate of change) with a common time frame and to test the ability of climate models to represent them. Past data can thus help validate climate-carbon cycle couplings and climate-ice sheet couplings estimated from simulations.

• Response and adaptation of Native people to climate warming

Adaptability to multiple stresses, of which climate change is not the least, has influenced the history of Arctic indigenous societies such that flexibility is high on the ladder of social and cultural values. Hunters, fishermen and livestock farmers who, even today, benefit from knowledge systems inherited from their predecessors must answer a difficult question: how to adjust this knowledge and these skills to new environmental conditions and how to transmit reliable knowledge to younger generations? Many believe that close collaboration with environmental science specialists is required. Some recent attempts have produced encouraging results. But for this endeavour to fully meet the expectations of those involved, it is necessary to initially develop a common language defining the principles upon which each system of knowledge is based and, secondly, to engage in dialogue benefitting from multiple viewpoints and diverse experiences of the same phenomenon: climate change and its effects on the first occupants of the circumpolar regions.

If pastoralism has ancient origins (raising semi-domesticated herbivores in Lapland and Siberia, raising sheep, goats, cows and pigs in the medieval period in Greenland and Iceland), the last century has led to many changes related to global warming and the possibility of developing activities that were previously impossible. Until now, the study of the impacts of agriculture and forestry on the Arctic and sub-Arctic environment was never really considered. Previously nomadic populations, who are sedentary today, had a lifestyle based on hunting, fishing and sometimes the semi domestication of wild herbivores such as reindeer (Scandinavia, Russia). Millions of hectares of taiga that make up the sub-Arctic forest, for example, have been exploited for over a century. Agriculture in these areas originally unsuitable for its development, has long taken the form of subsistence farming limited to certain products. Scandinavian populations (Faeroe Islands, Iceland, Greenland) who migrated across the North Atlantic starting from the 8th century AD have partly contributed to the development of this agriculture which is highly constrained by climate. In Greenland, the Medieval Warm Period allowed the development of pastoral activities that were interrupted by the Little Ice Age but have nevertheless continued in other areas such as Iceland. Climate warming has led to the revival of agriculture in Greenland since the early twentieth century with intensive cultivation (mechanization and fertilizer use) of fodder crops, sheep farming, but also in some areas the establishment of reindeer and muskoxen for local consumption. Warmer winters may, however, hinder more traditional reindeer herding activities in Scandinavia and Siberia. The maintenance and development of these activities require adaptation strategies to climate, including increased precipitation, hazards (freezing rain), intra- and interannual variability, changes in wind regimes (impact on summer drought), etc.

These new agrarian and pastoral practices are causing many environmental changes that need to be studied by a resolutely pluridisciplinary approach based on the use of biotic (pollen, diatoms, chironomids, etc.) and abiotic (sedimentology, geochemistry, etc.) parameters. This approach must take into account the original states of ecological systems. The study of lacustrine/peat/marine sequences collected in different Arctic and sub-Arctic areas seems to be one of the best ways to acquire sufficient time coverage to develop retro-observation approaches. The exploitation and changes in forest areas, the development of agriculture (mono-specific varieties of forage crops, potatoes, etc.), the introduction of invasive species as well as the massive use of fertilizers and pesticides are all themes that environmental science and palaeo-environmental specialists can develop using multi-parameter approaches.

Other methods also deserve to be developed including those related to molecular markers in plants and/or animals and DNA analyses to differentiate the types of livestock and/or wild herbivores, in the past and present, and more generally to study the evolution of biodiversity in lake systems.

Water cycle and land ice

Scientific objective

Improving our understanding of the different compartments governing the Earth water cycle and their impact on climate. Improving our understanding and modelling the evolution of Arctic land ice masses to anticipate their future and improve climate scenarios. Monitoring the contribution of the decline in Arctic land ice (glaciers and small ice caps, Greenland ice sheet) volume to sea level rise and their impacts. Characterizing the past evolution of land ice masses to help understand their current changes and to assess the ability of our tools (observation and modelling) to represent them.

Context

Understanding and anticipating the variability and changes in the arctic water cycle is crucial to Arctic societies and their sustainable development and, more generally, to the climate, the biodiversity and the global environment. Although estimates of the various components of the Arctic hydrological cycle remain subject to large uncertainties due to lack of observations, observations and models suggest that precipitation and runoff in the Arctic follow positive trends that are signs of an intensified hydrological cycle in response to global warming.

Arctic regions are characterized by a convergence of the atmospheric water vapour transport, which contributes to excess precipitation on both continental and oceanic areas. Water is redistributed between the two areas via the land-sea continuum which controls runoff and via melting and iceberg calving from glaciers and ice caps. The Arctic Ocean receives more than 5000 km^3 of meteoric waters annually, of which only 1/3 is due to an excess of precipitation compared to evaporation and about 2/3 to runoff from large eurasian and canadian rivers (11% of the freshwater input to the global ocean). This relatively fresh water is mostly drained from the Arctic Ocean through a few passages that connect this ocean to the rest of the world ocean.

The water reservoirs of the three compartments (oceanic, atmospheric and continental) are the links of a global freshwater cycle featuring interaction between the atmospheric water cycle, continental hydrology, the cryosphere (permafrost, snow cover, glaciers and the Greenland ice sheet) and the coupled ocean-sea ice system. The storage capacity in the reservoirs of the various compartments determines the residence time of the freshwater and controls the exchanged fluxes. Estimating changes in these reservoirs, however, remains a difficult exercise. There is a lack of observations even to assess the average water storage on land (terrestrial cryosphere, lakes and rivers, soils). Also, if the volume of the marine cryosphere is clearly decreasing, its rate of change remains to be determined by integrating new thickness measurements. The evolution of the freshwater reservoir in the Arctic Ocean is still very uncertain due to lack of measurements on a global scale over sufficiently long periods.

A better understanding of the atmospheric water vapour budget in the Arctic is needed to estimate the associated climate feedbacks (especially those related to the optical properties of arctic clouds), but also its impact on the storage of surface water, through precipitation and the snow cover, as well as the interactions between the water vapour and other compounds in the atmosphere. This understanding requires studying the major fluxes (precipitation, evaporation, transport) of the atmosphere hydrological cycle and the control mechanisms (atmospheric dynamics, clouds, aerosol-cloud feedbacks, boundary layer processes). Two key points include the roles of extratropical cyclones and Arctic recycling (oceanic and terrestrial local sources).

A specific feature of the Arctic is the presence of a snow cover that can store water from precipitation on top of the soil and cryosphere (terrestrial and marine). Yet, the distribution of the snow cover and its variability are poorly understood. Characterizing the snow cover on the pack ice is also a priority to better understand the sea ice evolution and be able to interpret the remotely sensed electromagnetic signals. Snow cover evolves following particular dynamics (accumulation, melting, transport) and physico-chemistry including complex radiative, thermal, gas and material transfers. A research challenge is to better understand the processes that have led to the current dramatic retreat of the snow cover under climate warming, especially because of its essential role in the water cycle, in the cycles of chemical elements (in particular contaminants) relevant to other compartments of the climate system and in organic matter recycling via nutrients and microbial activity.

A key link in the arctic freshwater cycle is the land-sea continuum. This area where water from the atmosphere is stored, circulated and exchanged should be considered in a broad perspective integrating the continental cryosphere, the fate of run-off water in the ocean and the associated feedbacks on the ocean circulation. The major rivers that flow into the Arctic Ocean drain a continental area of over 15 million km^2, which represents more than one and a half times the area of the Arctic Ocean. The fluxes exchanged through the continuum involve processes of storage, freezing-thawing of soils, ice melting, watershed dynamics, runoff, etc., which are still poorly observed and incompletely modelled. The freshwater discharged into the ocean is redistributed by the ocean circulation before being exported in liquid and solid (sea ice) forms mostly through the passages that separate the Arctic from the Atlantic Ocean. This freshwater sink and its evolution are discussed in more detail in theme 3 ‘A changing ocean’.

Another essential link in the water cycle is land ice, due to its important water reservoir and exchanges with the ocean and atmosphere. Land ice melting has accelerated dramatically in recent decades. The evolution of the Arctic ice caps involves a complex system governed by numerous feedbacks involving a variety of spatial and temporal scales that are interconnected. There are major challenges in terms of future sea level since the melting of Arctic ice including Greenland and all glaciers contributes 25 to 40% to sea level rise. These figures justify that monitoring of land ice and the development of more realistic and reliable models, including coupling with the other elements of the climate system, be a research priority.

The Greenland situation poses specific challenges because of the extent and volume of the continental ice sheet and the atmospheric, glaciological and oceanic mechanisms affecting its evolution. The portion of the ice sheet surface which melts during the summer increases from year to year. The past 25 years have seen the area affected by summer melt increase by 40%. Melting now affects more than the low altitude and latitude areas, it reaches all of the southern part up to the domes and the northern part up to 1500 m altitude. Moreover, the time scales and threshold effects characterizing the response of the ice sheet are major issues regarding the long-term evolution of the mean sea level. Existing simulations consistent with past sea level changes during warm periods indicate a threshold effect resulting in multimillennial deglaciation of Greenland for global warming between 1 and 4°C. Finally, through the atmospheric forcing that controls the ice evolution and through the massive freshwater flux brought to the ocean and the rivers, arctic land ice also plays a key role in local impacts (e.g. spring floods) and in the large-scale functioning of climate and its long-term consequences on sea level.

■ Detailed description of the objective and approach

• Atmospheric processes governing the water cycle and their relationship with the surface

Considering the atmospheric water vapour budget, one of the challenges is to distinguish regional sources related to evaporation/sublimation from nonlocal sources affecting the Arctic via atmospheric transport of water vapour, and their interactions (in particular between transport and precipitation). Measurements (in situ and by remote sensing) of stable water isotopes in precipitation and water vapour provide an integrated view of the water cycle and can therefore help identify the origin of the different sources of water vapour and their successive transformations. They thereby provide constraints to improve model representations of certain terms such as evaporation, continental recycling of water and moisture formation over the sea ice margins, which all show large deviations from observations, and offer the potential to assess cloud microphysical processes and atmospheric models. It is also important to improve our understanding and our estimates of precipitation in the Arctic, not only because of its crucial role in the water cycle but also for its potential impact on local populations. Regarding atmospheric moisture transport, its links with the cyclone activity and sudden anomalies such as atmospheric rivers must be explained. An interesting area of research could be to study the evolution of the atmospheric hydrological cycle in the context of a warmer Arctic climate where sea ice is less present, in particular changes induced in the partition of precipitation between snow and liquid water and in the moisture transport from extra-polar latitudes. Implementation of a coordinated international observation network is needed.

Furthermore, there is an urgent need to better understand the distribution and dynamics of water within arctic clouds: mixed phase clouds, reactions between clouds and aerosols, boundary layer processes. Problems remain concerning the detection of clouds in satellite observations, particularly over the reflective cryosphere surface, and in the characterization of the water phases and suspended aerosols. The combination of ground, airborne and satellite measurements should improve our understanding in these areas and, more generally, of the optical and microphysical properties of clouds, cloud-aerosol interactions and the partition between liquid and solid precipitation. The models, in turn, need to be improved to better reflect the seasonal cycle of clouds but also the amount and the almost permanent presence of low-level liquid clouds and the link with the amount of precipitated water.

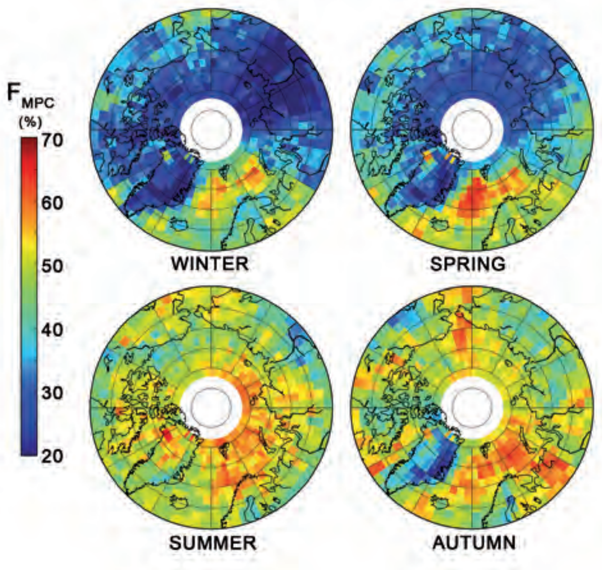


Figure 2.1: Stereographic projection of seasonal Mixed Phase Clouds (MPC) over the whole Arctic. Occurrences are computed taking into account 500 m to 12 000 m altitude range. After Mioche et al.*, 2014.*

• Snow cover dynamics

Regarding surface processes, the relationship between precipitation and the snow cover must be better understood. There is indeed currently a decrease in the snow cover extent even though increased accumulation and thickness of the snow cover are observed in certain regions. Monitoring the evolution of the snow and ice covers for continental water bodies (lakes, inland seas, rivers) as a sensitive indicator of climate change should be pursued by taking advantage of various active and passive satellite sensors. Moreover, as for the soils and ocean, the snow cover also plays an important role in exchanges (wet and dry deposition and emission of biochemical compounds) with the atmosphere. Assessing what is released by the snow in the atmosphere and the importance of snow for nutrient cycling and microbial activity remain important scientific challenges. The seasonal evolution of the chemical composition of snow (salt, reactive species, black carbon) must be related to the deposit (dry and wet) history and to post-deposition processes such as percolation, blowing snow and photochemical reactions. The contribution of microbial activity in the snow to the production of nutrients must be estimated as compared to inputs from precipitation. These issues cannot be addressed without field measurements focusing on particularly important seasons (spring) and on the Arctic Ocean where these transformations are suspected to be more persistent than elsewhere. The measurements should include vertical profiles of reactive compounds acquired from the surface or in the snow in synergy with measurements in the atmosphere and the ocean. Measurements in firns and ice cores should allow current observations to be placed in the context of the past variability of the atmosphere composition.

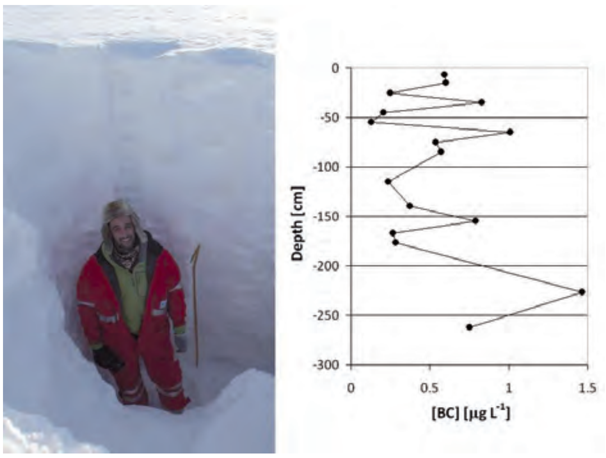


Figure 2.2: High vertical resolution measurements of black carbon (BC) in the snow on top of the Kongsvegen glacier close to Ny-Alesund. The snowpack with a total height of 263 cm corresponds to the period from October 2011 to March 2012 recording the temporal evolution of the BC concentrations during this period. Figure courtesy of H.-W. Jacobi.

• Land-sea continuum

In the Arctic, water from continental precipitation is divided between runoff, infiltration, snow and ice, and evapotranspiration. It is necessary to better constrain the various terms of this budget and to determine the consequences of global warming on each of them and their interactions, in particular the melting of water stored in the soil (release of fossil water, changes in surface state) and groundwater-river interactions. The study of the groundwater-river relationships should help assess the origin and the quality of runoff waters, especially identify the contribution of groundwater and that of permafrost (through its active layer). Similarly, the impact of permafrost degradation and associated processes (thermo-karst, cryoturbation, etc.) needs to be better documented to assess the relative contribution of each process to the water and material (sediments, nutrients) transports via taliks and watercourses.

Estuaries and coastal areas are particularly crucial places for the exchange of water between the land and the ocean. Such exchanges are regulated by fjord systems and estuaries whose dynamics should be clarified to assess their respective exchange effectiveness. Ongoing changes in the Arctic which are related to melting land ice and the contribution of freshwater input to estuaries will constitute decisive forcings on local and regional physical and ecological processes. The freshwater input to the Arctic Ocean and its temporal and spatial variability must be assessed and better taken into account in the study of the Arctic Ocean.

Solving all of these issues requires the combination of an observational and modelling approach, which must rely on long-term observational networks. Furthermore it is essential to improve the interactions between climate, hydrological and ecological models.

• Mass balance of Greenland and Arctic glaciers

Melting of the Greenland ice sheet is clearly related to the increase in local atmospheric temperature estimated at 2.4°C over the last 25 years. Similarly, the outlet glaciers that discharge ice accelerate every year. The reason for the acceleration is the surface snow meltwater that flows to the bedrock but also the heat flux released by the ocean. Recent field observations have revealed the presence of particularly warm water at the outlet glaciers in Greenland. The dynamics of these intrusions in glacial fjords, however, is largely unknown due to the crucial lack of observations with a sufficiently fine spatial coverage to sample the exchanges between the fjords, the continental shelves and the open ocean. The associated variability (seasonal, interannual to decadal) and its causes (changes in ocean and ice dynamics, changes in the temperature of the imported water, the role of the regional atmospheric circulation) are even less known due to the lack of continuous time series of observations. The multi-model analyses of the CMIP exercises predict an increase in the temperature of ocean waters around Greenland by several degrees by the end of the century, suggesting that this forcing could be important in the future.

The retreat of the arctic glaciers (excluding Greenland outlet glaciers) has accelerated over recent decades and it is very likely that their current state is also out of balance which means they will continue to decline even if the temperature stabilizes. Fine-scale field observations (laser scanners, lidar, photographs) may help to clarify the glacier evolution (glacier-slope interface, slope geomorphology) in the case of glaciers with steep slopes (Svalbard) and their contribution to the local hydrological and glaciological budget. A better understanding of their evolution can be obtained from knowledge of their behaviour during past periods as warm as the current period (Holocene thermal optimum) but nevertheless characterized by different forcings and seasonal cycle of the changes. Analysis of cosmogeic isotopes collected in the subglacial and proglacial bedrock allows precise dating of past variations of glacier fronts.

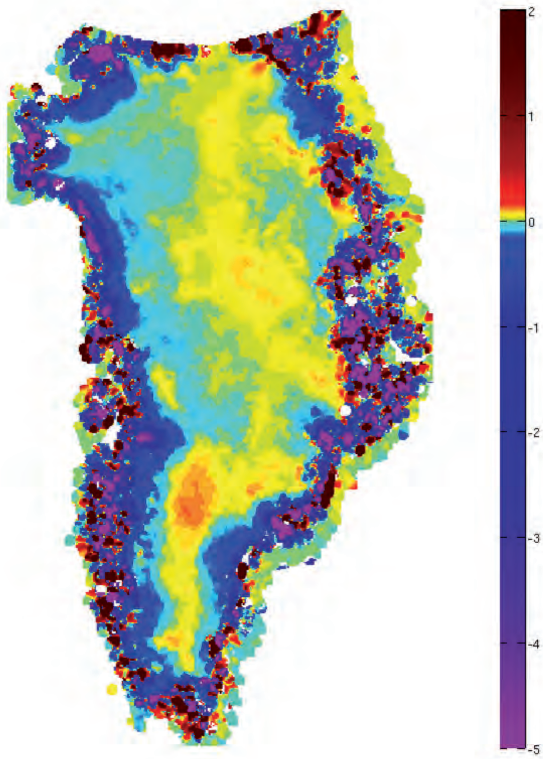


Figure 2.3: Elevation changes of the Greenland ice sheet from 8 yrs of Envisat altimeter observations (2002-2010). After T. Flament, 2013.

• Land ice in the climate system

It is essential to continue on-going activities to take into account ocean-atmosphere-ice couplings in global and regional models and in observation strategies. It requires altogether quantifying the losses, identifying their causes, assessing the feedbacks on the ocean in terms of freshwater and circulation, and better constraining models to anticipate changes in the ice sheet dynamics in a warmer climate. The inclusion of these forcings and mechanisms in global climate models, either explicitly, or through parameterizations, is an important issue for improving climate forecasts. The coupling between climate models and ice sheets poses significant challenges in terms of regionalization (downscaling), for example to refine the representation of the mass balance on the flanks of the Greenland ice cap. A hierarchy of models (from regional to global) is essential.

The study of past warm climate periods offers the possibility to characterize the feedbacks when important changes are observed and to test coupled ocean-atmosphere-ice models. In response to changes in the Earth orbit (early Holocene, last interglacial, long interglacial period 400 000 years ago) or to persistent concentrations of carbon dioxide at current levels (Pliocene), these past changes marked by strong Arctic warming also coincided with modifications in the volume of continental ice, with contrasting effects between a more intense water cycle (increased snow cover) and warmer summers leading to enhanced summer melt. The combination of new data and simulations is essential to understand the mechanisms involved and the long-term effects.

In order to analyse the vulnerability and resilience of Greenland societies and to develop adaptation strategies (particularly in connection with agriculture) for the Greenland coastal regions, it is essential to assess the climate in these regions. This assessment is a challenge given the scales and the complex processes involved. It requires an effort to regionalize climate simulations, to interpret them with regard to the large-scale climate evolution of Greenland, as simulated or reconstructed from observations, and to evaluate them with regard to the human perception of the ongoing changes. Analysis of palaeoclimatic data (historical records, lake sediments, ice cores) should help to put in perspective the changes underway in Greenland in the context of longer timescale variability and to identify the respective contributions of the natural and anthropogenic variability.

A changing ocean: from the physical environment to marine ecosystems

Scientific objective

Studying the variability of the Arctic Ocean and the changes related to climate evolution. Improving our understanding of the processes that control the distribution of Arctic sea ice to improve predictions of the ice conditions in the Arctic at local and global scales. Evaluating the links between regional changes and global ocean variability.

Identifying key interactions between the physical environment (ocean and marine cryosphere) and marine biogeochemical cycles. Studying the combined effects of ongoing changes in the Arctic Ocean on the all (benthic or pelagic, coastal to offshore) marine eco-systems in the Arctic Ocean, from the microbial loop and primary production to vertebrates, to help especially develop future ecological scenarios for coastal populations.

Context

Observations suggest that the Arctic Ocean has undergone profound changes in recent decades. The IPCC estimates predict an ice-free Arctic Ocean in late summer before mid-century, a perspective that suggests the unprecedented strategic importance of this region. Sea ice determines the accessibility of the Arctic Ocean, which is crucial for the exploitation of its resources and shipping routes in the North but also for coastal infrastructure development. These arguments alone justify the urgent need to improve our understanding of the evolution of the arctic sea ice cover in order to estimate, in particular, its potential predictability.

Sea ice largely controls air-sea fluxes (mechanical energy, radiation, heat, salt, freshwater, gases and organic matter) and the physics and dynamics of the ocean surface layer (light, mixing, stratification, coastal-open ocean exchanges, vertical transport, advection) with significant impacts on greenhouse gas cycles and nutrient cycles, organic matter production, the food chain and the future of marine ecosystems.

The very large oceanic reservoir of liquid freshwater in the upper layers of the Arctic Ocean has a complex variability with regional disparities still poorly understood and yet likely to strongly influence local and regional ocean dynamics and, more broadly, biogeochemical fluxes, biological productivity and Arctic ecosystems. We still know little about the process of freshwater redistribution by the oceanic circulation, the respective contributions from the Pacific and Atlantic inflows or from melting sea ice, and the role of the mixed layer and the halocline in the control of exchanges of properties between the surface and the deep ocean and their present and future evolution. The dynamics of the oceanic freshwater reservoir also largely constrain the fluxes exchanged with the global ocean. The complexity of the spatio-temporal distribution of currents and properties in the passages that separate the Arctic from the Pacific and Atlantic oceans is such that it is difficult to provide reliable estimates of these fluxes, the associated mechanisms and their variability.

The observed variations of the heat content of Arctic intermediate waters are an important climate signal whose potential impacts on sea ice must be better addressed, in particular to improve our understanding of the variability of the sea ice cover and its prediction. The current challenge is to characterize more systematically the distribution of warming in the Arctic Ocean, its link to air-sea exchanges which are intensified by the decrease in the sea ice cover, to stratification and transport by ocean advection, and the associated time scales. It is also essential to better assess the heat inputs to the Arctic from the Pacific and Atlantic oceans, both in terms of average and variability, and their relationship to the global ocean circulation.

The major changes which are underway in the Arctic Ocean are also an issue for the evolution of the global ocean. The analysis of future climate scenarios brought to light the possibility of significant changes in the global overturning circulation in the Atlantic which are induced by changes in the dense water formation in the Arctic and northern North Atlantic. The current reduction in ice cover could activate haline convection on the continental margins of the Arctic, but these mechanisms are poorly observed due to their relatively fine spatial and temporal scales and the difficulty in accessing these ice-covered regions. Conversely, the intensification of the hydrological cycle (increased precipitation and continental runoff), associated with the increase in melting of land and sea ice means that an increasing amount of freshwater flows into the Arctic Ocean and adjacent seas, with a potentially major impact on the convection zones in the subpolar North Atlantic, the dynamics of the subpolar gyres and more generally the global ocean circulation.

Continental shelves occupy more than half of the surface of the Arctic Ocean and some of them, such as the Barents Sea, are sites of significant changes in the physical environment as well as in the biogeochemical fluxes and ecosystems, with major challenges for resource exploitation. These changes involve strong coupling with the ice cover (particularly through the seasonal retreat of the sea ice cover) and continental areas (via runoff, erosion, sedimentary processes) involving the transmission of physical (freshwater) and biogeochemical (organic matter, pollutants, methane hydrates, etc.) signals as well as interactions between pelagic and benthic ecosystems. These couplings must be understood through an integrated approach which is still missing today. Such an approach should extend beyond the shelf to include the processes involved in coastal-open ocean exchanges at the shelf break (upwelling, ventilation and subduction of water masses, vertical transfers of organic matter, dense water cascading) that influence the open ocean environment.

Arctic Ocean ecosystems are characterized by high diversity in relation to the variety of habitats associated with ice: millennial ice platforms, multiyear sea ice, first year sea ice, marginal ice zones, open ocean. Under the influence of environmental changes, some of these unique habitats evolve rapidly and modify the structure, function and biodiversity of the Arctic marine ecosystems, the architecture of marine trophic networks, as well as the distribution, the geographic extent and the abundance of key species with cascading effects on species interactions. A current challenge is to identify the links between these major changes and certain key parameters of the physical environment (circulation, stratification, shelf exchanges, light) and biogeochemistry (fluxes and nutrients, acidification, turbidity, terrigenous inputs) of the Arctic Ocean.

■ Detailed description of the objective and approach

• The Arctic Ocean: a changing physical and dynamical environment

Circulation and distribution of physical properties

To study the physical changes in the Arctic Ocean requires a better understanding of the dynamics, the spatial structure and the variability of the circulation. However, due to insufficient observations, these aspects are still very poorly understood. Yet it can be anticipated that, given the current decrease in ice cover, which tends to increase wind mixing and internal waves, the Arctic Ocean is currently undergoing a spin-up with an increasingly intense circulation. It is essential to understand the mechanisms underlying such changes in order to estimate their effects on the transport of physical properties, nutrients and organic matter.

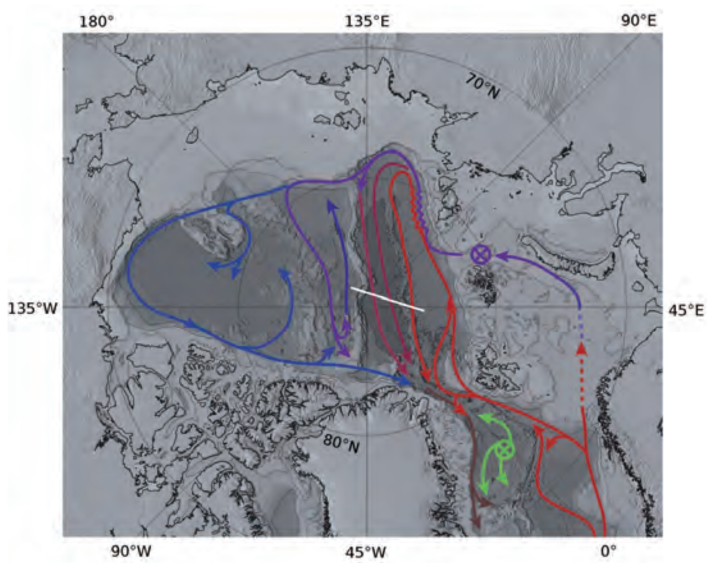
Among the strong signals of variability recorded in recent decades in the Arctic Ocean are the warming episodes associated with intermediate waters originating in the Atlantic and Pacific. The different branches of the Arctic circumpolar current that carry the Atlantic waters are poorly sampled or unobserved in heavy ice areas. Thus the traditional view that this current interacts very little with the interior of the basins needs to be substantiated. Meanwhile, the flow of Pacific waters in the western Arctic must be better understood, particularly in assessing the role of sea ice drift in the penetration of these waters into the basin interiors. A key challenge is to better understand the dynamics of the boundary currents, in particular the role of topography, instabilities and the meso- and submesoscale (eddies, double diffusion) in the transport of properties and the ventilation of the basin interiors, and their relationship with fluxes exchanged through the straits.

The absence of reliable estimates of the spatial and temporal distribution of the freshwater in the Arctic due to the lack of field data and space-based observations that are too limited in time prevents a clear understanding of the underlying mechanisms and their variability. He latter would involve, in particular, assessing the role of the Beaufort Gyre, a reservoir that concentrates a large proportion of the Arctic freshwater and shows variability over a wide (from seasonal to decadal) range of time scales. This variability is not adequately sampled and is poorly understood, especially the role of the atmosphere and the role of fluxes at the Pacific and Atlantic gateways. Another major challenge is to understand the mechanisms that govern the distribution of the freshwater export to the Atlantic between the Fram Strait and the Canadian Archipelago and to characterize its variability.

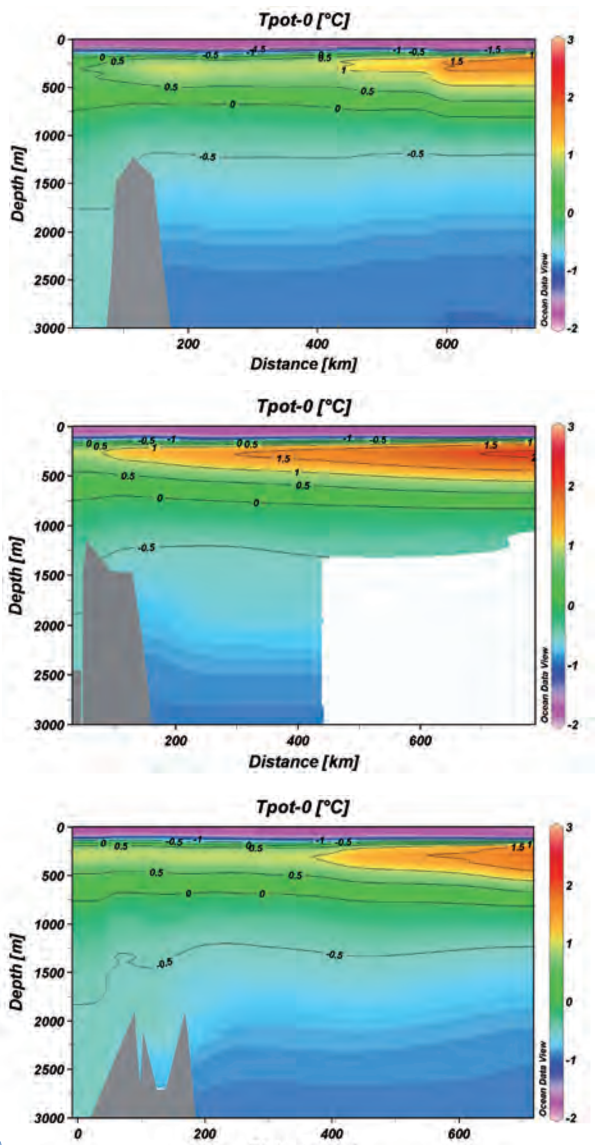
These questions can only be addressed by maintaining extensive observations networks (especially in the most ice-covered areas of the Arctic) allowing continuous (in particular including all seasons to take into account the seasonal variability) and perennial monitoring of key parameters of the Arctic Ocean. Focussed observation campaigns must also be implemented and associated with idealized or high resolution modelling to understand the relevant scales of the processes involved. Efforts must also focus on forced ocean and coupled ocean-atmosphere simulations and on ocean reanalyses for understanding the origin of the observed variability and to anticipate the evolution of the Arctic Ocean in the context of climate change. In this context, efforts should be continued to improve existing estimates of surface heat and water fluxes from atmospheric reanalyses and satellite observations. Field measurements should be encouraged in order to constrain estimates of these fluxes.

Links with global ocean circulation

Understanding the role of the Arctic Ocean in the global ocean circulation firstly requires a better understanding of the fluxes at the Pacific and Atlantic gateways of the Arctic Ocean to better understand the mechanisms of formation and transport of anomalies to and from the Arctic. In particular, a current challenge is to determine whether the long term warming trend observed in the Atlantic waters is the manifestation of a larger scale multi-decadal oscillation, originating in the Atlantic Ocean, or the result of a more regional variability. Another important issue is to estimate the distribution, the variability and the future changes in the Arctic freshwater sources and their impact on the future development of the global overturning circulation. Meeting this challenge requires access to reliable estimates of the quantity of freshwater exported to the Atlantic on both sides of Greenland. Beyond exchanges of liquid water, questions also arise regarding the export of sea ice in these passages. These include assessing how the current and future evolution of the sea ice cover, which becomes thinner but more mobile, and changes in the atmospheric circulation induced by climate change in the Arctic, affect this export. Overall, the current variability of these fluxes is known to a very uncertain degree due to the lack of long-term observations and predicting their evolution in the context of climate change suffers from



a)



b)

Figure 3.1: (a) Main pathways for the Atlantic water in the Arctic Ocean showing both the Fram Strait Branch (red) and the Barents Sea Branch (purple) and (b) sections of potential temperature across the Amundsen Basin from the Gakkel Ridge (right) to the Lomonosov Ridge(left) (see location of the section on the map) in 1991 (top), 2001 (middle) et 2005 (bottom). The sections illustrate the temperature variability in the Fram Strait Branch Atlantic water recirculating over the Gakkel Ridge. Note the warm event in 2001 spreading across the Amundsen Basin and most probably originating in a warm anomaly observed upstream along the Nansen Basin southern slope some 10 years before. After Rudels et al.*, 2013.*

models having difficulty correctly representing the freshwater distribution and the characteristics of the ice cover in the Arctic. It is essential to maintain the international collaborative efforts both in terms of year-round networks dedicated to monitoring the fluxes exchanged at the Arctic gateways and in assessing the ability of ocean models to represent them.

Following the fate of the freshwater exported to the Atlantic Ocean from either side of Greenland to assess its impact on dense water formation and the global ocean circulation requires expanding these observational and modelling efforts to regions receiving the freshwater such as the convection sites and the North Atlantic subpolar gyre. It is particularly necessary to make every effort to ensure that ocean models are improved in terms of resolution in these regions. Climate projections suggest a slowing-down of the oceanic overturning circulation in a warming climate, but it is becoming increasingly clear that the sensitivity of climate models is impaired by the coarse representation of the freshwater pathways and convection processes. This representation should be improved based on process studies to better understand the dynamics of the convective regions and those of the overflow regions.

Finally, linking the variability of the Arctic and sub-Arctic regions to the global ocean variability and understanding the main mechanisms requires coordinating the observation efforts at high latitudes with the international initiatives to study and monitor the variability of the Atlantic Ocean circulation (gyres, overturning). Beyond the need for observations, coupled modelling studies can assess the role of ocean-sea ice-atmosphere feedbacks in this variability but also, ultimately, the interactions between these compartments and the Greenland ice cap.

• Marine cryosphere: physical changes, variability and future

New physics for a transformed sea ice cover

Arctic sea ice is undergoing profound changes in its structure and variability. The disappearance of the perennial ice in favour of a seasonal sea ice cover, sea ice thinning and decreasing sea ice concentrations mean that the overall structure of the arctic sea ice cover more and more resembles a marginal ice zone (MIZ). New observations and new studies should be undertaken to redefine a suitable dynamical (rheology, frictional boundary layers) and physical (heat content, brine pockets, melt ponds, albedo, thickness distribution) framework that takes into account these structural changes. These studies should take advantage of new opportunities from satellite measurements that can characterize, in particular, the ice thickness but also its surface states and certain physical properties. They should also rely on new measurement techniques such as measuring seismic noise related to changes in the ice cover and autonomous buoys measuring physical, chemical and dynamical sea ice parameters. In situ measurements should help identify atmospheric processes responsible for the evolution of the sea ice surface.

Studies of atmospheric and oceanic boundary layers are needed to understand transfers of mechanical energy, heat and mass at the air-ice and ice-ocean interfaces in the new context of a transformed ice cover. A better understanding of the dynamics of the ocean surface layer and its interaction with the atmosphere and the deep ocean in this new context is a priority. Direct observations of the processes controlling the transfer of heat at the water-ice interface and the dynamic constraints (waves, tides, swell, friction) exerted by the ocean on the ice should be implemented in the context of regional studies which will be linked to larger scale observations of oceanic properties and modelling. Specific phenomena such as coastal polynyas, which are particularly sensitive to air-sea exchange, need to be better understood as well as their impact on Arctic dense water formation and the carbon cycle, both in the present climate and in the past. Stable carbon and water isotope measurements can help improve our understanding. Improved the model resolution also helps represent increasingly finer spatial and temporal scales a more explicit representation of the underlying physics (waves, eddies, atmospheric and oceanic boundary layers) that requires adapting the physics of sea ice models and the representation of the couplings with the ocean and the atmosphere.

Present and past variability of the Arctic sea ice

The variability and the future of the arctic sea ice should be considered in the broader context of their interactions with the ocean and the atmosphere. At interannual scales, an overall view is still missing which prioritizes the causes of the sea ice variability and assesses their robustness on the long-term. The following are among the major challenges to be faced: (i) the highly seasonal nature of the environment that results in radically different processes throughout the annual cycle, (ii) the current existence of a very strong trend for all sea ice parameters (extent, thickness, drift, age, etc.) which, by modifying the mean state, is likely to influence the sea ice response at interannual scales and (iii) the existence of strong couplings between the ice and the atmosphere (especially via moisture and heat fluxes), and between the ice and the ocean (especially via melting/freezing and the convective heat flux) making it difficult to distinguish the causes from the effects.

A current challenge is to define a coordinated framework for in-situ observations, combined with satellite measurements and modelling, in order to establish relationships of cause and effect between the sea ice variability, on the one hand, and the oceanic and atmospheric variability, on the other hand, and to understand the mechanisms. The focus should be on both regional modelling, for process studies, and global coupled modelling to identify the feedbacks related to the ocean-atmosphere coupling and to elaborate climate projections. One should study the links between some major atmosphere climate patterns (NAM, Arctic Di-pole, PNA, etc.) and the sea ice cover variability in different seasons and in different regions of the Arctic and their evolution in the context of current and future climate change. The impact of extreme events on the breakup of the sea ice cover must also be considered. One emerging area of research concerns the evaluation of the role of the ocean in the interannual to decadal variability of the sea ice. This role seems important in areas along the sea ice margins but the underlying processes (mixing, transport, eddies) need to be better identified. Effort should be put on identifying the couplings (involving the three compartments, ocean, sea ice and atmosphere) responsible for oscillations or abrupt changes in simulations of past and future climates.

Understanding the past variability of the arctic sea ice should help to elucidate the mechanisms of the current variability. Various proxies specific to biota growing in and under the pack ice (biomarkers) have recently been developed. They allow reconstructing the variability in the arctic sea ice extent at high temporal resolution from the analysis of marine sediments. Fine reconstructions for the recent period suggest that the current reduced sea ice cover in the Arctic has not been observed over the last millennia. It has become possible to understand the Holocene variability with a resolution of a few decades. It will be interesting to study periods of reduced arctic sea ice cover similar to the present conditions, such as those identified at the beginning of the Holocene, and the overall trend towards a recovery of the sea ice cover during the subsequent millennia, over which a strong multi-decadal variability was super-imposed. The analysis of the reconstructed variability of the sea ice cover must be compared with that of the concurrent atmospheric and oceanic conditions. Palaeoclimatic re-constructions are still subject to high methodological uncertainties and intercalibration efforts should be encouraged with other markers of climate variability.

Predicting the sea ice cover evolution

Recent studies based on coupled climate simulations suggest a significant, potential for predictability of the sea ice extent at intra-seasonal scales. This potential could apply to longer time scales (interannual to decadal) which involve the ocean circulation. However, the predictability remains highly dependent on the initialization of the ice cover structure (thickness, drift, surface conditions, etc.) and the ability of models to reproduce the actual processes controlling its evolution. In both respects, much remains to be done, especially on the forecasting systems themselves and on the improvement of sea ice model physics in climate models, and on the validation of these sea ice models with regard to the ice thickness distribution and ice drift, in terms of both mean state and variability, using validated observation data sets, in order to better constrain the initialization of the forecasts. To be useful, the sea ice forecasts must be produced at a sufficiently fine spatial scale for their potential to be fully exploited (resource management, new shipping routes). This requires acquiring observations and developing models with very high spatial resolution. In addition, the model physics must be adapted to explicitly take into account the fine-scale dynamical (fracture zones, shear layers, pressure ridges, etc.) and thermodynamical (snow, melt ponds) features of the ice that react strongly with the coupled ocean-atmosphere system.

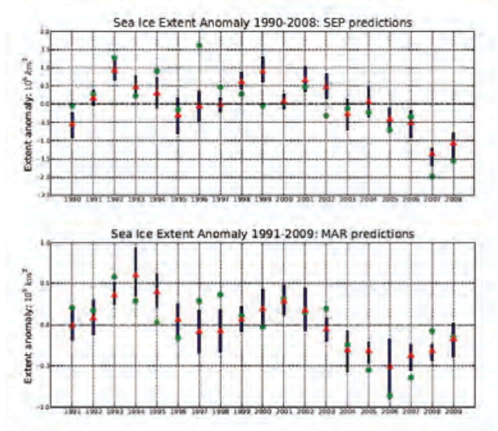


Figure 3.2: Sea ice extent forecast anomalies for (top) September and (bottom) March: ensemble forecast mean (red triangles) and spread (blue bars) and observed anomalies from NSIDC (green dots). After Chevallier et al*, 2013.*

• The coupling process between Arctic Ocean dynamics and biogeochemistry

Primary production: light and nutrient fluxes

Major changes in the Arctic physical environment will impact the marine biosphere through several processes. Recent data indicate a significant role of sea-ice covered areas of the global ocean in biogeochemical cycles. Apart from its physical impacts (i.e. limiting energy transfer between the atmosphere/ ocean interface), the sea-ice cover is crucial to biogeochemical processes (sea-ice algal growth, iron accumulation, crystal formation of calcium carbonate) that can play a role in the response of the Arctic Ocean and their ecosystems to global change. This role is poorly known due to limited in-situ observations and inaccurate simulations in models. Biological production in the Arctic, particularly phytoplankton primary production, is strongly constrained by the ice cover which limits light availability and modulates the energy transfer between the atmosphere and ocean and the nutrient fluxes in the ocean surface. Combining the thinning and reduction of the summer extent of the pack ice, the reduction of its snow cover, the increase in the sea-ice free summer period may affect biological production and, beyond this, the different levels of the food chain and resources. It has recently been learnt that there is a complex sequence, from spring to autumn, going from the development of ice algae, to a phytoplankton bloom as soon as the snow-pack ice system transmits sufficient light, continuing through the withdrawal of the pack ice, up to communities developing in open waters depleted of nutrients. This dynamic is probably deeply affected by the formation of pack ice that is increasingly young, thin and uniform, covered by a snowpack that is thinner and ephemeral, and more likely to be covered in the spring by melt ponds, which significantly modifies the transmission of light. Given the rapidity of the changes taking place, it is urgent to understand this dynamic and the current functioning of the various productive regimes in relation to the biogeochemical cycles of major elements and community structure. These changes in the dynamics of primary production are indeed likely to impact the transfer of organic matter and energy in trophic networks, mass transfers (biogeochemical quantities and properties) into deeper waters and sediment through pelagic-benthic coupling, but also on fluxes of greenhouse gases of biological activities.

In addition to the pelagic and sympagic production of fresh organic carbon, dissolved and particulate terrigenous inputs play a particularly important role in the Arctic Ocean given the importance of riverine freshwater inputs and the large amounts of organic carbon contained in catchment soils. In addition, the gradual thawing of permafrost and coastal erosion are likely to increase the land-sea flux of organic carbon over the coming decades. Generally regarded as a source of refractory organic matter that is not conducive to consumption by marine bacteria, it is recently known that particulate and dissolved terrigenous organic carbon has a high bioavailability and fuels a significant part of the marine ecosystem. However, mechanisms for transport, degradation and bacterial consumption of this terrigenous carbon are still poorly understood. More generally, there are great uncertainties about the quantitative importance of the main components of the terrigenous carbon cycle in the Arctic Ocean (terrigenous inputs, mineralization by different biotic and abiotic processes, transfer through the different compartments of the trophic chain, sequestration, export out of the Arctic Ocean). To reduce these uncertainties, it is necessary to combine multi-scale monitoring of the various organic carbon stocks from the coast to the open ocean with cutting-edge approaches in organic geochemistry and experimental microbiology, and coupled physical-biological modelling. Remote sensing, the use of specific lipid tracers, and measurements of bacterial carbon assimilation and photo-oxidation are among the advanced methods mastered in France that must be implemented. The role of terrigenous organic matter as a source of nitrogen through photoammonification must also be established.

From the point of view of relationships with biogeochemistry, we should not restrict the questioning to a simple carbon–nitrogen relationship, even if the availability of nitrogen is now the leading factor controlling primary production in its early stages. The current introduction of new species, including Pacific diatoms, such as *Neodenticula seminae*, but also the selection of new dominant species with their own biogeochemical

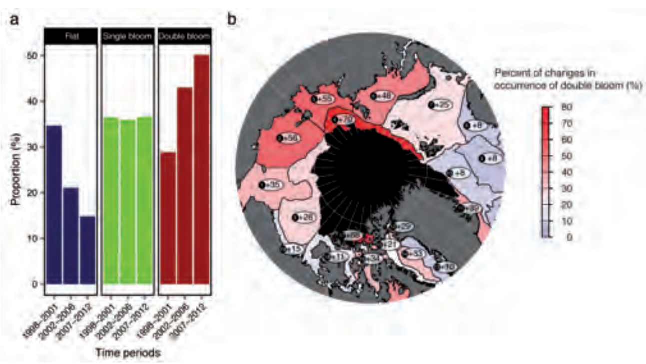


Figure 3.3: Current shifts in Arctic phytoplankton phenology above the Arctic Circle (>66.58°N). (a) Histogram of different types of annual cycles for three periods (1998–2001, 2002–2006, and 2007–2012). (b) Map adapted from the World Wildlife Fund agency showing percent change in double bloom occurrence between two periods (1998–2001 versus 2007–2012) for each Arctic region (numbered within dark circles): (1) Chukchi Sea, (2) East Siberian Sea, (3) central Arctic Ocean – Canadian Basin, (4) central Arctic Ocean – Eurasian Basin, (5) Laptev Sea, (6) Kara Sea, (7) North and East Barents Sea, (8) northern Norway and Finnmark, (9) Norwegian Sea, (10) Fram Strait – Greenland Sea, (11) East Greenland Shelf, (12) North Greenland, (13) West Greenland Shelf, (14) Baffin Bay, (15) Baffin Bay – Canadian Shelf, (16) Lancaster Sound, (17) Arctic Archipelago, (18) Beaufort – Amundsen – Viscount Melville – Queen Maud, and (19) Beaufort Sea – continental coast and shelf. The minimum September sea ice extent in 2012 is indicated in dark color. After Ardyna et al., *2014.*

characteristics (C/N/P/Si ratios) are likely to affect the biogeochemistry, shifting the balance between 'siliceous' and 'calcifying', through the availability of orthosilicic acid and acidification and to directly influence the rain ratio, with more global implications. The study of the silicon biogeochemical cycle is paramount here. The role of orthosilicic acids, a factor controlling the structure of diatom communities, is particularly important to understand because studies conducted in the past are far too restricted to give us any idea of the dynamics of one of the major components of pelagic primary production. The question arises as to the respective roles of the availability of nutrients and light in controlling biogeochemical functioning in relation to the structure of autotrophic communities over the spatio-temporal transition between ecosystems related to ice and pelagic ecosystems.

The constant evolution of the physical and chemical landscape of the Arctic Ocean (temperature, pH conditions) also affects the biogeochemical cycles of trace metals such as iron, zinc and cobalt whose inputs are dependent on river flows and the melting of various ice structures. These metal nutrients largely control phytoplankton assemblages and primary production in the ocean. Moreover, when the concentrations become high, they can become toxic to biota. In the Arctic, the cycling of these elements, particularly the intensity of their contributions, will be subject to strong changes related to changes in glacial and riverine inputs and the rapid withdrawal of the ice. Very large amounts of metals will be discharged in coastal areas potentially advected over long distances. The effects of these inputs are poorly understood at present, both on the functioning of the biological pump and biodiversity in the Arctic. The question arises as to the coupled influence of riverine inputs, subglacial layer, icebergs, sea ice and basal ice on the distribution, speciation and bioavailability of these trace metals. The processes that control the spatial and temporal distribution and fate of trace metals in glacial watersheds remain poorly understood. Understanding the evolution of biogeochemical cycles of metals requires monitoring on a seasonal or multi-year basis.

A major challenge for the study of biogeochemical cycles in the Arctic Ocean is to define an appropriate framework that combines the use of accurate, classical identification techniques, molecular biology, and 'biological' and 'biogeochemical' sensors to monitor ongoing changes in the dynamics of ecosystems and associated biogeochemical fluxes. This should be done in close relation to changes in the physical environment and marine cryosphere. For all these studies, beyond point observations from one or more cruises, fixed stations and repeated on site visits to establish time series must be considered. These field measurements at local scales are needed to understand the processes and associated spatial and temporal scales and, on a larger scale, to establish budgets and assess global trends.

The role of oceanic physical and dynamical processes (mixing, sub-mesoscale, mesoscale transport) in biogeochemical cycles in the Arctic Ocean remains unclear. Measurement/modelling programs of all processes (physical, chemical and biological) should therefore be put in place in a coordinated manner. Developments specific to models should be considered, especially for physical-biogeochemical and physical-biological interactions, both in the ocean and in sea ice.

Dissolution pump and acidification

The Arctic Ocean naturally has a relative low pH and as a consequence, will be affected first by the impacts of ocean acidification. Recent studies estimate that approximately 10% of its surface waters will be corrosive for calcium carbonate (aragonite) by 2018, 50% in 2050, and all Arctic surface water will be corrosive in 2100. These estimates are probably conservative because they do not take into account the increasing inputs of organic carbon from thawing permafrost. In addition, respiration by organisms releases CO_2 is a local acidification factor adding to the global source of atmospheric CO_2 and CO_2 from terrigenous carbon.

The impact of this shift in the chemistry of seawater on organisms and Arctic ecosystems is poorly understood. The vast majority of work has been conducted as part of the EPOCA project coordinated by INSU-CNRS. Two large-scale experiments were conducted in 2009 (benthic organisms) and 2010 (pelagic community). The main results concern pteropods (planktonic molluscs), phytoplankton and microbial processes (including viruses). However, the activities of relatively intense research in recent years are far from having provided all the answers. Knowledge about the future evolution of carbonate chemistry and the biological, biogeochemical and socioeconomic impacts remain extremely fragmented and projections are therefore very risky. Moreover, understanding the combined effects of CO_2/metals on primary production requires a better understanding of the combined effects of acidification and variations in trace metal inputs (and potentially temperature, another key factor) on phytoplankton biodiversity and carbon metabolism in the Arctic.

Predicting the consequences of acidification and associated phenomena is hampered by a lack of knowledge at every level, from carbon exchanges between the atmosphere, sea ice and the ocean, between the continent and the ocean (riverine inputs, erosion, etc.), to impacts on living organisms, strongly modulated by a wide range of acclimation and adaptation capacities. It is therefore necessary to develop an integrated approach to the study of acidification of the Arctic Ocean and its impacts on marine ecosystems, designed for both the comprehensive understanding of the process and to meet the needs of predictive modelling. The field approach could be coupled with laboratory experiments under controlled conditions to better understand the processes involved in interactions among metals, acidification and phytoplankton; the French scientific community has the experimental facilities to develop this type of approach. Finally the field and laboratory results could provide input for coupled biogeochemical/physical models developed in parallel.

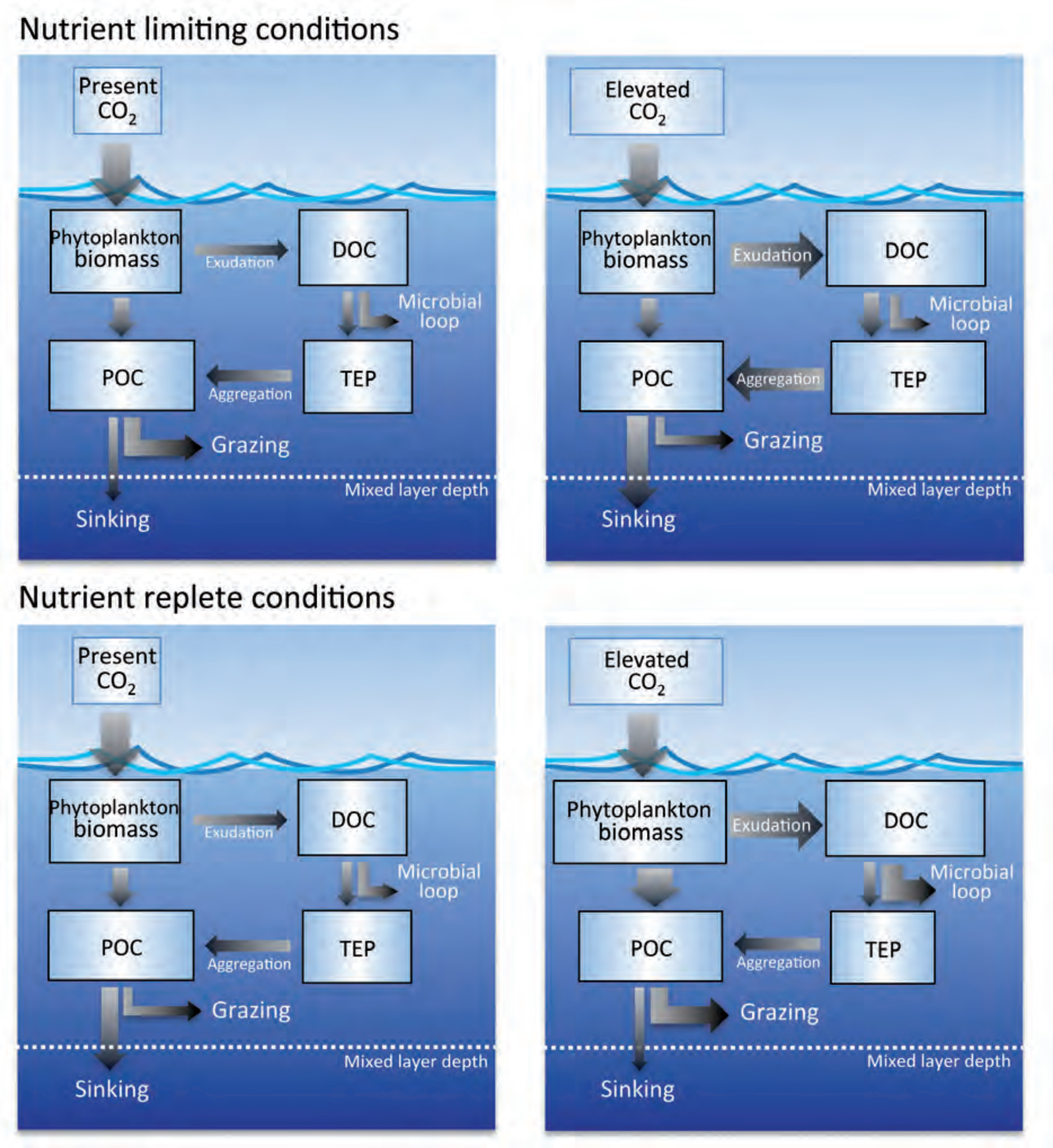


Figure 3.4: Sketch of carbon pools and fluxes at present day (left panels) and elevated CO_2 levels (right panels) under nutrient-limiting (upper panels) and nutrient-replete conditions (lower panels). The sizes of the boxes represent pool sizes, the thickness of the arrows represent the magnitude of the fluxes between pools; green arrows indicate fluxes stimulated by elevated CO_2, red arrows fluxes which are reduced at elevated CO_2. POM, particulate organic matter, DOM, dissolved organic matter. With a depth of 17 m, the water body enclosed in the mesocosms was entirely in the euphotic zone. Note that some of the fluxes were not measured directly but calculated or inferred from other measured parameters. Modified from Arrigo (2007) according to the outcome of this study. After Riebesell et al.*, 2013.*

• Impact of physical changes on marine ecosystems

Large-scale physical processes not only determine Arctic primary productivity but also the architecture of trophic networks that depend on them and fluxes of energy and matter within these networks. It is therefore essential to assess the impact of these changes on ecological processes at the scale of the Arctic basin. Arctic marine ecosystems are indeed affected both in their structure and functioning, from the individual to the diversity of organisms.

Understanding and predicting the past, present and future dynamics require analysis of the taxonomic and functional marine biodiversity, tracking invasions of boreal species and studying the impacts of these changes on the physiology of organisms and the functioning of the trophic interactions, from primary producers to top predators. This task requires assessing the adaptive potential and resilience of organisms and Arctic marine ecological systems to global change. For this purpose, only long-term studies related to short- and medium-term experiments can test phenotypic plasticity and micro-evolutionary processes in Arctic organisms.

Arctic trophic networks are strongly based on the transfer of energy from primary consumers to higher trophic levels (role of qualitative and quantitative changes), mainly as lipids. Desynchronization ('mismatch') between consumers and prey, hence reducing energy reserves accumulated by organisms, could have a negative impact on the population dynamics at the base of these networks (reproduction, recruitment, winter survival, etc.) and spread to communities of birds, fish and marine mammals. It thus seems essential to study the dynamics of ecological interactions based on monitoring different trophic levels. These interactions largely determine the resilience of ecosystems to global change.

Moreover the tight coupling between pelagic and benthic compartments (pelagic-benthic coupling) is particularly important in coastal areas, in the marginal ice zone and up to the limits of the continental shelf. In the Arctic, it has been changing rapidly over the past decade, in particular because warmer and more acidic waters favour 'retention' of carbon and organic matter in the water column (i.e. in the pelagic food chain) at the expense of the benthos. This shift between the three sources of primary production (epontic algae, phytoplankton and microphytobenthos) is amplified by changes in ice and snow cover that control the availability of light energy. The question remains of how the pelagic ecosystem, in the broad sense, influences benthic ecosystem dynamics and, in turn, how it responds, particularly in terms of nutrient regeneration. Understanding changes in pelagic-benthic coupling in response to physical forcing is essential to predict new functional equilibriums but also the impact on the carbon cycle and biogeochemical cycles in general, as well as on higher trophic levels that depend on benthic organisms (e.g. seabirds, marine mammals).

If abiotic parameters are critical in the distribution of animals and biodiversity, their alteration cannot occur without consequences for the equilibriums: between populations but also organisms with their environment. It is obvious that the decrease in ice cover, warming water and all the other environmental stresses act in concert leading to a change in the abundance, distribution and life cycle of marine organisms. Beyond observation of the phenomenon, better knowledge of the biology and physiology of animals must be a prerequisite to enable a solid interpretation and anticipation of the consequences of changes in environmental parameters. Efforts should focus on the fundamental steps of the life cycle (recruitment, reproduction, larval development, etc.), the response capacity and adaptation to environmental changes (temperature, pH, food chain, etc.) and on the estimate of their plasticity.

The research component for the description and monitoring of Arctic marine ecosystems should be focused on the development of ecological indicators. Indeed the scientific community interested in Arctic pelagic and benthic systems agrees that these complex systems cannot be assessed/described by a limited number of descriptors. If the characterization of biodiversity (regardless of its level of integration), the use of isotopes for descriptive purposes (trophic networks) and the use of embedded sensors have enabled remarkable progress, these approaches are insufficient when attempting to evaluate the status/functioning of a benthic system. The French scientific community has the expertise and current conditions favourable to the development of such new sensors (passive acoustics, accelerometry) and new descriptors (sclerochronology and sclerochemistry, acoustic landscapes, digital tools, trophic multimarkers, including fatty acids, isotopes, pigments and biogeochemical multimarkers, such as trace elements) that will fill this gap.

Predicting the responses of marine ecosystems to the ongoing Arctic changes requires a better understanding of the processes involved but also the use of multidisciplinary holistic approaches coupling ice and ocean physical forcing to the physiological, structural and functional responses, including trophic interactions in marine ecosystems. Long-term monitoring developed at the regional scale should be part of a pan-Arctic context. Like the IPCC, the international research community for Arctic ecology is now able to produce scenarios of Arctic ecological dynamics for future decades. The implementation of these scenarios is bringing together knowledge from long-term space-based monitoring, mentioned above, and its coupling with existing climate models, for example, in the context of species habitat models.

• Traditional knowledge for a better understanding of marine ecosystems

Marine ecosystems are an essential food source for the native communities that live along the shores of the Arctic Ocean. Traditional hunting and fishing are closely related to the dynamics of the marine habitat and its productivity. It is therefore easy to expect that the current disruption of marine ecosystems in the Arctic Ocean, will have a direct impact on these communities. The proximity of Arctic Ocean coastal communities to the marine environment is such that they have developed, over the centuries, a thorough understanding of the dynamics of the ecosystem on which they depend for food and as a source of various materials. It is now recognized that this traditional knowledge is rich and highly complementary to knowledge produced by the scientific world. An approach often referred to as 'Two Ways of Knowing' is increasingly advocated in the world of Arctic research. The work by the Arctic Initiative should integrate traditional knowledge through collaborations with native communities.

Solid earth geodynamics

Scientific objective

Reconstructing the long-term physiography and palaeogeography of Arctic basins. Modelling the impact of this physiography on water and sediment fluxes. Incorporating organic matter into margin sedimentology. Integrating mantle (dynamic topography, hotspots), lithosphere (subduction, thermal relaxation) and crustal processes in the model of Arctic basin formation. Considering mineral and energy resource in the original balance of internal and external processes in the Arctic.

Context

The Arctic Ocean is now a key element in understanding global external dynamics and its response to rapid changes documented by climatologists. Understanding its role in the movement of water masses on a global scale and carbon fluxes between them and the adjacent continental areas is crucial to any prediction or modelling on a global scale. The current physiography of Arctic basins is actually the result of a long history that involves several-billion-year-old continental blocks (the Canadian, Siberian, Baltic and Greenland cratons) and ocean basins that are relatively young on geological scales (100 Ma for the Amerasian basin, 50 Ma for the Eurasian basin). The boundaries of these areas and the history of their assembly are amongst the most poorly constrained in the world whereas economic issues (craton mineral resources, volcanic margins, hydrocarbon resource in the basins), strategic issues (expansion of exclusive economic zones) and environmental issues are considerable.

Detailed description of the objective and approach

• Horizontal and vertical movements: tectonic versus glacial cycles

Two major lithospheric plates govern the recent geodynamics of Arctic basins: the Asian and North American. The Gakkel Ridge between them, which is the recent extension of the Mid-Atlantic Ridge, is the slowest mid-ocean ridge in the world. Together with its counter-parts in the Laptev Sea, they offer a unique framework for studying the behaviour of the lithosphere during this slow divergence dominated by vertical movements. Indeed, charge and discharge cycles of the polar ice sheets cause vertical adjustments of the lithosphere on a very short time scale, which alter the geometry and thermal state of the margins. The stability of gas hydrates during the Pleistocene and the preservation of underwater permafrost are controlled, to the first order, by vertical movements of these margins. The geothermal flux at the base of the Greenland ice sheet is also an input parameter poorly constrained in creep models of the ice sheet. Icelandic volcanoes and the glaciers they bear show the effects of complex thermal and mechanical feedbacks to be considered at the regional scale. Documentation of different markers for these vertical and horizontal movements and implementation of thermomechanical lithospheric models should allow these movements to be reconstructed and to highlight the critical properties of the lithosphere underlying Arctic basins. As part of the French Arctic Initiative, thermo-mechanical models that couple the lithospheric and climatic processes to predict the response of basins at different time scales need to be developed.

• Palaeogeography of the Arctic

The reconstruction of Arctic palaeogeography is a work in progress, combining sedimentology, palaeontology and geochemistry. The deconvolution of records of past global climate events in the Arctic (oceanic anoxic events, Cenozoic thermal maxima, etc.) and the identification of phenomena specific to the Arctic (Eocene Azolla event) must allow the role (regulator, amplifier?) of the Arctic Ocean in global dynamics to be highlighted. This involves constraining palaeogeographic models by integrating data from geophysics, stratigraphy, sedimentology and tectonics. The corpus of data available ensures the success of the approaches already successfully used by the French community, for example, on the Tethyan basins. The reconstruction of past Arctic climate regimes and their links with the past basin geometry is one of the outcomes of this approach. The French Arctic Initaitive should be an opportunity for the French colleagues to count among the teams to propose new paleogeographic models. The recent growth of knowledge, motivated by the demands of the countries bordering the Arctic basin in terms of extension of exclusive economic zones, will have a direct impact on the validity of existing models and consititute the basis for a new generation of models. Being present in the debate now is a necessity for the French Arctic geologists.

• Sedimentary fluxes and sedimentation of organic matter

The geometry of the margins is smoothed by substantial detrital sedimentary inputs, which exchange with water masses and sequester organic matter. The specific characteristics of the Arctic environment (low productivity, slow degradation, massive input of organic matter by large rivers) are recorded in the history of this organic material: from its source, in its mode of transportation, its preservation in the sediment and finally maturation. As part of a continuous approach of terrestrial and marine processes (cf. §8), we have to combine the cycles of organic matter and sediments in the Arctic Ocean through research on relevant markers. This exercise is a fundamental step, both in the assessment of potential resources and in understanding the specific features of the carbon cycle at high latitudes. To do this, it is necessary to develop the conceptual tools of sequence stratigraphy, incorporating organic matter fluxes. The Arctic is an "end-member" of the case studies of a global conceptual model founders.

• Drivers of Arctic geodynamics: subduction? Hot spots?

The margin substratum and its initial architecture were shaped by internal dynamics. The hot spot of Iceland, its interaction with the Mid-Atlantic Ridge, the High Arctic Large Igneous Province and the peri-Pacific subduction zone are the major players in this structuration. The weight of their respective roles occurs through the detailed description of their expression: volcanic margins of the North Atlantic tell us of the tearing mode of the Eurasia plate, the accretion of land in the Alaskan and Chukchi peninsulas are witnesses of the coupling and decoupling phases of Arctic tectonics and peri-Pacific subduction dynamics. In this context, it remains to be understood how the Canadian Basin opened and why it ceased opening, long before the Eurasian Basin open in an orthogonal direction. In addition to plate kinematics, to reconstruct the long term Arctic evolution (cf. §"Palaeogeography of the Arctic") involves providing the real dynamics of the Arctic highlighting the drivers of kinematics. A coupled approach in terms of discipline (geology-geophysics) and in terms of objects (offshore-onshore) is recommended here (see § 8). The use of thermo-mechanical models incorporating lithospheric mantle dynamics and rheological stratification is now possible across the entire Arctic area.

• Mineral resources of the Arctic sub-soil: mineralization, preservation and impact of their exploitation

Glaciation-deglaciation cycles of the peri-Arctic continental masses denuded large portions of the ancient continental crust, peri-Arctic cratons, and made available mineral outcrops of economic interest (nickel, cobalt, palladium, platinum, diamonds, etc.). Although today their intensive exploitation is limited essentially to the Russian Arctic, recent climate changes suggest an expansion of these operations which raises questions. If the processes of concentrating these minerals are universal and studied based on the best-known historical cases, the specific characteristics of the Arctic environment must be taken into account to explain the rapid exposure and exceptional preservation. Understanding the possible reactions of minerals and tailings with the atmosphere and surface waters in the current climate, but also in the terms proposed for future decades, is necessary for sustainable exploitation of these resources. These considerations are a continuation of efforts in the context of the observatory for mines in fragile environments in a context of global change, a France-Quebec initiative involving the MRNF and several institutes (INSU, IRD, INE). They should serve as a basis to interact with the actors in themes 12. Pollution: sources, cycles and impacts and 13. Economic and sustainable development.

• Exceptional geological sites in the Arctic

The Arctic is exceptionally rich in crust segments that were witnesses to our planet's earliest history (Isua, Nuvvuagittuq, Acasta) and have helped to develop new and fundamental concepts regarding the initial differentiation of the planets, the history of the early bombardment in the solar system, the birth of plate tectonics and the first continents, and the origin of life. Some areas of the Arctic have provided ancient Metazoan fauna of exceptional quality from which the current living world has descended. The study of these areas is part of the Arctic geology, because they are often the location of concentrations of economic interest elements, but also because their exposure results from the interaction between lithospheric dynamics and arctic climate events.

Permafrost dynamics in the context of climate warming

Scientific objective

The regions below the Arctic Circle with permanent frozen soil (permafrost) bear the brunt of the consequences of climate warming leading to the development of periglacial landforms associated with the thawing of this frozen ground. The increase in air temperature has caused an increase in the temperature of the frozen soil (1°C) since the 1980s and a deepening of the active layer (surface layer thaws in summer). Model results according to IPCC climate scenarios indicate that, in the mid 21st century, the area of permafrost in the Northern Hemisphere is likely to decline by 35% to 80%, mainly due to melting permafrost. Studies indicate that in 2050, the depth of seasonal thawing could increase by 15% to 25% or even 50% in the northernmost regions. The thawing of permafrost may release greenhouse gases that will accelerate warming and disrupt hydrological systems and ground stability with implications for socio-ecosystems. All of these phenomena lead to strong feedbacks between the climate, vegetation, snow, permafrost and hydrology.

Context

The boreal environment is evolving rapidly; it is characterized by complex processes (thermodynamics of frozen porous media to phase changes, positive feedbacks, etc.) requiring multi-scale and pluridisciplinary approaches. This is why we have highlighted framework activities resolutely turned towards the quantification of processes and associated couplings. An integrated approach for permafrost and associated processes should be conducted using observations and measurements from instrumented sites, airborne measurements and remote sensing data, to feed the numerical and experimental models. Intercomparisons between these different approaches is a real challenge.

Detailed description of the objective and approach

• Evaluation of seasonal and interannual variability of sources and transport of CO_2 and CH_4

One of the specialties of research in France is the assessment of seasonal and interannual variability of sources and transport of CO_2 and CH_4 by ecosystem modelling taking into account the impact of permafrost degradation via the decomposition of soil organic matter and the quantification of GHG emissions. To document and prioritize the processes involved, we will highlight the coupling between the global modelling approach, airborne measurement campaigns (YAKAerosib) and experiments with

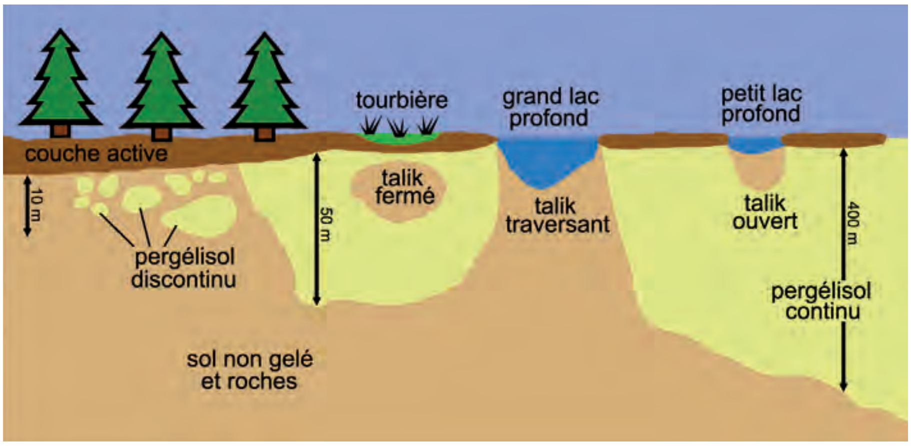


Figure 5.1: Cross section of permafrost. @Timorey

periglacial processes (thermokarst, cryoturbation, heat transfer in the active layer) in cold chambers.

The effect of GHG emissions requires an assessment of the intensity and speed of global feedbacks by multi-scale modelling including both global surface models (SURFEX and ORCHIDEE) and finer scale models of anthropogenic emissions of CH_4 (pipeline leaks of natural gas, for example). The sensitivity to climate change of carbon reservoirs in permafrost will be studied in particular.

• Feedbacks related to CO_2 and CH_4 emissions of Arctic soils

The study of the global feedbacks of Arctic changes must be pursued using climate-carbon cycle coupled global models. It is particularly important to include in the ESM a description of the feedbacks related to CO_2 and CH_4 emissions from Arctic soils and CH_4 emissions from wetlands (bogs, thermokarst lakes) in the preparation of future IPCC AR6 simulations.

The feedback phenomena of high-latitude ecosystems, via the release of greenhouse gases into the atmosphere, require understanding the thermal regime and hydrological behaviour of cryosols. This will include better assessing the influence of permafrost on feedback mechanisms between erosion, hydrology, chemical weathering, climate and vegetation. The study of feedbacks requires an improvement of global surface models (including SURFEX and ORCHIDEE) and taking into account the processes of decomposition of carbon and nitrogen in the soil (decomposition, thermal conductivity of soil, export of organic matter to rivers) and terrestrialization (e.g. infilling and revegetation of lake basins).

In studying feedbacks, the impact of permafrost degradation and associated processes (thermokarst, cryoturbation, etc.) will be analysed to document the relative contribution of each of these processes to diffusion of GHGs. Validation based on examples from the past (last interglacial, for example, based on data obtained in continental areas and by ice cores) may be considered.

Widening the scope of these models to underwater permafrost will also help to better understand the current contribution of thawing underwater permafrost (and/or the underlying hydrates) to the methane budget.

• Role of the decomposition of organic matter

Thawing permafrost makes possible the decomposition of organic matter and releases GHGs into the atmosphere.

Figure 5.2: Thermokarst lake related to permafrost degradation causing decomposition of organic matter and release of GHGs to the atmosphere. @Antoine Sejourne

However, the proportion of carbon from permafrost which can be decomposed into CO_2 or CH_4 (anoxic conditions) remains uncertain because of insufficient understanding of changes in the soil physical properties and biogeochemical properties of the organic matter they contain. Many questions remain as climate / permafrost / carbon couplings are complex to model.

We propose in particular to quantify the influence of seasonal freeze/thaw cycles in the active layer on carbon and nitrogen decomposition processes in the soil and (for longer time scales) the fluxes of elements from the weathering of minerals in the active layer by thermo-hydrological and 3D mechanistic modelling. We will focus on understanding the biogeochemical cycles of carbon and other elements (major and trace elements, and especially nutrients) among different geochemical reservoirs (soil / vegetation / atmosphere / hydrographic network) in response to climate warming.

• Study of snow-vegetation-permafrost feedbacks

Cryosols contain almost 40% of soil total organic carbon. Increased mineralization of terrigenous organic carbon sequestered in the tundra can be explained by photo-oxidation processes and bacterial activity. Another example is the thermal insulating capacity of snow (whose thickness increases in winter in some areas due to warming), which can accelerate the thawing of permafrost but enhances the remobilization of nutrients, in turn, accelerating plant productivity. Many questions remain because the processes remain poorly understood and we must mobilize the tools (biogeochemical, mineralogical, isotopic, microbiological) to identify them more accurately.

The study of these feedbacks requires accurate knowledge of the evolution of the permafrost thermal regime. It is highly sensitive to snow properties and to its interaction with vegetation. These studies will rely on measurement stations for the physical properties of snow and soil, which will quantify (1) a description of the impact of vegetation on the energy and heat budget of the soil and (2) the impact of snow, whose properties are affected by the vegetation cover and temperature, on the same budgets.

• Indicators and spatio-temporal impacts of permafrost degradation on the environment

The interactions among permafrost, vegetation and climate are relatively complex but studying them is nevertheless crucial to understanding the dynamics of boreal environments. In the context of climate change, the study of degradation indicators (ground and subsoil) is a challenge for accurate and quantitative monitoring of changes in Arctic and sub-Arctic ecosystems.

Pluridisciplinary approaches are currently being developed coupling field studies (continuous monitoring of permafrost and the active layer, isotopic and hydrological measurements, geomorphological and climatic analyses) with numerical modelling and experimental modelling in cold chambers. It will focus on past and current variability via the characterization of periglacial processes which are markers of periods of rapid warming and permafrost degradation capable of emitting CH_4 and CO_2 (thermokarst lakes, etc.). These approaches will be based on studies with high spatial and temporal resolution in the field, together with the analysis of high-resolution satellite images.

Such programs require analyses of instrumented sites but also studies along transects on the scale of watersheds. Indeed there is often a gap between the overall approach and studies of instrumented sites that require a regional approach.

Finally, the assessment of the socio-environmental impacts of permafrost degradation requires implementing ambitious interdisciplinary programs crossing environmental science, the humanities and social sciences. Various study sites may be considered, foremost among them Siberia, which is already the site of cross-disciplinary projects involving researchers from a wide variety of disciplines (ANR CLASSIQUE and BRISK, GDRI Car-Wet-Sib and Yak-Aerosib, LIA COSIE, etc.).

Arctic terrestrial ecosystem dynamics in the context of global change

Scientific objective

Assessing the impact of global change on ecosystems and the evolution of terrestrial organisms, the dynamics of trophic networks in which they participate and the consequences of these processes for changing Arctic landscapes.

Context

Polar regions, whether Arctic or Antarctic, land or sea, are home to Native biodiversity manifested in the taxonomic composition and the specific structure of communities, the high level of species endemism and their biogeographical characteristics and their degree of physiological tolerance to environmental conditions, which is often near their limit of growth. While different in the Arctic and Antarctic, these species have succeeded in becoming established at the boundaries of life.

In contrast to the Antarctic, interest in Arctic research is related to the lack of isolation of the fauna and flora of these regions. These characteristics explain the differences observed in terms of diversity, speciation, endemism and adaptation of Arctic communities compared to Antarctic communities. However, islands with high endemism exist in the Arctic (Svalbard Archipelago, for example) and allow North/South comparisons.

The survival of flora and fauna in these hostile environments, the result of selective pressure, accompanied by uncommon life history traits, is often due to highly sophisticated adaptations, which may limit their plasticity and make them more vulnerable to rapid climate change. The study of the impact of the spatial and temporal variability of the environment on the dynamics and genetics of populations as well as the adaptive value of individuals is thus essential.

The study of wild and domestic, large Arctic fauna, as is the case with reindeer-caribou and the Yakut horse, now in great danger, makes it possible to consider adaptation processes in attempts to 'rewild'. The importance of these animals to the economy and culture of circum-Arctic Native people fully justifies the relevance of these studies concerning both archaeological remains as well as modern animals.

The direct effects of warming on ecosystems are combined with those of human impacts. Among these anthropogenic effects, the intended and unintended introduction of species and the growing risk of invasions of allochthonous species, taking advantage of more favourable conditions to grow at the expense of Native species, cause a loss of diversity within communities. Beyond these population issues, the emergence of new trophic links in the populations already weakened by climate change is likely to fundamentally change the structure and functioning of these ecosystems. It is now essential to put in place the mechanisms to cope with these issues of identification, understanding, knowledge, preservation and remediation of Arctic environments.

Moreover, climate change opens up new areas to colonization by life with the introduction of invasive processes and new dynamics (from microorganisms to humans) developing very strong interactions (appearance of new pathogens, development of zoonoses). In the Arctic, mining exploits new areas or looks to develop them (gold, uranium, etc.). Global warming, by facilitating access to certain areas, can exacerbate the problem. The consequences are already very significant for caribou ethology in Nunavut (migration routes change, decreased use of calving areas, for example). Overall the impact on the environment and living organisms will be considerable. It is therefore necessary to develop the capacity to assess the effects and to identify the forms and processes, evaluate their consequences and help meet society's growing needs in these times of dramatic changes in anthropo-ecosystems.

The impact of global change on terrestrial ecosystems can be understood through three, highly complementary approaches. First, the impact of these changes on organisms must be assessed through an ecological and evolutionary approach. Secondly, the impact of global change on the ecology of interactions should be studied at the level of populations, trophic networks and communities. Finally, all of these processes determine the fluxes of energy and matter in terrestrial ecosystems. The results will be reflected in changes in landscapes. This three-ponged approach fully integrates Arctic individuals and societies; climate change will require them to adapt and will transform interactions with their environment, thus influencing fluxes of matter and the fate of Arctic landscape. This region is very marine and it is also essential to integrate terrestrial and aquatic ecological dynamics, which will be drastically altered by climate change in the coastal zone. All of these approaches require long-term observation activities based on pan-Arctic networks of measurement points, reinforced by remote sensing tools. These observations will be coupled with experiments in targeted field campaigns and modelling exercises designed to estimate future ecological dynamics. These integrative approaches are already partially implemented in the Arctic, where multidisciplinary observation systems for terrestrial ecosystems have been implemented. Good examples are GEM (Greenland Ecosystem Monitoring: www.g-e-m.dk) and the INTERACT network (http://www.eu-interact.org/), which provide information for the ecological reports of the Arctic Council working groups (http://www.arctic-council.org/index.php/en/) and for CAFF (Conservation of Arctic Fauna and Flora: http://www.arctic-council.org/index.php/en/conservation-of-arctic-flora-and-fauna-caff). French researchers are already involved in this work in the framework of the IPEV program (http://www.institut-polaire.fr/) and it is essential to facilitate and enhance participation. This will allow the use of expertise acquired through French research activities in the sub-Antarctic and Antarctic zones, and also encourage the participation of a wider range of specialized French colleagues, for example, in alpine ecology, biometrics, predator-prey relationships and landscape ecology.

Detailed description of the objective and approach

• Ecology and evolution of Arctic terrestrial biodiversity

It is essential to test the adaptability (phenotypic plasticity and microevolution) of Arctic organisms to the constraints of their living environments, whether old or new. This approach will be facilitated by recent developments in evolutionary ecophysiology, which test the impact of environmental change on the adaptive value of organisms. The species that constitute Arctic terrestrial biodiversity are indeed subject to major constraints such as increased temperature regimes, changes in snow cover, permafrost and water resources, to which are added other perturbations of anthropogenic origin, such as pollution. In this context, the main objective is to produce inventories of the present biodiversity, by conventional means assisted by new sequencing techniques, then to test the individual and combined effects of a wide range of biotic and abiotic forcing factors. These studies will benefit from existing, long-term, space-based monitoring data, which should be maintained and strengthened. They will be correlative or experimental, such as air or soil temperature manipulations on vegetation.

• Food web dynamics and Arctic landscapes

Arctic terrestrial ecosystems are currently characterized by strong trophic interactions, both between plants and small mammals (voles, lemmings) and also between small mammals and their predators, some of which are emblematic of the Arctic (snowy owl, arctic foxes, skuas). Reindeer/caribou, found throughout the Arctic, play a potentially important role for vegetation and certain predators and are essential for many Arctic peoples. Better understanding of the interactions between climate change, vegetation, herbivores and predators is therefore a major issue. Climate change is altering these interactions both in winter and summer. In winter, the already observed increase in temperature and precipitation can result in a higher frequency of rain on snow, leading to ice encasement of vegetation and therefore the decline of small and large herbivores. By contrast, heavier snowfall linked to an increase in winter precipitation may favour lemmings that breed under the snow. In the summer, rising temperatures should lead to higher vegetation productivity and transitions from herb tundra to shrub tundra. This should increase the number of species and certain herbivores (e.g. voles that dominate the boreal zone). The impact of herbivores on vegetation and of predators (whose communities should be enriched by species from the south, such as the red fox) on herbivore populations will be crucial to the dynamics of the ecosystem. Given the heterogeneity of the current climate and expected climate change, understanding and predicting ecosystem dynamics requires that monitored sites cover this heterogeneity and that monitoring of the biological components (plants, herbivores, predators) also incorporates bioclimatic factors having a direct influence, in particular the properties of the snowpack. Such monitoring has been put in place in Canada (Bylot), Greenland (Nuuk, Zackenberg) and Norway (Varanger Svalbard) with effective collaboration between the groups involved. The selection of sites and methods used by the French groups must allow a comparative approach for the dynamics of the monitored sites. Beyond these trophic

Figure 6.1: Arctic terrestrial ecosystems are often in direct contact with the marine environment. Here a polar fox tries to carry a large fish (a lumpfish, in the grass to the left of the animal) that was found dead on the shore to his den; a rest is required. West Greenland. @David Grémillet

Figure 6.2: The mechanical properties of snow cover strongly determine reindeer winter feeding. This animal benefits from a feeding area cleared by wind but an icy surface could block access to the resource, Svalbard. @David Grémillet

considerations, it involves studying the changing landscapes of the Arctic in the context of global changes. This strongly transdisciplinary theme incorporates the dynamics of Arctic terrestrial ecosystems and the dynamics of human societies that depend on and exploit them through pastoralism, hunting, mining and urban development activities.

• Scales of approach and objectives

Studies should address the processes involved at different spatial scales to specify how Arctic biotopes respond to environmental changes and, beyond this, to global change and to what extent people will be able to adapt. Biogeography is considered here in its current definition, which considers living beings in their functional and dynamic relationships and takes into account all time dimensions and all levels of the distribution of species on the surface of the globe (places, distances, territories, fluxes, networks and all modes of spatial organization).

Three complementary objectives must support this approach: 1/ maintain networks of existing observation stations and develop 'zone atelier' structures promoting the interdisciplinarity that is essential to ecosystem studies, 2/ understand the mechanisms, from the molecule to ecosystems, through which climate variability affects biological processes; 3/ model and predict the impact of changes in the climate system on populations and ecosystems.

Native people and global change

The economies of the peoples of the Arctic and sub-Arctic – the Aleuts, Evenk, Even, Yakut, Inuit, Koryak, Saami, Chukchi, Yupiget, Yupiit, amongst others – are now not only mixed but globalized. Nevertheless Native people remain strongly attached to a lifestyle that brings them as close as possible to nature everyday, and they derive reportable income from hunting, fishing and reindeer herding. Therefore, human-animal-environment relationships are crucial. Economically, culturally and symbolically significant, these relationships have a special place in the work of researchers in the humanities and social sciences, and many of their questions have similarities with the concerns of their colleagues in environmental science (climate change, ecosystem disruption, threats to biodiversity, industrialization, pollution effects on health, etc.).

Faced with the multiplicity and complexity of the problems of global change, collaboration between researchers from different disciplines that is backed by partnerships with Native communities (see below) is essential and has high scientific potential. The humanities and social sciences, however, have specific traits. Their methods involve a personal investment in the field and listening; issues emerge from discussions with various local stakeholders. In the North American Arctic, the Code of Ethics is a framework for fieldwork providing, amongst other things, compensation for Native interlocutors considered as research partners and not as mere informants. The humanities and social sciences have another unique characteristic: learning an Native language (see below) represents a challenge because it is added to the use of another language of the country (Russian, languages of northern Europe, English).

Scientific objective

- Evaluating the impact that global changes have on the evolution of Arctic ecosystems and on the experiences of Native people.
- Grasping the complex linkages between these changes and the values held by the societies involved, taking into account past and present situations.
- Analysing the solutions already implemented or proposed by comparing the diverse scientific and local knowledge.
- Establishing ethical partnerships opening the door to integrated points of view given a comprehensive approach to the phenomena.

Context

In Arctic and sub-Arctic regions, the acceleration of environmental processes disrupts and aggravates existing situations. This situation creates new risks for the natural environment and for the various Native people that base their economies on local resources and remain strongly attached to the associated values. These local resources are not distributed geographically in the same manner, exploited with the same techniques nor with the same intensity. Thus in northern Scandinavia, livestock and agriculture play a significant role whereas in Alaska, the Canadian Arctic and Greenland, the role of hunting and fishing is central. In Siberia, in addition to these two activities, reindeer herding plays an important role. Not to mention that in all regions harvesting is considered an essential practice for a balanced diet. Generally there are multiple economies.

Global change occurring on a planetary scale reflects the human footprint on the environment. In some areas, it is not only climate change, pollution and loss of biodiversity which have to be considered but also the tensions created by the occupation, privatization, even confiscating, of land inhabited by Native peoples. The exploitation of natural resources affects usage rights. If changes are global, there will be local scale consequences. Therefore analyses must be conducted on global, regional (biomes or ecoregions) and local scales.

Detailed description of the objective and approach

• Reindeer-Caribou

Among other important issues is that of wild and domestic reindeer and wild caribou, which are iconic animals of the

Arctic. Fragile and particularly sensitive to environmental changes, they are sentinels of change. In an environment in transition, economic developments and climate change threaten the very existence of these terrestrial mammals; their disappearance would create a disturbance upsetting the balance between the environment and societies that exploit these regions and species. In Saami territory, similar to the Siberian breeders, reindeer husbandry is a living tradition that continues and evolves. It requires constant adaptation, made more difficult by restrictive regulations that reduce

Figure 7.1: Reindeer system - Gathering a 1800-head herd of reindeer for the slaughter of 200 animals for sale. After the collapse of the Soviet Union, the state farm (sovkhoz) in Achaivaiam (Olyutorsky District, Northern Kamchatka, Russia) dedicated to raising reindeer continued to be organized in a way similar to that established during the time of collectivism. The 4 herds (3 collective herds of more than 1500 head and 1 private herd of about 800 head) supply meat to an entire region that has been neglected by the central government. ©Beyries-Karlin

the mobility of herders and their herds. However, adaptation depends on the autonomy available to respond adequately to variability. To understand the adaptability of Arctic societies and the resilience that characterizes them, we must integrate research on the autonomy / dependence relationship between minorities and majorities. In a mixed economy where self-sufficiency no longer exists, social and political autonomy encourages innovation. Native people have long been affected by non-native 'modernity', but they claim the right to decide for themselves the terms and conditions under which they dialogue with modernity, which is not rejected as a whole, far from it.

In the current balance, the caribou and reindeer way of life meet all local and regional needs. However, how much freedom does the environment give to the existing system? The analysis of the impact of caribou and reindeer on the landscape could be decisive. For a number of years, shrub vegetation has advanced as well as colonization by species from southern areas. These species are accompanied by the appearance of new animal species that profoundly affect ecosystems. To what extent does reindeer browsing delay this phenomenon? Similarly, for Siberia, one might wonder how the state of the vegetation as observed today is related to the presence of large herds, which tend to prevent the development of shrublands and trees and to benefit grazed species: lichens in winter, grass in summer.

By working on maps of recent changes, particularly those provided by aerial and satellite imagery, cross-disciplinary studies can be explored between the analysis of landscape change and innovative practices developed by various Native people based on their perception of phenomena such as changes in flora and fauna, changing pathologies and changes in the diet of reindeer and caribou.

These questions about the future of terrestrial mammals similarly apply to birds and marine mammals that feed many Arctic societies. These various local resources are also very sensitive to climate change and water pollution.

• Human-animal interactions in the Arctic: diverse representations and practices

In addition to caribou and reindeer, there is all of the natural diversity, from the largest mammals to the smallest insects, with which Native peoples of the Arctic and sub-Arctic interact through migrations and seasons. They develop, in this context, specific practices, skills and knowledge whether they be techniques, rituals or specialized vocabulary. Therefore, attention must be given, according to the region, to the various terrestrial species (musk oxen, elk, bear, small animals), marine species (seals, whales, walruses, polar bears), not to mention birds and some species of fish (salmon and Arctic char) that are at the ocean/sea/inland interface. Shrimp, salmon and halibut are commercially exploited; other animals, such as bowhead whales and polar bears, hold a strong spiritual significance.

If the human-environment-animal relationship is especially important for Arctic peoples, it is not enough to summarize all the challenges. Like the other inhabitants of the planet, Native peoples are facing difficulties of an economic, political and social nature that are related to the development of a global economy and the colonial and postcolonial contexts in which they find themselves. They are, as elsewhere - but in ways of their own - affected daily by a lack of financial resources and by unemployment. In some areas, they face problems with housing and access to education and health care.

Figure 7.2: Reindeer system - Throughout shamanic Siberia, before any major event a sacrifice helps promote good luck and vital heat. For example, sacrifices can be made directly by slaughtering a reindeer; however, often sacrifices are made on the substitution principle. In this case, a 'sausage reindeer' (zjozjat), the substitute for a live reindeer, is caught (see the lasso on the ground), slaughtered, skinned, and cut exactly like a live animal. ©Beyries-Karlin

These problems are expressed in current religious choices. Some choose to reactivate shamanism and use it as a strong identity marker (Siberia). Others, however, believe that their future lies in the perpetuation of an adopted Christian practice, such as the Aleut people (Alaska) whose membership in the Orthodox community is felt to provide an important framework. Others remain attached to the Anglican, Lutheran and Catholic churches. Still others are interested in the message of prosperity and well-being put forth by neo-evangelical churches, as in other parts of the world. The human-environment-animal relationship fully has its place in recent religious changes: for example, having become Christians during the twentieth century, the bowhead whale hunters of Saint Lawrence Island, Alaska, organize a service in the Presbyterian Church before the hunting season. The evangelical Protestant movements (like Pentecostals), more recent to the Arctic, are developing a 'biblical environmentalism'. We cannot therefore understand the ecological issues at the centre of the French Arctic Initiative without including contemporary religious studies, especially as this is a dynamic field of research in France that is pursued by a number of researchers.

• Scientific questioning and Native knowledge

Environmental science researchers have pointed out, in the late 1980s, the validity of Native ecological knowledge by integrating in their publications testimony from the Arctic and sub-Arctic. Referred to as Traditional Ecological Knowledge (TEK), this methodological and ethical choice has undergone significant expansion including the extensive reproduction of testimonies from the field and their bilingual publication (local language / English). A step further has been taken by the Interviewing Elders series (launched in Nunavut in 1999). Referred to as Native Perspectives, this approach takes into account the logical structure of native languages and the way the speakers establish a relation between themselves and their interlocutors. Knowledge within specific areas of experience are systematically associated with other knowledge, representations and practices; that is to say, together it all forms the complex and coherent whole referred to as 'culture'. Currently, the adjective 'traditional' associated with Native knowledge is disappearing and the status of 'informants' is changing. Ceasing to be regarded as 'interviewees', which belongs to the past, Native people become co-investigators included in grant applications, which are supported, in part, by local associations. Scientists' results show that it is pointless to pit against each other native, academic and scientific knowledge. Conducting science in a spirit of complementarity is possible and it seems, ultimately, that theoretical analysis is in no way impaired by taking into account native knowledge.

More than ever, the scientific process must focus its questions on the knowledge of those who intend to continue living from the resources of their environment. How do local people perceive the increased risk, for example, of the hydro-climatic changes underway and what strategies do they adopt? Which representations are affected by predictability, unpredictability, interventionism, or wait-and-see? The answers to these questions deserve to be compared with scientific knowledge. The heuristic value of this approach rests on the belief that the major issues raised by global change are often valued differently by scientists and Native people. There is a need to understand how practices, methodologies and approaches which appear distinct can contribute to common points of view and decisions when faced with complex processes. Partnerships should be created and common ethical codes should be developed to bring out the commonalities between theories, representations and practices.

The inclusion of Native knowledge and know-how allows adequately addressing a set of questions constantly reformulated, redesigned and re-evaluated in human and social sciences, such as the links between nature, social issues, culture and the supernatural (religion). To what extent does knowledge from 'others' allow us to take a step back from what we, in scientific circles, consider as being true and accurate? How do Native theories about the natural environment shape institutions and social practices? In what areas? What social uses are made within the societies and in their relationships with the rest of the world? Not to mention that Native thoughts add a level of complexity by considering that non-humans (animals, spirits) have a point of view on the world, that is to say, that there are social relationships based on reciprocity between human and non-human species. Forms of sociability have several approaches (*cf.* cosmopolitics and perspectivism).

• Retrodiction and prediction, reflections on past analogues

While the French community of researchers in the humanities and social sciences focuses on the contemporary situation of Arctic peoples, the fact remains that the understanding of current societal responses necessarily requires a thorough knowledge of past developments. The inclusion of archaeological issues is needed. In northern Siberia the sites are very old: 27 000 BP for the Palaeolithic Yana RHS site, about 14 000 BP for Berelekh and 8 000 BP for Zhokhov Island. These sites show that the adaptation of human societies to Arctic conditions dates back to very remote times. As for the American Arctic, the first settlement was established 4 500 years ago, and the Inuit culture emerged in the first millennium in the Bering Strait; these two key moments in the prehistory of the region were punctuated by significant climatic and environmental changes (neoglaciation, medieval climate anomaly or optimum, followed by the Little Ice Age). However, the Siberian and North American territories are huge and the archaeological map is far from complete. The Arctic, moreover, is likely to offer interesting analogies to European prehistoric research.

At the end of the Palaeolithic, for thousands of years while fairly drastic climatic conditions prevailed in Western Europe, hunting reindeer *(Rangifer tarandus)* was often at the heart of the subsistence economy. Given the chronological inaccuracies of these periods, it is often difficult to distinguish what resulted from adaptation strategies to particular ecological conditions (climate change or geographic features) from what was the result of cultural choices.

Part of the Arctic allows us to investigate the behaviour of humans and animals living in conditions comparable to those of the prehistoric periods considered. In addition, current climate problems are similar to the conditions experienced in Western Europe in the late Pleistocene. Can we make use of the current situation to understand the behaviour of the past? Similarly, how can our knowledge of the past allow us to anticipate certain changes? In terms of climate instability, what are the complex interactions between societies and the environment? To adequately answer the question, it is necessary to take into account, for the past and the present, the transformation of the economic, technical and cultural systems; the concept of culture must be taken in its broadest sense from linguistic to religious practices.

• A research tool to develop: from Native languages to thinking

France is in a unique position in the academic and scientific world by offering university courses dedicated to Native languages spoken in the Arctic and sub-Arctic regions. Taught by Inalco, lessons are based on the idea that these languages are no longer ‘rare’ because of their geographic, cultural and intellectual distance. They are the languages of our partners in a globalized world as shown by their participation in the Arctic Council, which includes eight Member States and six Native associations with permanent representatives (including Inuit, Saami and Siberian minorities). It is clear that sensitive issues, such as sovereignty in the Arctic, the exploitation of non-renewable resources and public health policies cannot be discussed without integrating the views and participation of Native peoples.

Knowledge of a Native language allows working on original material (oral and/or written) to enter a way of thinking and avoiding reasoning from a given language (English, Danish, Russian), which may lead to interpretation errors or distortion of meaning. Indeed, our ways of conceptualizing reality, and thus our language, are not necessarily those of the other and vice versa. Much more than just communication tools, languages are in themselves true systems of integrated knowledge showing their own classifications and operational categories. Inalco provides an opportunity for students and young researchers who are participating in long-term stays in the Arctic and sub-Arctic regions to study the Inuit language, using both a theoretical and practical approach, and also to be introduced to the Chukchi, Tundra Nenets and Sakha languages. One of the main advantages is the fact that knowledge of a Native language not only facilitates social integration but it provides access to research topics inaccessible without the mastery of analysis techniques for language materials.

INALCO currently offers a diploma course, through videoconferencing, on Inuit language and culture. This initiative is unique in the world, responding to a request made by the medical staff practicing in Inuit communities in Nunavik in northern Quebec. Half a dozen Inuit villages, the Telehealth Centre of McGill University and the Montreal Children's Hospital connect with Inalco to benefit from training on a weekly basis from September to mid-May. Building on this interest for what France is able to offer beyond its borders, this experience should be extended to other Native languages spoken in other parts of the North American and Siberian Arctic. It must be shown, by visible and ambitious projects, that Native languages are languages of culture and that learning them promotes mutual understanding, local partnerships and cross-disciplinary scientific research.

In addition, the ‘Master 2’ Arctic Studies program of OVSQ offers high-level training in English dedicated to an interdisciplinary approach (environmental science / humanities and social sciences) to the main challenges that Arctic societies are facing. This program has the particularity of hosting and training Native students from the Arctic (Yakutia, Greenland, Siberia).

Towards an integrated program on the Arctic Land-Sea continuum

■ Scientific objective

Transfers between the land surface and Arctic Ocean occur along a continuum and it is important not to separate the compartments: they are all interdependent. The scientific objective is to understand the mechanisms, to determine the fluxes and their impact on Arctic ecosystems and societies, from the continental watersheds to the ocean where the sedimentary archives are on the margins.

■ Context

The Arctic Ocean is strongly affected by changes in continental hydrological and biogeochemical processes. These changes are primarily caused by the increased discharge of freshwater and associated dissolved particulate matter. Each year, major rivers draining northern North America and northern Eurasia discharge into the Arctic Ocean 4 200 km^3 of freshwater and about 221 106 tons of sediment. These rivers have enormous watersheds that extend to temperate latitudes. This input represents 11% of the freshwater input to the global ocean whereas the Arctic Ocean represents only 1% of the total ocean volume. The Arctic Ocean is particularly sensitive to fluvial input and is one of the best places in the world to understand the link between the functioning of the land surface and the ocean. Added to this are a number of features specific to the Arctic.

Arctic terrestrial surface water is partly cryospheric, stored at the surface of the Earth's crust (permafrost) or in the form of snow, glaciers and sea ice, which makes the interaction between atmospheric water and Arctic ecosystems very unique. In addition to the major rivers, coastal glaciers and those carried by tidal waters also contribute to a significant influx of freshwater and sedimentary material. The volume of meltwater from Greenland is estimated as 400 km^3 but few estimates have been made for other Arctic glaciers (Svalbard, Canada, Alaska). These glaciers with their weight, the nature of the underlying rock and their hardness abrade and erode large amounts of material that is deposited in moraines.

The Arctic Ocean, which is relatively closed (due to its geological history), is much influenced by freshwater and what it carries, a feature that has implications for its salinity, stratification, acidity, biological productivity and affects its circulation and that of the world ocean.

For the centuries to come, observations and models suggest that precipitation and runoff will follow positive trends in the Arctic, signs of an intensification of the hydrological cycle. The prediction of changes that will affect the entire land-sea continuum, from soils to marine sediments and from terrestrial to marine ecosystems, is a major challenge; first of all, for Arctic societies and their sustainable development and, more generally, for the climate, biodiversity and the global environment.

■ Detailed description of the objective and approach

• The Arctic ‘critical zone’

The zone between ‘the rocks and sky’ is the very thin layer at Earth’s surface resulting from the interaction between the water cycle and lithosphere. It is one of the features that marks the uniqueness of our planet created by the confluence of water, life, minerals and atmospheric acidity, which is neutralized there. Its dynamics combine physical processes (such as erosion that destroys it), chemical weathering processes (which build it) and ecological processes (because critical zone processes are largely dominated by life). The functioning of this critical zone, which includes soil, ground and underground water, vegetation and more generally all living organisms in the soil, and the lower atmosphere determine the water composition, the quality and stability of soils, the emission of aerosols and greenhouse gases from the surface of the Earth, and the mass balance between the atmosphere and ocean in a more general way. It is in the critical zone that the water resource is generated and where tomorrow’s agricultural land is produced. This is humankind’s environment.

The concept of the critical zone and the degree of disciplinary interaction it involves makes perfect sense in the Arctic. The Arctic critical zone will be particularly sensitive to

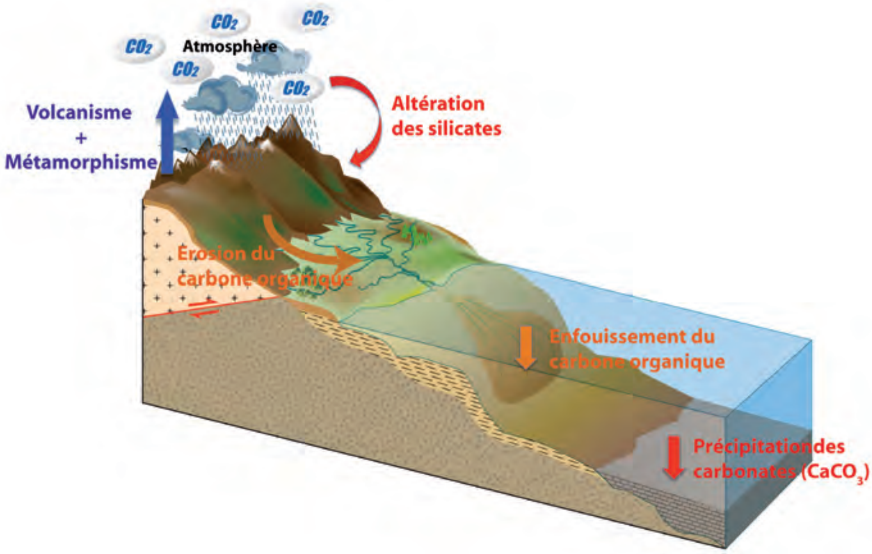


Figure 8.1: Schematic diagram illustrating the land-sea continuum. The arrows represent the main mechanisms of the geological carbon cycle. The inorganic processes of atmospheric CO_2 consumption by rock weathering and carbonate precipitation in the ocean are indicated in red. Whereas, the organic processes soil organic carbon erosion and burial in marine sediments are indicated in orange. The consummation of CO_2 by inorganic and organic processes are compensated by the degassing of the Earth. This cycle operates over very long time scales. @IPGP

environmental changes that are exacerbated there and upon which the overall functioning of the planet depends on, in part. The modelling of Arctic continental surfaces requires a better understanding of the mechanisms acting along environmental gradients (mimicking future changes) and the acquisition of temporal monitoring. The time scales of critical zone processes being interlinked, it is important to consider them all, both at the scale of recent climate change but also on geological time scales. More than elsewhere, understanding the current state of the system requires knowledge of its history, a legacy of the Quaternary and Tertiary periods when very cold and ice-covered periods alternated with warming periods.

• Soils and catchment scale

At the plot scale, Arctic continental surfaces have significant differences. In places frozen at depth (permafrost), the Arctic critical zone is covered with soils rich in ancient organic matter and prone to oxidation, releasing greenhouse gases. The interactions between water and rocks, which are a major sink for atmospheric CO_2, are controlled more than elsewhere by this organic matter that decomposes incompletely and has a great ability to complex metals, for example. A particular geomorphology is associated with the Arctic critical zone; its transformations are marked by the predominance of physical processes in relation to chemical processes, thermal erosion and glacial processes. The links between these mechanisms are poorly understood and require an integrated approach. In an integrated approach, small watersheds (catchments) allow, for example, the calculation of the rate of production of soil, and possibly thawing permafrost. These quantifications can be compared with measurements from instrumented sites for permafrost and the active layer. The use of isotopes as tracers of biogeochemical reactions and sources of material carried by rivers to the Arctic Ocean on a large scale can be exploited. Cosmogenic and short half-life catchments can also help to clarify the rate of erosion of Arctic surfaces, which we do not know precisely, and to determine the typical response times of ecosystems and the Arctic critical zone. Arctic terrestrial ecosystems are characterized by important trophic interactions (e.g. between caribou/reindeer and vegetation, or between lemmings, their predators and vegetation) which are partly responsible for the evolution of soils and are, not well described by a biogeochemical/climate approach but which are important feedback loops, especially locally for Arctic societies.

• Small watersheds to large watersheds

On a larger scale, the fluxes of matter associated with fluvial inputs to the Arctic are not well known. The main sources of solutes and sediments as well as the controlling factors specific to Arctic watersheds must be better understood. They are the entry point for some of the nutrients and sediments in the Arctic Ocean. These fluxes of matter have high temporal variability marked by extreme annual episodes that are poorly documented because they are difficult to sample. Sampling of Arctic rivers during spring breakup is still an obstacle. Research should focus on the thermomechanical and sedimentary impact of ice jam floods. Arctic societies are very dependent on large rivers (commercial routes), and the frequency and intensity of extreme processes (floods, droughts) results in new and/or increased risks. Moreover, carbon and nutrient fluxes to the ocean and the factors that control them should be better understood, whether from fluvial inputs or glaciers. Indeed, they represent a lateral 'leak' in the carbon cycle at the scale of Arctic continental surfaces, which could represent a significant flux in the global carbon cycle. The goal of establishing 'carbon budgets' for major Arctic river basins or certain Arctic watersheds could be a national objective of the Arctic Initiative.

• Water and soil resources

It is in the Arctic critical zone, as we have defined it, that the water resource is produced (underground, melting and flowing at the surface) and that soil resource for agriculture is created by biological-physical-chemical transformations. Climate change will no doubt impact these two resources essential to the future of Arctic societies. Soil evolution will impact plant and animal communities as well as human land use. The increase in population density in the Arctic will mean more pressure on agrosystems and therefore on soil and the associated ecosystem services (such as food resources). From a hydrological point of view, changes in runoff and erosion of banks and channels of major Arctic rivers will have consequences in terms of risk because the majority of cities in central and northern Siberia are located along watercourses. Increased flooding also threatens urban and port infrastructure and is a problem for drinking water resources for local populations.

• Estuaries, glaciers and the marine environment

Integrating the functioning of the Arctic critical zone, water from rivers and melting glaciers containing dissolved and particulate materials as well as living organisms is discharged into the ocean. Land-sea transfers, aqueous and particulate, may be significantly modified by climate change (melting ice, runoff, thawing soils, etc.), and disrupt marine primary production and benthic ecosystems by altering the input of nutrients, metals and organic and particulate matter. Estuaries and coastal areas are particularly crucial locations for the exchange of water and dissolved and particulate matter between land and sea, involving decisive forcings on local and regional physical and ecological processes. They are in fact home to a wide variety of complex biogeochemical mechanisms that remain poorly understood and whose study must involve chemical, physical and ecological approaches.

Arctic rivers, whose flow is tending to increase, are a potential source of nutrients for marine autotrophic organisms responsible for primary production at the surface of the Arctic Ocean. Ifrecent studies suggest that the fluvial inputs of inorganic nutrients are negligible at the pan-Arctic scale relative to inputs from the Atlantic and Pacific, and to those associated with vertical mixing, fluvial inputs could be a significant source of organic nutrients accessible to autotrophs and bacteria. Nevertheless, the importance of these inputs and the processes that make them available to microbial organisms (e.g. photoammonification) remain poorly understood. Moreover, the very large and growing quantities of organic carbon brought by rivers to the Arctic Ocean could support bacterial production such as to be a substantial source of CO_2 and a significant route of energy and matter input in the trophic chain. The capacity of heterotrophic organisms to consume organic compounds from melting permafrost and produce CO_2 by respiration remains to be assessed. The action of sunlight on dissolved and particulate organic matter, and the intermediate and volatile compounds produced (and in what quantities), must be estimated. Only an approach that combines process studies, observations (in situ, traditional and automated, and remote sensing) and modelling will determine the fate of organic matter of continental origin brought by rivers to the Arctic Ocean and its impact on marine ecosystems.

Estuaries also receive fluvial inputs of particulate organic matter that support a rich benthic fauna and are a burial site that provides a valuable record of the diagenesis of this material and clues about past environmental fluctuations.

• Sedimentation on margins and associated processes

Finally, sedimentation in the ocean is the mirror of terrestrial processes in the critical zone modulated by ocean dynamics and modulated by the estuarine filter. The interpretation of Arctic sedimentary series and the understanding of hydrocarbon formation requires taking into account the entire land-ocean continuum and, in particular, a better understanding and assessing of the estuarine filter. A special feature of the Arctic Ocean is that terrestrial inputs are relatively well confined as a result of its physiography. As a consequence, the sediments in Arctic margins are valuable records of the evolution of the watersheds and glaciers that supply them and of estuarine processes. There are few oceans in the world that preserve these continental influences. In particular, past climate crises from the Quaternary and Tertiary are recorded in the Artic ocean and the study of sediment cores is complements studies on land along climatic gradients. The use of molecular, mineralogical and isotopic proxies is expected to be very useful to address land-ocean interactions.

We emphasize the integrated nature of research on the land-ocean continuum. The terrestrial critical zone should be considered as a 'whole' so as not to separate the 'soil' compartment from the permafrost compartment, underground water, surface water, ecosystems, or exchanges of matter

Figure 8.2: The Liard river is tributary of the Mackenzie river. It transports the products of continental erosion towards the Arctic Ocean in the form of suspended particles, dissolved substances and organic matter. @ Jérôme Gaillardet

and energy between the surface and lower atmosphere. It is important to encourage research on the Arctic critical zone at all scales, from the plot level to the estuaries of major watersheds upon which the input of material to the ocean depends. Tracers and methods, whether geophysical, biological, geochemical or geomorphological, should be compared and combined with the spatial information. From this perspective, observatories for the Arctic environment must play a particularly important role in supporting research programs. Links with international initiatives, such as 'LTER' and 'Critical Zone', should be clear goals of the French community. Exploring estuarine areas and the land-ocean continuum in the Arctic Ocean also requires research infrastructure, which does not solely exist within the national community

Pollution: sources, cycles and impacts

Scientific objective

The Arctic is particularly sensitive to anthropogenic pollutants that can have deleterious effects on ecosystems, human health and climate. It is therefore important to improve the quantification of anthropogenic (and natural) sources of pollution, local and remote, and to better characterize the transformation processes and their impact on the physical environment (atmosphere, ocean, cryosphere, soil, lakes) and local populations in the Arctic region. Currently, a major challenge is to better understand human impacts related to economic development and Arctic warming.

Context

Pollutants (i.e. aerosols, ozone, heavy metals such as mercury, polycyclic aromatic hydrocarbons or PAHs, persistent organic pollutants or POPs) come mainly from industrialized countries to the south, carried by air and water currents. They can also be leached locally after being stored in the cryosphere and soil. Global warming and economic development in the Arctic may also foster new prospecting activities, including mining and oil and gas extraction, which are sources of anthropogenic emissions within the Arctic. Activities related to the steel industry and gas flaring (oil extraction) already represent important sources of sulfate and black carbon. The melting of Arctic sea ice also promotes the expansion of tour-ism and maritime traffic, including the opening of new shipping routes. This industrialization of the Arctic, and the associated development of infrastructure and urbanization, will lead to an increased level of pollutants and contaminants. Pollution will certainly have a local impact on health (the quality of air, water, soil and food resources), biodiversity and, at the larger scales, on ecosystems and climate. In addition, the risk of major accidents, related to the increasing exploitation of natural resources, the intensification of shipping and the storage of hazardous materials, is constantly increasing in this fragile region.

In the atmosphere, aerosols and trace species, such as tropospheric ozone, impact the climate in different ways: (i) They interact with solar and terrestrial radiation and thus generate a direct climate forcing (locally in the Arctic or following heat transport from the midlatitudes); and (ii) Aerosol deposition on the ice/snow and indirect interactions with clouds can change the albedo. Short-lived pollutants such as black carbon, ozone and methane may contribute up to two-thirds of the warming in the Arctic. Pollutants, emitted locally or transported from midlatitudes, may also alter the natural cycles of atmospheric compounds. These pollutants, even at low concentrations, may have an impact on air quality and health in urban and industrialized areas of the Arctic.

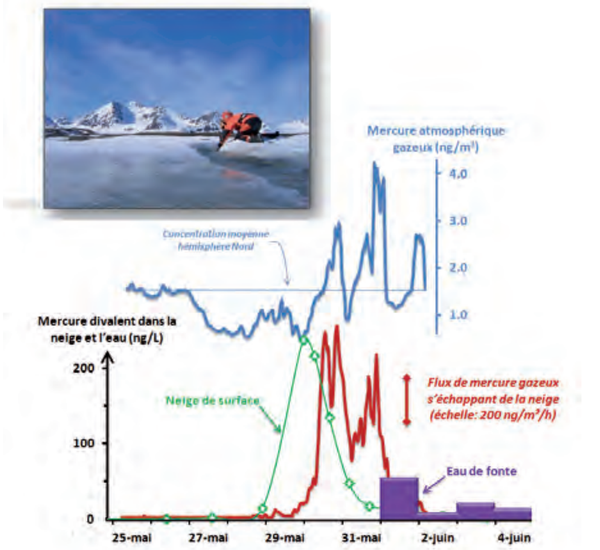


Figure 9.1: Concentrations of gaseous elemental mercury (blue) measured in ambient air at Ny-Alesund (Svalbard, Norway) showing the fast reactivity of this pollutant in the spring in the Arctic. These atmospheric phenomena ("Mercury Depletion Events") lead to a divalent mercury deposition on snow (in green) and then reemission into the atmosphere by photoreduction (red). A part of it remains in the snow and will be released via meltwater (purple) to the soil, rivers and oceans, representing one of the pathways of mercury into the ecosystems Modified from Dommergue et al., 2010. Credit photo: @X. Faïn

Pollutants such as heavy metals (e.g. mercury) and PAH/POPs are extremely persistent, especially in cold environments. This includes historical POPs such as certain pesticides (e.g. DDT and polychlorinated biphenyls/PCBs) and emerging ones such as perfluorinated compounds (PFCs) (e.g. Teflon). The simplicity of Arctic food webs makes them highly susceptible to the deleterious effects of these pollutants through biomagnification and bioaccumulation, particularly at the higher levels of food webs (fish, birds and mammals, including humans). It is therefore essential to assess both the magnitude of the disruption caused by pollutants and their ecological consequences in the context of functioning of Arctic ecosystems, including impacts on vegetation. Human societies integrated in such ecosystems are justifiably worried about these effects. 'Historical' pollutants such as heavy metals are well identified, but new compounds are constantly emerging, such as PAHs, even though their effects on organisms are still mostly unknown. This also applies to metabolites from primary pollutants and to pollutant cocktails for their synergistic and antagonistic effects. This lack of knowledge is particularly relevant to the effect of these stressors on the survival, movement and distribution of living organisms in the Arctic.

The increasing industrialization in the Arctic has led to changes in the natural and social environment (e.g. sedentation, population migration). Two major health risks arise from this situation. The most obvious health risks for Arctic peoples are cardiovascular and respiratory diseases, which are consequences of mining activities where people are exposed to pollutants and the health impacts of air and water pollution. The second risk is related to exposure to contaminants especially through food. Among Native hunters, fishermen and reindeer herders, animal protein and fat are a very large portion of the dietary intake. However, the species consumed by Native peoples such as whales, seals and birds of prey have high concentrations of persistent pollutants. To this is added mercury trapped in the snow that is absorbed by plants and animals during snowmelt; they are then eaten by local people. Food thus becomes a source of exposure to most contaminants by eating animals, berries and wild mushrooms. The health risk is highly correlated with lifestyle.

■ Detailed description of the objective and approach

• Detailed description of the objective

Characterize the local and distant sources of pollution in the Arctic

The nature of pollutants that reach the Arctic has changed and their trends remain rather poorly understood. Industrial activities in North America and Europe have been major sources of toxic heavy metals and aerosols (e.g. sulfate) in the Arctic since

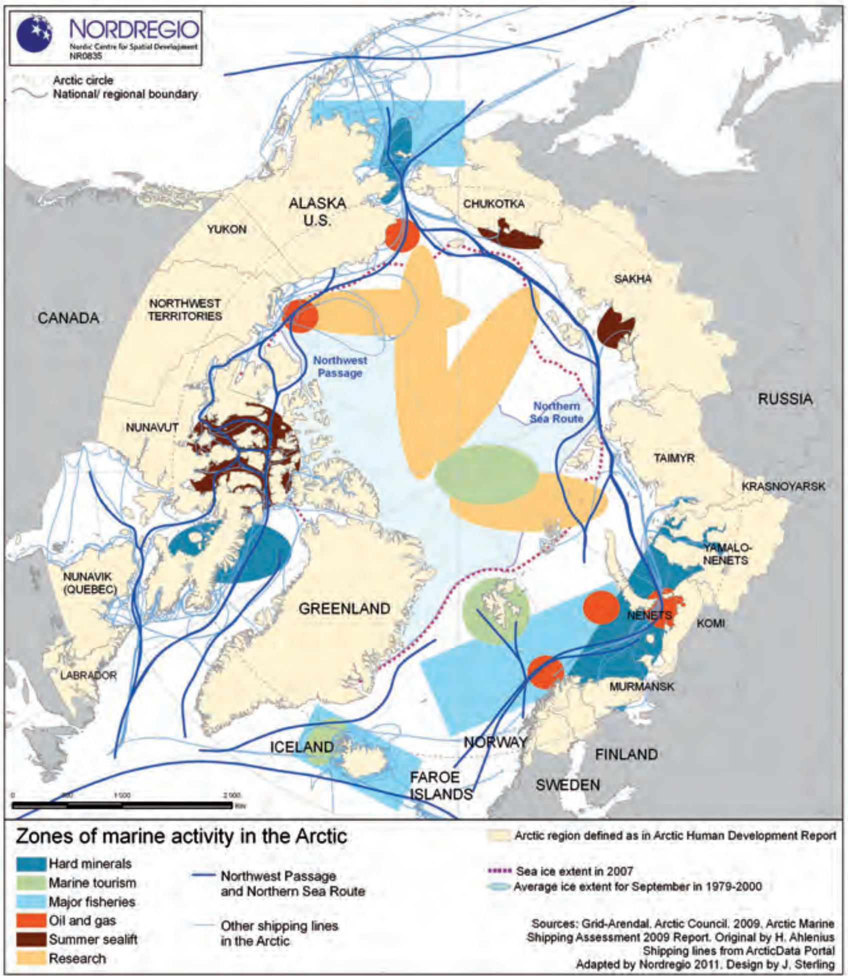


Figure 9.2: The map illustrates the complexity surrounding the future of the Arctic region, notably with respect to access to resources. It emphasises the areas where marine activity is particularly intense, i.e. the North Atlantic Ocean, the Barents Sea and along the coasts of northwest Russia. Map based on the 2009 Arctic Council Arctic Marine Shipping Assessment report with shipping lines taken from 2011 data on the Arcticdata Portal. After Arctic Council (2011).

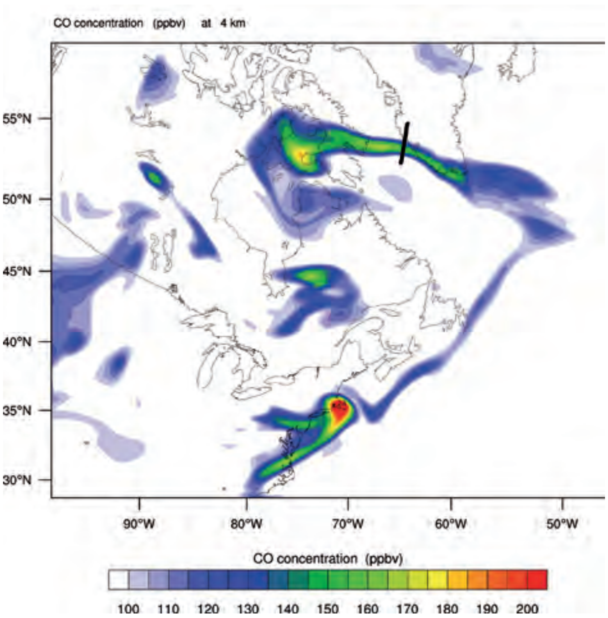
the 19th century, but with a recent downward trend. However, emissions in Asia have become growing sources of pollution in the Arctic due to the sustained economic development in that region. Past and present sources of pollutants, especially distant sources and their impact on the level of pollutants in the Arctic remain poorly characterized and quantified. A better estimate of anthropogenic sources is essential, especially in relation to natural emissions such as forest fires and oceanic emissions. The factors responsible for the variability of natural sources and their potential response to climate change also need to be clarified in order to improve model projections. The contribution of local sources of pollution, closely linked to industrialization and their future development, should also be better evaluated to establish, if necessary, priorities for emission reductions. It should be noted that local anthropogenic emissions could already be affecting atmospheric photochemistry and aerosol formation in parts of the Arctic.

Understanding the processes that determine the distribution and fate of pollutants

After emission far from the Arctic, many pollutants are transformed and recycled during their transport to the Arctic, both in the atmosphere and ocean. The physicochemical mechanisms and their interactions with transport processes are poorly understood, especially those at small-scales (e.g. pollution plumes). There are also uncertainties with regard to multiphase reactions and exchanges at interfaces between different physical environments (atmosphere, ocean, land, snow/ice). Furthermore, interactions between pollutant cycles and the natural system through physical, chemical and/or biological processes are still poorly understood. Finally, in synergy with laboratory studies and field campaigns, progress must also be made on modelling tools. Certain processes and features that control the distribution and fate of pollutants are poorly represented in models, including those that are specific to certain environments and those for processes operating at the interface between environments. Parameterizations need to be improved based on constraints from observations to correctly describe the feedbacks between different environments.

Evaluating the impact of atmospheric pollutants on climate, deposition and regional air quality

The impact of short-lived pollutants on climate is very difficult to assess, especially the indirect effects (such as those involving the interaction between aerosols and clouds or black carbon deposition and snow/ice albedo), which are particularly



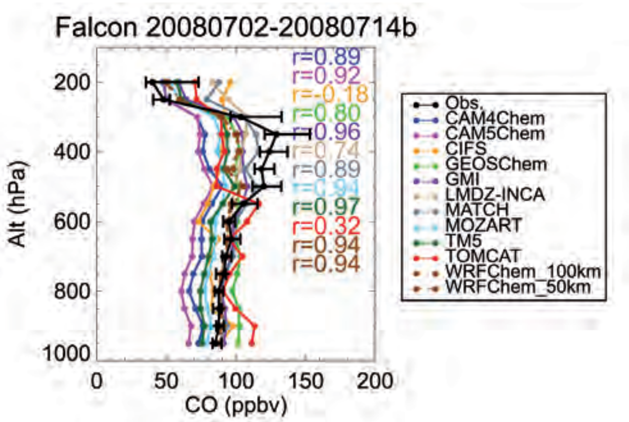


Figure 9.3: (left) Simulation with an atmospheric regional model of transport of pollution plumes from North America to Greenland during the summer, July 5, 2008 at an altitude of 4 km; plumes are indicated by the elevated concentrations of carbon monoxide (CO). These plumes, from anthropogenic sources and forest fires, were sampled by research aircraft, a French ATR-42 and a German DLR-Falcon, over the south of Greenland as part of POLARCAT. This pollution is a major source of ozone in the Arctic region. After Thomas et al., *2013.*
(right) Comparison of vertical CO profiles over Greenland in July 2008. Colored profiles correspond to those calculated by different atmospheric models in the POLMIP international project and the profile in black corresponds to average measurements obtained during the POLARCAT-GRACE campaign. The high values of CO concentrations in the mid and upper troposphere are due to anthropogenic pollution and forest fires from North America, Asia, and Siberia. The values of the correlation coefficient, r, between calculated and measured profiles are indicators of model accuracy. After Monks et al., *(2014), Atmos. Chem. Phys. Discuss., 14, 25281-25350, doi:10.5194/acpd-14-25281-2014.*

complex. Pollutants also affect air quality and human health at local and regional levels; however, the Arctic has been little studied compared to urban areas. Once again, assessing the impacts comes up against a limited understanding of the chemical environment (e.g. halogen chemistry) and dynamic environment (e.g. very stable boundary layer), which is very specific to the Arctic atmosphere. Deposition of local air pollutants can also affect acidification in some regions but these effects remain largely unknown. The quantification of impacts requires targeted field campaigns and greatly improved representations of relevant processes and feedbacks in atmospheric models.

Quantifying the impact of toxic pollutants on organisms and ecosystems

This research objective will be addressed in a bio-geographical context, with strong recognition of species' spatial ecology. In the case of vertebrates (fish, mammals and birds), population dynamics and movements can be followed throughout the annual cycle by using new advances in genetics, isotopic analyses and biotelemetry. This will allow comparison of the pathology and ecotoxicology of Arctic resident species and migratory species. Emphasis will also be placed on the evolutionary response of organisms to these various constraints, old and new, through phenotypic plasticity and micro-evolutionary processes. This will lead to an overall picture of the actual impact of these threats on Arctic organisms and ecosystems, as well as suggestions for scenarios of future dynamics.

Evaluating the impacts associated with the exploitation of natural resources

Industrial activity, related to the extraction of natural resources such as oil, gas and metal ores, is already a source of pollution in many parts of the Arctic, such as northern Alaska and Russia. Regional and global economic factors, coupled with climate change, will lead to the opening of new areas for exploration and exploitation (e.g. northern Greenland), although the Arctic environment is particularly difficult for these activities. Arctic warming may bring new industrial opportunities by facilitating access by sea, for example, but could also make ground transportation and construction much harder due to soil compaction related to thawing permafrost. The waste and risks associated with industrial activities and associated infrastructure must be assessed along with their possible impacts on marine/terrestrial ecosystems and local communities. These risks also include the possibility of oil spills from exploration wells or during transport (pipelines, tankers). Air, water and soil pollution accidents from gas platforms, mining and other industrial activities also need to be considered and the potential impacts estimated.

What is the impact of pollutants on human health and fauna?

We cannot today separate Arctic pollution from the exploitation of the environment by native peoples for food. Public health surveys indicate that mercury levels in the blood of adults are high and that breast milk contains organic pollutants. A key issue is to understand the impact of contaminants and their effects on human health in the Arctic. Epidemiological studies are essential to move forward on this topic. Linked to this issue is the question of the diet of local populations, who are major consumers of game, fish, birds and plants often already contaminated, not to mention the emergence of new diseases, such as in Siberia. What food choices are made and what are the health consequences? What is the impact of new eating habits? Can we identify emerging diseases in humans and animals?

The issue of Native food practices is a highly emotional issue (preferred topic of discussion), with strong social resonance (ritual exchanges of pieces of meat) and strong religious connotations (belief in animal 'souls'). Studies show that consumption of local products, in connection with physical and mental health, is a topic of conversation preferably addressed in the local language rather than in a second language. We must therefore develop, for researchers, training in Native languages because, on the one hand, many Native languages have very elaborate vocabularies related to the body, food and well-being as well as for malaise (recently altered taste of certain wild meat, harmful effects of local and imported foods, etc.) and because, on the other hand, our ways of conceptualizing reality, and therefore our language usage, are not necessarily those of the other and vice versa. We still have to address how Native peoples individually and collectively conceptualize health in the context of pollution that is expected to worsen.

• Method of approach

Answering these questions will involve a very wide range of methodological and disciplinary skills, and physicochemical and/or ecotoxicological measurements in different physical environments (atmosphere, ocean, glaciers, rivers and soils). This theme would also benefit from being faced with local knowledge and using analysis instruments from environmental and social sciences. The heuristic value of this approach rests on the conviction that fundamental issues are analysed differently by everyone. The benefit of a complementary approach must be understood to help inform decision-making to deal with complex issues such as climate change.

Existing data on the nature and level of pollutants, including historical surface data and ice cores, already contain important information about the evolution of sources and pollutant transformations. The collection and study of new observations as part of targeted campaigns on the ground and by air/balloon/drones, observation networks (e.g. ground, buoys) and satellite missions, will certainly be needed to better characterize the environment and processes as well as to improve the description of processes in models at the local, regional and global scale. The combined analysis of observational data and modelling should allow certain scientific questions to be answered and the pollutant impacts to be more accurately evaluated.

From an ecotoxicological point of view, new methods of analysis will help to identify a large number of potentially toxic compounds and test the ‘cocktail’ effect on the ecology and evolution of living organisms, as well as on interactions between organisms in ecosystems. The latest developments in biotelemetry and robotics will help to automatically identify and locate animals, at population and meta-population scales. These advances in biotelemetry, as well as in isotopic and genetic analyses, will enable an integrated study of the impact and response of Arctic biodiversity to pollutants over space and time. It also seems essential to better integrate the various disciplines (e.g. ecotoxicology and pathology of organisms) requiring a bio-geographical approach, ideally covering the entire Arctic. In this case, the logistics for sampling pollutant levels must be sufficiently light to be deployed over large areas.

To better understand the impacts of contaminants and pollutants on human health, epidemiological studies should be undertaken in collaboration with local people. Taking an interest in Native knowledge also offers the opportunity to consider a set of concerns such as risk assessment, vulnerability, predictability/unpredictability, the degree of control over nature, interventionism/wait-and-see, space (the land) and time (the perception of the future).

Geographic areas: There may be advantages and synergistic effects by focussing on specific areas to address related issues raised in several research areas. For example, human activities are already significant in parts of northern Siberia, Alaska and northern Canada where they can affect human health, ecosystems and even climate. Interactions between pollutants and the natural environment could also be addressed by focusing on areas where marine life is most exposed to pollution (e.g. Barents Sea/Norway, Kara Sea, Bering Straits) and/or where local communities may be affected by increasing industrial activity (e.g. Siberia, Canada). It will be important to consider studies in different seasons with, if possible, multi-annual monitoring.

Sustainable development in the Arctic region: impacts, implementation and governance

Scientific objective

The research objective is to assess the impact of economic activities in different sectors (ports, land and sea transport, extraction of mineral resources and hydrocarbons) on the environment (such as pollution) and on societies (social, health and cultural impacts) on a fine scale (community, city, tourist and industrial ports, mining site) and globally (shipping routes, possible extension of fishing activities to the high seas). The study includes social, environmental, legal, political and health components. It will contribute to the quality of life index and the analysis of governance mechanisms defined as the process of cooperation and accommodation by which individuals and institutions, public and private, manage their common affairs (Commission on Global Governance, 1995) to produce results in terms of strategic options (scenarios) presented to policy makers.

Context

The magnitude of climate change in the Arctic and the melting of sea ice, the price of raw materials and changes in the socio-economic contexts of Arctic countries are all factors (re) stimulating economic development in energy (acceleration of extraction and exploration of mineral and oil resources), transportation, fisheries, shipping and tourism sectors.

In recent years, maritime activity in the Arctic Ocean has been increasing whether it is local traffic or the use of sea routes: the Northwest Passage, but currently mainly the Northeast Passage. Meanwhile, marine tourism grows in the Arctic where cruise ships are increasingly likely to visit areas seldom mapped and with inadequate safety.

This growth raises manifold questions: economic, social and cultural (employment, education, preservation of Native cultures, new identities, migration flow, etc.) and environmental (terrestrial and marine ecosystems) particularly as the intensification of human activities is expected to function as a positive feedback for warming (e.g. creation of new sources of pollutant emissions with industrial development). Lastly, economic development raises questions in terms of food safety and public health (emission of pollutants in terrestrial, marine and fluvial environments, wildlife disturbance, new working conditions).

The Arctic region consists of highly differentiated demographic and economic areas. While some regions are based on a subsistence economy or reindeer herding farming, others have developed a mixed economy and some areas are highly industrialized. Some territories are becoming depopulated (between 1989 and 2002, the population of Chukotka decreased by 70%) whereas other areas have a positive net migration. Often associated with the boundary of the ecumene, the Arctic seems the antithesis of that which is urban, yet city growth is continuing at high latitudes and this creates new continental and littoral areas (e.g. the cities of Western Siberia since the 1960s, Fermont, Canada, etc.).

Figure 10.1: Oceanographic icebreakers survey the Arctic and, with increasing frequency, cross the Northwest Passage. @Martin Fortier

Furthermore, Arctic ecosystems are characterized by high fragility. Economic development related to the increase in port activities, transportation, mining and oil activities has an important impact on the natural environment (land, air, sea) and on societies in the Arctic, which must be assessed. The objective of sustainable development promoted by the Arctic Council, whose guiding principles are set out in international law, raises definitional issues (indicators, social representations and legal systems) and implementation in the specific context of the Arctic.

Figure 10.2: The community of Pond Inlet on the northern tip of Baffin Island, overlooking the majestic Bylot Island, Nunavut. @Martin Fortier

The expected changes and their impacts in the Arctic are indeed not sufficiently understood. However, the region has its own peculiarities that impede any attempts at transferring knowledge from elsewhere. For example, climate interannual variability with long periods under the freezing point, the dominant role of the cryosphere, rapid urbanization (people of southern Eurasia in industrial cities of northern Siberia, Thai emigration to Kiruna, sub-Saharan emigration to Hammerfest, etc.), low infrastructure development, as well as the isolation of nomadic and rural populations and its consequences in terms of access to education and information.

The increasing complexity of stakeholder interactions in this heterogeneous region where legislation is fragmented thus make the governance of sustainable development a major research issue in the Arctic region.

Detailed description of the objective and approach

This research objective has a multidisciplinary character that combines the expertise of several disciplines such as political science, law, geography, biology, ecology, marine and atmospheric chemistry, climatology, and health, etc. The research objective, described as four sub-objectives, is based mainly on the identification and testing of indicators and the development of governance scenarios.

• To consider the social and environmental impact of economic development linked to the exploitation of natural resources on populations, the level of air/marine pollution and ecosystems

The Arctic population has diversified significantly: Native peoples make up 10% of the total population of the Arctic, urban areas are growing and non-resident populations are sought by industry. The exploitation of natural resources (mining, on-shore and off-shore oil drilling, fishing), which in some cases acts as a driver of urbanization, induces differentiated impacts depending on the populations and changes the social and economic balances. The exploitation of natural resources on-shore and off-shore alters ecosystem balances, produces pollutants that impact the level of marine, water and air pollution, and can alter the natural environment in an enduring manner (e.g. construction of infrastructure). Moreover, the governance mechanisms, which are also exercised in heterogeneous territorial levels (local, territorial, national, supranational) are not always clearly identified (consistent levels of government, state responsibilities, national and territorial policies, international forums, public and private actors, weight of opinion in setting standards, conducting impact studies, etc.). The regulatory framework, in particular, may be patchy or inadequate. The development of predictive scenarios (scenarios for economic and social development, pollutant emissions) taking into account the networks of stakeholders (governance scenarios) is a key dimension of this research objective.

• Assess the social and environmental impact of economic development associated with the use of maritime routes

With the melting of the ice pack, the Arctic maritime routes open to navigation: the Northwest Passage and, mainly in recent years, the Northeast Passage have experienced an increase in activity. The frequency of commercial use of these routes over the medium term and especially over the long term, however, is not clear, whether for the transportation of raw materials, goods, or tourism purposes. The use of Arctic maritime routes increases the risk of major pollution related to the use of heavy fuel and generates local emissions of pollutants such as fine particles that must be assessed. Ecological forcing factors related to global changes should also be identified and quantified as well as the risks to the environment in terms of marine, river, land and air pollution, especially when new port facilities are being considered. The development of navigation in the Arctic is a challenge for the adaptation of governance mechanisms and the regulatory framework: UNCLOS, Polar Code, MARPOL, etc. Stakeholder networks are diverse and include, in particular, international forums such as the Arctic Council or the states of Southeast Asia. The development of predictive scenarios (economic and social development, pollutant emissions) taking into account the stakeholder networks (governance scenarios) is a key dimension of this research objective.

• Analysis of the impact of social and environmental changes on health and food security

The prevalence of chronic diseases in Arctic communities (tuberculosis, diabetes, lung cancer, etc.), the prevalence of mental health problems as well as food security (access to preferred, sufficient and healthy food) are becoming a major public health issue. The cumulative effects of rapid changes due to colonization and the complex interaction of social and economic factors have been put forward to explain the high rate of mental health problems in Arctic communities. It is therefore essential to assess the potential impact of changes brought about by economic development. Furthermore certain animal populations, terrestrial, marine and fluvial, which are the staple diet of the communities, are becoming scarce as a result of human pressure (climate change, habitat loss, increased hunting pressure, etc.). Accessibility to wildlife can be reduced by national quotas, or consumption of some species may be inadvisable because of their pollutant content. Indicators measuring water quality and accessibility of food, for terrestrial and aquatic environments, have been developed; their validity should be tested. Similarly, the potential of these indicators to operate in diverse Arctic contexts should be identified, to enable the measurement of risk in terms of health and food safety. It is also important to define specific indicators for the context of new economic activities, as in the case of the mining and oil industries that use night work and rotation (transit and shift workers) that generate new pathologies. In this context, the analysis of existing governance mechanisms should take into account the role of different stakeholders, health policies, social policies, education, training of social workers and health professionals, and assess to what extent Native concepts of health and social work are considered. Given the public health and environmental challenges, efforts should also focus on the analysis of the adaptation of environmental impact studies, the regulatory framework and communities' access to information. The findings could enable the development of predictive scenarios of health and safety governance.

• Define, assess and characterize sustainable development in the Arctic

Sustainable development, whose definition in the Brundtland Report (World Commission on Environment and Development, 1987) is closely associated with the concept of the preservation of the environment, has various definitions and falls within different national and international legal systems. The vulnerability of Arctic ecosystems and the relationship between Native communities and the environment require special attention in the concept of sustainable development whereas the current conditions favour the extension of economic, particularly industrial, activities in the Arctic. The comparison of the legal systems for sustainable development is a key dimension of this research objective. This objective includes other issues such as the consideration of representations of the environment in Arctic communities in the definition and implementation of sustainable development. It is also important to determine the conditions for the implementation of the guiding principles of sustainable development and how to determine appropriate indicators for the human and environmental features of the Arctic region. To what extent do immigration and demographic changes (aging or rejuvenation of populations) impact local sustainable development? How to assess the degree of adaptation of economic, social and cultural programs to the purpose and principles of sustainable development in the Arctic? Which governance scenarios can be developed and on what geographical scale relevant to the legal, economic, social and environmental framework?

Observations and modelling

Observations

Observations and scientific themes

Based on the presentations made at the 'Arctic Initiative' conference on June 3, 4 and 5, 2013, at the College of France *(Collège de France)* and on June 6, 2013 at the Oceanographic Institute in Paris *(Institut Océanographique à Paris)*, we made a summary of the observation activities by French researchers in the Arctic by creating a comprehensive review of past activities and future prospects for enhancing the strengths, working on the weaknesses and developing a better coordination of all these activities. This concerns all of the themes of the science plan conference.

In the theme on climate and ocean-atmosphere interactions, there is a strong interest in observations concerning processes in the polar stratosphere in the spring and summer and the temperature evolution of the stratosphere, extreme events (FrIACs) related to the breakup of the Arctic polar vortex and the evolution of stratospheric chemistry. There is also a strong interest in clouds and aerosols, atmospheric circulation and polar lows. In the context of the ocean, there is also large-scale circulation and exchange with the North Atlantic Ocean and the North Pacific Ocean, the production of dense water (brine) in polynas, convective double diffusion in the thermocline, internal waves and the (weak) turbulence in the Arctic that could, with the retreat of the ice, increase and accelerate vertical mixing, acidification linked to the melting of the ice pack and an increase in the partial pressure of CO_2 in the ocean, ocean dynamics in the marginal ice zone (MIZ) associated with the phytoplankton bloom. Process studies related to snow and sea ice are also of great interest to the community. Innovative activities include the study of the rheology of sea ice using seismic records in northern Greenland and the comparison of ice thickness measurements from upward-looking sonar (ULS), for the submerged part of the ice, and satellite altimeters (CryoSat), for the pack ice above the water surface, as well as from microwave radiometry for thinner ice. Continental ice is addressed with climate change sensitivity studies for the Greenland ice cap on the centennial time scale, the Barnes ice cap (Baffin Island) and Lovenbreen glacier in Spitsbergen as well as studies of outflow glacier - fjord interactions in Greenland.

The French scientific community is heavily involved in the Arctic in ecosystem observation studies, particularly for marine environments. These include both long-term monitoring of animal populations and using the ecology of the macrofauna as a proxy for climate change, and laboratory studies of the effects of environmental variables on the metabolism of phytoplankton and the genomics of microbial plankton (zooplankton). French researchers are very interested in transdisciplinary studies for observing marine and terrestrial ecosystems (microbiology and the carbon cycle, birds and pollution, phytoplankton and sea ice).

With regard to anthropization and its impact, there are several projects studying the impact in the Arctic of distant pollution sources (POLARCAT and CLIMSLP) and also local sources of pollution in the Arctic, particularly related to maritime transport, fishing, and oil and gas exploitation (ACCESS Arctic Climate Change and its impact on Economy and Society), and to boreal forest fires (YAK-AEROSIB). This also applies to the study of pollution and agricultural meadows in the Arctic (MEADOWARM project), the study of geochemical cycling of metals during mining, destruction of the ozone layer in the Arctic over the past 20 years and the origin of high concentrations of methyl mercury in Arctic marine ecosystems.

For permafrost, there are two major programs coordinated by French researchers in Siberia representing about ten groups and involving 3 CNRS departments (INSU-InEE-INSHS):

- GDRI 'CAR-WET-SIB' (2008-2011, 2014-2017) for impact studies of permafrost degradation, water fluxes, chemical and physical weathering processes, the decomposition of soil organic matter and fluxes of carbon and other chemical elements including metals between the main reservoirs (atmosphere, vegetation, deep aquifers, rivers, etc.) ;
- YAK-AEROSIB for airborne measurements of greenhouse gas emissions in Siberia and along the Arctic Ocean. Permanent ground measurements of CO_2 and CH_4 from a tower in a region of Siberian wetlands will gradually complete this system.

Siberia has huge stocks of carbon (320 GtC) and its regional greenhouse gas fluxes (in particular CO_2 and CH_4) also play an important role in the global budget of GHGs but with great uncertainty. The creation of UMI Takuvik at Université Laval in Quebec City also provides an excellent base for the study of permafrost with access to the Canadian Arctic and the host university's scientific bases. These bases are instrumented and the deployment of instrumented networks for studying the evolution of the permafrost thermal regime, including by quantifying vegetation-permafrost-snow feedbacks, is underway by Takuvik.

French researchers contribute significantly to the acquisition of data at sites monitored by our Siberian colleagues (islands on the Lena upstream of Yakutsk, Mukrino bog, Tura forest ecosystem, region of thermokarst lakes near Yakutsk). These sites are monitored in terms of measurements (e.g. river flow, erosion monitoring and debacles, changes in the depth of thawed soil during the active period, changes in biomass, etc.) and in terms of the collection of samples (water, suspended matter, vegetation, etc.). A network of catchments located on a north-south transect (sporadic permafrost to continuous permafrost) is also monitored in terms of hydrology and hydrochemistry. The instrumentation of these basins can help to address the future of basins with continuous permafrost in the context of profound climate change ('substitution of time by space' approach).

Regarding geodynamics and the exploitation of natural resources in the Arctic, French researchers focus their activities on two main issues. The first concerns the Icelandic Rift and studying active fractures on the Mid-Atlantic Ridge. The second concerns the Arctic margins, which are a major scientific and industrial issue. What is the role of the hydrocarbon sector in the Arctic? Tectonic/climate interactions are also addressed with an Arctic geodynamic study of the Palaeogene.

This leads us to the palaeo component of Arctic research by French researchers. These studies include the following: the Miocene climatic optimum and the opening of the Fram Strait, Greenland in the last interglacial, the information contained in Greenland lakes, ablation of the polar ice caps during the last glacial cycle, the palaeoclimatic and palaeo-oceanographic history of the Arctic, advection of Atlantic water in the Nordic Seas during the Holocene, the physicochemical parameters of surface waters in the Beaufort Sea over the past 1500 years, variability of the regimes of boreal fires and, more generally, changes in the composition of the boreal atmosphere over the last 1,000 years. We also mention the European CASE project, which is coordinated by French researchers. Isotopic measurements are also used to better understand atmospheric and oceanic processes and the water cycle in the present and past.

Part of the French scientific community is also interested in the scientific approach to Native populations, focusing on the analysis of vulnerability, adaptation and resilience to climate change (ANR – BRISK) and research on Arctic Native knowledge related to the living environment, in recent times and the past. The International Human-Environment Observatory *(observatoire hommes – milieux international*; OHMI) has been set up in Nunavik as part of LabEx DRIIHM. It aims to assess the environmental and societal impacts of climate change and mining through an integrated and participatory approach.

■ Observations and instrumentation

We cannot discuss Arctic observations without introducing a section on infrastructure in general, instrumented platforms in particular, whether they are in situ, airborne or satellite borne. French researchers are very innovative in this area and have very high-quality and diverse instruments that must, however, be expanded to reach the critical mass needed to meet ambitious and important goals given the challenges posed by the Arctic.

The French community is in a unique position that is often complementary to other countries. It is very important to distinguish fieldwork that is conducted either at very specialized sites (super sites), 'zones ateliers' at the regional scale, and large-scale networks (pan Arctic).

• Super sites for measurements, 'zones ateliers' and observation networks

A super site is an advanced highly instrumented station in the Arctic where the measurements are made continuously and more or less autonomously. A typical example is the Ny Alesund base in Svalbard. For the moment, all of these 'super site' stations are on land. They are no longer in the central Arctic Basin or on the continental shelves at the edge of the Arctic since the closing of the stations that were installed on islands of drifting ice, which consisted of detached pieces of the disappearing Arctic ice platforms. Several new super sites are in development and it is important to encourage French researchers to benefit from these developments (e.g. Station Nord in Greenland, Cambridge Bay in Canada, Tiksi and Tomsk and the Yakutsk region in Siberia, etc.).

A 'zone atelier' brings together researchers around interdisciplinary environmental issues in connection with anthroposystems (12 'zones ateliers' are identified by CNRS,

http://www.cnrs.fr/inee/outils/za_5.htm) in a region suitable for the development of integrated pluridisciplinary activities and in a strongly regional context, which is favourable to the coherent development of diverse activities. Typical examples are SIOS in Svalbard and the Siberian site under development in Yakutia. It is very important to encourage French researchers who are already involved in these projects that promote the type of multidisciplinary research the Arctic Initiative would like to foster.

Observation networks cover very large spatial scales up to the pan-Arctic scale. They usually operate autonomously and automatically with the transmission of data in real time and allow the monitoring of large-scale phenomena. Networks are usually very specialized. In the context of climate change, which is especially strong in the Arctic, the development of these networks and the participation of French researchers who are already heavily involved in these developments should be encouraged.

• Airborne and in situ instrumented platforms

For the atmosphere, there are airborne instruments such as the RALI radar-lidar and microphysical instruments (developed by LAMP) for the study of clouds and aerosols. These instruments can be deployed on French research aircraft (SAFIRE's ATR and Falcon) and the novel microphysical instruments are often requested for European aircraft (English, German). French aircraft were also used during POLARCAT to better understand pollutant transport in the Arctic. There was, and there is, an important activity involving instrumented stratospheric balloons to measure aerosols and ozone as well as the transport of tropical air masses to the Arctic. There are also the SAOZ UV-visible spectrometers of the NDACC-France network that have measured integrated ozone and nitrogen dioxide in the Arctic for about the last twenty years.

The IAOOS platform is part of an Equipex project to carry out, over long time periods (a few years) and autonomously, almost simultaneous profiles in the atmosphere (lidar), ocean (ARGO float) and ice (IMB) using instruments in a network of 15 buoys drifting across the Arctic Ocean. Biogeochemical sensors are being tested on Arctic ARGO floats within the Equipex IAOOS and NAOS projects. The Optimism project (ANR) has allowed the development of techniques (Ice T) for the measurement of the energy balance and air-ice-sea fluxes.

Figure 11.1: SAFIRE Falcon 20 in flight. Dedicated to environmental research, SAFIRE planes feature remote sensing instruments to validate the measurements made by satellites. They can also prepare space missions. @SAFIRE

The European ACOBAR project has enabled French scientists to develop techniques for using unmanned underwater vehicles (gliders) in the Arctic under the ice. The first French and European glider (the Sea Explorer) was developed by ACSA (Aix en Provence) and will be implemented during the summer of 2014 in the Barents Sea in the framework of the European ACCESS project.

Finally Equipex CLIMCOR provides the national glaciological community with the latest equipment for coring, drilling and logging, which is an important contribution from France to international drilling projects, particularly in Greenland. Equipex will also enable a significant improvement in the drilling capabilities of the Marion Dufresne, likely to be deployed in the future on the margins of the Arctic basin. Finally CLIMCOR provides, for the first time, the community studying palaeoclimates based on continental archives with new drilling tools capable of handling complex sediments (e.g. succession of organic layers and sand).

• Satellite remote sensing

Observations by satellites orbiting the Earth have a prominent place in Arctic observation systems. Indeed observations from space make it possible to observe globally and complement ground and sea observations, which are still insufficiently sampled. Satellite data are used increasingly for process studies and assimilation into models.

We can identify several areas of interest amongst French researchers: the atmosphere (dynamics and chemistry), clouds and aerosols, sea ice, biogeochemistry and biological productivity in the Arctic Ocean, wetlands in Siberia, ice caps (Greenland in particular), sea level, ocean dynamics. In this context, the following should be mentioned:

- Satellite observation of the extent and concentration (microwave radiometers), freeboard (altimeter to deduce the thickness), movement (SAR) and age (scatterometer) of sea ice;
- Satellite imagery for the characterization of ice cover;
- The interaction between aerosols and clouds in the Arctic;
- Observations of liquid clouds in the Arctic;
- Observations of Siberian wetlands;
- Estimates of primary production in the Arctic;
- Observation of variations in sea level in the Arctic;
- Altimetry for the characterization of ocean circulation;
- Observations of the Greenland ice cap and of the mass balance and European Ice2Sea project.

For this research, the community uses data from satellites such as Cryosat, A–Train, Calipso, Cloudsat, Modis, SMOS, MSG, MeTOP and the IASI instrument. We must not forget, in the coming years, SENTINEL as part of ESA's COPERNICUS program and also Merlin, OCO and SWOT.

■ Arctic observation data bases

In France, there are bases, centres and 'pôles' for data dedicated to the atmosphere (Ether /ICARE), the ocean (CORIOLIS for in situ data), SALP for altimetry, CADTS for soil moisture and salinity (SMOS), and remote sensing (CERSAT) complementing international data centres (NODC for the ocean, NSIDC for ice, etc.). These data centres include data for all satellites in which France is closely involved and also data from observation services. In France, within the framework of 'pôles' for data for the ocean, atmosphere, surface and solid Earth, it will be necessary to take into account the inter centre/'pôle' dimension and consider special visibility for data on the Arctic. This could take the form of a data portal that would build on initiatives under construction (e.g. Labex-IPSL, Centre Franco-Sibérien).

■ Highly transdisciplinary and cross-sectoral observation activities

We have already pointed out several strongly transdisciplinary projects such as the Centre Franco-Sibérien for the study of the environment, climate and continental biosphere in the Arctic (Siberia), tectonic and climate interactions for a geodynamics study of the Arctic Palaeogene, and cross-sectoral activities such as the European ACCESS project. We can add, in this context, interactions among the climate, environment and human activities in Greenland (Greenland green), biomonitoring of coastal water quality in the Arctic (ARTISTICC project) and changes in the river-talik continuum in the boreal environment.

Integration amongst disciplines and work at interfaces

ANR CLASSIQUE *(CLimat, Agriculture et Société SIbérienne – QUelle Evolution?*, Climate, Agriculture and Siberian Society – What Evolution?) involves 6 laboratories. This project aims to understand the impacts of climate change on the environment and Siberian society and the feedbacks in a pioneering effort to cross the natural sciences and the humanities and social sciences.

L'ANR BRISK (Linking the Scientific Knowledge on Arctic Change to That of Native peoples: Vulnerability and Adaptation of Societies and the Environment) involves 7 laboratories. It develops interdisciplinary and transdisciplinary, cutting edge methodologies to establish synergies between science and Native knowledge on climate and global change in the Arctic.

The GDR 3062 'Polar Mutations' *(Mutations Polaires)* created on January 1, 2007, falls under sections 39, 31 and 38 of CNRS. This GDR consists of about 60 researchers from InSHS, InEE and INSU. The program focuses on two activities involving the social sciences ('Avativut' program = 'that which surrounds us') and environmental science (current effects of climate change).

■ Infrastructure and logistics (icebreakers, planes, fixed and drifting stations)

France has two aircraft plus a third plane in the context of a Franco-Russian cooperation that have been used for expeditions in the Arctic. There is also strong expertise in the field of balloons deployed at high latitudes.

France is the only major European country not to have an icebreaker ship. However, one can note the remarkable work of French researchers on board foreign icebreakers such as the Polarstern (Germany), the Amundsen (Canada), the Xuelong (China), the KV Svalbard and the Lance (Norway).

The only perennial infrastructure that France has in the Arctic is the Corbel station and the Franco-German AWIPEV base located at Ny Alesund. Note also the excellent involvement of French researchers in Siberia (Tomsk, Yakutsk and islands on the Lena), in Greenland in partnership with local researchers, and Takuvik in Canada, which is the new international UMR recently established by INSU in Quebec.

French expertise has been demonstrated by carrying out perennial and autonomous observation systems allowing, for example, the extension to the Arctic of the concept of the ARGO planetary system (3000 floats) as part of the Equipex IAOOS and NAOS projetcs. We underline the development of the first European glider (submarine drone) by a French company (ACSA), which now joins the exclusive club of glider designers at the global scale, which had previously only included Americans.

The use of sensors and robotic tools will broaden the fields of observation very significantly. The use and development of airborne drones in France could be considered for measurements of trace species, aerosols and/or the radiation balance. Specifically, the widespread use of 'biologging' tools (e.g. GPS, geolocators) will lead to monitoring the movements of Arctic wildlife throughout the species' habitats and their life cycles, at the scale of ecological communities. This information will complement existing knowledge on the spatial ecology of species and feed models to predict their future distribution areas. In terms of robotics, the latest generation of drones and underwater robots will explore and study the most difficult to reach areas and the most cryptic species. These tools do not replace more conventional observation systems, on land and at sea, but will strengthen existing approaches.

It is therefore necessary to maintain and encourage research activities around Arctic bases that are already instrumented and willing to host new experiments (e.g. AWIPEV, TIKSI, EUREKA) but also to support the development of observation networks with wider spatial coverage on the pan-Arctic scale (e.g. IAOOS, ICOS). It is also necessary to encourage instrumented sites at the regional scale, such as the Centre Franco-Sibérien of Central, Western and Eastern Siberia, to allow documenting various geomorphological, hydrological, bio-geophysical and atmospheric variables relevant to the watershed scale.

■ National and international context of Arctic observations

Equipex, Labex and ANR (national). As we have noted, many Arctic projects have received substantial support from ANR and also from *the Grand Emprunt*, particularly with three Equipex (IAOOS, NAOS and CLIMCOR) of which IAOOS is entirely dedicated to the Arctic.

SAON international network. The SAON (Sustainable Arctic Observing Network) Task Force supported by the Arctic Council provides coordination of experimental projects in the Arctic and a backup of the main results collected by the international scientific community. It is important that French researchers are represented in the SAON network

European Projects (Horizon 2020). The first calls for proposals for Horizon 2020 have been launched. There are several with regard to the Arctic in particular.

Projects of opportunity (Tara). The polar schooner Tara completed two remarkable Arctic missions for French and international research. The first mission was carried out in the framework of the International Polar Year and in close liaison with the European DAMOCLES project. On this occasion, an exceptional Arctic transpolar drift for 500 days (from September 2006 to January 2008) from the Laptev Sea to the Fram Strait attracted considerable attention. It follows the legacy of Nansen's historic drift conducted from 1893 to 1896. Many scientific papers attest to the success of this extraordinary mission. A 2nd mission, after more than six months, just ended in December 2013 after leaving Lorient in May 2013. It was a peri-Arctic cruise for collecting biological samples for a study of the phytoplankton genome in the Arctic, and it was a project similar to that of Tara Oceans, which for 3 years travelled all the oceans of the globe. This study was funded by ANR GENOMICS. A new Tara transpolar drift is under consideration for the 2017-2018 horizon.

Networks (consortium). ECRA (European Climate Research Alliance) is a European consortium of laboratories and institutions concerned with aspects of climate change that have a strong impact on the Arctic. CNRS (INSU) is a partner in the consortium.

IPY, YOPP (Year Of Polar Prediction) international programs. The International Polar Year (IPY), which took place from 2007 to 2008, brought together the scientific community on key themes in the Arctic. It is vital not to wait for the next IPY (in 25 or 50 years) to repeat the experience. This is why the concept is

Figure 11.2: Ny-Ålesund, an international scientific village, located northwest of the island of Spitsbergen, where IPEV has research facilities. @AWIPEV

developing of a new Polar Year (YOPP: Year Of Polar Prediction) before the end of this decade supported by the WMO.

■ Summary

All the disciplinary areas in which French researchers participate in the Arctic involve studying processes through observations, which requires support for basic research activities. There are still many things to discover in the Arctic. For each study, a methodological approach with 3 points must be respected: 1/ identify the observable parameters, 2/ define the spatial and temporal scales for sampling observations and 3/ describe the observation zones/ sites or networks.

Strong links between observations and modelling should be clearly established and are a characteristic strength of the French community. This can involve the intercomparison of model results with data analyses. It can also involve assimilating data in models. It can include initializing, configuring and forcing a model from the results of observations. A model can also be used to better define the sampling strategy for observations. The diversity of models and observations does not allow rigid rules and recipes.

In situ, space-based and airborne observations are a strength of the French scientific community. Considerable innovation is seen in the development of aerial drones and AUVs, floats and balloons, and tools for drilling/coring/logging. This bodes well for the future; however, we must strengthen the organization and coordination of these activities, which have a cost, with the perspective of assuring that the activities undertaken are scientifically profitable. All of these activities require the deployment of networks of large numbers of instruments, in difficult conditions, with complicated logistics and for very long durations. However, there is a strong need for funding to develop innovative instrumentation for these operations.

The challenges require the development of transdisciplinary and/or cross-sectoral activities and the community of French researchers working in the Arctic has understood this need. It is essential that management at both the scientific and administrative levels takes proper account of this need and adapts as it inevitably involves working in broader groups and in consortia of scientists coming from various backgrounds.

The issue of infrastructure is a major problem for launching large-scale observation programs in the Arctic and in particular for French researchers because we have little (or no) major facilities to access the Arctic.

Regarding resources for going to sea, it is unrealistic (in the present context) to think that France could engage in building icebreakers. The European context is not favourable since Germany decided to launch the construction of a second Polarstern. But agreements between polar institutes under the auspices of Europe are still relevant. Establishing MoU (Memoranda of Understanding) with foreign countries as partners, as we did with the USA and China for example in the recent past, can be a solution. The most effective approach for French researchers in the Arctic would be to develop protocols and partnerships, at the European level, to access ships operating in polar regions with the support of the European Commission so that they can conduct field activities in the Arctic Ocean (in situ measurements, deployment of autonomous instruments, etc.). We must encourage the development of protocols with Germany, which has major Arctic facilities (Polarstern, Polar 5) by extending the concept of the Franco German AWIPEV base in Spitsbergen. Suitable protocols could be developed and established with Norway, which has significant resources in the Arctic.

Advanced research bases also provide essential support for monitoring of high-quality, long-term observations. Several observation sites/zones are already preferred. Consideration should be given to strengthening them. It is also necessary to consider strengthening existing cooperative efforts (Canada, AWI, Siberia, etc.)

Access to data is a major research problem in the community. It is strongly advised to integrate data centres (‘pôles’) into the national initiative being set up but taking into account the specific needs. This requires substantial work that should be treated in a very methodical way. The resources and skills needed in this crucial area are available in France.

■ Recommendations

To support and develop France’s Arctic research, and considering its strengths and weaknesses to address the challenges, we offer seven recommendations of equal importance:

• Arctic ‘zones ateliers’

The concept of ‘zones ateliers’ has recently become of great interest in the Arctic, and French researchers are very involved in this. The SIOS in Svalbard is an example well known to Europeans since the Norwegians proposed to Europe to provide a framework and a European dimension to researchers working on this platform in Svalbard. ‘Zones ateliers’ in Central Siberia are also very appreciated by French researchers. This type of research should be extended and structured in a manner adapted for ‘zones ateliers’ in the Arctic. New opportunities are opening up with Canada and Greenland. It is important at the institutional level to take better account of the needs in the development of 'zones ateliers', which can then be shared to the benefit of French researchers who are interested in these developments.

The selection of preferred observation sites / zones should take into consideration existing sites and international cooperative efforts.

• Large-scale (pan-Arctic), perennial observation networks

Technological advances are such that it is now possible to instrument the Arctic to achieve high quality observations over long periods and in a very hostile environment like the Arctic, especially in winter. This is exactly what researchers need for key studies of processes affecting the ongoing evolution of the Arctic environment (not just a climatological point of view). The last IPY was very revealing of these needs and how to meet them. The daily monitoring for a year (or more) of drifting buoys anchored in the ice and providing temperature profiles in the Arctic Ocean and through the ice is considered by many as the major success of IPY 2007-2008. It is to some extent similar to transferring the ARGO network to the Arctic region. French researchers are now engaged in very large activities with the Equipex IAOOS and NAOS projects, but it is necessary to strengthen the system in place and currently in action through institutional resources that are sufficient to meet the challenges.

• Observation super sites

The Arctic is a vast desert almost completely devoid of observation stations like those that cover the Earth on every continent. Currently there are 4 instrumented super sites in the peri-Arctic region: Point Barrow in Alaska, Eureka in northern Canada, Ny Alesund in Spitsbergen and Tiksi in Eastern Siberia. It is likely that Station Nord in northeastern Greenland will be expanded soon. Key decisions were made by the Canadian government to develop a super site in Cambridge Bay in the Northwest Passage (Canadian Archipelago). But it is necessary to maintain the pressure on governments through the enthusiasm of researchers to ensure that the current super sites continue to exist and develop. This, unfortunately, does not appear to be the case for Eureka. How can French researchers, with the support of their institutions, improve a situation where they would be the first beneficiaries?

• Airborne capabilities and balloons

In a very hostile environment such as the Arctic, airborne capabilities are a major asset for researchers from all countries. The use of aircraft and balloons is a strength of the French scientific community that has used them to better understand atmospheric processes (pollution, dynamics, clouds, stratospheric ozone) in the Arctic region for 10-20 years, often through international projects. France has three planes that can fly in the Arctic region, including SAFIRE's ATR-42 and Falcon-20 as well as the Russian plane that flies as part of LIA YAK AEROSIB in Siberia. It must be recognized that, so far, French planes have flown very little in the Arctic unlike, for example, the German research aircraft. Balloons of various dimensions with their payloads are also available to make profiles in the middle stratosphere.

• Aerial drones, unmanned underwater vehicles, floats and balloons

In France there is already expertise on measurements by micro-sensors on buoys or ice caps that can be pursued and developed to meet the objectives of this science plan. There are also ongoing projects with several laboratories in France involved in the development of unmanned aerial vehicles (UAVs). There is also strong French expertise in autonomous underwater systems. French expertise in robotics is internationally recognized with respect to both the academic and industrial environment. The ARGOS system was invented by France. The first European glider is French. French manufacturers develop ARGO floats for China, India and Japan (amongst others). This expertise must be promoted and valued especially as technological progress increasingly encourages the use of autonomous systems in the Arctic for long periods of time and in a hostile environment. The Equipex IAOOS and NAOS projects of the *Grand Emprunt National* and several ANR advance in this direction but we must persevere, particularly at the European level or/and with bilateral cooperation.

For all Arctic platforms, whether planes, balloons or drones, there is an interest in miniaturized instruments to measure trace species and aerosols as well as physical/dynamical parameters and the radiation balance. More generally, it is important to provide a funding mechanism for embedded instruments (scientific payloads) on these platforms and to improve them where necessary to meet the objectives of this science plan.

• Satellite observations including the transmission of ground information

Since the launch of the first Earth observation satellites in the early 70s, remote sensing in polar regions and the Arctic, in particular, has revealed fundamental aspects of seasonal and multiyear trends of snow and ice on land and sea. At a point in the history of the Earth when all components of the Arctic system exhibit surprising changes, it is more than ever necessary to continue to monitor by satellite the essential characteristics of snow, sea and land ice, and permafrost. It is also essential to use satellite observations of all components of the Earth system (altimetry, salinity, atmospheric chemistry, clouds, etc.).

Moreover, a current major problem is to provide near real-time transmission of data collected in situ. The means of communication in the Arctic are very (too) limited and only satellites can help to ensure spatial coverage throughout the entire Arctic and in all weather. The connection between the ground segment and the space segment is very important.

• Observations by boat

The use of ice strengthened and icebreaker vessels is a necessity for French researchers to develop sustained and high quality Arctic research. In the current situation we must find solutions through bilateral negotiations with our preferred partners (Germany and Norway) and with the support of the European Commission. The assets that French researchers can present at the negotiating table are important. They are based mainly on the quality of high-tech developments that have been undertaken and carried out in various strategic areas (underwater robotics, remote sensing, signal processing, etc.).

• Participation of Native peoples and the establishment of human-environment observatories

Representatives of Arctic Native populations are present at international scientific conferences that focus on the Arctic. They express their desire and willingness to participate in international research efforts but remain marginalized in most of the research activities that are conducted by many countries bordering, or not bordering, the Arctic. It would be highly desirable for France to support and develop initiatives in education and to offer concrete and practical solutions to promote the participation of Arctic Native peoples in observation services in centres where they would have a leadership role, which would imply considering the aspects of partnership, training and communication beforehand. The Belmont Forum, to which France adheres, might be a suitable framework for this development. But as of now, Native communities are involved in the co-construction of research programs with French researchers, particularly in the context of the International Human-Environment Observatory *(Observatoire Hommes-Milieux)* in Nunavik that promotes an integrated and participatory socio-environmental approach.

Modelling the Arctic environment: Key priorities

Introduction

Models are the main tools used to integrate our knowledge about the Earth's system, including both environmental and human dimensions, to improve understanding about feedbacks and interactions within the system and to make predictions of change in the short and longer term. They are also key tools used to analyse observations. Models vary in complexity from detailed process-level models up to Earth system models or even socio-economic models, covering local to regional and global scales. The Arctic is a region where, despite significant advances in some areas, models still have considerable difficulty reproducing recent physical changes such distributions of Arctic clouds (with consequences for the Arctic radiation budget), sea ice extent, Arctic Ocean circulation and stratification, fluxes of nutrients into the Arctic Ocean or the development of taliks (i.e. unfrozen ground) in tundra regions. The themes described in this science plan detailed many areas where key uncertainties remain and where models are often major tools used to advance our understanding. The aim of this section is to highlight a number of priority areas which can be tackled by the French community with improvements to model capabilities, and which contribute to the Chantier Arctique's scientific objectives as well as, in some cases, European or international initiatives.

Context and background

The French community has significant modelling expertise that can be mobilized to tackle the key science objectives laid out in this science plan. This includes building on expertise in simulating polar environments (Antarctic and Arctic) as well as expertise developed during the course of previous national research programs conducted in other regions of the World. Table 1 lists the models currently employed by the French community to investigate a range of issues in the Arctic. Amongst these, there are a number of areas where the national modelling community already has particular strengths and is actively contributing to Arctic research. These include:

a) Troposphere-stratosphere dynamical coupling in the Arctic and chemistry-climate interactions have been investigated using the two French Earth System models (ESMs from IPSL and CNRM) and stratospheric chemistry-climate models (CNRM-ACM, LMDz-REPROBUS). The bulk of these modelling activities have been carried out within the framework of the IPCC CMIP and represent major French contributions to the IPCC assessment and WMO Ozone assessment. French chemistry-climate simulations have provided valuable insights in the coupling between large-scale dynamics and chemistry into the stratosphere and in the evolution of Arctic stratospheric ozone in a changing climate. Results from French ESMs have also been used in evaluations of atmospheric characteristics such Arctic clouds or factors linked to Arctic climate amplification although it can be noted that, in general, ESMs perform rather poorly when compared to observations and there is a large variability between model results. Tropospheric chemistry models (LMDz-INCA, WRF-Chem) have also been used to study long-range transport of anthropogenic and fire pollution to the Arctic including international multi-model assessments (e.g. POLARTCAT Model Intercomparison Project, POLMIP).

b) Coupled ocean-sea-ice-biogeochemical studies using the NEMO-LIM-PISCES system forced with atmospheric reanalyses. The French community is involved in regional and global hindcast experiments or ocean reanalyses using the NEMO-LIM system to analyse recent Arctic variability in relation to atmospheric surface forcing. Results contributing to international model inter-comparison exercises (AOMIP) show large dispersion across models concerning key elements of the ice-ocean system (e.g. sea thickness distribution, variability of ocean fluxes at the Arctic Ocean boundaries). Process-oriented coordinated experiments, run with a common set-up, and linked to dedicated observational programmes, are among actions currently guiding improvements to model physics and biogeochemistry. The current implementation of LIM3 as a standard for future ocean-sea ice simulations with NEMO, with its more detailed sea ice physics and biogeochemistry, constitutes a major national effort.

c) Coupled atmosphere-ice-ocean models. Results from this modelling framework as part of CMIP5 have been used to, for example, examine future primary production in the Arctic Ocean. Diverse results highlight the need for a better representation of Arctic Ocean dynamics in order to improve fluxes (both vertical and advective) of nutrients. Coupled simulations are also shown to be very useful tools to analyse the links, and possible feedbacks, between the global ocean circulation, including its meridional overturning and gyre components, and the Arctic atmosphere and sea ice variability.

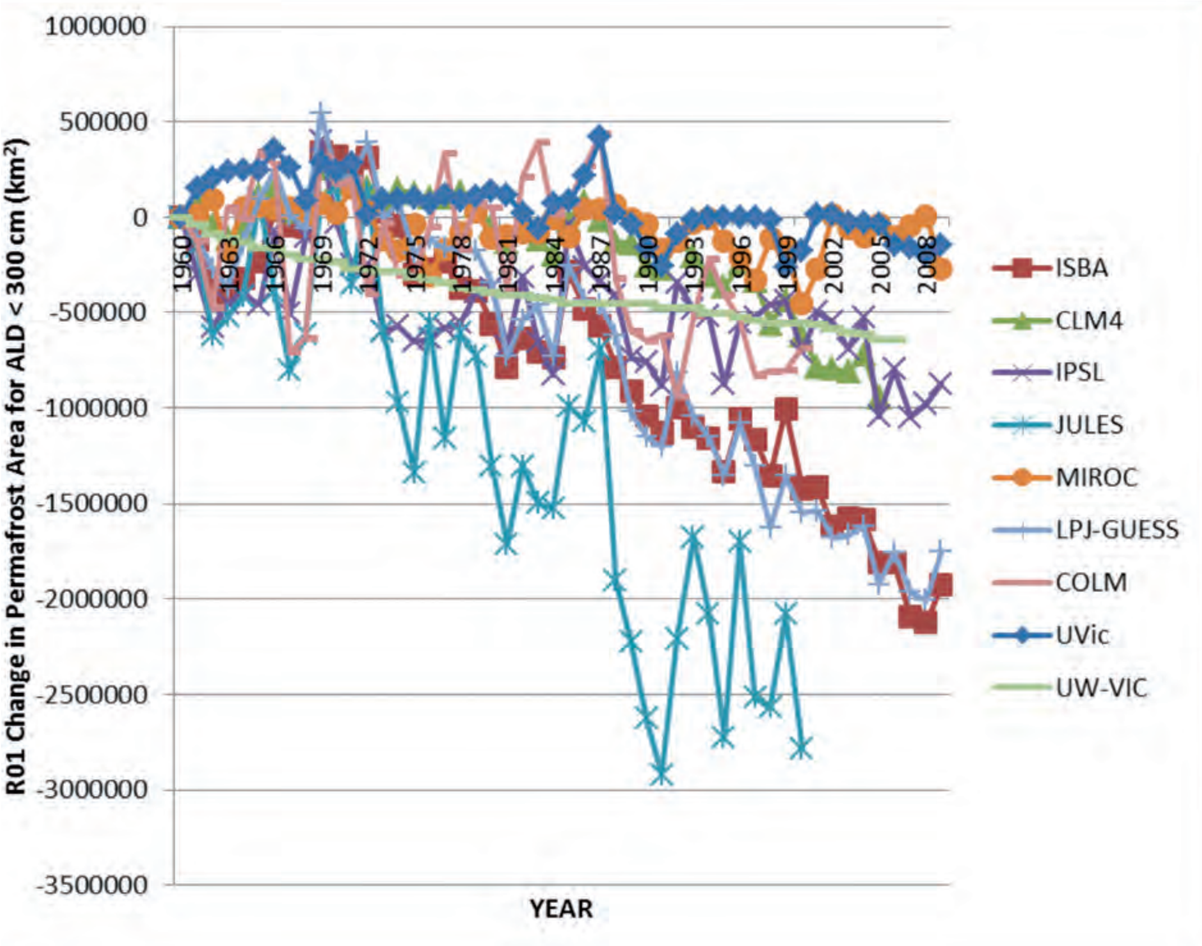


Figure 12.1: Evolution of the extension of permafrost near the surface (less than 3 m deep) between 1960 and 2009, simulated by different surface models (indicated by different colors) as part of an international project of inter-comparison models of surface processes at high latitudes (McGuire et al.*, in preparation).*

d) Interactions of ice sheets with atmosphere and ocean. Coupled model systems are being developed by the French community including global scale approaches with general circulation models (IPSL, CNRM), ESMs (e.g. CLIMBER), and also regional-scale models (MAR), which will all be later coupled to the GRISLI ice sheet model. The French community is among the leaders in this domain. The applications range from paleoclimate studies to future projections of eustatic sea-level rise, with large uncertainties still remaining due to by poorly understood and poorly modelled ice-sheet/ocean interactions.

e) Land-surface processes and interactions with atmosphere and ocean. The impact of climate change on surface processes, including hydrology, changing terrestrial snowpack, melting permafrost and the impact on the carbon budget have been investigated using French ESMs including detailed modules (ORCHIDEE, SURFEX) treating interactions in boreal high latitude regions. Interactions between permafrost and rivers have been modelled, especially heat exchanges between rivers and sub-surface (talik formation), including erosion during ice break-up of Arctic rivers. Lateral carbon fluxes to the oceans and coastal processes (erosion etc.) are being considered, but their treatment in large-scale land surface models is still in its infancy. Models such as LMDz-PYVAR and CHIMERE are also being used to perform inverse modelling of greenhouse gas emissions (ex. methane) in regions such as Siberia.

f) Forecasting. The French modelling community is involved in regional forecasting in the Arctic region, in some cases in collaboration with Canadian groups. In particular, the Mercator Ocean system is making routine forecasts of oceanic parameters, and currently developing a high-resolution version of NEMO-LIM for seasonal Arctic sea-ice predictions. The use of the CNRM-CM climate model in seasonal prediction mode has shown that, after initialisation, the pan-Arctic sea-ice extent is predictable up to 6 months in advance. This model was also used in WCRP/Ice-HFP to investigate the influence of sea-ice seasonal anomalies on Northern Hemisphere atmospheric circulation. At present, the only atmospheric forecasts are made using the French MIMOSA model simulating stratospheric dynamical variables or for short-term pollution plume forecasts for specific airborne campaigns using regional meteorological or chemical forecasts (e.g. WRF/WRF-Chem) although we note that a version of AROME is run in Norway making high-resolution atmosphere-sea ice-ocean forecasts.

The above areas of expertise cover primarily aspects related to modelling the Earth's climate system. We note that other modelling expertise and issues are also discussed in different scientific themes of this science plan and which cover areas such as tectonic modelling in the context of paleoclimatic studies. We also note that certain themes focus mainly on collection of data and empirical studies (e.g. studies of land ecosystems), and that themes addressing social dimensions also include "modelling" in a more empirical or statistical way with studies based on, for example, analysis of data or information or dialogue with local communities.

Overall, whilst the French modelling community has strengths in particular areas of Arctic, historically it has not been organised into a community focusing on the Arctic. The need to work towards a more coherent national modelling effort in the Arctic is highlighted in the next section together with a series of priorities that build on existing expertise as well as identifying areas that need reinforcing.

■ Key objectives and priorities

Models are a key element required to tackle the research areas described in this science plan. Here, we recommend several cross-cutting priorities as well as a top-level coordination action which will serve to enhance and strengthen the French Arctic modelling community and advance our understanding about the Arctic environmental system as a whole. It does not preclude modelling studies of a disciplinary nature which are detailed in the science plan themes.

• Improved process-level understanding and treatments in models

The improvement of existing models as well as the development of new codes or modules to represent specific processes will be a key outcome from the Chantier Arctique. This should be based on a combination of data analysis and evaluation of new or existing schemes using observations collected in key regions. In this respect, analyses, making use of local or regional models which can capture fine scales, should be one of the drivers behind planning new field experiments through identification of key questions and uncertainties. Previous research programs in other regions (ex. AMMA) have shown that it is extremely useful to include modellers in the planning stages of field experiments, and this approach is already applied successfully in certain areas of Arctic research. In the same way, model based studies can also contribute to the design, preparation and analysis phases of satellite missions. It may be beneficial to focus efforts on specific areas where the French community has observational expertise such as, stratospheric dynamics/chemistry, aerosol-cloud-radiative interactions, snow-atmosphere (boundary layer) interactions (physical + chemical), stratospheric processes, permafrost regions, atmosphere-sea ice-ocean fluxes, water mass formation and spreading, ocean boundary currents and mixing, or feedbacks between marine biogeochemistry and Arctic sea-ice. Fine-scale process scale modelling makes an important link between observations and large-scale models. Tight integration between modelling and observations is a key to the success of large-scale activities such as those mentioned in the previous sections of this document. Many research areas touch upon a large number of linked processes requiring an integrated approach including instrumented sites, aircraft and satellite remote sensing, ship-borne observations, coupled to physical modelling and numerical modelling across a range of spatial scales. Process understanding based on laboratory studies also provides the basis for improved treatments in models. Improved access of the modelling community to existing and new data is also a key requirement. The continued use and development of very high resolution modelling will form the basis of advances in process-level knowledge especially on the local and regional scale. This can also include regional climate modelling and the use of downscaling in different regions of the Arctic (for which French expertise exists and could be applied). Indeed, several examples of coordinated projects at national, and/or European/international level, involving observations and modelling, have already been carried out in the Arctic focusing on aspects such as sea ice-ocean interactions, stratospheric ozone or tropospheric pollution, marine carbon fluxes, or permafrost processes. The participation of the French community in international evaluation exercises is strongly desired (ex. CliC/Polar CORDEX, http://climate-cryosphere.org/activities/targeted/polar-cordex/arctic or by the Arctic Council (ex. AMAP). Innovative research areas in which the French modelling community is active are also supported by international working groups such as the SCOR BEPSII working group dedicated to the study of biogeochemical fluxes at the sea ice interface.

• Towards improved coupled Earth System Models in the Arctic

Improvements in our understanding about processes via observations and/or process-level modelling can be used to develop and improve treatments of interactions and feedbacks in Earth System or climate models. Several global or regional climate models are available in the French community that include a variety of different treatments or modules for different processes or interactions. A priority for the Chantier Arctique is to improve the performance of these models over/in the Arctic Ocean and terrestrial high northern latitude regions. In some cases, the regionalisation of certain climate models would be beneficial allowing feedbacks to be investigated at high resolution. Climate models of intermediate complexity are also valuable tools for investigating changes over long time scales (> multi-decadal or paleo). In particular, there is a need to evaluate and improve climate models in the following areas:

Atmosphere (stratosphere and troposphere) – surface interactions: A key requirement is improvement of dynamical and chemical processes in French global climate models (CNRM-CM5, IPSL-CM5) extending from the surface to the mesosphere and including both land and marine regions in order to improve understanding about past and future changes in the Arctic and links with lower latitudes/global climate change. Priority areas of concern include the water vapour cycle, aerosol-cloud interactions, precipitation and snow cover in the Arctic and coupling between the atmosphere and surface, especially the representation of boundary layer processes (ex. blowing snow) in the IPSL and CNRM global climate models. The treatments of chemical and aerosol processes in the troposphere and stratosphere are still very simplified in global and even in regional models, limiting our confidence in the realism of chemistry-climate simulations. Improved resolution and treatments of chemistry and aerosols (e.g. Arctic photochemistry, polar stratospheric clouds, mesospheric chemistry, and aerosol-cloud interactions) are needed both in global and regional models. The development of coupled regional climate models including coupled atmospheric and ice sheet or sea-ice/ocean processes will also be beneficial. The continued development of coupled models that include isotopes is a valuable addition to the community tools.

Ocean-biogeochemical-sea-ice-atmosphere coupling: Continued improvements to the coupled NEMO-LIM-PISCES system are needed. The dynamical (through mechanical energy transfer), physical (through light availability, brines and freshwater fluxes) and biogeochemical coupling between the atmosphere and the ocean are still poorly understood in the Arctic, most notably in the context of the rapidly changing sea ice cover, limiting the capacity of current models to properly simulate the transfer of energy and material between the atmosphere, the sea ice and the ocean and their impact on the underlying ocean (mixing, primary production, freshwater distribution). Improving the representation of these processes in models is a key priority. In order to improve understanding about marine nutrient and carbon cycles and their physical constraints, improved models of the ocean-land interface are also required. This includes representation of processes linked to continental input of freshwater, organic and particulate matter to the ocean and their fate, shallow water circulations and interactions with sediments, and coastal ocean (-ice) dynamics.

Land-surface-atmosphere interactions: Improvements to modules such as SURFEX and ORCHIDEE, developed to include feedbacks between water bodies, vegetation, permafrost and the atmosphere are required. These include improved treatments of snow cover and its interactions with vegetation and the underlying soil, hydrology, geophysical processes linked to soil freezing such as cryoturbation, thermokarst formation and, in particular, biogeochemical processes leading to accumulation of large amounts of organic carbon in permafrost regions. The representation of river-ice interactions in models, including erosional processes and heat exchange is an area that needs to be addressed. The high spatial heterogeneity in large parts of the circum-Arctic terrestrial areas, on all spatial scales, is another difficulty that needs to be tackled.

Atmosphere-ice-sheet-ocean coupling: Work on coupling French regional or global models to ice-sheet models, such as GRISLI, is still in its infancy. In particular, our understanding about the processes at play at the ice sheet/ocean/bedrock interfaces is incomplete. Efforts need to be made in order to improve representation of key processes such as surface snow cover, ice shelf-grounded ice transitions, iceberg calving and freshwater fluxes into the ocean.

Access to existing and new data for model evaluation is an important issue which should be addressed by the creation of, for example, a national Arctic data portal, making data more visible and available to the modelling community. This should complement and build on existing efforts. The participation of the community in Arctic-specific exercises of the type organised under CMIP5/PMIP, IGAC/SPARC/WMO or CLIC/CLIVAR (http://climate-cryosphere.org/activities) is strongly encouraged.

• Arctic weather and climate prediction

One of the main drivers behind the Chantier Arctique is improved capability to understand and predict change in the

Arctic. This includes changes on seasonal, annual or multi-annual/decadal timescales which are driven by a combination of anthropogenic forcing and natural variability. As well as changes on timescales relevant for climate change, improved prediction of weather systems on shorter timescales is also of interest since there are direct links between high latitude atmosphere-surface (ocean/ice/terrestrial) variability, mid-latitude weather systems and large-scale circulation patterns. The French modelling community has not been traditionally involved in short-term Arctic weather prediction except through the use of AROME-Arctic run in Norway. Exercises like CORDEX present an opportunity to test and evaluate existing models in this region (ex. Meso-NH, MAR, WRF). Improved prediction of sea-ice, ocean and atmospheric weather conditions (ex. sea-ice, wave heights, wind, cloudiness) are required as interest in Arctic resources, transport of goods, and developing infrastructure and communities increases. The WMO Year of Polar Prediction (http://polarprediction.net/en/about_ppp/yopp/) has as its main goal the improvement of environmental prediction capabilities in polar regions including an intensive observational and modelling phase in mid-2017 to mid-2019. The French community is well positioned to contribute to this initiative in terms of, for example, high resolution ocean/ice modelling and potentially atmospheric modelling (including, in particular, coupled stratosphere-troposphere modelling and aerosol-cloud interactions). The prediction of extreme events such as polar lows, ground-water melting/flooding, precipitation/drought extremes, sea-ice conditions, and sea-level rise are also potential topics where the French community could contribute. The continued development and use of the high-resolution ocean model NEMO in the Arctic Ocean for seasonal forecasting of, for example, sea-ice extent, are an important goal, including coupling to biogeochemical cycles. The CNRM global climate model is also used for this purpose. Improvements to data assimilation in, for example, the Mercator Ocean operational system is also encouraged as well as the application of downscaling and regionalisation in the Arctic region.

• Tools for studying climate – socio-economic feedbacks

A main goal of the Chantier Arctique is to promote and encourage cross-disciplinary research which reaches across traditional boundaries. In order to examine some of the topics highlighted under the thematic areas, it will be necessary to bring together expertise and tools that treat both physical and socio-economic aspects of the Arctic environment. This may include building future scenarios related to climate change affecting land-use and marine access, including food security, as well human impacts linked to increased industrialization and adaptation by local communities. Application of socio-economic models in the Arctic region for the prediction of industrial development would be beneficial in this respect. Improved assessment and management of risks linked to climate impacts (ex. sea-ice conditions, sea-level rise, extreme weather events, flooding) in both coastal and non-coastal environments are required. Lessons can also be learned through modelling impacts of past changes on land-use (ex. forestry, husbandry)/ocean (ex. fishing) practices and societies. In this case, approaches may vary from the use of full climate or intermediate complexity climate models to more empirically based approaches with the latter often applied to the analysis of data on human or animal behaviour.

• National coordination action on Arctic Earth system modelling

Historically, the French modelling community has been rather dispersed working different aspects of the Arctic environmental system. In order to strengthen the community, both at national and international level, the creation of a coordination action or working group specifically focused on treatments of processes and representation of feedbacks in regional and global models is highly desired. The aim of this group would be to bring together modelling expertise and facilitate the improvement of French modelling systems in the Arctic region. It would also help to raise the profile of certain expertise nationally and internationally and could motivate the community into participating more actively in international comparison/evaluation exercises and international committees (ex. IASC, WCRP Cryosphere Grand Challenge). Needless to say, there is a very close link between models and observations, as noted in the priorities listed here. This coordination action group would need to work in partnership with any potential working group on Observations.

Name (acronym)	Primary processes included	Region covered/type
CNRM-CM5 : ARPEGE + NEMO + GELATO + SUSURFEX + TRIP	Atmosphere + ocean + sea-ice + surface + + river fluxes	Global climate
IPSL-CM5 : LMDz + NEMO + LIM + PISCES + ORCHIDEE + INCA/REPROBUS	Atmosphere (strat. + trop.) + ocean + sea-ice + marine biogeochemistry + biosphere; Water vapour isotope version (LMDz-iso)	Global climate (+ regional zoom)
CLIMBER	Intermediate complexity: atmosphere + ocean + surface	Global (paleo- climates)
iLOVECLIM	Intermediate complexity: atmosphere-ocean-vegetation	Global (paleo-climate)
NEMO-LIM-PISCES	Ocean + sea-ice + marine biogeochemistry	Regional + global (operational forecasts + reanalysis)
MAR	Atmosphere + surface + ice-sheet surface mass balance	Regional climate (Greenland)
AROME-Arctic	Atmosphere + sea ice + ocean	Regional (Norway) Weather prediction
Meso-NH	Atmosphere + ocean	Regional/local scale (weather prediction)
Polar-WRF/ WRF-Chem	Atmosphere dynamics + chemistry + aerosols + clouds (+ ocean + sea-ice)	Regional/Arctic(polar weather prediction + pollution, climate)
SURFEX	Hydrological model (snow, lakes, rivers) + towns + atmosphere + sea-ice	Global + regional
CHIMERE + ORCHIDEE	Atmosphere + surface (biosphere)	Siberia (inverse modelling GHG emissions)
GRISLI	Continental ice-caps	Greenland (ice core records, past climates, sea-level)
ELMER-Ice	Land (bedrock) + ice	Greenland
Permafrost-river-ice modelling	Taliks/ fluvial erosion/river ice breakup	Siberia

Table 1: List of models currently used in the French community to study the Arctic environment

Appendix

List of references cited in the legends of figures

Figure 1.1 : Cohen *et al.*, 2014

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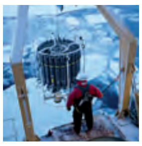
■ Legends of the mosaic coverage



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