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Winter climate change and sea ice-atmosphere interaction at high northern latitudes in ERA40 dataset

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Abstract Based on the reanalysis dataset ERA40 of European Center of Medium Range Weather Forcast (ECMWF), winter climate change and characteristics of sea ice-atmosphere interaction at high northern latitudes for recent several tens of years are analyzed. Superposed upon the background of global warming, the amplitude of temperature increase in winter at high northern latitudes is bigger and it exhibits different features in different regions. From the end of 1970's, the Greenland Sea, the Barents Sea and most part of Euro-Asian continent and North American continent are getting warmer, whereas the Labrador Sea, the Greenland and the area around the Bering Strait are getting colder. Meanwhile, the sea level pressure in the central part of the northern polar region and the place where the climatic Icelandic low exist decreases, but in places farther southward it increases. Since the 1970's, the sensible heat flux and latent heat flux sent to the atmosphere from the Greenland Sea and the Barents Sea has increased, this is mainly due to the reduction of sea ice concentration and the weakening of insulator and shield effect of the solid ice accordingly caused by the increase of air temperature. In sea ice free area of the Norwegian Sea, the sensible heat flux and latent heat flux sent to the atmosphere has reduced due to decrease of temperature and humidity differences between the air and the sea surface caused by increase of air temperature and humidity. In the Labrador Sea, due to decrease of air temperature and humidity and increase of temperature and humidity differences between the air and the sea surface accordingly, the sea gives more sensible heat flux and latent heat flux to the air. This will lead to the growth of sea ice extent there. The features of linear regression of sea level pressure, sea ice concentration and sum of sensible heat flux and latent heat flux toward time series of the leading mode of EOF expansion of surface air temperature are close to those of their own EOF expansion for the leading mode, respectively. This shows that these variables share similar features of variation with time linearly.
Key words ERA40, climate change, sea ice-atmosphere interaction.

1 Introduction

Green house gases, such as CO_2, CH_4, N_2O and so on are released to the atmosphere constantly by human activities. These gases insert positive radiative forcing to the climate. Meanwhile, aerosol, which are also released by human activities, insert negative radiative forcing to the climate. Combining the effects of the two kind of forcing and dynamic processes related with them, climate system model predicts that the variation of global mean surface air temperature from 1980 s to 2010 s has surpassed the atmospheric natural variabilities (Cubasch *et al.* 1995). Intergovernmental Panel on Climate Change (IPCC) warns that influence of human activities can be discerned from global climate change basing on testimonies of observations (IPCC 1996).

Results from observation show that the increase of surface air temperature in northern hemisphere beginning from 1970 s is most obvious on land at high latitudes (Folland *et al.* 1990, Folland *et al.* 1992). Results from numerical simulations show that the global warming is most distinguished in cold season at high latitudes (Manabe and Stouffer 1980, Robock 1983, Ingram *et al.* 1989). This is connected with the mechanism of ice-albedo positive feedbacks at high latitudes (Budyko 1969, Sellers 1969, Schlesinger and Jiang 1988). Some researchers suggest that the warming on land at high latitudes in cold season is at least partly related with the reoccurrence of anomaly of atmospheric general circulation in northern Pacific Ocean (Gutzler *et al.* 1988, Wallace *et al.* 1993). The circulation influences the temperature field through advection process and adiabatic process of compression or inflation connected with direct or indirect thermal circulation. The two processes give contribution to warming in some area and cooling in some other area. It's only when these regional scale temperature anomalies cannot counteract with each other completely that the circulation anomaly can affect global mean temperature. Thus, it's not appropriate to evaluate climate change with data over land only or over sea only (Wallace *et al.* 1996).

One outstanding feature of geophysical environment in the Arctic is the existence of sea ice. In the centre of the Arctic, the sea is covered by perennial sea ice. In the marginal sea, sea ice grows and decays seasonally. Through modulating exchange of flux of heat, water vapor and momentum between ocean and atmosphere and influencing stratification of ocean water and formation of deep water, sea ice plays an important role in the climate system. It's suggested that the observation data of sea ice might provide evidence for warming by green gases in the Arctic (Walsh 1995). In the past 40 years, the sea ice extent in the Arctic has decreased greatly and an area of nearly 3 times as big as Japan territory has disappeared (Ikeda *et al.* 2003). The variation of sea ice in the Arctic is a result of ocean-sea ice-atmosphere interactions in the climate system.

In the paper, features of climate change and sea ice-atmosphere interactions at high northern latitudes in ERA40 dataset from ECMWF will be analyzed. The ERA40 is a complete dataset and since it's a product of reanalysis, physical variables in it are consistent dynamically. Only results for winter will be presented here.

2 Data and Methods

Here, monthly mean surface air temperature, sea level pressure (SLP), surface sensible heat flux (SSHF), surface latent heat flux (SLHF) and sea ice concentration (SIC) ranging from 1958 to 2001 of ERA40 dataset are employed. The major techniques of analysis used in the work are empirical orthogonal function (EOF) and least square regression of two temporal series. The basic principle of EOF analysis is to decompose the element field, which is variable with time and space, into linear combination of functions of space (named EOFs, representing feature of spatial distribution) and temporal coefficients (named principal components, representing feature of temporal variation), and then to choose one or a few components which can account for major part of the total variance to study the major feature of the element field. The basic principle of least square regression of two temporal series is to regress one temporal series (treated as dependent variable) onto another temporal series (treated as independent variable) by use of least square method. The regression coefficients reflect relationships of deviations of the two temporal series. The products of regression coefficients and the total value of linear trend of independent variable are the total linear deviations of dependent variable corresponding to that of independent variable.

3 Features of climate change and sea ice-atmosphere interaction at high northern latitudes

From variations of winter surface air temperature anomalies averaged globally and regionally over area north of 45°N (Fig. 1), it can be seen that the global warming is apparent since 1970s. By contrast, the warming amplitude is larger at high northern latitudes. This is consistent with results from studies based on other observation data. The changes of temperature exhibit different features in different regions. It's clear, from Leading EOF of winter surface air temperature anomalies over area north of 45°N (Fig. 2a), that there is an opposite variation tendency between Greenland-Barents Seas, most part of Euro-Asian continent and Labrador Sea, Bering Sea with large anomalies situated mainly in Greenland Sea, Barents Sea and Labrador Sea. Considered together with the features in principal component time series of the leading EOF (Fig. 2b), it's clear that, since 1970's, air over Greenland Sea, Barents Sea, most part of Euro-Asia continent and North America continent has been warming whereas air over Labrador Sea, Greenland and Bering Strait has been cooling. This is similar to results of Wu *et al.* (2000)'s work, in which air temperature on 850 hPa from National Centers for Environmental Prediction (NCEP) reanalysis dataset has been employed. Consistent with results from Folland et al. (1990), air temperature over most continental area north of 45°N is experiencing a growing trend.

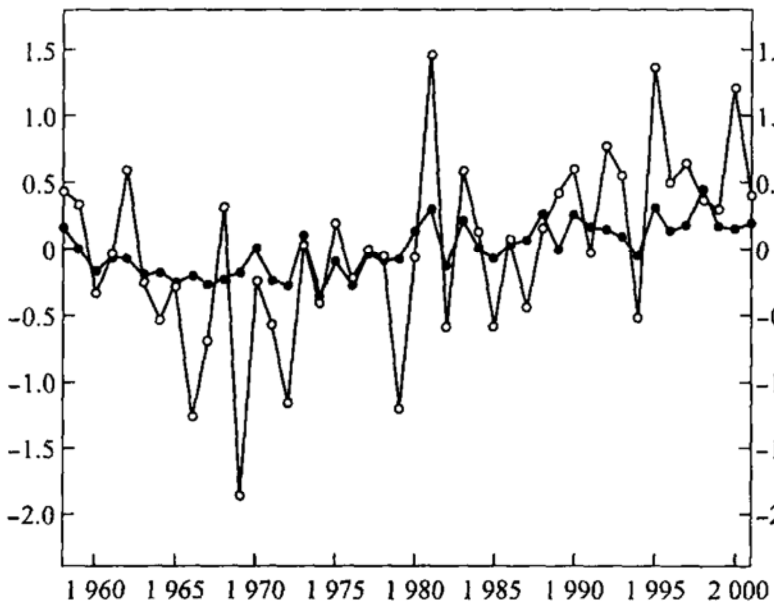

Fig. 1 Variations of winter surface air temperature anomalies averaged globally (solid circle) and regionally over area north of 45°N (open circle). Unit of horizontal axis is year and unit of vertical axis is °C

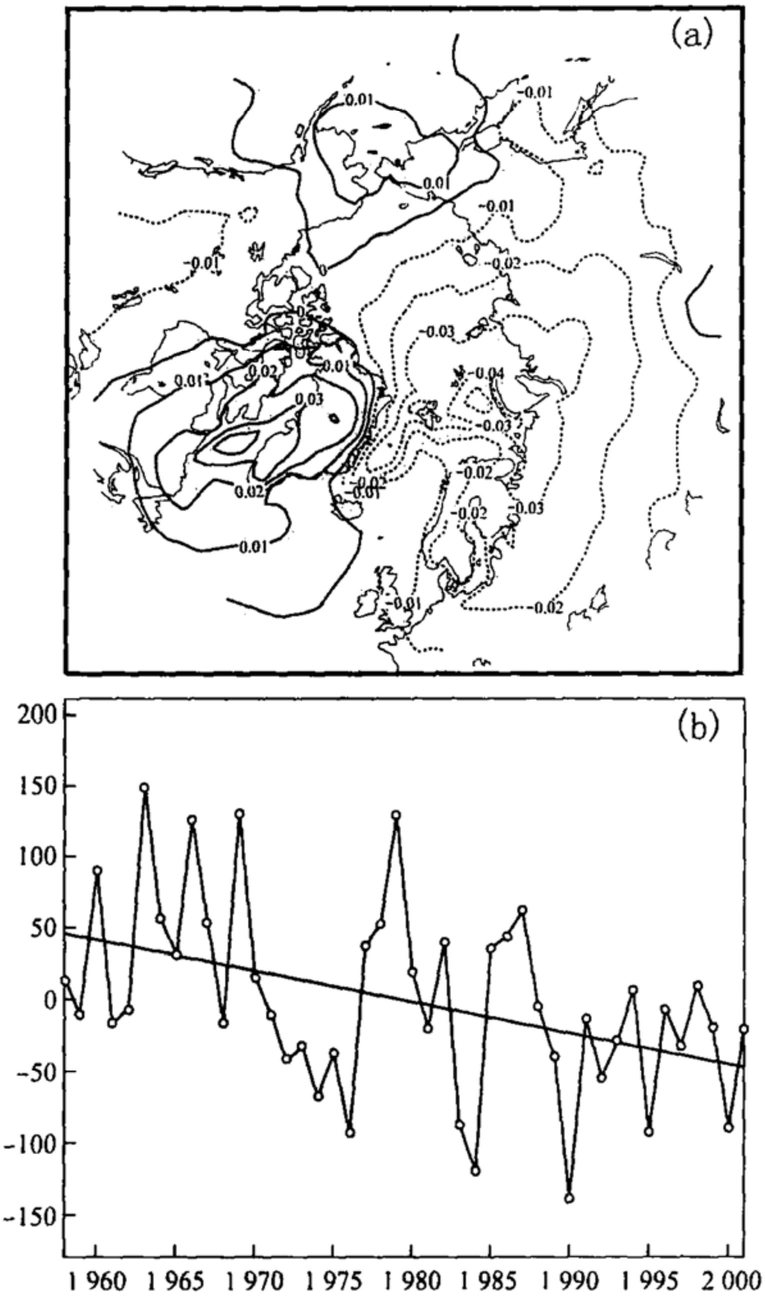

Fig. 2 (a) Leading EOF of winter surface air temperature anomalies over area north of 45°N. (b) Principal component time series of the leading EOF (the slanting straight line is result of linear fitting by least square method and linear variation value of the whole 44 years is − 93.1)

Accompanying the warming situation, the variability of atmospheric general circulation at high northern latitudes has changed greatly. Especially, the teleconnection patterns of Pacific-North American and North Atlantic Oscillation (NAO) or Arctic Oscillation (AO) (here, NAO is thought as one part of AO) have exhibited unprecedented features. Leading EOF of winter SLP anomalies (it accounts for 57.1% of the total variance) and principal component time series of the leading EOF are shown in Fig. 3a, 3b. The pattern of spatial distribution (Fig. 3a) is the AO named by Thompson and Wallace (1998). It's clear that, since the mid of 1970's, the strength of Icelandic low pressure has been strengthening and SLP over the central Arctic has been decreasing (the polar vortex is strengthening) whereas SLP over the region farther southward has been increasing (Fig. 3a, 3b). In 1989, the oscillation pattern is the most distinguished. The air warming over Euro-Asian continent and air cooling over Labrador Sea (see Fig. 2) are coincident with the change of atmospheric general circulation. Thompson *et al.* (2000) deemed that human activities may be one reason for the recent strengthening of the polar vortex and associated warming over continents of the Northern Hemisphere.

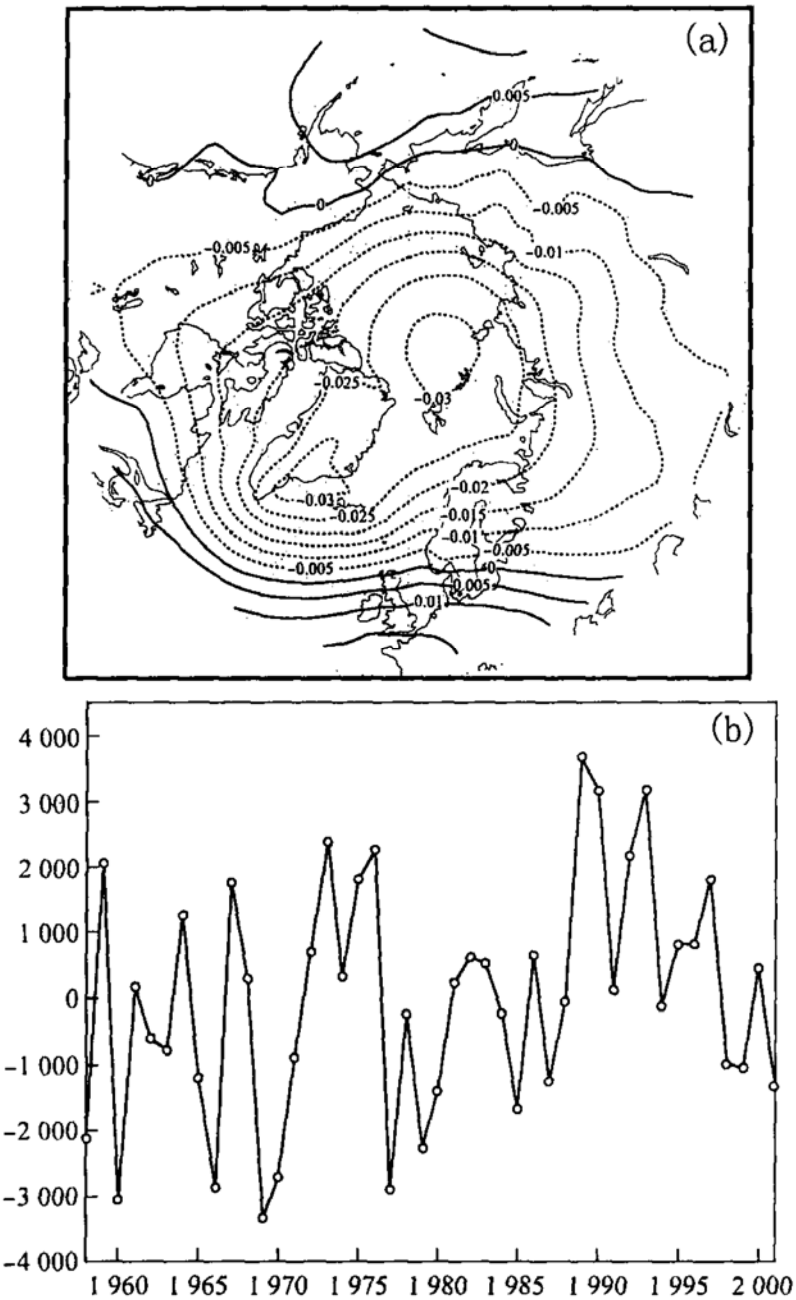

Fig. 3 (a) Leading EOF of winter SLP anomalies over area north of 45°N.
(b) Principal component time series of the leading EOF

Involving direct interactions among atmosphere, hydrosphere and cryosphere, the area at high northern latitudes is a place where direct ocean-sea ice-atmosphere interactions take place. To inspect the features of sea ice-atmosphere interactions under background of global warming, winter SSHF and SLHF are analyzed. Since variation tendencies are similar in results of SSHF and SLHF EOF analysis (Fig. omitted), results of SSHF-plus-SLHF alone are presented here. Leading EOF (account for 24.3% of the total variance) of sum of winter SSHF and SLHF anomalies over area north of 45°N and principal component time series of the leading EOF are shown in Fig. 4a & b. It can be seen that, variation tendencies in

Greenland Sea, Barents Sea and Labrador Sea are similar whereas they are contrary to those in Norway Sea and Okhotsk Sea. Since 1970's, the sensible heat flux and latent heat flux sent to the air from Greenland Sea and Barents Sea have been increasing. This is a result of air temperature increase. The warmer temperature reduces SIC and its insulation effect and increases flux exchanges accordingly. Whereas in Norway Sea, a place with no sea ice coved, the increase of air temperature and humidity reduces temperature and humidity differences between sea water and air and reduces the sensible heat flux and latent heat flux sent to the air from the sea as a result. In Labrador Sea, due to decrease of air temperature and humidity, temperature and humidity differences between sea water and air increase and heat flux sent to the air increase in favor of sea ice increase there.

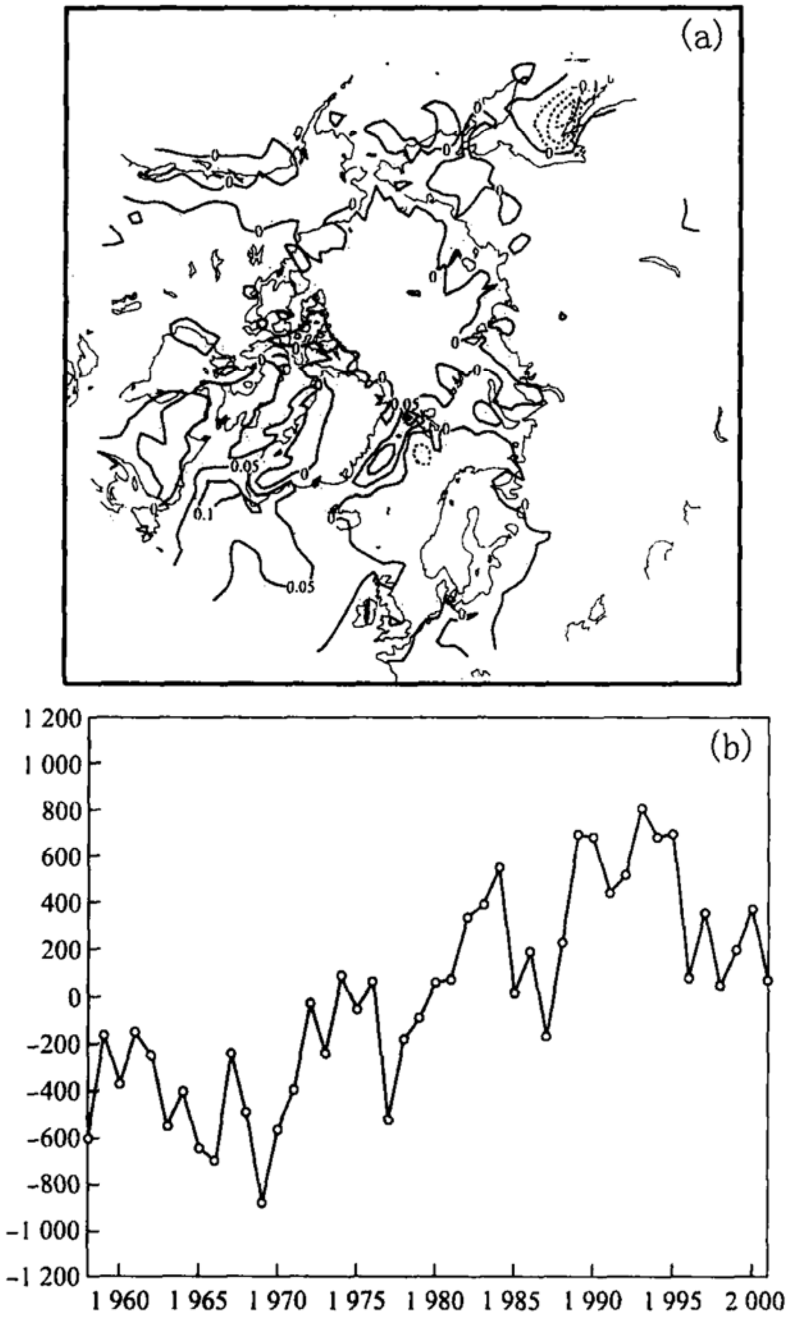

Fig. 4 (a) Leading EOF of anomalies of sum of winter SSHF and SLHF (positive is for upward) over area north of 45°N. (b) Principal component time series of the leading EOF

To seek relationships between air temperature anomalies and atmospheric general circulation anomalies, winter SLP anomalies are linearly regressed upon surface air temperature principal component time series of the leading mode (denoted by serT). The unit of regression coefficients is hPa per serT standard deviation. To use it conveniently and have a clearer physical meaning, the regression coefficients are multiplied by − 93.1 (44 years' linear variation of serT). Thus, the results of regression reflect biases of SLP corresponding to the 44 years' linear trend of serT (shown in Fig. 5). It can be seen that, there are negative biases in the centre of Arctic Ocean, the maximum negative bias situates east of Greenland and the maximum positive bias situates east of Atlantic Ocean south of 45°N. Compared with Fig. 3a, it's clear that, such pattern is the positive phase of NAO and AO. Under such circumstance, the temperature biases caused by southerly anomaly across the Greenland Sea, Norway Sea and Barents Sea and northerly anomaly across the Labrador Sea are consistent with the temperature anomalies occurred there.

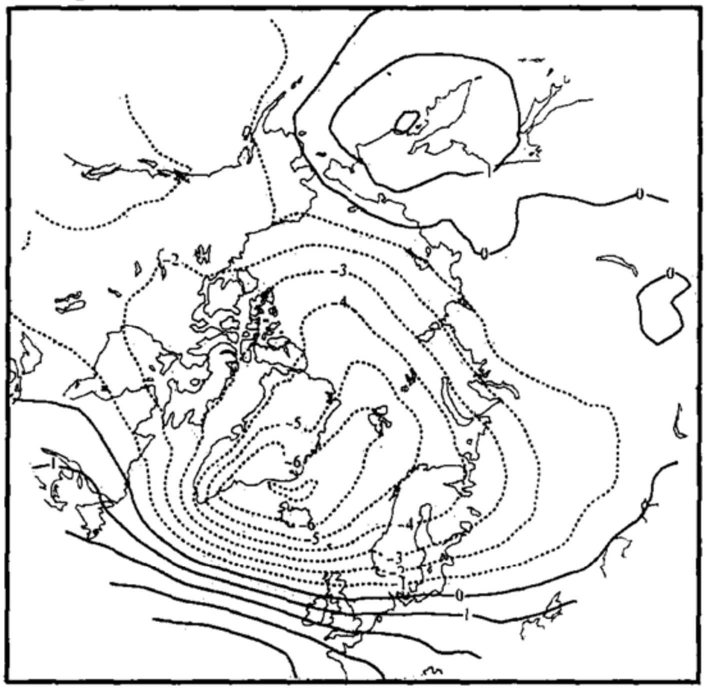

Fig. 5 Winter SLP anomaly associated with the leading surface air temperature EOF. The pattern was constructed by linearly regressing SLP anomaly upon surface air temperature principal component time series of the leading mode and multiplying the regression coefficients by − 93.1 (the linear variation value of the whole 44 years). Contour interval is 1 hPa/(44 yr)

Atmospheric general circulation anomaly can produce air temperature anomaly through abnormal advection of surface air temperature and then produce SIC anomaly through thermodynamic processes. Atmospheric general circulation anomaly can also produce sea ice drifting anomaly through dynamic processes forced by abnormal wind driving directly. The winter SIC anomaly associated with the leading surface air temperature EOF is shown in Fig. 6. It can be seen that there are inverse variation tendency between sea ice in Greenland Sea, Barents Sea and those in Davies Strait and Labrador Sea. Corresponding to the linear variation of air temperature, sea ice in Greenland-Barents Seas is decreasing and that in Davies Straits and Labrador Sea is increasing. This is consistent with the result of sea ice observation data (Deser *et al.*, 2000; Liu *et al.*, 2003). But it is still uncertain if such kinds of variation of sea ice are mainly due to thermodynamic processes or dynamic processes mentioned before. A global ocean-sea ice-atmosphere coupled model with thermodynamic sea ice included only cannot reproduce the reversed phase of variations between sea ice in

Greenland Sea, Barents Sea and that in Davies Strait and Labrador Sea (Liu *et al.* 2004). But it has been said that, sea ice anomaly pattern similar to that of observation has been reproduced by sea ice model with dynamic sea ice processes considered as well and geostrophic wind from observed SLP used as forcing (Deser *et al.* 2000). This seems to mean that the effect of direct wind forcing associated with atmospheric circulation anomaly plays an important role in forming of sea ice anomaly pattern. Wu *et al.* (2000) supposed that the decreasing of sea ice in Barents Sea is due to intensified transportation to high latitudes of warm ocean current induced by atmospheric general circulation anomaly. But an interesting question is that, which one of the two contributors, atmospheric natural variability or human activities, to the atmospheric general circulation anomaly plays a more important role? That's still an open topic deserving further studies.

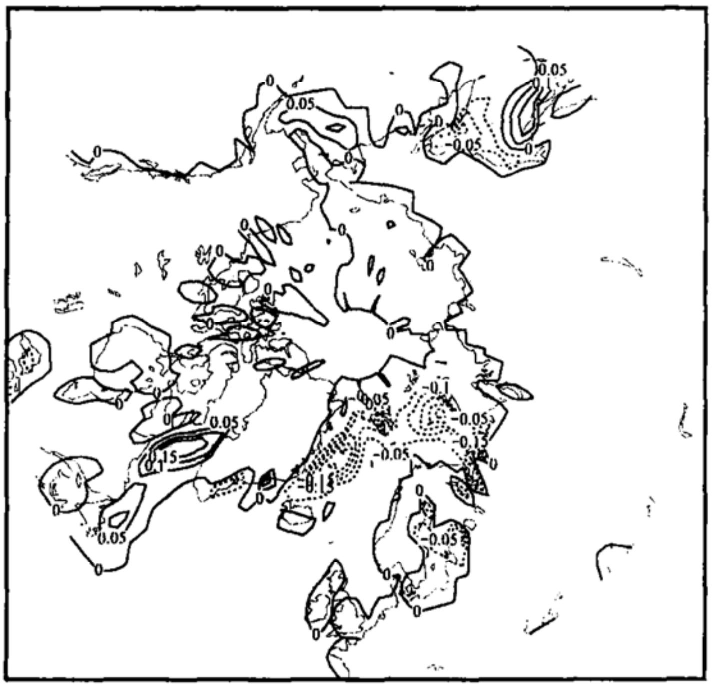

Fig. 6 Winter SIC anomaly associated with the leading surface air temperature EOF. The pattern was constructed by linearly regressing SIC anomaly upon surface air temperature principal component time series of the leading mode and multiplying the regression coefficients by − 93.1 (the linear variation value of the whole 44 years). Contour interval is 0.05/(44 yr)

The atmospheric general circulation anomalies can induce variation of SIC, whereas the changed SIC can influence the atmospheric general circulation in return through modifying surface albedo and flux exchanges of heat, water vapor and momentum between ocean and atmosphere. In winter, since solar radiation is small at high latitudes, the influence of sea ice albedo is small. Since SSHF and SSLF are proportional to differences of temperature and humidity between ocean (sea ice) and atmosphere, respectively, they are under influences of both underlying surface and surface air temperature or humidity. Winter surface sensible-plus-latent heat flux anomaly associated with the leading surface air temperature EOF is given in Fig. 7. It's apparent that there are inverse phase of upward heat flux anomaly between Greenland-Barents Seas and Norway Seas. There exists positive anomaly of upward heat flux in Greenland-Barents Seas and Labrador Sea and negative anomaly of upward heat flux in Okhotsk Sea. Comparing Fig. 7 with Fig. 4a, it can be seen that the two patterns are similar. This fact reflects features of ocean (sea ice)-atmosphere interactions associated with the linear trend of air temperature variation. In Greenland-Barents Seas, caused by increase of air temperature, the SIC reduces and the effect of insulator and shield of solid ice weakens, which leading to increase of sensible heat flux and latent heat flux sent to the atmosphere from the ocean. In sea ice free area of Norwegian Sea, caused by increase of air temperature and humidity and decrease of temperature and humidity differences between the air and the sea surface, sensible heat flux and latent heat flux sent to the atmosphere decrease. In Labrador Sea, due to decrease of air temperature and humidity and increase of temperature and humidity differences between the air and the sea surface accordingly, the sea gives more sensible heat flux and latent heat flux to the air. This will lead to the expansion of sea ice extent there. Through assemble simulations with atmospheric general circulation model, the influence of sea ice extent in Labrador Sea on NAO had been conducted (Kvamsto 2004), and it was shown that the sea ice has negative feedback on long term variation of NAO.

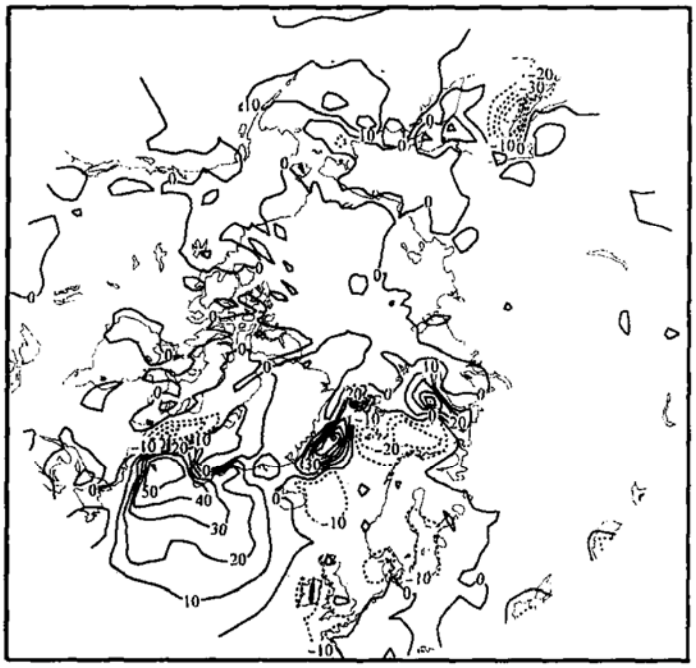

Fig. 7 Winter surface sensible-plus-latent heat flux anomaly associated with the leading surface air temperature EOF. The pattern was constructed by linearly regressing surface sensible-plus-latent heat flux anomaly upon surface air temperature principal component time series of the leading mode and multiplying the regression coefficients by − 93.1 (the linear variation value of the whole 44 years). Contour interval is 10 w/(m* * 2)/(44 yr)

4 Brief summary and discussion

Based on the dataset ERA40 of ECMWF, winter climate change and characteristics of sea ice-atmosphere interaction at high northern latitudes for recent several tens of years are analyzed. Under the background of global warming, the amplitude of temperature increase in winter at northern high latitudes is bigger and it has different features in different regions. From the end of 1970's, the Greenland Sea, the Barents Sea and most part of Euro-Asian continents and North American continents are getting warmer, whereas the Labrador Sea, the Greenland and the area around the Bering Strait are getting colder. Meanwhile, the SLP in the central part of the northern polar region and the place where the climatic Icelandic low situates decreases, but the SLP in places farther southward increases. Since the 1970's, the sensible heat flux and latent heat flux sent to the atmosphere from the Greenland Sea and the Barents Sea has increased, this is mainly due to the reduction of SIC and the weakening effect of insulator and shield of the solid ice accordingly caused by the increase of air temperature. In sea ice free area of the Norwegian Sea, the sensible heat flux and latent heat flux sent to the atmosphere has reduced due to decrease of temperature and humidity differences between the air and the sea surface caused by increase of air temperature and humidity. In the Labrador Sea, due to decrease of air temperature and humidity and increase of temperature and humidity differences between the air and the sea surface accordingly, the sea gives more sensible heat flux and latent heat flux to the air. This will lead to the expansion of sea ice extent there. The features of linear regression of sea level pressure, sea ice concentration and sum of sensible heat flux and latent heat flux toward time series of the leading mode of EOF expansion of surface air temperature are close to those of their own EOF expansion for the leading mode respectively. This shows that these variables share similar features of variation with time linearly. The foregoing results agree with Deser *et al.* (2000)'s conclusion, i.e., the atmospheric forcing play a dominant role in variation of sea ice in atmosphere-ocean-sea ice system and feedbacks of winter ice anomalies upon the atmosphere have been more difficult to detect. But Vinje (2001) supposed that, of all the processes affecting variation of sea ice extent, sea water temperature play bigger role than air temperature. With emphasis focusing on atmospheric boundary layer processes, Wu *et al.* (2004) analyzed the influences of sea ice anomalies in Greenland-Barents Seas on the atmosphere and supposed possible feedback mechanisms of sea ice.

The topic of this work is mainly on analysis of features of climate change at high northern latitudes with modulation of sea ice. Whereas climate change is still a topic deserving deepened study and to what extent can anthropogenic forcing influence the climate change is still an open question. As mentioned in the article, a global ocean-sea ice-atmosphere coupled model with thermodynamic sea ice included only cannot reproduce the reversed phase of variations between sea ice in Greenland Sea, Barents Sea and that in Davies Strait and Labrador Sea. But sea ice anomaly pattern similar to that of observation has been reproduced by sea ice model with dynamic sea ice processes considered and geostrophic wind from observed SLP used as forcing. This seems to mean that the effect of direct wind forcing associated with atmospheric circulation anomaly plays an important role in forming of sea ice anomaly pattern.

The results of this article are got from one dataset, in which all physical variables have good inner consistency. Part of the results agrees well with analyses based on other dataset, e.g., NCEP reanalysis dataset and sea ice data from American National Snow and Ice data centre (NSIDC). But work of further comparing with other dataset is still needed.

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References

Budyko M I (1969): The effect of solar radiation variations on the cliamte of the Earth. Tellus, 39: 611–619.

Cubasch U, Hegerl G, Hellbach A, H? ck H, Rainer-Meier E, Mikolajewicz U, Santer BD, Voss R (1995): A climate change simulation starting at an early time of industrialization. Clim. Dynam., 11: 71–84.
Deser C, JE Walsh, MS Timlin (2000): Arctic sea ice variability in the context of recent atmospheric circulation trends, J Clim., 13: 617–633.
Folland CK, Karl TR, Vinnikov KYa (1990): Observed climate variations and change. J. T. Houghton, G. J. Jenkins, and J. J. Ephraums (eds.), Climate Change: The IPCC Scientific Assessment, Cambridge University Press, 365.
Folland CK, Karl TR, Nicholls N, Nyenzi BS, Parker DE, Vinnikov KYa (1992): Observed climate variability and change. J. T. Houghton, B. A. Callander, and S. K. Varney, (eds.), Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment, Cambridge University Press, 200.
Gutzler DS, Richard D, Salstein DA, Peixoto JP (1988): Patterns of interannual variability in the Northern Hemisphere wintertime 850 mb temperature field. J. Climate, 1: 949–964.
Ikeda M, Wang J, Makshtas A (2003): Importance of clouds to the decaying trend in the Arctic ice cover. J Meteorol. Soc. Japan, 81: 179–189.
Ingram WJ, CA Wilson, JFB Mitchell (1989): Modeling climate change: An assessment of sea ice and surface albedo feedbacks. J. Geophys. Res., 94: 8609–8622.
Intergovernmental Panel on Climate Change (IPCC) (1996): Climate Change 1995. The Science of Climate Change, (ed.) J. Houghton *et al.*, Cambridge University Press.
Kvamsto NG, Skeie P, Stepheneon DB (2004): Impact of Labrador sea-ice extent on the North Atlantic oscillation, Int. J. Climatol., 24: 603–612.
Liu XY, Zhang XH, Yu YQ (2003): Simulated major climatic features of sea ice at high northern latitudes in a global sea-sea ice-air coupled model. earth science frontier (in Chinese), 10: 419–426.
Liu XY, Zhang XH, Yu YQ, Yu RC (2004): Mean climatic characteristics in high northern latitudes in an ocean-sea ice-atmosphere coupled model, Adv. Atmos. Sci., 21: 236–244.
Manabe S, Stouffer RJ (1980): Sensitivity of a global climate model to an increase of CO2 concentration in the atmosphere. J. Geophys. Res., 85: 5529–5554.
Robock, A. (1983): Ice and snow feedbacks and the latitudinal and seasonal distribution of climate sensitivity. J. Atmos. Sci., 40: 986–997.
Sellers WD (1969): A global climate model based on the energy balance of the earth-atmosphere-system. Tellus, 39: 392–400.
Schlesinger ME, Jiang X (1988): The Transport of CO2-induced Warming into the Ocean: An Analysis of Simulations by the OSU Coupled Atmosphere-Ocean General Circulation Model. Clim. Dyn., 3: 1–17.
Thompson DWJ, Wallace JM (1998): The Arctic Oscillation signature in wintertime geopotential height and temperature fields. Geophys. Res. Lett., 25: 1297–1300.
Thompson DWJ, Wallace, JM, Hegerl GC (2000): Annular modes in the extratropical circulation. Part II: Trends. J. Climate, 13: 1018–1036.
Vinje T (2001): Anomalies and trends of sea ice extent and atmospheric circulation in the Nordic Seas during the period 1864-1998. J. Climate, 14: 255–267.
Wallace JM, Zhang Y, Lau KH (1993): Structure and seasonality of interannual and interdecadal variability of the geopotential height and temperature fields in the Northern Hemisphere troposphere. J. Climate, 6: 2063–2082.
Wallace JM, Zhang Y, Bajuk L (1996): Interpretation of Interdecadal Trend in Northern Hemisphere Surface Air Temperature. J. Climate, 9: 249–259.
Walsh JE (1995): Long-term observations for monitoring of the cryosphere. Climatic Change, 31: 369–394.
Wu BY, Huang RH, Gao DY (2000): North polar sea ice joint North Atlantic Ocean and interannual climate change, Chinese Science bulletins (in Chinese), 45: 1993–1997.
Wu BY, Wang J, Walsh J (2004): Possible feedback of winter sea ice in the Greenland and Barents Seas on the local atmosphere. Mon. Wea. Rev., 132: 1868–1876.