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 Forecast (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 1970s, the Greenland Sea and 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 1970s, 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.

Keywords ERA40, climate change, sea ice-atmosphere interaction

1 Introduction

Green house gases such as CO₂, CH₄, N₂O 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 proces-
ses 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 (SSH), surface latent heat flux (SIHF) 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 princi-
pal 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 is 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 is clear that since 1970s 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 1970s 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 SIHF are analyzed. Since variation tendencies are similar in results of SSHF and SIHF EOF analysis (Fig. omitted), results of SSHF plus SIHF alone are presented here. Leading EOF (account for 24.3% of the total variance) of sum of winter SSHF and SIHF anomalies over area north of 45°N and principal component time series of the leading EOF are shown in Fig. 4a & h. 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, 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 covered, the increase of air temperature and humidity reduces temperature and humidity differences between seawater 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 seawater 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 SHF and SHF (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 tempera-
ture principal component time series of the leading mode (denoted by seft). The unit of regression coefficients is hPa per seft 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 seft). Thus, the results of regression reflect biases of SLP corresponding to the 44 years' linear trend of seft (shown in Fig. 5). It can be seen that there are negative biases in the centre of the Arctic Ocean, the maximum negative bias situates east of Greenland and the maximum positive bias situates east of the Atlantic Ocean south of 45°N. Compared with Fig. 3a, it is 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, Norwegian Sea and Barents Sea and northerly anomaly across the Labrador Sea are consistent with the temperature anomalies occurred there.

![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)](image)

A 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 is 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 asso-
ciated with the linear trend of air temperature variation. In the Greenland-Barents Seas, caused by the increase of air temperature, the SIC reduces and the effect of insulator and shield of solid ice weakens, which leads to the increase of sensible heat flux and latent heat flux sent to the atmosphere from the ocean. In the sea ice-free area of the Norwegian Sea, caused by the 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 the Labrador Sea, due to the 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 the simulation with an atmospheric general circulation model, the influence of sea ice extent in the Labrador Sea on NAO had been conducted (Kvensto 2004), and it was shown that the sea ice has a negative feedback on long-term variation of NAO.

![Image](image.png)

**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 -9.31 (the linear variation value of the whole 44 years). Contour interval is 10 w/(m² * 2)/(44 yr)

4 Brief summary and discussion

Based on the dataset ERA 40 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 high northern latitudes is bigger and it has different features in different regions. From the end of 1970s, 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 Ice-
landic low situates decreases but the SLP in places farther southward increases. Since the 1970s, 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 inter 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 formation 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
