Mean Climatic Characteristics in High Northern Latitudes in an Ocean-Sea Ice-Atmosphere Coupled Model

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ABSTRACT

Emphasizing the model's ability in mean climate reproduction in high northern latitudes, results from an ocean-sea ice-atmosphere coupled model are analyzed. It is shown that the coupled model can simulate the main characteristics of annual mean global sea surface temperature and sea level pressure well, but the extent of ice coverage produced in the Southern Hemisphere is not large enough. The main distribution characteristics of simulated sea level pressure and temperature at 850 hPa in high northern latitudes agree well with their counterparts in the NCEP reanalysis dataset, and the model can reproduce the Arctic Oscillation (AO) mode successfully. The simulated seasonal variation of sea ice in the Northern Hemisphere is rational and its main distribution features in winter agree well with those from observations. But the ice concentration in the sea ice edge area close to the Eurasian continent in the inner Arctic Ocean is much larger than the observation. There are significant interannual variation signals in the simulated sea ice concentration in winter in high northern latitudes and the most significant area lies in the Greenland Sea, followed by the Barents Sea. All of these features agree well with the results from observations.

Key words: coupled model, arctic oscillation, sea ice

1. Introduction

The climate system consists of the atmosphere, hydrosphere, lithosphere, biosphere, and cryosphere, which are all constantly interacting. When one part of the system varies, other parts will also vary accordingly. To study such a system with complicated nonlinear interaction or even to study a single component in it, a numerical coupled system model is one of the most powerful tools. The overall performance of a coupled system model is related to each model component's single performance and is influenced by the employed coupling scheme as well. Within the physical climate system model, the atmospheric general circulation model (AGCM) is the most mature component, followed by the ocean general circulation model (OGCM). Comparatively, we know less about land surface activities and cryosphere processes. But as it is well known, in climate system, the ocean surface, land surface, and cryosphere are the most important lower boundaries of the atmosphere and they can determine the future evolution of atmospheric general circulation through exchange of mass, momentum, and energy with the air. Due to interaction, once the atmospheric general circulation has changed, features of the lower boundary will also change accordingly. Many fields in theses studies need to be developed further.

High latitude regions play an important role in global climate change. This is because, on the one hand, high latitude regions are a zone of energy sink on the globe, being opposite to low latitude regions; on the other hand, high latitude regions are the place where strong sea-ice-air interaction takes place and where the three spheres' direct interferences transpire. Since the ocean-sea ice-atmosphere coupled model is a kind of simplified implementation of the real climate system and sea-ice-air interaction processes have been considered in it, it is particularly advantageous to employ it to study sea-ice-air interactions. To perform research work with a coupled model, it is necessary to first validate the model's capability to simulate well aspects related to the research interest. The main aim of this work is to validate a global ocean-sea ice-atmosphere coupled model's ability to reproduce the

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mean climate in high northern latitudes, whereas further discussions on mechanisms of sea-air interaction and ice-air interaction in the model will be given in another paper.

At present, there have been many widely used coupled system models in the world. For example, there are about 30 models participating in the Coupled Model Intercomparison Project (CMIP)(Phillips, 2002). The first widely used and well recognized, globally coupled model in China is the Global Ocean-Atmosphere-Land System (GOALS)/LASG model (Wu et al., 1997), which was developed by the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences. The improved version of the GOALS/LASG model participated in stage 1 and stage 2 of CMIP. With the enhancement of computing ability, improvement of numerical algorithms, and deepening understanding of the climate system, the world's coupled system models have undergone considerable development. Following the idea of advancing coupled model development on the basis of the GOALS/LASG model, the coupled model research group of LASG is taking measures to study the effects of coupling for different model component choices, for example, coupling its own ocean general circulation model with the atmospheric general circulation model and sea ice model from Climate System Model (CSM) of American National Center of Atmospheric Research (NCAR) (Yu et al., 2002). The coupled model used here is one coupling an atmospheric general circulation model from the China National Climate Centre (Ye et al., 2000) with the laboratory's own improved ocean general circulation model L30T63 (Jin et al., 1999).

The model and the observation data for model validation are introduced in section 2. The global climate simulated by the coupled model is given in section 3. After that, the simulated mean climate in high northern latitudes is analyzed in section 4. Section 5 gives a summary and related discussion.

2. Model and observation data

The AGCM component of the coupled model comes from the China National Climate Center (Ye et al., 2000). It is a spectral model of triangular truncation with 63 wave numbers (approximately $1.875° \times 1.875°$). A hybrid coordinate is used in the vertical and all variables except vertical velocity are situated on full levels (the top and bottom boundaries of the model atmosphere are designated as half levels). For the hybrid coordinate, it is a common σ coordinate near the ground and a P coordinate in the stratosphere, with a hybrid form elsewhere. The model atmosphere is divided into 16 layers with 4 within the planetary boundary layer. There is a simple land surface model contained in the AGCM.

The OGCM component of the coupled model is the most recently published version of the world ocean general circulation model of LASG (Jin et al., 1999). The OGCM is a baroclinic model using geographical spherical coordinates with quasi-static equilibrium and Boussinesq approximation employed, and has a horizontal resolution nearly identical to that of the AGCM (approximately $1.875° \times 1.875°$). The model's top boundary is a free surface (Zhang et al., 1996). An eta coordinate is adopted in the vertical and the model ocean is divided into 30 layers unevenly with 12 layers within the upper 300 meters. The model variables are arranged with an Arakawa B grid. A thermodynamic sea ice model with schemes similar to that of Semnter (1976) and Parkinson and Washington (1979) is used to simulate the distribution of sea ice concentration, sea ice thickness, and sea ice surface temperature. The OGCM has before been used to couple with another sea ice model considering both thermodynamic and dynamic processes (Liu et al., 2000).

With a flux aggregation scheme (Grotzner et al., 1996) employed to represent the effect of sea ice inhomogeneities on flux exchange, a modified daily flux anomaly coupling scheme (Yu et al., 2000) is used to realize the coupling of the AGCM with the OGCM considering sea ice inhomogeneities in high latitude regions. A 50-year coupled model integration has been achieved but only the results of the last 30 years will be used in later analysis so as to exclude the influence of model spinup.

The observed sea ice concentration data are from the American National Snow and Ice Data Center (NSIDC). Though the data range from January 1901 to August 1995, only the part from 1954 are used since the data prior to this are mostly climatic values or interpolation results. The sea ice concentration data are values from the last day of each month, and not monthly averages.

The monthly mean reanalysis datatset from American National Center of Environment Prediction(NCEP) ranging from 1958 to 1997 is also used in the work.

3. Global climate simulated by the coupled model

Since regional climate is connected with its global climate background, to study climate in one area it is necessary to comprehend the situation over the larger

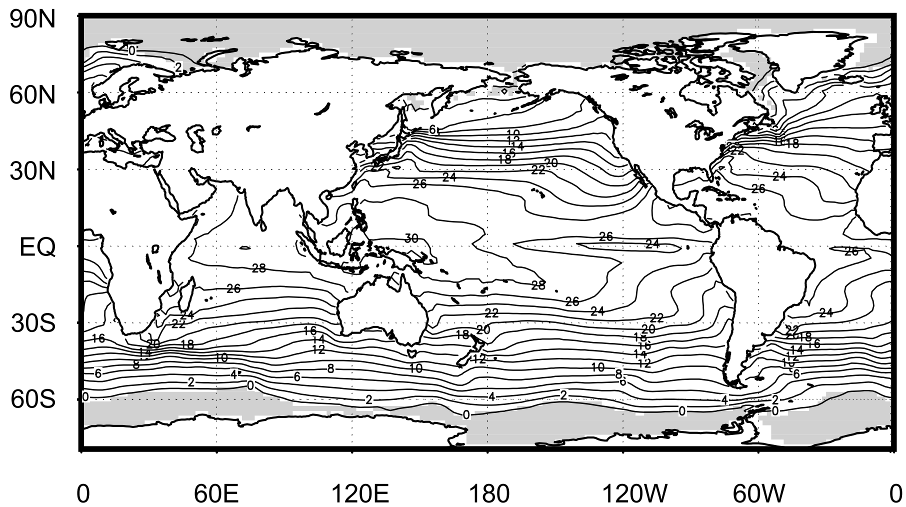

Fig. 1. Distribution of simulated annual mean sea surface temperature (contour interval is 2°C) and sea ice (denoted by shaded areas).

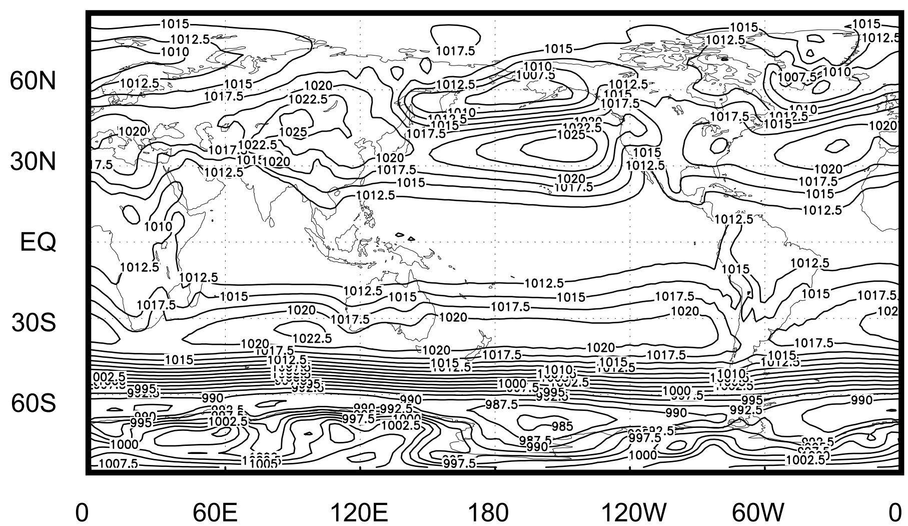

Fig. 2. Distribution of simulated annual mean sea level pressure. Contour interval is 2.5 hPa.

area containing it. Thus, the simulated global climate will be analyzed briefly at first.

The distribution of annual mean sea surface temperature (SST) and sea ice is shown in Fig. 1. Here, the SST is denoted by sea temperature at a depth of 12.5 meters in the model; when sea ice concentration in a grid is greater than zero it is marked as a sea ice zone. It shows that the major large scale features of SST, such as the equatorial warm belt, West Pacific warm pool, cold tongue in the Southeast Pacific near the equator, and cold tongue in the Northeast Pacific, are all reproduced well. Compared with the observed SST (Levitus, 1994; figure omitted), differences in most parts are less than 1°C and major differences lie in the equatorial East Pacific (120°–150°W, colder, maximum difference of about 2°C), open ocean 30°S and southward (warmer, maximum difference is about 2°C), and west boundary of the North Atlantic (warmer, maximum difference can reach 3°C). A stronger cold tongue in the equatorial middle and East Pacific is one of the major systematic errors commonly existing in OGCMs (Stockdale et al., 1998) and researchers are taking measures to understand it and seeking methods to diminish it (Zhang et al., 2003). The errors near the boundary which are severest may be due to boundary arrangement, and these errors have a close connection with model resolution. Compared with the observed sea ice distribution (figure

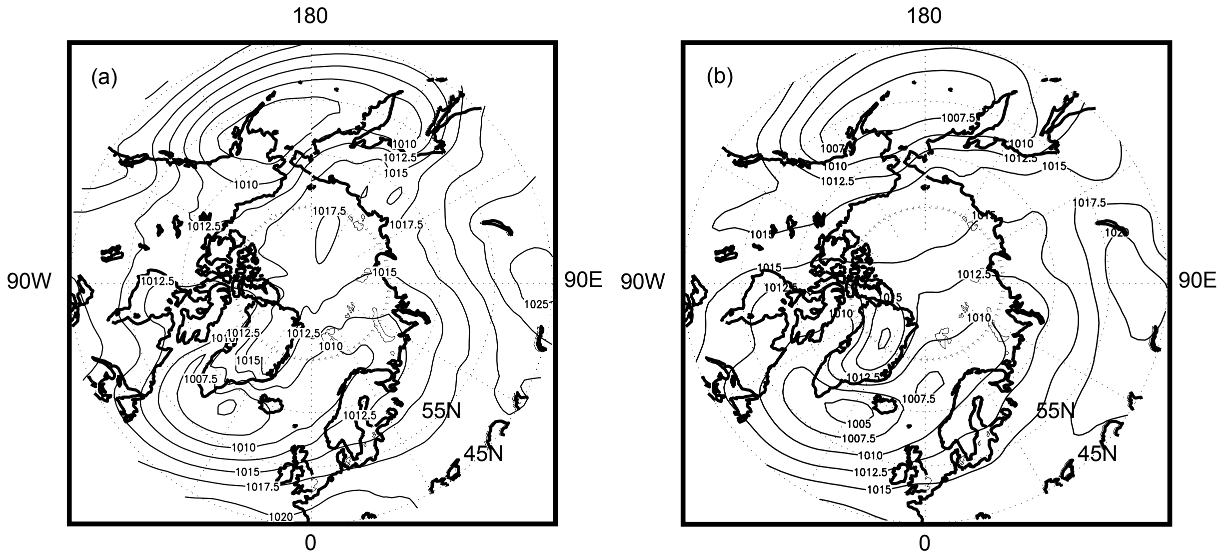

Fig. 3. Distribution of annual mean sea level pressure north of 45°N . Contour intervals are 2.5 hPa. (a) Coupled model; (b) NCEP reanalysis.

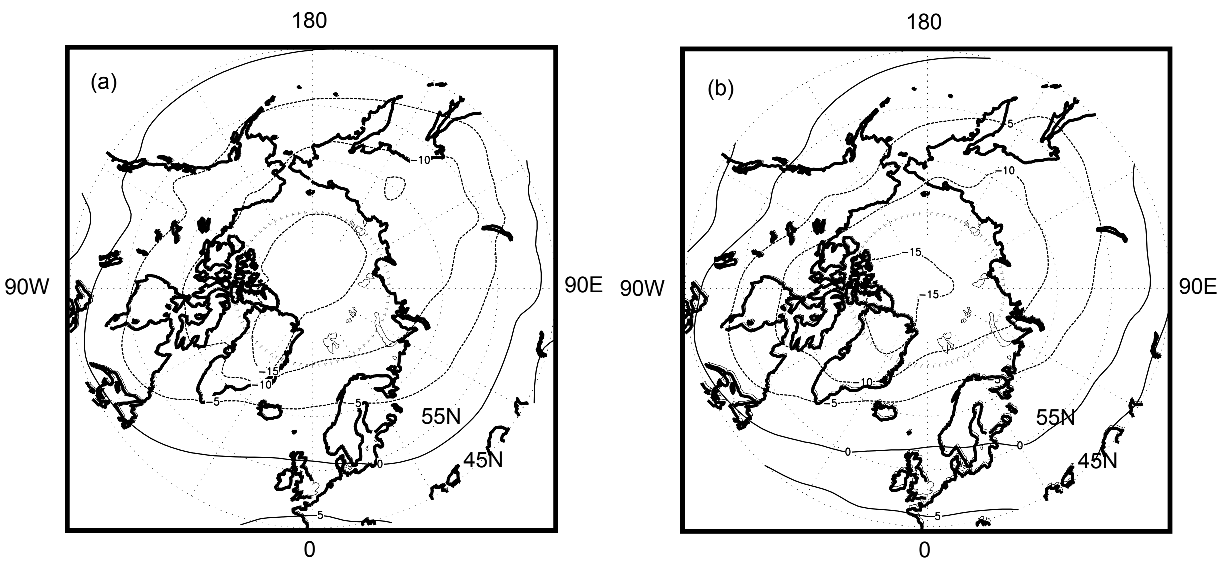

Fig. 4. Distribution of annual mean air temperature north of 45°N on 850 hPa. Contour intervals are 5 °C. (a) Coupled model; (b) NCEP reanalysis.

omitted), the simulated extent of sea ice coverage in the Southern Hemisphere is smaller.

Figure 2 illustrates the distribution of simulated annual mean sea level pressure. It shows that major activity centers are all reproduced. Compared with NCEP reanalysis results (not shown), the subtropical high is a little stronger, intensities of high centers in the North Pacific, North Atlantic and South Indian Ocean are all about 2.5 hPa stronger, and their positions have a slight displacement toward the poles of their respective hemisphere. But positions and intensities of major low centers (Aleutian low, Icelandic lowand Rose Sea low) all agree well with the NCEP reanalysis dataset.

For brevity, the results of annual mean sea surface temperature, sea ice, and sea level pressure only are shown here. It is clear that the coupled model can reproduce the major distribution characteristics of annual mean global climate quite well. But we have more interest in the regional climate within it. In the next section, the special concentration of the analysis will be on climate in high northern latitudes simulated by

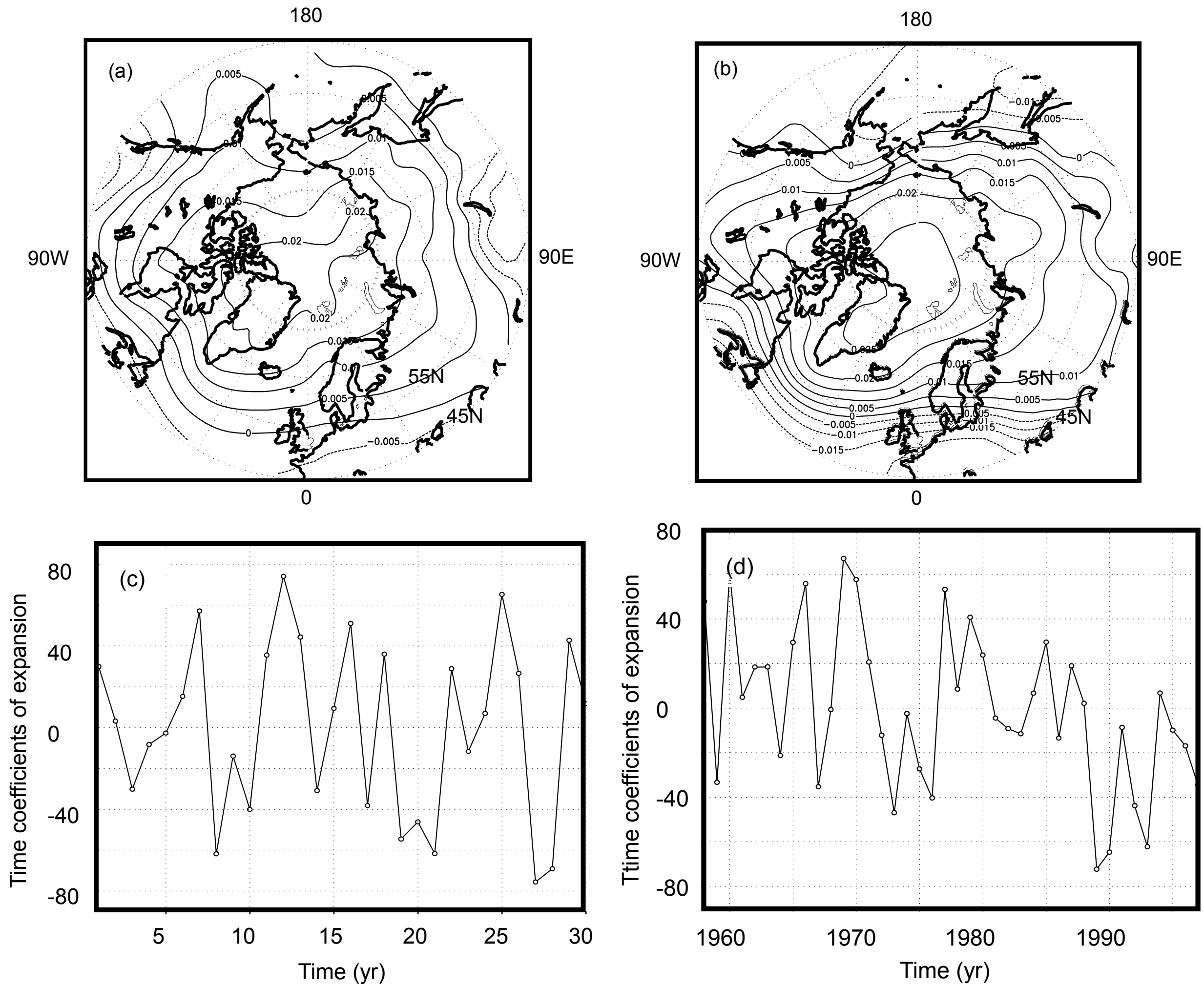

Fig. 5. Leading mode of empirical orthogonal function expansions for winter sea level pressure north of 45°N. (a) Simulation results (depicting 32% of the total variance). (b) NCEP reanalysis results (depicting 46% of the total variance). Upper panel is for space distribution and bottom panel is for time series.

the coupled model.

4. Climate in high northern latitudes

In this section, the analysis will be divided into two parts: one on the atmosphere component results and another on the ocean (including sea ice) component results. Since the sea surface in high northern latitudes is covered with sea ice to a great extent and sea surface temperatures there are close to the freezing point, analysis on results of the ocean component will be focused on sea ice only.

4.1 *Results of the atmospheric component*

Results of the atmospheric component are analyzed first, and the analysis will focus on the model's ability to reproduce the sea level pressure, air temperature, and Arctic Oscillation (AO) in high northern latitudes.

The major centers of activity in high northern latitudes are the Aleutian low, Icelandic low, and the high over the Eurasian continent. The positions and intensities of these activity centers have substantial influence on climate in high northern latitudes. Figure 3a is the simulated distribution of annual mean sea level pressure north of 45°N. From the figure, it can be seen that the coupled model can reproduce the major atmospheric activity centers in high northern latitudes quite well. Compared with the results of the NCEP reanalysis dataset (shown by Fig. 3b), the position and intensity of the simulated Aleutian low and Icelandic low are nearly equivalent, but the strength of the high center over the Eurasian continent is a little stronger and its displacement is very small as well.

The simulated distribution of air temperature north of 45°N at 850 hPa is shown by Fig. 4a. It is

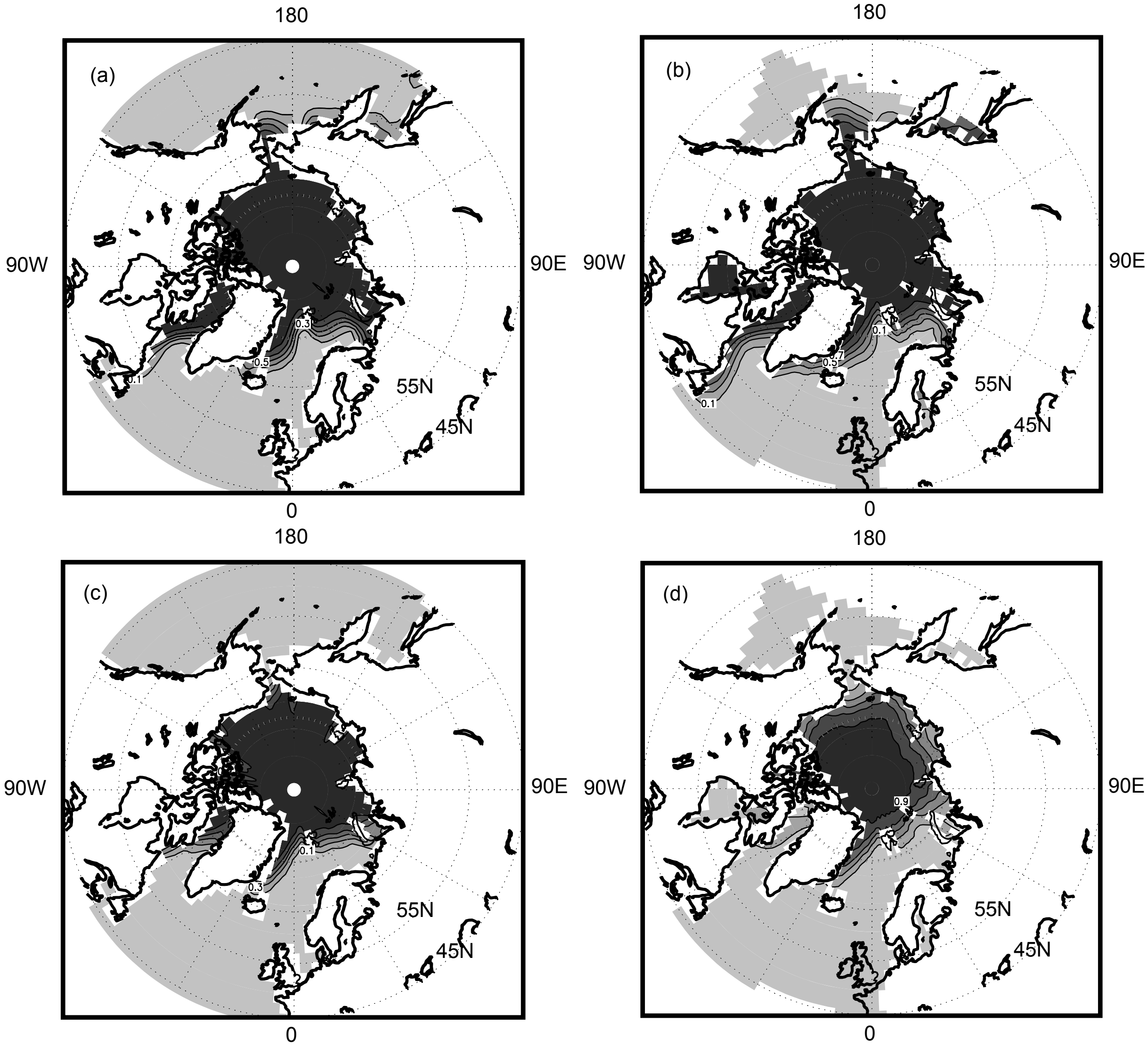

Fig. 6. Distribution of sea ice concentration in high northern latitudes (shaded areas denote ocean). Contour interval is 0.2. (a) Simulation results for winter, (b) Observation results for winter, (c) Simulation results for summer, and (d) Observation results for summer.

clear that the cold center leans toward Greenland within the Arctic Ocean and the minimum temperature is below $-15°C$. The position and intensity of the cold center and the extent of the area below $0°C$ are close to the NCEP reanalysis results (shown by Fig. 4b), whereas there is a larger stretch of area below $-15°C$ toward Greenland and the Far East region in the simulation.

The leading mode of winter sea level pressure in high northern latitudes is the Arctic Oscillation (AO)(Thompson and Wallace, 1998). The relationship between AO and climate in the Northern Hemisphere is a topic still deserving of further study. Figure 5a and Fig. 5b illustrate the leading mode of empirical orthogonal function (EOF) expansions for sea level pressure north of 45°N from the coupled model and NCEP reanalysis dataset, respectively. From the panels of the spatial distribution, it can be seen that both results of the simulation and NCEP reanalysis share common features: the sea level pressure anomaly exhibits contrary tendencies of variation for polar and extra-polar regions, and the contrary tendencies of variation are apparently zonally symmetric. This is the so called AO. There are significant interannual variations in the time series of the leading mode of EOF expansion for the simulation results. This trait also agrees with that of the NCEP reanalysis results qualitatively. All the results of this analysis show that the simulation of AO

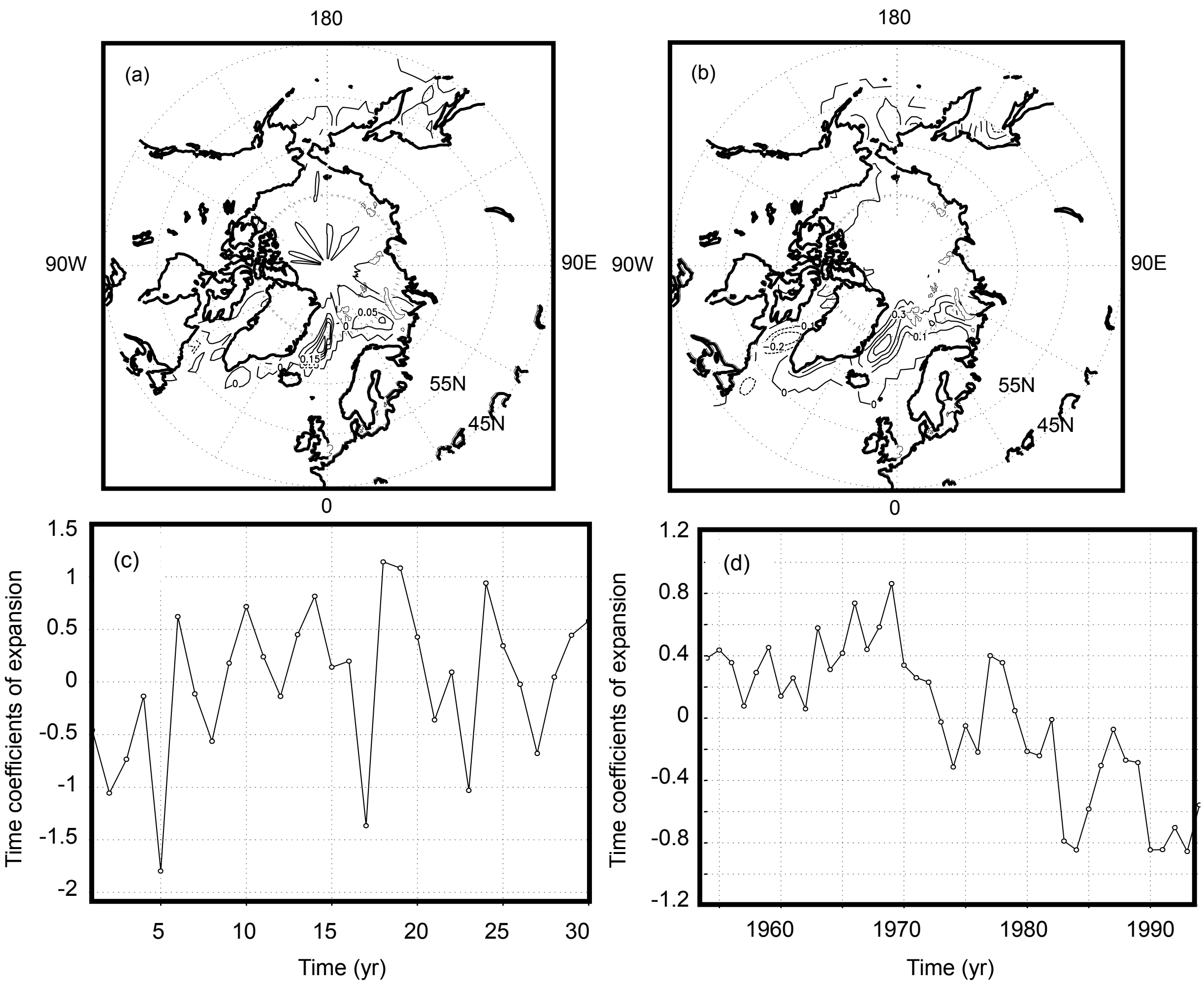

Fig. 7. Leading mode of empirical orthogonal function expansions for winter sea ice concentration in high northern latitudes. (a) Simulation results (depicting 36% of the total variance). (b) Observation results (depicting 31% of the total variance). Upper panel is for space distribution and bottom panel is for time series.

with the coupled model is successful.

4.2 *Results of the ocean component*

Since the sea surface in high northern latitudes is covered with sea ice to a great extent and since sea surface temperatures there are close to the freezing point, the analysis of the results of the ocean component will be focused on sea ice only.

Figures 6a and 6c give the distributions of sea ice concentration simulated by the coupled model for winter and summer respectively. Compared with the observed distributions (shown by Fig. 6b and Fig. 6d), the major characteristics of the geographical distribution for winter sea ice concentration are reproduced quite well. In particular, the simulated winter sea ice concentration north of 65°N is very close to the observations. The coupled model's deficiency in winter sea ice simulation lies in that the simulated sea ice extent in the Denmark Strait is a little small, it cannot reproduce the sea ice zone near the south edge of Greenland, the modelled sea ice extent cannot extend far enough southward along the coast of North America in the Labrador Sea (the observed winter sea ice area can extend as far as Newfoundland), and the simulated sea ice extent along the coast of America in the Bering Sea is also a little small. When summer comes, the sea ice coverage extent decreases and retreats northward. Sea ice in the Pacific Ocean vanishes, and the southern boundaries of sea ice in the Greenland Sea and the Barents Sea move northward. Furthermore, ice concentration in the Davis Strait and Baffin Bay decreases (as indicated by Fig. 6c). All of these characteristics agree with the results of observations well (shown by Fig. 6d). But the simulated sea ice concentration in the Davis Strait, Baffin Bay, and the marginal parts close to the Eurasian continent in the Arctic Ocean is larger than the observation. This may be related to boundary management of the ocean model and may be due to the absence of ice dynamics as well. It should be noted that Hudson Bay is treated as land in the ocean model due to the consideration of resolution.

To determine features of sea ice variability in space and time in high northern latitudes, an EOF expansion is made on winter sea ice concentration. Figure 7a and 7b illustrate the leading modes of EOF expansions for winter sea ice concentration north of 45°N from the coupled model and observations respectively. It can be seen from the curves of the time series that there are significant interannual variations for the simulated winter sea ice concentration in high northern latitudes. This is coincident with the observations. The most significant area of simulated interannual variation lies in the Greenland Sea, which is followed by the Barents Sea. These features agree well with the results from observations also. In the observations, there is a contrary tendency of variation between the Greenland Sea, Barents Sea, and Labrador Sea. But in the model results, only a small portion of the Labrador Sea experiences the opposite tendency of variation with respect to the Greenland Sea and Barents Sea. It is usually accepted that the contrary tendency of variation between the Greenland Sea, Barents Sea, and Labrador Sea has a connection with the North Atlantic Oscillation (NAO). When NAO is in its positive phase, there is more sea ice coverage in the Greenland Sea and Barents Sea. When NAO is in its negative phase, there is more sea ice coverage in the Labrador Sea. But it is still not clear whether the dynamic effect (wind drives the ice current to the Labrador Sea) plays the major role or the thermodynamic effect (thermodynamic effect to freeze sea water or to melt sea ice). Since the dynamic effect on sea ice is not considered in the model, it may be conjectured from the model results that the thermodynamic effect perhaps plays the major role in the former relationship. Besides, that there is a minor tendency of growth for the first ten years in the time series of the leading mode of the EOF expansion for the simulated sea ice concentration reveals that the coupled system has not achieved complete equilibrium. Associated with global warming, sea ice in the Greenland Sea is diminishing (there is a downward trend from the late 1960s in the observed time series). But this trend cannot be reproduced by the model since a global warming mechanism is not included.

5. Brief summary and discussion

In this paper, the simulation results from an ocean-sea ice-atmosphere coupled model are analyzed with an emphasis on evaluating the model's ability in mean climate reproduction in high northern latitudes. It is shown that the coupled model can simulate the main characteristics of the annual mean global sea surface temperature and sea level pressure well, but the extent of ice coverage simulated in the Southern Hemisphere is not large enough. The analysis of simulated climate in high northern latitudes consists of two parts: one on the atmosphere and another on the ocean. For the ocean part, the analysis concentrates on sea ice. The main distribution characteristics for simulated sea level pressure and temperature at 850 hPa in high northern latitudes agree well with their counterparts in the NCEP reanalysis data, and the model can reproduce AO mode successfully. The simulated seasonal variation of sea ice in Northern Hemisphere is rational and major features in the simulated sea ice distribution in winter agree well with those from observations. But the ice concentration in the sea ice edge area close to the Eurasian continent in the inner Arctic Ocean is much larger than the observation. There are significant interannual variation signals in the simulated sea ice concentration in winter in high northern latitudes, and the most significant area lies in the Greenland Sea, which is followed by the Barents Sea. All of these features agree well with the results from observations.

The simulation results from a coupled model have a close relationship to the coupling scheme. The scheme used here is daily flux anomaly coupling. If another coupling scheme is adopted, it may induce differences in the model results. Based on the same model components, a simulation experiment with the daily direct coupling scheme was made by Liu (2001). But analysis of these results are very primary and more work needs to be done to make pertinent comparisons between the results from the two different coupling schemes. Besides, it may be significant to compare the results in this paper with those from other coupled models to some extent. Due to limits in computing capacity, it is difficult to make an assembly simulation at present; so this is left for a later time.

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