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Sensitivity and nonlinearity of Eurasian winter temperature response to recent Arctic sea ice loss

SUI Cuijuan[1, 2*], ZHANG Zhanhai[1], YU Lejiang[3], LI Yi[2], SONG Mirong[4]
[1] College of Physical and Environmental Oceanography, Ocean University of China, Qingdao 266100, China
[2] National Marine Environmental Forecasting Center, Beijing 100081, China
[3] Polar Research Institute of China, Shanghai 200129, China
[4] Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

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Abstract

The recent decline in the Arctic sea ice has coincided with more cold winters in Eurasia. It has been hypothesized that the Arctic sea ice loss is causing more mid-latitude cold extremes and cold winters, yet there is lack of consensus in modeling studies on the impact of Arctic sea ice loss. Here we conducted modeling experiments with Community Atmosphere Model Version 5 (CAM5) to investigate the sensitivity and linearity of Eurasian winter temperature response to the Atlantic sector and Pacific sector of the Arctic sea ice loss. Our experiments indicate that the Arctic sea ice reduction can significantly affect the atmospheric circulation by strengthening the Siberian High, exciting the stationary Rossby wave train, and weakening the polar jet stream, which in turn induce the cooling in Eurasia. The temperature decreases by more than 1°C in response to the ice loss in the Atlantic sector and the cooling is less and more shifts southward in response to the ice loss in the Pacific sector. More interestingly, sea ice loss in the Atlantic and Pacific sectors together barely induces cold temperatures in Eurasia, suggesting the nonlinearity of the atmospheric response to the Arctic sea ice loss.

Key words: cold winter, CAM5, sensitivity experiment, jet stream

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1 Introduction

Sea ice is an important component of climate system and plays a significant role in the ocean surface heat budget by mediation of surface heat flux and ice-albedo feedback. The rapid reduction in the Arctic sea ice will profoundly affect other components of climate system, including the Arctic atmospheric circulation. The decrease in ice-albedo feedback in open water due to the reduction of sea ice leads to lower reflected energy and more heat stored in the sea during summer (Manabe and Stouffer, 1980; Curry et al., 1995) and higher surface temperature in autumn and winter resulting from more energy flux transports from the sea to the atmosphere (Serreze et al., 2009; Screen and Simmonds, 2010; Serreze and Barry, 2011), especially in October after the month experiencing the minimum ice extent (Stroeve et al., 2012). The increasing heat flux from the sea to the atmosphere may also lead to the reduction of vertical stability in the Arctic lower troposphere (Francis et al., 2009; Overland and Wang, 2010; Stroeve et al., 2007; Jaiser et al., 2012) and the increase in the 1 000–500 hPa thickness. Also according to the theoretical concept of thermal wind, the reduction of the meridional gradient of the 1 000–500 hPa thickness leads to the abatement of zonal wind in the mid-troposphere and the increase of the strength of meridional circulation (Vihma, 2014; Francis and Vavrus, 2012; Deser et al., 2007), thus helping transport more cold Arctic air to the top latitudes and induce colder winter there (Tang et al., 2013). In 2007/2008, 2009/2010, 2010/2011, 2011/2012, and 2012/2013, some regions of Eurasia experienced exceptionally cold winters (Wu et al., 2015).

Several scientific papers have conducted empirical analysis with observations and addressed the potential causal links between the Arctic sea ice decline and these cold winters in midlatitudes (Francis et al., 2009; Francis and Vavrus, 2012, 2015; Tang et al., 2013) and so-called “Warm Arctic, Cold Continents” has been hypothesized (Overland et al., 2011). However, this hypothesis has been recently challenged and it has been suggested that cold winters might be explained by atmospheric internal variability and not been caused by the Arctic change (Sun et al., 2016; McCusker et al., 2016). Indeed, given the fact that we only have decades of observations during the sea ice loss period and there is large internal variability in atmospheric circulation, any empirical analysis on the Arctic-midlatitude linkage must be conducted very cautiously and the connection between Arctic and midlatitude cold winters may appear just by chance (Barnes and Screen, 2015). Besides, the correlation itself cannot tell whether the Arctic change is causing lower latitude, or being affected by the lower latitudes (Perlwitz et al., 2015). It is only through model simulations that such causality can be clearly clarified.

Unfortunately, there are still considerable uncertainties

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*Corresponding author, E-mail: suicj@nmefc.gov.cn

among modeling studies of the impact of recent Arctic sea ice loss on atmospheric circulation and surface climate so that it is unclear whether the Arctic change is causing midlatitudes cold winters or not. Some modeling studies found a connection between the sea ice loss and cooling in midlatitude continents (e.g., Honda et al., 2009; Petoukhov and Semenov, 2010; Liu et al., 2012a; Kug et al., 2015), while others do not see significant linkage (e.g., Screen et al., 2013; Gerber et al., 2014; Perlwitz et al., 2015; Li et al., 2015; Sun et al., 2016; McCusker et al., 2016). This diversity in modeling results might be due to signal-to-noise issue (e.g., Screen et al., 2014), yet it is still interesting to understand if there is any sensitivity in the atmospheric response to the recent sea ice loss, more specifically sensitivity to the spatial distribution of the sea ice loss.

Besides, as a complex system there might be nonlinearity of the atmospheric response to the Arctic sea ice loss. For example, Petoukhov and Semenov (2010) and Peings and Magnusdottir (2014) found that there is not a linear relationship between a decrease of the Arctic sea ice and lower temperatures over midlatitudes, i.e., the greater the sea ice reduces, the more frequent the cold events not happen. More recently, Screen and Francis (2016) demonstrated that atmospheric response to the Arctic sea ice loss depends on the state of the Pacific Decadal Oscillation (PDO). Thus it might be worth investigating whether there is any nonlinearity for the Eurasian winter temperature response to the Arctic sea ice loss.

In this paper, we have conducted several modeling experiments to isolate the effect of recent sea ice loss in the Atlantic and Pacific sectors of the Arctic Ocean, aiming at examining the sensitivity and linearity of Eurasian winter temperature response to sea ice decline. We notice that the reduction magnitude of Arctic sea ice varies in different regions and seasons. For example, the melt speed in the Pacific sector is faster during summer and autumn while melt speed in the Atlantic sector is faster during spring and winter. The more sea ice melted from 2009 to 2012 in the Eastern Hemisphere, especially in the Barents Sea during winter and spring and in the Chukchi Sea during summer and autumn (Sui et al., 2015). Thus it is reasonable to look at the effect of sea ice loss in the Atlantic sector and Pacific sector separately. The main focus of this paper is Eurasia, especially central and East Asia. Kug et al. (2015) found that colder winters across East Asia are associated with anomalous warming in the Barents-Kara Seas region, whereas colder winters over North America are related to anomalous warming in the East Siberian-Chukchi Seas region. It indicates that the responses of the atmospheric circulation in the Northern Hemisphere to the reduction of the Arctic sea ice vary in different regions.

This rest of this paper is organized as follows. The model and experimental design are provided in Section 2. Results are presented in Section 3. The discussion and conclusion are presented in Section 4.

2 Model and experimental design

We utilize the Community Atmosphere Model Version 5 (CAM5), the latest version of atmosphere model at the National Center for Atmospheric Research (NCAR), which also serves as the atmospheric component of the Community Earth System Model (CESM). There are 30 vertical levels in the model with a horizontal resolution of 1.9° longitude and 2.5° latitude. Details of the model can be found in Neale et al. (2010).

CAM5 is used to examine the response of Eurasian winter surface air temperature to the rapid reduction of Arctic sea ice in autumn and winter. One control and three perturbation experiments have been conducted, each of which contains 50 samples. The first-year samples are discarded as spinning up and the samples of the other 49 years are averaged. Anomalies are calculated by subtracting the control run from the perturbation run. Two-sided student's t-test is used to evaluate the statistical significance.

For the control experiment (CTL), integration referred to the self-force filed in the model and the bottom boundary conditions are the monthly sea surface temperature (SST) and sea ice concentration (SIC) for the period of 1981 to 2006 from the Hadley Center. Compared with the control run, only SIC/SST boundary conditions in autumn and winter are modified in the perturbation experiments (the ice concentration is the same in September, October and November, and the same in December, January and February). Monthly ice concentration data in the experiments are derived from SSMI/R data for the period of 1979 to 2012, and the sea ice anomalies in autumn and winter for each year are obtained by subtracting the climatological values for the period of 1981 to 2010. Integration of specific melting years are selected as the bottom boundary and SST field where the changes of sea ice exceeded 0.1 lattice point was replaced by HADISST data to avoid SST being the control factor as climatology. The impact of the ice reduction on the warming of SST (Screen et al., 2013) is considered in the test, i.e., only the changes of sea ice and the SST changes directly related to sea ice would be taken into consideration.

The first perturbation experiment (Atlantic-Melt, hereinafter referred to as AM) is carried out to detect the impact of sea ice reduction in the Atlantic sector of the Arctic Ocean (60°E–60°W) on wintertime temperature in Eurasia. The second one (Pacific-Melt, hereinafter referred to as PM) is conducted to detect the impact of sea ice reduction in the Pacific sector of the Arctic Ocean (120°E–120°W) on wintertime temperature in Eurasia. The third one (Both-Melt, hereinafter referred to as BM) is conducted to detect the impact of the reduction in sea ice in both Atlantic and Pacific sectors on Eurasian winter temperature. It is worth noting that the reduction of sea ice in BM is not equal to the sum of those in AM and PM. First we chose the sea ice extent minimum of ten years in the Atlantic sector and Pacific sector separately. If the year ice reduction in both Atlantic and Pacific sectors belongs to BM experiment, otherwise the year belongs to AM or PM experiment. Table 1 gives the year of compose and Fig. 1 shows the sea ice anomalies in the three experiments.

3 Results

Figure 2 shows the impact of the rapid reduction of sea ice in different regions of the Arctic Ocean on surface temperature in Eurasia (perturbation run minus control run). In three experiments, surface temperature increases significantly in ice melting regions in autumn. For example, Arctic warming resides in the Atlantic sector in AM experiment and in the Pacific sector in PM experiment. In addition warming region in BM experiment is larger and extends to the midlatitudes. Moreover, cooling regions caused in autumn by all these three experiments are located at the region around 50°N, 90–100°E, and the extent and magnitude of the negative temperature is larger for PM test than those for AM and BM tests. The anomalous surface temperature in winter displays positive anomalies in the Arctic Circle and negative values in top latitudes, a pattern normally referred to as "Warm Arctic, Cold Continents" (Overland et al., 2011).

Next we demonstrate the sensitivity and nonlinearity of Eurasian winter temperature response to the Atlantic and Pacific sectors of the Arctic sea ice loss by comparing three perturbation

Table 1. The years with anomalous sea ice field used as the boundary conditions in three sensitivity experiments

Atlantic-Melt		Pacific-Melt		Both-Melt	
Autumn	Winter	Autumn	Winter	Autumn	Winter
1984	1999/2000	2003	1983/1984	2004	2004/2005
2000	2000/2001	2005	1990/1991	2007	2005/2006
2001	2007/2008	2006	1995/1996	2008	2006/2007
	2009/2010		1996/1997	2009	2008/2009
	2011/2012		2003/2004	2010	2010/2011
				2011	
				2012	

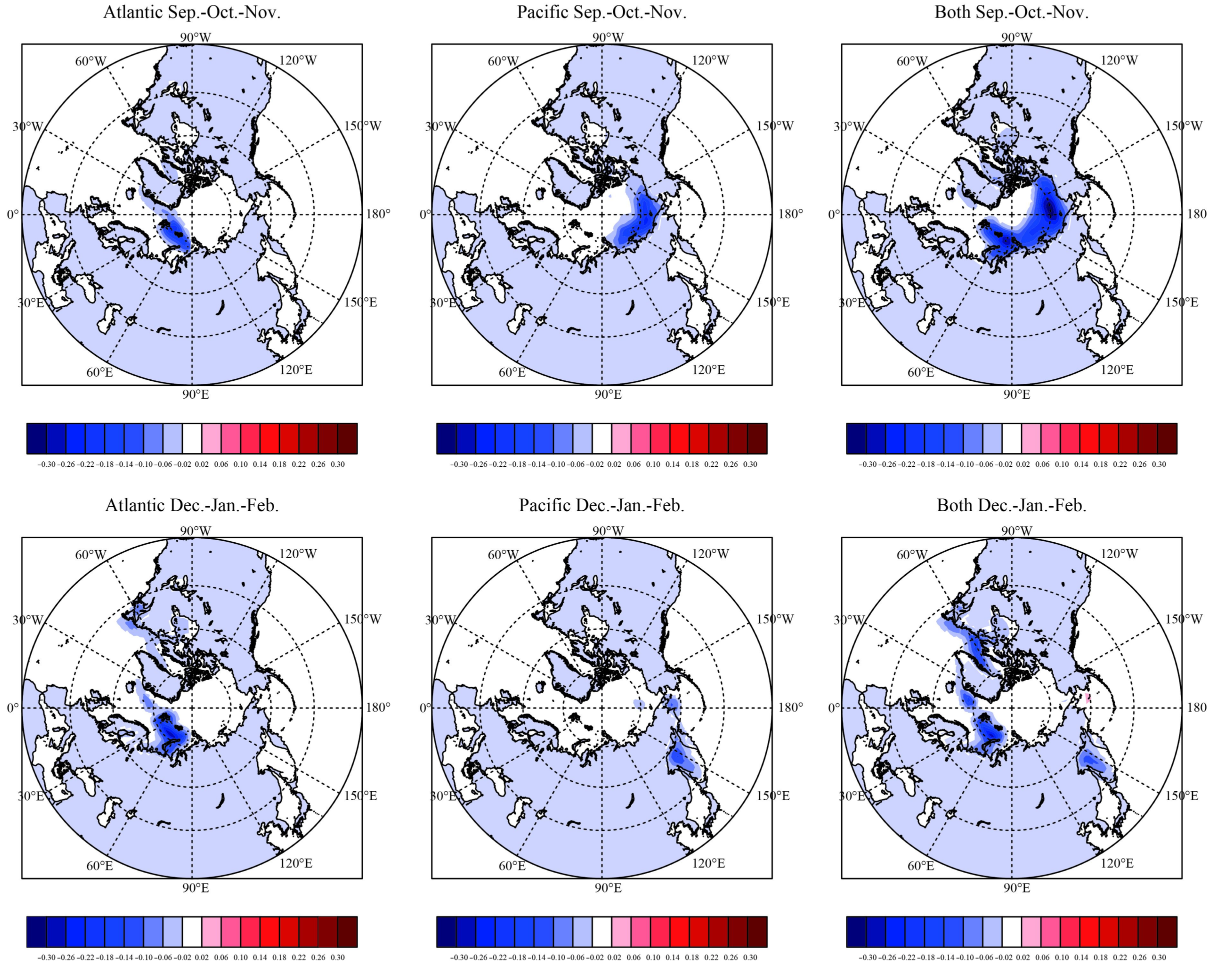

Fig. 1. Anomalous ice concentration field (SIC, %) in autumn and winter in the sea ice sensitivity experiments.

experiments. The Eurasian winter temperature decreases by more than 1°C in the AM experiment. It is consistent with the result of previous studies: the Barents Sea and Kara Sea are the key regions where the early changes of sea ice extent can lead to the wintertime cold anomaly in Eurasia (Wu et al., 1999; Honda et al., 2009; Petoukhov et al., 2010). Like AM, ice melting in the Pacific sector in PM experiment leads to the wintertime cooling in Eurasia but the cooling was not as significant as in the Atlantic sector, and the cold region was further southern. More interestingly the cooling response exerts little impacts on the low temperature in Eurasia in BM experiment.

The Eurasian cold temperatures in these experiments are closely related to the atmospheric circulation changes. Figure 3 presents the results of sea level pressure anomaly in winter. AM experiment indicates that higher sea level pressure in Greenland and Russia and lower sea level pressure in Aleutian could result from sea ice melting in the Barents-Kara Seas. PM experiment shows that wintertime lower pressure in central area of the North Pole and higher pressures over Russia would be caused by the sea ice melting in the Okhotsk Sea. BM experiment indicates that the ice melting would lead to lower pressure along the northern Europe, North Pole, North America and higher pressure in Greenland and north of Russia in winter. In short, the area and intensity of Siberian High caused by AM experiment is more significant than that by PM and BM experiments in winter and the intensity of Siberian High in BM experiment was the weakest.

According to anomalous wind field in 850 hPa (Fig. 4), anomalies northwesterly winds appear in East Asia bring frigid air southwards in all sensitivity experiments but the intensity is different. The wind speed is the largest in AM experiment, which is

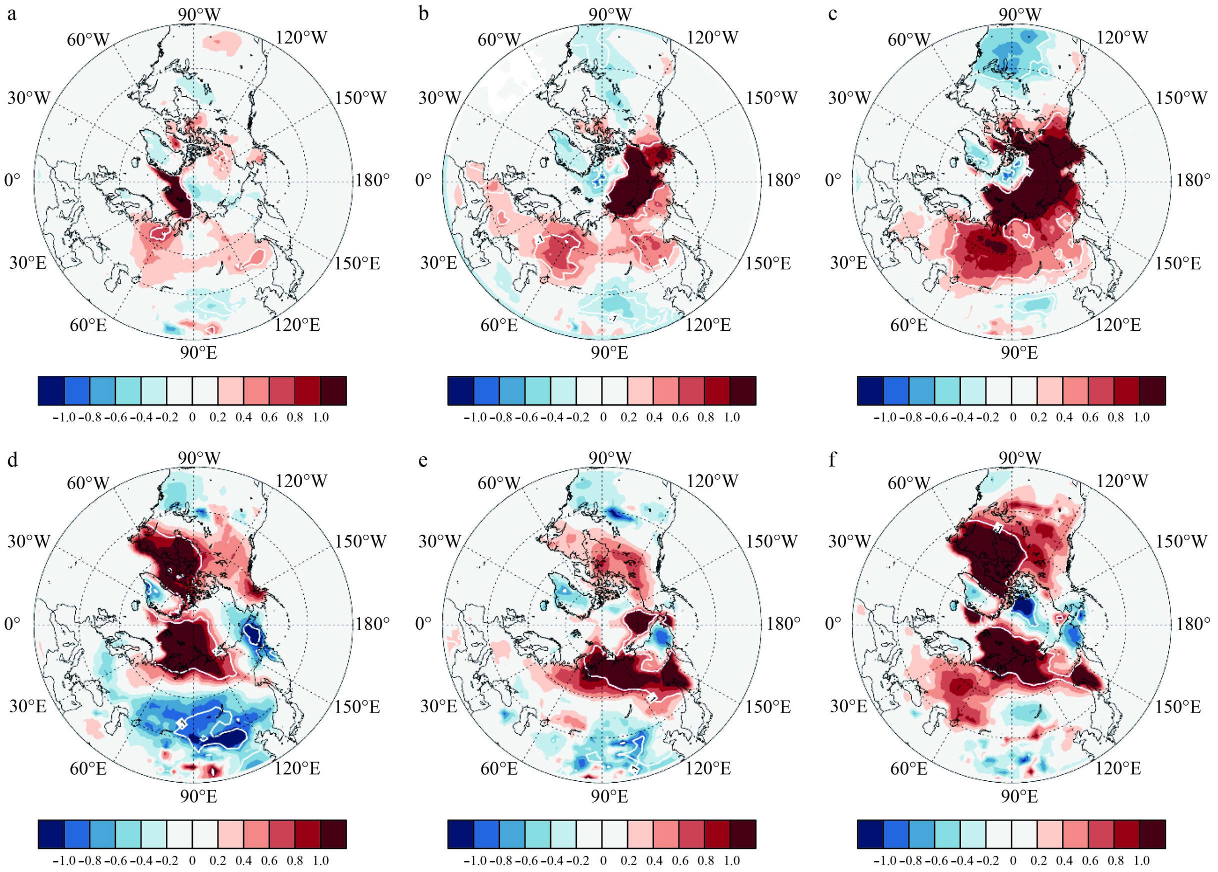

Fig. 2. Anomalous surface temperature field (°C). White line indicates the 90% confidence level. a and d. Ice melting experiments in the Atlantic sector respectively during autumn and winter; b and e. ice melting experiments in the Pacific sector respectively during autumn and winter; and c and f. ice melting experiments along both Atlantic and Pacific Oceans respectively during autumn and winter.

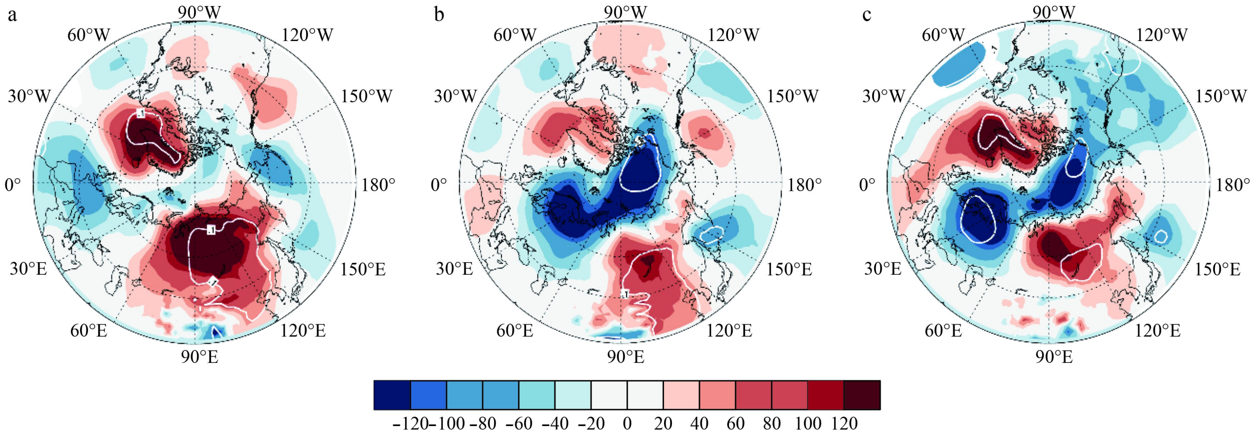

Fig. 3. Anomalous sea level pressure fields (hPa) in winter. White line indicates the 90% confidence level. a. Ice melting experiments in the Atlantic sector; b. ice melting experiments in the Pacific sector; and c. ice melting experiments in the both sector.

caused by the Siberian High and Aleutian Low. Therefore, the cooling was most obvious during AM experiment in Eurasia. Wintertime positive anomaly centers exist around 90°E and 120°E, indicating that the spatial pattern of the anomalous 500-hPa height is similar to that of the anomalous sea level pressure and it is a barotropic structure induced by the reduction of the Arctic sea ice. In the anomalous sea-ice cover in winter in AM experiment, a stationary Rossby wave train is excited which leads to anticyclonic anomalies over the Barents Sea and cyclonic anomalies over East Asia. It is in accordance with the result of Honda et al. (1999). The PM experiment also tends to excite a stationary Rossby wave train in anomalous sea-ice cover. In contrast to AM experiment the positive height anomalies weaken, but the negative anomalies strengthen. But in BM experiment we could not find the cyclonic anomalies in Eurasia.

Jet stream in the tropopause is an important driving factor of

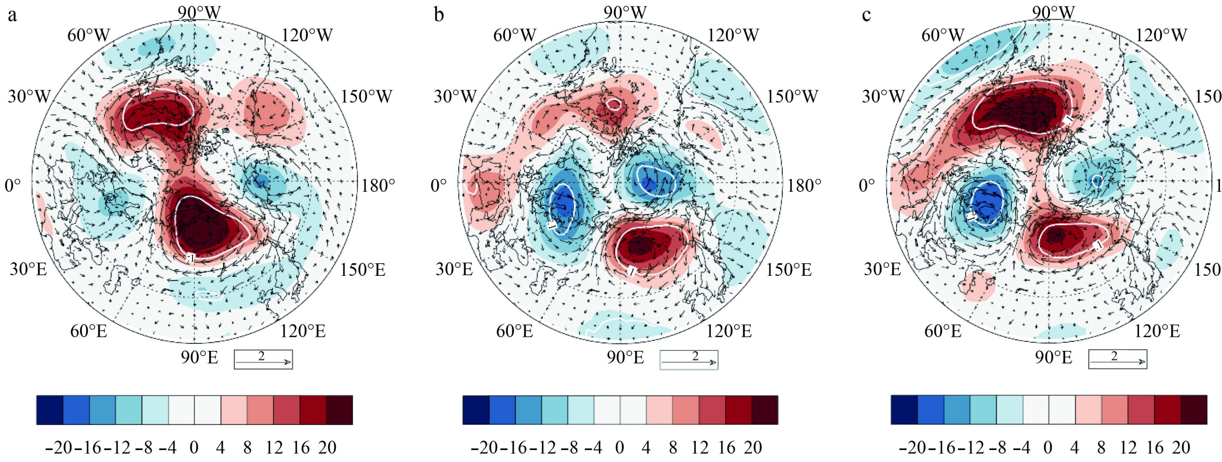

Fig. 4. Anomalous wind fields (m/s) in 850 hPa and anomalous height fields (m) in 500 hPa in winter. White line indicates the 90% confidence level. a. Ice melting experiments in the Atlantic sector, b. ice melting experiments in the Pacific sector, and c. ice melting experiments in the both sector.

weather in top latitudes. Jet stream and its anomaly field in the northern hemisphere in the control run are calculated according to the definition between 400 and 100 hPa put forward by Archer and Caldeira (2008) (Fig. 5):

$$\mathrm{WS}_{i,j} = \frac{\sum_{k2}^{k1} m_k \times \sqrt{u_{i,j,k}^2 + v_{i,j,k}^2}}{\sum_{k2}^{k1} m_k},$$

where $u_{i,j,k}$ and $v_{i,j,k}$ are the average horizontal wind components at grid point (i, j, k), and m_k is the mass at level k. $k1$ is 100 hPa and $k2$ is 400 hPa.

The result of control run (Fig. 5a) is consistent with those of the observed data. The successive maximum wind speed of the wintertime jet stream occur around 30°N, forming a nearly continuous band between northern Africa and Hawaii. The strength of the polar jet stream decreased around 60°N in AM experiment (Fig. 5b). The PM experiment and BM experiment also witnessed the decreased strength of the polar jet stream. The weakened jet helps the southward movement of the cold air from the North Pole, thus leading to the cooler Eurasia. On the contrary the jet stream over East Asia shows a stronger tendency, leading to the

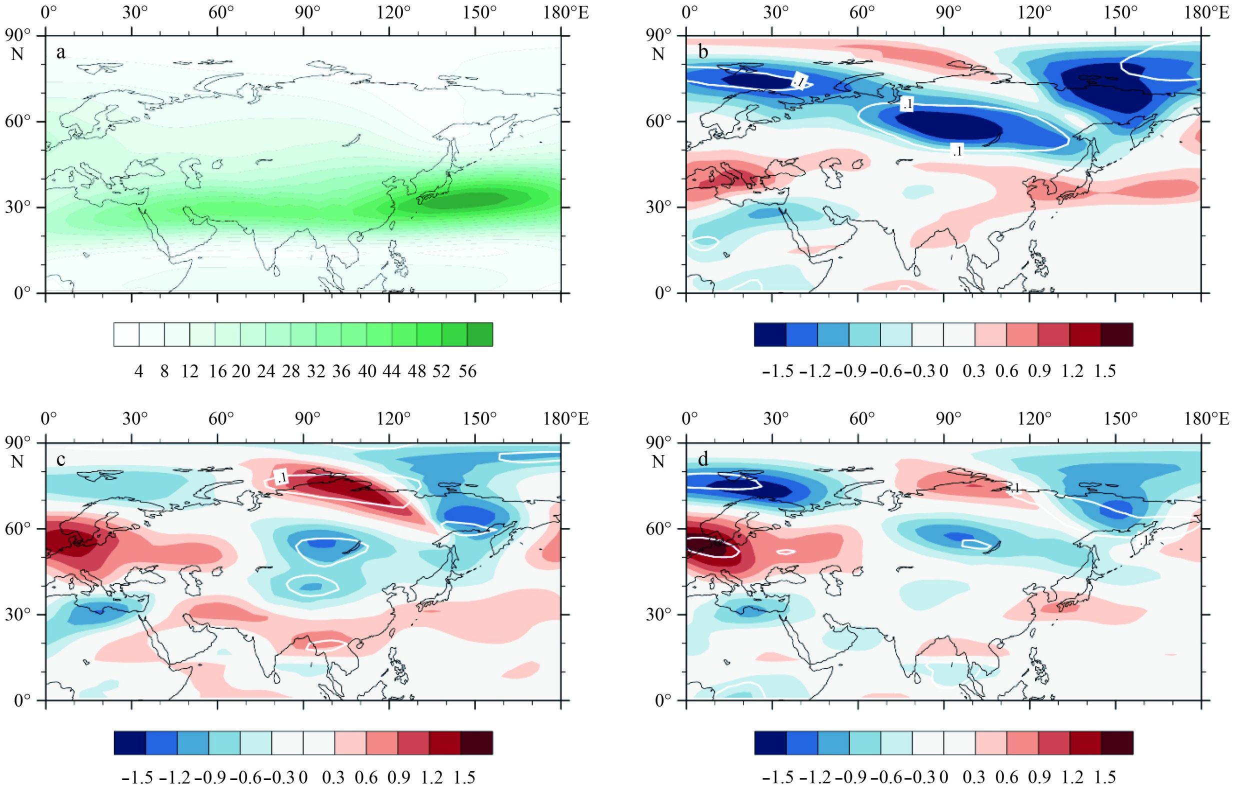

Fig. 5. Jet stream (m/s) in the Northern Hemisphere. a. Control tests, b. ice melting experiments in the Atlantic sector, c. ice melting experiments in the Pacific sector, and d. ice melting experiments along both Atlantic and Pacific Oceans.

more occurrence of cold air break here. The magnitude of the anomalous jet stream shows a markedly difference among three experiments. The strongest decreased jet occurs in AM experiment indicating that AM experiment is most influential on the cold winter in Eurasia. In PM experiment the significantly positive jet occurs over Asia south of 30°N, which is favorable for the invasion of cold air into here.

4 Conclusions

Since the 1980s the Arctic temperature has increased at a rate more than double that of the Northern Hemisphere average, Arctic warming may be responsible for bouts of abnormally cold weather a thousand kilometers south of the Arctic Circle. Extensive simulations strongly suggest that near-surface Arctic warming and loss of sea ice can modify the midlatitudes circulation. For Example, the dramatic reduction of sea ice in 2007 produced an atmospheric response that contributed to the severe January 2008 snowstorm in China (Liu et al., 2012b). Sensitivity experiments for the ice reduction in the Atlantic sector, Pacific sector and both sectors in autumn and winter are conducted with CAM5 to analyze the impact of the reduction in sea ice in different regions on Eurasian temperatures. The results can be summarized as follows:

(1) Our experiments have revealed the sensitivity of Eurasian temperature response to the Atlantic sector and Pacific sector of the Arctic sea ice loss. In particular, we find that sea ice loss in the Atlantic sector has a larger impact in causing more Eurasian cold winter than ice loss in the Pacific sector. This is consistent with earlier findings that the ice loss in the Barents-Kara Seas may be responsible for the recent cold winters in central and East Asia.

(2) Our experiments also highlight the nonlinearity of atmospheric circulation response to the Arctic sea ice loss. Even though in our experimental design, the ice loss in BM is not equal to the sum of AM and PM, the disappearing of the Eurasian winter cold temperatures response in BM experiment does show some hints that more sea ice does not mean more cold winters in Eurasia. This might have implication to understand why some modeling experiments do not see a clear connection between sea ice loss and midlatitude cold winters (Screen et al., 2013; Gerber et al., 2014; Perlwitz et al., 2015; Li et al., 2015; Sun et al., 2016; McCusker et al., 2016).

(3) The sensitivity and nonlinearity of the Eurasian winter temperature response to the Arctic sea ice loss are closely connected to the responses in atmospheric circulation. The anomalous sea level pressure, 850-hPa wind fields, 500-hPa geopotential height fields and jet streams indicated that the impact of the sea ice reduction in sensitivity experiment on Eurasian cold winter was associated with the reduction of jet streams and the southward intrusion of cold airs. In AM and PM experiments anomalous sea-ice covers excite a stationary Rossby wave train, leading to anticyclonic anomalies over the ice melting region and cyclonic anomalies over East Asia (southern parts of China in PM experiment). But we could not find these in BM experiment. Although in three experiments ice melting can increase the strength of Siberian High, their intensities are different.

In conclusion, the results of CAM5 showed that the influence of reduction in Arctic sea ice in different region on winter temperature in Eurasia was different, and the effect was more obvious in Atlantic sector. Wu et al. (2015) described two dominant patterns of Asian winter climate variability: the Siberian High (SH) pattern and the Asia-Arctic (AA) pattern. They found sea ice loss in the prior autumn emerges in the Siberian marginal seas, and winter loss mainly occured in the Barents Sea, Labrador Sea, and Davis Strait could bring the positive phase of the SH pattern and sea ice loss in the prior autumn was observed in the Barents-Kara Seas, western Laptev Sea, and Beaufort Sea, and winter loss only occurs in some areas of the Barents Sea, Labrador Sea, and Davis Strait could bring the positive phase of the AA pattern.

Francis et al. (2015) proposed that warming of the Arctic can modify the shape of the jet stream enough to directly influence the weather at midlatitudes. Because of the complexity of the atmospheric physics behind circulation patterns, it is unclear exactly how a warming Arctic and loss of sea ice may give rise to a wavy jet stream. After all, cold snaps even more severe than those in the 1980s in Europe, when the Arctic sea ice was thicker and more extensive than it is today (Overland, 2016). It also implies that the relationship between the Arctic sea ice loss and winter atmospheric variability over East Asia is unstable (Wu et al., 2015). At the same time, North America has been under the influence of the extreme weather during recent years, and further analysis will be conducted to study the relationship between cold weather and the Arctic sea ice.

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