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Response of the Dominant Modes of Atmospheric Circulation in the Northern Hemisphere to a Projected Arctic Sea Ice Loss in 2007

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Abstract This study revisits the Arctic sea ice extent (SIE) for the extended period of 1979–2015 based on satellite measurements and finds that the Arctic SIE experienced three different periods: a moderate sea ice decline period for 1979–1996, an accelerated sea ice decline period from 1997 to 2006, and large interannual variation period after 2007, when Arctic sea ice reached its tipping point reported by Livina and Lenton (2013). To address the response of atmospheric circulation to the lowest sea ice conditions with a large interannual variation, we investigated the dominant modes for large atmospheric circulation responses to the projected 2007 Arctic sea ice loss using an atmospheric general circulation model (ECHAM5). The response was obtained from two 50-yr simulations: one with a repeating seasonal cycle of specified sea ice concentration for the period of 1979–1996 and one with that of sea ice conditions in 2007. The results suggest more occurrences of a negative Arctic Oscillation (AO) response to the 2007 Arctic sea ice conditions, accompanied by an North Atlantic Oscillation (NAO)-type atmospheric circulation response under the largest sea ice loss, and more occurrences of the positive Arctic Dipole (AD) mode under the 2007 sea ice conditions, with an across-Arctic wave train pattern response to the largest sea ice loss in the Arctic. This study offers a new perspective for addressing the response of atmospheric circulation to sea ice changes after the Arctic reached the tipping point in 2007.

Key words Arctic sea ice loss; Arctic Oscillation; Arctic Dipole; atmospheric response

1 Introduction

The Arctic sea ice extent (SIE) has shown a dramatic decline in all months, with the unexpected lowest extents in the summers of 2007, 2012, and 2015, periods when continuous satellite measurements were available (Serreze *et al*., 2007; Comsio *et al*., 2008). Sea ice is not only a sensitive component of the climate system, but also an efficient trigger for climate and ecosystem changes. Previous studies have noted that sea ice can modulate climate by altering the surface albedo (Serreze and Barry, 2011; Cohen *et al*., 2014; Walsh, 2014), exchange of heat, moisture, and momentum between the atmosphere and the ocean (Kurtz *et al*., 2011; Kwok *et al*., 2013); it can also alter upper ocean stratification in areas of deep water formation (Rudels and Quadfasel, 1991). Along with Arctic sea ice loss, the Arctic near-surface air temperature has risen twice as much as the global average for recent decades, a phenomenon referred as the Arctic Amplification (Screen and Simmonds, 2010; Overland *et al*., 2015). An increasing amount of observational evidence suggests that the ongoing decline of Arctic sea ice associated with Arctic warming may have impacted various aspects of the climate, such as changes in atmospheric circulation patterns, precipitation, and storm activities (Sewall, 2005; Singarayer *et al*., 2006; Gerdes, 2006; Overland *et al*., 2008; Seierstad and Bader, 2009; Screen, 2013) as well as the occurrence of Eurasian extreme cold winters (Honda *et al*., 2009; Liu *et al*., 2012).

Observational evidence and climate modeling studies suggest that the rapid changes in Arctic sea ice are associated with large-scale atmospheric variations, such as the Arctic Oscillation (AO) and the Arctic Dipole (AD). Due to the strong circumpolar nature of the AO and the strong meridionality of the AD, these two internal climate modes can greatly influence the distribution and movement of Arctic sea ice (Rigor *et al*., 2002; Wu *et al*., 2006; Ogi and Yamazaki, 2010; Wang *et al*., 2009). However, some studies have noted that the negative phase of the AO is the

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response to Arctic sea ice reduction (Alexander *et al*., 2004; Deser *et al*., 2004; Overland and Wang, 2010; Kim *et al*., 2014; Mori *et al*., 2014). The results from observational studies and numerical simulations suggest that Arctic sea ice variability and internal climate modes (AO/AD) are linked (Cohen *et al*., 2012). However, some studies have suggested that the relationship between the AO and Arctic sea ice was uncoupled during the rapid sea ice decline period. Deser and Teng (2008) noted that the Arctic sea ice loss since 1979 is not directly attributable to trends in the AO. However, some recent studies have shown that AO has switched to the negative phase in the last decade (Nakamura *et al*., 2015). Many of these linkages have been hypothesized based on statistical associations found in observations, which is difficult to unambiguously assign causality and separate the influences of multiple interconnected processes in the climate system using observations alone because of the mixture of forcing and response contained in observational data. All of factors complicate the connection between Arctic sea ice and atmospheric response. Thus further research and better understanding are required.

Modeling studies offer a new way to investigate the effects of prescribed changes in Arctic sea ice cover upon the atmosphere. Many modeling studies have used atmospheric general circulation models to investigate the effect of prescribed Arctic sea ice changes upon the atmosphere. The specified sea ice concentrations range from realistic values for winter (Alexander *et al*., 2004; Deser *et al*., 2004; Singarayer *et al*., 2006; Screen *et al*., 2013) and summer (Bhatt *et al*., 2008), to the future projected sea ice conditions in the Arctic (Deser *et al*., 2010; Sun *et al*., 2015). However, few works have focused on the sea ice conditions in the Arctic after 2007, when more abrupt and persistent increases in seasonal sea ice occurred in the Arctic (Livina and Lenton, 2013). Our present work aims to understand the atmospheric response to the projected Arctic sea ice condition in 2007, mainly examining the dominant modes of atmospheric circulation in the Northern Hemisphere. Following Peings and Magnusdottir (2013), we present a pair of 50-yr AGCM simulations using an atmospheric general circulation model (ECHAM5), although our experiments differ from their study in that: 1) we use the 1979–1996 seasonal cycle in the control experiment instead of using the 1979–2000 seasonal cycle; and 2) we use the same seasonal cycle of sea surface temperature in both sets of experiments. The purpose of this study is to offer a new perspective for addressing the response of atmospheric circulation to rapid sea ice loss in the Arctic.

The paper is organized as follows. The experimental design, data sets, and methods used in this study are given in Section 2. The results are presented in Section 3. A summary is provided in Section 4.

2 Materials and Methods

2.1 Model and Experiments

This study uses ECHAM5, with 19 vertical levels from the surface to 10 hPa. The model is running at a T63 horizontal resolution, corresponding to grid sizes at the equator of approximately 208 km. To investigate the impact of the projected Arctic sea ice change upon atmospheric circulation, we use a pair of 50-yr experiments. The control experiment (hereafter CTRL) is specified with a repeating climatological seasonal cycle of sea ice concentration (SIC) and sea surface temperature (SST), averaged over the period of 1979–1996, and radiative forcing is fixed in time. The perturbation experiment (hereafter EXPT) is driven by a repeating seasonal cycle of Arctic SIC in 2007 as the lower boundary forcing, and radiative forcing is again fixed in time. In both integrations, a repeating seasonal cycle of SST for 1979–1996 was prescribed to isolate the impact of projected 2007 Arctic sea ice loss. All specified data in the model are obtained from the Met Office HadISST1.1 (Rayner *et al*., 2003). The output of the first ten years of each experiment was omitted.

2.2 Observational Datasets

SIC based on satellite passive microwave retrievals using the 'bootstrap v2' algorithm (Comiso and Nishio, 2008) on a 25×25 km grid for the period of 1979–2015, obtained from the National Snow and Ice Data Center. We primarily rely on the SIE, which is defined as the area of the ocean with at least 15% of sea ice concentration.

Monthly mean sea level pressure (SLP) and 2-meter temperature were obtained from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim Reanalysis Product (Dee *et al*., 2011) on a 0.75˚× 0.75˚ latitude-longitude grid spanning the years 1979–2015. The surface air temperature (SAT) record is an area-averaged 2-meter temperature from the north of 65˚N.

2.3 Methods

In this study, we calculated the Empirical Orthogonal Function (EOF) of the monthly anomalous SLP northward of 25˚N. Area weighting was applied to the SLP field before performing the EOF analysis. The AO and AD indices are the normalized principal components of the leading two EOF modes. The spatial patterns of the leading two modes are regressions of the monthly SLP anomaly onto the corresponding principal components, which are the dominant modes of atmospheric circulation in the Northern Hemisphere. We made use of Probability Distribution Function (PDF) analysis to compare the frequency of the AO and AD between the CTRL and the EXPT runs. In this study, we computer the linear differences (DIFF) between the CTRL and the EXPT in these two runs to isolate the relative role of the abrupt sea ice decline with a large interannual change in atmospheric circulation.

3 Results

3.1 Interdecadal Changes of Arctic Sea Ice

Fig.1 shows the time series of the Arctic SIE for the period of 1979–2015 (top, Fig.1a). The Arctic SIE has retreated following a maximum in 1996, and the three lowest records occurred in 2007, 2012, and 2015. The rate of the SIE decrease was nearly 0.492 million square kilometers per decade during the whole period of 1979–2015. Consistent with Comiso and Nishio (2008), the rate of Arctic SIE loss shows a starling contrast in two periods: 1979–1996 and 1997–2006. The linear trend of Arctic sea ice loss for 1997–2006 was approximately 1.008 million square kilometers per decade, which was nearly 3 times greater than that of the SIE for the previous period. We also note that the recent Arctic SIE shows a modest decrease (the decreasing rate is about 0.18 million square kilometers per decade) but a large year-to-year change after 2007. It is apparent that the observed Arctic SIE loss is not monotonic; rather, it is accompanied by notable interannual modulations (Wang and Ikeda, 2000; Ogi and Rigor, 2013).

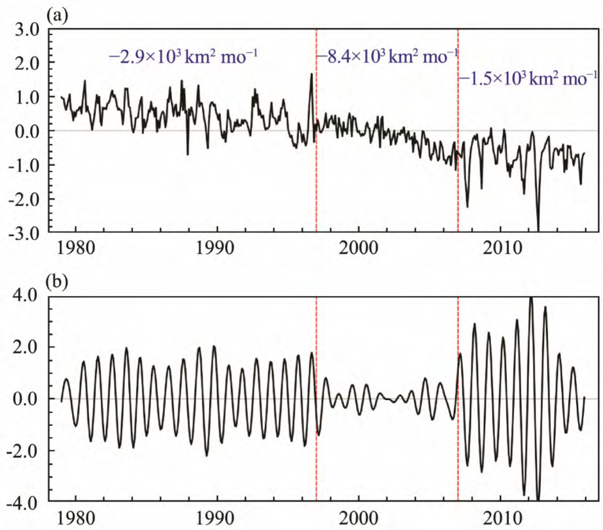

Fig.1 a) Time series of the annual Arctic SIE for the period 1979–2016. b) The bandscale average wavelet power for the interannual component frequency.

We computed the 1–5' year band-averaged wavelet power of the SIE based on a Morlet wavelet analysis to compare the interannual frequencies of the aforementioned three periods (Fig.1b). During the accelerated sea ice decline period of 1997–2006, the interannual variation of the SIE is weaker than that in the other two periods. In particular, the recent Arctic SIE has shown the largest interannual variation since 2007. To quantify the strength of the interannual variation of the Arctic SIE for each period, we computed the total variance and the contribution of detrending to the total variance (see Table 1). For the periods of 1979–1996 and 2007–2015, the interannual variations represent the dominant parts of the total variation, and the ratio of the variance of the detrended SIE to the total variance is 81.8% and 99.2%, respectively. During 1997–2006, consistent with the interannual frequency discussed above, the accelerated decline trend takes the larger part of the total variation, and the contribution of the trend to the total variance is approximately 61.8%.

Collectively, the observed Arctic SIE shows not only a significant decrease but also a notable interannual variation since 1979. In particular, during the recent decade, the Arctic SIE has reached several of the lowest records in the summertime after an accelerated decline period, accompanied by large interannual variations. The feature of Arctic sea ice changes after 2007 agrees well with the hypothesis that the Arctic reached a tipping point in 2007, with a more abrupt and persistent increase in the seasonal sea ice in the Arctic.

Table 1 The total variance of the Arctic SIE, the variance ratio of the trend to the SIE, and the variance ratio of the detrended SIE to the SIE for the periods of 1979–1996, 1997–2006, and 2007–2015

Period	σ^2 (10^6 km^2)	$\sigma^2_{\text{trend}}/\sigma^2$	$\sigma^2_{\text{detrend}}/\sigma^2$
1979–1996	0.1744	18.2%	81.8%
1997–2006	0.1378	61.8%	38.2%
2007–2015	0.2587	0.8%	99.2%

3.2 Observed Winter Season (DJF) Air Temperature, AO, and AD Changes

The response of atmospheric changes to Arctic sea ice loss is found to be largest in the wintertime (Deser *et al*., 2010; Peings and Magnusdottir, 2013), so we examine the atmospheric response over the entire winter season (DJF). Fig.2 shows the DJF mean time series of Arctic SIE, SAT, AO and AD indices during 1979–2015, which are expressed as standardized anomalies. The SAT record is area-averaged near surface air temperature over the north of 65˚N. The SIE and SAT show generally similar and physically consistent behavior over the entire examined period ($r=-0.83$), with moderate downward trends during 1979−1996, accelerated downward trends from 1997 to 2006, and flat trends thereafter. As discussed in Screen *et al*. (2012), the high correspondence between the SIE and the SAT is mainly because Arctic sea ice can strongly influence the ocean-to-atmosphere turbulent heat fluxes and the radiative fluxes, and consequently influence the near-surface air temperature. Lower tropospheric warming increases the thickness of the atmospheric column, and influences atmospheric circulation (Overland and Wang, 2010).

In this study, we use the AO and AD, the leading two modes of the EOF analysis for the SLP anomaly field, to represent large-scale atmospheric circulation changes. During the moderate SIE decline period, we found good correspondence between the AO and the SAT ($r=0.46$), in agreement with the finding of Thompson and Wallace (1998) that sea ice loss is linked to AO-induced warming. However, during the accelerated sea ice decline period for 1997–2006, the AO index became mostly natural and flat, suggesting a weak linkage between the AO and rapid sea ice loss (Maslanik *et al*., 2007); in contrast, we found good correspondence among the AD, SAT, and SIE, and the correlation coefficients between each pair of these three records are above 0.71, and are significant at the 95% confidence level taking into account serial autocorrelation.

The AD index became mostly positive, meaning more warm temperature advection from the south to the Arctic pole which will in turn warm the sea ice (L'Heureux *et al.*, 2008; Ogi *et al.*, 2008) and more sea ice export from the Arctic Ocean to the Greenland Sea due to its strong meridionality (Watanabe *et al.*, 2006; Wang *et al.*, 2009). After 2007, unlike the SIE and SAT, both the AO and AD become mostly negative, which is consistent with our discussion in 3.1 that the Arctic SIE had a large interannual variation during the last decade. All correlation coefficients shown in this section are significant above the 95% confidence level taking into account serial autocorrelation.

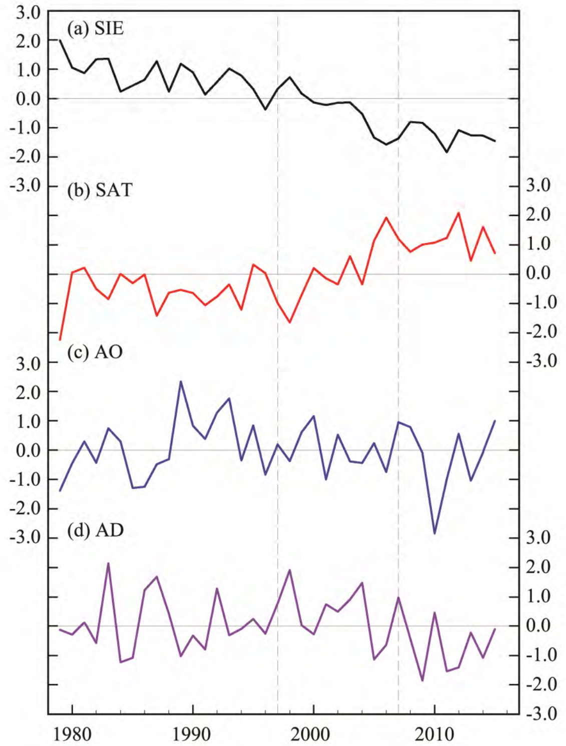

Fig.2 Time series of the observed DJF SIE, SAT, AO, and AD during 1979–2015. All records are normalized by dividing by their standard deviation.

3.3 AO and AD Responses to 2007 Arctic Sea Ice Loss

The amplitude of seasonal sea ice changes, defined as the differences between sea ice in March and sea ice in September, becomes extremely high after 2007 (not shown), which agrees well with the concern that Arctic sea ice may be on the verge of a fundamental transition toward a seasonal sea ice cover. Livina and Lenton (2013) noted a recent tipping point in Arctic sea ice cover, with more abrupt and persistent increases in seasonal sea ice after 2007. This trend, together with large interannual variations of the Arctic sea ice after 2007, suggests that recent Arctic sea ice will have a potential impact on large-scale atmospheric circulation, which is the primary focus of this study. To address the response of atmospheric circulation to an abrupt sea ice change after 2007, we use two 50-yr simulations based on ECHAM5, the only difference between these two experiments is the sea ice conditions (see Section 2.1).

In this study, the EOF analysis was applied to the monthly mean anomalies of SLP field north of 25˚N based on model outputs. Fig.3 shows the spatial pattern of the first-leading EOF mode for the EXPT and CTRL experiments and the differences between these two experiments (hereafter DIFF). Both EXPT and CTRL have an annular structure covering the entire Arctic Ocean, and two opposing centers located in the North Pacific and the North Atlantic, which correspond to the AO. However, the strength of the AO in the EXPT run is much stronger than that in the CTRL run; that is, the circled negative anomalies extend far to the mid-latitude of northern Russia, which is the origin of the cold air that can strongly influence winter temperature changes over the east-Asian. Two centers of positive anomalies in the EXPT run are also stronger than centers of positive values in the CTRL run. For example, the center located over the North Atlantic expands to the east coast of North America for the EXPT run, while for CTRL, the center concentrates over the northern Europe. Furthermore, the positive center located in the North Pacific in the EXPT run moves westward compared with that in the CTRL run. The leading mode of the EOF analysis for the DIFF shows that large significant circulation responses exist over the North Atlantic, which resembles the NAO pattern, the primary mode of winter atmospheric variability over the North Atlantic. This NAO-type circulation response to abrupt sea ice loss is consistent with several studies by Singarayer *et al.* (2006) and Screen *et al.* (2012). The decrease in planetary-scale wave phase speeds will force a negative phase of the NAO. The probability distribution of PC1 for EXPT, CTRL, and DIFF was also shown in Fig.3c. Comparing the EXPT run to the CTRL run, a higher frequency of negative AO events occurred in the EXPT run, which is in agreement with recent work that reported the reduction of Arctic sea ice leads to more negative AO events (Nakamura *et al.*, 2015). Associated with negative phase of AO, cold air advection from the Arctic region to the mid-latitudes increase. More negative NAO events would occur under the largest sea ice loss condition.

Moving to the second-leading EOF mode for the EXPT, CTRL, and DIFF, as shown in Fig.4. Both EXPT and CTRL display an obvious seasaw pattern between the Atlantic side and the Siberian side of the Arctic region, which bear a resemblance to the AD pattern (Watanabe *et al.*, 2006; Wu *et al.*, 2006). While, the centers of positive values locate in different regions for EXPT and CTRL runs. In the EXPT run, the spatial pattern shows a positive anomaly in the Canadian Archipelago that extends toward the North Pacific, which leads more sea ice export through the Fram Strait to the Greenland Sea, while in the CTRL run, the location of the positive anomalies concentrates on Bering Strait, which means the strength of meridianality is relative weak comparing with that of in the EXPT run. The second mode for the DIFF shows a wavetrain pattern across the Arctic, characterized by one prominent center of negative anomalies located in the North

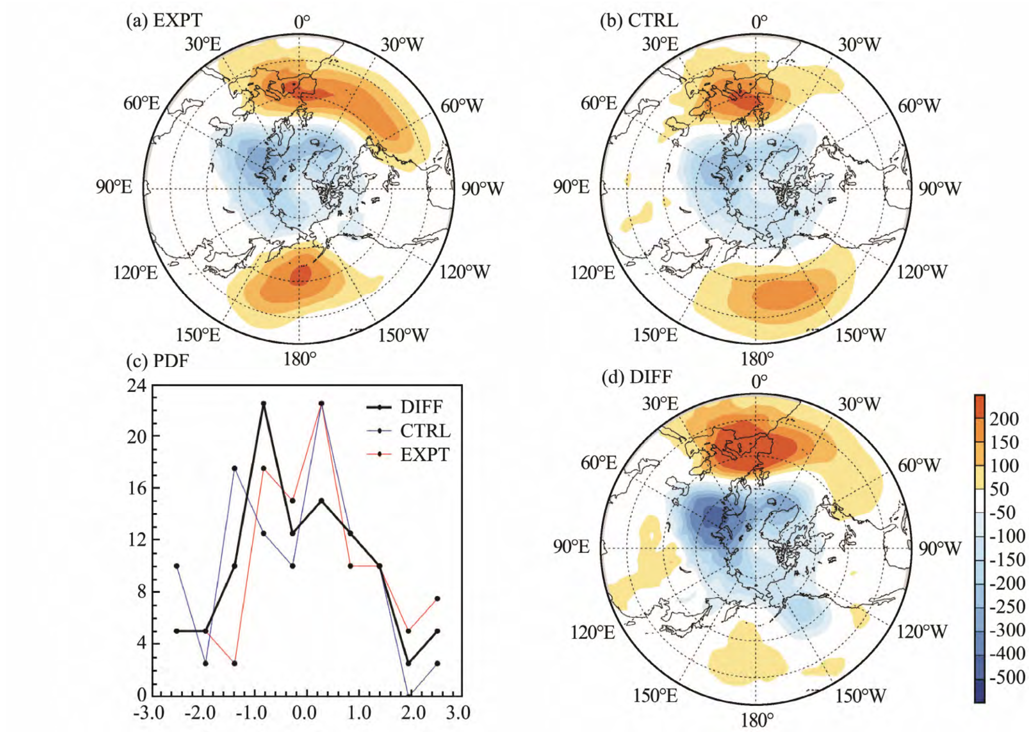

Fig.3 The first leading EOF mode of the sea level pressure (SLP) for a) EXPT run, b) CTRL run, and d) the differences between EXPT and CTRL. c) The probability distribution function of PC1 for both sets of experiments, and DIFF; red, blue, and black lines for EXPT, CTRL, and DIFF, respectively.

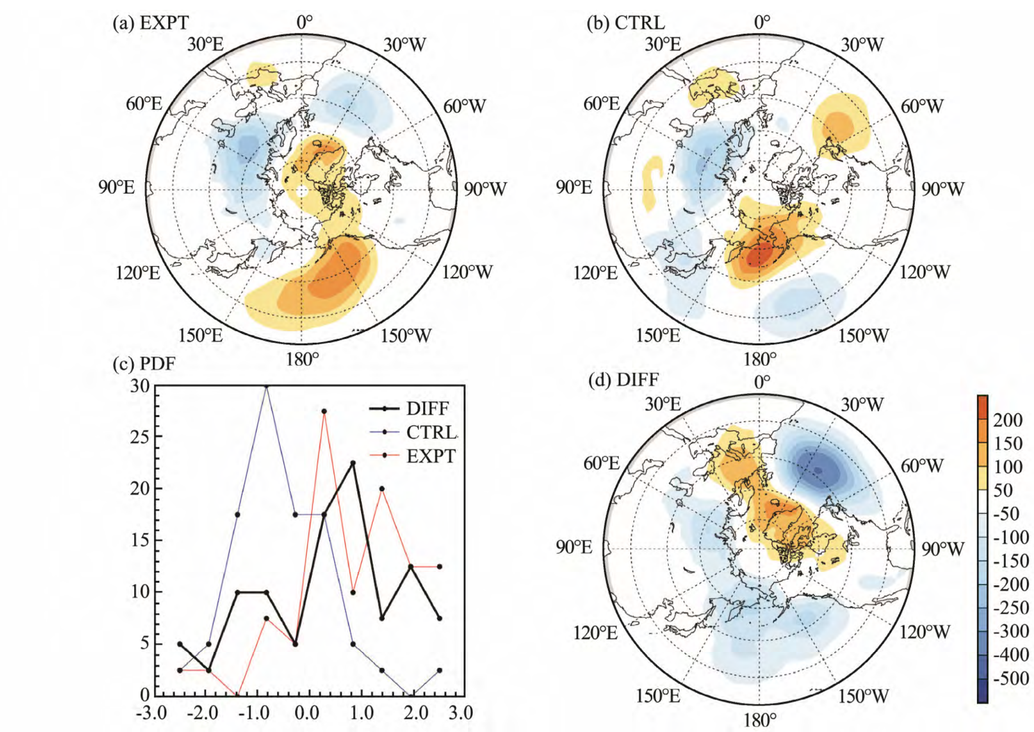

Fig.4 Same as Fig.3, but for the second mode of the EOFs.

Sea and the Greenland Island, and another negative anomaly center over northern Russia and the North Pacific. This wave-train response will favor cold air advection from the Arctic region to the lower mid-latitudes, which is in agreement with the increase in blocking occurrences in the observations (Barnes, 2013). Comparing the probability distribution for EXPT to that for CTRL, many more occurrences of the positive phase of the AD mode would happen in EXPT, implying higher frequency of the positive AD response underlying the huge sea ice loss condition in 2007. The distribution of probability in DIFF also shows more occurrences of positive across-

Arctic wave train patterns.

4 Summary

Based on the satellite measurements of Arctic sea ice concentrations from the National Snow and Ice Data Center (NSIDC), we revisit the change in Arctic SIE for a long period from 1979 to 2015. Both the linear trends and the strength of the interannual variation of the SIE indicate that the Arctic SIE experienced three different periods: a moderate sea ice decline period for 1979–1996, an accelerated sea ice decline period from 1997 to 2006, and a large interannual variation period after 2007. In particular, for the period of 2007–2015, the Arctic SIE reached several of its lowest records in the summertime after the accelerated decline period, accompanied by large interannual variations ($\sigma^2_{\text{detrend}}/\sigma^2=99.2\%$).

The Arctic sea ice loss is greatest in summer, yet the atmospheric response over the Arctic Ocean is most extensive in the wintertime. Therefore, we compare the DJF mean area-averaged surface air temperature north of 65˚N, and the indices of the AO and AD (the dominant modes of atmospheric circulation over the Arctic region), together with the Arctic SIE. The SAT shows good correspondence with the SIE ($r=-0.83$) for the entire period examined. Consistent with the Arctic sea ice change, the AO and AD also experience three different periods, as well as a linkage with Arctic sea ice. During the moderate sea ice decline period, the AO shows good correspondence with the SAT and SIE. For the accelerated decline period, the AO has a week linkage with the SAT and SIE, but the AD shows a better relationship with the SAT ($r=0.74$) and SIE ($r=0.71$). After 2007, both the AO and AD show significant interannual variations, similar to the SIE.

To address the response of atmospheric circulation to the lowest sea ice conditions with large interannual variations involved, we investigate the dominant modes for the large atmospheric circulation response to the projected 2007 Arctic sea ice loss using an atmospheric general circulation model (ECHAM5). The response was obtained from two 50-yr simulations: one with a repeating seasonal cycle of specified sea ice concentration for the period of 1979–1996 and one with that of sea ice conditions in 2007. In both integrations, the same repeating seasonal cycle of SST is prescribed, and radiative forcing is fixed in time. The results suggest the following: 1) more occurrences of a negative AO response to the 2007 Arctic sea ice conditions, accompanied by an NAO-type atmospheric circulation response under the largest sea ice loss; and 2) more occurrences of a positive AD mode under the 2007 sea ice conditions, with an across-Arctic wave train pattern response to the largest sea ice loss in Arctic. The mechanisms underlying the negative NAO and wave-train responses will be addressed in future works; this present work offers a new perspective for understanding the atmospheric response to the Arctic sea ice change in 2007, when abrupt sea ice loss and large interannual variations occurred.

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