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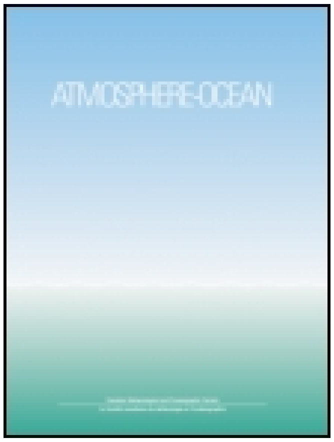

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Mechanism of an Abrupt Decrease in Sea-Ice Cover in the Pacific Sector of the Arctic during the Late 1980s

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ABSTRACT *The recent decline in Arctic sea-ice cover (SIC) shows seasonal and regional characteristics. The retreat of summer sea ice has occurred mainly in the Pacific sector of the Arctic. In this study, using the moving* t*-test, we found an abrupt change event in the long-term sea-ice area in the Pacific sector in summer 1989. This event was linked to the phase shift of the Arctic Oscillation (AO) or the Northern Annular Mode (NAM). Corresponding with the AO/NAM phase shift from negative to positive, the area of the northern hemisphere stratospheric polar vortex decreased abruptly in winter 1988/89. Comparisons of two periods before (1979–1988) and after (1989–1993) the abrupt decrease in sea ice show that an anomalous winter sea level pressure (SLP) was induced by changes in the polar vortex leading to an anomalous cyclonic ice drift in the Pacific sector. The changes in SLP and wind field persisted into the following spring, resulting in a decrease in SIC and warming of the surface air temperature (SAT). The influence of the spring SLP and SAT on ice persisted into the following summer. Meanwhile, the increased summer net surface heat flux over the ocean and sea ice as a result of the decreased spring ice cover further contributed to the summer sea-ice melt.*

RÉSUMÉ *[Traduit par la rédaction] Le récent déclin dans la couverture de glace de mer arctique affiche des caractéristiques saisonnières et régionales. Le retrait de la glace de mer pendant l'été s'est principalement produit dans le secteur pacifique de l'Arctique. Dans cette étude, à l'aide du test t mobile, nous avons trouvé un événement de changement brusque dans l'étendue de glace de mer à long terme dans le secteur pacifique au cours de l'été 1989. Cet événement était lié au changement de phase de l'oscillation arctique (AO) ou du mode annulaire boréal (NAM). Parallèlement au changement de phase de négatif à positif de l'AO/NAM, l'étendue du tourbillon polaire stratosphérique de l'hémisphère Nord a brusquement diminué au cours de l'hiver 1988–1999. Des comparaisons avec deux périodes avant (1979–1988) et après (1989–1993) la diminution brusque de la glace de mer montrent qu'une pression anormale au niveau de la mer durant l'hiver a été produite par les changements dans le tourbillon polaire, ce qui a entrainé une dérive cyclonique anormale de la glace dans le secteur pacifique. Les changements dans la pression au niveau de la mer et dans le champ de vent ont perduré jusqu'au printemps suivant et ont occasionné une diminution de l'étendue de la glace de mer et un réchauffement de la température de l'air en surface. L'influence de la pression au niveau de la mer et de la température de l'air en surface sur la glace s'est fait sentir jusqu'à l'été suivant. En même temps, le flux de chaleur net accru à la surface en été au-dessus de l'océan et de la glace de mer, résultant de la plus faible couverture de glace au printemps, a aussi contribué à la fonte de la glace de mer pendant l'été.*

KEYWORDS Arctic; Pacific sector; sea ice; AO; polar vortex

1 Introduction

Sea ice plays an important role in the global climate system because of its high albedo. Along with global warming, the amount of Arctic sea ice has been decreasing steadily over the past 30 years; moreover, this trend has been marked by record low values of sea-ice cover in the last decade (2007 and 2012). Trends in the area of the Arctic ice cover, including both seasonal and perennial ice categories, have shifted from about −3.0% per decade in September 1979–1996 to about −10.7% per decade in 1997–2007 (Comiso, Parkinson, Gersten, & Stock, 2008). Rapid decline in the extent and area of multi-year ice was also identified (Comiso, 2012). The retreat of sea ice has been the most dramatic in the Pacific sector of the Arctic (Fig. 1). Sea-ice concentration (SIC) in the East Siberian Sea and part of the Chukchi Sea decreased by 2% per year, on average, according to 1979–2008 SIC data from the National Snow and Ice Data Center (NSIDC; Su, Wei, Li, & Xu, 2011). Therefore, the variation in sea ice in the Pacific sector should be given more attention.

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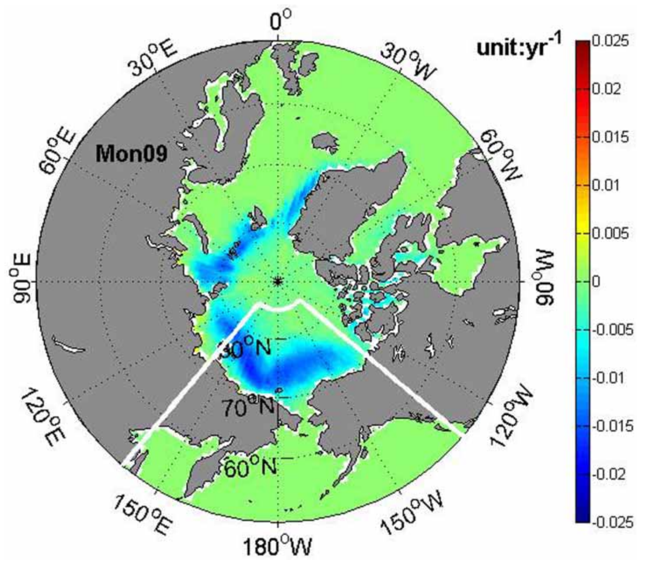

Fig. 1 The domain of the Pacific sector of the Arctic (the colour bar indicates the trend of September SIC for 1953 to 2010).

In this study, the Pacific sector is defined as the region bounded by 50°N–85°N, 140°E–130°W, the area outlined in white in Fig. 1. It consists of the East Siberian Sea, the Chukchi Sea, the Beaufort Sea, the Bering Sea, and the Sea of Okhotsk. The majority of the sea ice in this region is seasonal, forming in winter and disappearing in summer.

Recent studies have shown linkages between atmospheric circulation and Arctic sea-ice extent and area as well as sea-ice drift. Some researchers have analyzed the leading empirical orthogonal function (EOF) mode of sea level pressure (SLP) in the northern hemisphere (known as the Arctic Oscillation (AO); Thompson & Wallace, 1998) and associated it with the interannual variability of sea-ice cover. Rigor, Wallace, and Colony (2002) pointed out that AO phase changes influence the strength and extent of the Beaufort High, which drives the anticyclonic gyre and local sea-ice motion. They also found that summer sea-ice concentration is strongly correlated with the AO index for the previous winter. The delayed response reflects the dynamical influence of the AO on the thickness of winter sea ice, whose persistent "footprint" is reflected in the heat liberated by the freezing of open water during the subsequent autumn. Zhang, Ikeda, and Walsh (2003) found that the Arctic sea-ice area and volume were significantly reduced when the phase of the AO changed from negative to positive. They elucidated the mechanisms associated with the sea-ice changes in the asymmetric response of the Arctic Ocean to the AO forcing, such as anomalous ice advection and ice growth in different regions of the Arctic Ocean. Zhang, Sorteberg, Zhang, Gerdes, and Comiso (2008) found drastic, systematic spatial changes in atmospheric circulation in their study. These changes suddenly jumped from the conventional tripole AO/North Atlantic Oscillation (NAO) to an unprecedented dipole leading pattern, following accelerated northeastward shifts in the AO/NAO centres of action. This new atmospheric circulation leading pattern—the Arctic Rapid change Pattern (ARP)—plays a decisive role in driving recent rapid Arctic climate change by accelerating the gradual changes forced by global warming. Wu, Wang, and Walsh (2006) defined the Dipole Anomaly (DA) in the Arctic atmospheric circulation and suggested that increased ice export from the Arctic basin is associated with the phase shift of the DA from positive to negative. Wu, Overland, and D'Arrigo (2012) investigated the role of surface wind on sea ice and found that the negative trend in September sea-ice extent over the past two decades is associated with increased frequency and enhanced intensity of a wind variation pattern, called the Central Arctic (CA) pattern (which described the Arctic surface wind variability by means of a complex vector EOF analysis), during the melt season from April to September.

While most researchers focused on the trend and the seasonal and interannual variability of sea ice (e.g., Overland & Wang, 2010; Parkinson & Cavalieri, 2008; Slonosky, Mysak, & Derome, 1997), abrupt changes in ice cover are also important. Abrupt changes in Arctic sea ice were detected by Zhao, Sun, and Wang (2001) using 1953–1994 gridded sea-ice data. A sudden decrease in Arctic ice extent and area at the end of the 1990s was found by Fang, Zhang, and Cheng (2005) using SIC data from 1968 to 2000 from the Hadley Centre. Abrupt changes in sea-ice extent were also identified in regional basins (e.g., SIC in the Arctic shows that the retreat of ice was very severe in September 1989 (Cavalieri, Parkinson, & Vinnikov, 2003; Maslanik, Serreze, & Barry, 1996)) especially in the Siberian Sea, Chukchi Sea, and the southern Beaufort Sea.

However, research on the mechanisms of abrupt changes in sea ice is still very preliminary. From 1979 to 2008, the ice area in the Pacific sector experienced a frequency shift (the significant period of sea-ice area in the Pacific sector changes from about three years in the 1979–1985 period to about two years after 1992), which was attributed to its different relationship with the AO and North Pacific Index (NPI) in different time periods. An abrupt change in sea-ice extent at the end of the 1970s in the Bering Sea is associated with the deepening and relocation of the Aleutian low. The low pressure centre moved to the southeastern Bering Sea and the area with pressure lower than 1005 hPa expanded. The cyclonic wind anomaly led to more heat being transferred from mid-latitudes to the northeastern Bering Sea and part of the polar region (Hu, Su, Zhao, & Genevieve, 2007). Maslanik et al. (1996) pointed out that the sudden decline in sea ice in the Siberian sector around 1989 could be attributed to the increased number of low pressure systems over the central Arctic. Shimada et al. (2006) found that the catastrophic reduction in sea-ice cover in the western Arctic Ocean was related to the distribution of warm Pacific summer water. In this study, we will focus on the process for the abrupt decrease in sea ice in the Pacific sector of the Arctic Ocean. The possible mechanisms will be discussed from the perspective of atmospheric circulation.

2 Datasets and methods

Monthly SIC data from the Met Office Hadley Centre observations datasets were used in this study. This dataset comprises sea-ice data taken from a variety of sources including digitized sea-ice charts and passive microwave retrievals. The spatial resolution is 1° × 1°, and the time period is from 1870 to the present. Because the data before 1953 are unreliable (Rayner et al., 2003), we only use the SIC data from 1953 to 2010. The Pacific sector sea-ice area (SIA) was calculated and compared with 25 × 25 km Special Sensor Microwave/Imager (SSM/I) SIC data obtained from NSIDC for 1979 to 2010. The correlation coefficients for SIA and the ice area anomaly in the Pacific sector from these two datasets were 0.99 and 0.96, respectively, which means that the data from the Hadley Centre are eminently suitable for examining changes in sea ice over long time periods. To estimate ice area, we multiplied the SIC (in percent) in each pixel that had a SIC greater than 15% by the pixel area and totalled the results from all grid cells. We also used the 1979–2006 monthly sea-ice velocity obtained from SSM/I data to analyze the characteristics of sea-ice motion.

The atmospheric data come from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 and includes monthly surface air temperature (SAT), SLP, surface wind, and the geopotential height for 17 isobaric surfaces. The sea surface temperature (SST) from the Simple Ocean Data Assimilation dataset (SODA, version 2.1.6) and the heat content calculated for the northern hemisphere were analyzed. The spatial resolution of SODA data is 0.5° × 0.5°, and the available time period is 1958 to 2008.

Monthly AO index information was downloaded from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml).

The moving t-test (MTT; Afifi & Azen, 1979) method was used to test abrupt changes in sea ice and other atmospheric and oceanic variables. This method finds abrupt changes by comparing the average values of two groups of samples: an abrupt change has happened if the difference between two groups of samples passes the significance level of the MTT. For a time series x with n samples, a reference point is set artificially. There are two groups, denoted by x_1 and x_2, that have n_1 and n_2 samples before and after the reference point. The average values and variances of the two groups are $\bar{x}_1$, s_1^2 and $\bar{x}_2$, s_2^2, respectively. The statistic variable t is defined as follows:

$$t = \frac{\bar{x}_2 - \bar{x}_1}{s\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}, \tag{1}$$

where

$$s = \sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}}.$$

The variable t in Eq. (1) follows the t-distribution, which has a degree of freedom of $n_1 + n_2 - 2$. When the absolute value of t is greater than t_α, which corresponds to the confidence level α, the reference point is regarded as an abrupt change point (Fu & Wang, 1992).

The EOF modes of SIC and geopotential height were calculated to reveal their significant spatial distribution patterns and their development with time.

3 Results

a *Abrupt Decrease in Sea Ice in the Pacific Sector of the Arctic*

Summer (August–October) SIA from 1953 to 2010 was analyzed to study the interannual variation in ice conditions in the Pacific sector because interannual variations in ice cover are much larger in this season than in other seasons. As shown in the upper panel of Fig. 2, SIA was relatively stable before 1989. It then dropped to a lower level in 1989 and remained at this level until 2001. An abrupt decrease in SIA did occur in 2002, but the decrease in 2007 was much more conspicuous. The result for SIA using MTT calculated from the Hadley Centre dataset (1953–2010) is shown in the lower panel of Fig. 2; the green line is the statistical variable t and the red lines indicate the 99% confidence limits (here $n_1 = 7$, $n_2 = 7$). If the t value is greater than (less than) the upper (lower) confidence line, a positive (negative) abrupt change has taken place. Our result shows that there were two significant abrupt decreases in summer SIA, one in 1989 and the other around 2002. These two changes, seen in Fig. 2, were also detected by MTT results for SIA in 1979–2010 from both datasets (Hadley Centre and SSM/I; figure not shown). The abrupt change that occurred in

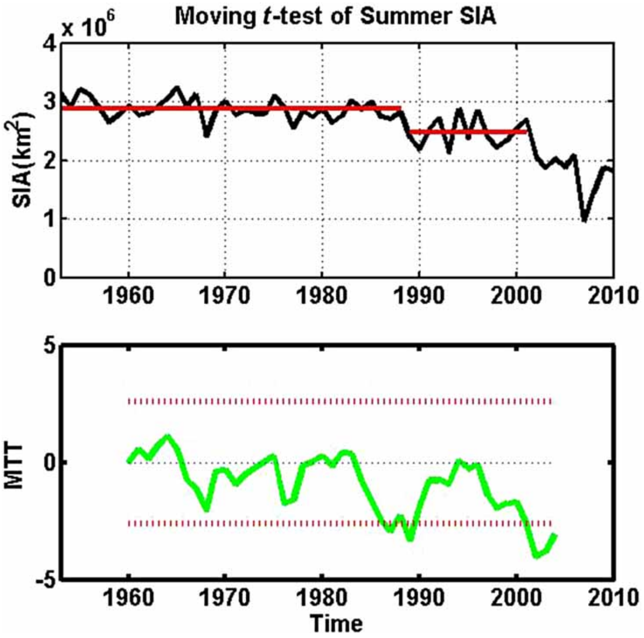

Fig. 2 MTT of summer SIA from 1953 to 2010: (upper panel) summer SIA, the two red lines are the averaged SIAs for 1953 to 1988 and 1989 to 2001; (lower panel) MTT result for summer SIA. The green line is the t value and the two dotted red lines show the 99% confidence limits.

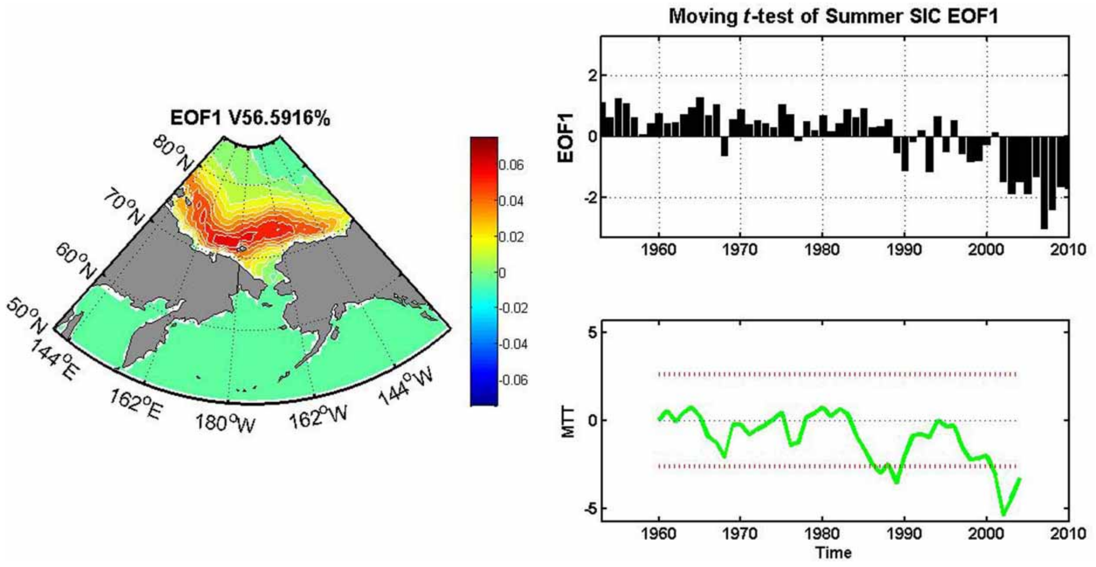

Fig. 3 Spatial pattern (left) and time series (upper right panel) of the leading EOF mode for summer SIC in the Pacific sector from 1953 to 2010 and its MTT result (lower right panel). The green line is the *t* value and the two dotted red lines show the 99% confidence limits.

2007 was not detected by the MTT method. This might be because 2007 is much too close to the end of our time series. Maslanik et al. (1996) also found that summer sea-ice extent declined in the Siberian sector of the Arctic around 1989 but did not use the abrupt change test. They proposed that increased cyclones during the 1989–1993 period favoured ice divergence and shear within the consolidated ice pack which in turn increased ice melt as the resulting open water areas were heated by absorption of solar radiation. The mechanism needs further study from the aspect of large-scale atmospheric circulation. In this paper, we will only focus on the decrease in sea ice during the late 1980s. Averaged SIA before and after this abrupt decrease (red lines in upper panel of Fig. 2) are 2.87×10^6 km^2 and 2.48×10^6 km^2, respectively.

To further understand the process of this decline in sea ice, the EOF modes for summer SIC in the Pacific sector were also calculated. The leading EOF mode, whose contribution to the variance is about 56.6%, reflects a spatially consistent variability (Fig. 3, left panel) in the northern part of the Pacific sector. The leading EOF mode for the time series (Fig. 3, right panel) also experiences a sudden decrease after 1989 and displays similar changes in SIA. For the other modes, there is no obvious sudden change. This result confirms the existence of an abrupt decrease in sea ice during 1989 from a different perspective.

b *Variations in Atmospheric Circulation*

In the northern hemisphere, the AO is one of the most important atmospheric circulation patterns. Significant variations in the AO occur in winter. It has been found that the winter AO was in an extreme "high index" state during 1989/90 (Thompson & Wallace, 1998). In this study, we intend to determine whether the winter AO also exhibited an abrupt change and whether the change in AO made any contribution to the reduction in summer sea ice in the Pacific sector during the late 1980s.

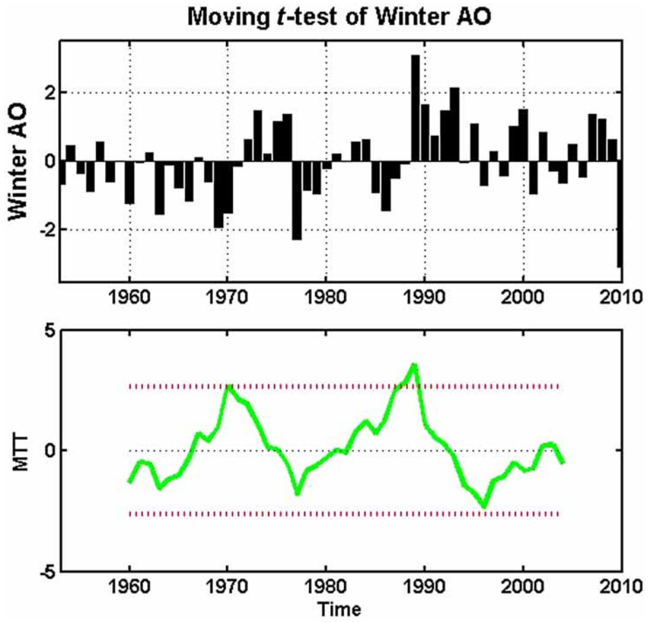

Fig. 4 Winter AO index from 1953 to 2010 (upper panel) and its MTT result (lower panel). The green line is the *t* value and the two dotted red lines show the 99% confidence limits.

The MTT result for the winter AO index (December–February) shows that the AO experienced a phase shift from negative to positive in winter 1988/89 (Fig. 4). Before the phase shift, the AO index had a small amplitude and oscillated between positive and negative. Thus, the AO remained in a neutral phase during this period. After the winter of 1988/89 the phase remained strongly positive until 1992/93.

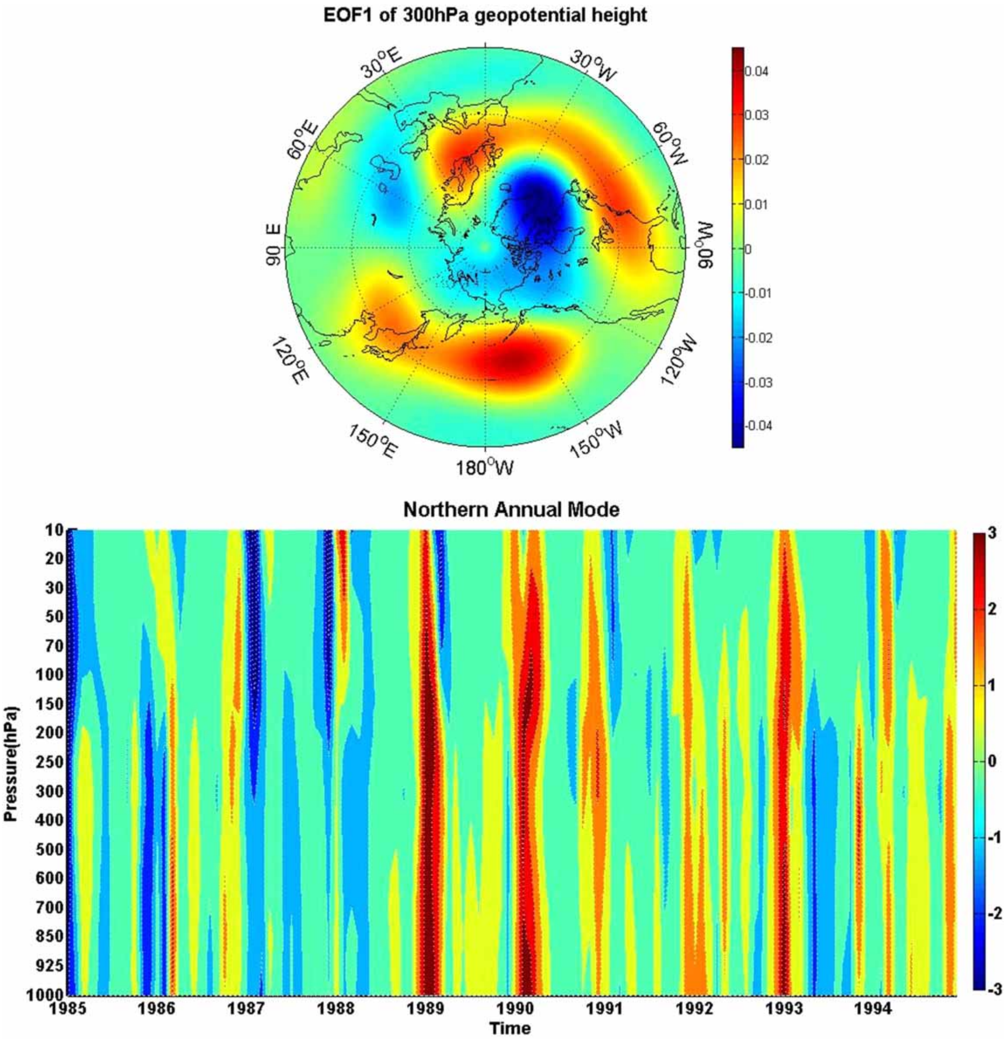

Fig. 5 Leading EOF pattern of the 300 hPa geopotential height (upper panel); Northern Annular Mode in each pressure layer from 1985 to 1994 (lower panel).

Actually, the AO is the sea surface component of the Northern Annular Mode (NAM). The entire structure of NAM consists of the leading EOF mode for geopotential height at each pressure level (Baldwin & Dunkerton, 1999, 2001). Large NAM anomalies first appear in the high and middle stratosphere, moving down to the troposphere with time (Sun, Wu, & Li, 2006).

The NAM for 1953 to 2010 was calculated using geopotential height data from NCEP/NCAR. The MTT results for the corresponding NAM time series at each pressure level also showed the sudden change around the winter of 1989 (figure not shown). The lower panel of Fig. 5 shows the NAM from 1985 to 1994. It became strongly positive from the winter of 1988/89 until the winter of 1992/93. Because the vertical structure of the NAM showed quasi-barotropic characteristics from the stratosphere to the bottom of the troposphere, we singled out the leading EOF mode of the 300 hPa level, which is helpful in viewing the spatial pattern of NAM (Fig. 5, upper panel). The 300 hPa polar vortex is the stratospheric component of NAM and will be discussed in the following section. It is shown that the anomalous lower pressure was located over the entire Arctic, with a large anomaly obvious over southwest Greenland.

c *Mechanisms*

According to the analyses in Section 3b, the AO experienced an abrupt phase shift during the late 1980s, and the NAM became positive from the stratosphere to the surface. Actually, the AO and NAM have close relationships with the stratospheric polar vortex, which is a cold low pressure centre in the Arctic (Baldwin & Dunkerton, 2001; Sun et al., 2006). The polar vortex could be regarded as the stratospheric component of NAM. When the NAM at a particular pressure level is positive, the polar vortex at that level strengthens and vice versa. The change in NAM analyzed in Section 3b corresponds to the strengthening of the polar vortex since the winter of 1988/89. To study the changes in the polar vortex quantitatively the indices for the area, intensity, and location of the centre of the

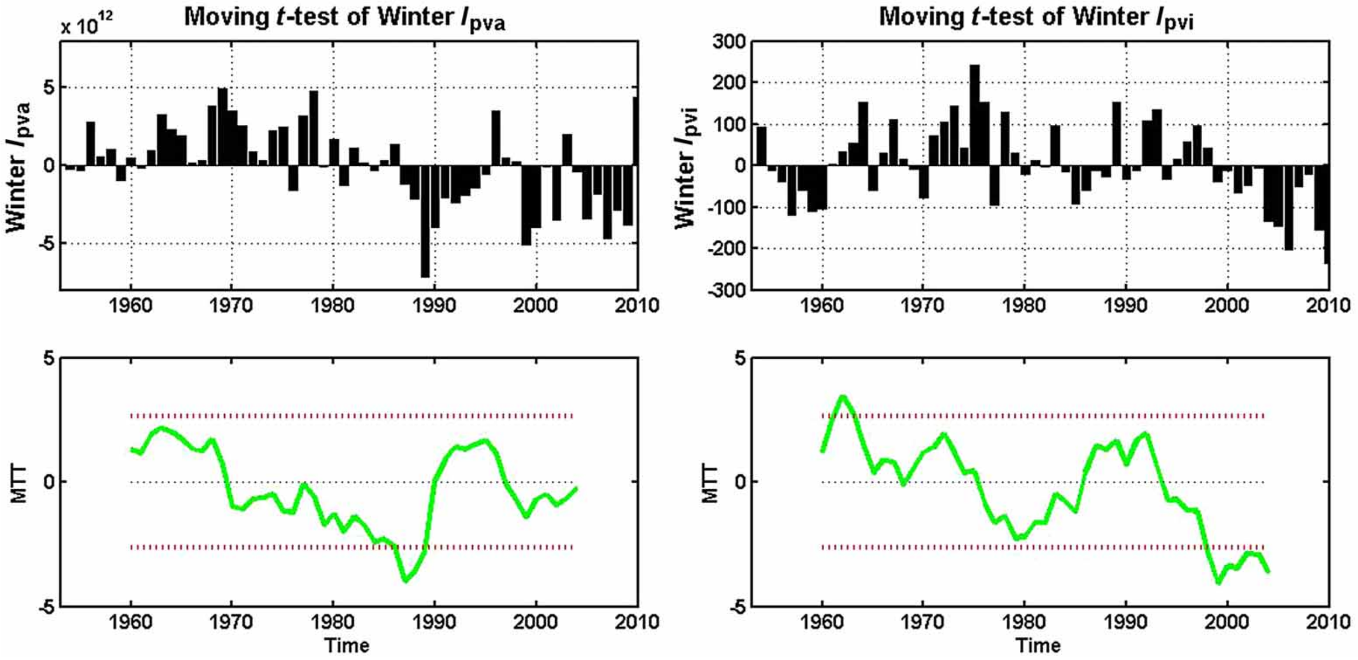

Fig. 6 Time series of winter 300 hPa I_{PVA} (left panels) and I_{PVI} (right panels) and their MTT results. Time series of the two indices (upper panels); MTT results for the time series of the two indices (lower panels). The green lines are the *t*-values, and the dotted red lines show the 99% confidence limits.

polar vortex were calculated and analyzed. Our results indicate that there was a similar drastic change in the polar vortex during the late 1980s, as shown in detail in Section 3c1. Was there any corresponding change in local SLP, surface wind, or SAT, as well as in the ice drift pattern associated with the polar vortex? If so, how were they linked with the retreat of summer sea ice in the Pacific sector? These questions will be further analyzed in the following section.

1 VARIATIONS IN THE POLAR VORTEX

The polar vortex establishes itself in the lower stratosphere, strengthening in winter and weakening in summer. The polar vortex indices were calculated using the 300 hPa isobaric surface because it better reflects the characteristics of the vortex (Zhang, Gao, & Zhang, 2006). The vortex area is defined as the area enclosed by the westerly jet axis, and the vortex intensity represents the mass of air between the 300 hPa isobaric surface and the plane where the contour of the southern boundary of the polar vortex is located. The contour value of the southern boundary of the polar vortex in each month is taken from Zhang et al. (2006). The formulae to calculate the indices of the polar vortex area and intensity are as follows (Angell & Korshover, 1977; Zhang et al., 2006):

$$I_{\mathrm{PVA}}(i) = R^2(1 - \sin\varphi(i))\Delta\lambda, \tag{2}$$

$$I_{\mathrm{PVI}}(i) = \rho R^2 \Delta\varphi\Delta\lambda \sum_i \sum_j (H_0 - H_{ij})\cos\varphi(i), \tag{3}$$

where I_{PVA} and I_{PVI} are, respectively, the indices for the polar vortex area and the polar vortex intensity; R is the radius of the Earth; $\varphi(i)$ is the latitude of the southern boundary of the polar vortex; $\Delta\lambda$ and $\Delta\varphi$ are, respectively, the longitude and latitude differences between adjacent grid cells; ρ is the air density; H_0 is the contour value of the southern boundary of the polar vortex; H_{ij} is the potential height at point (i, j). Here we scale the equation by ρR^2 to simplify the calculation. In addition, we analyzed the position of the centre of the 300 hPa polar vortex (PVC).

The time series for I_{PVA} and I_{PVI}, as well as their MTT results are shown in Fig. 6. Our results show that the area of the polar vortex contracted dramatically in the winter (December–February) of 1988/89. At the same time, the intensity of the polar vortex experienced a sudden increase consistent with the change in NAM; it only demonstrated a weak, positive abrupt change in the MTT result without passing the 99% confidence level but was close to the 95% level. The vortex intensity showed two other abrupt changes at the beginning of the 1960s and at the end of the 1990s, both of which passed the 99% confidence test. However, these two points of abrupt change should not be related to the decline in sea ice in the Pacific sector during the late 1980s. In addition, it was observed that the average position of the PVC in February moved closer to the Atlantic sector (figure not shown).

Jia and Sun (2006) suggested the existence of a weak positive interannual correlation between the 500 hPa polar vortex area and the Arctic SIA. According to our study, the polar vortex might be the important factor in the abrupt decrease in sea ice in the Pacific sector during the late 1980s.

2 VARIATIONS IN SURFACE METEOROLOGICAL FIELDS

Significant changes in the surface atmospheric circulation fields are associated with the contraction, strengthening,

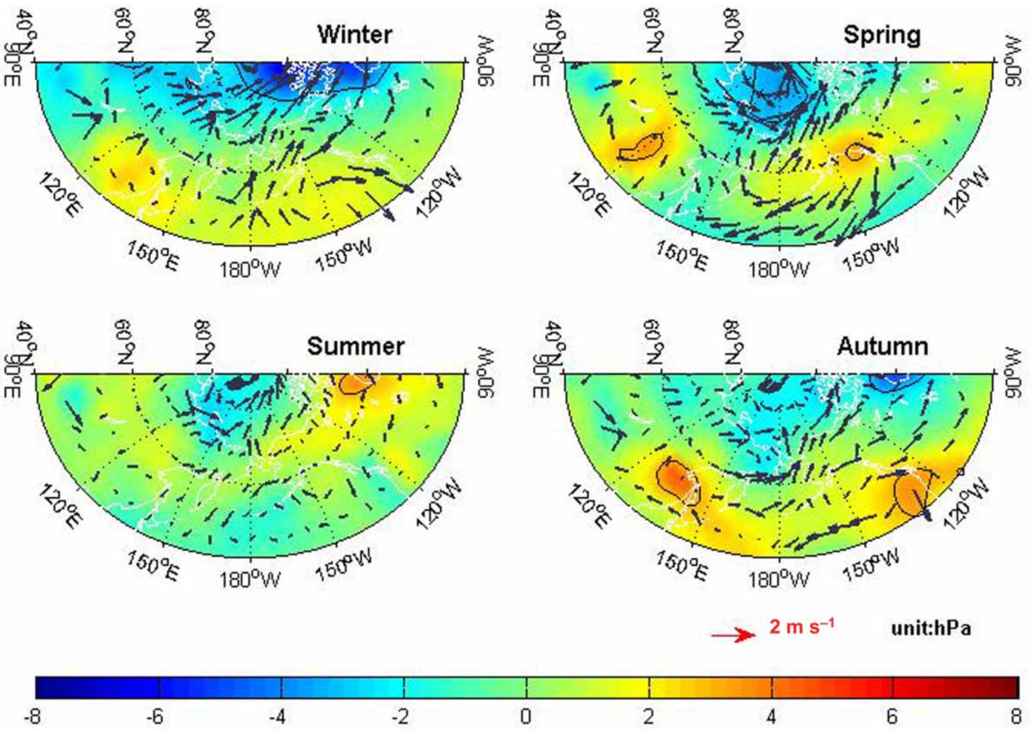

Fig. 7 The difference fields for SLP (colour shading) and surface wind (arrows) in spring, summer, autumn, and winter between 1989 and1993 and 1979 and1988. (The black lines indicate the estimated 1% significance level).

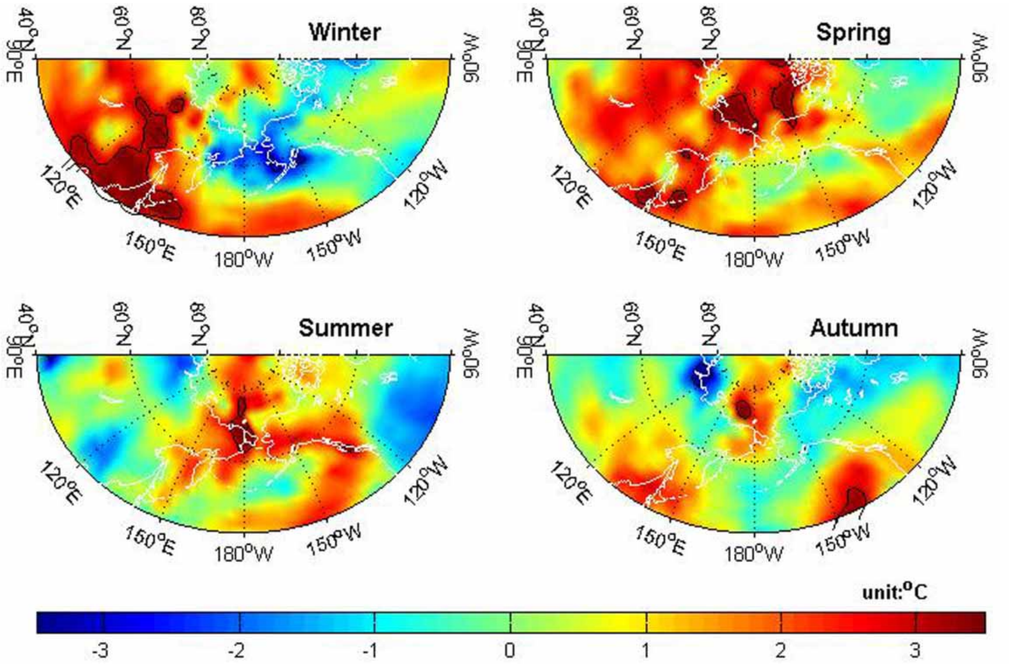

Fig. 8 The difference fields for SAT in spring, summer, autumn, and winter between 1989 and 1993 and 1979 and 1988. (The black lines indicate the estimated 1% significance level).

and shifting of the polar vortex. According to the changes in the SIA, AO, and polar vortex, the entire time series was divided into two periods, 1979–1988 and 1989–1993. Differences in the seasonal SLP, surface wind, and SAT north of 20°N in these two periods are analyzed in this section (see Figs 7 and 8). The four seasons are defined as follows: winter (December–February), spring (March–May), summer (June–August), and autumn (September–November).

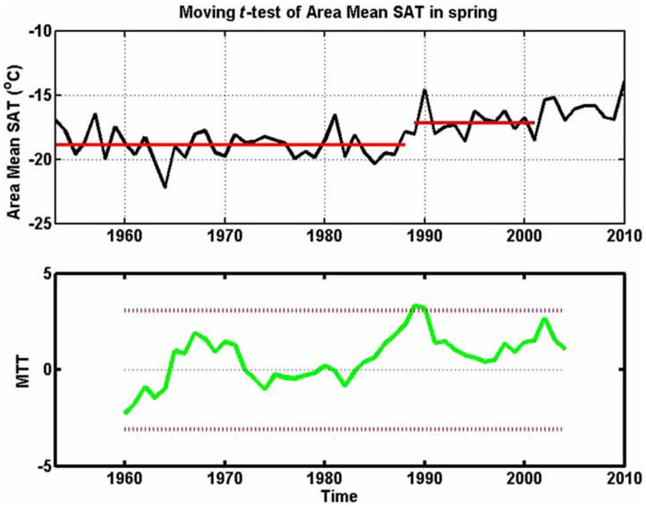

Fig. 9 Spatially averaged spring SAT bounded by 70°–85°N, 90°E–90°W from 1953 to 2010 (upper panel) and its MTT result (lower panel). The green line is the *t* value and the two dotted red lines show the 99% confidence limits.

In winter and spring of 1989 to 1993, the SLP over the entire Arctic was lower than before the decrease in ice (1979–1988), and the difference field for the surface wind shows an anomalous cyclonic wind (Fig. 7). In the northern part of the Pacific sector, there was an anomalous local southwest wind. The SLP near the Aleutian Islands was higher, while the difference field showed anticyclonic winds in this region. In summer and autumn, the differences were very small.

Figure 8 shows that winter SAT in the northern part of the Eurasian continent increased after the abrupt decline in ice cover, while SAT was lower than before the abrupt decline near Bering Strait and in the Beaufort Sea. In spring, the region with increasing SAT shifted from the Eurasian continent to the East Siberian Sea, the Chukchi Sea, the greater part of Beaufort Sea, and the central Arctic basin. We tested the spatially averaged spring SAT in the region bounded by 70°–85°N, 90°E–90°W and found that there is a positive abrupt change point in 1989 (Fig. 9), which means that the spring SAT does have a significant effect on summer sea ice. Changes in summer SAT were weaker than those in other seasons. Warming of the Pacific sector in autumn indicates that the decrease in sea ice increases SAT in this region.

Viewing the SLP differences and surface wind differences together (Fig. 7), we can see that the responses of SLP and surface wind on the polar vortex show seasonal persistence from winter to the following spring. The significant SAT difference in the Pacific sector was found in spring, lagging the sudden changes in the polar vortex. Song and Robinson (2004) explored the dynamical mechanisms through which stratospheric forcing can influence tropospheric annular modes. They thought that tropospheric responses were

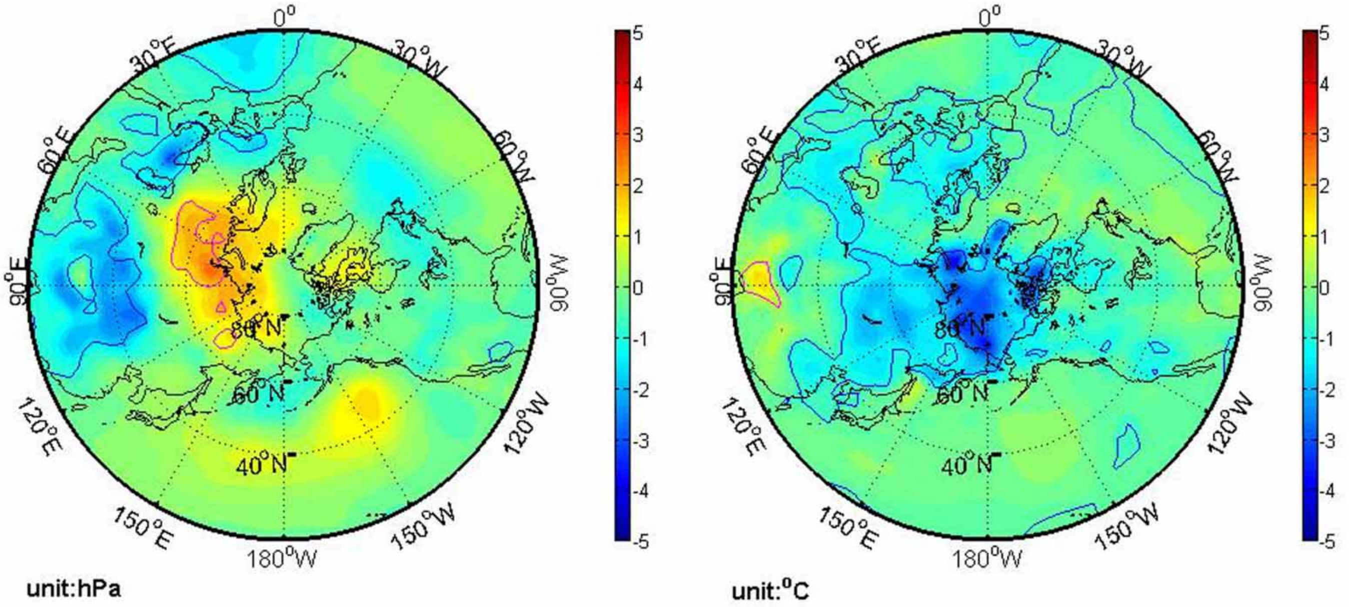

Fig. 10 Linear regression field for spring SLP (left panel) and SAT (right panel) on summer SIA in the Pacific sector from 1953 to 2010. (The areas inside the red and blue lines indicate where the regression coefficient passes the 1% significance level).

maintained locally by interactions with transient eddies and that planetary waves were important for transmitting dynamical signals to the troposphere.

How are the changes in atmospheric factors in spring linked to the decline in summer sea ice in the Pacific sector? Using linear regression, the relationship between summer SIA and spring SLP and SAT was analyzed (Fig. 10). For the linear regression of SLP with summer SIA, SLP was higher over the northwestern part of the Eurasian continent and the western Pacific sector in the years with more sea ice. For those years with less ice, the opposite SLP situation occurred. The SAT increased over the entire Arctic Ocean when SIA was lower than normal. In the Pacific sector, the area of strong negative correlation between SAT and SIA is located mainly in the East Siberian Sea. These results indicate that when lower SLP occurs over northern Eurasia, there is more heat transport from lower latitudes to the Arctic Ocean, especially to the East Siberian Sea, resulting in a higher than normal SAT.

3 VARIATIONS IN SEA/ICE SURFACE HEAT FLUXES

Changes in SAT and SIA are closely connected to the air–sea interaction. The sea/ice surface heat fluxes (including net shortwave radiation, net longwave radiation, latent heat flux, and sensible heat flux) were analyzed to show their possible influence on the decline of sea ice. The net surface heat flux from 1989 to 1993 has an obvious increase in the East Siberian Sea and Chukchi Sea in the Pacific sector compared with 1979 to 1988 (Fig. 11, left panel). This type of phenomenon occurred in summer rather than spring. Among the four types of heat flux noted above, shortwave radiation (Fig. 11, right panel)

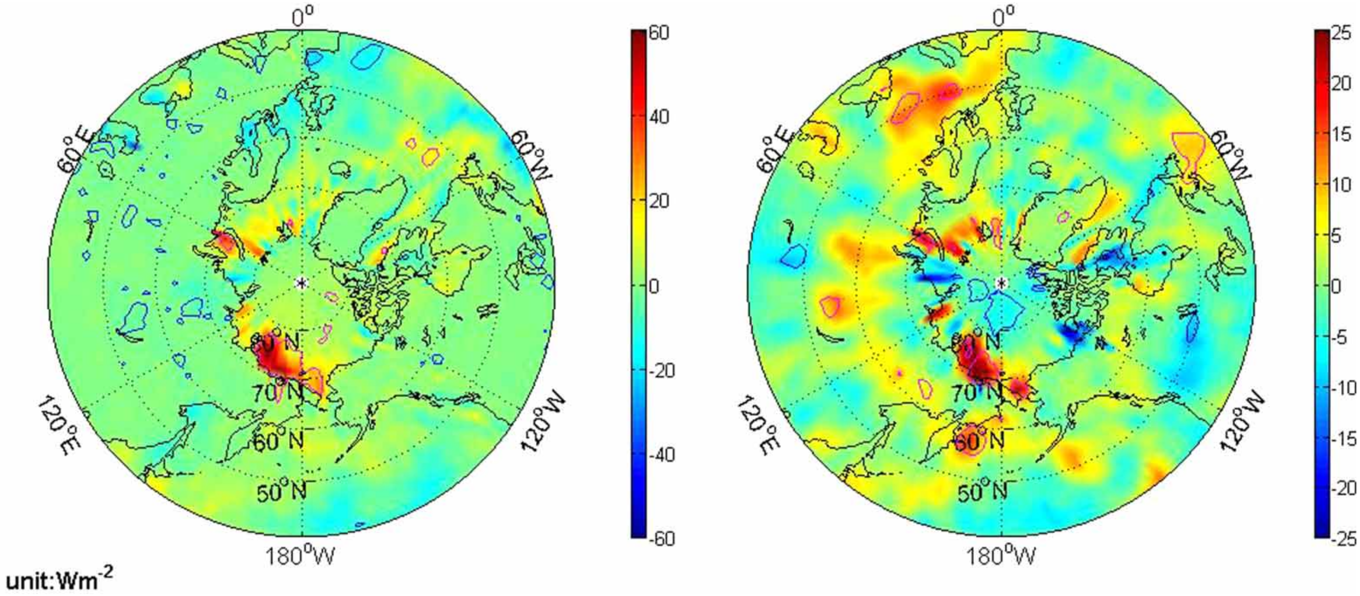

Fig. 11 The difference fields for net heat flux (left panel) and net shortwave radiation (right panel) for summers between 1989 and 1993 and 1979 and 1988. (The red and blue lines indicate the estimated 1% significance level).

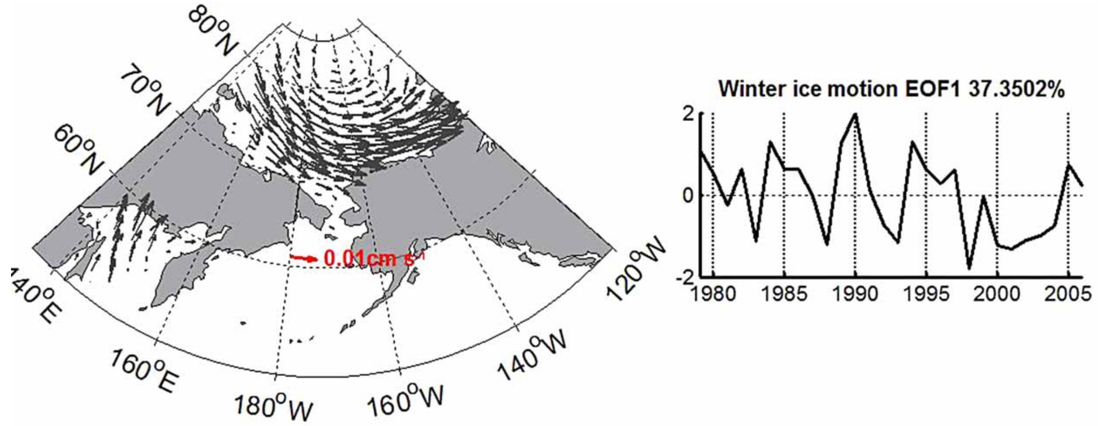

Fig. 12 The leading EOF mode for winter Arctic sea-ice velocity from 1979 to 2006 (left panel) and its time series (right panel).

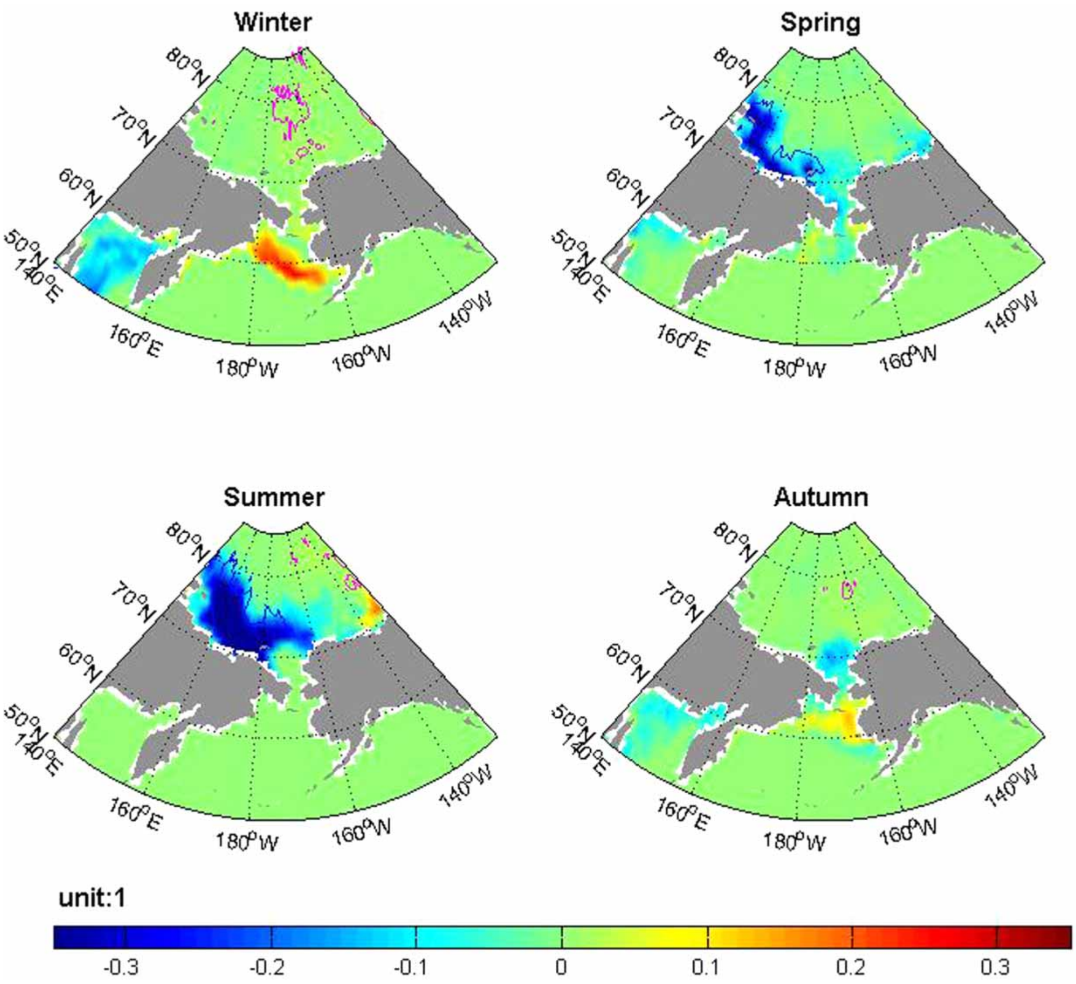

Fig. 13 The SIC difference fields in spring, summer, autumn, and winter between 1989 and 1993 and 1979 and 1988. (The thick lines indicate the estimated 1% significance level).

makes the greatest contribution to the difference field of the surface net heat flux, followed by the latent heat flux (figure not shown). Considering that the maximum surface heat flux (June–August) occurs earlier than the maximum ice melt (August–October), the increase in heat exchange between the air and sea is also one of the reasons for the abrupt reduction in summer sea ice in the Pacific sector during the late 1980s.

4 VARIATIONS IN SEA-ICE MOTION

Wang and Zhao (2012) studied the seasonal and interannual variations in sea-ice drift in the Arctic Ocean. They found that ice motion demonstrates a more anticlockwise (clockwise) drifting pattern as a whole, when the AO remains in a high positive (negative) phase.

The EOF modes of winter sea-ice velocity from 1979 to 2006 in the Pacific sector were calculated using SSM/I data. For the leading EOF mode (Fig. 12), sea ice in the Pacific sector showed an anomalous cyclonic/anticyclonic drift. This mode stayed in the highly significant cyclonic phase in 1989/90. During this period, sea ice in the northern Pacific sector demonstrated a cyclonic drift, moving from west to east, and the direction of the ice motion was almost parallel to the coast. The anomalous ice drift was driven by the SLP and surface wind anomalies in winter. More sea ice left the East Siberian Sea, which strengthened the heat transfer from the atmosphere to the ocean. The heat released from the ocean warmed the local surface air by approximately 1°–3°C. The heating of the atmosphere, in turn, would decrease the local sea ice in the following seasons.

5 SEASONAL PERSISTENCE OF SEA ICE

Although the abrupt decrease in SIA occurred in the summer of 1989, the greatest reduction in SIC occurred in the spring, as seen in the SIC difference fields (Fig. 13). In summer, SIC in the entire area north of Bering Strait decreased, especially in the East Siberian Sea. The decline in SIC in the autumn was very limited, centred in the Chukchi Sea. The evolution of SIC difference fields showed the seasonal persistence of sea ice from spring to summer.

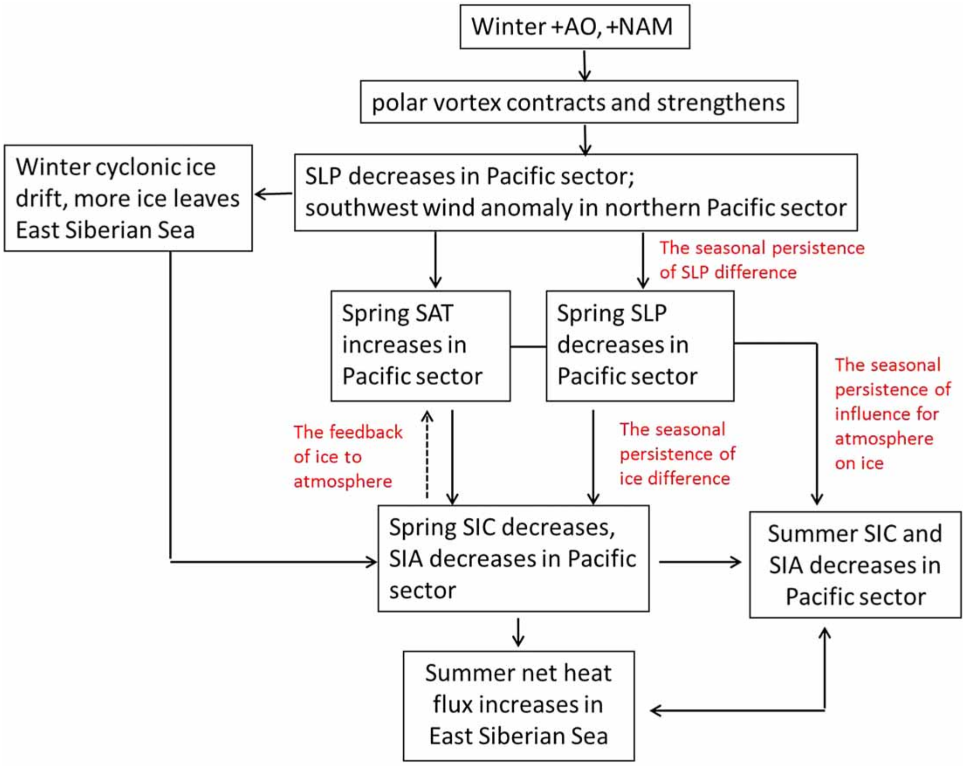

Fig. 14 Mechanisms for the abrupt decrease in summer sea ice in the Pacific sector.

4 Conclusions

In this study, using MTT, we have confirmed that an abrupt decrease in summer (August–October) SIA took place in the Pacific sector of the Arctic in 1989. The spatial distribution of the leading EOF mode of SIC shows that the most obvious change occurred in the East Siberian Sea.

Our results indicate that the sudden decrease in sea ice was induced by a phase shift in the AO and the NAM. The changes in the polar vortex (the stratospheric component of NAM) and the associated atmospheric circulation, the heat fluxes from the sea/ice surface, and the ice motion were analyzed. The mechanisms for this decrease in sea ice are shown in Fig. 14.

When the AO (NAM) shifted phase from negative to positive, the area of the 300 hPa polar vortex in the northern hemisphere decreased abruptly, and vortex intensification occurred in winter 1988/89. As a result, SLP decreased in almost the entire Arctic, while SLP near the Aleutian Islands was higher than before. Changes in SLP reduced the pressure difference between the areas north and south of Bering Strait, which favoured a southward wind anomaly around the strait and an anomalous southwest wind in the East Siberian Sea, the Chukchi Sea, and the Beaufort Sea. These atmospheric circulation anomalies drove the winter ice drift from west to east in the East Siberian Sea.

The changes in SLP and wind fields persisted into the following spring. All of these anomalies contributed to the decrease in sea ice and the increase in SAT in the following spring through the feedback of sea ice to the atmosphere. The warmer air reached the northern part of the Pacific sector through the anomalous southerly wind, contributing to the melting of the sea ice. The SIC in spring also decreased because of the higher SAT.

The influence of spring SLP and SAT on sea ice persisted into summer. Sea-ice variation itself also showed seasonal persistence. All the aspects mentioned above resulted in the abrupt decrease in summer sea ice at the end of 1980s. Changes in spring SAT and SIA were closely related to the increase in the net heat flux from the sea/ice surface in summer (June–August) in the East Siberian Sea, which was also an important reason for the decrease in summer sea ice.

Of course, the Pacific water inflow through Bering Strait also contributed to the sea-ice variations (Shimada et al., 2006). Further study is needed to determine whether there is any link between the sea-ice changes and ocean conditions. Also, the abrupt change in sea ice that took place in 2002 or later in the Pacific sector needs to be studied in the future when the time series is sufficiently long.

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