Tellus
SERIES A
DYNAMIC
METEOROLOGY
AND OCEANOGRAPHY
PUBLISHED BY THE INTERNATIONAL METEOROLOGICAL INSTITUTE IN STOCKHOLM

Tellus (2010), 62A, 661–672

TELLUS

Spatial variation of the Arctic Oscillation and its long-term change

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(Manuscript received 22 September 2009; in final form 31 May 2010)

ABSTRACT

The Arctic Oscillation (AO) is spatially varied, but lack of study. The authors defined the spatial variation of AO as the temporal variation of the ensemble of grids with sea level pressure (SLP) varying consistent with the AO index in certain time span. The region of the ensemble is called as 'AO-dominant region', identified by the running correlation coefficient of gridded SLP with the AO index. The positive and negative AO-dominant regions show that the SLP oscillated sometimes between the polar and mid-latitude regions and sometimes between land and ocean. Along the Atlantic–Pacific section, the North Atlantic Oscillation exists as a stationary seesaw-like dipole, while on the Pacific side the oscillation is intermittent with lower intensity and swinging boundary. The long-term spatial variation of the AO with three stages is clearly identified by the relative area of the SLP anomaly regions. Positive SLP anomaly area dominated before 1970, showing the state before the global warming. Negative SLP anomaly area dominated during 1971–1995, indicating the effect of global warming before the Arctic warming being apparent. Since 1996 both positive and negative SLP anomaly areas are all small, being possibly caused by the sea-ice retreat during the Arctic warming.

1. Introduction

The Arctic region is experiencing obvious warming during the past decade at a rate nearly twice of the global average (Hassol, 2004). With the exception of sea-level pressure (SLP), most climate indicators show linear trends; the notable ones include the decline of the perennial ice coverage at a rate of 9% per decade (Comiso, 2002) and the thinning of the ice draft for more than a metre from two to four decades ago to the 1990s (Rothrock et al., 2003). The variation of the SLP signal, however, behaves like an oscillation.

The Arctic Oscillation (AO) is commonly seen as a seesaw-like fluctuation in SLP between the polar region and the mid-latitude in the Northern Hemisphere (NH). The spatial pattern of the AO is defined by the first mode of the Empirical Orthogonal Function (EOF1) of SLP North of 20°N and the temporal coefficient of this EOF1 is defined as the AO Index (AOI; Thompson and Wallace, 1998). The AO is also called the Northern Hemisphere annular mode (NAM; Thompson and Wallace, 2000). The AOI has become a representative climate index for atmospheric circulation, with its polarity representing the phase of the AO. For much of the time since 1950, the AO exhibited a negative phase, with an obvious positive phase appeared only during the time period of 1989–1995 (Thompson et al., 2000). However, since 1996 the AO has turned gradually to a near-neutral or negative phase (Overland and Wang, 2005).

The North Atlantic Oscillation (NAO) is a seesaw-like dipole oscillation along the Atlantic sector (Barnston and Livezey, 1987; Hurrell, 1995), which was discovered in the 1920s (Walker and Bliss, 1932) and has been studied extensively (e.g. Stephenson et al., 2003). Since the NAO index correlates well with the AOI (Hurrell et al., 2003), some studies focused on the physical reality of the AO and the connection between AO and NAO. The AO has a negative centre of action over the North Pole (N) and two positive centres over the Atlantic (A) and the Pacific (P) sectors. If the AO is a 'true AO', the oscillations at the three centres of action should be coherent. Deser (2000) presented the result that the positive centres correlate with the negative centre, but the correlation between the A and P centres is weak. By considering an three-component system representing the three centres of action, Ambaum et al. (2001) also indicated that two independent variations between N and A and between N and P show apparent coherent structure in the three regions, and the observed AO is mainly a reflection of similar behaviours in the Atlantic basin (namely the NAO) and the Pacific basin. Itoh (2002) formulated two simple conceptual models representing the NAO and the AO paradigms, respectively, and indicated that the NAO paradigm has physical reality while the AO is only an apparent mode from the EOF analysis. Christiansen (2002) pointed out the impossibility of distinguishing them with purely statistical

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DOI: 10.1111/j.1600-0870.2010.00472.x

methods, as the two models are mathematically identical. Wallace and Thompson (2002) argued that the lack of correlation between A and P centres of action could be due to the coexistence of a second dynamically significant pattern. If this coexisting pattern is defined as EOF2 of the SLP field, the coupling between the A and P centres in the residual field is nearly as strong as that between A and N centres. They suggested that the AO is the leading mode of NH variability and emphasizes upon the zonally symmetric components of the geopotential height, and the NAO emphasizes upon the prominent North–South dipole structure in the SLP field over the North Atlantic Ocean.

EOF is a popular method to analyse spatiotemporal variation (Hannachi et al., 2007) and gives a space-stationary and time-fluctuating characteristic of a variable (Monahan et al., 2000). However, as the AO is a spatially variable phenomenon, only using the leading mode of EOF is not sufficient (Dommenget and Latif, 2002) to reflect the spatial variation of the AO.

Zhao et al. (2006) adopted a method by calculating the running correlation coefficient (RCC) between gridded SLP and the AOI to reveal a specific region including the GIN Seas (Greenland Sea, Iceland Sea and Norwegian Sea), part of Barents Sea and the area North of the Fram Strait, where the SLPs are always consistent with the AOI in the past 54 yr. Moreover, the averaged SLP of this region correlates significantly with the AOI, with a correlation coefficient (CC) of -0.949, the two being nearly interchangeable. They defined the region as the AO Core Region (AOCR). The AOI and the SLPs outside of the AOCR are less correlated because some events inconsistent with the AOI occurred in some years. The high correlation of normalized averaged SLP and the AOI assigns the AOI a new physical significance, namely the negative-averaged SLP of the AOCR. The AOCR only covers about 0.54% area of the NH North of 20°N, but its averaged SLP is nearly equivalent to the climate index obtained by the hemispherical data, suggesting the importance of this region to the overall climate change in the NH. The authors showed that the RCC analysis can be used to describe spatial variation of a spatiotemporal phenomenon. In this paper, we continue to study the spatial variation of the AO using the RCC method.

Two kinds of data are used in this study, the AOI from NOAA climate prediction centre and the SLP North of 20°N from the NCEP/NCAR reanalysis with a spatial resolution of 10° in longitude and 2.5° in latitude. Both data are monthly averaged and cover the period from January 1950 to August 2008. A 13-point smoothing is applied to filter out high-frequency variation.

2. Spatial variation of the AO and the running correlation coefficient

2.1. Description to the spatial variability of AO

AO is the result of EOF analysis for SLP North of 20°N. The EOF method is based on a principal component analysis applied to a group of time series data. The EOF method provides a set of modes of variability with space-stationary patterns and time-fluctuating amplitude and phase. However, the AO should be a spatially varied oscillation, because the space-stationary pattern cannot describe the inconsistent variation of SLP between different locations.

Although the AO is spatially varying, it still lack of common ground about what is the spatial variation of AO and how to describe the spatial variation. A clear physical frame is necessary to setup the basis for describing the spatial variability of AO. A prospect is expected to describe the spatial variation of the AO in a way being coherent with the definition of AO itself, because AOI has been widely accepted as the temporal variation of AO. The spatial variation of AO is defined here as 'the temporal variation of the ensemble of the grids with SLP varying consistent with the AO index in a certain time span'. By this definition, the spatial variation of AO is expressed as a varying size of region in which its SLP varies consistent with AOI in a period of time. We will name the region as 'AO-dominant region'. From the definition, the spatial variation of AO exhibits the temporal variation of AO-dominant region: shape changing, area shrinking and extending and boundary swinging.

This definition is reasonable and embodies two advantages to understand the spatial variation of AO. First, it states that the spatial variation is a temporal variation of spatial extent of AO-dominant region. Secondly, the definition links the spatial variation to the temporal variation of AO, which allows us to understand the connection between spatial and temporal variations of AO. To study the spatial variation of AO by this definition, the 'consistent' needs to describe by a CC, the 'certain time span' needs to choose a time window to calculate the CC and the 'ensemble of the grid' needs to express by the area of region consistent to AOI.

As we will see shortly the space-stationary pattern is consistent with the CC between the original variable and the time coefficient of EOF modes for the full time span. If only part of the time period is considered, the spatial variation of EOF mode will emerge and the RCC between the AOI and SLP field could describe spatial variation of the AO.

2.2. The factor loading of EOF

Analysing the monthly mean SLP $\mathbf{X} = (\mathbf{x_1}, \mathbf{x_2}, \cdots, \mathbf{x_m})^{\mathrm{T}}$ by the EOF method, where $\mathbf{x}_{\mathrm{k}} = (x_{k1}, x_{k2}, \ldots, x_{kn})$ is the SLP time series, $i = 1, \ldots, n$ is the number of the data and $k = 1, \ldots, m$ denotes each spatial grid. The hth principal component $\mathbf{z_h} = (z_{1h}, z_{2h}, \ldots, z_{nh})$ and hth eigenvector $\mathbf{v_h} = (v_{1h}, v_{2h}, \ldots, v_{mh})^{\mathrm{T}}$ can be expressed, according to Gao (2004), as

$$\mathbf{z}_h = \mathbf{v}_h^T \mathbf{X}. \quad (1)$$

When $h = 1$, $\mathbf{z}_1$ is the AOI and $\mathbf{v}_1$ is the AO pattern. Right after the EOF analysis, another important parameter could be obtained, which is the CC between the principal component $\mathbf{z}_h$

and the gridded SLP data $\mathbf{x}_k$ (Gao, 2004)

$$\rho(z_h, x_k) = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_{ki} - \overline{x_k})(z_{ih} - \overline{z_h})}{\sqrt{\sigma_k}\sqrt{\lambda_h}}, \tag{2}$$

where λ_h is the variance of the hth principal component, σ_k is the variance of SLP of the kth grid. CC field is performed by eq. (2) for each grid, which presents the consistency of gridded SLP with the principal component. Three types of data can be used for EOF analysis: the original data, the anomaly data and the standardized data. Because the analysis by the EOF method uses the SLP anomaly data and the AOI is also anomaly data (see http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/history/method.shtml), the following relation exists between CC and AO pattern (Gao, 2004),

$$\rho(z_h, x_k) = \frac{\mathrm{Cov}(\mathbf{z}_h, \mathbf{x}_k)}{\sqrt{\lambda_h}\sqrt{\sigma_k}} = \frac{\sqrt{\lambda_h}}{\sqrt{\sigma_k}} v_{kh}, \tag{3}$$

where

$$\mathrm{Cov}(\mathbf{z}_h, \mathbf{x}_k) = \lambda_h v_{kh}. \tag{4}$$

It is clear from eq. (3) that the signs of the CC field and AO pattern are the same, showing both can be used to express the polarity of the AO, although we always use the AO pattern. The CC is inversely proportional to the variance of the SLP: the more dispersed the SLP data is, the greater the variance is and the weaker the correlation becomes. As the eigenvector of the EOF, the physical significance of the AO pattern is not very clear. However, the CC field embodies well-known significance to present the consistency of both signals. Therefore, the CC between the principal component and original data is also called the factor loading. A principal factor is interpreted from the variables that are highly correlated with it and that have high loadings on it (Tabachnik and Fidell, 2007). If the SLP and AOI are standardized, then the CC is equal to the AO pattern.

From factor loading point of view, the region with high CC is the main contributor to the AO, whereas the vast region with low CC contributes little to the AO process. The AO component only represents the SLP variation in the area whose SLP is highly correlated with the AOI. Although the AO is the result of EOF analysis for the SLP North of 20°N, its representativeness to the SLP in different region is quite different, which is revealed by the CC field. The CC field could indicate which region is significantly influenced by the AO. Therefore, the CC field can be a useful indicator to the spatial extent influenced by AO.

2.3. *Part-time correlation coefficient and AO-dominant region*

The CC in eq. (3) is calculated by full-length time series, which is the same time span with the EOF analysis. If only the data of a particular period ($t \pm p$) is used, the result could be called as the part-time CC (PCC),

$$\rho'(z_h, x_k) = \frac{\sum_{i=t-p}^{t+p}(x_{ki} - \overline{x'_k})(z_{ih} - \overline{z'_h})}{\sqrt{\sum_{i=t-p}^{t+p}(x_{ki} - \overline{x'_k})^2}\sqrt{\sum_{i=t-p}^{t+p}(z_{ih} - \overline{z'_h})^2}}, \quad t = 1+p, \ldots, n-p, \tag{5}$$

where the prime denotes the part-time values. When $p = \frac{n-1}{2}$ is chosen, the PCC in eq. (5) is equal to the full-time CC displayed in eq. (3). Since the data length of the PCC is shorter, there is no direct relationship between the PCC and AO pattern as given by eq. (3). The PCC represents the consistency of the AOI and SLP only in the corresponding period, which could detect intermittent processes. If the SLP variation of a grid includes some intermittent processes, it is possible that the correlation of SLP of a grid with the AOI is low for the full-time data, but high for a shorter period.

The assembly of the grids with high correlation (when the CC is greater than the confidence level) in a period of time forms areas where SLPs vary consistently with the AOI, which is here referred to as the AO-dominant region. Positive and negative parts are included in the AO-dominant region to show the SLPs varying the same or opposite with the AOI. The AO-dominant region is adequate to show the variable spatial distribution of the AO, because it contains all the grids that are highly consistent to the AOI.

2.4. *The running correlation coefficient*

The period used for calculating the PCC is called the window width (=2p in eq. 5), which determines the value of the PCC obviously. In fact, since the covariance for the CC is a mean of the cross product of the data, the PCC has a smoothing or filtering effect. Irrelevant high-frequency signals will be kept in the PCC result if the window is too narrow, and some useful higher frequent signals will be filtered out if the window is too wide. The adequate window width is based on the phenomenon we intend to study. For example, a 3-month window is suitable for seasonal process and a 1-yr window will filter out seasonal signal. Since our goal is to study multiyear variation and we also want to remove the quasi-biannual oscillation that is often in the SLP signal, a 2-yr window is adopted. From the result of Zhao et al. (2006), a 2-yr window worked well to reveal low-frequency processes correlated with the AO.

To exhibit the low-frequency continuous variation of AO-dominant region, a RCC could be obtained by moving the central time, t, month by month to calculate the PCC. The continuous RCC patterns could be used to represent the temporal variation of AO-dominant region, that is, the spatial variation of AO.

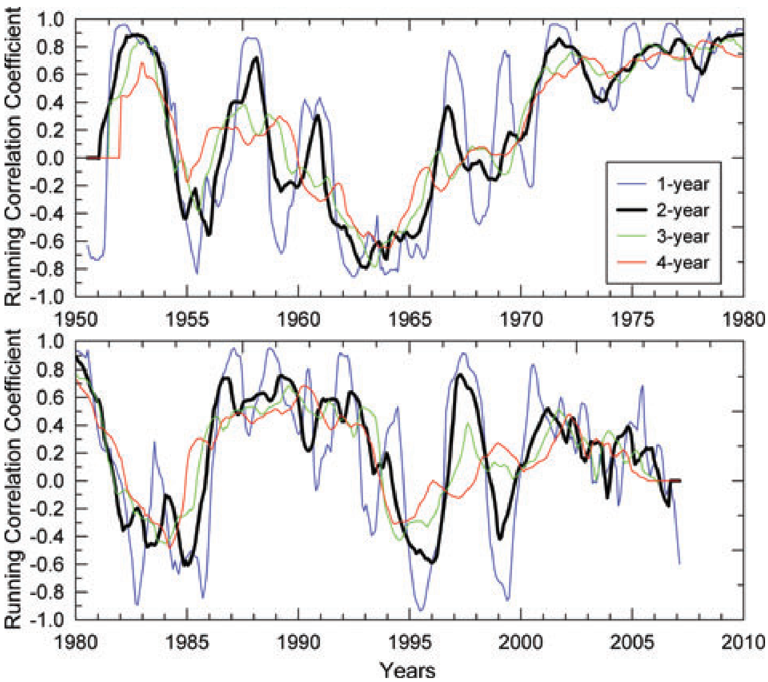

Fig. 1. An example of the RCC of AOI with SLP at (160°W, 62.5°N). RCC for the time window widths of 1, 2, 3 and 4 yr.

2.5. *Possible influence of time window width on the spatial variation of AO*

The RCCs with the time window widths of 1, 2, 3 and 4 yr are shown in Fig. 1. Results with any width of the time window all expressed the same fundamental feature of the low-frequency variation. The RCC with 1-yr window is roughest as it includes higher frequency signals. The RCC with 2-yr window is smoother and the main extremes appear at the similar time with those of 1-yr window. However, when the 3- and 4-yr windows are adopted, the curves are smoother, but the extremes of the RCC deviate from those of 1-yr window. It states that the longer width of time window will be benefit to reflect the low-frequent variation, but is worse to reflect the variation with higher frequency. It means that when we use a 2-yr window, the RCC will reveal the variation signal from 3 to 4 yr scale to long-term ones, whereas RCC with 3- or 4-yr windows will only show its long-term variation. If we are only concerned about the long-term signal, the longer width of time window is also a good choice.

The influence of different window width on RCC can also be seen in Fig. 2. Thirteen centre months in Fig. 2 are random

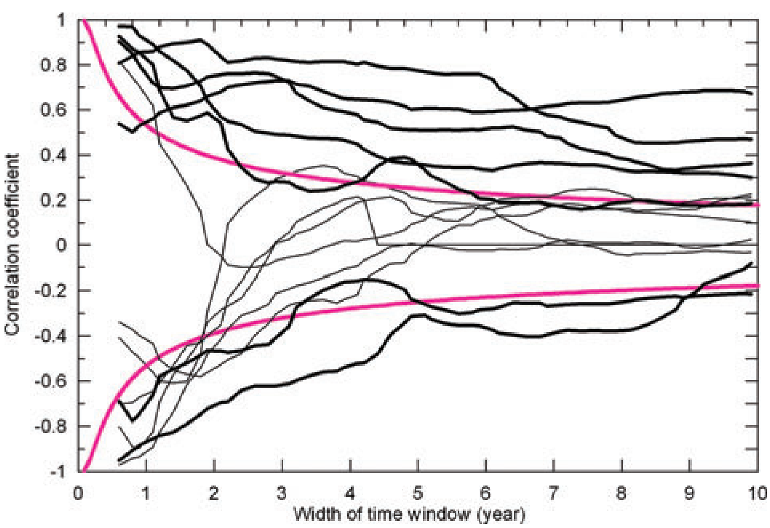

Fig. 2. The RCCs on random months with different width of time window. The location is the same with that in Fig. 1. The two red thick lines are the confidence level for positive and negative CC with different data samples. Thirteen centre months are random chosen and their RCCs with different window width are expressed by the black lines. The thick black lines are the RCCs higher than the confidence level and the thin lines are for the RCCs lower than the confidence level.

chosen and their RCCs with different window width are expressed by the black lines. The two red thick lines are the confidence level for positive and negative CC. It is interesting that the higher RCCs are always higher than the confidence level and the lower RCCs are always lower than the confidence level with different window width. This result indicates that the higher RCC will keep higher than the confidence level using different window width and the area of the AO-dominant region will not change much by different width of window. Therefore, the conclusions obtained by 2-yr window can be representative to those with other window width.

2.6. AO index and the averaged SLP in the AO Core Region

The AOI and averaged SLP in the AOCR are highly correlated, with a negative CC of −0.949, and are nearly interchangeable. It shows that the AOI is equivalent to the negative of the averaged SLP in the AOCR once they are both normalized. The AO-dominant region clustered by high PCC of gridded SLP and AOI is the regions whose SLP varies significantly consistently or oppositely with the averaged SLP in the AOCR.

Using negative value of the averaged SLP in the AOCR to represent the AOI, the RCC of gridded SLP with the AOI is equivalent to the one-point correlation (Wallace and Thompson, 2002), except the centre point is now in the AOCR. In general, the CC isobars for one-point correlation are a series of closed isolines with the value attenuated with the distance from the central point. The tele-correlation existed in a large area usually exhibits an oscillation.

In the following sections, the RCC between the AOI and gridded SLP with the 2-yr window width is adopted to describe the spatial variation of the AO. The spatial distribution of the RCC patterns may change in the manners of extending, contracting, boundary movement, and in some other ways. From the result of the RCC, spatially variation of AO, instead of space-stationary pattern, can be displayed for understanding low-frequency evolution of the SLP.

3. Spatial distribution of the AO

The RCC pattern is given by the map of central month with the RCC isolines. Because the 95% confidence level of the 2-yr RCC is 0.395, only the regions with RCC magnitude greater than 0.4 are highlighted in Fig. 3, where thicker contours indicate the values of ±0.4. We define the regions with RCC magnitude larger than 0.4 as the positive (red) or negative (blue) AO-dominant regions.

Figure 3 shows several typical RCC patterns with different spatial structures. The RCC pattern in 1990 displays the closest similarity to the AO pattern, in which the entire polar region is negatively correlated with the AOI while those of the surrounding mid-latitude regions positively correlated with the AOI. However, the RCC patterns with such resemblance to the AOI are rare; most RCC patterns are quite different from the AO pattern. In 1977, nearly all RCCs on landmass are

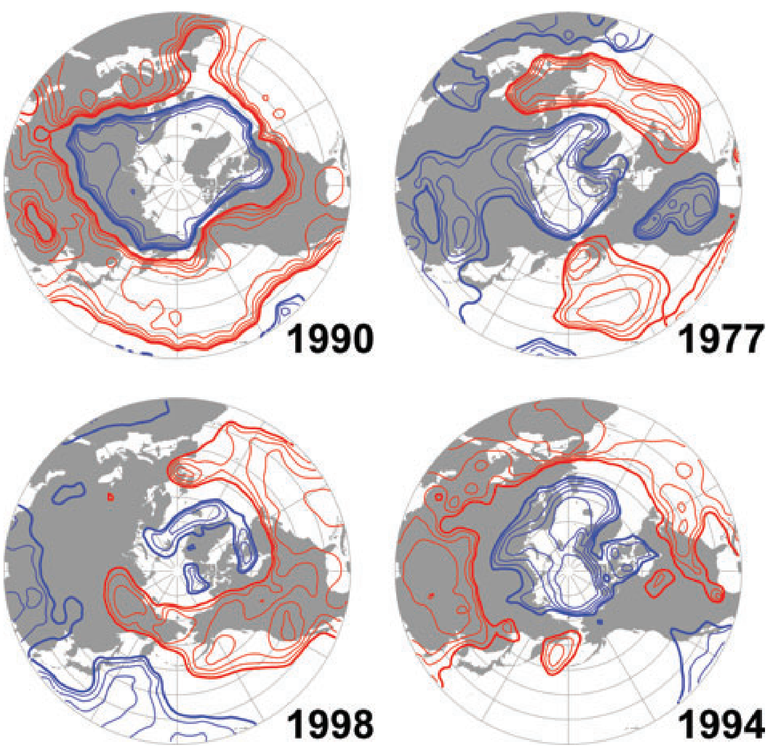

Fig. 3. Typical spatial distributions of the RCC. The pattern of each year is centred in January of that year with a 2-yr time window. Blue contours are for the region with negative RCCs (consistent with the AOI) and red contours are for the region with positive RCCs (opposite to the AOI). The absolute values of the isolines are between 0.4 and 1.0, the contour interval is 0.1 and the thicker contours are for ±0.4.

negative while those over the North Atlantic and North Pacific are positive, showing an oscillation between land and ocean. The RCC in 1998 has positive values over North America and oceans, and negative values over Eurasian continent and the polar region, showing an oscillation between the Eastern and Western Hemispheres. The pattern in 1994 consists of positive RCCs for all lands and Atlantic, and negative RCCs for the polar region and the Pacific.

The above description of the RCC patterns demonstrates nicely the spatial variation of the AO-dominant regions. Because of the smoothing effect of the RCC calculation, the RCC pattern of 2-yr window filters out all seasonal variations and keeps only multiyear changes. The AO is usually much intense in wintertime (Ogi et al., 2004); however, data of all months are used in this study, as the winter intensification as a seasonal phenomenon no longer dominates by the 2-yr window RCC. We choose the RCC patterns for every year centred in January since 1952 to highlight the variation of the AO-dominant regions in Fig. 4. Obvious multiyear spatial variation exists, which embodies the regional difference of SLP variation in the NH. In the past 56 yr, the seesaw-like oscillation between the polar and mid-latitude regions similar to the AO pattern appeared during 1957–1960, 1969–1970, 1989–1995, 1999–2001 and 2006–2007. In some years, for example, 1961–1962, 1971–1978 and 1984–1988, the oscillation was between land and ocean. The AO-dominant regions vary year-to-year with different spatial patterns, representing a low-frequency spatial variation of the AO.

In recent years, the RCC pattern becomes somewhat puzzling. In 2004 and 2005, the AO-dominant region becomes much smaller, which indicates that the oscillation phenomenon becomes less clear, especially in 2004. As pointed out by Overland and Wang (2005) for temporal variation, starting from 1996 the polarity of the AO became uncertain and blurry. The result here further indicates that the spatial structure of the AO-dominant regions also demonstrates similar ambiguity. The weakening of the oscillation in recent years could likely be explained by the decline of the Arctic sea ice (Comiso, 2002). The reduction of the sea-ice coverage and thickness resulted in more heat transport from the ocean to the atmosphere, which in turn impacted the SLP distribution.

The negative and positive AO-dominant sub-regions in Fig. 4 exhibit the existence of oscillation. One pole of the oscillation is stably centred in the AOCR, whereas the other pole changes spatially from year-to-year. The AO, therefore, is a spatially varying oscillation, whose spatial structure during different years needs to be studied using the spatial distribution of the RCC patterns.

In order to understand the significance of the spatial variation of the AO, the temporal variations along two longitudinal sections are analysed. One is called the Eurasia–America section along 90°E and 90°W (Fig. 5a) and the other is called the Atlantic-Pacific section along 0° and 180° (Fig. 5b). The variation of RCC along the Eurasia–America section is much complicated. In some years, for example 1955–1960 and 1988–1995, there were obvious oscillations between the polar and mid-latitude regions. During the entire 1970s, the phase of the SLP over land was the same as that over the polar region, with no oscillation along this section. In yet some other years, such as 1981–1984 and 1995–1998, both landmasses embodied opposite variations in terms of the RCC.

Along the Atlantic-Pacific section, three primary centres of action (Wallace and Thompson, 2002) of the AO (or the NAM) are included, North Atlantic (A), North Pole (N) and Pacific (P), respectively. There is a steady and continuous oscillation between the Arctic and North Atlantic and the boundary between the positive and negative regions moves very little. It can also be seen in Fig. 4 that there is always a region, whether small or large, in the North Atlantic Ocean where the phase of the SLP is always opposite to that in the AOCR. This steady oscillation is just the NAO, which is the prominent North–South dipole structure in the SLP field over the North Atlantic Ocean (Walker and Bliss, 1932; Hurrell, 1995; Wallace and Thompson, 2002), representing a robust fluctuation (Ambaum et al., 2001).

On the Pacific side, an oscillation between the Arctic and Pacific oceans also exists (Fig. 5b), but less prominent than those on the Atlantic side. An outstanding characteristic of the oscillation is that the boundary between the positive and negative correlation regions swings in a North–South direction to a large extent. Sometimes the boundary was at around 50–60°N, and sometimes it moved near the pole, or even moved to the other side of the pole. The temporal boundary swinging of the RCC pattern indicates that in some regions of North P the SLP varies sometimes consistently with the AOI and sometimes opposite to the AOI.

The SLP at the centres of action A and P are less correlated. Deser (2000) and Ambaum et al. (2001) pointed out the inconsistency to demonstrate that the NAO is the more robust paradigm. Itoh (2002) tried to explain the inconsistency by the concepts of true AO and apparent AO. Wallace and Thompson (2002) indicated that the lack of correlation is due to the coexistence of EOF2 of the SLP field. The result in this paper indicates that the temporal boundary swinging of the AO-dominant region acts to reduce the correlation between the SLP at the centres of action A and P. The swinging of the boundary may be related to the Pacific Decadal Oscillation (PDO) or El Nino and Southern Oscillation (ENSO) as suggested by Zhao et al. (2006). The EOF result is not able to display the boundary swinging, but one might use the Pacific–North American pattern as EOF2 (Wallace and Thompson, 2002) and other modes to exhibit the difference of P and A centres.

The RCC patterns exhibit the temporal variation of AO-dominant region: shape changing, area shrinking and extending and boundary swinging. From the long-term paradigm as embodied by the EOF pattern, the AO is an oscillation with three relatively fixed poles (centres of action). However, from the

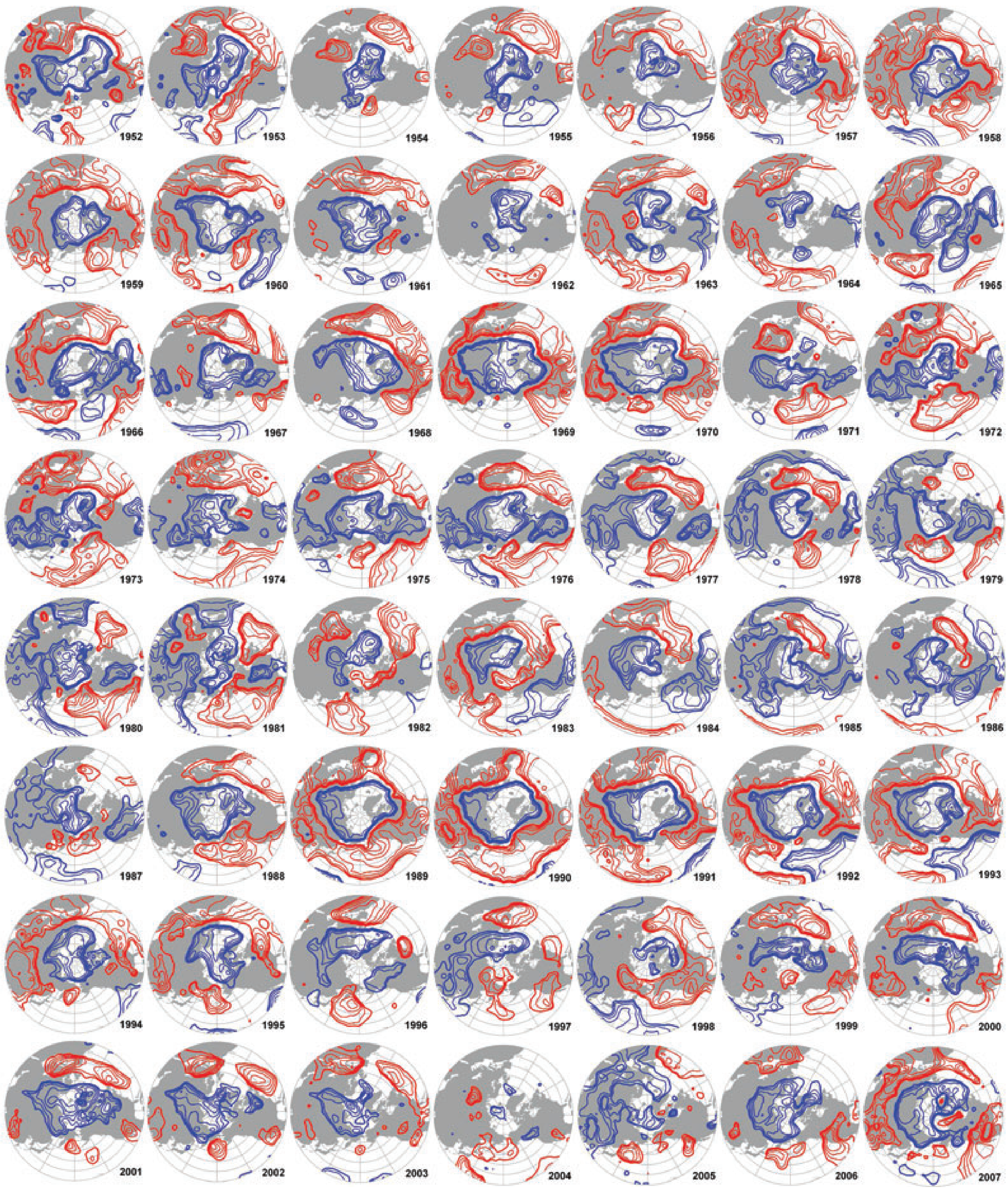

Fig. 4. RCC patterns of each January since 1952. The pattern of each year is centred in January of that year with a 2-yr time window. The absolute values of the isolines are 0.4–1.0, the contour interval is 0.1 and the thicker contours are for ±0.4.

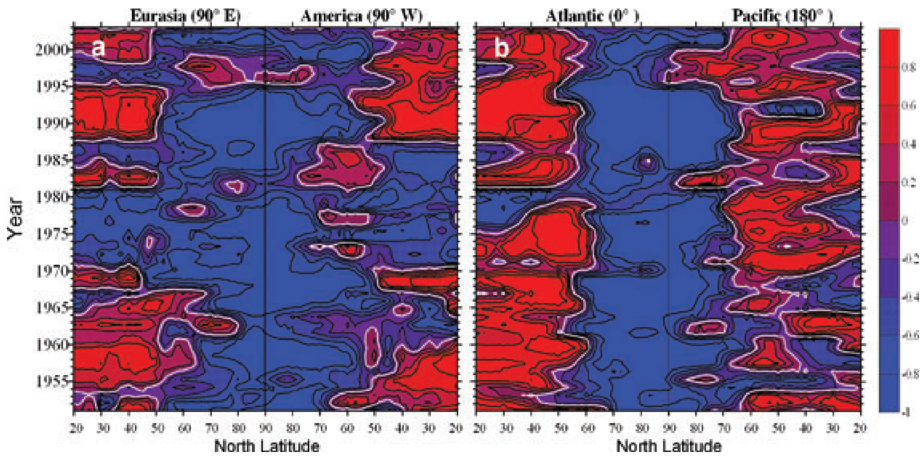

Fig. 5. Spatiotemporal plot of the RCC centred in January of each year with a 2-yr time window. (a) Along the Eurasian–American section (90°E-90°W) and (b) along the Atlantic–Pacific section (0°–180°). Blue (red) area is for negative (positive) correlation and white contours are for zero correlation. The contour interval is 0.2 and the central black line marks the North Pole.

spatial variation point of view, the AO has two fixed poles among the three centres, one is over the AOCR, mostly extends to the North Pole, and the other is over the mid-latitude Atlantic, strongly supporting the NAO paradigm. The other pole on the Pacific side also exists, but always changes its boundary as it is greatly influenced by processes occurring in the Pacific sector.

4. Long-term spatial variation of the AO

In Fig. 4, the year-to-year change of the RCC patterns clearly displays the spatial variation of the AO. However, it is still difficult to figure out the spatial variation of the AO only by these sequential maps. It would be better if a simple index could be used to reflect the multiyear variation of the RCC patterns. Therefore, we attempt to find a new index with clear physical significance to reveal the temporal characteristic of the spatial variation of AO-dominant regions.

4.1. Relative areas of AO-dominant region and relative areas of SLP anomaly region

The positive and negative areas of the AO-dominant region with RCC magnitude greater than 0.4 (at 95% confidential level) are summed up separately and divided by the total area North of 20°N to produce the relative areas, respectively as shown in Fig. 6a. It can be seen that in most years positive relative area of AO-dominant region was dominant. The negative relative area was dominant during 1975–1987. Both relative areas were all small since 1996. This result indicates the multiyear variation of AO-dominant region.

An interesting phenomenon is that the relative areas of AO-dominate region is positive for 1952–1970 and negative for 1975–1987 (Fig. 6a) when AOI tends to be in their negative phase (Fig. 7a). A reasonable explanation can be obtained from the consecutive patterns in Fig. 4. During 1952–1970, the negative correlation region was localized in a small area around the North Pole and then the positive correlation region was dominant. However, during 1975–1987, the negative correlation region extended to the America and Eurasia landmasses, a much larger area, and the negative correlation region was dominant. It implies that the negative correlation region will be dominant when it covers most of the landmass in NH, whereas the positive correlation region will be dominant when the negative correlation region only covers a small polar area. Therefore, with the same polarity of AOI, the spatial variation of AO expressed by RCC could be quite different.

In order to extract more information of the long-term spatial variation of AO, we tried to shift the relative area of AO-dominant region onto the relative area of SLP anomaly. As addressed by Zhao et al. (2006), the AOI is equivalent to the negative of the averaged SLP of the AOCR once they are both normalized. It means the correlation with AOI is equivalent to the negative correlation with the averaged SLP of AOCR. This shift is important in physics. AOI is only a climatologic index, whereas the SLP reflects the changing distribution of air mass. The relative areas for the positive and negative SLP anomaly regions will reveal the changing of the SLP in NH. When SLP in a grid is positively correlated with AOI, the signs of the SLP anomaly at this grid will be determined by the polarity of the AOI: when AOI is positive (negative), the SLP anomaly is negative (positive), and vice versa. Both relative areas for SLP anomaly are obtained as shown in Fig. 6b. It can be seen from Fig. 6b that the multiyear variation of the relative area can be divided into three stages naturally. Before 1970, the positive SLP anomaly region was dominant. During 1971–1995, negative SLP anomaly region was dominant. From 1996 to 2007, the areas of the two regions were similarly small, with the minima

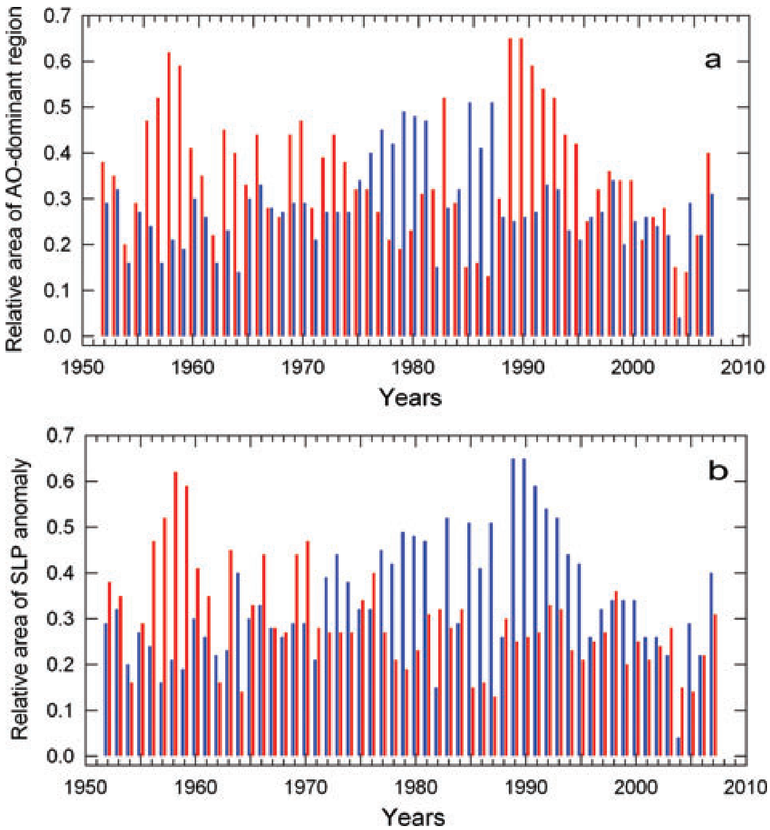

Fig. 6. Long-term spatial variation of the AO. The AO-dominant region is obtained by RCC centred in January each year with a 2-yr time window when the RCC is greater than 0.4. (a) The positive (red) and negative (blue) relative areas are the ratio of the area of AO-dominant region to the total area North of 20°N. (b) The positive (red) and negative (blue) relative areas are the ratio of the area of ±SLP anomaly regions to the total area North of 20°N.

in 2004–2006. This result makes us to extend our understanding from the spatial variation of AO-dominant region to the spatial variation of SLP anomaly areas.

4.2. *Indices for the long-term spatial variation of AO*

The two relative areas of SLP anomaly could be used to construct two indices, the difference of the relative areas (DRA; positive minus negative of the relative area of the SLP anomaly) and the sum of the relative areas (SRA). They are shown in Figs. 7b and c, to be compared with the AOI in Fig. 7a. The DRA is to present the dominant SLP anomaly in the NH and the SRA is to present the total influencing area of the AO. The DRA indicates that the dominant SLP anomaly is positive before 1970, negative during 1971–1995 and becomes weak after 1996. The DRA is very clear to reflect the three stages. Compared with Fig. 7a, the DRA is different from AOI, provides us more information and is a good index for the long-term variation of SLP anomaly (Fig. 7b).

The SRA indicates the total relative area dominated by the AO (Fig. 7c). Before 1996, the SRA was about 0.6–0.8; the AO covered a huge area and was dominant in the NH. The maximum SRA occurred during 1989–1995, with a value over 0.9 at its peak, consistent with the period when the AO was in its positive phase. Since 1996, the SRA became small, mostly less than 0.6 and had its minimum of ~0.2 in 2004.

The cause behind the three stages is unknown. Here we speculate that the three stages are correlated with the global climate change. Before 1970, the positive SLP anomaly was dominant in the NH, which shows the state before global warming. The temperature plot for the global warming supports the speculation, as the warming started from early 1970s (Hansen et al., 2001). During 1970–1995, the negative SLP anomaly became dominant. In that stage, global warming was increasing, but the Arctic sea ice changed little (Chapman and Walsh, 1993). A recent study confirms that the ice thickness was nearly unchanged before 1996 (Kwok and Rothrock, 2009). After 1996, both the intensity (measured by the AOI) and dominant extent (measured by the SRA) of the AO decreased greatly and the climate of the NH changed accordingly by the weakened AO (Overland and Wang, 2005). The Arctic warming and sea-ice retreat in recent year might be the fundamental mechanism for the third stage after 1996. Arctic warming is a result in respond to the global warming. It accelerated and became significant since mid-1990s with the decline of sea-ice area, concentration and thickness (Kwok et al., 2009). The third stage since 1996 has unlikely finished, as the coverage of the Arctic sea ice reached the minimum in 2007 (Comiso et al., 2008), 2008 (http://nsidc.org/

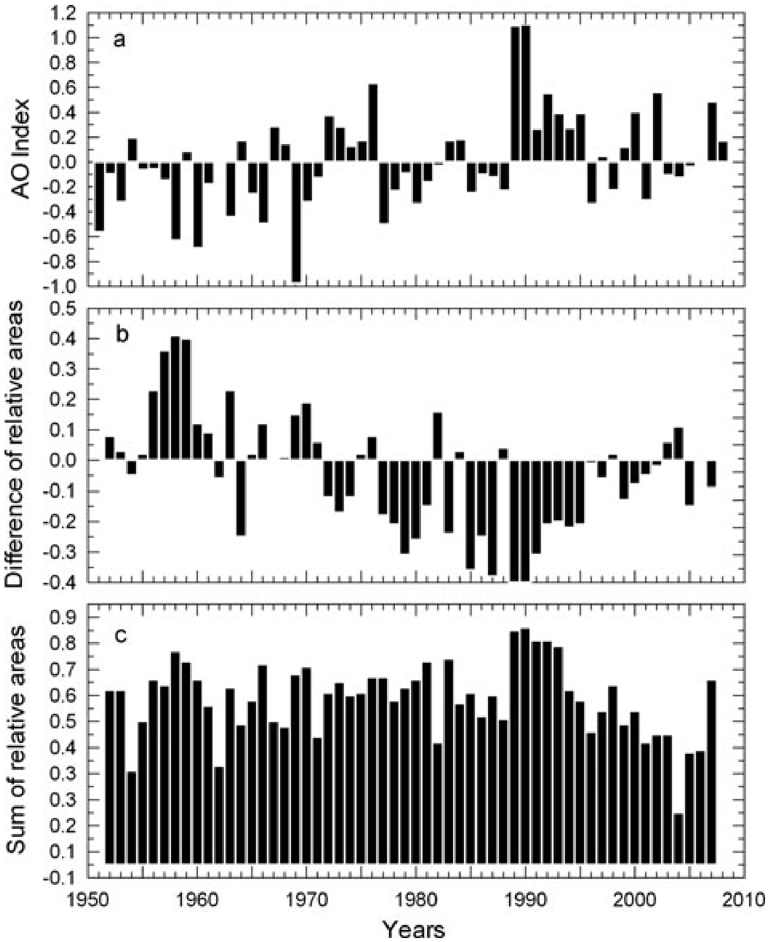

Fig. 7. AOI and spatial-variation indices, DRA and SRA. (a) The annually averaged AOI centred in January, (b) DRA, the difference of the relative area of SLP anomaly regions and (c) SRA, the sum of the relative area of SLP anomaly regions. The positive and negative relative areas are the same with that in the caption of Fig. 6.

news/press/20081002_seaice_pressrelease.html), and continued its decline in 2009 (http://nsidc.org/arcticseaicenews/).

The DRA is likely a good index to represent the three stages of spatial variation of the AO in the past 56 yr. The AO could be described not only by the temporal process (the AOI), but also by the spatial variation (the DRA and SRA). Based on these indices, how the AO influences the hemispherical climate is clearly exhibited.

We also noticed that the three stages of DRA in Fig. 7b looks also like a multidecadal process. The multidecadal oscillations on the earth have been revealed as AMO (Atlantic Multidecadal Oscillation) in Atlantic Ocean (Knight et al., 2006) and PDO(Pacific Decadal Oscillation) in Pacific Ocean (MacDonald and Case, 2005). The SLP data are not long enough to study multidecadal process. More researches are necessary to see the possible connection between the spatial variation of AO and the multidecadal oscillation.

5. Conclusion

The AO is commonly defined by a space-stationary and time-fluctuating result of EOF method for SLP. Because the SLP is a spatiotemporal variable, the AO should be a spatially varying oscillation. The spatial variation of AO is defined here as the temporal variation of the ensemble of the grids with SLP varying consistent with the AOI in a certain time span. By this definition, the spatial variation of AO is expressed as a varying size of region in which its SLP varies consistent with AOI in a period of time. We named the region as 'AO-dominant region'. From the definition, the spatial variation of AO exhibits the temporal variation of AO-dominant region: shape changing, area shrinking and extending and boundary swinging. When the part-time RCC is calculated, the variable spatial patterns of AO-dominant regions emerge. The sequential maps of RCC patterns identify the time-dependent AO-dominant regions to illustrate the spatial variation of the AO.

The spatial pattern of the AO-dominant region changes interannually, which explains the regional difference of SLP in the NH. Of the RCC patterns in the past 56 yr, the oscillation occurred sometimes between the polar and mid-latitude regions, and sometimes between the landmass and ocean. In most cases, the RCC spatial patterns are quite complicated. The spatiotemporal variation of the RCC is displayed along two longitudinal sections. Along Atlantic-Pacific section, a stationary seesaw-like oscillation exists between the Arctic and North Atlantic, that is the NAO. On the Pacific side, an oscillation occurs between the Arctic and Pacific oceans intermittently with lower correlation and swinging boundary between the positive and negative RCC regions. In the section across the Eurasian and North American continents, the oscillation is unclear with complicated multiyear variation.

Based on the result that the AOI is negatively correlated with averaged SLP of the AOCR, long-term spatial variation of the AO can be identified by the relative area of positive and negative SLP anomaly regions. The DRA and the SRA are chosen as useful indices to describe the spatial variation of the AO. The DRA clearly shows the dominating SLP anomaly in different stages of the spatial variation. The SRA indicates the relative area dominated by the AO, about 0.6–0.8 before 1995 and less than 0.6 after 1996. The spatial variation of the AO is divided into three stages naturally and is speculated to correlate with global climate change. Before 1970, the positive SLP anomaly was dominant in the NH, indicating the state before the global warming. During 1971–1995, negative SLP anomaly region was dominant; this is a period when the global warming started but the Arctic did not show obvious warming due to time lag. From 1996 to present, the areas of the positive and negative SLP anomaly regions are similar and small. The sea-ice retreat during the Arctic warming is speculated to be the fundamental mechanism for the stage after 1996, but it needs to be verified. The third stage since 1996 has unlikely finished as the sea-ice coverage of the Arctic reached its minimum in 2007 and 2008 and may continue diminish.

6. Acknowledgments

The support for this project was provided by the National Natural Science Foundation of China under grant No. 40876006 and 40631006.

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