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A Preliminary Study on the Relationship Between Arctic Oscillation and Daily SLP Variance in the Northern Hemisphere During Wintertime

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ABSTRACT

In the present study, the authors investigated the relationship between the Arctic Oscillation (AO) and the high-frequency variability of daily sea level pressures in the Northern Hemisphere in winter (November through March), using NCEP/NCAR reanalysis datasets for the time period of 1948/49-2000/01. High-frequency signals are defined as those with timescales shorter than three weeks and measured in terms of variance, for each winter for each grid. The correlations between monthly mean AO index and high-frequency variance are conducted. A predominant feature is that several regional centers with high correlation show up in the middle to high latitudes. Significant areas include mid- to high-latitude Asia centered at Siberia, northern Europe and the middle-latitude North Atlantic east of northern Africa. Their strong correlations can also be confirmed by the singular value decomposition analysis of covariance between mean SLP and high-frequency variance. This indicates that the relationship of AO with daily Sea Level Pressure (SLP) is confined to some specific regions in association with the inherent atmospheric dynamics. In middle-latitude Asia, there is a significant (at the 95% level) trend of variance of –2.26% (10 yr)$^{-1}$. Another region that displays a strong trend is the northwestern Pacific with a significant rate of change of 0.80% (10 yr)$^{-1}$. If the winter of 1948/49, an apparent outlier, is excluded, a steady linear trend of +1.51% (10 yr)$^{-1}$ shows up in northern Europe. The variance probability density functions (PDFs) are found to change in association with different AO phases. The changes corresponding to high and low AO phases, however, are asymmetric in these regions. Some regions such as northern Europe display much stronger changes in high AO years, whereas some other regions such as Siberia show a stronger connection to low AO conditions. These features are supported by ECMWF reanalysis data. However, the dynamical mechanisms involved in the AO-high frequency SLP variance connection have not been well understood, and this needs further study.

Key words: Arctic Oscillation, sea level pressure (SLP), Northern Hemisphere, synoptic variance

1. Introduction

High frequency fluctuations in climate variables are of practical importance because they are strongly related to weather extremes. As a dominant mode of the atmospheric circulation in the Northern Hemisphere, the Arctic Oscillation (AO) plays crucial role in influencing large-scale atmospheric circulation anomalies (Thompson and Wallace, 1998, 2000), and is tightly associated with the high-frequency transients in the troposphere (e.g., Wu and Straus, 2003). As a consequence, it can be connected to the regional extremes in weather phenomena over the Northern Hemisphere (Thompson and Wallace, 2001; Thompson et al., 2002). For example, Wettstein and Mearns (2002) and Higgins et al. (2002) found that there are significant relationship between the frequency of daily temperature extremes and the time mean AO index

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over some regions in North America. Gong and Ho (2004) reported that during the high AO index years, the intra-seasonal variance of daily temperature tends to decrease in East Asia. Bamzai (2003) found that snow cover in the northern continents is significantly related to the AO index, with the AO index leading snow cover by one week. Frequency of weather type (classified on the basis of daily temperature, dew point, sea level pressure (SLP), wind speed and direction, cloud cover) in some areas of North America is found to relate strongly to the North Atlantic Oscillation (NAO) (Sheridan, 2003). These studies enrich our knowledge about regional climate extremes and their connections to AO/NAO. It should be indicated that these surface weather fluctuations and extremes are directly connected to the synoptic activities of the near surface circulation systems. Up to now, the AO connection to the synoptic fluctuation of daily circulation in the lower troposphere in the context of the Northern Hemisphere has not yet been reported in the literature. The present study aims to address the possible association between AO and the high frequency transients of SLP in the Northern Hemisphere, including its synoptic variance and extremes.

The datasets used in the present study and the filtering method are described in section 2. Section 3 presents the main results, including the spatial structures in the synoptic SLP variance and their temporal changes, the relationship between AO and extreme SLP anomalies, and the asymmetric influence of high and low AO. Discussions on the possible mechanisms involved and a summary are presented in sections 4 and 5 finally.

2. Data and method

2.1 *Data*

In the present study, the daily mean SLP data for the period 1 January 1948 to 31 December 2001, from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis datasets (Kalnay et al., 1996), have been used. The spatial resolution of the data is $2.5° \times 2.5°$ with coverage of the entire Northern Hemisphere.

The daily mean SLPs are presented as the averages of values at 4 times. However, the data for 1948–1957 were done originally at 8 times daily in the model, and then only those at the specific 4 times were taken (refer to http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html). In addition, very few observation SLP data were used in the reanalysis system in the early period. This gives rise to noticeable discontinuities in the monthly mean SLP in many regions, particularly in the Southern Hemisphere (Marshall and Harangozo, 2000). This problem is also found existing in some continental areas in the Northern Hemisphere. Yang et al. (2002) reported that there are notable differences between the NCEP/NCAR reanalysis monthly SLP and other grid SLP productions in mid- to high-latitude Asia before 1968, resulting from the limited observation during the early period. We did not test the reliability of the reanalysis daily SLP data due to the non-availability of observed surface pressure data. Since in the present study we consider only the synoptic variability, we assume that the problem in the monthly mean pressures would not notably impact the results for the analysis on the high frequency variability of daily SLP. This is also supported by a comparison with the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis datasets (see section 3.7).

The AO indices used here include two different time series. One is the monthly AO index , which is the corresponding time coefficient of the first empirical orthogonal function (EOF) of the monthly SLP (northward of 20°N), available since 1899 (Thompson and Wallace, 1998). Hereafter this time series is referred to as the mean AO index since it is based on the monthly mean SLP anomalies. The other is the daily AO index, which is constructed by projecting the daily (0000 UTC) 1000 hPa height anomalies (poleward of 20°N) onto the loading pattern of the AO, using the NCEP/NCAR reanalysis dataset. Daily indices used here are kindly provided by the Climate Prediction Center (CPC) (available via internet at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/dailyaoindex/aoindex.html, since 1 January 1950). Hereafter this time series is referred to as the daily AO index. The wintertime (November through March) means of the two time series are correlated at a rather high value of 0.86 for the period of 1950/51–2000/01, suggesting fair consistency between the two datasets.

2.2 *Filtering*

Since the target of the study is to investigate the day-to-day variability of SLP, we first removed all low frequency variations. The typical synoptic activity is of a timescale of less than 2–3 weeks. Therefore, here, we applied a high-pass filter to the raw daily SLP series at each grid. A Butterworth filter is considered. After giving the cutoff frequency ($1/20\ \mathrm{d}^{-1}$) and setting a moderate order of 9, we obtained the filter coefficients. These coefficients are applied to the filter to separate the low ($f < 1/20\ \mathrm{d}^{-1}$) and high frequency ($f > 1/20\ \mathrm{d}^{-1}$) components. Only those components with times-

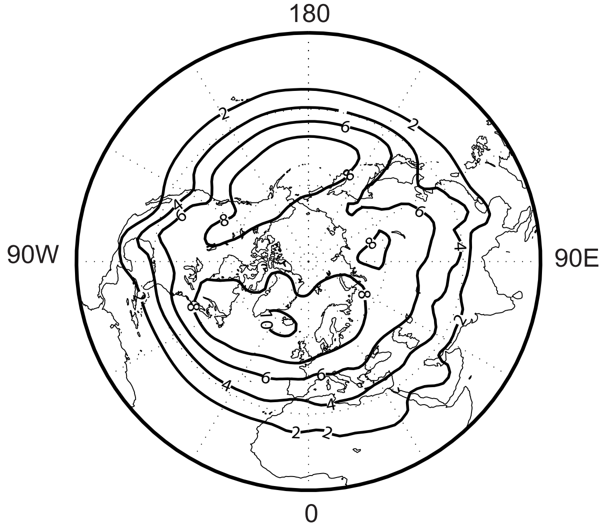

Fig. 1. Synoptic SLP variance in November–March. Computed from filtered daily SLP and shown as the means from the data period of 1948/49–2000/01. Units are in hPa.

cales shorter than about 20 days are retained after filtering. In the following sections we analyze only the data from 1 November to the next 31 March (to 30 March in leap years), 150 days in total each winter. All analysis is based on the high-pass filtered daily SLP data.

2.3 *Mean synoptic variance of SLP*

Variance in the present study is defined in the form of $\overline{P'^2}^{1/2}$, where P' is the high-frequency components of SLP from the filtering. In the low latitudes (0–30°N), the average variance is below 1.5 hPa. The average variance increases notably from the middle to the higher latitudes. Typically the variance in 30°–60°N is 6.9 hPa, rising to 7.6 hPa in 60°–90°N. The highest values appear in the two sub-polar regions, one is located in the North Atlantic, and the other in the North Pacific, where the variance is greater than 8 hPa (Fig. 1). Clearly, the large synoptic variance in these two regions is related to the frequent activities of cyclones.

3. Results

3.1 *Correlation between the mean AO index and synoptic SLP variance*

To investigate the relationship between the mean AO index and synoptic variance of daily SLP anomalies, we performed a correlation analysis. The correlation is calculated for each grid. Figure 2a presents the spatial distribution of the correlation coefficients. Areas statistically significant at the 95% confidence level are shaded. A predominant feature is that the regional, rather than continental or hemispheric, connections are scattered in the middle to high latitudes. The strongest correlation occurs in mid- to high-latitude Asia centered in Siberia, northern Europe and the mid-latitude North Atlantic. The correlation coefficients in a vast number of grids in these areas exceed +0.4 or fall below –0.4. Some relatively small areas also show significant correlations, including the northwestern Pacific, northern North America, and southwestern Europe. In the following section, we will address the temporal feature of synoptic SLP variance in these high-correlation areas in detail. It is interesting to note that in the areas near the Aleutian and Icelandioc lows, the synoptic SLP variance tends to increase with the mean AO index, whereas in the areas where the Siberian and North Atlantic Highs are located, the variance tends to be reduced in the high AO winters.

We also tested the possible influence of data reliability on the results. As indicated in the preceding section, the early reanalysis SLP data may be impacted by data availability, so we repeated the correlation analysis using only the recent data. The exclusion of the early 20-yr period of 1948–1967, however, does not evidently change the results. As can be seen in Fig. 2b, the results are almost identical. Therefore, it is very likely the features as revealed by correlation analysis here are stable and independent from the possible data uncertainties in the mean pressures.

3.2 *Temporal variations of the regional mean variance of SLP*

The high correlation over some areas as revealed by Fig. 2 encourages us to make a regional mean time series of variance. This will be helpful for analyzing their temporal features in detail. Here we chose six regions. They are: (a) mid-latitude Asia, 42.5°–57.5°N by 80°–120°E; (b) northern Europe, 62.5°–77.5°N by 20°W–37.5°E; (c) southwestern Europe, 35°–50°N by 15°W–12.5°E; (d) northern North America, 50°–65°N by 90°–120°W; (e) the northwestern Pacific, 27.5°–40°N by 140°–165°E; and (f) the northern Atlantic, 20°–35°W.

Figure 3 presents their time series. The six regions all display significant relationships to the mean AO index. Two regions located in the Atlantic sector, (i.e., northern Europe and the middle North Atlantic), have the strongest correlations, 0.56 and –0.52 respectively. The other regions display relatively low, but also statistically significant correlations. As a summary, in association with the positive phase of mean AO index, the SLP variance tends to decrease in regions of middle-latitude Asia, southwestern Europe and the northern Atlantic, whereas it tends to increase in other

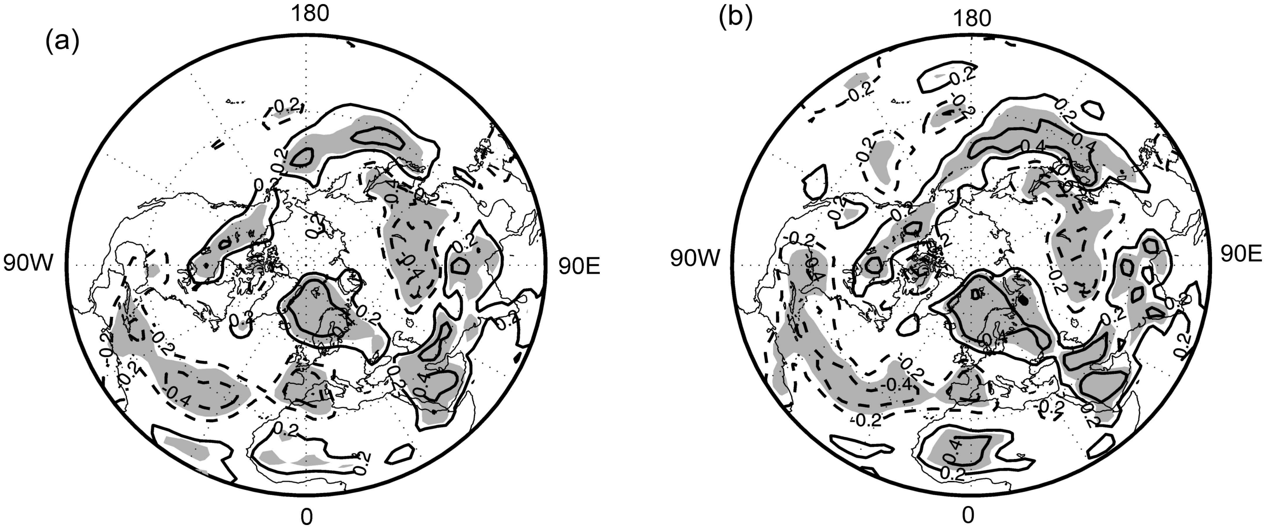

Fig. 2. Correlation coefficients between the mean AO index and synoptic variance of SLP over the Northern Hemisphere. Areas statistically significant at the 95% confidence level are shaded. Negative contour intervals as dashed lines. Zero contours are removed for simplicity. Two time periods of (a) 1948/49–2000/01 and (b) 1968/69–2000/01 are shown simultaneously for comparison.

Table 1. Correlation between the mean AO index and synoptic variance of SLP for various regions. Data period for the correlation with mean AO is 1948/49–2000/01; for the AO variance it is 1950/51–2000/01. The trends of the variance are shown at the bottom.

	Synoptic SLP variance					
	Mid-latitude Asia	Northern Europe	Southwestern Europe	North America	Northwestern Pacific	Northern Atlantic
Mean AO	–0.48**	0.56**	–0.47**	0.32**	0.43**	–0.52**
AO variance	0.09	–0.18	0.21	–0.08	–0.34**	0.28**
Trend	–2.26**	0.87	–0.85	0.21	0.80*	–1.27
$\%\ (10\ \mathrm{yr})^{-1}$		(1.51**)				

$**$ Significant at the 95% confidence level, $*$ at the 90% level. That shown in parenthesis is for 1949/50–2000/01.

regions, i.e., northern Europe, northern North America and the northwestern Pacific (Table 1).

Generally speaking, there are no similar yearly variations or overall trends among these regions (Fig. 3). In middle-latitude Asia, there is a steady decreasing trend from 1948 to 1983, and a remarkable rise occurs after the early 1980s. For northern Europe, the linear trend in variance in the period 1948–2000 is not evident. However, the winter of 1948/49 is an apparent outlier. It is well known that an outlier can largely impact the estimation of the linear trend of a time series. If the winter of 1948/49 is excluded, a steady linear trend shows up, with a value of +1.51% $(10\,\mathrm{yr})^{-1}$ that is significant at the 95% confidence level. In the northern Atlantic, the values decrease notably after the mid-1980s compared to the earlier period. The mean variance for 1948/49–1982/83 is 3.03 hPa, while for the period 1984–2000 it reduces to 2.85 hPa, representing a decline of about 6.0%. This change can also be supported by the t-test. The t-value between these two periods is –2.2, indicating the change is significant at the 95% level. For the northwestern Pacific, the trend displays a downward turn after the mid-1980s.

Comparing these low-frequency changes with the mean AO index, there is a lack of simultaneous low-frequency components in the mean AO index and daily AO variance. Figure 4 presents the time series of these two variables. The mean AO index shows a predominant strengthening trend of 0.27 $(10\ \mathrm{yr})^{-1}$ since the 1950s, and this value is about 31% of the standard deviation of the series. Particularly, the increasing since the late 1960s is remarkable. The linear trend estima-

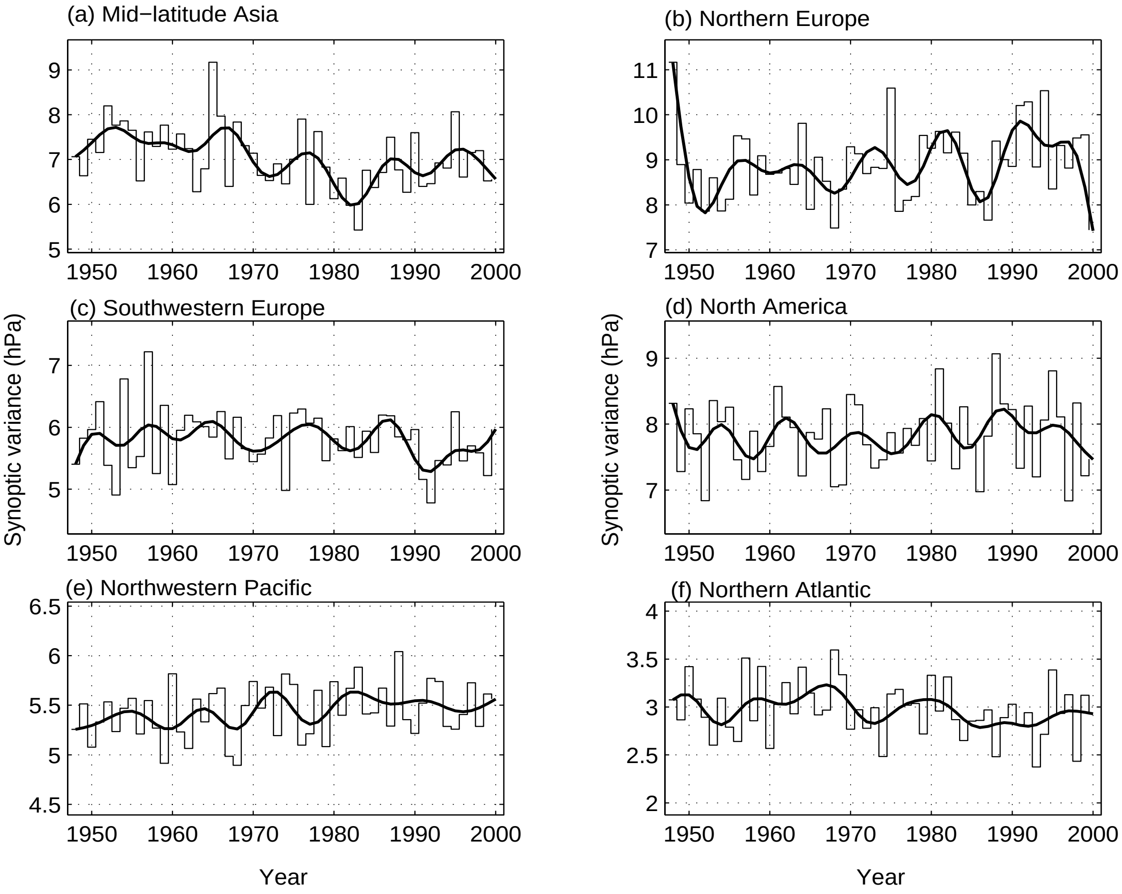

Fig. 3. Time series of regional mean synoptic variance of SLP. solid smooth lines are low frequency variations. For exact location of each region, refer to section 3.2.

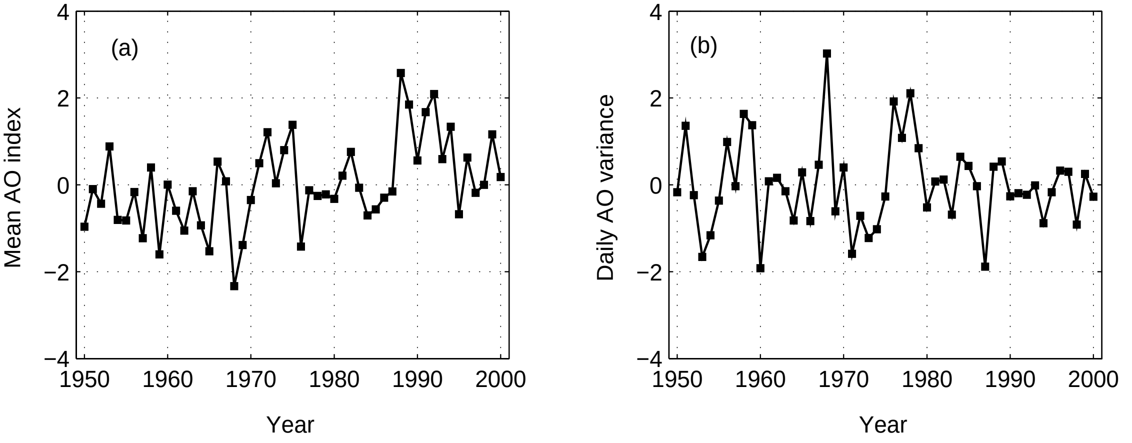

Fig. 4. Temporal variations in the mean AO index (a) and variance of daily AO index (b). Correlation between the two time series is –0.29. Both are normalized.

ted from period of 1968/69–2000/01 is 0.35 (10 yr)$^{-1}$, significant at the 95% confidence level. Clearly, in three regions (i.e., middle-latitude Asia, northern Europe, and the northwestern Pacific, which show significant linear trends) the trends are weaker than the mean AO index in magnitude. If presented in terms of the ratio to the standard deviation of the respective time series, the values are in the range of 16%–23%, smaller than the value for AO (31%). This shows that the mean AO alone can only explain part of the long-term trends in the synoptic SLP variance. In addition, the daily AO variation may also be related to the low-frequency variation in SLP. Although the variance in the daily AO index experiences no evident long-term trend, the year-to-year fluctuations experience evident change in magnitude. In period of 1950/51–1979/80, the standard deviation is 0.32, but for the period of 1980/81–2000/01, it is reduced to only 0.16. In the northwestern Pacific, the SLP variance displays a similar change around 1980. For the middle-latitude North Atlantic, the variance since the 1980s is also evidently lower than in previous periods. Thus, the recent decadal-scale change in these two regions may, at least partly, be related to the reduction of variance in the daily AO index since about 1980. Furthermore, the possible roles played by the regional factors should also be considered. For example, in East Asia, the winter monsoon is a dominant circulation system. The weakening of the winter monsoon during recent decades should exert considerable influence on SLP variance there. These regional circulation systems are important media for connecting AO and SLP variance.

3.3 *Singular value decomposition analysis*

In the preceding sections, we investigated the influence of AO on the synoptic SLP variance, based on the correlations. Some regions show apparently mutual connections, for example, SLP variance in middle-latitude Asia and northern Europe are correlated significantly (r=–0.39, or –0.43 when 1948/49 is excluded), and between the northern Atlantic and northwestern Pacific the correlation is –0.35. The variations of regional SLP variance among these six high correlation areas may be coherently consistent. To obtain the structure in the SLP variance that varies tightly with the planetary AO, we performed a singular value decomposition analysis of the covariance matrix between the synoptic SLP variance and monthly mean SLP anomalies over the Northern Hemisphere. If there is no internal coherence among the variance variations in these high correlation regions, these centers will not show up in the leading spatial mode. Details of the method are described in Bretherton et al. (1992) and Wallace et al. (1992). The monthly mean SLP data are averaged from the daily data for each calendar month. To facilitate the computation, we re-sampled the monthly mean SLP data by using a coarser mesh of 5° × 5°. Given the good spatial consistency of the pressure, the resampling will not distinguishably change the analysis results. In preparing the covariance, both variance and mean SLP at each grid are represented in the forms of anomalies with respect to the entire analysis period, and are area-weighted.

Figure 5 illustrates the leading pairs of the spatial modes from the singular value decomposition analysis. For comparison their corresponding time coefficients are also plotted together (Fig. 6). Compared to the results from the ordinary empirical orthogonal function analysis of monthly mean SLP data, the structures in the mean SLP clearly show a large similarity with the NAO pattern. Interestingly, the center in the northern Pacific does not appear in the leading mode of SLP (this center shows up as the dominant feature in the second mode of SLP). This is alike to results from other relating studies. For instance, Chang and Fu (2002) pointed out that the monthly mean AO index correlates well with storm track intensity over the Atlantic, but not over the Pacific, based on the analysis of high-pass-filtered 300-hPa meridional velocity in December–February 300-hPa height in the Northern Hemisphere. Their principal component corresponding to the leading empirical orthogonal function of the strength of the transient 1000-hPa height over the Northern Hemisphere also correlates with the AO index strongly, at 0.86. However, the main centers are located in the northern Atlantic and Europe while only weak structures occur over the Pacific.

The existence of the Pacific center and its weak correlation to the Atlantic centers have become one important aspect in the recent debate on the relation between AO and NAO (Deser, 2000; Ambaum et al., 2001; Wallace and Thompson, 2002; Christiansen, 2002). However, it should be pointed out that the absence of a northern Pacific center in the lower troposphere does not necessarily mean an absence of the AO pattern. The structures in the Atlantic sector and polar region are generally in good agreement with the NAO or AO patterns from empirical orthogonal function analysis of 1000-hPa height or SLP. Furthermore, the principal component time series of the SLP mode is virtually identical to the AO index, with a correlation of –0.87. Here the leading SLP pattern is simply regarded as NAO/AO.

In association with this NAO/AO pattern, the leading spatial structure in the synoptic SLP variance consists of several high or low value centers. The anomalous centers are all located in extra-tropical latitudes. The dominant feature is that there are maximum centers in Siberia and northern Europe, with opposite signs. Other smaller and weaker centers in southwestern Europe and the northern Pacific are also consistent with the results from the correlation analysis. In all six regions investigated in the preceding section, five are correlated significantly with the SLP principal component coefficient (Table 2). However, in North America, the relation is much weaker (r=–0.1). We found that

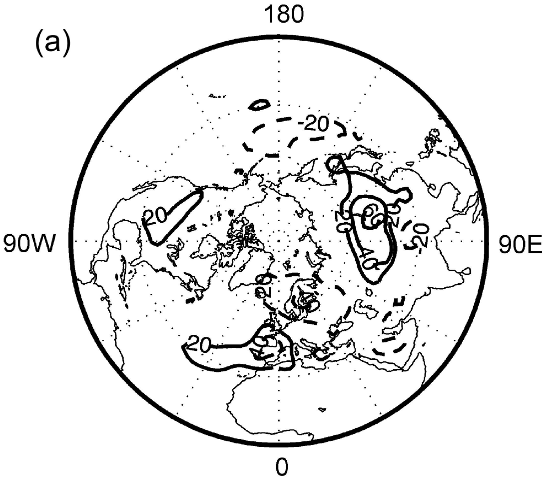

Fig. 5. The first paired modes of the singular value decomposition analysis for (a) synoptic variance and (b) mean SLP. Units are arbitrary. The first paired modes account for 41.8% of the total squared covariance.

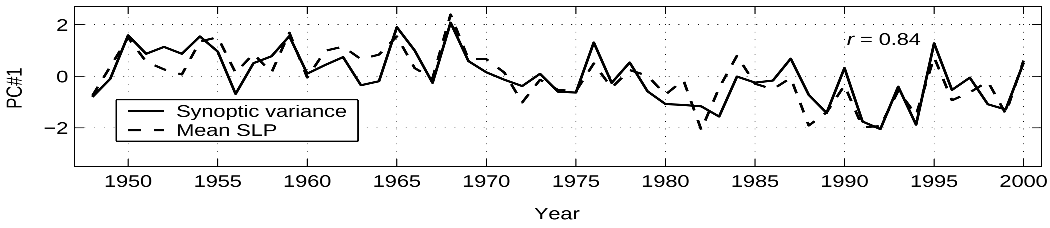

Fig. 6. First principal component time coefficients (PC#1) corresponding to the leading spatial modes from the singular value decomposition analysis. Both are normalized, the data period is 1948/49–2000/01.

the high frequency changes there are tightly associated with the second mode of monthly mean SLP. The striking feature of this mode is that the regional anomaly centers are located in the northern Pacific, North America and the neighboring North Atlantic (figure not shown), which account for a considerable portion of the total squared covariance (23%). The second principal component of monthly mean SLP is correlated with high frequency variance at a very high value of –0.48.

There are also evident linear trends in the principal component time coefficients. The trend for the principal coefficient of variance is statistically significant. The rate of change of –2.3 $(10\,\mathrm{yr})^{-1}$ is about 33.0% of the standard deviation of the time series in value. For the SLP, the time coefficient displays a strong trend of –8.3 $(10\,\mathrm{yr})^{-1}$, which is about 36.9% of the standard deviation. This is very similar to the strong trends in synoptic SLP variance as observed in Siberia and northern Europe (Table 1).

Table 2. Correlation between principal time coefficients of the singular value decomposition analysis and regional mean synoptic SLP variance. Correlation period is 1948/49–2000/01.

	AO	Mid-latitude Asia	Northern Europe	Southwestern Europe	North America	Northwestern Pacific	Northern Atlantic
Variance PC	–0.72**	0.80**	–0.72**	0.47**	–0.10	–0.38**	0.41**
SLPPC	–0.87**	0.61**	–0.54**	0.44**	–0.10	–0.45**	0.40**

** Significant at the 95% confidence level.

Table 3. Correlation between frequency of extremely high SLP anomalies and AO indices. Data period for the correlation with mean AO is 1948/49–2000/01; for the AO variance it is 1950/51–2000/01. Trends of the frequency of extremes are shown in the last row.

	$SLP' \geqslant +2\sigma$					
	Mid-latitude Asia	Northern Europe	Southwestern Europe	North America	Northwestern Pacific	Northern Atlantic
Mean AO	–0.49**	0.57**	–0.27**	0.24*	0.30**	–0.50**
AO variance	0.07	–0.18	0.11	0.05	–0.28**	0.44**
Trend [d (10 yr)$^{-1}$]	–0.45**	0.16(0.27*)$^{1)}$	–0.13	0.00	0.15*	–0.14

$**$ Significant at the 95% confidence level, $*$ at the 90% level. 1) for 1949/50–2000/01

Table 4. Correlation between frequency of extremely low SLP anomalies and AO indices. Data period for the correlation with mean AO is 1948/49–2000/01; for the AO variance it is 1950/51–2000/01. Trends of the frequency of extremes are shown in the last row.

	$SLP' \leqslant -2\sigma$					
	Mid-latitude Asia	Northern Europe	Southwestern Europe	North America	Northwestern Pacific	Northern Atlantic
Mean AO	–0.38**	0.45**	–0.40**	0.30*	0.34**	–0.49**
AO variance	0.01	–0.17	0.23	–0.09	–0.21	0.14
Trend [d (10 yr)$^{-1}$]	–0.36**	0.14(0.28*)$^{1)}$	–0.11	0.01	0.09*	–0.24

$**$ Significant at the 95% confidence level, $*$ at the 90% level. 1) for 1949/50–2000/01

3.4 *Relation between AO and extreme SLP events*

In association with the changing synoptic variance of SLP with respect to the high and low AO phases, there should be notable changes in the frequency of extreme SLP anomalies. To clarify this, we counted the frequency of extreme SLP anomalies. The extremes are defined as those below -2σ or above $+2\sigma$. Here σ is the standard deviation of synoptic variations, based on the reference period of 1961–1990. This kind of definition will measure how frequent the very sharp day-to-day fluctuations are, and is different from those defined on the basis of minimum and maximum daily SLP. The frequency is calculated locally at each grid and then averaged to produce the regional means.

Extreme events show similar and coherent temporal features as the time series of variance in the respective regions (figures not shown). Higher frequency in extremes is found to accompany larger variance, while in the cases of smaller variance the occurrences of both high and low SLP extremes tend to decrease. This is in good agreement with the common notion concerning the variance-extreme relation (Houghton et al., 2001). As the preceding section shows, the regional SLP variance is related to the phase and strength of the mean AO index. Therefore, it is reasonable to expect a tight correlation between the mean AO index and frequency of extremes. Tables 3 and 4 present the correlations between them. Clearly, the results are consistent with the above notion. The occurrences of synoptic SLP extremes exhibit a tight relation in variation with the mean AO index in all regions, except for the frequency of high SLP extremes in northern North America where the correlation (r=0.24) is somewhat weak, only just above the 90% confidence level. Recalling the results of the singular value decomposition analysis, we may conclude that, in addition to the AO, other modes or circulation systems should play considerable roles in influencing high-frequency SLP variations in North America.

In the two regions of middle-latitude Asia and northern Europe, where the SLP variance experiences the most remarkable and stable correlation with the mean AO index, there are notable trends in the frequency of synoptic extremes of SLP events. For northern Europe, the occurrences of extremes are steadily increasing. Particularly, the trends in frequency of both high and low SLP anomalies in middle-latitude Asia are significant. There, in association with a rate of change of –2.26 (10 yr)$^{-1}$ in SLP variance, the linear trends in the frequencies of extremely high and low SLP anomalies are both decreasing simultaneously, at the rates of –0.45 and –0.36 d (10 yr)$^{-1}$ respectively. Clearly, the long-term changes in extremes are tightly related to the changes in SLP variance in the two re-

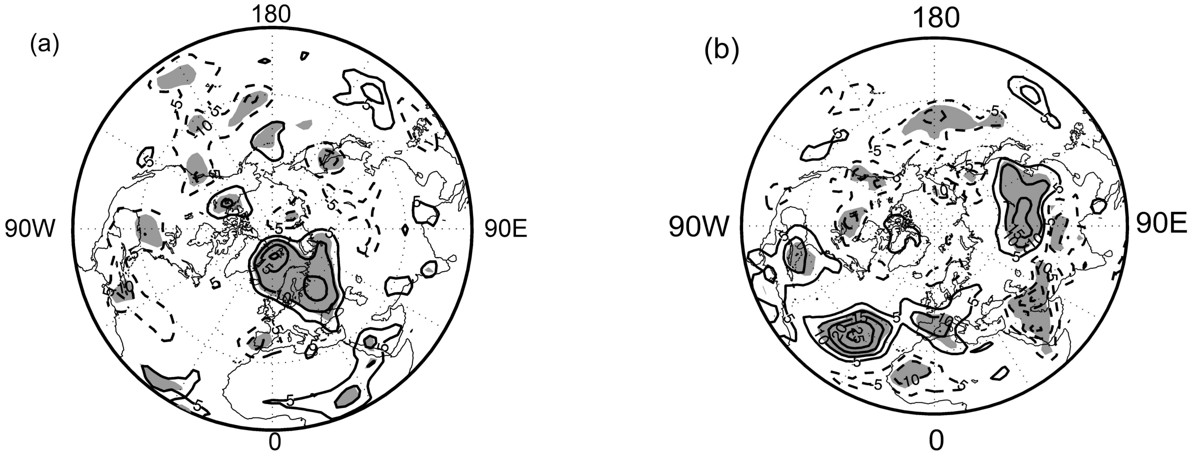

Fig. 7. Composite mean synoptic variance of SLP for (a) high AO, and (b) low AO phases. Shown are the variance percentages compered with the normal years (AO-neutral winters). Regions significant at the 95% confidence level by a t-test are shaded. high and low AO phases are defined as those winters with variance above $+1\sigma$ and below -1σ, respectively. Zero contours are omitted.

gions. However, in other regions the same phenomenon cannot be found.

In addition, AO variance is only significantly correlated with the frequency of high SLP extremes in the northwestern Pacific and northern Atlantic. These suggest that the mean AO condition can influence the frequency of extreme SLP anomalies in specific regions, via influencing the SLP variance. However, in most cases, the mean AO plays a more important role.

3.5 *Asymmetric influence of high and low AO phases*

Given the non-linear interaction between the transient activity and mean circulation flow in the atmosphere (either their interaction or the cause-and-effect), an interesting question is whether there are different patterns of changes in synoptic SLP variance associated with the high- and low-phase AO. To address this problem, we carried out the composites of SLP variance in high- and low-AO index years, both compared with normal years. Here the high and low AO winters are arbitrarily defined as those above +1 standard deviation and below −1 standard deviation respectively, yielding 8 high- and 7 low-AO winters. These high-AO winters are 1972/73, 1975/76, 1988/89, 1989/90, 1991/92, 1992/93, 1994/95, and 1999/2000. And the low index winters are 1957/58, 1959/60, 1962/63, 1965/66, 1968/69, 1969/70, and 1976/77. The SLP variance in these years are compared to the normal years, and presented in the form of percentage:

$$\frac{V - V_{\text{neutral}}}{V_{\text{neutal}}} \times 100\% \, .$$

Here, V is the mean variance of SLP anomalies during high AO or low AO years; V_{neutral} is the SLP variance for the neutral years (normal AO years). Figure 7 displays the differences and their statistical significance.

For the high-AO cases (Fig. 7a), the dominant feature is a large center of greater variance located in northern Europe and the Norwegian Sea. Compared to normal years, during the high AO winters, the synoptic SLP variance there is about 10%–15% larger. Interestingly, there is no similar spatial pattern in its counter phases. As can be seen in Fig. 7b, in northern Europe there are no negative variance anomalies comparable in magnitude during the low AO winters. Instead, large anomalous centers in middle-latitude Asia and the northern Atlantic show up, with more than 10% stronger day-to-day variations occurring there. These results clearly suggest that the high- and low-AO conditions can exert an asymmetric influence on the synoptic SLP variance. Here we applied the standard of $\pm 1\sigma$ to define the high- and low-AO cases. We also tested other criteria. Alternatively, by using the standard of $\pm 0.5\sigma$, we yielded similar results too. Thus the asymmetric influence of AO phases on the synoptic SLP variance is likely substantial and independent of the criteria.

These asymmetric features are also supported by the changes in probability density functions (PDFs) in association with different AO phases. We chose two regions where the largest signals appear, viz. northern Europe and middle-latitude Asia, to make composites

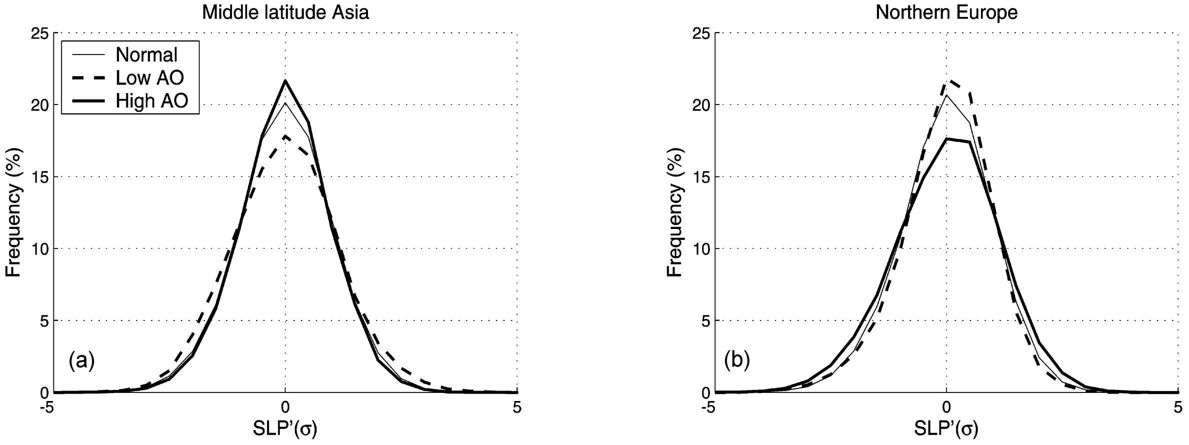

Fig. 8. Composites of SLP anomalies for high AO, low AO and normal years in (a) middle latitude Asia and (b) northern Europe.

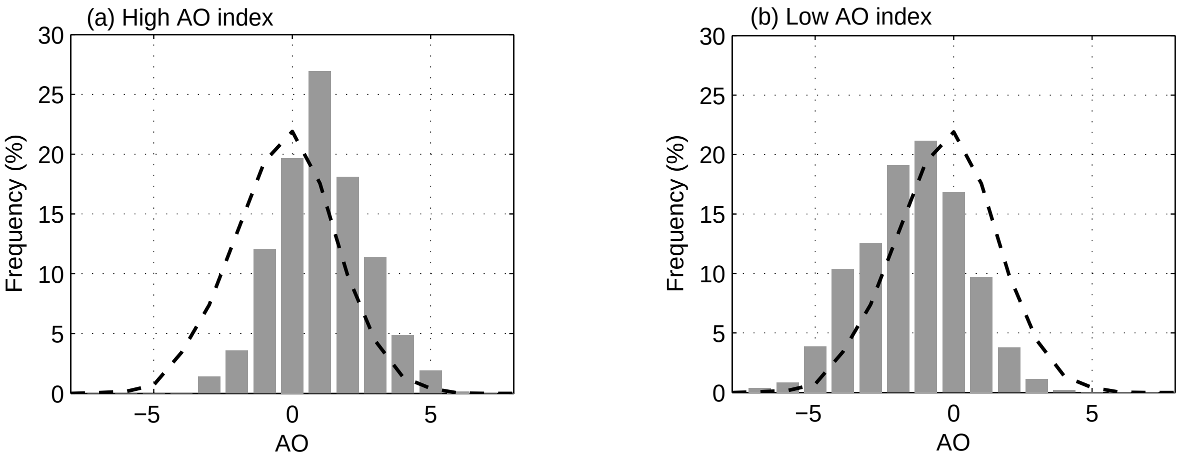

Fig. 9. Histogram displaying the distribution of the daily AO indices in association with the (a) high and (b) low mean AO indices, in gray bars. The high and low AO winters are defined as those exceding the +1 and −1 standard deviation. Dashed lines are the distribution of the normal conditions.

of the daily SLP anomaly distribution in high-, low- and normal years. Since the variance differs from one grid to another, prior to analysis, the SLP anomalies at each grid are rescaled with respect to the standard deviation (i.e., being divided by σ, where the reference period is 1961-1990). This makes the anomalies for different sites comparable. Based on the rescaled SLP anomalies, we calculated the histogram of the SLP anomalies. And finally, histograms for all grids within each region are averaged to produce the regional mean. Figure 8 displays the comparison of the histograms between high-phase and low-phase AO years for the two regions. These two regions show good examples for the two different conditions. In northern Europe, the PDF in low-AO years is very similar to that of normal years, while for the high-AO years, the occurrences in smaller anomalies are apparently lower than low- and normal AO conditions and the occurrences of larger anomalies get higher. This feature indicates a larger variance in high-AO years than the other two cases. Contrarily, in middle-latitude Asia the conditions are reversed. The PDFs in low-AO years are notably different from those in high- and normal AO years, indicating a larger variance in the low-AO case. Besides these two regions, other regions display similar results and are consistent with the features shown in Fig. 7.

3.6 *On the relation between the mean AO index and its day-to-day variance*

The above analysis shows that the mean AO index is tightly related to the regional synoptic SLP variance. One may suppose that the corresponding changes in

SLP may be due, at least partly, to the daily AO variability (rather than the monthly mean AO). Thus it is of interest to check the relation between mean AO index and its variance.

There are notable differences in the daily AO indices in association with the high and low mean AO winters (Fig. 9). The most remarkable feature is a shift of the frequency to the right in high AO winters (the mean is 1.035), and a shift to the left in low AO years (the mean is –1.454). In addition, it is also found that the shape of the distribution is also changed. For high AO index winters, the standard deviation is 1.599, and the skewness is 0.1265; for the low AO index winters, those values are 1.8411 and –0.1142, respectively. Apparently, there is an evident change in AO variance. The correlation analysis also supports that. The correlation coefficient between the mean AO index and its day-to-day variance (Fig. 4) is –0.29, significant at the 95% level and indicating an out-of-phase relation. This implies that the daily AO index tends to become less variable and more stable when the mean AO index is in high positive phases.

Although the variance and distribution of the daily AO index are significantly connected to the mean AO conditions, the synoptic SLP variance does not show evident changes in relation to the changing day-to-day AO variance. Figure 10 displays the correlation between them. Obviously, there is no notable overall relation. Only several scattered small areas exhibit an apparent correlation to AO variance, such as in the northwestern Pacific and northern Atlantic. As can be seen in Table 1, the regional mean SLP variances for these two areas correlate with the AO variances at moderate values of –0.34 and 0.28 respectively. Therefore, those analyses imply that the AO variance is weakly connected to the SLP variability.

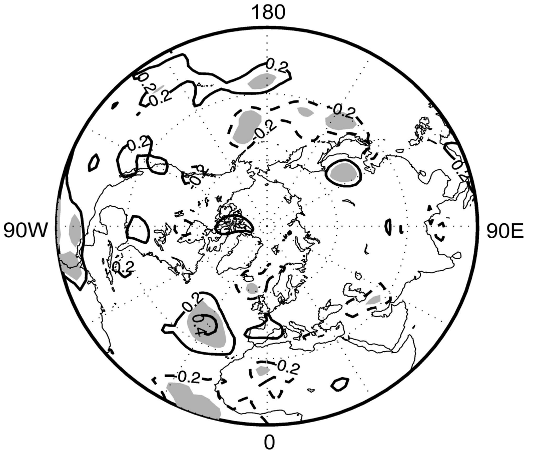

Fig. 10. Correlation coefficients between AO variance and SLP variance over the Northern Hemisphere. Data period is 1950/51–2000/01. Areas significant at the 95% confidence level are shaded.

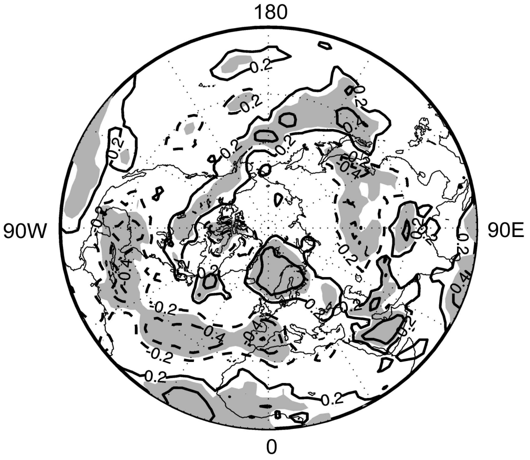

Fig. 11. Correlations between monthly mean AO index and ERA40 SLP variance. Data period is 1957/58–2000/01.

Feldstein (2002) found that the interannual variance of AO (based on the monthly AO index) displays a substantial increase during the past 30 years in winter (December-February). The ratio of the interannual variance of the AO index for the 1967–1997 time period to that for the 1899–1967 time period is as large as 2.02. When the whole cold season of November through March is considered, the ratio is still large, at 1.86. If compared to the 1948–1967 time period, the ratio is 1.90, also confirming the strong increasing tendency that has occurred in recent decades in association with the strengthening of the mean AO index. However, the day-to-day variance of the AO index estimated for the time period 1950/51–2000701 is only –1.3% $(10\,\mathrm{yr})^{-1}$, which is not statistically significant. Therefore, the high frequency fluctuations in daily AO have not been changing, though the monthly AO index has increased significantly and its interannual variability has become larger simultaneously. Thus the influence of daily AO fluctuations on the long-term trends in synoptic events of surface circulations and/or temperatures might be small, too.

3.7 *Comparisons with ERA40 SLP*

In order to check the robustness of the results, we have also compared the AO-high frequency variability with the ECMWF 40-year reanalysis data (ERA40). The ERA40 datasets are available for the time period

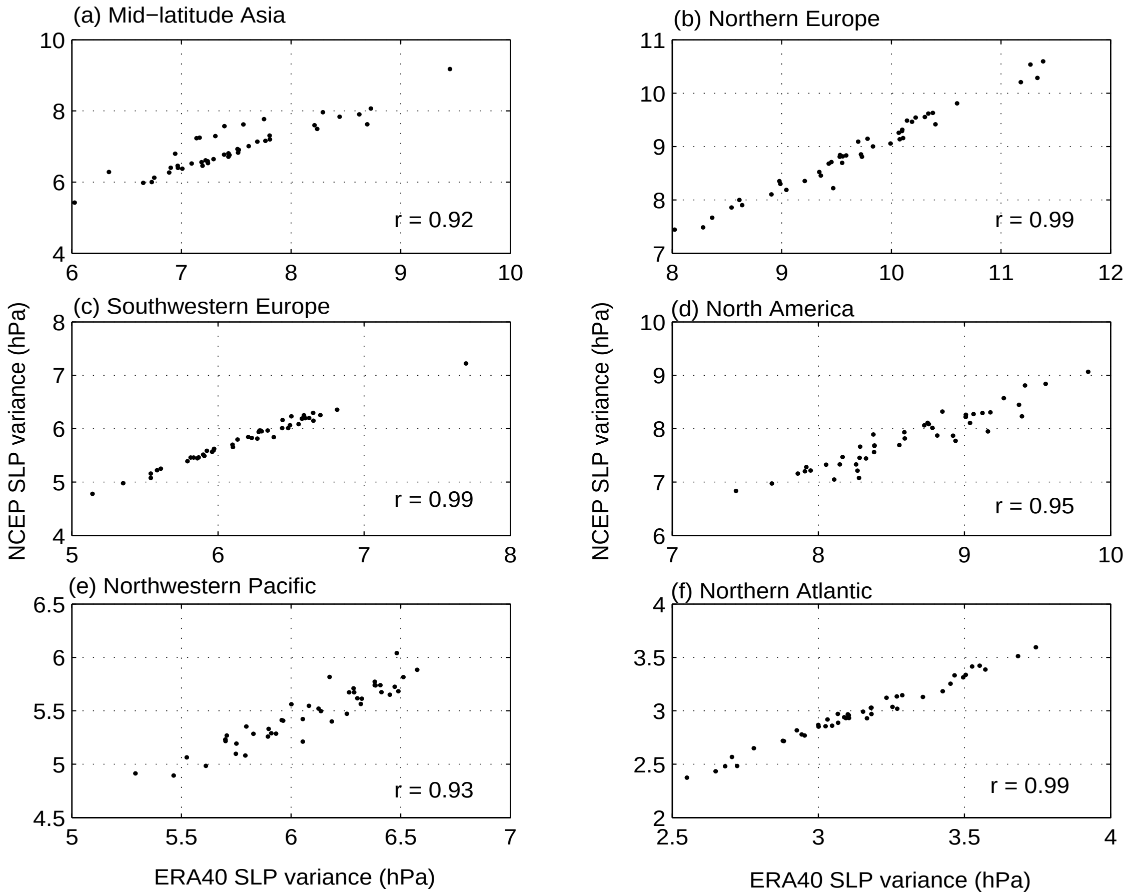

Fig. 12. Comparison of regional time series of SLP variance as derived from the ERA40 reanalysis data for period 1957/58–2000/01. ERA40 variance versus NCEP variance.

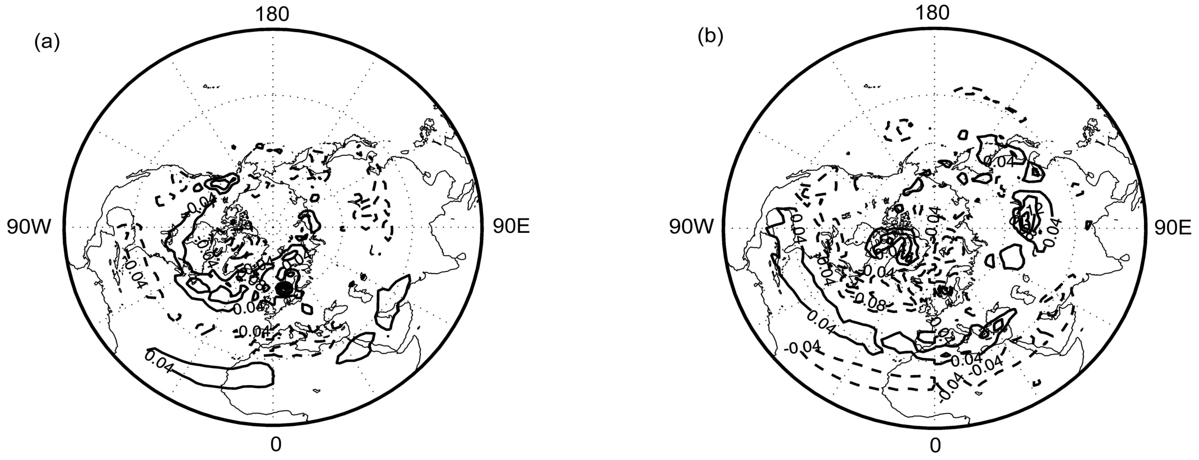

Fig. 13. Eady growth rate between 850 and 700 hPa in (a) high and (b) low AO winters. Shown as the departure from the means of 1957–2000. High and low AO years are defined as those in excess of $+1\sigma$ and below -1σ, respectively. Contour interval is 0.04 d^{-1}, zero lines are omitted for simplicity. Based on ERA40 data.

of 1957–2002. We used the daily SLP data for 0000 UTC and compared them with the NCEP/NCAR reanalysis.

We conducted the correlation between monthly mean AO index and synoptic variance in ERA40 SLP. The results are shown in Fig. 11. Clearly, the spatial pattern of the relations is identical to that from the NCEP/NCAR reanalysis SLP (Fig. 2). The many centers with high correlation keep the same locations as well as the same magnitude of correlations. The temporal features in the regional variance over the six regions are also carried out. The ERA40 variance is somewhat greater than the NCEP/NCAR SLP, on average about 8% greater. But this has arisen from the systematic difference, not from big errors. The correlation of the regional variance series between the ERA40 and NCEP/NCAR datasets are very high, varying from 0.92 to 0.99 for the six regions (Fig. 12). The fairly good agreement between the two reanalysis SLPs may suggest that our results on the AO-synoptic SLP variance relationship are robust.

4. Discussions

Mechanisms responsible for AO-high-frequency SLP variance relations are not well understood yet. Transients with short life-times are tightly related to the baroclinicity and wave activities. In order to get an idea of atmospheric instability concerning the AO, we checked the Eady eddy growth rate (Eady, 1949) between 850 and 700 hPa. The means of eddy growth rate for 8 high and 7 low AO winters (see section 3.5) are computed and presented in Fig. 13 as the departures from the average of the whole data period. Comparing with Fig. 7, the large anomalies are generally consistent with the SLP variance centers. In high AO winters, the largest eddy growth rate appears in the high latitude North Atlantic and northwestern Europe, coincident with the high variance in the Norwegian Sea and northern Europe (Fig. 7a). In the low AO cases, a large eddy growth rate takes place in Siberia and in long belts across the Atlantic at about 30°N, again consistent with the high SLP variance there. Evidently, the baroclinic activities play important roles in initializing and reinforcing high-frequency transients in these two regions. Comparing the difference between the high and low AO cases, the associated eddy growth rates are also asymmetric. In northern Europe and the neighboring North Atlantic, the baroclinic activities and transients show more tight links to high AO, while in Siberia there is a much stronger association with the low AO.

Although the above analysis provides some clues for the connection between AO and the high frequency of SLP, it is difficult to make firm statements about causal relationships. For a further and detailed understanding, some major questions remain to be addressed.

(1) What is the interaction between the AO and transients, and what is the feedback of the high frequency transients? The AO can be regarded as a measurement of zonal symmetric air-flow, particularly in the upper levels (Cohen and Saito, 2002). Therefore the monthly mean AO index provides us with a sense of the basic background of westerly air-flow (Wallace, 2000; Thompson and Wallace, 2000; Li and Wang, 2003). It is necessary to study how the transients respond to AO and to determine what is the feedback of the transients.

(2) What is the role of thermal effects in the lower levels? Many studies have addressed the AO-related transient components in upper circulations, particularly for storm tracks. However, the relations are apparently different from the features as shown in the study. For example, the synoptic SLP changes in the northern Pacific and northern Atlantic are not as clear as in the upper troposphere geopotential heights and winds. The center over the inner Asian continent does not show up in the upper troposphere in previous analyses too. This might imply that the surface boundary conditions also play a role in influencing the synoptic fluctuations in SLP. For example, local baroclinic activity may largely impact the transient fluctuations in the low-level atmosphere, while baroclinic waves grow through the sensible heat transport to the poles and decay by transporting momentum (Randel and Stanford, 1985). It is interesting to note that these regions where SLP variance shows a strong connection to monthly mean AO conditions are also places where the lower tropospheric temperatures vary significantly with the AO, particularly in the Eurasian continent (Thompson and Wallace, 1998; Thompson et al., 2000; Wu and Huang, 1999; Gong et al., 2001; Wu and Wang, 2002). In the lower troposphere, the thermal anomalies are strongly related to the transients. One needs to determine the role that the thermal effects may play in influencing local transient activities and synoptic variance.

(3) Why are the transients in association with high and low AO located in some confined regions? The steady waves, ocean-land contrast, and orography are often emphasized as playing roles in confining the geographical distribution and propagation of the high frequency transients. Detailed data analysis and numerical experiments should be introduced to check their respective effects.

(4) What is the role of the upper troposphere and stratosphere circulation in the AO-synoptic SLP variance connection? The AO is manifested through the troposphere and lower stratosphere. There are strong dynamic processes in the upper level atmospheric circulation. AO-associated SLP variance may be related to the upper circulation through a coupling between lower and upper circulation, as well as through the downward spreading of the signals. Recent studies show that the downward propagation of AO-related high frequency signals may be one path connecting the upper circulation and the surface. Ambaum and Hoskins (2002) proposed a hypothesis explaining the upper connection to the surface, suggesting that potential vorticity anomalies in the stratosphere may change the tropopause and the vorticity in the troposphere, consequently influencing the surface pressure. The signals from the stratosphere to the surface have a timescale on the order of a couple of weeks as indicated by NCEP/NCAR reanalysis (Baldwin and Dunkerton, 1999; 2001). Recent sensitivity experiment studies by Norton (2003) also found that the stratosphere strongly contributes to the persistence of the AO related surface pressure at lags of 10–25 days. However, it is still unknown to what extent the observed AO-SLP variance is related to the upper processes.

(5) Are the observed variations in high frequency variance related to the external forcing? A variety of external forcings can exert influence on the mean AO conditions. Among them, the increasing CO_2 is the most outstanding. Many simulation experiments forced by the greenhouse gases yielded notable trends in the AO index (Paeth et al., 1999; Fyfe et al., 1999; Shindell et al., 1999; Gillett et al., 2000; 2002). How and to what extent can these external forcings alter the mean AO and its relationship with synoptic SLP variance also needs further sensitive simulations.

5. Conclusion

The above analyses show that the background of hemispheric circulation in the lower troposphere, as represented by the monthly mean AO index, are significantly related to the synoptic component of the surface pressure systems and their variance. However, there is no overall pattern in day-to-day SLP variability. Instead, strong connections occur in several confined regions, particularly in middle-latitude Asia (with the center situated over Siberia) and northern Europe. In Siberia, the SLP variance is negatively correlated with the AO index, while in northern Europe the positive correlations take place. However, the composite analysis revealed that the high-frequency changes corresponding to high and low AO phases are asymmetric in these regions. In northern Europe, the synoptic SLP displays much stronger changes in high AO years, while in Siberia, there is a stronger connection to low AO conditions. However, the mechanisms responsible for the AO-SLP variance relationships are not well understood yet. An elaborate explanation will require a complex analysis of data and numerical experiments in the future.

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REFERENCES

Ambaum, M. H. P., and B. J. Hoskins, 2002: The NAO troposphere-stratosphere connection. *J. Climate*, **15**, 1969–1978.

Ambaum, M. H. P., N. J. Hoskins, and D. B. Stephenson, 2001: Arctic Oscillation or North Atlantic Oscillation? *J. Climate*, **14**, 3495–3507.

Baldwin, M. P., and T. J. Dunkerton, 1999: Propagation of the Arctic Oscillation from the stratosphere to the troposphere. *J. Geophys. Res.*, **104**, 30937–30946.

Baldwin, M. P., and T. J. Dunkerton, 2001: Stratospheric harbingers of anomalous weather regimes. *Science*, **294**, 581–584.

Bamzai, A. B., 2003: Relationship between snow cover variability and Arctic Oscillation index on a hierarchy of time scales. *International Journal of Climatology*, **23**, 131–142.

Bretherton, C. S., C. Smith, and J. M. Wallace, 1992: An intercomparison of methods for finding coupled patterns in climate data. *J. Climate*, **5**(6), 541–560.

Chang, K. M., and Y. Fu., 2002: Interdecadal variations in Northern Hemisphere winter storm track intensity. *J. Climate*, **15**, 642–658.

Christiansen, B., 2002: On the physical nature of the Arctic Oscillation. *Geophys. Res. Lett.,* **29**(16), 10.1029/2002GL015208.

Cohen, J., and K. Saito, 2002: A test for annular modes. *J. Climate*, **15**, 2537–2546.

Deser, C., 2000: On the teleconnectivity of the Arctic Oscillation. *Geophys. Res. Lett.*, **27**, 779–782.

Eady, E. T., 1949: Long waves and cyclone waves. *Tellus*, **1**, 33–52.

Feldstein, S. B., 2002: The recent trend and variance increase of the annular mode. *J. Climate*, **15**, 88–94.

Fyfe, J. C., G. J. Boer, and G. M. Flato, 1999: The Arctic and Antarctic Oscillations and their projected changes under global warming. *Geophys. Res. Lett.,* **26**, 1601–1604.

Gillett, N. P., G. C. Hegerl, M. R. Allen, and P. A. Scott, 2000: Implications of changes in the Northern Hemisphere circulation for the detection of anthropogenic climate change. *Geophys. Res. Lett.*, **27**, 993–996.

Gillett, N. P., M. R. Allen, R. E. McDonald, C. A. Senior, D. T. Shindell, and G. A. Schmidt, 2002: How linear is the Arctic Oscillation response to greenhouse gases? *J. Geophys. Res.*, **107**(D3), doi: 10.1029/2001JD000589.

Gong, D. Y., S. W. Wang, and J. H. Zhu, 2001: East Asian winter monsoon and Arctic Oscillation. *Geophys. Res. Lett.*, **28**, 2073–2076.

Gong, D. Y., and C. H. Ho, 2004: Intra-seasonal variability of wintertime temperature over East Asia. *International Joural of Climatology*, **24**(2), 131–144.

Higgins, R. W., A. Leetmaa, and V. E. Kousky, 2002: Relationship between climate variability and winter temperature extremes in the United States. *J. Climate*, **15**, 1555–1572.

IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* J. T. Houghtom et al., Eds., Cambridge University Press, Cambridge, 881pp.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437–431.

Li, J. P., and J. X. L. Wang, 2003: A modified zonal index and its physical sense. *Geophys. Res. Lett.,* **30**(12), 1632, 10.1029/2003GL017441.

Marshall, G. J., and S. A. Harangozo, 2000: An appraisal of NCEP/NCAR reanalysis MSLP data viability for climate studies in the South Pacific. *Geophys. Res. Lett.,* **27**, 3057–3060.

Norton, W. A., 2003: Sensitivity of Northern Hemisphere surface climate to simulation of the stratospheric polar vortex. *Geophys. Res. Lett.*, **30**, 1627, doi:10.1029/2003GL016958.

Paeth, H., A. Hense, R. Glowienka-Hense, R. Voss, and U. Cubasch, 1999: The North Atlantic oscillation as an indicator for greenhouse-gas induced regional climate change. *Climate Dyn.,* **15**, 953–960

Randel, W. J., and J. L. Stabford, 1985: The observed life cycle of a baroclinic instability. *J. Atmos. Sci.*, **42**, 1364–1373.

Sheridan, S. C., 2003: North American weather-type frequency and teleconnection indices. *International Journal of Climatology*, **23**, 27–45.

Shindell, D. T., R. L. Miller, G. A. Schmidt, and L. Pandolfo, 1999: Simulation of recent northern winter climate trends by greenhouse-gas forcing. *Nature,* **399**, 452–455.

Thompson, D. W. J., and J. M. Wallace, 1998: The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.,* **25**, 1297–1300.

Thompson, D. W. J., and J. M. Wallace, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate,* **13**, 1000–1016.

Thompson, D. W. J., J. M. Wallace, and G. C. Hegerl, 2000: Annular modes in the extratropical circulation. Part II: Trends. *J. Climate,* **13**, 1018–1036.

Thompson, D. W. J, and J. M. Wallace, 2001: Regional climate impacts of the Northern Hemisphere annular mode. *Science,* **293**, 85–89.

Thompson, D. W. J., M. P. Baldwin, and J. M. Wallace, 2002: Stratospheric connection to Northern Hemisphere winter weather: Implications for prediction. *J. Climate*, **15**, 1421–1428.

Wallace, J. M., 2000: North Atlantic Oscillation/annular mode: Two paradigms-one phenomenon. *Quart. J. Roy. Meteor. Soc.*, **126**, 791–805.

Wallace, J. M., and D. W. J. Thompson, 2002: The Pacific center of action of the Northern Hemisphere annular mode: Real or artifact? *J. Climate*, **15**, 987–991.

Wallace, J. M., C. Smith, and C. S. Bretherton, 1992: Singular value decomposition of wintertime sea surface temperature and 500-mb height anomalies. *J. Climate*, **5**(6), 561–576.

Wettstein, J. J., and L. O. Mearns, 2002: The influence of the North Atlantic-Arctic Oscillation on mean, variance, and extremes of temperature in the northeastern United States and Canada. *J. Climate*, **15**, 3586–3600.

Wu, B. Y., and J. Wang, 2002: Winter Arctic Oscillation, Siberian High and East Asian winter monsoon. *Geophys. Res. Lett.*, **29**, 1897, doi:10.1029/2002GL015373.

Wu Bingyi, and Huang Ronghui, 1999: Effects of the extremes in the North Atlantic Oscillation on East Asia winter monsoon. *Chinese J. Atmos. Sci.*, **23**, 641–651. (in Chinese).

Wu, Q. G., and D. M. Straus, 2003: Multiple planetary flow regimes and the eddy forcing in Northern Hemisphere wintertime variability. *Geophys. Res. Lett.,* **30**(16), 1861, doi:10.1029/2003GL017435.

Yang, S., K. M. Lau, and K. M. Kim, 2002: Variations of the East Asian jet stream and Asian-Pacific-American winter climate anomalies. *J. Climate*, **15**, 306–325.