The Nature of the Arctic Oscillation and Diversity of the Extreme Surface Weather Anomalies It Generates

PANXI DAI AND BENKUI TAN
Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing, China

(Manuscript received 21 June 2016, in final form 20 March 2017)

ABSTRACT

Through a cluster analysis of daily NCEP–NCAR reanalysis data, this study demonstrates that the Arctic Oscillation (AO), defined as the leading empirical orthogonal function (EOF) of 250-hPa geopotential height anomalies, is not a unique pattern but a continuum that can be well approximated by five discrete, representative AO-like patterns. These AO-like patterns grow simultaneously from disturbances in the North Pacific, the North Atlantic, and the Arctic, and both the feedback from the high-frequency eddies in the North Pacific and North Atlantic and propagation of the low-frequency wave trains from the North Pacific across North America into the North Atlantic play important roles in the pattern formation. Furthermore, it is shown that the structures and frequencies of occurrence of the five AO-like patterns are significantly modulated by El Niño–Southern Oscillation (ENSO). Warm (cold) ENSO enhances the negative (positive) AO phase, compared with ENSO neutral winters. Finally, the surface weather effects of these AO-like patterns and their implications for the AO-related weather prediction and the AO-North Atlantic Oscillation (NAO) relationship are discussed.

1. Introduction

The Arctic Oscillation (AO), also termed as the northern annular mode (NAM), is the leading mode of natural climate variability in the extratropics of the wintertime Northern Hemisphere from intraseasonal to decadal scales. The AO pattern consists of three centers of action: one is located over the North Pacific and the other two are located in the North Atlantic, which has a large projection onto the North Atlantic Oscillation (NAO). Since the initial work of Thompson and Wallace (1998), the AO has become a subject of numerous studies and some studies have questioned the physical relevance of the AO with a focus on the AO–NAO relationship and dynamical linkage between the Pacific and Atlantic centers (Thompson and Wallace 1998, 2000; Wallace and Thompson 2002; Deser 2000; Ambaum et al. 2001). One perspective (Thompson and Wallace 1998, 2000; Wallace and Thompson 2002) claims that the AO is an annular mode that describes the mass seesaw between the Arctic and midlatitudes while the NAO is simply a regional manifestation of the AO pattern. The other perspective (Deser 2000; Ambaum et al. 2001) argues that the AO is not a new mode but is in fact the NAO. This is because that the Arctic and Atlantic centers in the AO are highly correlated with each other, but the Pacific and Atlantic centers are not. In contrast to these two perspectives, other studies (Wallace 2000; Feldstein and Franzke 2006) demonstrate that persistent events of the AO and NAO are indistinguishable, and these events are neither confined to the North Atlantic nor annular.

The abovementioned debate has stimulated many studies exploring the nature of the AO, particularly its formation mechanisms. Some studies (Baldwin and Dunkerton 1999; Christiansen 2001) found that the AO is not a phenomenon isolated only in the troposphere. Rather, it is closely coupled to the stratosphere: most AO events appear first in the stratosphere and then propagate downward into the troposphere. The downward propagation from the stratosphere to the troposphere takes weeks or even one month. This finding not only provides one possible mechanism of the AO pattern formation in the troposphere, but also implies a potential predictability of the tropospheric AO (Baldwin et al. 2003), although the downward propagation mechanism still remains unclear.

Some studies (Honda and Nakamura 2001; Sun and Tan 2013) focused on the tropospheric internal dynamics itself by examining the possible role that the Pacific–North America (PNA)-like quasi-stationary wave train plays in the AO pattern formation. These studies found that the Pacific center of the AO is much
stronger in winters when the PNA-like stationary wave train is very active, compared to winters when the wave train is inactive (Honda and Nakamura 2001; Sun and Tan 2013). This is because the wave activity fluxes, associated with the PNA and propagating from the North Pacific across North America into North Atlantic, may establish a seesaw oscillation between the Aleutian and Icelandic lows and thus cause a stronger Pacific center.

Most of the studies mentioned above are based on monthly mean data. Although this time averaging is sufficient for understanding anomalies with a time scale longer than two months, such averaging can also obscure some of the underlying physical processes if the anomalies have a time scale much shorter than 2 months. Actually, the atmospheric teleconnection patterns, such as the PNA and NAO, have an e-folding time scale of 7–10 days (Feldstein 2000; Cash and Lee 2001; Johnson and Feldstein 2010). Motivated by this fact, a recent study (Riviè re and Drouard 2015) examined the evolution process of the AO with daily data and found that the three centers of the AO grow almost simultaneously and the feedback from high-frequency eddies over the North Pacific and North Atlantic plays a crucial role in the rapid growth stage of the AO centers. This finding is interesting, although it is still subject to the limitation of the empirical orthogonal function (EOF) analysis that the AO-related low-frequency variability is described by a unique EOF with two opposite phases. Several studies (Johnson and Feldstein 2010; Kushnir and Wallace 1989; Franzke and Feldstein 2005; Johnson et al. 2008) suggest, however, that the teleconnections, such as the AO/NAO and PNA, may be better described from a continuum perspective with many patterns of similar but distinct structure. Each member of the continuum may have different dynamics and needs to be considered separately. The EOF-based studies may obscure these differences.

Motivated by the above, in this study, we will treat the AO as a continuum. We apply a cluster algorithm called the self-organizing map (SOM) analysis (Kohonen 2001) to daily NECP–NCAR reanalysis data with the hope of a full understanding of the nature of the AO. It turns out that the AO continuum can be well approximated by five discrete, representative AO-like patterns. This study will examine the differences in the structures, formation mechanisms, and weather and climate influences between the five representative members of the AO continuum. This study will also explore the relationships of the AO with the NAO, PNA, El Niño–Southern Oscillation (ENSO), and stratospheric polar vortex (PV). The next section describes the dataset and methods, and section 3 examines the AO from the continuum perspective by the SOM approach. The formation mechanisms of the AO continuum members are explored in section 4; particularly, the role of high-frequency eddies and low-frequency quasi-stationary wave trains are investigated. Sections 5 and 6 present the results about the influence of ENSO on the AO continuum and the troposphere–stratosphere linkage, respectively. The final section gives a summary and discussion.

2. Data and methodology

a. Data

The data used in this study are the daily data from National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996) for the winters (December–March) from 1958 to 2015. The use of daily rather than monthly data is based on the fact that teleconnection patterns, such as the AO, NAO, and PNA, have an intrinsic time scale of 10 days or so (Feldstein 2000; Cash and Lee 2001; Johnson and Feldstein 2010). We calculate anomalies for all the variables by removing the seasonal cycle at each grid point, which is defined as the climatological mean of the same calendar day smoothed by a three-point binomial running average. As in Johnson et al. (2008), Johnson and Feldstein (2010), and Athanasiadis et al. (2010), the analysis of the low-frequency variability in this study is based on these unfiltered daily anomalies. As in Christiansen (2002) and Riviè re and Drouard (2015), the analysis of the AO, NAO, and PNA is based on the 250-hPa level, rather than the usually used sea level. At this level, the PNA-like wave train can be clearly detected, which is believed to play an important role in the AO dynamics (Honda and Nakamura 2001; Feldstein 2003; Benedict et al. 2004; Sun and Tan 2013). Prior to the EOF and SOM analysis, the gridded data are weighted by square root of cosine of latitude.

The sea surface temperature (SST) is derived from the Extended Reconstructed Sea Surface Temperature Dataset, version 3b (Xue et al. 2003; Smith et al. 2008) (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa. ersst.v3.html). The Niño-3.4 index is defined by the SST anomaly (relative to the wintertime climatology of 1958–2015) averaged over the region extending from 5°N to 5°S and from 120°W to 170°W. The winter-mean Niño-3.4 index is used to define the ENSO phases. A winter with a winter-mean Niño-3.4 index larger (less) than 0.4 (−0.4) is referred to a warm (cold) winter of the ENSO cycle (here the winter is denoted by the month January of the year). Accordingly we obtain 19 warm ENSO winters (1959, 1964, 1966, 1969, 1970, 1973, 1977, 1978, 1983, 1987, 1988, 1992, 1995, 1998,


In this study, we evaluate the statistical significance for linear regression following Kosaka et al. (2012). The number of effective of degrees of freedom $N_{\text{eff}}$ corresponds to

$$N_{\text{eff}} = \frac{N}{1 + 2 \sum_{\tau=1}^{\tau_{\text{max}}}(1 - \tau/N)r_x(\tau)r_y(\tau)}.$$  \hspace{1cm} (1)

Here $N$ is the length of time series $x$ and $y$, and $r_x(\tau)$ and $r_y(\tau)$ are the corresponding autocorrelation functions for $x$ and $y$, with a lag of $\tau$ days. For simplicity, the maximum lag $\tau_{\text{max}}$ is set as the maximum number that does not exceed $N/2$.

b. SOM analysis

In this study, we will use self-organizing map analysis (Kohonen 2001) to examine North Hemisphere teleconnection patterns from a continuum perspective (Johnson et al. 2008; Johnson and Feldstein 2010; Lee and Feldstein 2013; Chang and Johnson 2015; Yuan et al. 2015). Following this approach, the AO, NAO, and PNA will be each represented by a number of similar SOM patterns (SOMs). Here we describe briefly how this method works and the reader is referred to the abovementioned references for details.

First, we use the SOM method to classify daily 250-hPa geopotential height data for the 58-yr period from 1958 to 2015. In this way, we can obtain the continuum of the Northern Hemisphere low-frequency 250-hPa geopotential height anomaly patterns. The SOM method reduces a potentially large set of data samples to a much smaller collection of representative patterns on a spatially ordered two-dimensional grid. This study uses a $4 \times 5$ SOM grid. This size represents a balance between the economy and the level of resolved detail in the representative patterns (Johnson et al. 2008; Lee and Feldstein 2013) and the results obtained are insensitive to the size (not shown). At the same time, because of the topology-preserving properties of the SOM, the most similar patterns are neighbors whereas the most dissimilar patterns are located far apart (Johnson et al. 2008), see Fig. 1.

Then, we determine quantitatively the representative patterns of the AO, NAO, and PNA continuum. To this end, both the pattern correlations between the SOM patterns and the AO, NAO, and PNA patterns and the projections of SOM patterns onto the AO, NAO, and PNA patterns are calculated. In this study, the AO, NAO, and PNA patterns are defined as the leading EOF of the 250-hPa height anomalies over the whole Northern Hemisphere, the North Atlantic (105°W–30°E), and the Pacific–North America region (120°E–60°W) north of the equator, respectively. The pattern correlation is calculated as follows:

$$\text{Corr} = \frac{\sum_i \sum_j \text{EOF}(i,j)\text{SOM}(i,j)\cos\theta}{\sqrt{\left[\sum_i \sum_j \text{EOF}^2(i,j)\cos\theta\right] \left[\sum_i \sum_j \text{SOM}^2(i,j)\cos\theta\right]}}.$$ \hspace{1cm} (2)

where EOF denotes the AO, NAO, or PNA pattern, and SOM is a particular SOM pattern considered. The indices $i$ and $j$ correspond to grid points in the zonal and meridional direction, respectively, and $\theta$ is the latitude. The pattern correlation measures the degree of the similarity between the SOM pattern and the particular teleconnection pattern. The projections of SOM patterns are calculated similarly:

$$\text{Proj} = \frac{\sum_i \sum_j \text{EOF}(i,j)\text{SOM}(i,j)\cos\theta}{\sum_i \sum_j \text{EOF}^2(i,j)\cos\theta}.$$ \hspace{1cm} (3)

which is the amplitude ratio of the SOM pattern to the teleconnection pattern. Here the EOF is defined as the linear regression of 250-hPa geopotential height on the standardized PC, so the EOF and SOM have comparable amplitudes and units. The SOM pattern is stronger (weaker) than the teleconnection when the ratio is larger (smaller) than 1. Accordingly, a SOM pattern is considered to be an AO-like (NAO-like, or PNA-like) pattern if the correlation and projection coefficients reach 0.6 or above simultaneously. Although the 0.6 threshold value is somewhat arbitrary, the results appear to be insensitive to the choice of threshold value.

To obtain the $e$-folding time scale of each SOM, we first generate a time series by projecting the anomalous
daily 250-hPa height field onto that SOM pattern. The $e$-folding time scale is defined as the time over which the autocorrelation decays to $1/e$.

It should be noted that most of previous studies of the low-frequency variability are based on low-pass filtered daily data rather than unfiltered daily data as in this work. Actually, we have also performed our analysis based on 10-day low-pass filtered data and found no significant differences between the two kinds of data. For the EOF modes, the AO patterns, for example, match very well between the unfiltered data and low-pass filtered data (not shown). The pattern correlation between the two types of data is 0.99 while the correlation between the two PC time series is 0.97. For the 20 SOM patterns, the spatial structures of most SOMs are not influenced by the data filtering (not shown). Particularly as the AO-like SOMs are concerned, their spatial structures remain basically unchanged. So the following analyses in this paper are all based on the raw daily data.

3. SOM perspective of the AO

Figure 1 shows the $4 \times 5$ grid SOM maps of the daily 250-hPa height anomalies. The percentage shown at the

![Figure 1 SOM patterns of daily anomalous 250-hPa height for winters (December–March) from 1958 to 2015. Red (blue) colors denote positive (negative) values. Contour interval is 50 m. The percentage in the top-left corner of each map describes the frequency of occurrence of that pattern.](image-url)
upper left of each map depicts the pattern frequency, which is defined as the percentage of the observations classified to that particular pattern for the whole dataset. The percentage varies from 3.51% to 6.37% with an average of 5.0%. These SOM patterns capture spatial variations of well-known teleconnection patterns including the AO, NAO, and PNA, which resemble variations in the real day-to-day weather. To determine quantitatively the AO-like, NAO-like, and PNA-like SOM patterns, we calculate the pattern correlations and projections between the SOM patterns and the AO, NAO, and PNA patterns from the EOF method. The resultant pattern correlation and projection coefficients are shown in Table 1. Table 1 indicates that five SOM patterns, SOMs 1, 6, 10, 11, and 15, are AO-like patterns (Fig. 2, first column). SOMs 1, 6, and 11 have the negative polarity of the AO whereas SOMs 10 and 15 have the positive polarity. The $e$-folding timescales of these AO-like patterns range from 7 days to 11 days (Table 1, fifth column).

An examination of the AO-like SOMs (Fig. 2, first column) shows that SOMs 1 and 6 resemble each other and consist of a dipole with two poles over the Arctic and North Atlantic, respectively, plus a Pacific center. Compared to SOM 6, SOM 1 has a relatively weak Pacific center and a stronger North Atlantic center covering North America, the entire North Atlantic, and Europe. For SOMs 10 and 15, they also consist of a dipolar anomaly over the Arctic and North Atlantic plus a Pacific anomaly. A comparison between the two patterns shows that for SOM 15, its Atlantic center is completely broken by the southward extension of the Arctic center, whereas for SOM 10 no such break is observed there at all. In addition, we see that the Pacific center of SOMs 10 and 15 is much stronger than that of SOMs 1 and 6. Quite differently, SOM 11 takes the form of a double wave train running from the Pacific across North America and North Atlantic into Europe. For this case, the Arctic center of SOM 11 splits into two subcenters located in the North America and the Arctic region south of Greenland, while for the rest of the AO-like patterns no such split is observed. Like SOM 15, the Atlantic center of SOM 11 is also broken completely by the southward extension of the Arctic center. It will become clear later that SOMs 10, 11, and 15 form in a similar way, which is different from SOMs 1 and 6.

Not only the height anomalies but also the surface weather anomalies associated with these AO-like patterns vary from pattern to pattern (Fig. 2, middle column). We see that over North America, SOMs 1 and 15 cause a dipole-like surface air temperature (SAT) anomaly, but SOMs 6, 10, and 11 cause only a monopole-like SAT anomaly over northern North America. Over Eurasian continent, both SOMs 10 and 11 cause strong warming anomalies there, whereas for SOM 15 the SAT anomaly is very weak. SOMs 1 and 6 both cause cooling anomalies, but the cooling is limited to Europe and its neighboring

<table>
<thead>
<tr>
<th>AO</th>
<th>NAO</th>
<th>PNA</th>
<th>Time scale</th>
<th>$R$ (Niño-3.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOM 1</td>
<td>$-0.74 (-1.41)$</td>
<td>$-0.75 (-1.32)$</td>
<td>0.27 (0.40)</td>
<td>8</td>
</tr>
<tr>
<td>SOM 2</td>
<td>$-0.49 (-0.94)$</td>
<td>$-0.75 (-1.15)$</td>
<td>$-0.26 (-0.43)$</td>
<td>9</td>
</tr>
<tr>
<td>SOM 3</td>
<td>0.07 (0.13)</td>
<td>$-0.12 (-0.12)$</td>
<td>$-0.77 (-1.39)$</td>
<td>6</td>
</tr>
<tr>
<td>SOM 4</td>
<td>0.19 (0.26)</td>
<td>0.46 (0.48)</td>
<td>$-0.26 (-0.32)$</td>
<td>7</td>
</tr>
<tr>
<td>SOM 5</td>
<td>0.58 (0.97)</td>
<td>0.82 (1.07)</td>
<td>$-0.61 (-0.89)$</td>
<td>7</td>
</tr>
<tr>
<td>SOM 6</td>
<td>$-0.83 (-1.51)$</td>
<td>$-0.95 (-1.62)$</td>
<td>0.75 (1.02)</td>
<td>10</td>
</tr>
<tr>
<td>SOM 7</td>
<td>$-0.41 (-0.70)$</td>
<td>$-0.87 (-1.08)$</td>
<td>$-0.33 (-0.40)$</td>
<td>7</td>
</tr>
<tr>
<td>SOM 8</td>
<td>0.35 (0.65)</td>
<td>0.07 (0.08)</td>
<td>$-0.78 (-1.27)$</td>
<td>7</td>
</tr>
<tr>
<td>SOM 9</td>
<td>0.49 (0.74)</td>
<td>0.41 (0.32)</td>
<td>$-0.73 (-1.03)$</td>
<td>7</td>
</tr>
<tr>
<td>SOM 10</td>
<td>0.74 (1.37)</td>
<td>0.86 (1.40)</td>
<td>$-0.66 (-0.92)$</td>
<td>11</td>
</tr>
<tr>
<td>SOM 11</td>
<td>$-0.68 (-1.08)$</td>
<td>$-0.66 (-0.73)$</td>
<td>0.79 (0.91)</td>
<td>7</td>
</tr>
<tr>
<td>SOM 12</td>
<td>$-0.38 (-0.55)$</td>
<td>$-0.27 (-0.25)$</td>
<td>0.49 (0.51)</td>
<td>9</td>
</tr>
<tr>
<td>SOM 13</td>
<td>0.26 (0.37)</td>
<td>0.28 (0.33)</td>
<td>0.35 (0.24)</td>
<td>6</td>
</tr>
<tr>
<td>SOM 14</td>
<td>0.36 (0.51)</td>
<td>0.28 (0.22)</td>
<td>0.14 (0.15)</td>
<td>7</td>
</tr>
<tr>
<td>SOM 15</td>
<td>0.85 (1.49)</td>
<td>0.84 (1.09)</td>
<td>$-0.61 (-0.92)$</td>
<td>11</td>
</tr>
<tr>
<td>SOM 16</td>
<td>$-0.43 (-0.65)$</td>
<td>$-0.17 (-0.25)$</td>
<td>0.75 (0.52)</td>
<td>7</td>
</tr>
<tr>
<td>SOM 17</td>
<td>$-0.15 (-0.20)$</td>
<td>0.19 (0.18)</td>
<td>0.96 (1.01)</td>
<td>6</td>
</tr>
<tr>
<td>SOM 18</td>
<td>0.17 (0.29)</td>
<td>0.66 (0.79)</td>
<td>0.79 (1.11)</td>
<td>7</td>
</tr>
<tr>
<td>SOM 19</td>
<td>0.24 (0.38)</td>
<td>0.49 (0.53)</td>
<td>0.47 (0.63)</td>
<td>9</td>
</tr>
<tr>
<td>SOM 20</td>
<td>0.08 (0.12)</td>
<td>$-0.69 (-0.40)$</td>
<td>$-0.30 (-0.46)$</td>
<td>8</td>
</tr>
</tbody>
</table>
area for SOM 1 whereas for SOM 6 the cooling extends from Europe across all of Siberia, even into the Bering Sea region.

Now we turn to examine the temporal variability of the AO-like SOMs. Figure 2 (right column) shows the winter-season numbers of occurring days of the five AO-like patterns for the period 1958–2015. Here the number of occurring days of an AO-like pattern is defined as the number of days that AO-like pattern occurs in each winter. Clearly, these AO-like patterns assume apparent
and different interannual and decadal variability. No significant linear trends are observed for these patterns. Although each representative member of the AO continuum assumes different structure and temporal variability, we now show that the AO properties, such as the height and SAT anomalies and interannual variability, can be well described by the statistics of these five AO-like patterns. Shown in Fig. 3 are the regressions (Figs. 3a,c) and composite differences (Figs. 3b,d) of the 250-hPa height and SAT anomalies. The regression is done upon the daily principal component (PC) of the EOF1 of 250-hPa height anomalies over the Northern Hemisphere and the composite difference is obtained by subtracting the frequency-weighted average of the AO-like patterns with negative phase polarity from the frequency-weighted average of the positive phase polarity. Apparently, both the height and SAT anomalies match reasonably well between the EOF and SOM approaches except for some minor differences. Shown in Fig. 3e are the two standardized time series of the winter season AO indices for the EOF (blue line) and SOM (red line) approaches, respectively. Here the winter season AO index for the EOF is defined as the winter mean of the daily PC, whereas the winter season AO index for the SOM is defined as the occurring days of the two SOMs with positive polarity (SOMs 10 and 15) minus the occurring days of the three SOMs with negative polarity (SOMs 1, 6, and 11) for each winter. Both seasonal mean time series are then standardized. Clearly, the two time series are highly correlated \((r = 0.88)\) at the 99% confidence level based on the Student’s \(t\) test, which show apparent interannual variability of AO: the AO index remained relatively low for the period prior to 1970, from the late 1970s to the late 1980s, and from the middle 1990s to the middle 2005. It remained relatively high for the periods from 1970 to the middle 1970s and from the late 1980s to the middle 1990s. The index has exhibited large-amplitude seasonal-mean variations since \(\sim 2005\). These results strongly suggest that the AO can be described as a linear combination of five AO-like patterns that bear a closer resemblance to daily weather variations than the AO itself.

4. Dynamical characteristics of the AO-like pattern formation

To further understand the AO nature, we now examine the formation characteristics of the five AO-like patterns. Figure 4 shows the lead–lag regression maps of the anomalous 250-hPa height field upon the AO-like pattern indices. The AO-like pattern indices are defined as the projections of the daily height anomalies onto the AO-like patterns, and only positive values are reserved for the reason that each AO-like pattern is one signed. The most distinctive features shown in Fig. 4 are that these AO-like patterns develop from some weak precursory disturbances in the Arctic, Pacific, and/or North Atlantic and experience a rapid growth and decay, which lasts two weeks or so. SOMs 1 and 6 (Fig. 4, first two columns) assume a similar evolution process. They develop from the initial disturbances in the Arctic and North Atlantic. For SOM 1, the initial disturbances are found to occur around day \(-12\), whereas for SOM 6 the initial disturbances appear much later, around day \(-9\). The dipole-like anomaly over the North Atlantic forms at day \(-9\) for SOM 1 and at day \(-6\) for SOM 6. Then, the dipole for both patterns grows rapidly and matures at day 0. Obviously, during the evolution process, the Arctic center grows much faster than the Atlantic center and there exist significant low-frequency wave activity fluxes (black arrows) (Plumb 1985) propagating from the Arctic southward into the North Atlantic and Europe, which might lead to a local intensification of the height anomalies in Europe. Previous studies (Egger and Schilling 1983; Lau 1988; Branstator 1992) have found that in teleconnection patterns such as the NAO and PNA the feedback from high-frequency eddies (2–10 days) plays an important role in the teleconnection development. To see if this is the case for SOMs 1 and 6, we examine the evolution characteristics of both the anomalous zonal winds and divergence of the pseudo \(E\) vector \((v^{2} - u^{2}, -uv)\), where the primes denote the high-frequency components of the wind field. As shown in Hoskins et al. [1983, Eq. (A8) of their paper], the local zonal wind tendency is approximately proportional to the convergence of the \(E\) vector. As can be seen in Fig. 5 (first two columns), over the Atlantic for the interval from day \(-6\) to day 0, there exists a zonal wind dipole associated with the NAO-like anomaly, with anomalous easterlies to the north and anomalous westerlies to the south. The anomalous westerlies generally coincide with the divergence of the \(E\) vector and the anomalous easterlies coincide with the convergence of the \(E\) vector. This implies that the rapid development of the dipole-like anomaly over the Atlantic is energetically driven by the high-frequency eddies. Over the Pacific, no obvious zonal wind anomalies and divergence of the \(E\) vector are observed for all the developing period. As a result, there exists only a weak anomalous low there. From day 0 on, the divergence of the \(E\) vector over the Atlantic decays rapidly and the high-frequency eddies’ feedback weakens sharply. Instead, low-frequency energy dispersion is observed southward from the Atlantic toward Africa, which leads to the rapid decay of the dipole-like anomaly, as seen in the first two columns in Fig. 4. For SOMs 10 and 15, their evolution processes (Fig. 4, third and last columns) are very similar, but they are
different from those of SOMs 1 and 6: in addition to the Arctic and Atlantic disturbances, the Pacific disturbance also plays a crucial role in the pattern formation processes here. The two SOM patterns develop simultaneously from the initial disturbances in the Pacific, Arctic, and North Atlantic. These initial disturbances are found to occur around day $-12$, and the AO-like patterns form at day $-6$. From day $-6$ on, the patterns grow rapidly and
FIG. 4. (top to bottom) Lead–lag regressions of the anomalous 250-hPa height upon (left to right) the time series of the SOM indices (the reader is referred to the text for details of definition of the indices). Contour interval is 15 m and gray shading denotes values that are statistically significant at the 99% confidence level based on the Student’s $t$ test. Vectors denote the Plumb wave activity fluxes with the scale at the top left. Values < 0.2 m$^2$s$^{-2}$ are omitted.
Fig. 5. As in Fig. 4, but for zonal wind anomalies (black lines) and divergence of the pseudo E vector (color shadings). Solid (dashed) lines denote positive (negative) values with contour interval of 2 m s$^{-1}$. Red (blue) colors denote positive (negative) values.
mature at day 0. During these growth processes, the Pacific anomaly builds rapidly and from day $-6$ on there exists significant propagation of low-frequency wave activity fluxes from the Pacific across North America and then from the Arctic toward Europe. Table 1 indicates that the wave train from Pacific across North America has a large projection of the PNA pattern for these two cases. In addition, for SOM 15, the low-frequency wave train activity from North America across the Atlantic is possibly responsible for the formation and maintenance of the anomalous low in the Eurasian continent. Furthermore, the high-frequency eddies’ feedback also plays an important role in the rapid growth of SOMs 10 and 15 in both the Pacific and Atlantic (Fig. 5, third and last columns).

It is seen that SOM 11 initiates from the disturbances in the Pacific and Arctic (Fig. 4, fourth column). The Arctic disturbance appears as early as day $-12$ whereas the Pacific disturbance does not appear until day $-9$. Afterward, the two disturbances get further amplified and begin to disperse energy downstream, which plays an important role in the pattern formation. The wave activity fluxes from the Pacific across North America also have a large projection of the PNA (Table 1) and the anomalous high over Asia may be the consequence of the wave train propagation across the North Atlantic to the Eurasian continent. The double wave train pattern forms around day $-3$ and matures at day 0. A further examination indicates that the feedback from high-frequency eddies over the Pacific and Atlantic also plays an important role in the pattern formation (Fig. 5, fourth column).

In summary, the above results suggest that the PNA-like wave train plays a significant role in the formation of the two positive phase AO-like SOMs (SOMs 10 and 15) and one negative phase AO-like SOM (SOM 11).

5. ENSO modulation

The above results indicate that for SOMs 10, 11, and 15, the low-frequency wave propagation from the Pacific across North America and North Atlantic plays a significant role in the pattern formation. Here a question arises: are these low-frequency wave trains, and therefore the associated SOM patterns, modulated by ENSO? Before answering this question, we first examine how ENSO influences the frequencies of occurrence of the AO-like SOMs separately. Shown in Fig. 6 are the standardized time series of winter season numbers of occurring days of the AO continuum members and the Niño-3.4 index. We see that the Niño-3.4 index and numbers of occurrence of SOMs 1, 6, 10, and 11 are not significantly correlated. However, the Niño-3.4 index is found to vary out of phase with the frequency of occurrence of SOM 15 with a correlation of $-0.38$. This implies that the frequency of SOM 15 may be modulated by
the ENSO: SOM 15 occurs more frequently in cold ENSO winters than in warm ENSO winters.

ENSO may also influence the structures of the five AO-like SOMs. Figure 7 shows the 250-hPa height anomalies of the five AO-like SOMs and their occurrence days (numbers in the upper-left corners) in warm ENSO, cold ENSO, and ENSO neutral winters. We see that the SOMs’ structures change to different degrees depending on the SOM patterns and ENSO phases. Significant changes are found to occur over Asia for two SOMs, SOM 11 and 15: for SOM 11, its positive height anomaly over Asia weakens in cold ENSO winters, compared with warm ENSO winters. Weakening of the positive height anomaly leads to considerable weakening of the warm anomaly over the Eurasian continent (Fig. 8). For SOM 15, however, the Asian negative height anomaly deepens considerably over western Asia and almost disappears over central Asia in warm ENSO winters, compared with cold ENSO winters. Corresponding to these changes, the cooling over western Asia strengthens and disappears in central Asia for warm ENSO winters, compared to cold ENSO winters (Fig. 8). Further examination of the wave activity fluxes shows that ENSO may influence Asia through modulating the low-frequency wave trains propagating from the Pacific across North America and North Atlantic and into Asia.

We now examine the ENSO influence on the AO pattern from the SOM perspective. To examine the asymmetry of the warm and cold ENSO effects, we use the ENSO neutral winters as the reference state and perform the composite difference of the 250-hPa height anomalies based on the five AO-like SOMs between warm (cold) ENSO and ENSO neutral winters. Following the decomposition method of Cassano et al. (2007) and Horton et al. (2015), the warm ENSO effects on AO can be calculated as follows:

\[ W = \sum_{i=1}^{K} (\bar{P}_i \delta P_i + \delta f_i \bar{P}_i + \delta f_i \delta P_i), \]

where the sum is performed for the five AO-like patterns, \( W \) is the AO composite difference between warm and neutral ENSO episodes, \( f_i \) is the occurrence frequency of the SOM pattern \( i \), \( P_i \) is the gridded SOM pattern \( i \), \( \delta \) is the difference between warm ENSO and neutral episodes, and overbars indicate the neutral episodes. Equation (4) indicates that the ENSO effect can be described by a combination of a change in SOM spatial pattern, holding frequency of occurrence fixed (term 1), a change in the frequency of the SOM patterns, holding the SOM pattern fixed (term 2), and combination of the two changes (term 3). The results are shown in Figs. 9a–d. As can be seen, the warm ENSO modulation effect assumes the form of negative phase AO-like anomaly (Fig. 9a) and the frequency change term dominates the total effects (Fig. 9c). To further detect how the occurring frequencies of the SOMs change with ENSO, we examine the occurring days and frequency of occurrence of the positive phase AO-like SOMs (SOMs\(^+\); SOMs 10 and 15) and the negative phase AO-like SOMs (SOMs\(^-\); SOMs 1, 6, and 11) under different ENSO phases, shown in Table 2. We can see that the occurring frequency of the SOMs\(^+\) decreases markedly from ENSO neutral winters (11.8 days per winter) to warm ENSO winters (5.8 days per winter), and the occurring frequency of the SOMs\(^-\) increases from ENSO neutral winters (21.8 days per winter) to warm ENSO winters (19.1 days per winter) to the warm ENSO winters (5.8 days per winter). This implies that warm ENSO reduces heavily the occurring frequency of SOMs\(^+\), and in favor of the formation of the negative phase AO-like anomaly. This is consistent with the finding of Gouirand and Moron (2003) and Brönnimann (2007) that in warm ENSO winters the negative phase of the NAO occurs more often than the positive phase. The structure change term makes a secondary contribution to the formation of the negative AO-like anomaly, with negative height anomalies over the eastern North Pacific, North America, and East Asia (Fig. 9b). The contribution from the combined structure–frequency change term is negligibly weak (Fig. 9d).

Similarly based on Eq. (4), we obtain the cold ENSO modulation effects on AO (Figs. 9e–g). We see that for this case a positive phase AO-like anomaly forms with the Pacific center located more equatorward than usual (Fig. 9e), and both structure- and frequency-change terms make almost equal contributions (Figs. 9f,g). The height anomalies caused by the structure change term assume a positive height anomaly over North Pacific and some negative height anomalies over eastern North America, southern Europe and northern Africa, and Asia (Fig. 9f). As shown in Table 2, from ENSO neutral to cold ENSO winters, the occurring frequency of SOMs\(^+\) increases from 11.8 days per winter to 13.1 days per winter, whereas the occurring frequency of SOMs\(^-\) decreases markedly from 19.1 days per winter to 14.5 days per winter. This suggests that cold ENSO suppresses the occurrence of SOMs\(^-\) and is in favor of the formation of the positive phase AO-like anomaly (Fig. 9g). The contribution from the third term is also negligibly weak (Fig. 9h), as in the warm ENSO case.

We now compare the composite differences based on the five AO-like SOMs obtained from Eq. (4) (Figs. 9a,e) with the actual total winter season composite differences for warm/cold ENSO episodes (Figs. 9i,j). We can see that the structure of the actual ENSO influence is
Fig. 7. Composites of the anomalous 250-hPa height under different ENSO phases: (left) warm (middle) cold, and (right) neutral winters. Contour interval is 40 m. Yellow (green) shading denotes values that are significantly greater (smaller) than the ENSO cold year at the 99% confidence level based on the Student’s $t$ test. The number in the upper-left corner of each SOM pattern indicates the number of occurrence days of that SOM pattern in ENSO warm, cold, or neutral winters. Vectors denote the Plumb wave activity fluxes with the scaling on the top left. Values $< 2 \text{ m}^2 \text{s}^{-2}$ are omitted.
Fig. 8. As in Fig. 7, but of the anomalous SAT. Contour interval is 1K.
quite similar to the influence on the AO continuum. However, for the cold ENSO case, the Arctic center is located over the Baffin Bay in the AO continuum (Fig. 9e) but shifts to western Canada for actual ENSO influence (Fig. 9j). This inconsistency implies that the cold phase of ENSO impacts other low-frequency teleconnection patterns outside of the AO continuum. Nevertheless, the high similarity of the composite differences suggests that most of the actual composite differences for the two ENSO phases can be explained by changes in the AO continuum.

The above findings suggest a tropospheric pathway of the ENSO influence on both the structures and frequencies of the AO-like SOMs (Fig. 6 and Table 2) and associated weather over Eurasian region through modulating the PNA-like wave train (Fig. 7), as suggested by Li et al. (2006) and Graf and Zanchettin (2012).

6. Troposphere–stratosphere linkage

As mentioned earlier, AO events in the troposphere and the stratosphere (Baldwin and Dunkerton 1999;
Christiansen 2001; Baldwin et al. 2003) are closely correlated: the AO events usually occur first in the stratosphere and then propagate downward into the troposphere. Does the same physical process occur for the AO continuum members? To find this possible stratosphere–troposphere linkage, we performed lead–lag regressions of the daily polar vortex intensity, which is defined as the area-mean zonal wind anomalies north of 60°N, upon the daily SOM indices (Fig. 10). Figure 10 indicates that all the AO continuum members are significantly correlated with the disturbances at 10 hPa as early as a few weeks prior (SOMs 1 and 6) or even one or more months prior (SOMs 10, 11, and 15). The disturbances propagate downward all the way from the stratosphere deeply into the lower troposphere in different ways. For SOMs 1 and 6, they experience a sudden rapid growth and decay in two weeks or so centered at day 0, which causes a relatively strong Arctic center (Fig. 4, first two columns), compared to the other AO continuum members. For SOMs 10 and 15, the growth and decay of the disturbances are relatively slow, which takes a couple of months. As a result, a relatively weak Arctic center of longer lifespan is observed (Fig. 4, third and last columns). For SOM 11, its area-mean zonal winds in the polar region from the stratosphere to the troposphere are positive, implying westerly and low pressure anomalies there, which is contrary to the negative polarity of the pattern. This polarity disagreement in the troposphere and stratosphere is also observed by Rivière and Drouard (2015). We now examine further the structures of the five AO-like SOMs separately under different polar stratospheric conditions (strong, weak, and median PV). We see from Fig. 11 that the SOMs’ structures do vary to different degrees for different polar conditions. Again as in ENSO case, significant changes are also found to occur over Asia for SOMs 11 and 15: the Asian height anomaly intensifies and extends to a much larger area in weak PV winters, compared with strong PV winters. An examination of the wave activity fluxes suggests that the pathway of PV impact on the SOMs’ structures may be through the modulation of the low-frequency wave

<table>
<thead>
<tr>
<th>Warm ENSO (19 yr)</th>
<th>Cold ENSO (23 yr)</th>
<th>Neutral (16 yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOMs⁺</td>
<td>110 (5.8)</td>
<td>302 (13.1)</td>
</tr>
<tr>
<td>SOMs⁻</td>
<td>414 (21.8)</td>
<td>334 (14.5)</td>
</tr>
</tbody>
</table>

TABLE 2. Numbers of occurring days for the sums of the positive AO-like SOMs (SOMs⁺; SOMs 10 and 15) and negative AO-like SOMs (SOMs⁻; SOMs 1, 6, and 11) under different ENSO phases. The values in parentheses are the frequency of occurrence in ENSO warm, cold, or neutral winters (unit: days per winter). The values in bold indicate that they are significantly different from the number of occurrence days in the neutral ENSO episodes at the 90% confidence level based on a Monte Carlo test.
trains from the Pacific across North America and North Atlantic into Asia, as in the ENSO case.

Similarly as in ENSO case, we use Eq. (4) to examine the PV modulations on the AO pattern from the SOM perspective, with the median PV winters as the reference state. Figures 12a–e show the strong PV case. We see that the 250-hPa height anomaly takes the form of positive AO phase with a stronger Arctic center and a much weaker center outside of the Arctic. Both the structure change term and frequency change term [terms 1 and 2 in Eq. (4), respectively] contribute equally to the formation of this anomaly and the contribution of the combined structure and frequency change term [term 3 in Eq. (4)] is negligibly small. The anomalies associated with the structure change term have two positive height anomalies over the western North America and the eastern Asia, respectively, and a strong negative height anomaly over the Arctic and some weaker negative anomalies over the Pacific and North Atlantic. The anomaly associated with the frequency change term takes the form of positive AO phase, which is due to both the increase in the SOMs\(^+\) frequency from 11.1 days per median PV winter to 15.5 days per strong PV winter and decrease in the SOMs\(^-\) frequency from 17.7 days per median PV winter to 15.5 per strong PV winter (Table 3).

Figures 12e–h show the weak PV case. Clearly, the weak PV effect is to cause a negative phase AO-like anomaly of more annular symmetry and the frequency change term makes a dominant contribution through a sharp decrease of frequency of the SOMs\(^+\) from median PV winters (11.1 days per winter) to weak PV winters (3.9) and an increase of frequency of the SOMs\(^-\) from 17.7 days per median PV winter to 21.6 days per weak PV winter (Table 3). The structure change term makes a secondary contribution through generating negative height anomalies over North Atlantic, North Pacific, and Asia and a positive anomaly over southern Asia. The effects of the combined structure change and frequency change term is still very weak, as in strong PV case.

Figure 12i shows the actual total winter season composite difference of the 250-hPa geopotential height anomalies between strong and median PV episodes. A comparison of Figs. 12i and 12a indicates that the composite difference based on the AO continuum has a much stronger Arctic center and much weaker negative height anomaly over Asia than the actual composite difference, whereas for weak PV case the two kinds of composite differences resemble each other to a high degree. The result suggests that much of the actual composite differences for the weak PV condition can be explained by changes in the AO continuum.

It should be noted that, among the 20 weak PV winters, 18 winters are found to be linked the major stratospheric sudden warmings (SSWs). This further confirms the finding that the negative phase AO occurs mostly often after the SSW events. Based on the fact that the frequency of the SSWs is doubled during both warm and cold ENSO winters, compared with ENSO neutral winters (Butler and Polvani 2011), and that more SSWs lead to more negative phase AO events and more extreme weather events over Eurasian regions, Ineson and Scaife (2009) and Butler et al. (2014) suggested that the pathway of ENSO’s impact on Eurasian weather is through the stratosphere.

7. Summary and discussion

From the continuum perspective, this study demonstrates that the AO pattern, defined as the leading EOF of 250-hPa geopotential height, is not a unique pattern but a continuum that can be well approximated by five discrete, representative AO-like patterns.

These AO-like patterns capture spatial variations in the AO that more closely resemble observations than the canonical AO, and their development involves different physical processes. For SOMs 1 and 6, they initiate simultaneously from the disturbances in the Arctic and North Atlantic, and both the high-frequency eddies’ feedback in North Atlantic and the propagation of the low-frequency wave trains from the Arctic into Europe contribute to the pattern formation. For SOMs 10 and 15, they grow simultaneously from the disturbances in the Pacific, the North Atlantic, and the Arctic; both the high-frequency eddies’ feedback in the North Pacific and North Atlantic and the propagation of the low-frequency wave trains from the Pacific across North America into North Atlantic contribute to the pattern formation. SOM 11 evolves in a similar way as SOMs 10 and 15 except that it initiates from the disturbances only in the Pacific and the Arctic.

ENSO influences both the structures and frequencies of occurrence of the AO-like SOMs. Warm ENSO enhances the negative AO phase and cold ENSO enhances the positive AO phase.

The downward propagation of the stratospheric disturbances contributes to the formation and development of all the five AO-like patterns. A strong polar vortex (PV) enhances the positive AO phase and a weak PV enhances the negative AO phase, compared with median PV condition.

It should be pointed out that this study does not distinguish between the tropospheric pathway and stratospheric pathway of the ENSO influence on AO and associated weather over Eurasian regions. This is
**FIG. 11.** Composites of the anomalous 250-hPa height under different polar vortex phases: (left) strong, (middle) weak, and (right) neutral polar vortex winters. Contour interval is 40 m. Yellow (green) shading denotes values that are significantly greater (smaller) than the weak PV year at the 99% confidence level based on the Student’s $t$ test. The number in the upper-left corner of each SOM pattern indicates the number of occurrence days of that SOM pattern. Vectors denote the Plumb wave activity fluxes with the scaling on the top left. Values $< 2 \text{ m}^2 \text{s}^{-2}$ are omitted.
because we do not remove the PV impact when we examine the ENSO influence on AO and the associated weather anomalies. Similarly, we do not remove the ENSO impact when we examine the PV influence on the AO and the associated weather anomalies. Because of the limited size of data samples for the study period 1958–2015, numerical models may provide a useful tool for further study of isolating the pure ENSO impact or pure PV impact on AO and the associated weather anomalies.

This study shows that in addition to the similarity, the AO-like pattern-associated SAT anomalies do vary from

**TABLE 3. Numbers of occurring days for the sums of the positive phase AO-like SOMs (SOMs+; SOMs 10 and 15) and negative phase AO-like SOMs (SOMs−; SOMs 1, 6, and 11) under different polar vortex (PV) conditions. The values in parentheses are the frequency of occurrence in strong, weak, or median PV winters (unit: days per winter). The values in bold indicate that they are significantly different from the occurring days in the median PV episodes at the 90% confidence level based on a Monte Carlo test.**

<table>
<thead>
<tr>
<th></th>
<th>Strong PV (23 yr)</th>
<th>Weak PV (20 yr)</th>
<th>Neutral PV (15 yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOMs+</td>
<td>357 (15.5)</td>
<td>78 (3.9)</td>
<td>166 (11.1)</td>
</tr>
<tr>
<td>SOMs−</td>
<td>357 (15.5)</td>
<td>431 (21.6)</td>
<td>266 (17.7)</td>
</tr>
</tbody>
</table>
case to case, like the AO-like patterns themselves. This suggests that when making the AO-related weather prediction, one should predict the exact type of the AO-like patterns first. To this end, the present study suggests that the precursory tropospheric disturbances over the Pacific, North Pacific, and Arctic, even in the polar stratosphere, should be taken into consideration. Also, the ENSO modulation effects on both the frequency of occurrence and structure of the AO-like patterns are some other important factors to be considered. Whether or not these results can be useful for predictions is still an open question. The key point is whether or not these variations within the AO continuum are predictable on the relevant time scales, which is a challenge to be addressed in future work.

This study may also throw some light on the AO–NAO relationship, a subject of debate over the past two decades (Thompson and Wallace 1998, 2000; Wallace and

---

Fig. 13. As in Fig. 3, but for the NAO.
A comparison of the NAO pattern (Fig. 13a) with the AO pattern (Fig. 3a) indicates that the two patterns are highly similar except that the Pacific center of the NAO is much weaker. The correlation between the two daily PCs of the AO and NAO reaches as high as 0.88. Actually, the AO and NAO are indistinguishable from each other from the EOF perspective (Wallace 2000; Feldstein and Franzke 2006). From the continuum perspective, on the other hand, Table 1 indicates that the NAO continuum can be well approximated by nine discrete, representative NAO-like patterns (SOMs 1, 2, 5, 6, 7, 10, 11, 15, and 18) and the NAO properties can be well described by the statistics of these nine NAO-like patterns (Fig. 13). A comparison of the NAO-like SOMs with the AO-like SOMs shows that all the AO-like SOMs (SOMs 1, 6, 10, 11, and 15) are also NAO-like patterns; however, four SOM patterns (SOMs 2, 5, 7, and 18) belong to the NAO continuum but do not belong to the AO continuum. The correlation between the winter season frequencies of the AO and NAO reaches as high as 0.81. This is why the AO and NAO are really indistinguishable in the EOF analysis. An examination of the AO-like and NAO-like patterns shows that the Pacific center occurs quite frequently for the AO-like and NAO-like patterns, indicating that the AO and NAO are neither annular nor regional.

Here, we will have a brief discussion about how ENSO influences the frequencies of occurrence of the NAO-like SOMs. As we can see in the last column of Table 1, among the nine NAO-like SOMs, only three of them (SOMs 7, 15, and 18) are significantly correlated with ENSO.

Further examination indicates that the formation processes (not shown) of the four positive phase NAO-like patterns (SOMs 5, 10, 15, and 18) are closely linked to the propagation of the PNA-like wave trains, but for the five negative phase NAO-like patterns (SOMs 1, 2, 6, 7, and 11), only one pattern (SOM 11) is linked to the PNA-like wave train. This result is in good agreement with the findings of Feldstein (2003) and Benedict et al. (2004) based on the EOF analysis that the positive phase NAO is preceded by a PNA-like wave train but the negative phase NAO develops in situ.

Acknowledgments. This research is supported by Chinese NSF Grants 41130962 and 41375060. The NCEP–NCAR reanalysis data used in this study were obtained from http://www.esrl.noaa.gov/psd/data/gridded/reanalysis/. The sea surface temperature data from the Extended Reconstructed Sea Surface Temperature Dataset (v3b) are from http://www1.ncdc.noaa.gov/pub/data/cmb/ersst/v3b/. Both authors are very grateful to Dr. Jiacan Yuan and Prof. Jayou Huang for discussions. We would also like to thank three anonymous reviewers and Dr. H. Nakamura, the editor, for their helpful comments that strengthened this manuscript.

References


