The COWL Pattern Identified with a Large AO Index and Its Impact on Annular Surface Temperature Anomalies

SHI Ning[1,2,3](施　宁) and BUEH Cholaw[4*](布和朝鲁)

1 *Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science & Technology, Nanjing* 210044

2 *Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

3 *Climate Change Research Center, Chinese Academy of Sciences, Beijing* 100029

4 *International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

(Received August 18, 2011; in final form December 6, 2011)

ABSTRACT

In this study, the cold ocean/warm land (COWL) pattern was identified from the leading empirical orthogonal function (EOF) of the monthly 1000-hPa geopotential height field poleward of 20°N. Traditionally, the leading EOF has been recognized as the Arctic Oscillation (AO), or Northern Annular Mode (NAM), which causes annular surface air temperature (SAT) anomalies over high-latitude regions of the Northern Hemisphere. A new finding of the present study is that the total AO events defined by the large AO index actually include a distinct type of events that are characterized by a less-annular spatial structure, i.e., the COWL pattern, which shows an NAO-like distribution in the Atlantic sector and a center of action over the North Pacific with the same sign as that over the Arctic. In addition, unlike canonical AO events, the COWL events also show a less-annular pattern in the stratosphere. Statistically, at least one-third of the AO events can be categorized as the COWL events. The SAT anomalies associated with the COWL pattern have an annular distribution over the high-latitude region of the two continents in the Northern Hemisphere. In contrast, if the COWL events are removed from the total AO events, the remainder shows less annular SAT anomalies. Thus, the typical annular SAT anomalies associated with AO events are in large part due to the contribution of the COWL pattern. Furthermore, the monthly variability and the interannual variability of all the AO events are equally important.

Key words: Arctic Oscillation, spatial pattern, COWL, annular SAT anomalies

Citation: Shi Ning and Bueh Cholaw, 2012: The COWL pattern identified with a large AO index and its impact on annular surface temperature anomalies. *Acta Meteor. Sinica*, **26**(4), 410–419, doi: 10.1007/s13351-012-0402-y.

1. Introduction

The Arctic Oscillation (AO), also known as the Northern Annular Mode (NAM), is defined as the leading empirical orthogonal function (EOF) of the sea level pressure (SLP) field poleward of 20°N (Thompson and Wallace, 1998, 2000). The AO consists of three centers of action, one over the Arctic and two over the Euro-Atlantic and Pacific sectors with opposite signs, which constitute a high-degree annular structure (Wang et al., 2008). Thompson and Wallace (1998, 2000) found that the AO had a significant influence on the winter climate over northern Eurasia and North America, and the increasing trend of the AO index can explain a large fraction of the warming trend of the surface air temperature (SAT) over the land of the Northern Hemisphere during the last century. If the positive phase of the AO dominates, both the Aleutian low and the Siberian high would be weak. Consistently, the East Asian winter monsoon would

Supported by the National Basic Research and Development (973) Program of China (2009CB421406), National Science and Technology Support Program of China (2009BAC51B02), and National Natural Science Foundation of China (40975033).
*Corresponding author: bueh@lasg.iap.ac.cn.

be weak, and vice versa (Gong et al., 2001; Wu and Wang, 2002; Chen and Kang, 2006; Yang and Li, 2008). Correspondingly, the breakup date of the rivers in Northeast China was significantly modulated by the AO (Wang and Sun, 2009).

However, the observed fact that the Pacific and Euro-Atlantic centers of action of the AO are uncorrelated raises the question of whether its Pacific center could be an artifact of the EOF analysis (Deser, 2000; Ambaum et al., 2001). To clarify this issue, Wallace and Thompson (2002) argued that the Pacific center can be significantly correlated with the Atlantic center if the pattern that represents the inversely correlated fluctuations over the North Atlantic and North Pacific, called the augmented Pacific/North American pattern (PNA), is eliminated. In other words, the AO is still an annular mode and its interaction with the augmented PNA leads to the insignificant relationship between the two centers of action over the two oceans. Similarly, Honda et al. (2001) and Honda and Nakamura (2001) argued that the AO may be interpreted as a superposition of the Aleutian low-Icelandic low seesaw upon a dominant signal of the Arctic-midlatitude dipole. Despite this debate, the AO index is currently widely utilized for weather monitoring and forecasting. Even on a shorter time scale, i.e., the intraseasonal time scale, McDaniel and Black (2005) investigated the dynamical evolution of the AO event and observed a remarkable degree of annular structure of planetary scale anomalies. They emphasized that the anomalous stationary wave forcing plays the primary role in both the maturing and decaying stages of the AO event.

Another dominant circulation pattern of natural variability in the Northern Hemisphere is the cold ocean/warm land (COWL) pattern (Wallace et al., 1995, 1996). In its positive phase, this pattern is characterized by prominent negative SLP anomalies over the Arctic and North Pacific and positive anomalies over the North Atlantic, and vice versa. Thus, the two centers of action of the COWL pattern over the two oceanic basins are negatively correlated, which is different from the situation of the AO, but the North Atlantic part of the COWL pattern is very similar to that of AO. Notably, Quadrelli and Wallace (2004) found that the COWL pattern is indistinguishable from the leading EOF of the monthly SLP field. In other words, the COWL pattern would be, to a certain degree, projected onto the AO. Wallace et al. (1995, 1996) revealed that the observed monthly time series of SAT anomalies averaged over the Northern Hemisphere could be partitioned into a very slowly varying "radiative" component, and a component exhibiting rapid year-to-year and month-to-month fluctuations. They found that the latter component corresponds to the COWL pattern. The observed Northern Hemisphere-averaged SAT trend in the recent decades is consistent with the strong positive bias of the COWL pattern index during the cold season (Wallace et al., 1996; Wu and Straus, 2004).

However, the following three questions remain unanswered: (1) If all AO events are identified with monthly AO indices, whether the two midlatitude centers of action always show the same polarity in the same phase as shown by Thompson and Wallace (1998, 2000)? (2) Since the COWL pattern shares much resemblance with AO in the spatial structure and in the increasing trend of their indices, can the COWL pattern be identified from the monthly AO events with strong amplitudes of AO indices? (3) Compared with all AO events, how does the COWL pattern identified in this manner contribute to the global SAT anomalies? The present study primarily focuses on these three questions.

This paper is organized as follows. Section 2 describes the data and analysis methods. The results based on the composite analysis are presented in Section 3. The final section consists of a summary and discussion.

2. Data and methods

The data used in this study are the monthly mean meteorological reanalysis product from the US National Centers for Environmental Prediction (NCEP) and the US Department of Energy (DOE) Atmospheric Model Intercomparison Project (AMIP-II) (Kanamitsu et al., 2002) during the period of 1979–

2009. The variables include SLP, geopotential height, and SAT, which are available on a global regular longitude/latitude grid with intervals of 2.5°.

The AO indices were derived in a similar manner as in Baldwin and Thompson (2009). First, the principal component (PC) time series of the leading EOF of the zonal-mean 1000-hPa geopotential height (Z1000) anomalies north of 20°N were calculated for 5 winter months from November to March. Figure 1 shows the regression anomalies of Z1000, SLP, and SAT on the AO index in the 5 winter months; the results are consistent with those of Thompson and Wallace (1998, 2000). Moreover, the regression of Z1000 anomalies was regarded as the monthly spatial pattern of the AO. The AO indices (AOI), spanning the entire 31-yr data period, were derived by projecting the monthly mean Z1000 anomalies onto the monthly spatial pattern. A positive (negative) AO event was then defined with the normalized AOI $\geqslant 0.5$ ($\leqslant -0.5$) for a particular calendar month. Other thresholds of the AOI were also examined, and the corresponding results do not qualitatively alter the conclusion obtained here; this issue will be further discussed in Section 4.

To examine the COWL pattern contained in all AO events defined with the AOI (i.e., $|\mathrm{AOI}| \geqslant 0.5$), we calculated the area-mean (area-weighted) height anomalies over the Arctic (65°–90°N) and the North Pacific (30°–50°N, 160°–220°E). For brevity, these area-mean monthly height anomalies are called AI and NPI, respectively, after normalized by their means and standard deviations for the 31-yr data period. A monthly COWL event (or pattern) can be defined if the monthly AI and NPI have the same sign and their absolute values exceed 0.3 (approximately 10 m in the Z1000 anomalies). The positive (negative) COWL pattern corresponds to the positive (negative) AI and NPI. As shown in Table 1, 10 positive COWL events were identified from the total 24 positive AO events, and 10 negative COWL events were identified from the total 28 negative AO events. Therefore, it is clear that more than one-third of the AO events can be classified as COWL events (Table 1).

Two types of composites were performed to analyze the spatial patterns of all AO and COWL events. For the first composite, the 5-month mean meteorological fields around each calendar month were removed prior to the analysis to focus only on the month-to-month variability. The second composite method is almost identical to the first one except that the 5-month mean fields are retained. Thus, in addition to the month-to-month variability, interannual variability that might depend on the external forcing (for example, the El Niño/Southern Oscillation) was also considered in the second composite. For brevity, the first and second composites are called composite-M and composite-N, respectively. The statistical significance of the composite anomalies is assessed by applying Student's t-test.

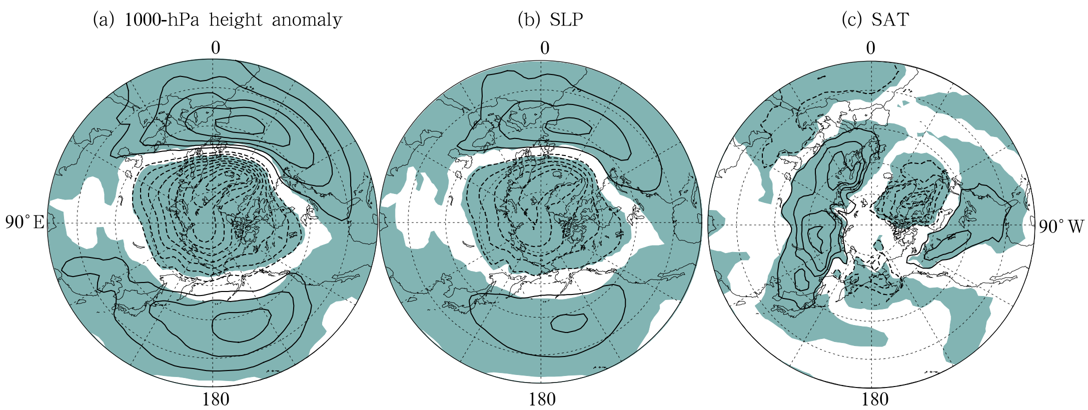

Fig. 1. Regression of (a) height anomalies at 1000 hPa, (b) SLP, and (c) SAT on the AO index. Contour intervals are 5 m, 1 hPa, and 0.5°C in (a), (b) and (c), respectively. Solid (dashed) lines are positive (negative) anomalies and zero lines are omitted. The shadings in (a) mark the three areas to be averaged to represent the strength of the local centers of action (see text for further detail), while the shadings in (b) and (c) indicate the regions at the 95% confidence level.

Table 1. Numbers and percentages of all AO (ALL) events and COWL events. See text for the definitions of AO and COWL events

	ALL	COWL	Remainder
Positive	24	10 (42%)	14 (58%)
Negative	28	10 (36%)	18 (64%)

3. Results

3.1 Positive phase

Figure 2 depicts the composite anomalies of Z1000 and SAT for the positive events. Here, the composite-M was performed to consider only the month-to-month variability. The composite map of the total AO events (Fig. 2a) projects to a greater degree on the NAO pattern rather than the NAM pattern derived from the regression map of the leading EOF of the Z1000 field (Figs. 1a and 1b). Compared with Fig. 2a, the COWL pattern (Fig. 2b) still shares the elements of the NAO pattern, but its distinct feature is that it has a center of action over the North Pacific with the same sign as the Arctic center and the opposite sign as the North Atlantic center. The composite for the remainder of the AO events (hereafter, RM events, for brevity), as shown in Fig. 2c, shows a typical annular structure of the AO pattern in Fig. 1a. However, for the RM events, the center of action over the North Atlantic is considerably weak, whereas that over the North Pacific becomes strikingly prominent. Notably, as seen in Figs. 2a–2c, the NAO pattern seems to have a closer association with the COWL event than the RM event, as apparently strong height anomalies have been observed over the midlatitude North Atlantic in the composite of the COWL events. Figures 2d–2f present the composite SAT anomalies related to

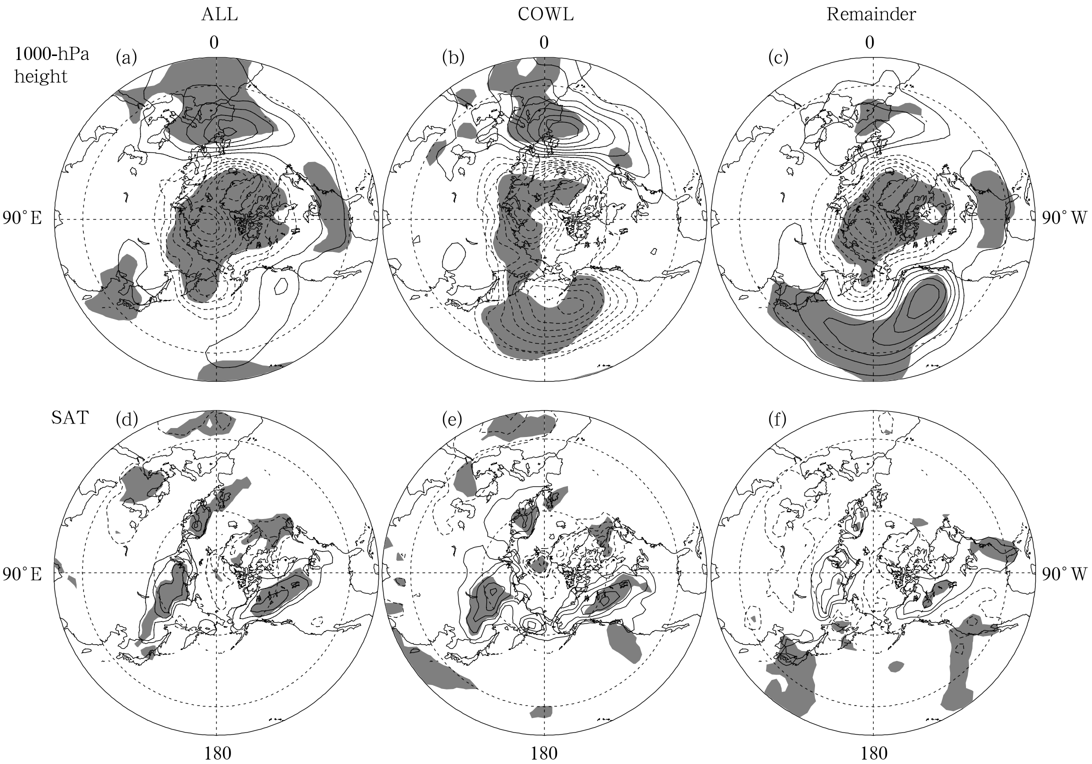

Fig. 2. (a)–(c) Composite geopotential height anomalies (m; contours with intervals of 5 m) and (d)–(f) the corresponding anomalous SAT (℃; contours with intervals of 0.5 ℃) of the positive AO events at 1000 hPa. Solid (dashed) lines represent positive (negative) anomalies and zero lines are eliminated in all panels. Shading marks the region at the 95% confidence level.

the AO events. For the total AO events, positive SAT anomalies cover the high-latitude regions of the two continents of the Northern Hemisphere while significant negative ones cover the region around the Greenland, consistent with those shown in Fig. 1c and the results of earlier studies (Thompson and Wallace, 1998, 2000). As shown in Figs. 2d and 2e, the anomalous SAT distribution in the COWL events bears strong resemblance to that in the total AO events, particularly over the high-latitude land while the SAT anomalies in the RM events show little significance. This result suggests that the annular SAT anomaly distribution over the high-latitude regions of the two continents in the Northern Hemisphere primarily results from the COWL event. For the COWL pattern, the negative height anomalies over the North Pacific correspond to the enhancement of the Aleutian Low and, thus, the enhanced warm advection over the western and northwestern parts of the North American continent. Consequently, the positive SAT anomalies are formed in that region (Fig. 2e). For the COWL pattern, the negative height anomalies over the Arctic are extended even more toward the Eurasian continent (Fig. 2b) than those in Figs. 2a and 2c. Such a flow pattern is favorable for an anomalous warm air advection and hence the positive SAT anomalies over the high-latitude region of the Eurasia continent.

Figure 3 shows the composite Z1000 and SAT anomalies for the positive events, for which the composite-N was performed. If the year-to-year variability is taken into account, the horizontal pattern of Z1000 anomalies (Figs. 3a–3c) also retains the structure in the composite-M, but the corresponding amplitudes of the center of action become conspicuously stronger than in the composite-M (Figs. 2a–2c). For instance, the height anomalies over the North Atlantic and North Pacific centers in Fig. 3 are twice as strong as those in Fig. 2, for both the COWL event and the RM event. In line with this feature, the regions at the 95% significance level are also extended to cover even wider extents. These features are also true for the composite SAT anomaly distribution (Figs. 3d–3f). Some differences, however, can be found between the SAT anomalies of the two types of composites. Specifically, in contrast to that in Fig. 2f, the RM event in the composite-N can significantly influence the

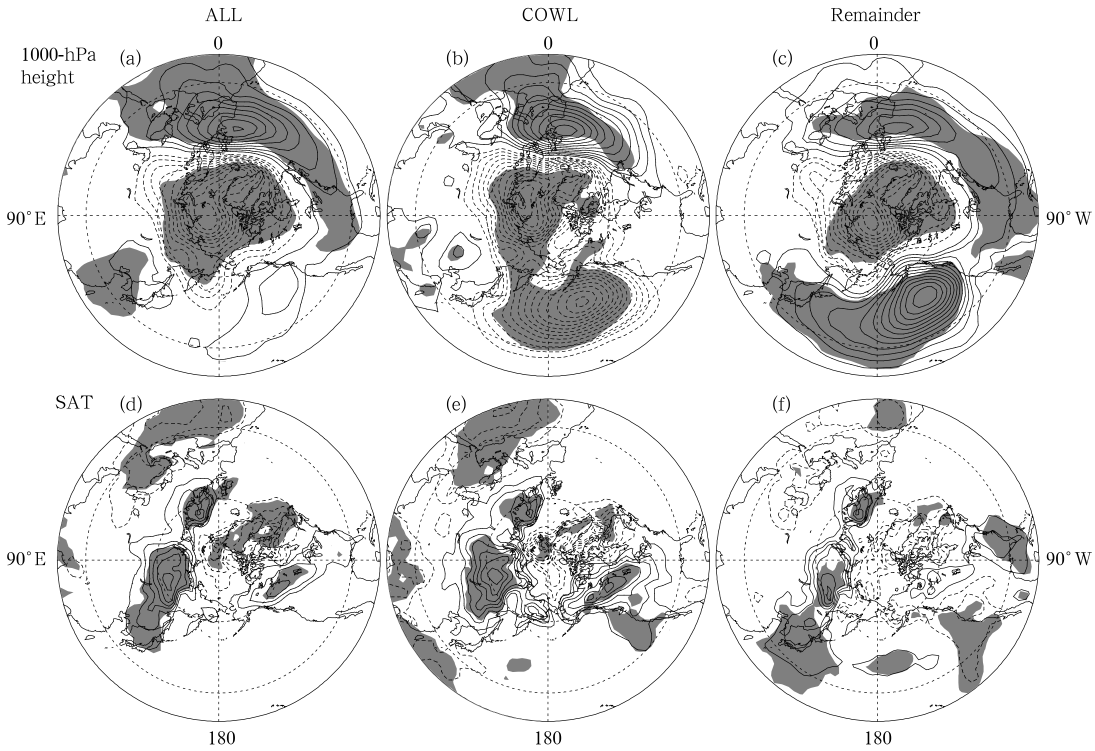

Fig. 3. As in Fig. 2, but for the composite in which the year-to-year variability is taken into account.

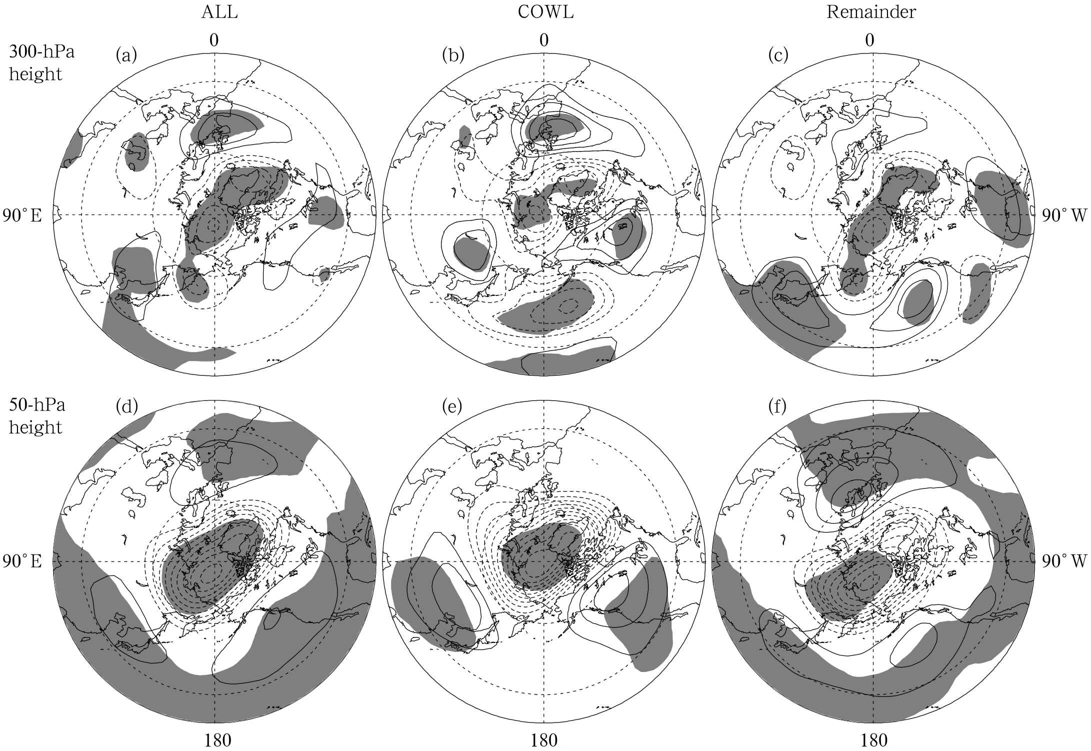

Fig. 4. As in Fig. 2, but for the height anomalies at 300 (upper panels) and 50 hPa (lower panels) with intervals of 15 m.

high-latitude Eurasian continent, from northern Europe to northeastern Asia (Fig. 3f). However, the positive SAT anomalies over the North American continent shown in Fig. 3d are absent in Fig. 3f, implying that the COWL pattern would be responsible for the positive SAT anomalies. Importantly, it can be inferred from Figs. 2 and 3 that both the month-to-month and year-to-year variability are of equivalent importance to the total AO events.

The height anomalies in the upper troposphere and mid-stratosphere are displayed in Fig. 4, using the composite-M. Overall, as indicated in Figs. 2a–2c and Fig. 4, all AO events are manifested in the quasi-barotropic height structure from the troposphere to the stratosphere. The annularity of height anomalies in the RM event is more obvious than in the COWL event in the whole troposphere and stratosphere. Interestingly, as shown in Fig. 4b, the COWL pattern also contains elements of a PNA-like pattern, which suggests that both the NAO pattern and the PNA-like pattern have possibly contributed to the occurrence of the COWL pattern and thus the related global SAT anomaly distribution. At 50 hPa, the COWL event exhibits positive height anomalies over the Asian continent and the North American continent (Fig. 4e), while the RM event is accompanied by positive anomalies over the Europe/North Atlantic sector and over the North Pacific (Fig. 4f). Consequently, the composite map of height anomalies in the total AO events (Fig. 4d) has a high degree of annularity. Similar features in the upper troposphere and mid-stratosphere are also found for the analysis of composite-N (figure ommited).

3.2 Negative phase

Figures 5 and 6 present the Z1000 and SAT anomalies for the negative events in the composite-M and composite-N, respectively. Many features of AO events in the negative phase are similar to those in the positive phase, except for the opposite polarities. In contrast to the situation of the positive phase, a distinct feature shown in Figs. 5a and 6a is that the negative height anomalies cover the mid- and high-latitude Asian continent, indicating a suppressed Siberian high. As such, the Z1000 anomalies in the Northern Hemisphere show a high degree of annularity over a vast region from North Europe, via North Asia, to northwestern Pacific. Consistent with the suppressed Siberian high, warm SAT anomalies are observed over East Asia in Figs. 5d and 6d. It can be inferred from Figs. 5a–5c and 6a–6c that the COWL pattern has primarily contributed to the weakened Siberian high and hence the warm SAT anomalies over East Asia. The well-organized annularity of the SAT anomalies over the high-latitude land in Figs. 5d and 6d is mainly ascribed to the influence of the COWL pattern (Figs. 5e, 5f, 6e, and 6f). Again, the comparison between Figs. 5 and 6 suggests that the month-to-month and year-to-year variability are equally important to all AO events.

The height anomalies at 300 and 50 hPa in the negative phase are presented in Fig. 7 in the composite-M. As analogues to these anomalies in the positive phase, both the COWL and RM events show a quasi-barotropic height structure throughout the troposphere and stratosphere. At 300 hPa, the RM event is associated with a greater annular structure of height anomalies than in the COWL event, constituting the annularity feature of the total AO events (Figs. 7a–7c). The positive anomalies over the Arctic are also stronger in the RM event than in the COWL event. At 50 hPa, the anomalous stratospheric signal over the Arctic in the COWL event has less significance than that in the RM event, which means that the significant height anomalies in the composite of total AO events mainly result from those of the RM events. In other words, the anomalous signal of the COWL event becomes considerably weak in the stratosphere.

4. Summary and discussion

In this study, based on the wintertime monthly mean reanalysis data of the NCEP-DOE AMIP-II and the leading empirical orthogonal function (EOF) of the monthly Z1000 field poleward of 20°N, the total AO events were identified by the magnitude of the leading PC. These events were further partitioned into COWL events and RM events. The COWL events

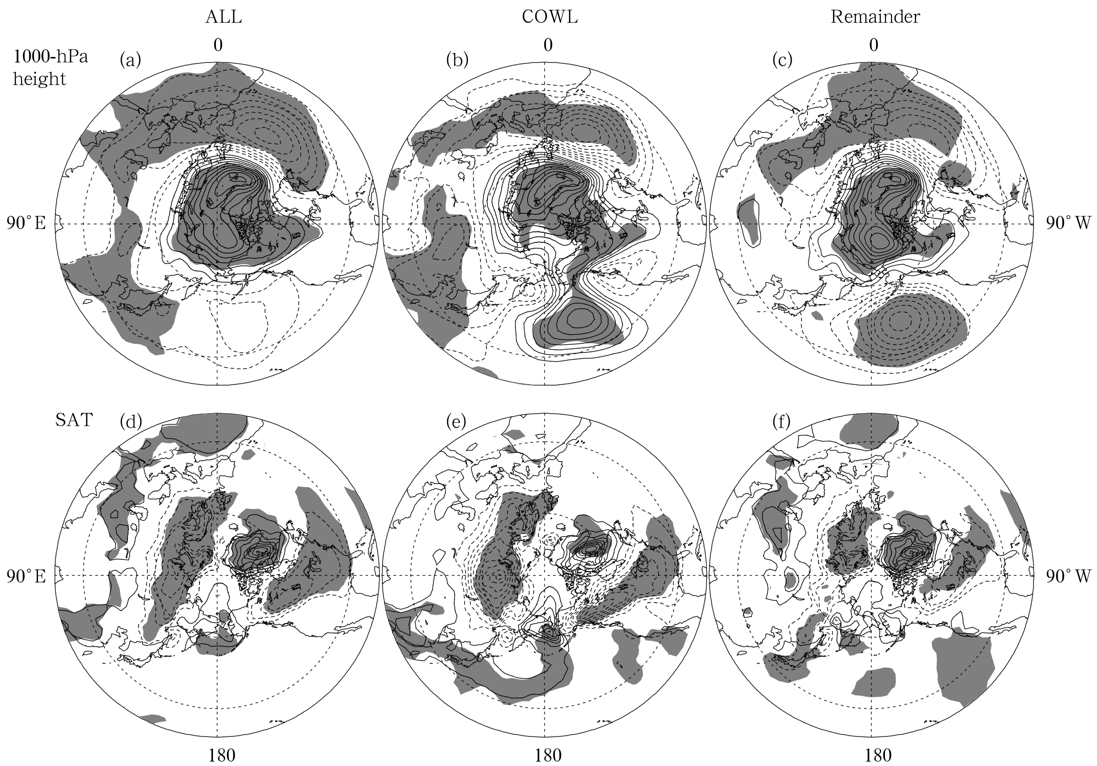

Fig. 5. As in Fig. 2, but for the negative phase.

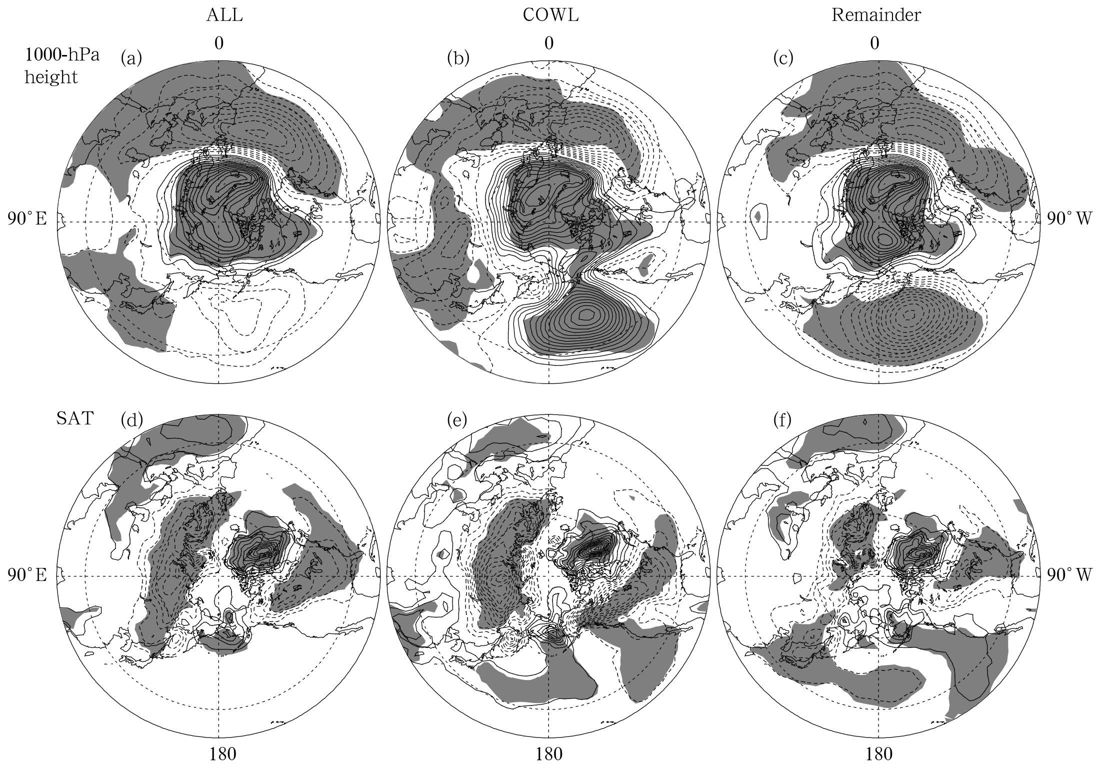

Fig. 6. As in Fig. 5, but for the composite in which the year-to-year variability is taken into account.

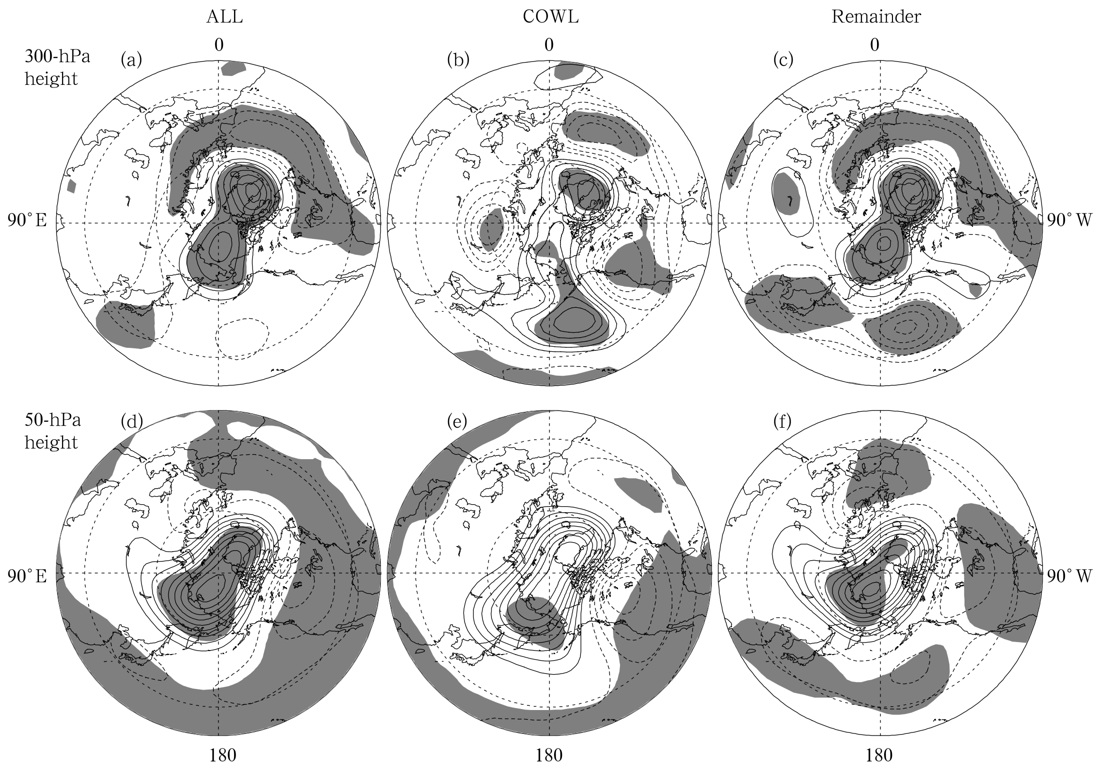

Fig. 7. As in Fig. 4, but for the negative phase.

accounts for 42% of the total AO events in the positive phase and for 36% in the negative phase. Similar to the traditional AO events, the COWL events show a quasi-barotropic NAO pattern in the Atlantic sector throughout the troposphere and stratosphere. However, the COWL events have an anomalous Pacific center of action that is out-of-phase with the North Atlantic center of action, especially in the troposphere, which leads to the less-annular feature in the height anomaly distribution for total AO events. Moreover, the COWL pattern has a weaker anomaly signal in the stratosphere than the RM pattern. The COWL pattern contributes to the annular surface air temperature anomalies over the high-latitude region of both continents in the Northern Hemisphere.

Since the amplitude of the COWL and RM events in the composite-N are almost twice as large as those in the composite-M, the monthly variability and the interannual variability are equally important to all the AO events. In other words, AO events can be intensified under the influence of external forcing.

As for the dynamic mechanism of the COWL, Wallace et al. (1996) and Broccoli et al. (1998) revealed that the anomalous contrast in thermal inertia between land and ocean was the primary factor for the existence of the COWL pattern. However, such a mechanism could not completely explain its quasi-barotropic structure. Many studies have demonstrated that the anomalous vertical propagation of planetary waves (PWs) is a key role in the formation of the AO (Limpasuvan and Hartmann, 1999, 2000; Christiansen, 2001; Lorenz and Hartmann, 2003; Vallis et al., 2004; McDaniel and Black, 2005). Analogously, we speculate that the anomalous vertical propagation of PWs, which can be induced by those external forcing, such as the anomalous thermal contrast, ENSO, snow cover, also favors the formation of COWL pattern. But this hypothesis still requires in-depth examination and validation.

The identification of the total AO events and the partitioning of them into the COWL and RM events are perhaps sensitive to the AOI threshold chosen in the present work. To examine this possibility, we reidentified the numbers of all AO events, COWL events and RM events with varying AOI thresholds, as presented in Fig. 8. Obviously, for both the positive and negative AO events, the COWL events account for at least one-third of all AO events when the AOI threshold varies between 0.3 and 1.5. If the AOI exceeds 1.5, only 10 or fewer samples of AO events (thick solid lines in Fig. 8) can be identified, and thus there is no statistical meaning. Therefore, we confirm that the AOI threshold of 0.5 chosen in this study is appropriate, and choosing other AOI threshold values will not alter our final conclusion qualitatively.

The existence of the COWL events contained in the total AO events might well explain the reason for the lack of positive correlations between the two centers of action over the two oceanic basins revealed by Deser (2000) and Ambaum et al. (2001).

In addition, based on the coupled general circulation models participating in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4), Zhu and Wang (2010) reported an increasing tendency of the AO index under the

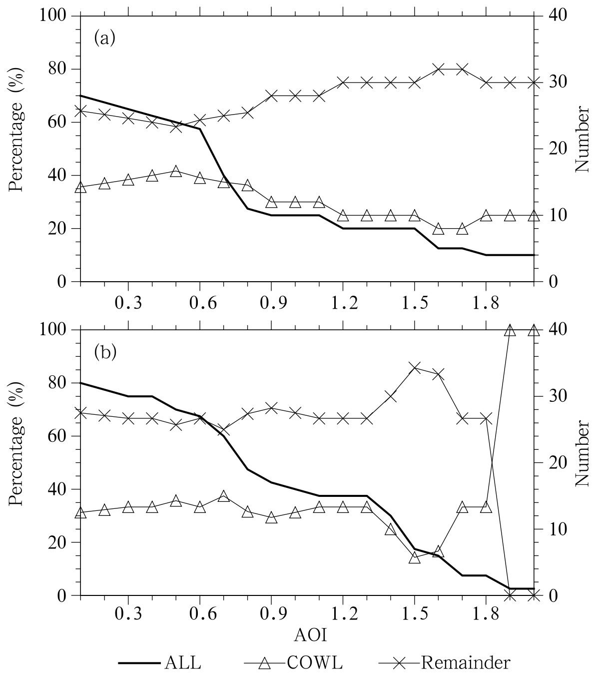

Fig. 8. Total numbers of "ALL" AO events (thick solid line) and percentage of numbers of COWL events and RM events (thin marked lines) in the total numbers of all AO events. (a) The positive phase and (b) the negative phase. The abscissa is the varying threshold value of AOI for identifying AO events.

A1B scenario. However, it is not known whether the percentage of COWL events increases or decreases in the global warming background, a question that also deserves further investigations.

REFERENCES

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

Baldwin, M. P., and D. W. J. Thompson, 2009: A critical comparison of stratosphere-troposphere coupling indices. *Quart. J. Roy. Meteor. Soc.*, **135**(644), 1661–1672.

Broccoli, A. J., N. C. Lau, and M. J. Nath, 1998: The cold ocean-warm land pattern: Model simulation and relevance to climate change detection. *J. Climate*, **11**, 2743–2763.

Chen Wen and Kang Lihua, 2006: Linkage between the Arctic Oscillation and winter climate over East Asia on the interannual timescale: Roles of quasi-stationary planetary waves. *Chinese J. Atmos. Sci.*, **30**(5), 863–870. (in Chinese)

Christiansen, B., 2001: Downward propagation of zonal mean zonal wind anomalies from the stratosphere to the troposphere: Model and reanalysis. *J. Geophys. Res.*, **106**(D21), doi: 10.1029/2000jd000214.

Deser, C., 2000: On the teleconnectivity of the "Arctic Oscillation". *Geophys. Res. Lett.*, **27**(6), 779–782.

Gong, D., S. Wang, and J. Zhu, 2001: East Asian winter monsoon and Arctic Oscillation. *Geophys. Res. Lett.*, **28**(10), 2073–2076.

Honda, M., and H. Nakamura, 2001: Interannual seesaw between the Aleutian and Icelandic lows. Part II: Its significance in the interannual variability over the wintertime Northern Hemisphere. *J. Climate*, **14**(24), 4512–4529.

—–, —–, J. Ukita, et al., 2001: Interannual seesaw between the Aleutian and Icelandic lows. Part I: Seasonal dependence and life cycle. *J. Climate*, **14**(6), 1029–1042.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, et al., 2002: NCEP-DOE AMIP-II reanalysis (R-2). *Bull. Amer. Meteor. Soc.*, **83**(11), 1631–1643.

Limpasuvan, V., and D. L. Hartmann, 1999: Eddies and the annular modes of climate variability. *Geophys. Res. Lett.*, **26**(20), doi: 10.1029/1999gl010478.

—–, and —–, 2000: Wave-maintained annular modes of climate variability. *J. Climate*, **13**(24), doi:10.1175/1520-0442(2000)013<4414:WMAMOC>2.0.CO;2.

Lorenz, D. J., and D. L. Hartmann, 2003: Eddy-zonal flow feedback in the Northern Hemisphere winter. *J. Climate*, **16**, 1212–1227.

McDaniel, B. A., and R. X. Black, 2005: Intraseasonal dynamical evolution of the northern annular mode. *J. Climate*, **18**(18), doi:10.1175/JCLI3467.1.

Quadrelli, R., and J. Wallace, 2004: A simplified linear framework for interpreting patterns of Northern Hemisphere wintertime climate variability. *J. Climate*, **17**(19), 3728–3744.

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.

—–, and —–, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate*, **13**(5), 1000–1016.

Vallis, G. K., E. P. Gerber, P. J. Kushner, et al., 2004: A mechanism and simple dynamical model of the North Atlantic Oscillation and annular modes. *J. Atmos. Sci.*, **61**(3), 264–280.

Wallace, J., and D. Thompson, 2002: The Pacific center of action of the Northern Hemisphere annular mode: Real or artifact? *J. Climate*, **15**, 1987–1991.

—–, Y. Zhang, and J. A. Renwick, 1995: Dynamic contribution to hemispheric mean temperature trends. *Science*, **270**(5237), 780–783.

—–, —–, and L. Bajuk, 1996: Interpretation of interdecadal trends in Northern Hemisphere surface air temperature. *J. Climate*, **9**(2), 249–259.

Wang, H., J. Sun, and J. Su, 2008: The northern annular mode: More zonal symmetric than the southern annular mode. *Chinese Sci. Bull.*, **53**(11), doi: 10.1007/s11434-008-0114-y.

Wang, H. J., and J. Q. Sun, 2009: Variability of Northeast China river break-up date. *Adv. Atmos. Sci.*, **26**(4), 701–706.

Wu, B., and J. Wang, 2002: Possible impacts of winter Arctic Oscillation on Siberian high, the East Asian winter monsoon and sea-ice extent. *Adv. Atmos. Sci.*, **19**(2), 297–320.

Wu, Q., and D. M. Straus, 2004: AO, COWL, and observed climate trends. *J. Climate*, **17**(11), 2139–2156.

Yang Hui and Li Chongyin, 2008: Influence of Arctic Oscillation on temperature and precipitation in winter. *Climatic Environ. Res.*, **13**(4), 395–404. (in Chinese)

Zhu Yali and Wang Huijun, 2010: The Arctic and Antarctic oscillations in the IPCC AR4 coupled models. *Acta Meteor. Sinica*, **24**(2), 176–188.