Front. Phys., 2013, 8(5): 590–603
DOI 10.1007/s11467-013-0376-y

Research article

The extremely cold 2009–2010 winter and its relationship with the Arctic oscillation

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Received June 20, 2013; accepted August 6, 2013

The Northern-Hemisphere high-latitude continents experienced extremely cold weathers in winter 2009–2010. In the present paper, we show that the cold winter was associated with the activity of the Arctic oscillation (AO), which demonstrated the strongest negative polarity over the past six decades and persisted from December, 2009 to March, 2010. It is found that variations of the surface AO was closely linked to stratospheric polar vortex anomalies, and that the surface AO phases followed downward propagation of stratospheric Northern-Hemisphere Annular mode (NAM) anomalies during the winter. The case of 2009–2010 winter provides us with a typical example that anomalous stratospheric signals can be used to improve skills of long-range weather forecast and intra-seasonal climate prediction in winter time. We also show that the El Niño event, which started developing from May 2009, might contribute the formation of exceptionally negative and persistent AO and stratospheric NAM, particularly over North Pacific and North America.

Keywords Arctic oscillation, Northern-Hemisphere Annular mode (NAM), stratosphere, planetary waves, weather forecast

PACS numbers 92.60.Xg, 92.60.Uy

Frontiers of Physics

1 Introduction

The Arctic Oscillation (AO) or the North Atlantic Oscillation (NAO) is the leading mode of climate and circulation variability for Northern-Hemisphere (NH) middle and high latitudes [1, 2]. The see-saw pattern of AO reflects air mass shifts between NH mid-latitudes and the Arctic region. Because of its dominance, large variability, and persistence in winter, AO has significant influences on NH winter weather and climate. For example, Thompson and Wallace [3] showed that as the AO is in the negative phase, westerly winds are anomalously weak over middle and high latitudes along with strong wave activity, and there are frequent occurrences of blocking events and cold air outbreaks in NH middle and high latitudes, causing cold weathers over eastern North America and northern Eurasia continents. By contrast, for the positive phase of AO, prevailing westerly winds are anomalously strong, which blow warm ocean air to high-latitude continents and cold continent air to oceans. Meanwhile, wave activity associated with the positive AO is relatively weak, and cold polar-air intrusions are less frequent. As a result, high-latitude continents are warmer than usual, and oceans are colder. Therefore, AO offers an opportunity to improve long-range weather forecasting and intraseasonal climate prediction in boreal winter [4].

The surface AO has close relationship with the leading mode of atmospheric circulation variability at higher layers. The leading mode of variability at higher levels is the so-called Northern-Hemisphere Annular Mode (NAM) [1, 3]. Baldwin and Dunkerton [5, 6] found that signals of NAM variations first occur in the upper stratosphere and propagate downward to the tropopause over a period of about 2 to 3 weeks. Their composite results demonstrated that tropospheric NAM usually responds to stratospheric NAM with the same sign. The downward propagation of anomalous NAM from the stratosphere to the troposphere has two important implications [7, 8]: i) it is indicative of stratospheric influences on extratropical tropospheric weather systems and atmospheric circulations on intraseasonal time scales; ii) the leading time of stratospheric NAM anomalies and their long persistence can be used to extend weather forecasting to more than 2 weeks and to predict intraseasonal climate variability in the troposphere. For the first point, it has been well established that vertical propagation of planetary waves from the troposphere to the stratosphere is preconditioned by the stratospheric zonal flow [9–14]. That is, a strong stratospheric polar night jet tends to prohibit upward planetary-wave propagation and deflects planetary waves equatorward (easterly stratospheric winds such as that after stratospheric sudden warmings also prohibit planetary waves), while a weak polar night jet prefers upward and poleward propagation of planetary waves. Consequently, changes in planetary wave activity due to stratospheric flows leads to changes in tropospheric wave activity and zonal winds. For the second point, it is well known that the stratospheric circulation is dominated by low-frequency oscillations over time scales of several months [15–18]. As a result, the influences of stratospheric circulation anomalies on the troposphere would also persist over intraseasonal time scales. Thus, stratospheric NAM signals can be used as a predictor of tropospheric weather systems.

Although the above observational studies with composite analysis have demonstrated robust evidence that signals associated with AO or stratospheric NAM are potentially useful to extend prediction of tropospheric and surface weather systems and intraseasonal climate variabilities in winter time, it has not been proven sufficient in practice. Thus, it requires further studies to understand the relationship between winter weather, especially extremely cold events, and AO as well as stratospheric NAM. The purpose of the present study is to provide a comprehensive case study of how AO and NAM signals can be used to predict the extremely cold 2009–2010 winter.

The 2009–2010 winter marks one of the coldest winters in NH high-latitude continents in the past six decades. Previous works on the extremely cold winter have studied how synoptic processes cause cold polar-air outbreaks and how it influence high-latitude Eurasian continents [19, 20]. It was also shown that the cold surface weathers are likely related to downward propagation of stratospheric circulation anomalies [21]. Different from these previous works, the present study shall focus on how the extremely cold winter was related to surface AO activity and stratospheric NAM anomalies and whether stratospheric NAM signals can be used as a precursor for predicting severe cold periods over intraseasonal time scales. In addition, we will also show the influence of the El Niño event occurring in winter 2009–2010 on the cold weather over NH high-latitude continents.

The paper is organized as follows. Data and methods are described in Section 2. In Section 3, we analyze the evolution processes of the cold 2009–2010 winter and its relation to the surface AO, stratospheric NAM and three-dimensional wave activity. We will also analyze the contribution of the 2009–2010 El Niño event to NH atmospheric circulations, waves, and the cold winter. Discussion and conclusions are summarized in Section 5.

2 Data and method

The data used in this paper is the daily reanalysis from the National Center for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) [22, 23]. The surface AO is calculated from sea level pressure (SLP) [1], and NAM is calculated from geopotential heights at the standard pressure levels, using the same method as in Baldwin and Dunkerton [5, 6]. Three-dimensional wave fluxes are calculated using the formula in Plumb [24]. The climatological mean is 30-year average over 1979–2008.

3 Results

3.1 Surface air temperatures and AO

Figure 1(a) demonstrates seasonal-mean surface air temperature (SAT) departures (anomalies) from the climatological mean, averaged over December–January–February (DJF). The northern Eurasia continent (roughly in the north of 35°N) is dominated by a band of negative SAT anomalies. The maximum value of −5°C is centered at Siberia. North American is also dominated by negative SAT anomalies, except for the west coast and Alaska. In contrast, the polar region displays positive SAT anomalies, warmer than usual. The maximum positive SAT anomaly is centered at Greenland and northeastern Canada. Meanwhile, lower latitude continents, such as North Africa, Middle East, as well as central and southern China experienced a warm winter. The spatial patterns of SAT anomalies indicate that as cold polar air was transported out of the polar region, the polar region became warmer, while high-latitude continents became colder than usual during winter 2009–2010. However, it appears that cold air outbreaks did not influence lower latitudes (south of 35°N).

Figure 1(b) shows the spatial distribution of SLP anomalies, averaged over DJF of 2009–2010. It displays a robust spatial pattern that resembles the negative phase of AO. A band of negative SLP anomalies is over NH middle latitudes approximately between about 30°N and 55°N. There are two centers. One is located over North Atlantic, and the other is located in northeastern Pacific. In contrast, the polar region demonstrates positive SLP anomalies. This is the typical see-saw pattern of AO, indicating anomalously high air mass over the polar region and low air mass over middle latitudes. Figure 1(c) shows time series of seasonal mean (DJF) AO indices over the past 60 years. It is obvious that the AO index of winter 2009–2010 has the largest negative value over the past 60 years. The above results suggest that the exceptionally cold winter 2009–2010 over NH high-latitude continents is associated with the anomalously negative phase of AO.

AO does not always stay in the negative phase during winter time, but varied between positive and negative phases with a wide spectrum of periods. Figure 2 shows time series of daily AO indices between October 1, 2009 (10/01/2009), and March 31, 2010 (03/31/2010). In October, AO indices are relatively weak, and AO has twice phase changes over time scales of about one week, which is the typical time scale of tropospheric weather processes. Over the period from November to

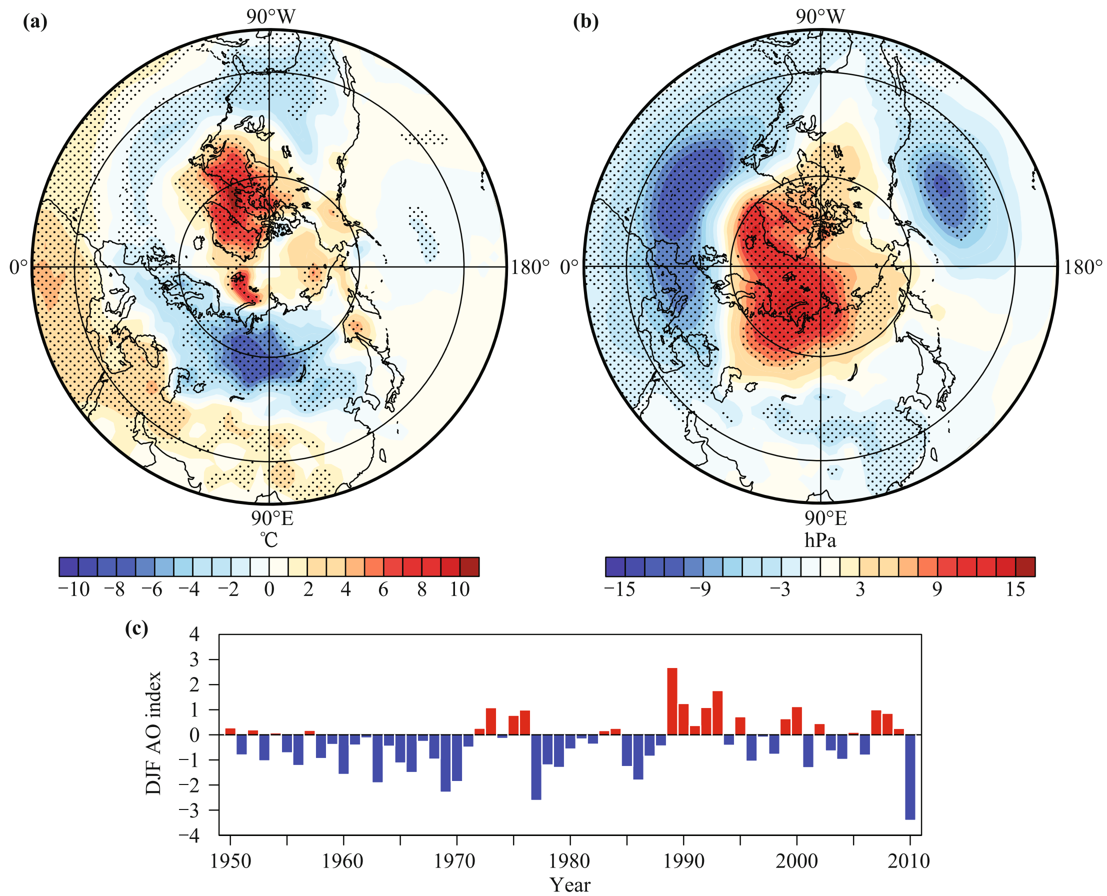

Fig. 1 2009–2010 DJF mean SAT **(a)** and SLP **(b)**. Anomalies greater than one standard deviation are dotted. **(c)** Time series of DJF averaged AO indices over 1950–2010.

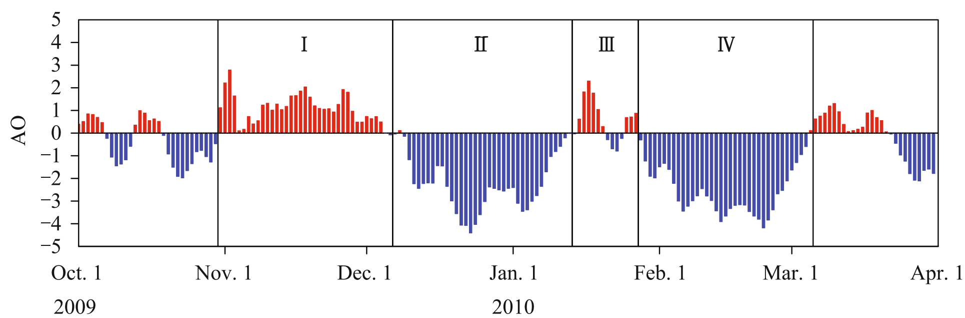

Fig. 2 Time series of daily AO indices from October 1, 2009, to March 31, 2010. The four periods are marked with vertical lines.

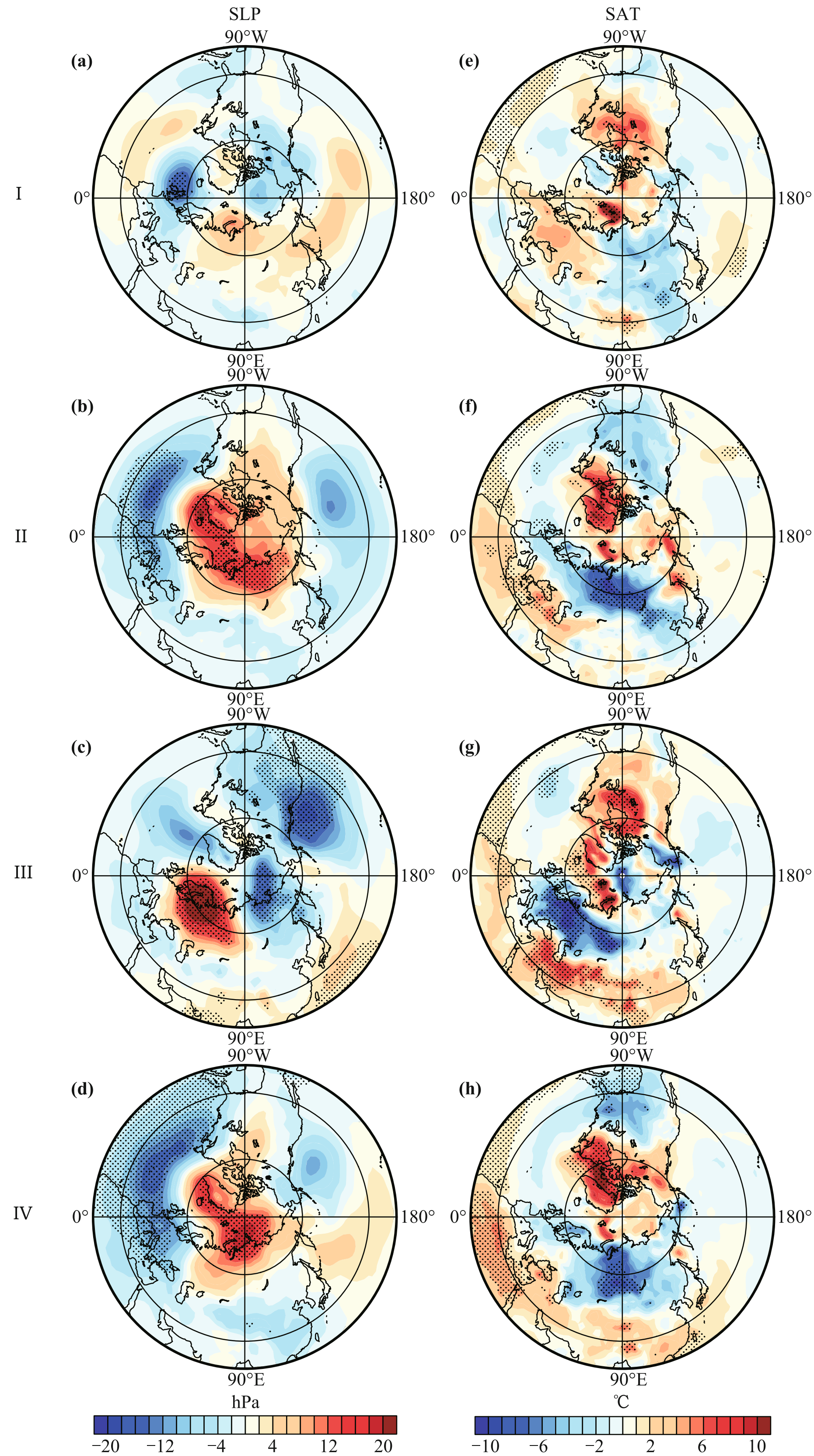

Fig. 3 Spatial patterns of SLP and SAT anomalies for the four periods according to surface AO phases shown in Fig. 2. Anomalies greater than one standard deviation are dotted. Left column: SLP, and right column: SAT.

March, AO experienced four times of phase changes. The corresponding four periods are: 10/31/2009–12/08/2009 (positive), 12/09/2009–01/13/2010 (negative), 01/14/2010–01/27/2010 (positive), 01/28/2010–03/10/2010 (negative). Hereafter, the four periods are denoted by period I, II, III, and IV, respectively. Except for period III, AO persisted over time scales of about one and half months. For the two periods of positive phases, AO indices are weak, barely greater than 2.0, and the two periods are relatively short. In contrast, negative AO indices are all large, generally greater than 2.0 (with monthly mean SLP of −15 hPa over north of 60°N), with the largest value greater than 4.0.

SLP anomalies corresponding to the four periods are demonstrated in Figs. 3(a)–(d). For period I, SLP anomalies are relatively weak, except for that over North Atlantic. For period II, SLP anomalies are strong, especially over North Atlantic and the polar region where SLP anomalies are greater than one standard derivation. The spatial pattern resembles that of the negative AO phase very well, indicating that AO is the dominant mode of SLP variability during this period. For period III, the spatial pattern of SLP anomalies is very different from that of the AO although AO indices are positive. It indicates that AO is not the dominant mode over this period. Indeed, AO indices are relatively weak in Fig. 2. For period IV, the spatial pattern of SLP anomalies over North Atlantic is very like that of the North Atlantic sector of AO, whereas negative SLP anomalies over North Pacific are biased toward eastern Pacific, different from the spatial pattern of the Pacific sector of AO.

SAT anomalies corresponding to the four periods are shown in Figs. 3(e)–(h). For periods II and IV, SAT anomalies demonstrate similar spatial patterns. Negative SAT anomalies were over high-latitude Eurasia continent and North America, and positive temperature anomalies were over the polar region, especially over Greenland and northeastern Canada. For periods I and III, SAT anomalies both show positive values over North America. However, SAT anomalies show differences over the high-latitude Eurasia continent. In period I, Europe is warmer than usual, while Asia is colder. In period III, however, Europe is cold (even colder than in period II), while Asia is slightly warmer than usual. This is probably because the positive AO phase in period III is relatively weak and lasted over only a relatively short period, and the positive AO is not dominant. Thus, the high-latitude Eurasia continent remains cold. Overall, the extremely cold 2009–2010 winter for NH high-latitude continents was closely associated with the two persistent negative AO phases (periods II and IV).

3.2 Stratospheric precursor and troposphere–stratosphere coupling

The above results demonstrate how the cold 2009–2010 winter is related to the surface AO activity. In this subsection, we study how the surface AO is related to the stratospheric NAM and whether stratospheric NAM variations can be used as a leading signal for extending prediction of the cold winter. Figure 4a shows the height-time cross section of NAM indices at standard pressure levels. Although stratospheric NAM indices have moderate values in all the four periods compared with climatological values, stratospheric NAM signals all propagated downward and reach the surface. Daily variations of stratospheric NAM from 10/01/2009 to 03/31/2010 can also be divided into 4 periods according to NAM phases at 10 hPa. The four periods are also denoted by I, II, III, and IV respectively. But note that these dates are different from that of the surface AO. Time intervals of the four periods are listed in Table 1. For period I, the weak positive NAM phase started before October 1 and reached the surface by October 30. The leading time of NAM at 10 hPa to the surface AO is more than one month. For period II, the negative NAM phase started on October 31 and reached the surface on December 5. The leading time is 33 days. For period III, the stratospheric NAM led the surface AO by 27 days (December 17 vs. January 12). The leading time of period I, II, and III are all nearly one month. For period IV, the stratospheric NAM led the surface AO only by 6 days, much shorter than the previous three periods. The leading time suggests that stratospheric NAM signals, especially for the first three periods, can be used as the precursor for predicting tropospheric and surface weather systems, as proposed before.

In addition, it appears that the tropospheric NAM or surface AO persists over nearly same time scales as that of the stratospheric NAM. Thus, the duration of the stratospheric NAM can also be used for predicting surface weather systems. For example, as negative stratospheric NAM propagates downward to the surface, there will be more frequent storms or cold air outbreaks over a period that has similar time scales to that of the negative stratospheric NAM. Figure 4(b) shows height-time cross-section of zonal-mean zonal wind anomalies at 60°N. Similar to that of NAM signals, negative zonal wind anomalies in period II and IV all demonstrate downward propagation. However, positive zonal-wind anomalies in period III only stay in the stratosphere, while negative anomalies dominate in the troposphere.

Table 1 The starting date of the four periods of NAM phases in winter 2009–2010.

	Period I	Period II	Period III	Period IV
Stratosphere (10 hPa)	N/A	Nov. 3, 2009	Dec. 17, 2009	Jan. 22, 2010
Surface (1000 hPa)	Oct. 31, 2009	Dec. 6, 2009	Jan. 13, 2010	Jan. 28, 2010
Leading time	N/A	33 days	27 days	6 days

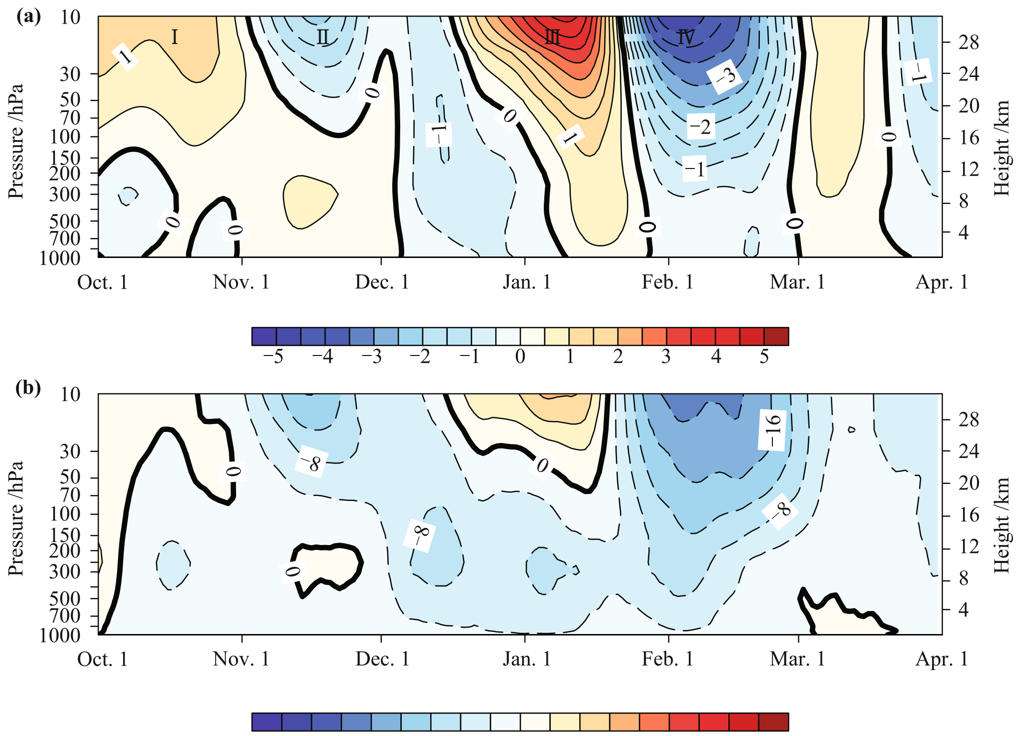

Fig. 4 Height-time cross-sections of NAM **(a)** and U wind anomalies at 60°N **(b)**. A 15-day low-pass filter is applied to remove high-frequency variations.

In the above, we have shown how tropospheric the NAM and surface AO follow the stratospheric NAM in winter 2009–2010. To understand how the stratospheric Arctic polar vortex evolved in the wintertime and how it coupled with tropospheric circulations and waves, we first show geopotential heights and temperatures at 20 hPa in periods II, III, and IV in Fig. 5. Figures 5(a) and (b) show 20 hPa geopotential heights and temperatures on Dec. 12, 2009, respectively. The geopotential height field demonstrates a nearly split polar vortex, with two lows located over northern Canada and northern Europe, respectively. It is a typical wavenumber-2 warming pattern. In contrast, the temperature field only shows an elongated or weakened vortex. These indicate that the stratospheric Arctic experienced a minor sudden warming, rather than a major warming. The weakened polar vortex corresponded to the negative NAM phase in period II. As noticed by Wang and Chen [21], the negative NAM in phase II is moderate. Figures 5(c) and (d) show temperatures and geopotential heights on Jan. 9, 2010, respectively. One can find that the polar vortex had recovered from the minor warming due to radiative cooling, and a nearly circular vortex was almost right over the polar cap. Figures 5(e) and (f) demonstrate temperatures and geopotential heights on February 20, 2010. They demonstrate the typical patterns of a major stratospheric warming. The polar vortex was completely splitted, and the polar region was dominated by relatively high temperatures and geopotential heights. It was this major warming event that led to the strong negative stratospheric NAM in period IV. Kodera and Kuroda [25] have argued that strong dynamical coupling between the stratosphere and the troposphere usually happens in late winter. It appears that the extremely negative NAM in both the stratosphere and troposphere in period IV is consistent with the argument.

To show detailed time evolution of the Arctic polar vortex in winter 2009–2010, we plot time series of area-weighted mean polar temperature, subpolar zonal-mean zonal winds at 20 hPa, and eddy-heat fluxes at 150 hPa in Fig. 6. From late October to February, the polar temperature experienced three stages [Fig. 6(a)]. It is warmer

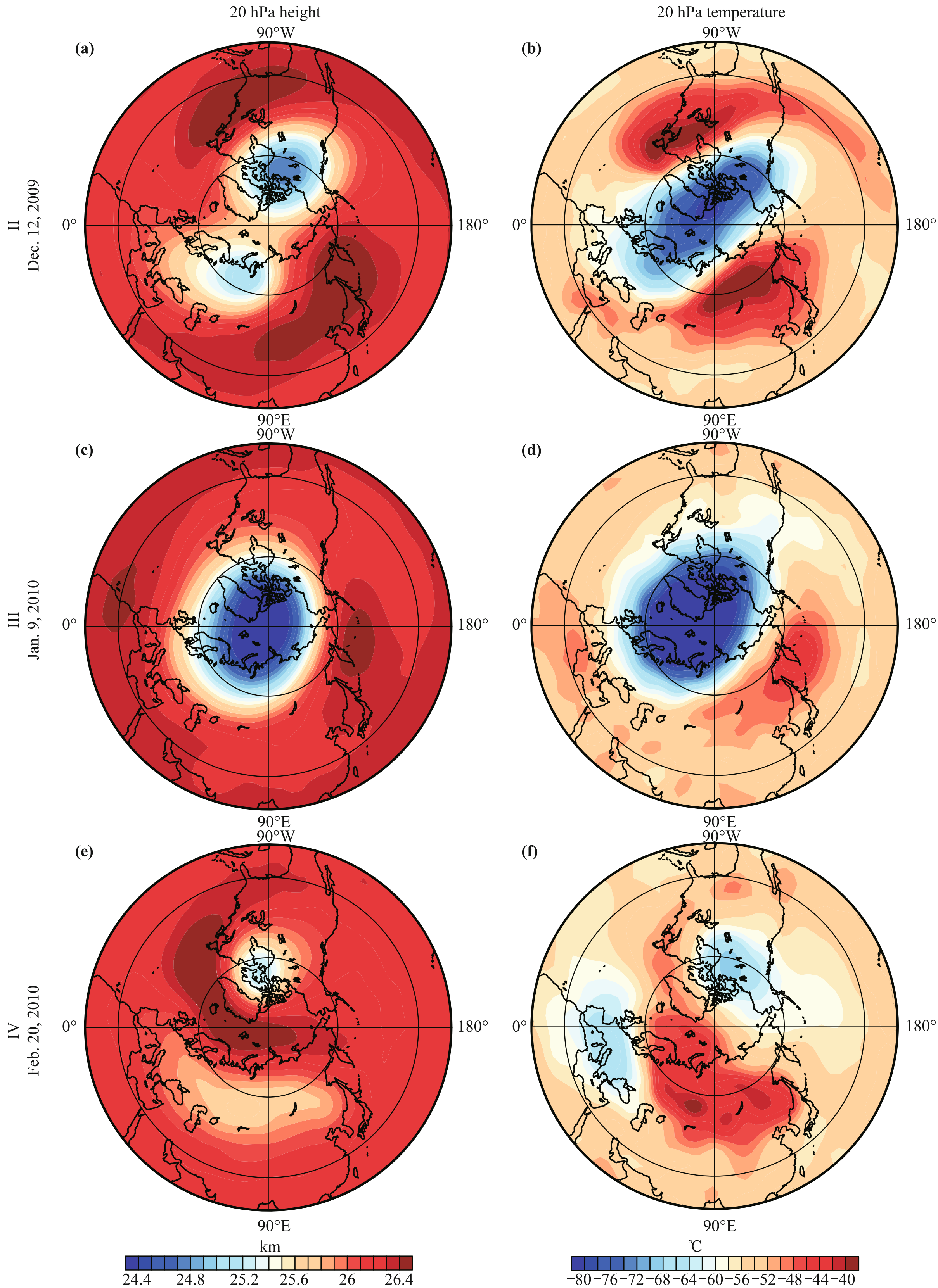

Fig. 5 Snapshots of 20 hPa geopotential heights and air temperatures for periods II **(a, b)**, III **(c, d)**, and IV **(e, f)**.

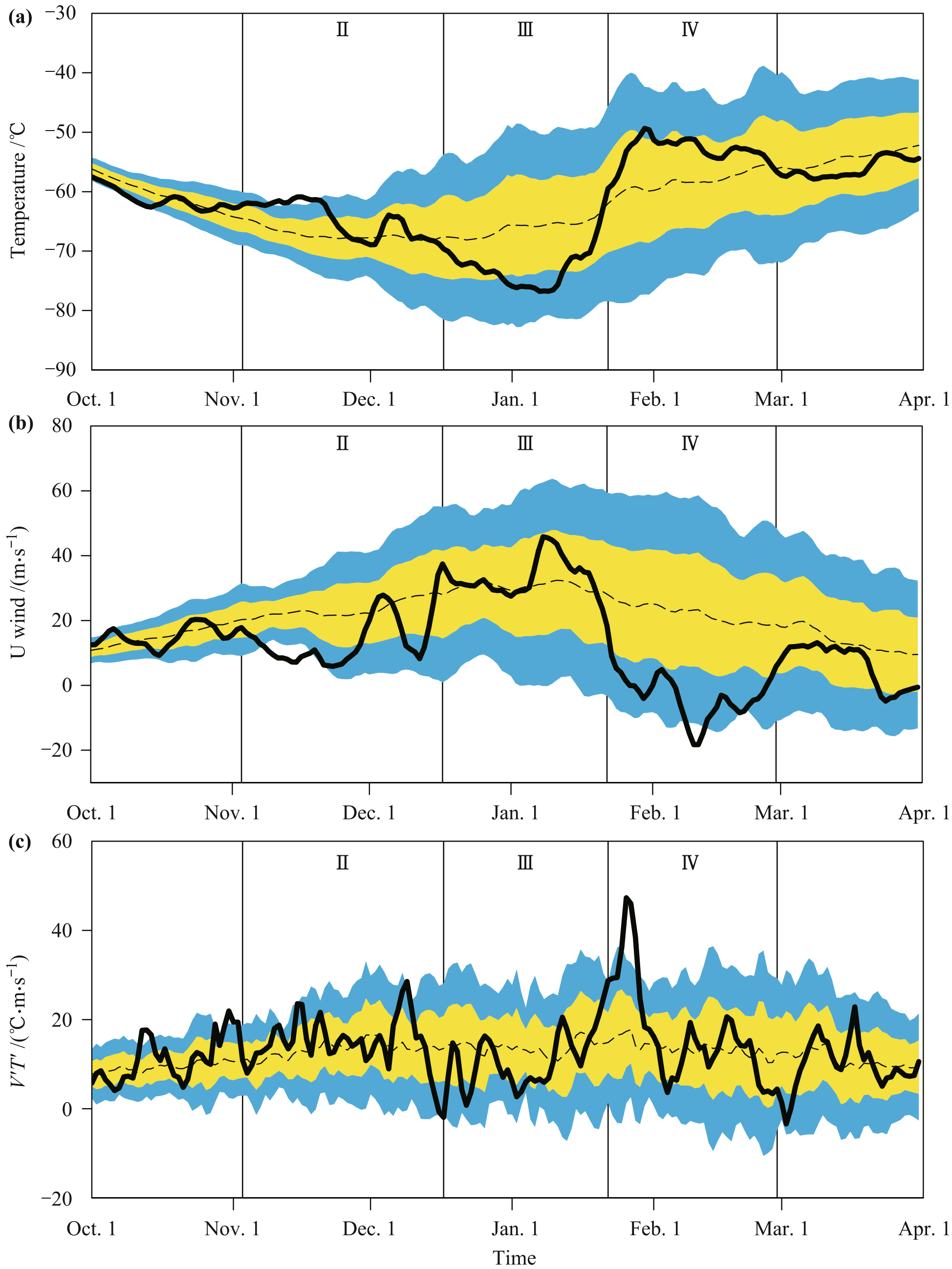

Fig. 6 Time series of 20 hPa area-weighted polar air temperatures (65°N–90°N) **(a)**, 20 hPa zonal-mean zonal wind at 65°N **(b)**, and 150 hPa eddy-heat fluxes summed between 65°N and 90°N **(c)**. Dashed lines denote the climatological mean over 1979–2008. One and two standard deviations are shaded by yellow and blue colors, respectively.

than the climatological mean from late October to early December. This period corresponds to the minor warming event in period II. It became colder than usual between 12/10/2009 and 01/22/2010, indicating recovery of the polar vortex. Then, the polar temperature became warm again, corresponding to the major warming event.

The strength of the polar vortex or the polar night jet is usually characterized by subpolar zonal-mean zonal winds. Figure 6(b) shows zonal-mean zonal winds at 65°N. It is also obvious that subpolar zonal winds experienced three stages. In periods II and IV, subpolar zonal winds are generally weaker than the climatological mean. In particular, zonal winds were beyond one standard deviation between January 20 and the end of February and were even beyond two standard deviations around February 10. The largely decelerated polar night jet was due to the major stratospheric sudden warming. Overall, the polar vortex or polar night jet in winter 2009–2010 was generally weaker than the climatology. The weaker polar night jet would benefit upward propagation of planetary waves into the polar stratosphere.

Figure 6(c) shows time series of eddy-heat fluxes at 150 hPa. Eddy heat fluxes at 150 hPa are usually used to quantify the amount of wave activity from the troposphere to the stratosphere [12, 26]. One can find that wave activity in winter 2009–2010 is generally stronger than the climatological mean, except for period III when wave activity was weaker than usual. This is consistent with the anomalously weak polar night jet. There was an anomalously strong event of wave disturbance at the beginning of period IV (end of January), indicating strong wave activity from the troposphere into the stratosphere. It was this strong wave disturbance that caused the major sudden warming in the stratospheric Arctic, the large deceleration of the polar night jet, and the negative stratospheric NAM. These reveal the strong coupling between the troposphere and stratosphere.

Dynamical coupling between the troposphere and stratosphere is mainly through upward propagation of planetary waves. Here, we show planetary wave activity and its upward propagation using the formulation of three-dimensional EP fluxes by Plumb [24], instead of using the conventional two-dimensional EP fluxes. It is because three-dimensional EP fluxes give a better view of upward propagation of planetary waves from the troposphere to the stratosphere and interaction between planetary waves and stratospheric flows. Note that the formulation of three-dimensional EP fluxes is for stationary wave activity, unlike two-dimensional EP fluxes that include both stationary and transient wave activity. We calculate three-dimensional EP fluxes over three periods. Temperatures and wind speeds are averaged over the three periods in calculating three-dimensional EP fluxes for stationary waves. According to Fig. 6(c), the strengthening stages for three periods are 11/03/2009–11/16/2009, 12/17/2009–01/07/2010, and 01/22/2010–02/02/2010, which starts from their onset day to the day with maximum NAM indices.

Figure 7 shows three-dimensional EP fluxes at 50 hPa during the strengthening stage of each period (left column). Climatological mean EP fluxes over the three stratospheric periods are also plotted for comparison (right column). For climatology, all the three plots show that stratospheric strong wave activity mainly occures on high latitudes. Upward wave propagation centers over the Far East, while wave activity is relatively weak over North Atlantic, which shows downward propagation (blue color). Compared with the climatological mean, wave activity displays similar spatial patterns in all the three periods. However, wave activity in periods II and IV is stronger, but weaker in period III. Especially, wave activity in period IV is much stronger than the climatological mean over northern Asia, and wave activity over North American is also anomalously strong, showing a wavenumber-2 pattern. Changes in stratospheric wave activity are consistent with that of polar vortex changes shown in Figs. 5 and 6.

Figure 8 shows vertical cross-sections of three-dimensional EP fluxes. Let us first look at EP fluxes in the height-longitude cross-section along the 65°N latitude circle (left column). In period II [Fig. 8(a)], strong upward stratospheric wave activity is located between 40°E and 180°E in longitude, while wave activity between 180°E and 40°E is relatively weak. In period III [Fig. 8(c)], stratospheric wave activity became weaker compared with that in Fig. 8(a). This is because polar vortex was recovered and the strong polar night jet tends to prohibit upward wave propagation. Indeed, downward wave propagation is even found in the troposphere between 40°E and 100°E as well as between 320° (40°W) and 360° (0°) in longitude. By period IV [Fig. 8(e)], wave activity became strong again. Two maxima of wave activity are found. One is located between 0°E and 100°E in longitude, and the other one is located at about 3005°E (60°W). This is consistent with the wavenumber-2 sudden warming in Figs. 5(e) and (f). Figures 8(b), (d), and (f) show height-latitude cross-sections of EP fluxes along 150°E in longitude. Stratospheric EP fluxes in Figs. 8(b) and (f) were stronger than that in Fig. 8(d). In period II and IV, stratospheric wave activity is much stronger than that in period III. Especially, wave fluxes are poleward in period IV. It was the strong upward propagating waves that caused the minor warming in December and major warming in February. By contrast, tropospheric wave fluxes are equatorward in period III [Fig. 8(d)], indicating equatorward deflection by strong stratospheric zonal winds.

3.3 The role of El Niño

We have seen in Figure 6c that vertical wave fluxes near the tropopause in late January was exceeded two standard deviations. An important question is what caused the anomalously strong wave activity. Recent studies suggested that El Niño might has significant influences on middle and high latitude planetary wave activity and thus on stratospheric polar vortex variability [27–30]. These works showed that El Niño events force anomalously strong planetary wave activity at middle and high latitudes through the Pacific North America (PNA) teleconnection, and that such waves could cause weakened stratospheric Arctic vortex or stratospheric sudden warming. In the second half of year 2009, a moderate El Niño gradually developed in the tropical Pacific. Figure 9

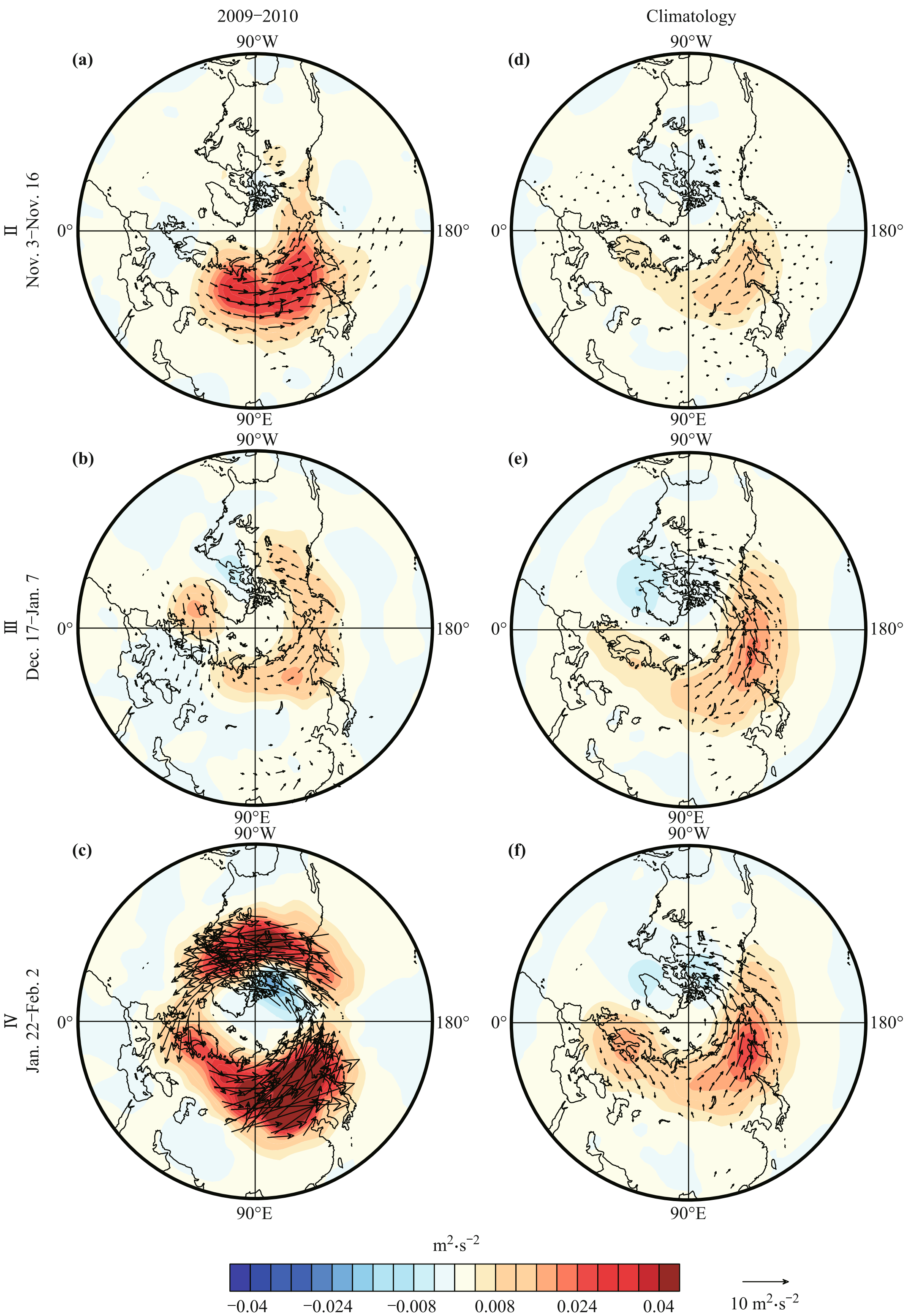

Fig. 7 Three-dimensional EP fluxes at 50 hPa during the strengthening stages in periods II, III, and IV (left column). For comparison, climatological means over the same periods are plotted in the right column. The color shading indicates the vertical component of EP fluxes, and arrows indicate horizontal EP flux vectors. The length scale of horizontal EP flux vectors is marked in the plots. Horizontal EP flux vectors with length scales less than half of the average are not plotted for clearness.

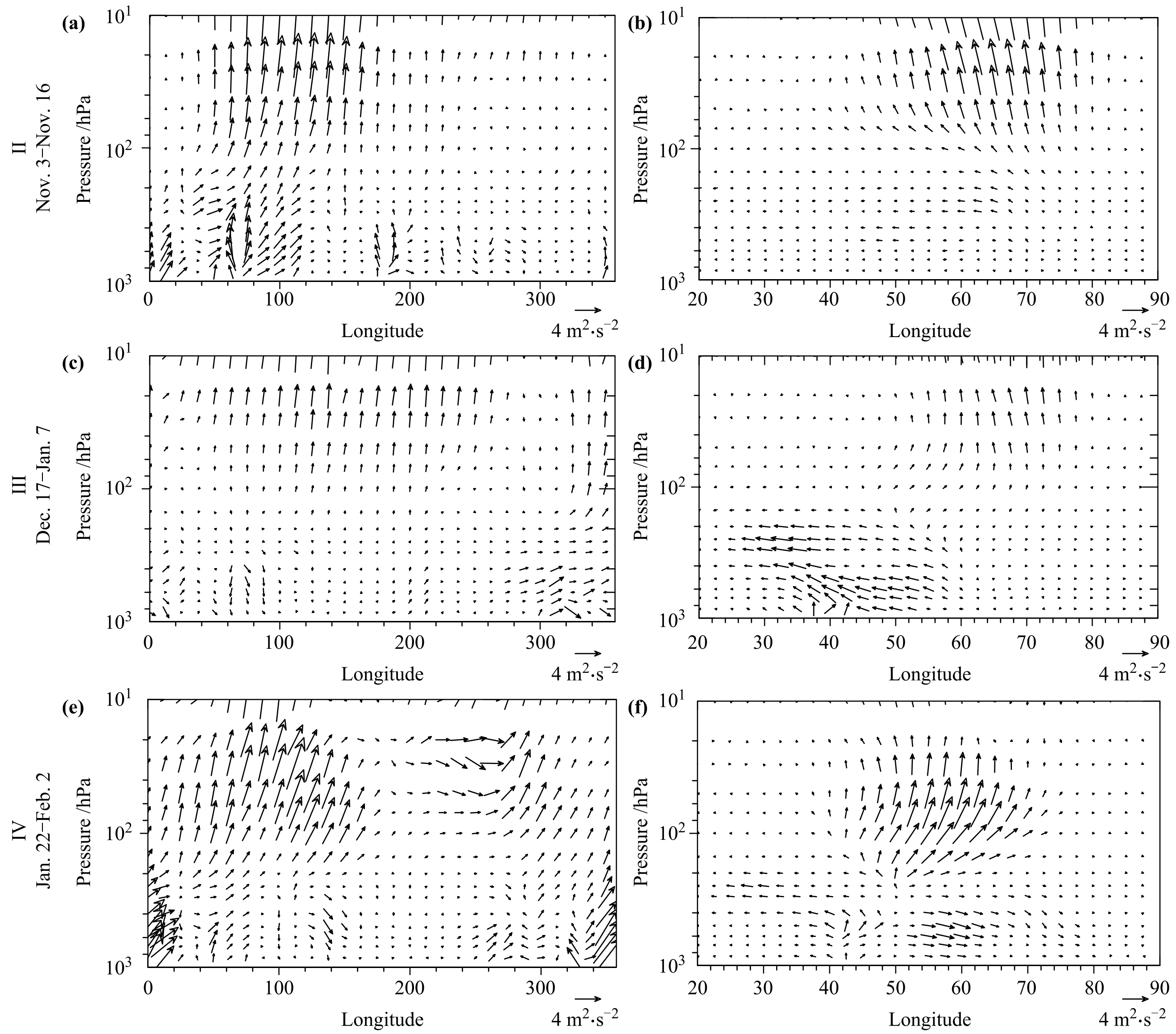

Fig. 8 Vertical cross-sections of EP flux vectors along with 65°N (left column) and 110°E (right column) during the strengthening stages of periods II, III, and IV. The horizontal component is divided by 100, and the vertical component was multiplied by a factor of 10. All components are divided by background air density at each level.

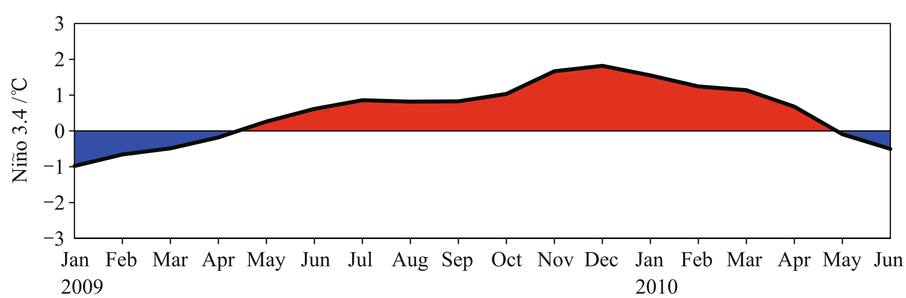

Fig. 9 Time series of monthly mean Niño 3.4 index.

shows time series of sea surface temperature (SST) averaged over the Niño 3.4 region. The El Niño event peaks in December. Thus, it was very likely that the minor warming in December, 2009, and the major warming in February, 2010, were associated with the El Niño event [21].

To demonstrate whether the anomalously strong planetary wave activity in winter 2009–2010 was influenced by El Niño event, we plot the three-dimensional EP fluxes at 500 hPa and vertical cross-sections along 150°W (close to the PNA path) in December, 2009, in Fig. 10. It is shown that horizontal EP flux vectors in northeastern Pacific point from the tropics toward northeast [Fig. 10(a)]. It sharply contrasts with the climatology mean [Fig. 10(b)], which shows relatively weak wave activity and southeastward wave fluxes. The vertical cross-section of EP flux vectors shows wave propagation from the subtropics to high latitudes [Fig. 10(c)]. These all suggest that the El Niño event likely played an important role in causing anomalously strong wave activity in NH middle and high latitudes and thus the minor and major warming events in the stratospheric Arctic as well as negative stratospheric NAM. Therefore, the El Niño event was one of the possible reasons that contributed to the persistent negative AO/NAM phase and such an extremely cold winter.

4 Discussion and conclusions

The 2009–2010 winter is one of the extremely cold winters for most parts of NH middle- and high-latitude continents in the past few decades. The seasonal-mean maximum SAT anomaly is −5°C, centered at Siberia. It is found that the extremely cold winter was associated with two long periods of negative AO phases (12/06/2009–01/12/2010 and 01/28/2010–03/04/2010). The AO in winter 2009–2010 is characterized by two remarkable features. One is that the DJF mean AO index has the largest negative value for the past 60 years, and another is its persistence of negative AO phases, while two positive phases are rather weak and short. As pointed out in previous studies [3, 4, 20, 31], negative AO leads to frequent occurrences of cold air outbreaks. Thus, it was the anomalously strong negative AO that caused the extremely cold winter. Meanwhile, the Arctic polar region, especially the area over Greenland and northeastern Canada, was anomalously warm as cold polar air was transported out.

Surface AO variations in winter 2009–2010 were closely coupled with NAM changes at higher levels. From October to March, the stratospheric NAM experienced two negative and two positive phases. The four phases of stratospheric NAM all propagated downward into the troposphere and reached the surface, and the leading time ranged from about one week to more than one month. The case of winter 2009–2010 is a typical example that stratospheric NAM signals can be used as a precursor to predict surface weather and intraseasonal climate.

The dynamic coupling of the stratospheric and tropospheric NAM is throughout upward propagation of

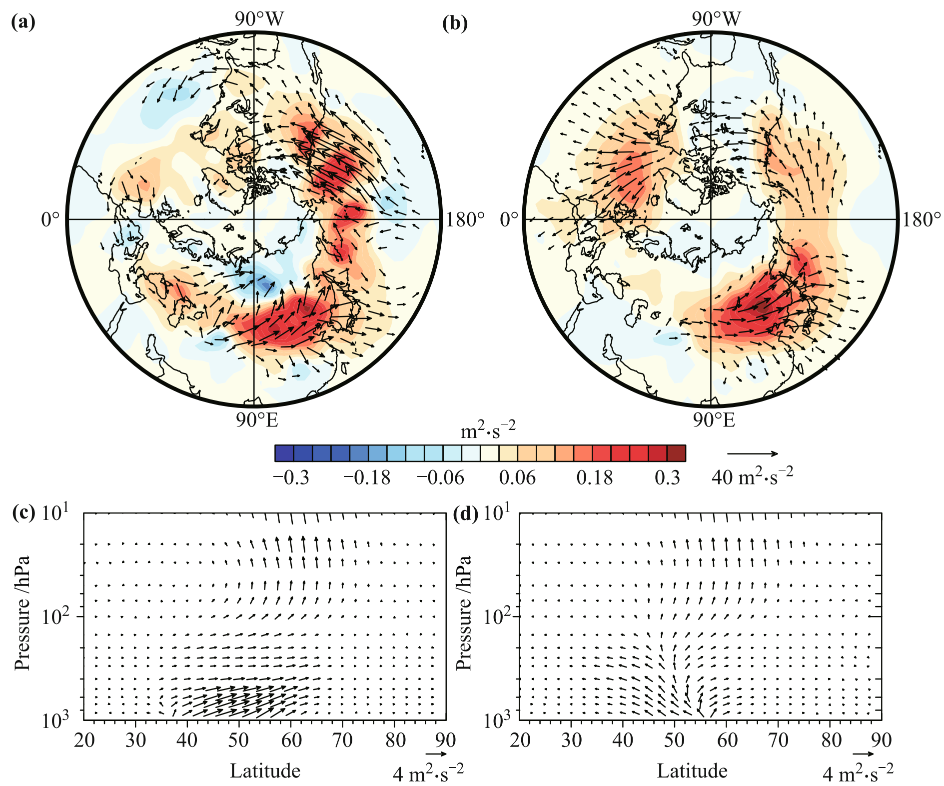

Fig. 10 Three-dimensional EP fluxes at 500 hPa for December, 2009 **(a)** and climatology **(b)**. Vertical cross-sections along 150°W are shown in **(c)** and **(d)**.

planetary waves. EP fluxes in Figs. 6(c) and 7 all show that stratospheric NAM phase changes followed variations in tropospheric wave activity. On the other hand, Fig. 6(b) demonstrates that the stratospheric polar night jet in winter 2009–2010 was generally weaker compared with the climatological mean, which benefits vertical development or upward propagation of planetary waves. In other words, the relatively weak polar night jet set preconditions for anomalously strong planetary wave activity, which propagated into the stratosphere and caused the minor and major warming events. As stratospheric NAM anomalies developed and propagated downward, the tropospheric NAM responded with the same sign.

We have demonstrated evidence that the El Niño event in the second half of 2009 might contribute to the anomalously strong wave activity, negative stratospheric and tropospheric NAM, and the extremely cold weather. The anomalously strong wave activity propagated poleward and upward over northeastern Pacific. The waves caused not only meridional air motion in the troposphere but also decelerated polar night jet in the stratosphere. Both benefited the development and persistence of negative AO/NAM phases and thus cold air transport from the polar region to middle and high latitude continents.

Acknowledgements X. Wen and Y. Hu were supported by the National Basic Research Program of China (Grant No. 2010CB428606) and the National Natural Science Foundation of China (Grant Nos. 41025018, 41130962, and 41005035). J. Liu was supported by NSF Polar Programs (Grant No. 0838920). We thank Dr. Lingling Suo for helpful discussions on three-dimensional E-P fluxes.

References

1. D. W. J. Thompson and J. M. Wallace, The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett.*, 1998, 25(9): 1297
2. D. W. J. Thompson and J. M. Wallace, Annular modes in the extratropical circulation (Part I): Month-to-month variability, *J. Clim.*, 2000, 13(5): 1000
3. D. W. J. Thompson and J. M. Wallace, Regional climate impacts of the Northern Hemisphere annular mode, *Science*, 2001, 293(5527): 85
4. J. M. Wallace and D. W. J. Thompson, Annular modes and climate prediction, *Phys. Today*, 2002, 55(2): 28
5. M. P. Baldwin and T. J. Dunkerton, Propagation of the Arctic Oscillation from the stratosphere to the troposphere, *J. Geophys. Res.*, 1999, 104(D24): 30937
6. M. P. Baldwin and T. J. Dunkerton, Stratospheric harbingers of anomalous weather regimes, *Science*, 2001, 294(5542): 581
7. D. W. J. Thompson, M. P. Baldwin, and J. M. Wallace, Stratospheric connection to Northern Hemisphere wintertime weather: Implications for prediction, *J. Clim.*, 2002, 15(12): 1421
8. M. P. Baldwin, D. B. Stephenson, D. W. J. Thompson, T. J. Dunkerton, A. J. Charlton, and A. O'Neill, Stratospheric memory and skill of extended-range weather forecasts, *Science*, 2003, 301(5633): 636
9. J. G. Charney and P. G. Drazin, Propagation of planetary scale disturbances from the lower to the upper atmosphere, *J. Atmos. Sci.*, 1961, 18: 83
10. R. E. Dickinson, Planetary Rossby waves propagating vertically through weak westerly wind wave guides, *J. Atmos. Sci.*, 1968, 25(6): 984
11. P. Chen and W. A. Robinson, Propagation of planetary waves between the troposphere and stratosphere, *J. Atmos. Sci.*, 1992, 49(24): 2533
12. Y. Hu and K. K. Tung, Interannual and decadal variations of planetary wave activity, stratospheric cooling, and Northern Hemisphere annular mode, *J. Clim.*, 2002, 15(13): 1659
13. D. J. Lorenz and D. L. Hartmann, Eddy–zonal flow feedback in the Northern Hemisphere winter, *J. Clim.*, 2003, 16(8): 1212
14. Y. Hu, K. K. Tung, and J. Liu, A closer comparison of early and late winter atmospheric trends in the Northern-Hemisphere, *J. Clim.*, 2005, 18(16): 2924
15. J. R. Holton and C. Mass, Stratospheric vacillation cycles, *J. Atmos. Sci.*, 1976, 33(11): 2218
16. D. G. Andrews, J. R. Holton, and C. B. Leovy, Middle Atmospheric Dynamics, Academic Press, 1987
17. K. Kodera, K. Kuroda, and S. Pawson, Stratospheric sudden warmings and slowly propagating zonal-mean zonal wind anomalies, *J. Geophys. Res.*, 2000, 105(D10): 12351
18. K. Kuroda, Relationship between the polar-night oscillation and the annular mode, *Geophys. Res. Lett.*, 2002, 29(8): 1240
19. E. W. Kolstad, T. Breiteig, and A. A. Scaife, The association between stratospheric weak polar vortex events and cold air outbreaks in the Northern Hemisphere, *Q. J. R. Meteorol. Soc.*, 2010, 136(649): 886
20. T. W. Park, C. H. Ho, and S. Yang, Relationship between the Arctic Oscillation and cold surges over east Asia, *J. Clim.*, 2010, 24(1): 68
21. L. Wang and W. Chen, Downward Arctic Oscillation signal associated with moderate weak stratospheric polar vortex and the cold December 2009, *Geophys. Res. Lett.*, 2010, 37: L09707
22. E. Kalnay, M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, R. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, R. Jenne, and D. Joseph, The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, 1996, 77(3): 437

23. R. Kistler, E. Kalnay, W. Collins, et al., The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, 2001, 82(2): 247

24. R. A. Plumb, On the three-dimensional propagation of stationary waves, *J. Atmos. Sci.*, 1985, 42(3): 217

25. K. Kodera and H. Kuroda, Tropospheric and stratospheric aspects of the Arctic Oscillation, *Geophys. Res. Lett.*, 2000, 27(20): 3349

26. Y. Hu and K. K. Tung, Possible ozone induced long-term change in planetary wave activity in late winter, *J. Clim.*, 2003, 16(18): 3027

27. W. Chen, M. Takahashi, and H.F. Graf, Interannual variations of stationary planetary wave activity in the northern winter troposphere and stratosphere and their relations to NAM and SST, *J. Geophys. Res.*, 2003, 108(D24): 4797

28. F. Sassi, D. Kinnison, B. A. Bolville, R. R. Garcia, and R. Roble, Effect of El Niño – Southern Oscillation on the dynamical, thermal, and chemical structure of the middle atmosphere, *J. Geophys. Res.*, 2004, 109(D17): D17108

29. C. I. Garfinkel and D. L. Hartmann, Different ENSO teleconnections and their effects on the stratospheric polar vortex, *J. Geophys. Res.*, 2008, 113(D18): D18114

30. X. Q. Lan, W. Chen, and L. Wang, Quasi-stationary planetary wave-mean flow interactions in the Northern Hemisphere stratosphere and their responses to ENSO events, *Sci. China Earth Sci.*, 2011, 55(3): 405

31. M. Wen, S. Yang, A. Kumar, and P. Zhang, An analysis of the large-scale climate anomalies associated with the snowstorms affecting China in January 2008, *Mon. Weather Rev.*, 2009, 137(3): 1111