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ORIGINAL PAPER

A regional extreme low temperature event and its main atmospheric contributing factors

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Abstract The regional extreme low temperature event from December 30, 2010 to February 2, 2011 was a very rare and protracted cold event with the largest integrated index (Z) since 1979. Two meteorological factors could be responsible for this extreme winter event. First, a persistent blocking pattern existed in the mid-latitudes. This not only allowed cold air to persist in southern China but also enabled each perturbation from the west propagating around the blocking high to trigger downstream cold air intrusions from the north. Second, the consistently downward negative Arctic Oscillation (AO) was favorable for the eastward moving of Rossby waves in middle latitudes, which made the upper reaches positive center in SLP and negative center in Z500 move to East Asia. This stable and consistent situation favored the polar area cold air invasion to the mid-latitude region. Of these two factors, the blocking pattern was likely to be the direct cause, the co-effects of consistently strong downward negative AO from the stratosphere, and the corresponding eastward moving wave train in Z500 and SLP might be the prophase teleconnection culprit.

1 Introduction

During the past few winters, North America, Europe, and East Asia have experienced anomalously cold conditions. A series of snowstorms hit East Asia, and the regional extreme low temperature events (RELTEs) frequently occurred in China. One of the most impressive RELTEs in recent years was the regional low temperature and freezing rain event in early 2008, which caused interruption of communication, great loss of crops, hundreds of related deaths, and an economic loss of >100 billion Yuan (Gu et al. 2008; Ding et al. 2008; Bueh et al. 2011; Qian and Fu 2009). Moreover, the RELTEs over most parts of China in winters of 2010/2011, 2011/2012, and 2012/2013, characterized by persistence, coverage, and intensity, deserve more attention. However, the causes of the recent severe winters are unclear, particularly in the context of the surface temperatures with large regional variations and considerable warming trends in East Asian countries (Trenberth et al. 2007; Gao et al. 2002; Mizuta et al. 2005; Boo et al. 2006). Therefore, more attention has been gradually paid to the research of regional extreme events. Ren et al. (2012), Feng et al. (2006, 2011), Peng and Bueh (2011), Qian and Fu (2009), and Gong et al. (2012) tried to identify RELTEs using different defining and detecting methods.

During December 2010 to January 2011, frequent severe cold weather occurred over many areas of China with record-breaking blizzards and low temperatures. There was also one serious RELTE during this time period. Since it coincided with the time of annual migration of large populations in China, this event caused extensive damage to traffic and agriculture among other things. As the most serious RELTE since 1979 (Fig. 2), the main character of this event is cold and dry, which is quite different from the cold and rainy event in South China during January 2008 (Gu et al. 2008; Ding et al. 2008; Qian et al. 2009). Therefore, more research is needed to diagnose the cause and the precursor signals of this event, in order to understand the dynamical mechanisms of RELTEs.

Beuh et al. (2011) and Gong et al. (2013) discussed the key features common to wintertime RELTEs in China. In geopotential height at 500 hPa, the event is marked by a pair of northeast–southwest-tilted ridges and troughs in the mid-troposphere on the continental scale, and the spatial feature of the RELTEs is somewhat decided by the composite mode

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of the geopotential anomalies over Euro-Asia block high areas. Meanwhile, in the surface level pressure (SLP) field, the splitting flow over the inner Asian continent and the influent flow over the southeastern coast of China correspond well with the expanded and amplified Siberia high with tightened SLP gradients and strong cold advections over southeastern China (Beuh et al. 2011). Besides, the Arctic Oscillation (AO) is the dominant mode in Northern Hemisphere winter on the inter-annual timescale, which extends from the surface to the stratosphere with its positive (negative) phase representing pole-ward (equator-ward) shift of the mid-latitude westerly winds (Thompson et al. 2000). It serves as one of the most important factors that influence the wintertime surface air temperature fluctuations over East Asia, modulating the frequency of cold surges (Jeong and Ho 2005) and extreme low temperature (Chen et al. 2005; Gong et al. 2001). All these facts motivate an analysis of the extended-range time scale systems/patterns associated with RELTE occurrence. However, previous studies have not distinguished the precursor and in-phase factors for the RELTE, let alone the probable contributions of AO to the RELTE.

In this study, we will look at the correlation between the index of this cold event in China and the key area average of 500 hPa (Ural, Baikal, and Okhotsk) and 1,000 hPa (Siberia and Aleut) geopotential anomalies. Then we discuss the probable precursor signals of the downward propagation of AO anomalies from the stratosphere and the corresponding eastward movement of the mid-latitude geopotential height anomalies centers. The datasets and detection method are first described in Section 2. Details of the RELTE in China in January 2011 (this event mainly happened in 2011, so it will be referred to as the 2011 No. 1 RELTE) are given in Section 3. Analyses of the in-phase atmospheric anomaly and precursor atmospheric teleconnection anomalies are presented in Sections 4 and 5 to explain the possible causes of this unusual event. Concluding remarks are given in Section 6.

2 Data and methodology

2.1 Data

Daily surface minimum temperature data of 723 China meteorological stations compiled by the China Meteorological Administration are used. The time period studied is from November 1, 1960 through March 31, 2011. Atmospheric circulation data used in this study are mainly from the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kistler et al. 2001). These include the daily mean and long-term mean values of temperature and geopotential height at 17 levels, wind speed, and SLP. The horizontal resolution of the data is 2.5° latitude×2.5° longitude.

2.2 The objective identification technique for regional low temperature extreme events

An evolving RELTE has two structural characteristics: (1) A RELTE always has a given duration (days); (2) on a daily anomaly chart during the duration, every day the RELTE may cover a specific area, namely a certain impacted area. We use the objective identification technique for regional low temperature extreme events (OITRELTE) to detect RELTE (Ren et al. 2012; Gong et al. 2012). The main steps of OITRELTE are as follows:

1. Definition of the threshold of extreme low temperature at individual stations. In this step, daily minimum temperature is selected as the daily index for individual stations. The threshold for defining daily extreme low temperature at individual stations is set to be the tenth percentile of all daily low temperature from November 1 of current year to March 31 of next year during 1981–2010.
2. Identification of the daily belt of extreme low temperature. Based on the daily minimum temperature for individual stations, thresholds of abnormality for individual stations are defined. Then daily abnormality regional low temperature belts (many stations in a nearby region reach the threshold value of the extreme low temperature but do not belong to any ongoing events) and ongoing regional low temperature events (the RELTE that is continuing) are identified based on two parameters: the threshold for the distance to define neighboring stations is 250 km and the threshold for the number of stations in a daily abnormality regional low temperature belts is 20, respectively.
3. Distinguishing of the low temperature event's temporal continuity. Then, the temporal continuity of low temperature events is judged by identifying the overlap (the stations overlapping ratio larger than the threshold) between daily abnormality belts and ongoing events. As shown in Fig. 1, by integrating the information of the abnormality belts and low temperature belts of each day, the temporal continuity of extreme low temperature events can be identified. In this analysis, a RELTE can be treated as "a string of daily abnormality belts," as a result, both beginning and ending dates as well as information about daily abnormality belts during the event are obtained. When this analysis proceeds to the final day under study, all ongoing events are finalized as formal RELTEs.

   There are two parameters in this step. The threshold for the number of days for a gap in an event is set to zero which means no gap is allowed in an event, and the threshold for the ratio of overlapping stations for a daily low temperature belt is chosen to be 0.1.
4. Establishment of the index system for RELTEs. According to Ren et al. (2012), a RELTE has both spatial and temporal features, so the daily (process) index of RELTE includes daily (process) extreme value $Q_d(Q)$, which

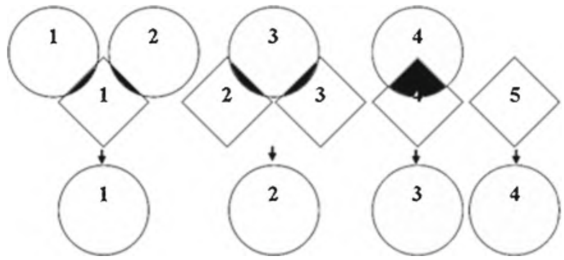


Fig. 1 Schematic diagram of relationship between ongoing events and abnormality belts. (*Circle* denotes ongoing RELTE, *diamond* denotes abnormality belt, which mean stations in a nearby region reach the threshold value of the extreme low temperature but do not belong to any ongoing event, and *shaded area* denotes overlap between an ongoing event and an abnormality belt)

means the daily (process) lowest temperature of the RELTE; daily (process) accumulative intensity $L_d(L)$, which means the daily (process) accumulated abnormality effect of RELTE; the daily (process) impacted area $A_d(A)$, which means the sum of daily (process) affected area of the RELTE; and the maximum process impacted area (A_{max}), which means the maximum daily affected area during the RELTE. The daily (process) integrated index $Z_d(Z)$, which denotes the integrated effect for other indices, and the calculation equations are

$$Z_d = e_1 Q_d + e_2 L_d + e_3 A_d \quad (1)$$

$$Z = e_1 Q + e_2 L + e_3 A + e_4 A_{max} + e_5 N \quad (2)$$

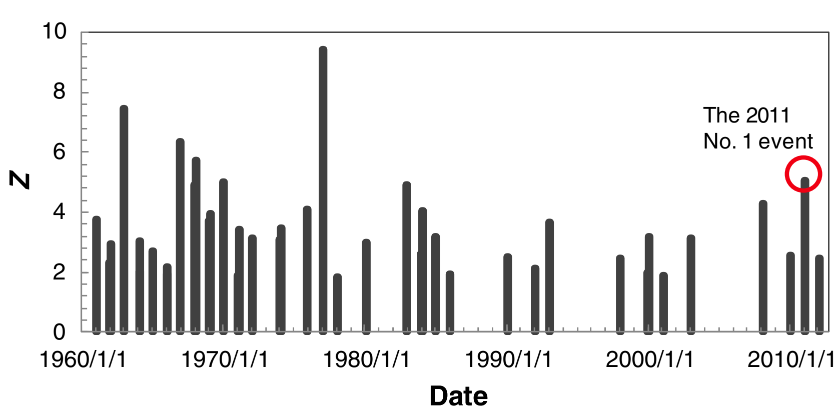
In Eqs. 1 and 2, e_1,e_2,e_3,e_4,e_5 are the weighted coefficients. In the calculation of the integrated index, the indices are standardized first. The OITRELTE method is applied in this study (Ren et al. 2012; Gong et al. 2012), and after a great number of tests in identifying China regional low temperature events, values of the parameters e_1,e_2,e_3,e_4,e_5 are determined as −0.21, −0.18, 0.15, 0.22, and 0.24, respectively.

3 Description of the 2011 No. 1 RELTE

During the period of November 1, 1960 through March 31, 2011, all the RELTEs were detected by using OITRELTE, and the daily (process) indices were also calculated. As shown in Fig. 2, the RELTEs had frequently occurred since 2008. The 2011 No. 1 RELTE started on December 30, 2010 and ended on February 2, 2011. It had the highest integrated index (Z) value after 1979, which seems to indicate this event has been the most serious RELTE since 1979.

Figure 3a shows the spatial distribution of accumulative intensity of the 2011 No. 1 RELTE. The affected area of this event covered most of China except the Tibetan and south of Southwest China. Figure 3b shows the meantime temperature anomalies, which were very much consistent with the situation in Fig. 3a. It can be said that the 2011 No. 1 RELTE was effectively identified (Gong et al. 2012; Wang et al. 2012) by the OITRELTE. For this event, the lowest extreme temperature (Q) was −49.6 °C, the duration (N) was 35 days, and the process-impacted area (A) was 725.3×10^4 km^2, respectively. Figure 4a1–a16 displays the distributions of the daily impacted extent and intensity during the period, and Fig. 4b is the display of variations of the daily index (Z_d) during the duration. It is easy to see from these figures that the daily impacted area and intensity varied day by day with daily Z_d peaked on January 10, 2011. Besides, the accumulated impacted area was quite similar to the spatial distribution in Fig. 3a, which makes us to believe the detection results look quite reasonable. Furthermore, the main character of this event was cold and dry that is quite different from the cold and rainy event that happened in southern China during January 2008 (Gu et al. 2008; Ding et al. 2008; Qian et al. 2009). For this reason, more

Fig. 2 Annual RELTEs with duration more than 12 days and integrated index (Z) more than 1.85 during 1960–2011



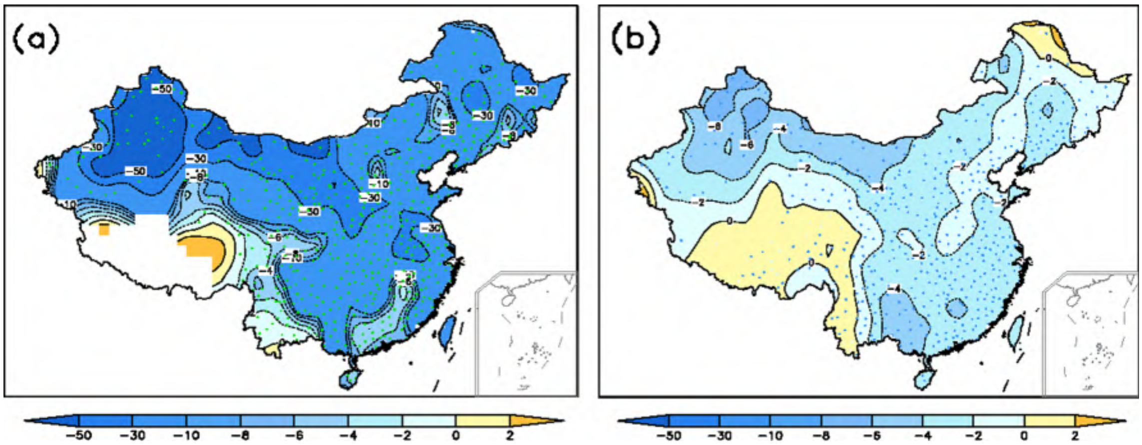


Fig. 3 The distribution of the accumulative intensity (**a**) and the corresponding in-phase temperature anomalies (**b**) during the time period of December 30, 2010 to February 2, 2011. *Points* in **a** and **b** denote stations contained in the RELTE

research is needed to understand the probable dynamical mechanism of this new event.

4 In-phase atmospheric anomaly

In order to understand the probable dynamical mechanisms for the 2011 No. 1 RELTE, we shall look at probable concurrent atmospheric anomaly patterns that could be responsible for this event. Specific atmospheric circulation patterns are known to produce warm and cold wintertime temperature anomalies for China and other mid-high latitude areas, and they are primarily related to anomalies of the semi-permanent features in the geopotential height patterns at 500 and 1,000 hPa.

During the RELTE, a positive abnormal center at 500 hPa formed over the Ural–Siberia region and extended eastward to North Pacific (Fig. 5a). This positive center had an extraordinary persistence, which was favorable for the forming of blocking high over the Ural–Siberia region. This situation not only allowed cold air to persist in southern China but also enabled each propagating perturbation from the west to go around the blocking high and to trigger downstream cold air intrusions from the north. Figure 5a also shows that a negative abnormal belt formed from West Asia to the Sea of Japan region and then extended westward to Northwest Pacific, with two negative centers in western Asia and Northwest Pacific. These negative centers also had an extra-ordinary persistence (Fig. 5a), which means the Aleutian Low was extra-ordinarily strong during the RELTE. Circulation pattern of high-to-the-north and low-to-the-south at 500 hPa was in favor of cold air intrusions from the north, where the cold air was originating from the Lake Baikal region and extending downward to central and southern China. Furthermore, East Asia major trough was stronger, deeper, and its location was more to the east than normal years (the figure is not shown), which indicates that the cold monsoonal flow moved eastward and northeastward off the continent and penetrated into southern China (Tea et al. 2011).

The daily average of 500 hPa geopotential height anomalies over the Ural region (50–60°N, 40–70°E), the Baikal region (50–60°N, 80–110°E), the Okhotsk region (50–60°N, 120–150°E), and the North Pacific (NP) region (40–50°N, 140–160°E) were all calculated. Figure 6a shows that the daily geopotential height anomalies in the Ural region remained to be positive since December 30, 2012. The anomalies in the Baikal region and Okhotsk region subsequently changed to positive value since January 13, 2011 after a short period in negative, which means the positive anomalies of the 500-hPa geopotential originated in the Ural region and then developed in the Okhotsk region. The positive anomalies in these three regions persisted until near the end of the 2011 No. 1 RELTE. However, the daily geopotential height anomalies in the north Pacific were persistently negative since January 4, 2011 and remained so until the end of January. Furthermore, the daily average of 1,000 hPa geopotential height anomalies over the Siberia (55–65°N, 60–95°E) and the Aleutian (35–50°N, 150°E–170°W) regions were also calculated. As shown in Fig. 6b, the daily geopotential height anomalies in the Siberia region had been positive since December 30, 2012, whereas the anomalies over the Aleutian were a persistently negative. Table 1 shows the correlation coefficients between these daily geopotential height anomalies and the daily integrated index (Z_d) of the 2011 No. 1 RELTE. The anomalies of geopotential height may lead the RLETE; both concurrent and lag correlation coefficients are calculated. Most of the maximum absolute coefficients passed the 0.01 confidence test. In addition, the correlation coefficients for Ural, Baikal, and Okhotsk were all positive, while the correlation coefficient for NP was negative. So, this persistent high-to-the-north and low-to-the-south geopotential anomaly pattern had a close relationship with the 2011 No. 1 RELTE.

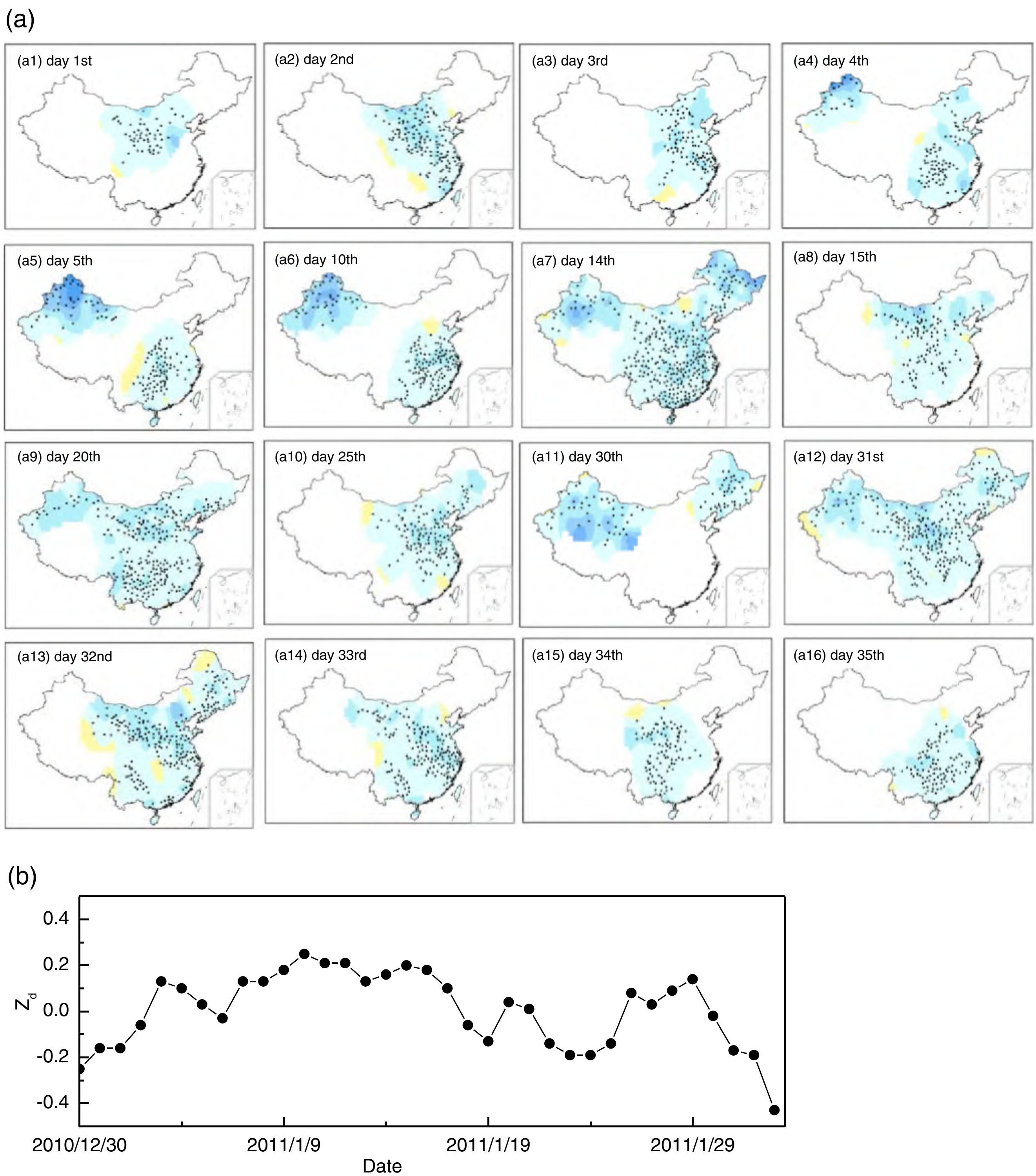


Fig. 4 Daily evolution of impacted areas and integrated index of the 2011 No. 1 RELTE. *a1*~*a16* are the distributions of the most daily impacted areas and intensity (*day 1st* corresponds to December 30, 2010). *b* The evolution of daily integrated index (Z_d)

The positive value of the 1,000-hPa anomalies in Fig. 5b shows a sharp rise of pressure in Siberia with extension to southern China; meanwhile, there is a negative center over the region of the Aleutian low. Table 1 shows that the maximum correlation coefficients of Siberia and Aleutian region both passed the 0.01 confidence test. The correlation coefficient for Siberia is positive, while for the Aleutian is negative. It can be inferred that the positive anomalies at the 1,000-hPa geopotential developed from the Siberia region, and the negative anomalies located in the Aleutian region for a long

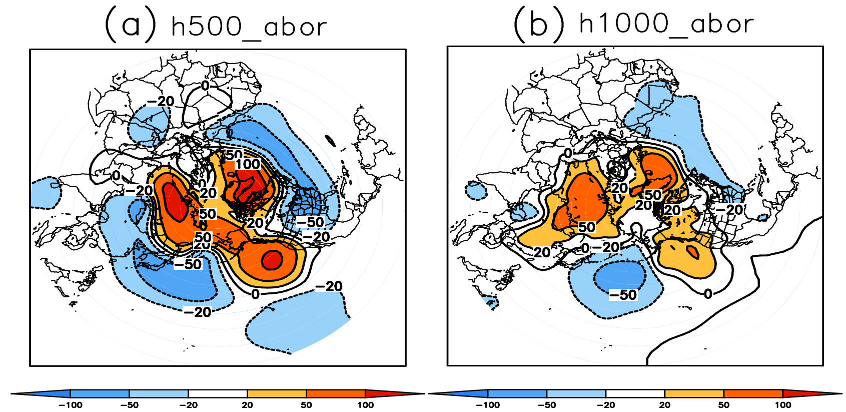


Fig. 5 In-phase geopotential height anomalies at 500 and 1,000 hPa during the 2011 No. 1 RELTE (unit: geopotential meters)

period. The strengthening of Siberia high and Aleutian low, the rather persistent west high, and east low geopotential pattern was also favorable for the relatively cold mid-high latitude air mass to enter East Asia and to form the RLETE. So, the Eurasia anomalies in 500 and 1,000 hPa geopotential height might be the direct cause for the 2011 No. 1 RELTE.

In Fig. 7, an abnormal wind anticyclone was over the Ural region in 850 hPa wind field, and the southward abnormal wind extended to northwest China through Mongolia. Besides, there was an abnormal wind cyclone over the North Pacific, and the southward abnormal wind extended to the Northeast China and South China. As a result, the cold wind from mid-high latitudes was stronger than normal in west and east part of China during the 2011 No. 1 RELTE, leading to a quick drop of temperatures. This situation persisted for a long period of time and resulted in the 2011 No. 1 RELTE. Furthermore, south China was under the control of northward wind anomalies, which indicated that the prevalence of the La Niña condition in the central equatorial Pacific caused a weaker-than-normal subtropical high weakening the westerly flow from the Bay of Bengal and south China sea to move northeastward (He et al. 2008). Under such pattern of circulation, warm and moist air was not easy to be brought to southern China. Consequently, the 2011 No. 1 RELTE was cold and dry, which was quite different from the RELTE of January–February 2008 (Zhou et al. 2008).

5 Out-of-phase atmospheric teleconnection anomalies

The cool events often occur in the time of year when climate signals have their most prominent impact on extended time scale characteristics in China (Ding et al. 2008). Since the RELTE studied here was regional-scale patterns that persisted over an unusually long time period, a likely cause might be found in the presence of a strong advanced atmosphere signal. The phases of the AO patterns were investigated to check for possible linkages to the anomalous periods. The AO index was strongly negative (−2.6) for December 2010 and January 2011 (Higgins et al. 2002), consistent with the positive anomalies of 1,000 hPa geopotential height in the polar area (Fig. 5b). Furthermore, Fig. 8a shows the daily evolution of AO index. The AO index was always negative from December 1, 2010 to January 26, 2011. Figure 8b shows −30- to 0-day leading correlation coefficients with the daily integrated index Z_{d}. The −9- to 0-day leading correlation coefficients are

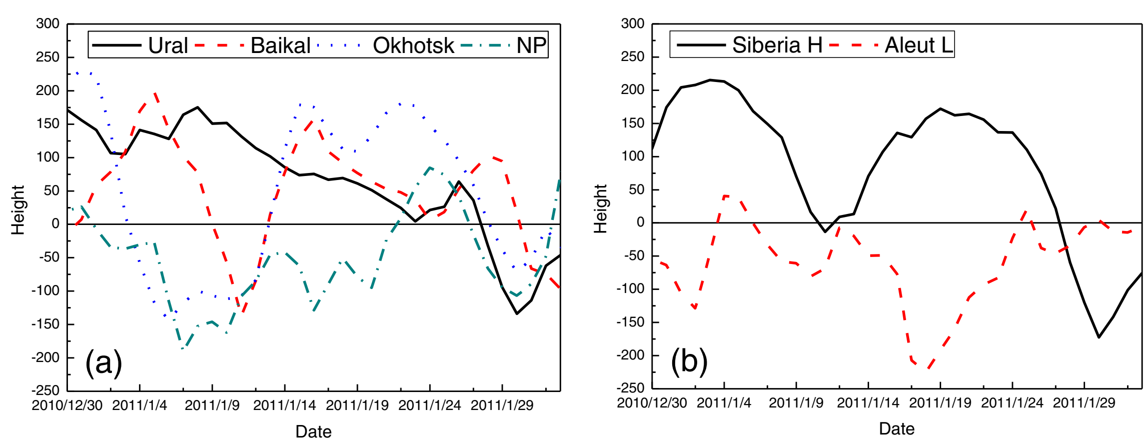


Fig. 6 Daily average of geopotential height anomalies of the Ural (50–60°N, 40–70°E), Baikal (50–60°N, 80–110°E), Okhotsk (50–60°N, 120–150°E), and NP (40–50°N, 140–160°E) regions of 500 hPa (**a**), and Siberia (55–65°N, 60–95°E) and Aleut (35–50°N, 150°E–170°W) regions of 1,000 hPa (**b**) from December 30, 2010 to February 2, 2011 (ordinate unit: geopotential meters)

Table 1 Correlation coefficients between the daily key areas average of geopotential height anomalies and the daily integrated index (Z_d)

	Ural	Baikal	Okhotsk	NP	Siberia	Aleut
Max coeff.	0.76	0.27	0.46	−0.67	0.33	−0.58

Max coeff. denotes the max positive (negative) coefficient for −5 days to 5 days leading correlation

around −0.4, and the most significant correlation is −0.63 at around −18 days. Because the AO shows a weak positive correlation with temperatures over China, the AO anomaly, especially the out-of-phase AO anomaly, may be regarded as a contributing factor to the 2011 No. 1 RELTE.

In recent years, many studies suggested that certain extreme stratospheric anomalies associated with AO propagate downward and influence the tropospheric weather regimes, which may be used to improve the tropospheric extended range weather forecast (Baldwin and Dunkerton 2001; 2003). Here we will show the downward propagation of AO anomalies from the stratosphere and its possible relations with the extra-ordinary persistent negative AO, in order to discuss the probable out-of-phase atmosphere anomalies to the 2011 No. 1 RELTE.

Previous studies have shown that in the zonal-mean sense, planetary waves propagate upward from the lower boundary over mid-latitudes and split into two branches in the upper troposphere, with one branch propagating along the polar waveguide (Dickinson 1968) into the stratosphere and the other going towards the equator along the low-latitude waveguide in the troposphere (Huang and Gambo 1983; Wang and Chen 2009). As shown in Fig. 9a, there was a weak anomalous downward EP flux around 65°N from stratosphere to the troposphere in November 2010. It led to a weak EP convergence at around 65°N, which in turn was helpful to decelerate the night jet and to induce the negative AO. In December 2010, the equator-ward wave propagation along the low-latitude waveguide was significantly weakened, and the

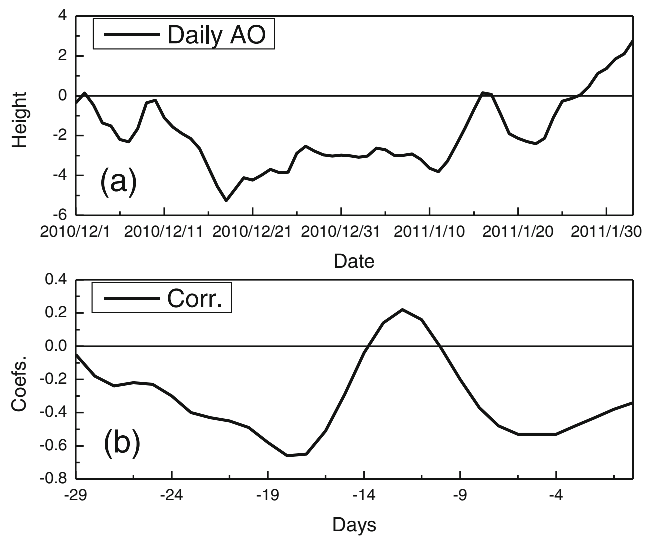
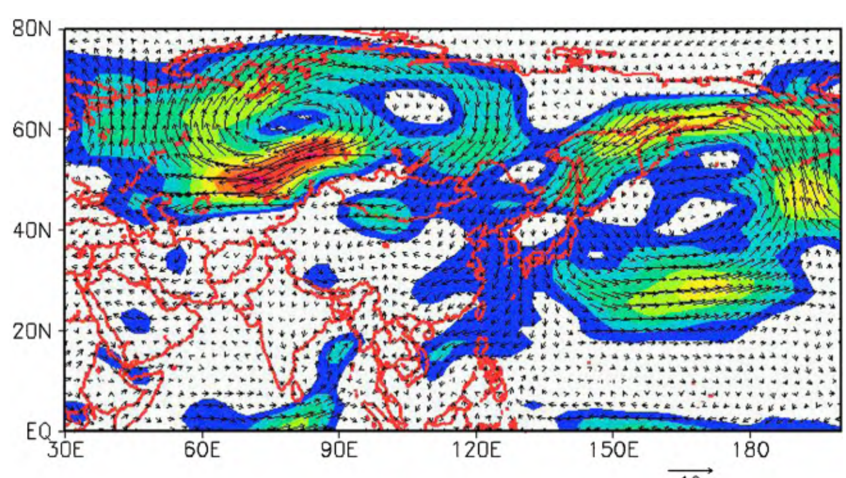


Fig. 8 The daily evolution of AO index (**a**) and −30 days to 0 day leading correlation coefficients with Z_d (**b**)

downward EP flux at around 65°N from stratosphere to the troposphere was enhanced. This led to a stronger EP flux convergence in high latitude, and induced more robust negative AO (Fig. 9b). Besides, the EP flux convergence anomalies also decelerated (accelerated) the westerly (easterly) wind in mid-high latitudes, which also induced the stratospheric sudden warming (Palmer 1981). In January 2011, there also existed the weak downward EP flux at around 65°N from stratosphere to the troposphere, while the EP flux convergence changed into positive implying the negative AO became weaker. Therefore, the anomalous wave activities in the three months (especially in December 2010) indicated that the negative AO might be associated with some downward propagating processes from the stratosphere.

Then we will distinguish individual downward propagating events from daily evolution of temperature anomalies in the North Pole region (north of 75°N) in order to make sure the relationship between the downward propagation EP flux and

Fig. 7 Eight hundred fifty-hectopascal wind anomalies (*vector*, meters per second) and wind value (*shade*) during the 2011 No. 1 RELTE



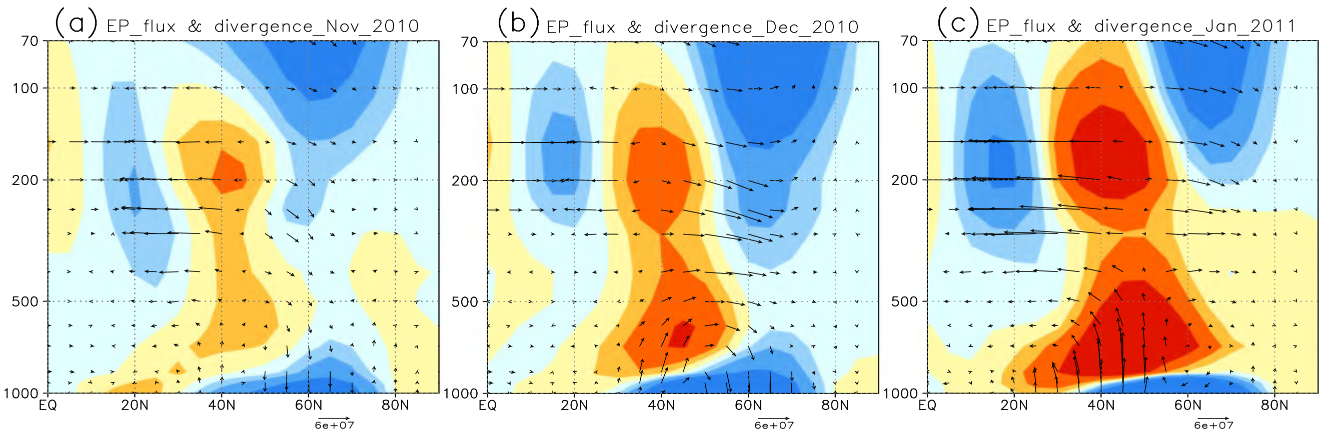


Fig. 9 The anomalies of EP flux (*vector*) and EP flux convergence (*shaded*) for stationary planetary waves in (**a**) November 2010, (**b**) December 2010, and (**c**) January 2011. *Shading color* is *red* (*blue*) indicating positive (negative). EP flux are scaled by the inverse of the air density with the unit per square meter per square second

the consistent negative AO. As shown in Fig. 10a, in November 2010, there was one period of warming in the polar stratosphere around November 1. Following the warming, positive temperature anomalies gradually propagated downward and reached the troposphere in about 20 days. As the downward propagation of AO signal from the stratosphere is usually accompanied with proceeding upward EP flux anomalies (Christiansen 2001), this downward process might be interrupted by upward propagating planetary waves from the bottom of the troposphere around the tenth of November (not shown). Besides, there were also upward propagating planetary waves around the first of December, which led to another warming around the 20th of December. This warming in the polar stratosphere also made the positive temperature anomalies gradually propagate downward and reach the surface in about 25 days. In addition to the temperature signals over polar cap region, these downward propagation processes can also be seen in other zonal-mean variables (e.g., zonal wind or geopotential height). As pointed out by Baldwin et al. (2003), the propagation of the AO in negative phase from the stratosphere to the troposphere is often corresponding to the negative zonal-mean wind anomalies (around 60°N). Figure 10b shows the daily evolution of zonal mean zonal wind anomalies (60–70°N). There were also two occasions for negative zonal mean zonal wind anomalies downward propagating processes, which are around November 1 and December 20, 2010, respectively. These two processes (especially the former) were also somewhat influenced by the upward propagating planetary waves and showed small disrupts.

In Fig. 10c, these two mainly downward propagating processes might be correlated with the negative behavior of AO. In November 2010, the height anomalies were negative (means the AO index was positive) from November 1 to November 16, then the positive temperature anomalies propagated downward and reached the surface, and the height anomalies became positive from stratosphere to the surface (means the AO index was negative). The positive height anomalies became weak during the disrupted period of November 30 to December 15. Then the height anomalies became strongly positive from stratosphere to the surface (means the AO index was strongly negative) during the period of December 16 to December 20. This process might be equivalent to an AO downward propagating, although it was not obvious in the anomalies of temperature and zonal mean wind evolution processes in Fig. 10a and b, due to the disruption by the upward propagating planetary waves. Then during the time when the positive temperature anomalies propagated downward, starting from December 20, the height anomalies became strongly positive from stratosphere to the surface once again and lasted until 15th of January. Therefore, this result confirms the speculation that the surface negative AO in December 2010 and January 2011 was closely associated with the downward propagation of AO signal from the stratosphere. Besides, Wang and Chen (2010) also analyzed the downward AO signal associated with the cold event in December 2009 and reached the same conclusion. So, it is obvious that the formation of the negative AO was leading the 2011 No. 1 RELTE. This possibly explains why the most significant correlation between the AO index and Z_d had about −18 days of the former leading the latter.

The 2011 No. 1 RELTE in January 2011 mainly happened in January 2011; however, the negative AO index for December 2010 (−2.6) was lower than that for January 2011 (−1.6). This seems to indicate that the persistent AO anomaly pattern might not be the only reason for the 2011 No. 1 RELTE. The associated monthly SLP anomalies (Fig. 11) show that the SLP was anomalously high in the polar region and low in mid-latitudes in December 2010 (Fig. 11a) and January 2011 (Fig. 11b). However, there are also significant differences in terms of geopotential height between December 2010 and January 2011. In December 2010, the SLP anomalies over China were negative, whereas over the east Europe and North

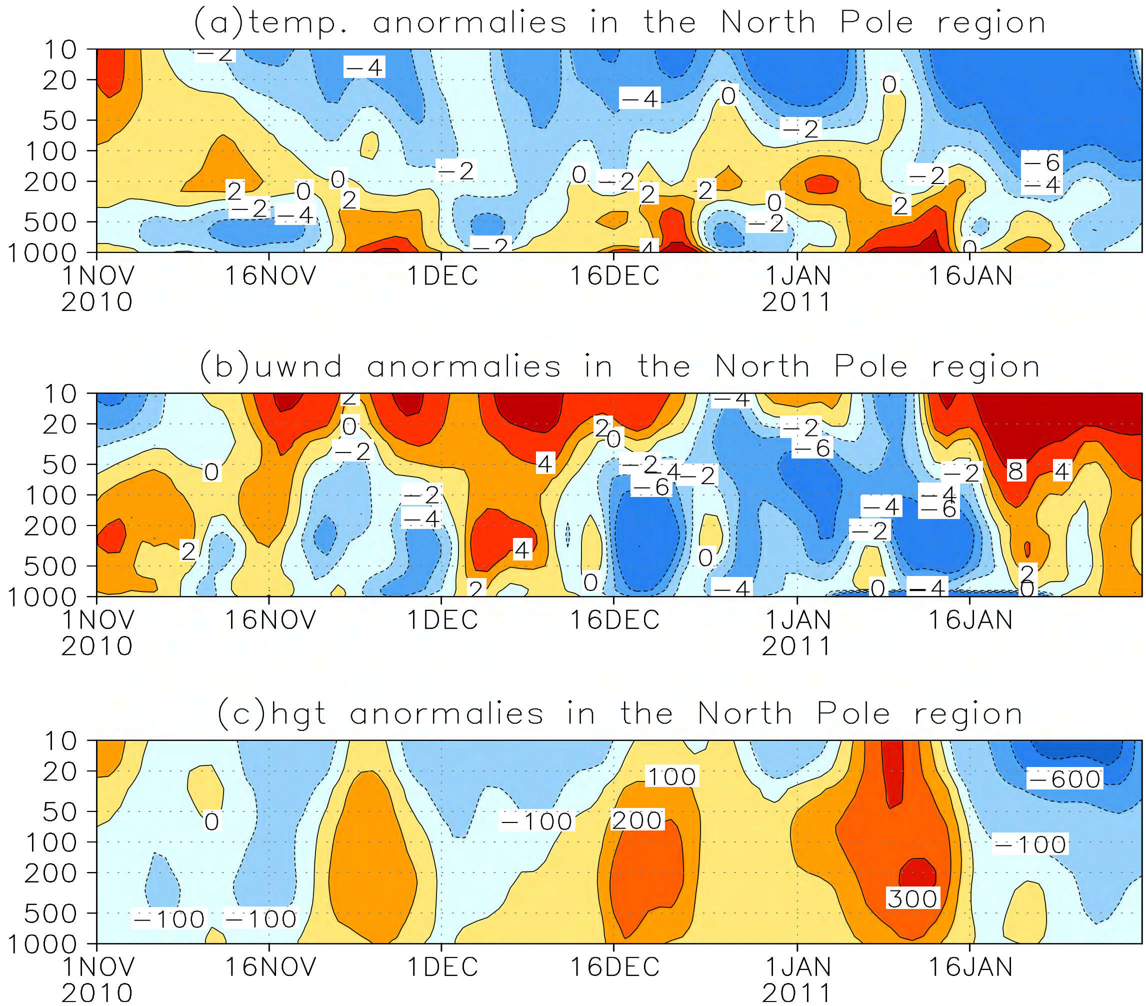


Fig. 10 The daily evolution of anomalies of (a) air temperature, zonal mean wind (b), and (c) height in the North Pole region (north of 70°N) during the period of November 1, 2010 to February 28, 2011

of 50°N above the North Pacific, they were positive, which showed the mid-latitude long stationary planetary wave pattern of "+−+." Meanwhile, in January 2011, the SLP anomalies over China were positive, and the mid-latitude long stationary planetary waves showed the opposite pattern of "−+−." The longitudinal distribution of SLP anomalies average (within 40–55°N; Fig. 11c) showed a pattern of obvious three waves both for December 2010 and January 2011, while the phase was opposite from East Europe to North Pacific (100°E–100°W), indicating the eastward extension for the positive and negative anomalies center. This eastward movement was consistent with the eastward group velocity in Rossby waves (Rossby et al. 1939; Platzman 1968), which was also shown in the 500-hPa geopotential height. In order to identify the eastward movement of the anomalies center, a phase-independent wave activity flux **W** for stationary and migratory quasi-geostrophic eddies proposed by Takaya and Nakamura (2001) is analyzed. The formula of W is as follows:

$$W=\frac{p\cos\varnothing}{2|U|}\begin{pmatrix}\frac{U}{a^2\cos^2\phi}\left[\left(\frac{\partial\Psi'}{\partial\lambda}\right)^2-\Psi'\frac{\partial^2\Psi'}{\partial\lambda^2}\right]+\frac{V}{a^2\cos\phi}\left[\frac{\partial\Psi'}{\partial\lambda}\frac{\partial\Psi'}{\partial\phi}-\Psi'\frac{\partial^2\Psi'}{\partial\lambda\partial\phi}\right]\\ \frac{U}{a^2\cos\phi}\left[\frac{\partial\Psi'}{\partial\lambda}\frac{\partial\Psi'}{\partial\phi}-\Psi'\frac{\partial^2\Psi'}{\partial\lambda\partial\phi}\right]+\frac{V}{a^2}\left[\left(\frac{\partial\Psi'}{\partial\phi}\right)^2-\Psi'\frac{\partial^2\Psi'}{\partial\phi^2}\right]\\ \frac{f_0^2}{N^2}\left\{\frac{U}{a\cos\phi}\left[\frac{\partial\Psi'}{\partial\lambda}\frac{\partial\Psi'}{\partial z}-\Psi'\frac{\partial^2\Psi'}{\partial\lambda\partial z}\right]+\frac{V}{a}\left[\frac{\partial\Psi'}{\partial\phi}\frac{\partial\Psi'}{\partial z}-\Psi'\frac{\partial^2\Psi'}{\partial\phi\partial z}\right]\right\}\end{pmatrix}+C_UM \quad (3)$$

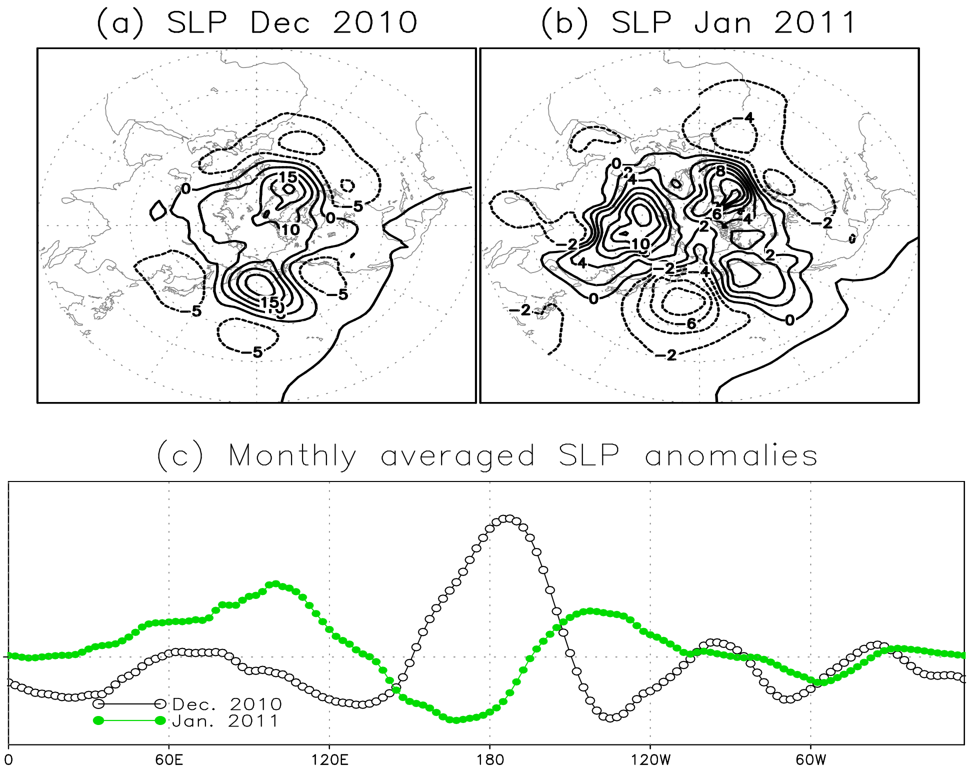


Fig. 11 SLP anomalies of (**a**) December 2010, (**b**) January 2011, and (**c**) the corresponding longitudinal distribution of SLP anomalies mean (40–55°N)

Where $\mathbf{C_U}=\mathbf{0}$ is the vector that represents the phase propagation in the direction of $\mathbf{U}$, Ψ' is the perturbation stream function, a is the earth radius, (ϕ, λ) are latitude and longitude, and U, V are zonal and longitudinal winds, respectively.

As shown in Fig. 12a, Rossby waves moved eastward from East Europe to North Pacific in December 2010, which resulted in a positive stream function response over the Ural Mountains. The wave train pattern was also shown in the 500-hPa anomalies in Fig. 12a. Then the wave activity flux **W** decreased in January 2011 (Fig. 12b), which means the eastward-moving Rossby waves become weaker. This change was good for strengthening the positive stream function response over the Ural Mountains and for its long lasting effect. This situation was consistent with the distribution of the

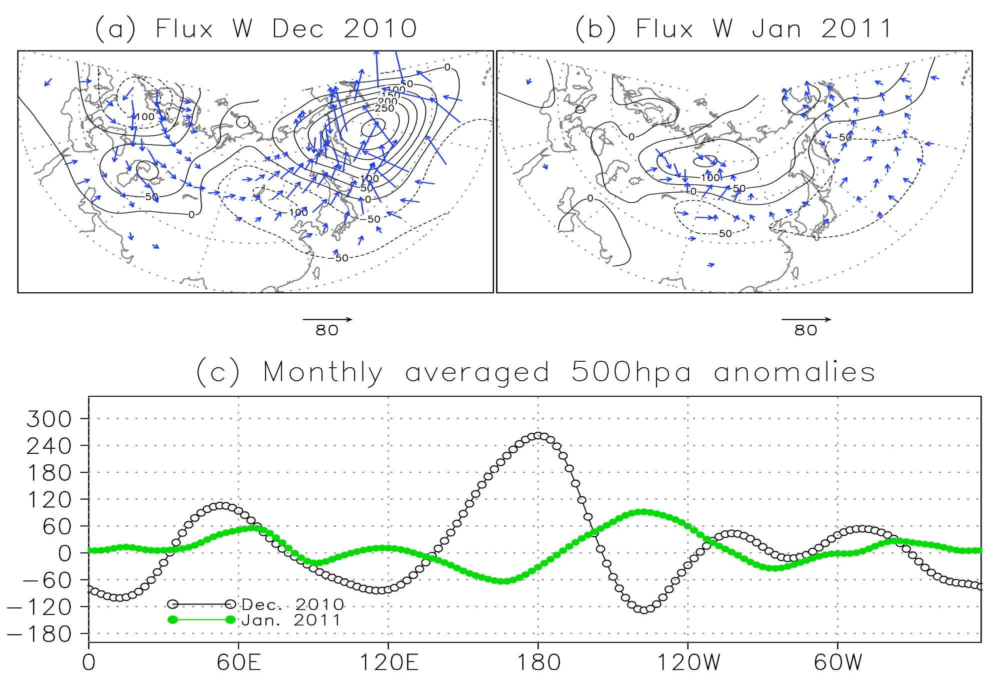


Fig. 12 Wave activity flux **W** (*arrow*) superimposed on contour for the anomalies of 500 hPa geopotential height of (**a**) December 2010, (**b**) January 2011, and (**c**) the corresponding longitudinal distribution of 500 hPa anomalies mean (40–55°N)

positive and negative anomaly centers at 500 hPa in January 2011 (Fig. 12b). Besides, the longitudinal distribution of the average of 500 hPa anomalies (Fig. 12c) shows the long stationary planetary waves pattern both in December 2010 and January 2011, and the wave phase (wave crest and trough) of December 2010 seemed to be leading that of January 2011, indicating the eastward extension of the wave train.

Thompson et al. (2000) revealed that during the negative phase of AO, its signature over North Atlantic Ocean was characterized by a weaker sea-saw pressure pattern, with a weaker subtropical ridge giving rise to an anomalous low near the Iberian Peninsula. A Rossby wave train might be generated there that propagated eastward across Eurasia to Asia. As Cheung et al. (2012) discussed, the 500-hPa wave train pattern appeared to be closely correlated with the negative AO, and the train signal was more likely to resemble the corresponding mode with a center of action near 60°E. On the other hand, the AO is a measure of the strength of the polar vortex. A larger amount of wave activity flux propagates upward from the lower troposphere such that the polar vortex gets warmer (cooler) and weaker (stronger) during its negative (positive) phase, and vice versa (Chen et al. 2005; Chen and Kang 2006). Accordingly, the weaker (stronger) westerlies circulating the polar region favor (inhibit) the advection of polar air southward, resulting in a cooler (warmer) Eurasia (Hurrell 1995) and a stronger (weaker) Siberian high (Gong et al. 2001). These impacts are evidenced by the strong correlations between the AO and Z_d in Fig. 8b, and also by the obvious Siberian high pattern in Fig. 11b.

Based on the prophase anomaly analysis, we can come to the conclusion that the prophase downward propagation of AO signals from the stratosphere in November and December 2010 kept the persistently negative AO for an extra-long period of time, which was in favor of the eastward moving of Rossby waves train. Then the upper reaches positive center in SLP and negative center in Z500 moved to East Asia, which was also good for the cold air expanding to the mid-latitude region from the polar area. So, the co-effects of these factors might be the teleconnection out-of-phase effect on the 2011 No. 1 RELTE.

6 Conclusions and discussion

This paper described a RELTE that occurred from December 30, 2010 to February 2, 2011 (called as the 2011 No. 1 RELTE) and covered most areas of China. It was quite a new kind of low temperature event proposed by Gong et al. (2012), which had both the spatial and temporal evolution characteristics of low temperature events. The 2011 No. 1 RELTE was a very rare and protracted cold event with the highest integrated index (Z) since 1979, and it has gathered much more public attention.

The probable forming mechanism for this cold and dry event was also discussed, and two meteorological factors could be responsible for this extreme winter event. The first factor was an extra-ordinary persistent blocking pattern in the mid-latitudes. This not only allowed cold air to persist in southern China but also enabled each perturbation from the west to propagate around the blocking high to trigger downstream cold air intrusions from the north. Second, the prophase downward propagation of AO signals from the stratosphere in November and December 2010 maintained a persistent negative AO for an extra-long period of time, which was good for the eastward moving of Rossby waves train. Then the upper reaches positive center in SLP and negative center in Z500 moved to East Asia, which was also good for the cold air expanding to the mid-latitude region from the polar area. Among these factors, the blocking pattern was likely to be the direct cause because it was responsible for establishing and maintaining the cold conditions over most of China. The co-effects of consistently strong downward negative AO from the stratosphere and the corresponding eastward moving wave train in Z500 and SLP might be the out-of-phase teleconnection factor for the 2011 No. 1 RELTE.

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