

# Relationship between extensive and persistent extreme cold events in China and stratospheric circulation anomalies

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**Abstract:** This study examines the relationship between the extensive and persistent extreme cold events (EPECEs) in China and geopotential height anomalies in the stratosphere using daily mean fields of outgoing long wave radiation (OLR) produced by the NCAR and daily atmospheric circulations produced by the NCEP/NCAR. The OLR composite analysis for the EPECE in China demonstrates that the negative OLR height anomalies (cold air) originated from Siberia influence China progressively from north to south. The largest negative OLR height anomaly (cooling event) occurs in the region to the north of the Nanling Mountains. This suggests that the OLR height anomalies can be used to represent the temporal and spatial characteristics of extreme low temperatures and cold air activities in winter in China. The composite analysis of large-scale atmospheric circulations during the EPECE reveals characteristic evolutions of stratospheric and tropospheric circulations during the extreme cold event. We demonstrate the important role of atmospheric circulation anomalies in the outbreak and dissipation of the EPECE in China. We also demonstrate that significant perturbations in the stratospheric circulation occur more than 10 days prior to the outbreak of the EPECE, with positive height anomalies in the Arctic stratosphere. These positive anomalies propagate downward from the stratosphere and affect the formation and development of the high pressure ridge in the middle troposphere over the Ural Mountains. Significant changes also occur in the atmospheric circulation in the mid-latitude stratosphere. These changes propagate downward from the stratosphere and strengthen the low pressure trough in the troposphere in the region to the east of Lake Balkhash and Lake Baikal. Therefore, the changes in the stratospheric circulation during the EPECE in China occur prior to changes in the tropospheric circulation and are very useful for predicting extreme wintertime cold temperatures in China.

**Keywords:** satellite remote sensing, OLR, extreme cold event, stratosphere, troposphere

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## 1. Introduction

The study of dynamic processes in the stratosphere has received much attention, mainly due to their significant impact on the tropospheric circulation, weather and climate. Major progress in examining the effect of stratospheric processes on the tropospheric circulation has been made only after the seminal study made by Thompson and Wallace (1998) using the empirical orthogonal function (EOF) analysis. Baldwin and Dunkerton (1999) demonstrated that the Arctic Oscillation (AO) pattern in the troposphere is correlated with modulation of the strength of the stratospheric polar vortex. They also found that the AO anomalies typically appear first in the stratosphere and then propagate downward. Previous observations demonstrated that the tropospheric circulation and climate are influenced by the stratospheric circulation (Colucci, 2010; Hinssen, van Delden, Opsteegh *et al.*, 2010). Ren and Xiang (2010) concluded that sea-surface temperature anomalies in the tropic not only cause air temperature anomalies in the same region, but can also lead to abnormal temperature changes over regions from the tropical to polar region in the stratosphere and a series of simultaneous poleward and downward propagations of temperature anomalies from tropics to the polar region. The East Asian winter monsoon (Chen, 2013) and winter temperatures and precipitation in China (Tan, 2010; Xiong, Chen, Zhu *et al.*, 2012), as well as the East Asian summer monsoon (Luo, Tian, Zhang *et al.*, 2012), are also under the influence of the stratospheric circulation anomalies. Lu and Ding (2013) suggested that the downward propagation of circulation anomalies associated with sudden warming in the stratosphere to the lower atmospheric layer is determined by intensities, locations, and durations of perturbations in the polar vortex. The downward propagation of the AO anomalies associated with sudden warming in the stratosphere intensifies the Siberian high, the Aleutian low, and the East Asian trough in the troposphere, resulting in abnormal low air temperatures in most parts of northern China (Li, Li, Tan *et al.*, 2010). As the abnormal signal of the stratospheric AO propagates downward, the phase of the tropospheric AO turns to negative. Consequently, the Ural blocking high anomalies develop significantly, and bursts of cold airs from the polar region has caused dramatic cooling in East Asia and Europe, resulting in extreme wintertime cold events in China (Lan and Chen, 2013). Previous studies also indicated that stra-

tospheric circulation anomalies occur about 15 days prior to the changes in tropospheric temperatures, and maximum anomalies of surface temperatures occur at the late stage of the weak polar vortex in the stratosphere, with cooler (warmer) winter temperatures than those in the normal year over the region to the north (south) of 40°N (Yi, Chen, Zhou *et al.*, 2013).

Previous studies were also made in determining how changes in the stratospheric circulation affect the troposphere. Lan and Chen (2013) found that activities of quasi-stationary planetary waves are strongest in winter than other seasons, and these waves are originated from Eurasia and the North Pacific to the north of 45°N. Through its interaction with the planetary waves, the stratospheric polar vortex has significant impact on the atmospheric circulation in East Asia. Wei, Chen, Cheng *et al.* (2014) investigated the evolution of planetary waves and their relationship with associated weather changes in China during the abnormal changes in the stratosphere on the Northern Hemisphere. Deng, Chen, Yi *et al.* (2015) found abnormal activities of planetary waves occur in the stratosphere when the stratospheric polar vortex is abnormal. As the downward propagation of the abnormal signal in the polar vortex, significant changes occur in amplitudes and phases of planetary waves in the troposphere. These amplitudes and phases changes are different at different latitudes. It was also found that the waves propagate westward and downward from the source region of abnormal signals of the stratospheric circulation (Tan, Chen, Sun *et al.*, 2010). The impact of anomalies in the stratosphere to the tropospheric circulation can be explained based on potential vorticity dynamics, in which anomalies in the potential vorticity affect the tropospheric height and wind changes, and thus have an important impact on the weather system in the troposphere (Hinssen, van Delden, Opsteegh *et al.*, 2010; Lu and Ding, 2015; Shi and Bueh, 2015). Yi, Chen, Zhou *et al.* (2013) examined the influence process and mechanism of abnormal propagations of planetary waves based on distributions and changes of the potential vorticity, as well as the 500 hPa trough changes in East Asia. Lu and Ding (2015) suggested that, after the outbreak of sudden warming in the stratosphere over East Asia and Atlantic, the air masses with the large positive potential vorticity in the stratosphere bring cool air downward, and move southward and eastward. During their movement, the air masses stretch in the vertical with the strengthened positive vorticity and enhance the cold vortex system in the lower atmospheric layers, leading to the outbreak of

cooling events in eastern China. Shi and Bueh (2015) discussed how the prior abnormal circulation in the stratosphere affects the mechanism of low temperature events using the inversion of the potential vorticity.

As discussed above, the abnormal circulation in the stratosphere can influence the troposphere and the gradually downward spreading of AO signals can be used as the precursor for circulation anomalies at middle and high latitudes and therefore extend the predictability of surface weather forecasts. Some previous studies were conducted on the impact of the stratosphere on the troposphere, but more studies are needed in order to have better understanding of physical processes how the stratosphere affects continuous anomalies at high latitudes in the troposphere and the weather and climate in China. In this study, a diagnosis analysis is carried to determine the effect of the stratosphere on the circulation anomalies in the troposphere and its relationship with the EPECEs in China.

## 2. Data and Method

Two types of gridded data fields are used in this study. The first type is the gridded daily mean fields of Outgoing Long wave Radiation (OLR) during the period 1974–2010 (except for March–December 1978), with the horizontal resolution of  $2.5^\circ \times 2.5^\circ$ . The OLR fields were produced by the National Center for Atmospheric Research (NCAR) and interpolated from the polar-orbiting satellite remote sensing data provided by the National Oceanic and Atmospheric Administration (NOAA) of the United States. The second data type is the daily mean stratospheric and tropospheric circulation fields extracted from the atmospheric reanalysis data set with a spatial resolution of  $2.5^\circ \times 2.5^\circ$  from November 1 1948 to March 1 2009 produced by the National Centers for Environment Prediction/National Center for Atmospheric Research (NCEP/NCAR). The NCEP/NCAR reanalysis data set was produced by the state-of-the-art atmospheric numerical model with assimilation of various atmospheric observations of synoptic and asynoptic data sources. The former include observations made by such as radiosondes, drop-sondes, surface stations and ships. The latter include satellite and radar remote sensing data, and observations made by aircrafts and drifting buoys.

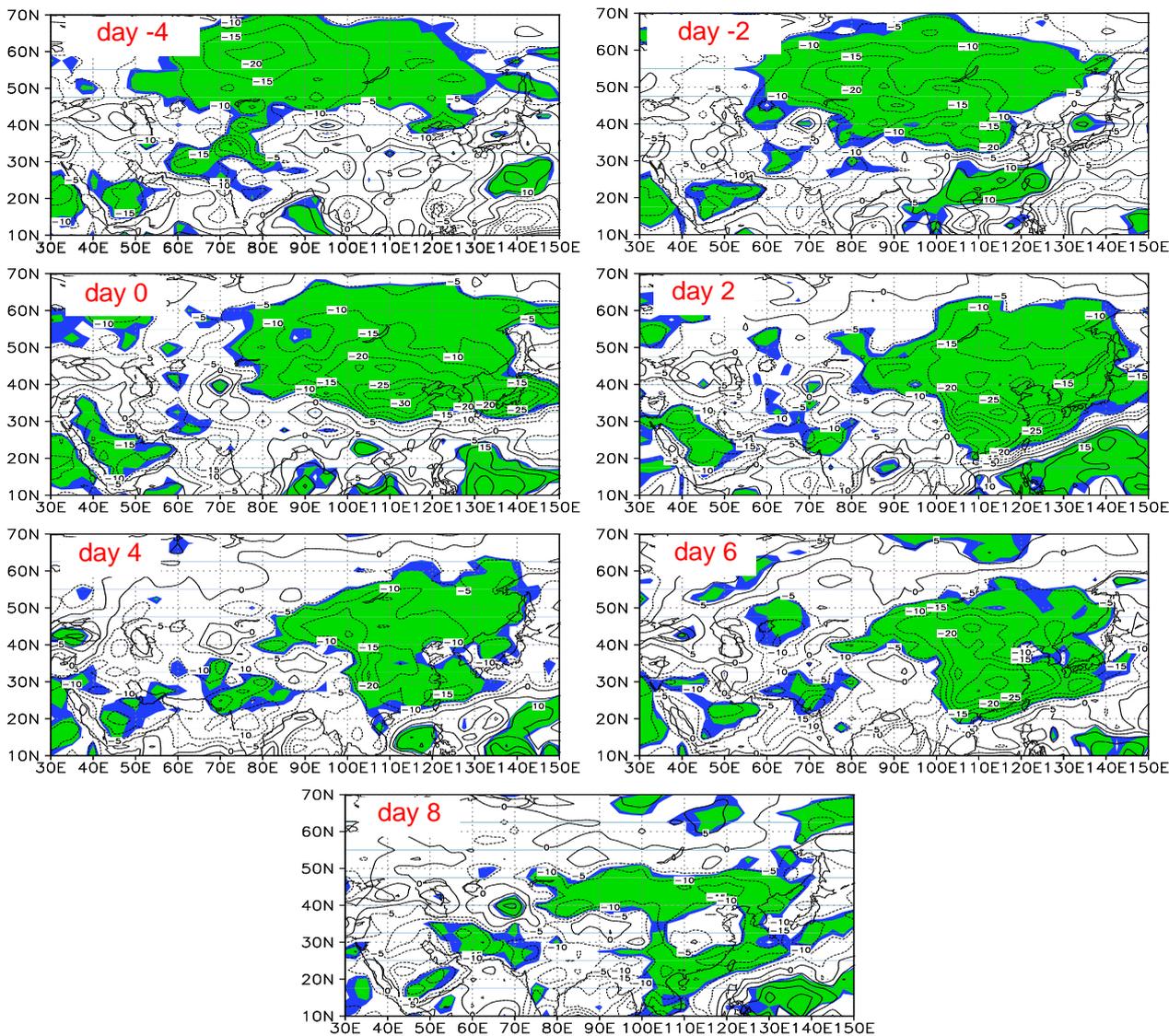
The extensive and persistent extreme cold event (EPECE) in winter in China in this study is defined in the same way as in Peng and Bueh (2011). Peng and Bueh (2011) suggested that an EPECE in China can be identified from air temperature observations at surface

stations in China using following three major steps. (1) A surface station for weather observations is considered as an extreme cold station (ECS) if the observed air temperature is colder than its 10th percentile threshold. (2) An extensive extreme cold event occurs if the approximated area occupied by the ECSs is more than 10% of the total area of China on the starting day of the cold event, and the maximum area occupied by all the ECSs is at least 20% of the total area of China. (3) An EPECE is present if the extreme cold event lasts for eight days or longer. Based on the above definition and using the observed daily temperatures at 756 surface stations in China during the period 1950–2009, Peng and Bueh (2011) identified 52 EPECEs from 58 winter seasons during this period. These 52 EPECEs were verified using other independent data (Peng and Bueh, 2011). Among these 52 EPECEs, 24 members have nationwide distributions of wintertime extreme cold air temperatures over the most part of China except for the northern part and Tibetan Plateau. A composite analysis of these 24 events is conducted in this study to determine the temporal and spatial distributions of atmospheric circulations before and after an EPECE. The main motivations of this study are to investigate the impact of the stratospheric circulation on the troposphere and to identify useful signals prior the occurrence of an EPECE.

## 3. OLR Anomalies

Outgoing Long-wave Radiation (OLR) represents the total radiation outgoing to space emitted by the atmosphere and is a measure of the temperature of the emitting region. The general distribution of OLR on the Earth features relatively high values at low latitudes and a gradual decrease from mid-latitudes of about  $30^\circ$  to the polar region on each Hemisphere of the Earth. OLR is persistently low in the northern and southern polar regions since these two regions are cold. At mid-latitudes, OLR is low over the Tibetan plateau since this region has high altitudes and long durations of snow cover. At low latitudes, OLR has seasonably-varying lows over the convergence line near the Equator, due to strong deep convection, stretching high of the cloud tops and low cloud temperature. OLR is high in the subtropical regions, especially over deserts of eastern and western sub-Saharan Africa and the cooler parts of the ocean, due to the fact that these regions are relatively dry and cloud-free.

We first examine the correlation between OLR and EPECEs in China. [Figure 1](#) presents the time evolution



**Figure 1.** Distributions of OLR height anomaly composites (units:  $W/m^2$ ) during 12 extensive and persistent extreme cold events at days -4, -2, 0, 2, 4, 6, and 8 (relative to the day of the extreme cold event occurrence). Green and blue shading areas represent that significant levels reach 5% and 10% respectively.

of OLR anomaly composites before and after the outbreak of 12 nationwide EPECEs in China since 1974. The negative OLR anomalies in this figure correspond to cooling. For simplicity of discussions below, the time for the outbreak of the EPECE is defined as day 0. At day -4 (or 4 days before the occurrence of the EPECE), largest negative OLR anomaly occurs in Siberia, indicating an accumulation of the cold air masses over central Siberia for cooling. Consequently, negative OLR anomalies over central Siberia move continuously southeastward and reach northern China at day -2. By this time, negative OLR anomalies in North China are intensified, but the negative anomalies in central Siberia are weakened (Figure 1). After the

outbreak of the EPECE, the negative OLR anomalies extend to coastal areas of southern China and ocean waters to the south of Japan, with the strongest negative OLR anomaly moving southward and eventually reaching the Yangtze River Basin. At day 8 (i.e., 8 days after the occurrence of the EPECE), the nationwide negative OLR anomalies cross China are markedly weakened significantly. The above analysis indicates that the cold air masses from Siberia sweep southward from northern to southern part of China, with the maximum cooling occurring in broad regions to the north of Nanling mountains. As a result, OLR anomalies can be used to represent the characteristics of cold events and movements of cold air masses.

### 3.1 Evolution of 500 hPa Height Anomalies

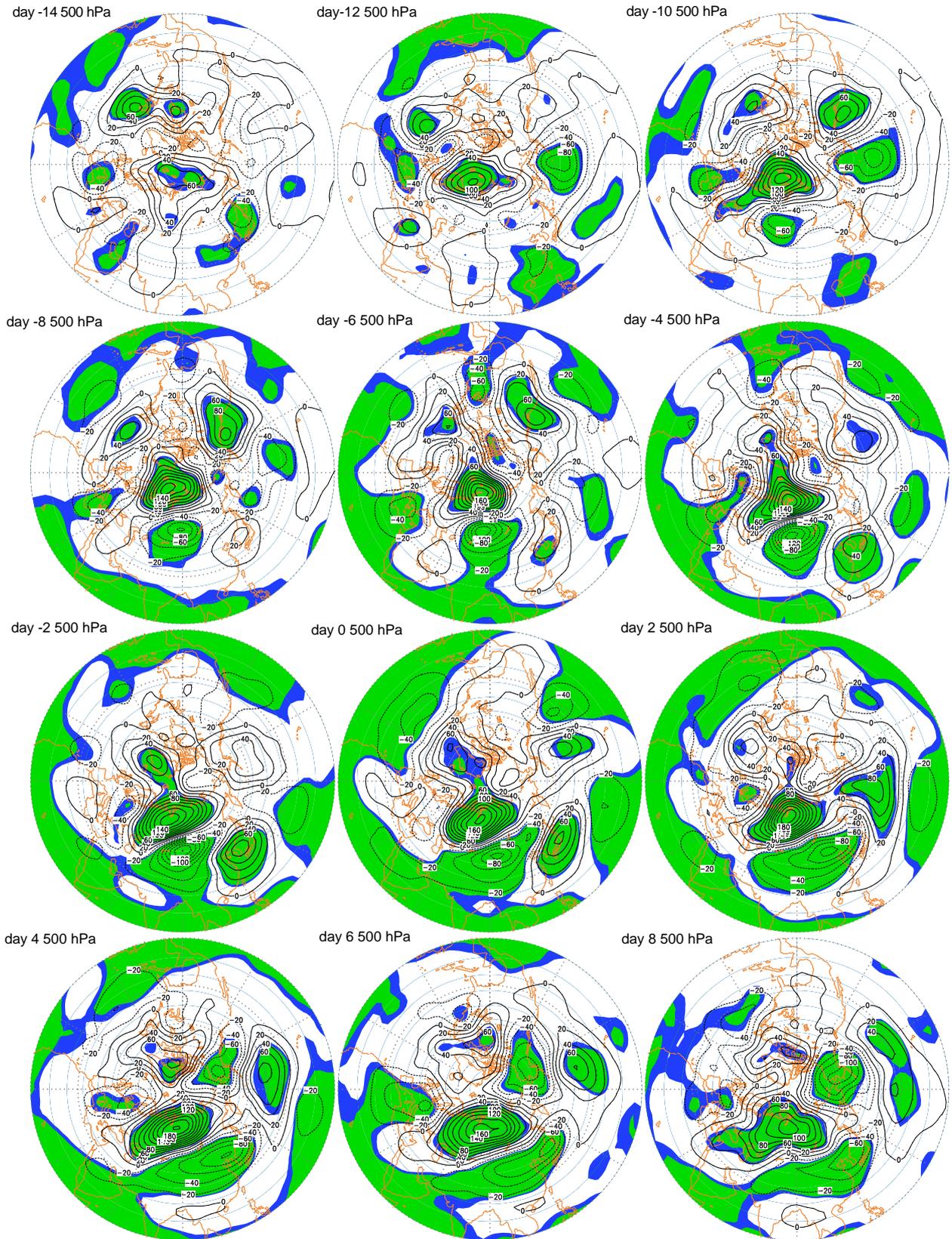
Fu and Bueh(2013) demonstrated that the outbreak of the EPECE in China is highly correlated with the large-scale tilted trough and ridge in the middle troposphere over the Asian continent (with the titled trough to the southeast and tilted ridge to the northwest of the region occupied by Lake Balkhash and Lake Baikal). To further examine the generation, intensification and dissipation of the EPECE and corresponding atmospheric general circulation and differences, we carry out the composite analysis of 500 hPa height anomalies during the EPECE and determine the temporal characteristics of height anomalies before, during and after the wintertime extreme cold event in China.

Figure 2 presents evolution of 500 hPa height anomalies associated with the EPECE in China during the 23-day period from day -14 to day 8. At day -14 (i.e., 14 days prior to the EPECE), significant positive height anomalies occur in the circulation over the Arctic region, with the positive height anomaly at the center of the Arctic circulation to be ~60 gpm. Firstly, we examine temporal changes in magnitude of the positive height anomaly at the center of the Arctic circulation (called as the central positive anomaly for the simplicity) during this 23-day period. The magnitude of the central positive anomaly increases with time, with the maximum value reaching ~200 gpm at day 2. After this time, the magnitude of the central positive anomaly decreases with time and reduced to ~60 gpm at day 10. Secondly, we examine the spatial variability of positive height anomalies in the Arctic circulation system during this 23-day period. From day -14 to -8, the center of the positive anomalies is located in the Arctic Ocean to the north of the island of Novaya Zemlya. After this period, the center of anomalies moves southeastward and reaches the Ural Mountains region at day -2. During the outbreak of the EPECE, the centre of anomalies reaches western Siberia. This center becomes quasi-stationary in western Siberia, with a very slow southeastward movement in the next 10 days, but still within western Siberia. Thirdly, we examine the temporal variations of the extent influenced directly by the positive 500 hPa height anomalies over the Arctic region. At day -14, the atmospheric circulation associated with positive height anomalies affects the whole Arctic area. The extent of influence expands with time in the next few days. At day -4 the extent of influence covers a wide-spread region including eastern Siberia to east and the

Caspian Sea to south. This large extent coverage under the influence of positive anomalies maintain with time until day 8. By day 10, the extent of influence reduces significantly, with only the western part of the extent remained (not shown). Therefore, the development and southeastward movement of positive height anomalies over the Arctic region affect the development of height anomalies over the Ural Mountains, which provides favorable conditions for the establishment, expansion and stability of the large-scale tilted ridge.

Another important feature in Figure 2 is the generation and expansion of negative height anomalies and associated circulation in the region to the southwest of Lake Baikal. At day -12, significant negative height anomalies occur in the region to the southwest of Lake Baikal, which connects the negative height anomalies over the North Pacific. The latter have the centre of negative anomalies located over the northern Pacific. At day -10, the negative height anomalies in the region to the southwest of Lake Baikal rapidly intensify to -60 gpm, with the extent of influence spreading outwards from the region. Subsequently, the negative height anomalies over this region continue to intensify and move eastward. By day -2, the central negative anomaly reaches a maximum and about -160 gpm. After this time, these negative height anomalies continue to move southeastward and their extent of influence expands to extensive regions including northeastern Asia to the east, Middle East to the west, Qinghai-Tibet Plateau to the south, and Lake Baikal to the north. At day 6, the centre of negative height anomalies reaches the Japan Sea and the magnitude of the central negative anomalies weakens to -80 gpm. Thus, the development and southeastward movement of negative height anomalies in the region to southwest of Lake Baikal result in the development of negative height anomalies over Asian continent, which, in turn, provide favorable conditions for the establishment, expansion and stability of the large-scale tilt trough.

In summary, based on above discussions, the EPECE is strongly correlated with the abnormal atmospheric circulation over Asian continent. Ten days before the outbreak of the EPECE (i.e., day -10), the 500 mPa height anomalies are positive around the island of Novaya Zemlya and negative in the region to the west of Lake Baikal. Both the positive and negative height anomalies strengthen and move southeastward progressively, resulting in the development of positive height anomalies in the Ural Mountains region and



**Figure 2.** Distributions of 500 hPa height anomaly composites (contour interval of 1 gpm) associated with the extensive and persistent extreme cold events at days -14, -12, -10, -8, -6, -4, -2, 0, 2, 4, 6, and 8 (relative to the day of the extreme cold event occurrence). Green and blue shading areas represent that significant levels of 5% and 10% respectively.

negative height anomalies in the Lake Baikal region. Both provide favorable conditions for the generation, expansion and stability of large-scale titled ridge and trough in the region. At the end of the EPECE, both the positive and negative height anomalies have weakened significantly and the negative anomalies located originally in the Lake Baikal region have moved eastward to the sea (Figure 2).

#### 4.2 Evolution of 20 hPa Height Anomalies

As discussed in the previous section, the positive and negative height anomalies and associated circulation in the middle troposphere have significant impact to the occurrence of the EPECE in China. Some other studies also demonstrated that the development of the large-scale trough and ridge in the troposphere are correlated with the anomalous circulation in the stratosphere (Li, Li, Tan *et al.*, 2012). In this section, we carry out a composite analysis using the 20 hPa height anomalies and further examine the typical stratospheric circulation and variability during the generation, development and dissipation of the wintertime EPECE in China.

Figure 3 presents temporal changes of 20 hPa height anomaly fields during the 25-day period between day -14 to 10. At day -14 (i.e., 14 days prior to the EPECE), the 20 hPa height anomalies over the Arctic region are significantly positive, with the maximum positive anomaly of ~160 gpm at the center of the anomalous circulation. These positive anomalies and associated Arctic circulation intensify with time in the following four days, and the central positive anomaly reaches ~260 gpm at day -10. After this time, the positive height anomalies and associated circulation weaken with time and the central positive anomaly decreases to ~160 gpm at the time the EPECE occurs. The positive anomalies then increase with time and the central positive anomaly reaches ~260 gpm at day 6 after the EPECE. After this time, the positive anomalies decrease again with time. It should be noted that the center of these positive anomalies is near the island of Novaya Zemlya at day -4 before the EPECE and then moves southeastward. At day 8 after the EPECE, the center reaches Siberia. The general features of 20 hPa height anomalies are consistent with these at 500 hPa surface as discussed in the previous section.

It is worth noting that significant negative height anomalies appear in the middle latitude. These negative anomalies are significant during periods prior to the EPECE and reach a maximum at day -10, with the

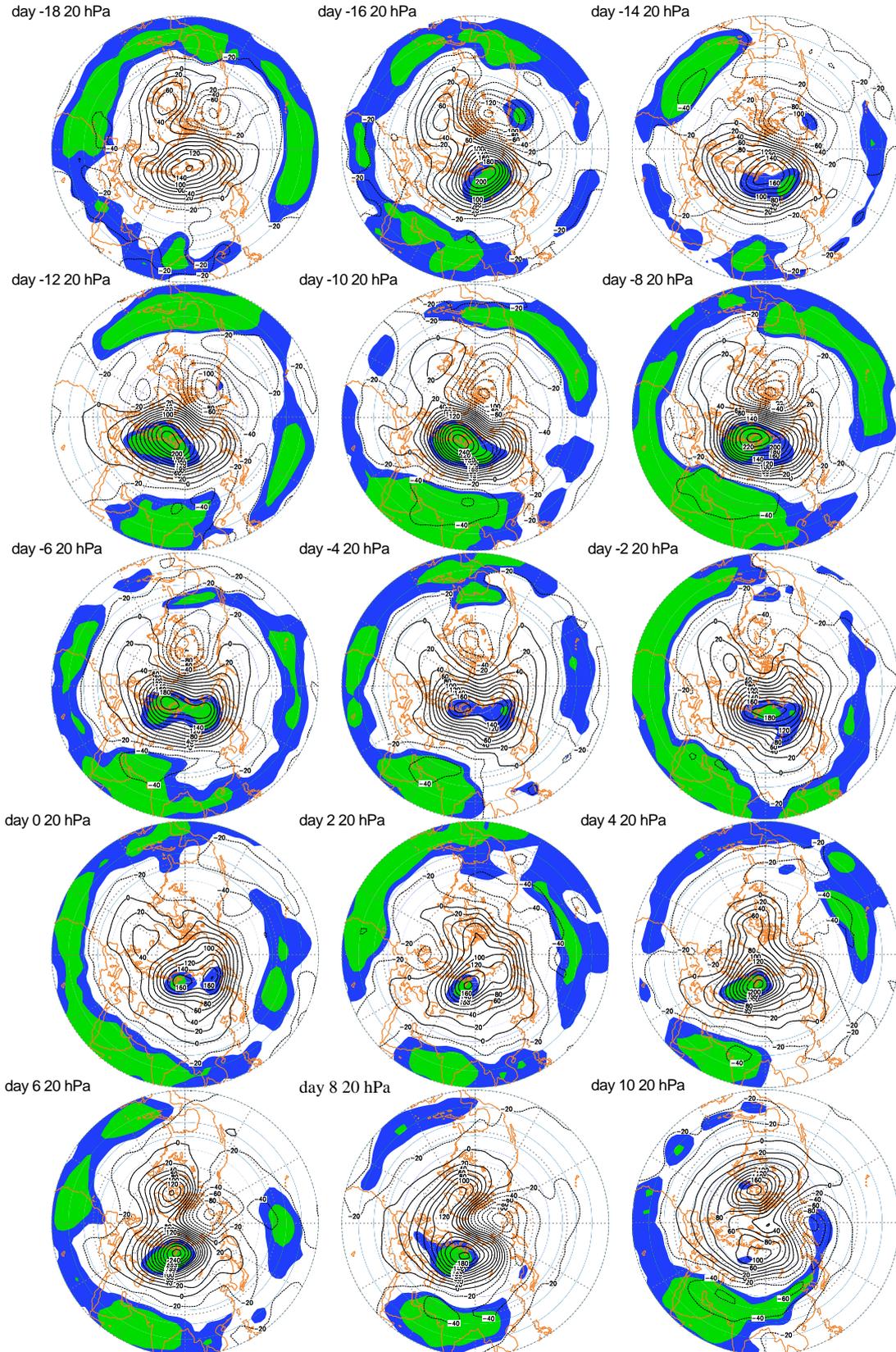
central negative anomaly of about -60 gpm. At day -2, these negative anomalies move southward due to the southward expansion of the positive anomalies over Siberia. This suggests, therefore, that the outbreak of the EPECE in China is strongly correlated with the development and movements of positive height anomalies in the stratosphere over Asian continent and the negative height anomalies in the middle latitudes.

#### 4.3 Three Dimensional Characteristics of the Abnormal Circulations During the Extreme Cold Event

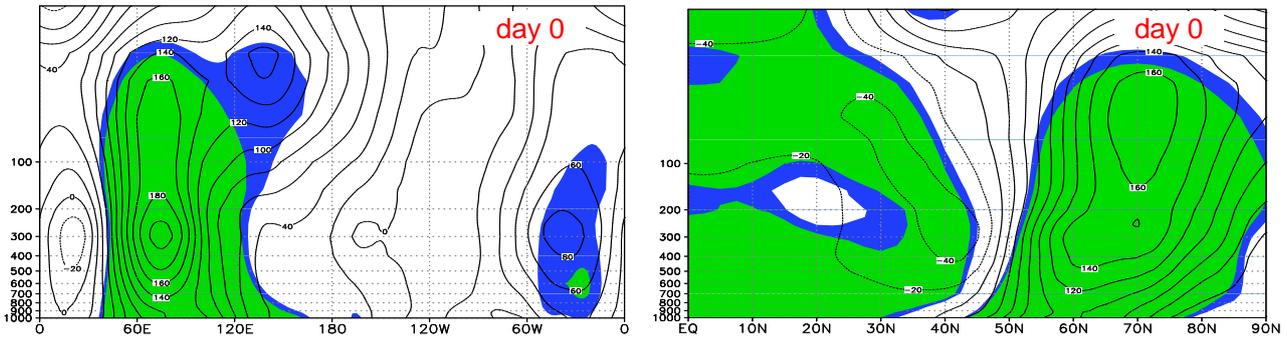
As mentioned above, there were two anomalous atmospheric circulation systems that affect the EPECE in China. In this section, we examine the vertical structures of these anomalous circulation systems. Figure 4 presents vertical distributions of height anomaly composites along two transects crossing the Ural Mountains during the outbreak of the EPECE in China. These two transects chosen for this study are a meridional transect between 60° and 70°N (Figure 4A) and a zonal transect between 20° and 80°E (Figure 4B). The height anomalies are positive from the stratosphere to troposphere at these two transects crossing the Ural Mountains.

#### 4.4 Characteristics of Vertical Transmission

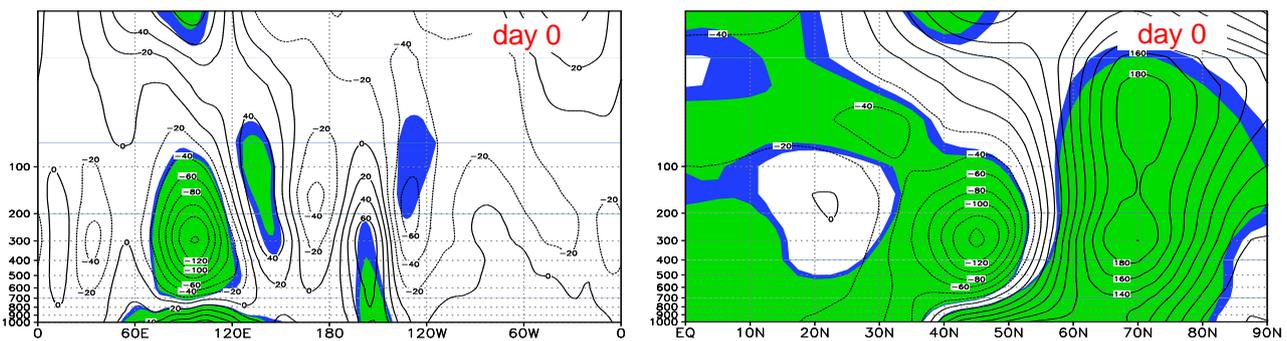
The above discussions demonstrate that the abnormal circulation in the troposphere is correlated with the stratosphere. A natural question raised is whether the abnormal signals in the troposphere can propagate downward to the stratosphere during the EPECE in China. We address this question by examining vertical structures of height anomaly composites at a zonal section, which are averaged meridionally between 65° and 75°N (Figure 6). During the EPECE, the height anomalies are consistent and all positive from the troposphere to stratosphere over Asia, but with different magnitudes. The vertical distributions of anomaly magnitudes indicate that the positive height anomalies propagate downward from the stratosphere to troposphere. For the period from day -14 to -10, the central positive anomaly is located in the upper stratosphere, with magnitudes ranging between 160 and 280 gpm (Figure 6). These positive height anomalies have strong tendency of downward propagations and affect the geopotential height fields in the lower stratosphere. The centre of positive height anomalies reaches the middle stratosphere at day -6 and then continues to propagate downward after this time. At day -4, a center



**Figure 3.** Distributions of 20 hPa height anomaly composites (contour interval of 1 gpm) during extensive and persistent extreme cold events at days  $-18$ ,  $-16$ ,  $-14$ ,  $-12$ ,  $-10$ ,  $-8$ ,  $-6$ ,  $-4$ ,  $-2$ ,  $0$ ,  $2$ ,  $4$ ,  $6$ ,  $8$ , and  $10$  (relative to the day of the extreme cold event occurrence). Green and blue shading areas represent that significant levels reach 5% and 10% respectively.



**Figure 4.** Vertical distributions of (A) latitude-averaged ( $60^{\circ}$ – $70^{\circ}$ N) height anomaly composites at the zonal transect at  $65^{\circ}$ N and (B) longitude-averaged ( $40^{\circ}$ – $80^{\circ}$ E) height anomaly composites at the meridional transect at  $60^{\circ}$ E on the North Hemisphere (contour interval of 1 gpm). Green and blue shading areas represent that significant levels reach 5% and 10% respectively.

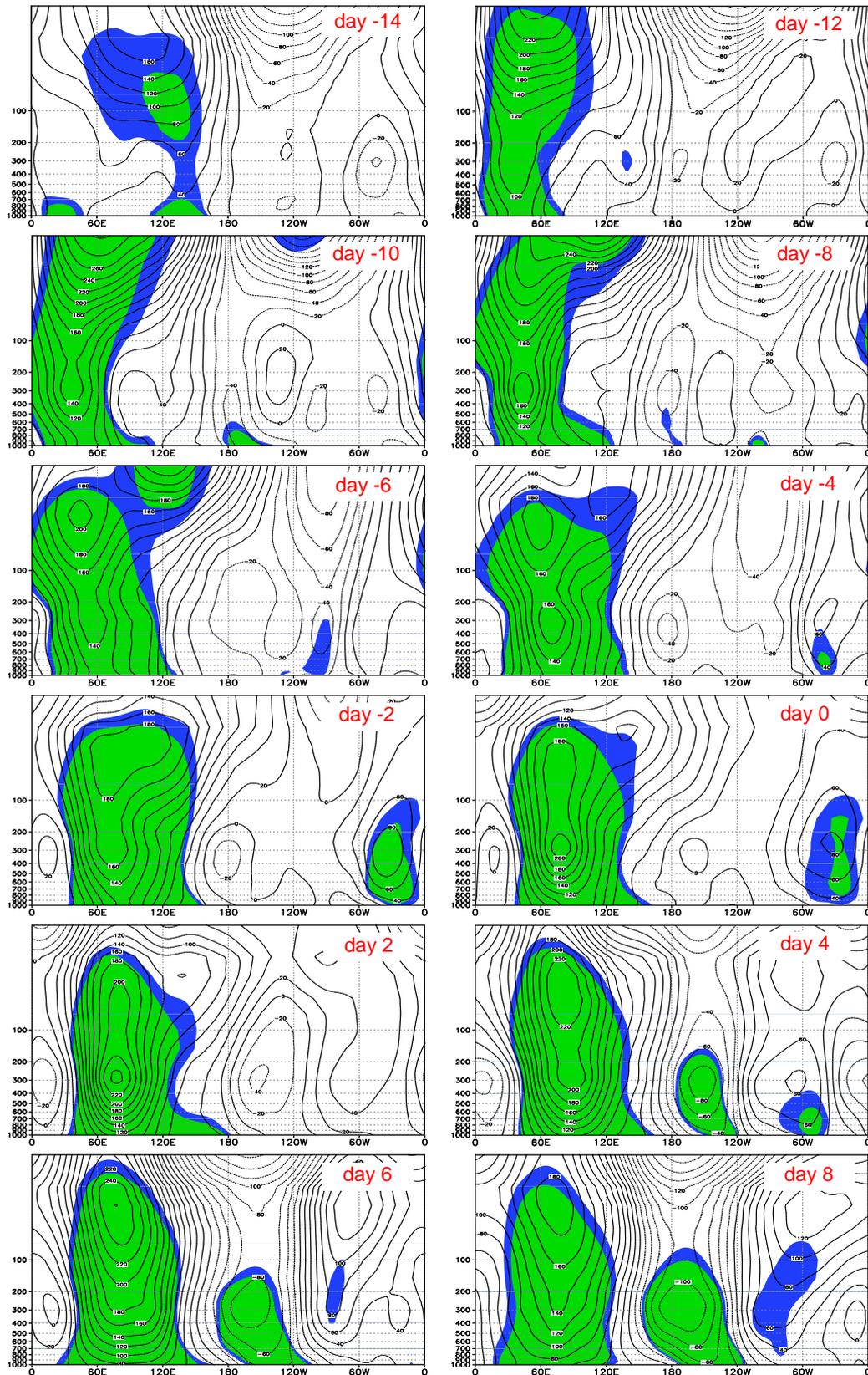


**Figure 5.** Vertical distributions of (A) latitude-averaged ( $40^{\circ}$ – $50^{\circ}$ N) height anomaly composites at the zonal transect at  $45^{\circ}$ N and (B) longitude-averaged ( $80^{\circ}$ – $100^{\circ}$ E) height anomaly composites at the meridional transect at  $90^{\circ}$ E on the North Hemisphere (contour interval of 1 gpm). Green and blue shading areas represent that significant levels reach 5% and 10% respectively.

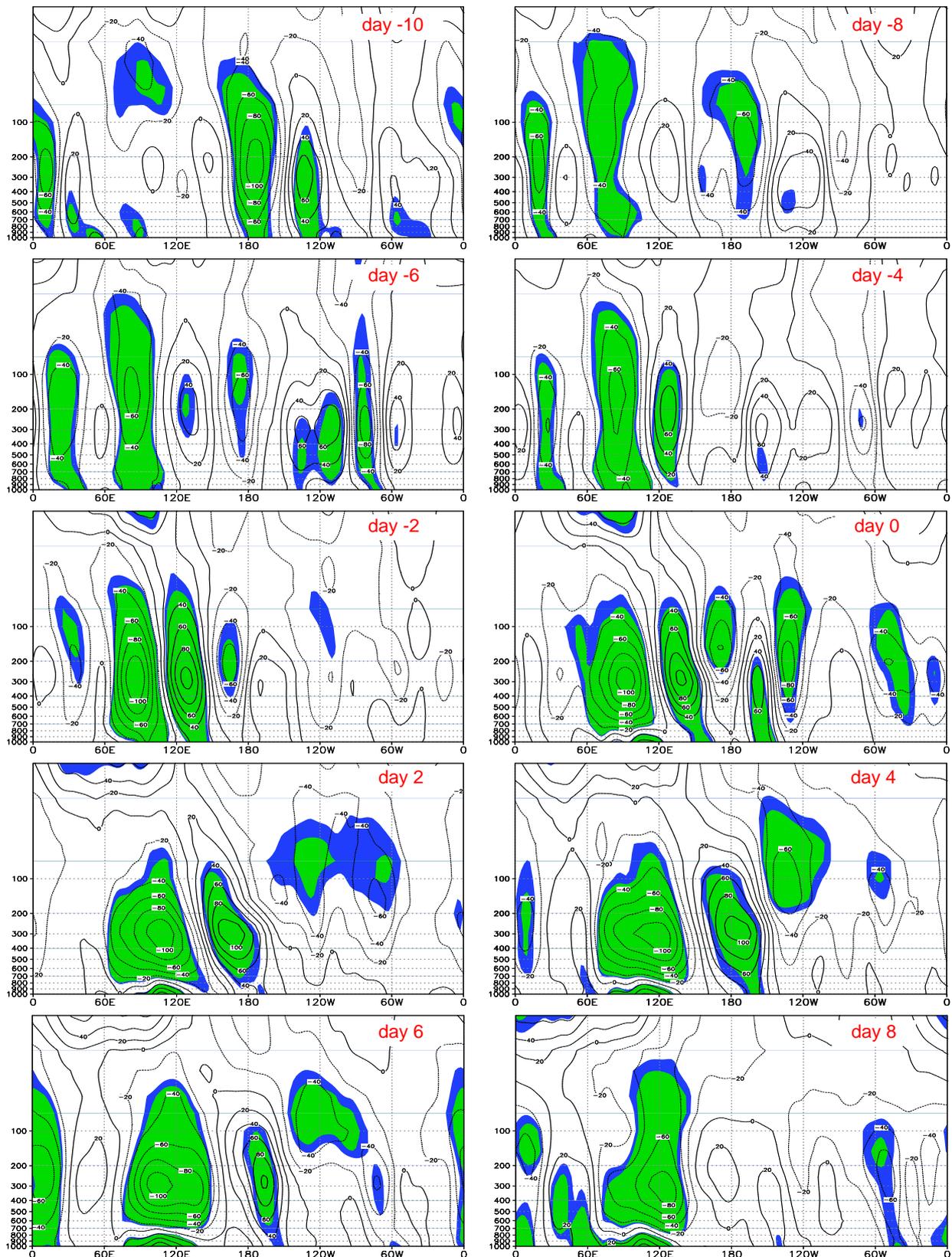
of height anomalies appears in the middle and upper troposphere between  $60^{\circ}$ E– $80^{\circ}$ E, with the amplitude of  $\sim 160$  gpm. The main part of these positive anomalies at this time, however, still remains in the middle stratosphere, with amplitudes of  $\sim 180$  gpm. During the outbreak of the EPECE, the positive height anomalies in the stratosphere are minimum. At this time, the central part of the anomalies reaches the upper and middle troposphere after continuous downward propagations, with magnitudes of  $\sim 200$  gpm. By day 2, the anomalies in the middle troposphere reaches a maximum value of 240 gpm. Figure 6 also shows that, by day 4, the center of positive anomalies in the troposphere weakens significantly and then disappears, and a new center of positive anomalies is formed in the stratosphere. The magnitude of this new centre of positive anomalies reaches a maximum at day 6. After this time, the positive anomalies in both the stratosphere and the troposphere weaken.

Figure 7 presents vertical structures of height anomaly composites along a zonal section, which are averaged meridionally between  $35^{\circ}$  and  $45^{\circ}$ N. An examination of anomalous amplitudes shown in the fig-

ure demonstrates that negative height anomalies propagate downwards from the stratosphere to troposphere. At day  $-10$ , there is an intense negative height anomalous system in the stratosphere, with the central value of more than  $-60$  gpm. By comparison, the negative height anomalies in the troposphere are relative weak at this time, even with some positive anomalies above this layer. After day  $-10$ , the negative height anomalies in the stratosphere propagate downward to troposphere, resulting in the development of negative anomalies in the troposphere. By day  $-6$ , a new center of negative height anomalies is formed in the stratosphere, with a maximum value of about  $-60$  gpm. These negative anomalies in the stratosphere gradually intensify with time and the central value reaches about  $-100$  gpm at day  $-2$ . At the same time, positive height anomalies appear in the stratosphere, and propagate downward gradually. The center of negative height anomalies in the troposphere continues to propagate to the middle troposphere, with the content expanding eastward and westward. By day 8, however, the negative height anomalies in the troposphere weaken significantly with the central magnitude reducing to  $-80$  gpm.



**Figure 6.** Vertical distributions of latitude-averaged ( $65^{\circ}$ – $75^{\circ}$ N) height anomaly composites at the zonal transect at  $70^{\circ}$ N during the extensive and persistent extreme cold event at days  $-14$ ,  $-12$ ,  $-10$ ,  $-8$ ,  $-6$ ,  $-4$ ,  $-2$ ,  $0$ ,  $2$ ,  $4$ ,  $6$ , and  $8$  (relative to the day of the extreme cold event occurrence). Green and blue shading areas represent that significant levels reach 5% and 10% respectively.



**Figure 7.** Vertical distributions of latitude-averaged ( $35^{\circ}$ – $45^{\circ}$ N) height anomaly composites at the zonal transect at  $40^{\circ}$ N during the extensive and persistent extreme cold event at days  $-10$ ,  $-8$ ,  $-6$ ,  $-4$ ,  $-2$ ,  $0$ ,  $2$ ,  $4$ ,  $6$ , and  $8$  (relative to the day of the extreme cold event occurrence). Green and blue shading areas represent that significant levels reach 5% and 10% respectively.

These negative anomalies in the troposphere propagate upward to the stratosphere. At this time, the height anomalies are consistently negative from the stratosphere to troposphere.

The central positions and magnitudes of height anomalies discussed above demonstrate that the negative geopotential height anomalies in the stratosphere propagate downward and gradually influence the negative anomalies in the entire troposphere during the 12-day period just before the outbreak of the EPECE. During the 4-day period just after the outbreak of the EPECE, by comparison, the negative anomalies in the troposphere develop continuously. After this 4-day period, the negative anomalies in the troposphere weaken and propagate upward to the troposphere, resulting in significant changes to the geopotential height anomalies in the entire stratosphere.

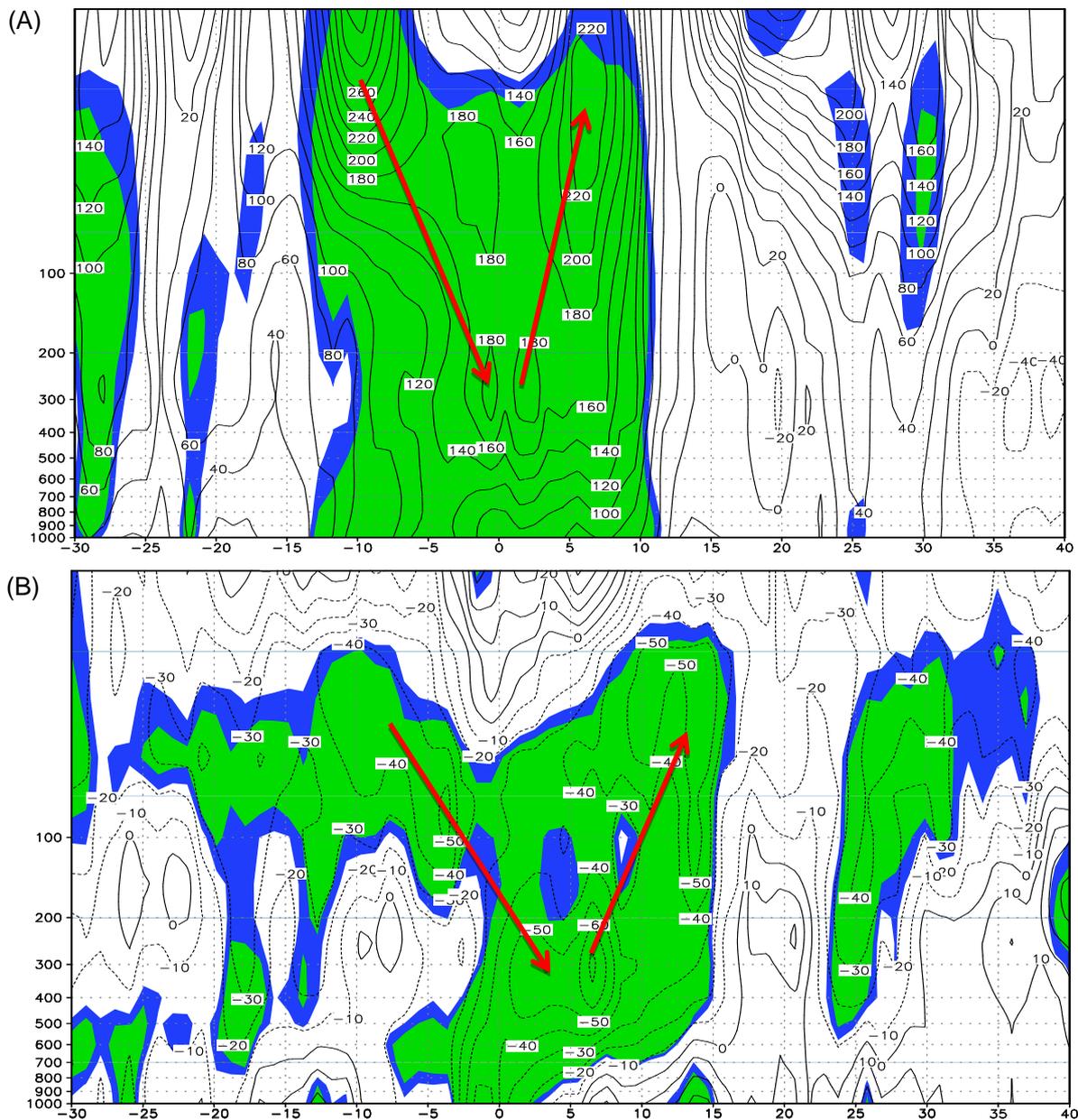
As mentioned above, in the middle troposphere, positive geopotential height anomalies appear in the region to the northwest of Lake Baikal and Lake Balkhash and negative anomalies in the region to the southeast of these two Lakes. Over the Ural Mountains, the geopotential height anomalies in the stratosphere are all positive. These positive anomalies in the stratosphere propagate downward and affect the generation and development of the high pressure ridge in the middle troposphere over the Ural Mountains. Consequently, significant changes occur in the abnormal circulation in the stratosphere in the mid latitudes. These changes in the stratosphere propagate downward, leading to intensification of the low pressure trough in the troposphere over the region to the east of Lake Balkhash and Lake Baikal. After the outbreak of the EPECE, both the positive and negative anomalies in the troposphere propagate upwards to the stratosphere, leading to weakening of the large-scale tilted trough, as an indication of the end of the EPECE in China.

To further examine the relationship between these geopotential height anomalies in the stratosphere and troposphere, we next examine the time-height distribution of positive and negative height anomaly composites averaged spatially over the region of  $65^{\circ}$ – $70^{\circ}$ N and  $50^{\circ}$ – $70^{\circ}$ E (Figure 8A). By day  $-14$ , significant abnormal geopotential heights have already developed in the upper stratosphere. These height anomalies propagate downward with time to the lower stratosphere and the downward propagation continues until day  $-10$ . During the period between day  $-10$  and 0, the positive height anomalies in the stratosphere weaken gradually and propagate downward to the troposphere.

During this period, by comparison, the positive anomalies in the troposphere intensify. After the outbreak of the EPECE, the positive height anomalies in the troposphere weaken in time and propagate gradually upwards to the stratosphere. During the same period, positive height anomalies in the stratosphere enhance and reach a maximum at day 6. Therefore, during the whole episode of the EPECE, the propagation of height anomalies from the troposphere to stratosphere results in the development and expansion of positive anomalies and associated abnormal circulation in the middle troposphere over the Ural Mountains region. The downward propagation of abnormal circulation in the troposphere onto the stratosphere causes the positive height anomalies in the middle troposphere to weaken over the Ural Mountains region.

Figure 8B presents the time-height distribution of height anomalies at the position of  $35^{\circ}$ N and  $100^{\circ}$ E to demonstrate the evolution of negative anomalies during the episode of the EPECE. For the period between day  $-10$  and 0 (prior to the outbreak of the EPECE), the negative height anomalies in the stratosphere weaken with time and propagate downward to the troposphere, resulting in intensification of negative anomalies in the troposphere. After the outbreak of the EPECE, the negative anomalies in the middle and upper troposphere further strengthen and reach a maximum at day 6. The upward propagation of negative height anomalies from the troposphere to stratosphere leads to the significant weakening of negative height anomalies in the troposphere and strengthening of negative height anomalies in the stratosphere. Therefore, the downward propagation of abnormal signals in the stratosphere to the troposphere causes the negative anomalies and associated abnormal circulation in the middle troposphere to weaken, and the upward propagation of abnormal signals in the troposphere to the stratosphere causes the negative height anomalies and associated abnormal circulation in the middle troposphere to weaken.

The above discussions indicate that the occurrence of the EPECE in China is strongly correlated with the changes in the stratospheric circulation. Previous studies demonstrated that the potential vorticity (PV) changes are the main dynamic mechanism for the impact of the abnormal circulation in the stratosphere to the abnormal tropospheric circulation. The abnormal PV in the middle and lower stratosphere provides favorable conditions for maintaining height anomalies in the middle and upper troposphere over the region. The



**Figure 8.** Time-height distributions of height anomaly composites (A) averaged spatially over the region of 65°–70°N and 50°–70°E, and (B) at 35°N and 100°E during the period from day –30 to day 40 (relative to the day of the extreme cold event occurrence). Green and blue shading areas represent that significant levels reach 5% and 10% respectively.

former explains about 25% of the latter amplitude (Shi and Bueh, 2015).

### 5. Summary

This study conducted a composite analysis of the large-scale atmospheric circulation and examined the evolution of the stratospheric and tropospheric circulation during the extensive and persistent extreme cold event (EPECE) in China. The result of the composite analysis revealed the important role of geopotential

height anomalies and associated atmospheric circulations in the generation and dissipation of the EPECE. In particular, our results demonstrated the relationship between the propagation of height anomalies between the stratosphere and troposphere associated with the generation and dissipation of the EPECE in China.

We demonstrated that the occurrence of the EPECE in China is correlated with the abnormal atmospheric circulation over the Asian continent. At day 10 before the outbreak of the EPECE, geopotential height ano-

malies are positive around the island of Novaya Zemlya and negative in the region to the west of Lake Baikal. Both the positive and negative height anomalies strengthen and move southeastward, resulting in the development of positive height anomalies in the Ural Mountains region and negative height anomalies in Lake Baikal regions, which provide favorable conditions for the generation, development, and stability of the large-scale tilted trough. At the end of the EPECE, both the positive and negative height anomalies weaken significantly, and the negative anomalies located originally in Lake Baikal move eastwards into the sea.

We also demonstrated that a significant abnormal signal appears in the stratospheric circulation more than 10 days before the occurrence of the EPECE. The geopotential height anomalies in the stratosphere are positive over the Arctic region. These positive height anomalies propagate downward into the troposphere, strengthening the generation and expansion of the low pressure trough in the middle troposphere over the Ural Mountains. After the occurrence of the EPECE, both the positive and negative height anomalies in the troposphere propagate upwards to the stratosphere and weaken of the large-scale tilted ridge and trough, which is an indication of the end the EPECE.

### Conflict of Interest

No conflict of interest was reported by all authors.

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