Comparison of two severe low-temperature snowstorm and ice freezing events in China: Role of Eurasian mid-high latitude circulation patterns

Zunya Wang | Yihui Ding | Botao Zhou | Lijuan Chen

1National Climate Center, China Meteorological Administration, Beijing, China
2Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters/Key Laboratory of Meteorological Disaster, Ministry of Education/Joint International Research Laboratory of Climate and Environment Change, Nanjing University of Information Science and Technology, Nanjing, China

Abstract
A severe low-temperature snowstorm and ice freezing event occurred in China in early 2018. This event was similar to that occurred in early 2008 but with a weaker intensity and salient difference in location and extent. The reason for this discrepancy was investigated in this study using station data and atmospheric reanalysis data. The results reveal that two different circulation patterns (i.e., zonal dipole pattern and meridional dipole pattern) over the mid-high latitudes of Eurasia played an important role. The zonal dipole pattern, which is closely related to the 2018 event, is characterized by positive anomalies over the Ural Mountains and negative anomalies over Lake Baikal in the 500 hPa geopotential height field. This pattern can cause intense low temperatures in northern China through its influence on the anomalous cyclone over Northeast Asia. The meridional dipole pattern, which is highly associated with the 2008 event, is characterized by positive anomalies over Siberia and negative anomalies over Asia in the 500 hPa geopotential height field. This pattern corresponds to a strong East Asian winter monsoon (EAWM) and can drive cold air to move further southward, causing nearly nationwide chilly weather, particularly in northwestern China and south of the Yangtze River valley. The two patterns, combined with the strengthened western Pacific subtropical high (WPSH), have a synergistic role in the occurrence of snowfall. However, these patterns have weak correlations with the number of icy days but provide favourable conditions for ice freezing events.

KEYWORDS
Eurasian mid-high latitude dipole pattern, ice freezing, low temperature, snowstorm

1 | INTRODUCTION
The weather and climate over China are greatly affected by the East Asian winter monsoon (EAWM) (Ding, 1994; Chan and Li, 2004; Chang et al., 2006). A strong EAWM typically features a strong Siberian high and surface northerlies (Ding and Krishnamurti, 1987). Due to the influence of intensified northerly airflows, cold air moves...
southward from the polar region and causes a dramatic drop in temperature, chilly weather, snowstorms and ice freezing, which can result in great economic losses and adverse social impacts (Chang and Lun, 1982; Ding, 1994; Zhang et al., 1997; Huang et al., 2007; Bueh et al., 2011; Wang et al., 2011; Li and Wang, 2012; Wang and Chen, 2014; Lu et al., 2016; Wang et al., 2017). Thus, the variability in cold-related extreme events has been highly

**FIGURE 1** Daily mean temperature anomaly (a and d, unit: °C), snowfall amount (b and e, unit: mm) and the number of glaze and rime days (d and f, unit: day) during 13 January to 4 February, 2008 (a–c) and 4–28 January 2018 (d–f) from the CMA station dataset. In (c) and (f), the blue dots denote the number of glaze days and the green dots denote the number of rime days.
In recent winters, cold surges and snowstorms frequently affected the Northern Hemisphere continents and led to large amounts of damage (Easterling and Wehner, 2009; Kerr, 2009; Knight et al., 2009). In China, an unprecedented cold-related event with a concurring low-temperature snowstorm and ice freezing occurred from mid-January to early February in 2008 (hereafter known as the 2008 event). This event affected more than 100 million people and resulted in a direct economic loss of over 20 billion US dollars (Zhou et al., 2011). Due to the severity of this event, a number of studies have explored the physical factors responsible for the occurrence of this event. It has been documented that the circulation anomalies over the mid-high latitudes of Eurasia play a significant role (Ding et al., 2008; Ye et al., 2015; Liao et al., 2018; Chen et al., 2019). The long-lasting Ural blocking and trough over Lake Baikal-Lake Balkhash led cold air to move intensely southward, thereby causing persistent chilly weather (Liao et al., 2018). Actually, the broad meridional meander of the Eurasian mid-high latitude circulations has been revealed to be closely associated with cold-related events during the wintertime (Park et al., 2008; Liu et al., 2012). The Arctic oscillation (AO) and the middle east jet stream also had important contributions (Wang et al., 2009; Wen et al., 2009). Although the La Niña event was in the mature phase during the winter of 2007/2008, this event was not thought to be the direct cause but believed to have provided a favourable background (Ding et al., 2008; Wen et al., 2009).

Interestingly, another severe low-temperature snowstorm and ice freezing event occurred during January 2018 (hereafter known as the 2018 event), with low temperatures covering northern and central-eastern China, the snowstorm spreading across the extensive regions, and ice freezing appearing in parts of southern China (Figure 1). More than 4.3 million people from 11 provinces (municipalities) were affected, and the direct economic loss reached 0.54 billion US dollars. However, few studies have investigated the cause of this event. Thus, the authors of this study are motivated to examine the large-scale atmospheric features related to this event, with the aim of addressing the following three questions: (a) What are the large-scale atmospheric circulation conditions responsible for the 2018 event? (b) What are the similarities and differences in atmospheric circulations for the 2018 event and the 2008 event? (c) What implications can we obtain from the two cases?

The remainder of this paper is arranged as follows. The data and methods used in the current study are introduced in Section 2. The climate features and associated atmospheric circulation conditions for the 2018 event are presented in Section 3. The comparison with the counterparts for the 2008 event is also conducted in this section, through highlighting of the different roles of the two circulation patterns over the mid-high latitudes of Eurasia. The physical nature and climate implications of the two Eurasian mid-high latitude circulation patterns are further addressed in Section 4. Finally, the conclusions and a discussion are given in Section 5.

## 2 | DATA AND METHODS

The daily temperature and precipitation data from January 1, 1961 to January 31, 2018 from China’s 2,419 observation stations were used in this study. Of the 2,419 observation stations, 212 stations are national reference stations, 632 stations are national basic stations and 1,575 stations are national observatories. The dataset was compiled by the China Meteorological Administration (CMA) after quality control in terms of spatial consistency, temporal consistency and internal consistency testing (Cao et al., 2016; Ren et al., 2017). In the current study, the missing records were processed as follows: the winter (December–January–February, DJF) in a certain year with continuous missing records up to 20% was omitted, and the stations with consecutive non-omitted winters shorter than 30 years were removed. The stations with missing records for more than 3 days from 13 January to February 4, 2008 (time period for the 2008 event) or from 4–28 January 2018 (time period for the 2018 event) were also excluded. Finally, 2,343 stations remained for the temperature analysis and 2,360 stations remained for the precipitation analysis. The remaining missing records were replaced by their monthly averages.

The daily weather phenomena (including snowfall, glaze and rime) dataset from the 2,419 observation stations of the CMA was also employed. This dataset indicates whether a weather phenomenon occurs on a certain day. In this study, glaze and rime are used to characterize ice freezing in China. A day with the occurrence of either rime or glaze is defined as one icy day. The number of icy days derived from this dataset was adopted to measure the intensity of ice freezing. Similarly, the stations with more than three missing days during the period of the 2018 (2008) event were excluded, leaving 2,115 and 2,011 stations for the analyses of glaze and rime, respectively.

To determine the large-scale atmospheric circulation anomalies associated with the low-temperature snowstorm and ice freezing events in China, the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis daily data...
from January 1, 1961 to January 31, 2018 with a spatial resolution of 2.5° × 2.5° (Kalnay et al., 1996) were applied. The variables analysed include the geopotential height, zonal wind, meridional wind, vertical velocity, air temperature, sea level pressure (SLP), and specific humidity.

Regression and correlation analyses were adopted in this study to examine the mutual relationship between two variables, with a Student’s $t$-test used to check the statistical significance. For two variables $x$ and $y$, the regression (Reg) of the time series $y_i$ against the time
series $x_i$ was calculated in terms of the following formula:

$$\text{Reg} = \frac{\sum_{i=1}^{n} y_i x_i - \frac{1}{n} \left( \sum_{i=1}^{n} y_i \right) \left( \sum_{i=1}^{n} x_i \right)}{\sum_{i=1}^{n} x_i^2 - \frac{1}{n} \left( \sum_{i=1}^{n} x_i \right)^2}$$

and the correlation (Cor) between them was calculated as follows:

$$\text{Cor} = \frac{\sum_{i=1}^{n} (x_i - \frac{1}{n} \left( \sum_{i=1}^{n} x_i \right)) (y_i - \frac{1}{n} \left( \sum_{i=1}^{n} y_i \right))}{\sqrt{\sum_{i=1}^{n} (x_i - \frac{1}{n} \left( \sum_{i=1}^{n} x_i \right))^2} \sqrt{\sum_{i=1}^{n} (y_i - \frac{1}{n} \left( \sum_{i=1}^{n} y_i \right))^2}}$$

### 3 | COMPARISON OF THE 2018 EVENT AND THE 2008 EVENT

We first compared the anomalies in temperature, snowfall and the number of glaze and rime days during 4–28 January 2018 (the 2018 event) with the counterparts during 13 January to February 4, 2008 (the 2008 event) to address the similarity and difference between the two events. Then, to understand the cause of this similarity and difference, the large-scale atmospheric circulation patterns during the processes of the two events were examined in this section.

#### 3.1 | Temperature, snowfall and ice freezing

During the 2018 event, as shown in Figure 1d, the negative temperature anomalies were mainly located in northern and central-eastern China, where the daily mean temperature was generally below normal by more than 1°C. The maximum below-normal anomalies exceeding 4°C were found in the northern part of northwest China (Figure 1d). In comparison, much broader negative temperature anomalies with greater amplitudes were observed for the 2008 event. During this event, most of China was covered in temperature anomalies of more than 2°C below normal. In particular, over the arch-shaped region from northwest through central China to southern China, the temperature was more than 4°C below normal (Figure 1a).

Heavy snowfall affected a large area of southern China during the two events, and the maximum accumulated amounts reached above 50 mm (Figures 1b and e). However, compared with the 2008 event (Figure 1b), the snowfall is relatively less extent, and the area with great snowfall shifted northeastward during the 2018 event. In addition, large amounts of snowfall were also observed in

| northeast and northwest China during the 2018 event (Figure 1e).

Glaze and rime are two major types of ice freezing in China. Glaze is primarily distributed along and to the south of the Yangtze River valley, while rime is mainly observed in scattered locations to the north of the Yangtze River valley. Climatologically, the number of annual mean glaze and rime days ranges from 1 to 5 days in most regions and exceeds 5 days in a few locations with special terrains, such as high mountain and leeward slopes (Wang et al., 2014, 2017). During the 2008 event, the glaze persisted for up to 15 days at 114 stations south of the Yangtze River valley (Figure 1c). For the 2018 event, the glaze lasted 3–5 days to a lesser extent (Figure 1f).

In short, the intensity of the low-temperature snowstorm and ice freezing during the 2018 event is weaker than that during the 2008 event. The severe low-temperature and heavy snowfall during the 2018 event is concentrated in northern and central-eastern China. During the 2008 event, severe low temperatures occurred nearly nationwide, and heavy snowfall was located in southern China.

#### 3.2 | Large-scale atmospheric circulation patterns

Figure 2 shows the patterns of 500 hPa geopotential height, 850 hPa horizontal winds, and SLP from the NCEP/NCAR reanalysis during the two events. In the mid-troposphere (500 hPa), during the 2008 event, a meridional dipole pattern with positive and negative geopotential height anomalies residing on the north and south region, respectively, was observed to dominate the mid-high latitudes of Eurasia (Figure 2a). As the warm air was pushed continuously poleward, the Ural blocking expanded and controlled most parts of the Eurasian high latitudes, while the cold air was cut off and thus maintained across extensive regions of Asia. This pattern favoured the intense southward outbreak of cold air invading China. On the other hand, the negative geopotential height anomalies over Asia deepened the Indian–Burma trough, thereby enhancing the northward transportation of moisture from the Bay of Bengal to China. During the 2018 event, a zonal dipole pattern was observed with positive anomalies over the Ural Mountains and negative anomalies over Lake Baikal (Figure 2d). This pattern was favourable for intensification of the East Asian trough. Because of its location, the anomalous trough only affected northern and eastern China. In addition, compared with the normal status, the western Pacific subtropical high (WPSH) was stronger and located northward in both events.
The lower-tropospheric circulation presents highly dynamic consistency with that in the mid-troposphere. During the 2008 event, the 850 hPa circulation over the Eurasian mid-high latitudes was characterized by an anticyclonic anomaly to the north and a cyclonic anomaly to the south (Figure 2b), corresponding to the meridional dipole pattern shown in Figure 2a. The intense northerly and easterly airflows prevailed over most of China, exhibiting a classic strong EAWM (Ding and Krishnamurti, 1987). For the 2018 event, an anomalous anticyclone to the west and an anomalous cyclone to the east were noticed over the mid-high latitudes of Eurasia (Figure 2e), matching the zonal dipole pattern at 500 hPa (Figure 2d). The northerly airflows were weaker and did not stretch as far southward as that in the 2008 event. This may account for why the intensity of low temperature is weaker and its extent is narrower during the 2018 event than during the 2008 event. In addition, anomalous anticyclonic circulation existed over the western subtropical Pacific for both events, but the location was more eastward and northward during the 2018 event than during the 2008 event.

The distribution of SLP anomalies for the 2008 event and the 2018 event (Figure 2c and f) also resembles the 500 hPa meridional and zonal dipole patterns, respectively. The dynamic up and down consistency illustrates that the circulation system affecting the two events was deep and barotropic. The strengthened Siberian high during the 2008 event corresponds to a stronger-than-normal EAWM. The Siberian high during the 2018 event was located further westward. Following three indices defined by the SLP over Siberia (Wu and Wang, 2002), the surface meridional wind over East Asia (Chen et al., 2000), and the zonal difference of 500 hPa zonal

**FIGURE 3** Anomalies in water vapour transportation flux integrated from surface to 300 hPa (a and c, vector, unit: kg⋅s⁻¹⋅m⁻¹) and its divergence (a and c, shading, unit: 10⁻⁵ kg⋅s⁻¹⋅m⁻²) as well as the 500 hPa vertical velocity (b and d, unit: 10⁻² pa⋅s⁻¹) during 13 January to 4 February, 2008 (a–b) and 4–28 January 2018 (c–d) from the NCEP/NCAR reanalysis. The negative (positive) values in (a) and (c) indicate the convergence (divergence) of water vapour and that in (b) and (d) indicate ascending (descending) motions.
wind over East Asia (Zhu, 2008) to measure the EAWM intensity, we calculated the EAWM intensity during both events and found that all of them consistently indicated a stronger EAWM in the 2008 event than in the 2018 event.

The aforementioned circulation anomalies could provide advantageous moisture and dynamic conditions for the occurrence of heavy snowfall. As shown in Figure 3a and c, anomalous southerly water vapour transportation toward China was apparent for both events. Due to the stronger WPSH and deepened Indian–Burma trough, the water vapour supply was stronger during the 2008 event than during the 2018 event. The ascending motion was intensified across large parts of China, and the airflows ascended more intensely over a much broader region in southern China during the 2008 event than during the 2018 event (Figures 3b and d). Better moisture supply and dynamic conditions induced heavier snowfall in southern China for the 2008 event than for the 2018 event.

The inversion layer is crucial for the occurrence of glaze and rime. The relatively warm layer between the lower and upper cold layers melts the ice crystals falling into the water droplets. The water droplets turn into super-cooled water droplets when they reach the lower cold layer and are frozen into ice while striking ground objects (Wang et al., 2014, 2017). The intensity of the inversion layer can be approximated by the temperature difference between 925 and 850 hPa, with a negative value indicating an inversion layer and the larger absolute value corresponding to a stronger inversion layer. Figure 4 shows the intensity of the inversion layer during the two events as calculated from the NCEP/NCAR reanalysis. As shown in Figure 4a, during the 2008 event, a remarkable inversion centre dominated southern China, resulting in the large number of glaze days locally. However, during the 2018 event, the inversion layer was not evident. Only a relatively low-value centre was maintained over southern China (Figure 4b). As a result, the glaze days was reduced during the 2018 event.

4 | PHYSICAL SENSE AND CLIMATE IMPLICATION OF THE EURASIAN MID-HIGH LATITUDE CIRCULATION PATTERNS

From the above case studies, two dipole patterns (i.e., meridional dipole pattern and zonal dipole pattern) in the Eurasian mid-high latitudes were found to be the key circulations affecting the concurring low-temperature snowstorm and ice freezing events in China. A question naturally arises as to whether the dipole patterns have specific physical senses and implications for the inter-annual variability in winter climate in China. In this section, an answer to this question is sought.

To quantify the two dipole patterns, the normalized difference between the 500 hPa geopotential height averaged over 60°–110°E/50°–70°N and that averaged over 60°–110°E/30°–50°N was defined as the meridional intensity index (MI) to describe the meridional dipole pattern; the normalized difference between the 500 hPa geopotential height averaged over 40°–80°E/50°–75°N and that over 90°–135°/40°–65°N was defined as the zonal intensity index (ZI) to depict the zonal dipole pattern.

Figure 5 shows the regressions of winter 500 hPa geopotential height anomalies onto the series of the MI and ZI indices, respectively, which were calculated based on the NCEP/NCAR reanalysis. Figure 5a indicates that the meridional dipole pattern is part of the wave train from the North Atlantic to East Asia via Europe, which is highly similar to the Eurasia teleconnection (EU). We
calculated the EU index (EUI) following the definition of Wallace and Gutzler (1981):

\[
\text{EUI} = -\frac{1}{4} Z^{*}\text{55°N,20°E} + \frac{1}{2} Z^{*}\text{55°N,75°E} - \frac{1}{4} Z^{*}\text{40°N,145°E}
\]

where \(Z^{*}\) represents the normalized winter 500 hPa geopotential height. The high correlation (0.69, higher than the 99% confidence level) between the EUI and MI confirms the close linkage of the meridional dipole pattern to the EU teleconnection.

The regression of winter 500 hPa geopotential height against the ZI (Figure 5b) exhibits a circulation pattern similar to the AO negative phase (Thompson and Wallace, 1998). The correlation between the winter AO index (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_aod_index/ao.shtml) and the ZI is −0.44, exceeding the 99% confidence level. In addition, we also see that negative, positive and negative centres successively cover Europe, the Ural Mountains and Northeast Asia in a zonal direction, which is characteristic of a zonal wave train (Figure 5b). The correlation between the ZI and the EUI reaches 0.46, which also exceeds the 99% confidence level. This finding suggests that the zonal dipole pattern may exhibit a mixed characteristic of the AO and the EU teleconnection.

To further clarify the physical nature of the meridional and zonal dipole patterns over Eurasia, we performed an empirical orthogonal function (EOF) analysis on the winter 500 hPa geopotential height over the 0°–180°/20°–80° region. Interestingly, the first leading mode (PC1), explaining the 35.7% variance (figure not shown), is highly similar to the zonal dipole pattern. The correlation coefficient between PC1 and ZI reaches 0.85, exceeding the 99.9% confidence level. The second mode (PC2), accounting for the variance of 15.8% (figure not shown), resembles the meridional dipole pattern. The correlation between PC2 and MI is up to 0.63, which exceeds the 99% confidence level. Therefore, the meridional and zonal dipole patterns actually represent the major modes of the Eurasian mid-high latitude circulation.
**FIGURE 6** Regressions of 850 hPa wind against the MI (a) and ZI (b) during winter (DJF) from the NCEP/NCAR reanalysis. Blue shadings indicate that the regressed horizontal wind anomalies are significant above the 95% confidence level. The regions with altitudes exceeding 1,500 m are blanked and outlined by thick black lines.

**FIGURE 7** Regressions of sea level pressure against the MI (a) and ZI (b) during winter (DJF) from the NCEP/NCAR reanalysis. Blue (green) shadings indicate that the positive (negative) anomalies in the regressed sea level pressure are significant above the 95% confidence level.
Figure 6 shows the low-level circulations related to the MI and ZI indices during winter. Associated with the meridional dipole pattern, an anomalous cyclone covers East Asia, and the northerly anomalies prevail in China, exhibiting the typical feature of a strong EAWM. However, when the zonal dipole pattern is dominant, the anomalous cyclone only controls Northeast Asia. The situation for the change in SLP is similar. As shown in Figure 7, the high and low centres of the SLP anomalies correspond well to the ridge and trough at the 500 hPa level. The location of the Siberian high related to the meridional dipole pattern being further eastward than that related to the zonal dipole pattern is also consistent with the result from the aforementioned case study (see Figure 2c and f).

The above analyses indicate that the meridional and zonal dipole patterns over the Eurasian mid-high latitudes, which were identified from the case study of the 2008 and 2018 events, indeed have significant impacts on the East Asian winter circulations. Both exhibit barotropic structures and enable cold air to invade China. In particular, the meridional dipole pattern is apparently connected to a stronger EAWM. The correlation coefficients between the MI and three indices of the EAWM intensity defined by Wu and Wang (2002), Chen et al. (2000) and Zhu (2008) are 0.70, 0.52 and 0.88, respectively, and all are larger than their correlations with the ZI, which are 0.42, 0.24 and 0.47, respectively. The two patterns are also significantly related to the formation of the inversion layer over southern China.
which is favourable for the occurrence of glaze.

To reveal the implication of dipole patterns on climate variability, regression analyses were also applied to examine their linkages to station temperature and precipitation in China. As shown in Figure 9a, the meridional dipole pattern has a significant relationship with low temperatures across most of China, particularly in northwestern China and south of the Yangtze River valley. When the zonal pattern is maintained (Figure 9b), significant low-temperature occurs in northern and central-eastern China, with particularly cold regions located in northeast and northwest China.

For precipitation, the meridional dipole pattern generally results in less-than-normal precipitation in most areas of northern and central-eastern China but more-than-normal precipitation in southern China (Figure 10a). An extensive dry condition results from the zonal dipole pattern, except that the greater-than-normal precipitation is maintained in parts of Northwest and Northeast China and the southeastern part of the Yangtze River valley (Figure 10b).

Since the dipole patterns may generally result in a large extent of dry conditions, an interesting question is how the abundant snowfall occurred in the 2018 and 2008 events. As the strong and northward-located WPSH was dominant during both events, the impacts of WPSH on precipitation in China were analysed. The normalized 500 hPa geopotential height averaged over 120°–140°/25°–40°N was defined as the index to indicate the WPSH intensity. Shown in the regressions of precipitation against the WPSH index during winter (Figure 11), significant greater-than-normal precipitation is observed across most of China, with the greatest amount of precipitation maintained over southeastern China, when the WPSH is stronger than normal.
Thus, it is speculated that the Eurasian mid-high latitude dipole patterns and the WPSH may play a synergistic role in the variation in precipitation. To test this speculation, we constructed a combined index by averaging the MI (ZI) and WPSH indices and calculated its regression with the station precipitation in China. As shown in Figure 12a, a distinct feature seen based on the combined meridional dipole pattern and strong-than-normal WPSH is that the more-than-normal precipitation extent over southern China expands largely northward. When the zonal dipole pattern combines with the stronger-than-normal WPSH, the precipitation also increases in central-eastern and southeastern China (Figure 12(b)). In general, these distributions are similar to those of the observed heavy snowfall that occurred during the 2008 and 2018 events, respectively, suggesting a synergistic role of the Eurasian mid-high latitude dipole patterns and the WPSH in the occurrence of snowfall in China.

Neither the two dipole patterns nor their combinations with the WPSH have significant correlations with the number of glaze and rime days in China. However, both patterns are highly correlated with the intensity of the inversion layer over southern China (figure not shown). Thus, the major roles played by the two dipole patterns in glaze in China are in leading the southward outbreak of cold air and forming the inversion layer over southern China.

5 | CONCLUSIONS AND DISCUSSION

In this study, we analysed the climate features and large-scale atmospheric circulations associated with the severe low-temperature snowstorm and ice freezing event that occurred in China during early 2018 (the 2018 event) and compared them with the event that occurred during early 2008 (the 2008 event). The results show that the intensities of low-temperature snowstorm and ice freezing during the 2018 event were weaker compared to the 2008 event. The severe low-temperature and heavy snowfall were concentrated in northern and central-eastern China during the 2018 event. However, during the 2008 event,
the severe low temperature was a nearly nationwide occurrence, and heavy snowfall covered southern China. The zonal and meridional dipole patterns over the Eurasian mid-high latitudes were revealed to play an important role in the discrepancy between the two events. The zonal dipole pattern featured by the positive anomalies over the Ural Mountains and negative anomalies over Lake Baikal contributed to the 2018 event, while the meridional dipole pattern characterized by the positive anomalies over Siberia and negative anomalies over Asia exerted a significant effect on the 2008 event.

The physical nature and climate implications of the two dipole patterns were further investigated. The zonal dipole pattern, largely resembling the first mode of the 500 hPa geopotential height over the Eurasian mid-high latitudes, exhibits a mixed characteristic of the AO and Eurasian (EU) teleconnections. The meridional dipole pattern generally corresponds to the second mode of the 500 hPa geopotential height over the EU mid-high latitudes, showing a close relationship with the EU teleconnection. The two dipole patterns have different effects on the East Asian winter circulation and China’s climate. In association with the meridional dipole pattern, the Siberia high is strengthened, the cyclonic anomaly dominates East Asia in the lower troposphere and the northerly anomalies prevail in China, which corresponds to a strong East Asian winter monsoon (EAWM) and may result in a nationwide decrease in temperature. The zonal dipole pattern is associated with the westward-shifted Siberian high and anomalous cyclone over Northeast Asia, causing a great decrease in temperature in northern China. The two patterns, combined with a strengthened western Pacific subtropical high (WPSH), have a synergistic role in the occurrence of snowfall. However, they have weak correlations with the number of glaze and rime days but provide an advantageous background for the intrusion of cold air and establishment of the inversion layer over southern China.

Notably, this study focused on the role of the dipole patterns over the Eurasian mid-high latitudes in the 2018 and 2008 events. The contribution from the external forcing is also important. For example, the mature phase of La Niña may provide a favourable background for these events (Ding et al., 2008; Sun et al., 2019) through its influence on the EAWM (Bueh and Ji, 1999) and moisture transport (Sun et al., 2019). Global warming, especially the decline in Arctic Sea ice (or Arctic amplification) in this context, also has great impacts (Cohen et al., 2012; Liu et al., 2012; Outten and Esau, 2012; Li and Wang, 2013; Ma et al., 2018). Liu et al. (2012) revealed that the decrease in the autumn Arctic Sea ice under the background of global warming favours the establishment of blocking and provides advantageous moisture conditions for increased snowstorms over North America, Europe and East Asia. Ma et al. (2018) argued that the dynamic effects of Arctic amplification can lead to more frequent blockings over the Ural region and a stronger Siberian high in North Asia, contributing to the occurrence of cold extremes in East Asia. Thus, further investigation on the synergy of internal and external factors as well as the combination of different external forcings are needed in the future to better understand the mechanism of cold-related events.

ACKNOWLEDGEMENTS

This research was jointly supported by the National Key Research and Development Program of China (2016YFA0600701), the National Natural Science Foundation of China (41730964 and 41675069), the Startup Foundation for Introducing Talent of Nanjing University of Information Science and Technology, and the National Program for Support of Top-notch Young Professionals.

ORCID

Botao Zhou https://orcid.org/0000-0002-5995-2378

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How to cite this article: Wang Z, Ding Y, Zhou B, Chen L. Comparison of two severe low-temperature snowstorm and ice freezing events in China: Role of Eurasian mid-high latitude circulation patterns. Int J Climatol. 2020;40:3436–3450. https://doi.org/10.1002/joc.6406