Impact of sea ice decline in the Arctic Ocean on the number of extreme low-temperature days over China

Feifan Ge1,2 | Tao Yan1 | Lu Zhou3 | Yuelin Jiang1 | Wei Li1 | Yufen Fan2 | Yishu Wang4 | Kebiao Mao5 | Wenge Wu6

1School of Resources and Environment, Anhui Agricultural University, Hefei, China
2Tongxiang Meteorological Bureau of Zhejiang, Tongxiang, China
3Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing, China
4Quzhou Meteorological Bureau of Zhejiang, Quzhou, China
5National Hulunber Grassland Ecosystem Observation and Research Station, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, China
6Anhui Academy of Agricultural Sciences, Hefei, China

Correspondence
Yuelin Jiang, School of Resources and Environment, Anhui Agricultural University, No. 130, Changjiang West Road, Hefei 230036, China.
Email: jiangyuelin239@163.com

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Abstract
The variation in the number of extreme low-temperature days (NELD) during winter over China is examined. The NELD mainly has a significant decreasing trend across China. The leading NELD empirical orthogonal function (EOF) mode also shows consistent change characteristics over China, and a Mann–Kendall (MK) test of its time coefficients indicates that the NELD abruptly changed in approximately 1980. The impact of sea ice concentrations in the Arctic Ocean on the NELD is investigated. Sea ice concentration declines in the Barents Sea and the sea east of Greenland have significant negative effects on the NELD. Sea surface temperatures in these regions are negatively correlated with the NELD. The study analyses the influence mechanism by researching the composite atmosphere variable anomalies between years with below-normal NELD and those with above-normal NELD.

KEYWORDS
Arctic, China, extreme low-temperature days, sea ice concentration, winter

1 INTRODUCTION

One of the greatest environmental problems facing humanity is climate change. Against the background of global warming, extreme climate events since the 20th century have become more frequent and stronger, and a number of weather events have caused large losses of life as well as a tremendous increase in economic losses from weather
hazards in recent years; the changes in the frequency or intensity of extreme weather and climate events have profound impacts on both human society and the natural environment (Easterling et al., 2000).

Various studies have focused on trends in the number of extreme low-temperature days (NELD) and extreme low temperatures; many studies have shown that the NELD has a decreasing trend and that the values of low-temperature extremes have been increasing on global and regional scales in the past decade (Alexander et al., 2006; Griffiths and Bradley, 2007; Jakob and Walland, 2016; Ashfold et al., 2017; Salman et al., 2017; Zhong et al., 2017). Some studies have predicted future changes in the NELD through different models, and most results have revealed that the NELD would decrease and the extreme low temperatures would become warmer (Easterling et al., 2000; Saha et al., 2006; Fonseca et al., 2016). There is general agreement that atmospheric circulation directly influences the risk of temperature extremes. George et al. (2004) thought that the North Atlantic Oscillation could significantly influence the winter climate of the UK winter climate; a negative North Atlantic Oscillation contributes to either high-pressure anomalies over Iceland, low-pressure anomalies over the Azores or both, which reduces the meridional pressure gradient across the North Atlantic and weakens the climatological westerlies across northern Europe, resulting in less moisture and heat transport to the United Kingdom. The Arctic Oscillation can also influence Northern Hemisphere winter temperatures; a negative Arctic Oscillation is associated with a weak stratospheric polar vortex, which allows intrusions of colder air to reach Europe, Asia and North America (Wang and Chen, 2010). Griffiths and Bradley (2007) found that the Arctic Oscillation plays a significant role in determining extreme winter temperatures in the eastern United States. The negative phase of the Arctic Oscillation corresponds to an almost zonally symmetric anomaly in temperature and pressure over the middle to high latitudes of the Northern Hemisphere, and below average temperatures were also observed over North America and parts of Eurasia during June, July, October, and December 2009, consistent with the strong negative phase of the Arctic Oscillation (L'Heureux et al., 2010). In addition, previous studies have emphasized the influence of sea ice variability on the Northern Hemisphere atmospheric circulation. Alexander et al. (2004) investigated the impacts of the observed 1982–1983 and 1995–1996 winter ice anomalies on the atmospheric circulation by using an ensemble of integrations of the CCM3.6 model, and the results showed a significant response of the atmospheric circulation as positive feedback in the North Pacific sectors. Francis et al. (2009) concluded that the summer anomalies in ice cover are related to the atmospheric circulation in the following autumn and winter and that sea ice losses during late summer may lead to regional changes in Arctic winter climate.

Harsher winters in future decades may not be among the most likely or the most serious consequences of global warming; however, we could experience an extraordinary run of cold winters even in a warming climate (Wallace et al., 2014). China had experienced several periods of extremely cold weather in the last few decades; the severe cold weather of recent years occurred in 2008 and 2009 (Wen et al., 2009; Zhou et al., 2009; Wang and Chen, 2010), and long-lasting snowstorms causing above-normal precipitation, below-normal temperature, and severe icing conditions affected China in January 2008 (Wen et al., 2009). Cold surges, blizzards, and freezing rain pose serious threats and great challenges to the sustainable development of the economy, society, agriculture and the ecological environment (Wen et al., 2009). Forecasting extremely cold weather is thus of paramount importance for China, in which the world’s strongest East Asian winter monsoon prevails, but (Luo and Wang, 2018) found that the multi-model ensemble prediction has notoriously low applicability across China; they confirmed that China is a region of great challenge for winter temperature prediction. A further understanding of cold weather features and principles is essential. Few studies have focused on the effect of sea ice decline in the Arctic Ocean on the NELD over China or presented a specific influence mechanism. This study works on the points where the sea ice declines have an important effect on the NELD over China and the impacts of those declines.

## 2 | DATA AND METHOD

### 2.1 | Data

This study used meteorological data for the daily surface air temperature and precipitation obtained from the National Meteorological Information Center of the China Meteorological Administration (Li et al., 2017; http://data.cma.cn). The data set contained data from 824 meteorological stations covering mainland China, most of which were established in the 1950s. The data were quality controlled (including gross error limit checks, internal and time consistency checks, space and time consistency checks, manual verification and correction) by the National Meteorological Information Center of the China Meteorological Administration (Ge et al., 2018). Based on the completeness of the data, 760 of the 824 stations in the study area (Figure 1) were ultimately selected, and the limited amount of missing data was corrected by the average values of 4 nearby stations. This study was also based on the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis. The variables used were the
monthly fields for air temperature, geopotential height, horizontal winds on pressure levels, surface pressure, surface temperature (air temperature at a 2-m height, minimum air temperature at a 2-m height), upwards longwave radiation flux, latent heat net flux anomalies and sensible heat net flux. In addition, the monthly sea surface temperature and sea ice concentration fields from the Hadley Centre Global Sea Ice and Sea Surface Temperature data set (HadISST; Rayner et al., 2003) were utilized. The analysis period covered 56 winters from December 1961 to February 2017. When the winter of a specific year is mentioned in the text, it refers to December of the specified year plus January and February of the following year. The Arctic Oscillation index was obtained from the National Oceanic and Atmospheric Administration Climate Prediction Center.

2.2 Method

2.2.1 Definition of the extreme low-temperature day

We determined the threshold from the 5th percentile of all daily minimum temperature data (from December 1961 to February 2017, for a total of 20,178 days) for a single station and then defined a day for that station as one extreme low-temperature day if the daily minimum temperature in that day was lower than this threshold (Ge et al., 2018). The NELD of each station in each winter was counted in this study. We used the inverse distance weighted interpolation method to obtain the results on the surface in sections 3.1 and 3.2.

2.2.2 Empirical orthogonal functions analysis

The empirical orthogonal functions (EOF) method (Lorenz, 1956; Kutzbach, 1967; Hannachi et al., 2007), as one form of general principal component analysis, seeks to decompose a space–time data set into a linear combination of orthogonal standing oscillations (EOF modes), which can then be identified or interpreted in terms of certain physical processes. This method is widely used to reduce data dimensionality and to extract primary spatial patterns. We present the first three NELD EOF modes in section 3.2. The leading mode contributes a majority variance, and its corresponding time coefficients are important components in the other parts. We also conducted an EOF analysis of the global NELD to further understand the global NELD change background.

2.2.3 Mann–Kendall test

The Mann–Kendall (MK; Mann, 1945; Kendall, 1975) test is often used to determine the approximate time of occurrence of a change point by locating the intersection of the forwards and backwards curves of the test statistic. The test statistic is expressed as follows:

\[ UF_k = \frac{s_k - E(s_k)}{\sqrt{\text{Var}(s_k)}} \]

for \( k = 2, 3, ..., n \),

\[ s_k = \sum_{i=1}^{k} \sum_{j=1}^{i-1} \alpha_{ij}, \quad \alpha_{ij} = \begin{cases} 1 & x_i > x_j \ 0 & x_i \leq x_j \end{cases}, \]

\[ E(s_k) = k(k+1)/4, \]

\[ \text{Var}(s_k) = k(k-1)(2k+5)/72, \]

where \( x_i \) and \( x_j \) are elements of a sequential data series, with \( i = 1, 2, 3, ..., n - 1 \) and \( j = 1, 2, 3, ..., n - 1 \); \( n \) is the sample size; and where \( s_k \) is a cumulative number, \( E \) is average, \( \text{Var} \) is variance, \( \alpha \) is judgement, \( UF_k \) is the forwards sequence, and the backwards sequence, \( UB_k \) is calculated using the same equation but with a reversed series of data. The null hypothesis (no step change point) is rejected if any of the points in the forwards sequence \( UF_k \) are outside the confidence interval. A positive \( UF_k \) value denotes a positive trend and a negative value denotes a negative trend; if the value exceeds the significance level, it indicates a significant trend. An intersection point of \( UF_k \) and \( UB_k \) located within the confidence interval indicates the beginning of a step change point (Ye et al., 2013), which was defined as the mutation time in this paper. Generally, the confidence level was set at 0.05. We investigated mutation times of the time coefficient series of the first three NELD EOF modes by using the MK test.
RESULTS

3.1 Linear trend of the NELD

From Figure 2, the trend of the NELD is significantly downwards across China, and areas where the changes are not significant are sporadically distributed throughout the country. The high negative trend values are distributed in north China and southwest China, and some regions are less than $-4 \, \text{d} \cdot 10^a^{-1}$, while the decreasing trend is relatively weak in southern China.

3.2 EOF analysis and the MK test for the NELD

The differences between the first three modal variances in the NELD are large. In the first mode (the leading mode), the variance contribution is 49.78%, whereas in the second and third, the contributions are 10.94 and 7.06%, respectively (Table 1). All the first three EOF modes pass the North test (North et al., 1982). NELD changes present have a consistent characteristics across China in the leading EOF mode, and the high positive areas are located in the Heibei, Qinghai and Yunnan regions (Figure 3d). Thus, the variation in the time coefficients of the leading NELD EOF mode is representative of the variation in NELD across China. After 1987, the time coefficient is almost negative except for 2007 and 2011, which means that the NELD has generally been low since 1987 (Figure 3a). The MK test shows that the UF curve intersected with the UB curve in 1980 within the confidence interval and then crossed the negative significance level line, which indicates that the NELD over China had abruptly changed in approximately 1980 and decreased during the following period (Figure 3g). The spatial pattern of the second EOF mode (10.94%) shows an inverse change in the NELD between the area from Qinghai to the southeast coastal area and northeast China in the northern part of Xinjiang. There are high positive values north of Xinjiang and in northeast China, and the high negative values are located mainly in Qinghai and the southeast coastal areas (Figure 3e). The results of the MK test indicated an abrupt inverse change in approximately 1982, although in subsequent periods the change was not significant (Figure 3h).

Moreover, the time coefficient alternated between positive and negative from 1961 to 2016 (Figure 3b). The spatial pattern of the third EOF mode (7.06%) shows a reverse change in the NELD between the first ladder and the second ladder of China (Figure 3f). The high positive values are located mainly in south-central China and the northern parts of Xinjiang. Figure 3c shows that the time coefficient has an upwards trend. The MK results indicate that the abovementioned reverse change mutated significantly around 1992 (Figure 3i).

To understand the global NELD change background, we performed NELD calculations on global grid data (minimum air temperature at a 2-m height), and conducted EOF analysis of global NELD. Since December–February is summer in the Southern Hemisphere, global NELD is almost zero in the Southern Hemisphere, so we show the pictures of the Northern Hemisphere. The variance contribution of the leading mode (pass the North test), which generally represents the change in the global NELD, is 19.17%. The time coefficients of the leading global NELD EOF mode show the same decreasing trend as the time coefficients of the leading NELD EOF mode, although it is more moderate (Figure 4a). The spatial pattern of the leading global NELD EOF mode generally shows an inverse change in the NELD between the mid-high latitudes and the mid-low latitudes (Figure 4b). Positive values are in northern Eurasia, most of North America except the Labrador Peninsula and Greenland, most of China except the Tibetan Plateau region, and the region of South America in the Northern Hemisphere. Negative values are observed other land areas in the Northern Hemisphere. The MK test shows that the UF curve intersected with the

TABLE 1  EOF mode variance contribution

| EOF mode | Variance contribution (%) | Accumulative variance contribution (%) |
|----------|---------------------------|----------------------------------------|
| First    | 49.78                     | 49.78                                  |
| Second   | 10.94                     | 60.72                                  |
| Third    | 7.06                      | 67.78                                  |

FIGURE 2  Horizontal distribution of the NELD linear trends during 1961–2016. Trends that are not significant at the 95% confidence level are masked (units: d $\cdot 10^a^{-1}$)
**FIGURE 3** The time coefficients of the first three NELD EOF modes: (a) the first, (b) the second and (c) the third; their corresponding (d–f) horizontal distributions of spatial coefficients; (g–i) the MK results

**FIGURE 4** Leading global NELD EOF mode: (a) time coefficients, (b) spatial coefficient distribution and (c) MK results
UB curve in approximately 1980 within the confidence interval, which indicated that the inverse change in the NELD between the mid-high latitudes and the mid-low latitudes abruptly changed around 1980 (Figure 4c). The high positive values are concentrated in Siberia and northeast China, where are the most severely reduced areas of NELD after 1980.

3.3 | The correlation between the NELD and sea ice concentration

The sea ice loss during the last few decades is known to have a potentially significant influence on the global climate system, including in the Arctic and adjacent high-latitude areas (Ye et al., 2013). We obtained Pearson correlations...
between the time coefficient of the leading NELD EOF mode and the four seasonal (spring, summer, autumn and winter) mean sea ice concentrations. Figure 5 shows that the time coefficients of the leading NELD EOF mode and the seasonal mean sea ice concentration in the Northern Hemisphere (45°–90°N) have different correlation characteristics. The significant positive correlation area is smaller in spring and winter than in summer and autumn. In spring and winter, the positive correlation coefficients are located mainly in the Barents Sea (75°–82°N, 30°–60°E) and the sea east of Greenland (Figure 5a,d). In addition to the abovementioned areas, the positively related areas in summer and autumn also include the sea areas from the Soave Ridge to the Canadian Basin (70°–82°N, 150°E–130°W) (Figure 5b,c), while these areas are covered by scattered negative correlation coefficients in winter and spring. However, the winter sea ice concentration linear trend in the sea areas from the Soave Ridge to the Canadian Basin is almost insignificant compared to that in the Barents Sea and the sea east of Greenland (Figure 6). Thus, in the regions with significant positive correlations, the decline in sea ice concentration in the Northern Hemisphere in the four seasons promotes the decrease in the NELD. Previous research has also found a strong relationship between the sea ice concentration near the Barents and Kara Seas and the temperature anomaly across Eurasia, including northeastern Asia (Lim et al., 2012).

3.4 Correlation between the NELD and sea surface temperature

High significant negative correlations are detected between the time coefficients of the leading NELD EOF mode and the sea surface temperatures during the four seasons in the Indian Ocean and western Pacific Ocean. However, different aspects of the impacts of sea surface temperature in the Indian Ocean and western Pacific Ocean on Asian climate have been widely studied (Chen and Wu, 2000; Li et al., 2010; Yin and Wang, 2016; Chu et al., 2018; Ji et al., 2018; Wang and Chen, 2018; Xiao et al., 2018); we focus on the Arctic Ocean region. The sea surface temperatures in the Barents Sea and the sea east of Greenland are negatively correlated with the time coefficients of the leading NELD EOF mode during the four seasons, and the negative correlations in summer and autumn are stronger than those in spring and winter (Figure 7). The correlation is positive in the sea areas from the Soave Ridge to the Canadian Basin in spring and winter, and is obviously weaker in summer and autumn. The summer and autumn sea ice concentrations in the Arctic Ocean areas including the Barents Sea, the sea east of Greenland and the sea areas from the Soave Ridge to the Canadian Basin are positively related to the NELD (Figure 5b,c). With more sea ice melts in the Arctic Ocean in summer and autumn, more heat is released into the atmosphere in winter. The thermal energy absorbed during summer and autumn in these vast new expanses of open water maintains higher sea surface temperature and releases more heat to the atmosphere than before (Francis and Vavrus, 2012).

3.5 Composite atmosphere variable anomalies

We standardized the time coefficients of the leading NELD EOF mode and defined the year in which the value is higher (lower) than 1.0 standard deviation of the above-normal (below-normal) years of NELD (Table 2).

The atmosphere anomalies between years with below-normal NELD and those with above-normal NELD are determined in this section. As mentioned in section 3.3, with more sea ice melts in the Arctic Ocean in summer and autumn, more heat is released into the atmosphere in winter. Figure 8a,b reflects the changes in heat exchange between the ground and atmosphere, and both latent heat net flux anomalies and sensible heat net flux exhibit distributed significant high positive anomalies in winter in the sea area east of Greenland and small area of the Barents Sea. The
upwards longwave radiation flux in winter also shows significant high positive values anomalies in the sea area east of Greenland and small area of the Barents Sea (Figure 8c). Based on the positive correlation between the NELD and the summer and autumn sea ice concentrations (Figure 5b, c), aboveground temperatures should be affected first. Figure 8d shows the horizontal distribution of the composite surface temperature anomalies over the Northern Hemisphere in winter; the anomalies are significantly positive in the sea area east of Greenland, the Barents Sea and Middle Siberia, and the central anomaly values are greater than 5 K. In addition, composite air temperature anomalies are significantly positive from 1,000 to 300 hPa in the sea area east of Greenland, the Barents Sea and the Baltic Sea (Figure 9a).
Two abnormal 850-hPa cyclones exist in southern Greenland and the northern Ural Mountains, respectively (Figure 9b). The abnormal wind field in the black line area and significant positive temperature anomalies in the Barents Sea and the sea east of Greenland reveal that the cold air transported from both regions in the years with below-normal NELD is weaker than that in the years with above-normal NELD.

The surface pressure changes as the above ground temperature increases. The horizontal distribution of the composite surface pressure anomalies in winter (Figure 9c) shows that there are significant negative anomalies in the northern Siberian region and the regions from the sea area east of Greenland to the Barents Sea, and the minimum negative anomaly values of the two centres are both less than −5 hPa. In contrast, changes in surface pressure in high latitudes can affect mid-latitudes via meridional circulation (Qian and Liang, 2012), and there are significant positive anomalies in the mid-latitude region (35°–50°N), with three centres in western Europe, the Tibetan Plateau region and the Aleutian region, respectively. According to Jhun and Lee (2004), variability in the intensity of the East Asian winter monsoon is influenced by both the Siberian high and the Aleutian low. Reduction in the pressure gradients between the Siberian high and Aleutian low induces a weaker winter monsoon in East Asia (Figure 9d). Changes in surface pressure reveal that the Arctic Oscillation is more positive in the years with below NELD than that in the years with above-normal NELD. The Arctic Oscillation is almost negative during years with above-normal NELD and entirely positive during years with below-normal NELD (Table 2). The upper atmosphere is affected and shows similar changes in geopotential height to the surface pressure (Figure 10a). In Asia (section 105°E), from 1,000 to 150 hPa, there area significant positive geopotential height anomalies in the area south of 60°N and significant negative geopotential height anomalies in the area from 60°N to 75°N (Figure 10b).

Several aspects of the connections between the Arctic Oscillation and the zonal wind have been confirmed by previous studies (Christiansen, 2001; Overland and Adams, 2001; You et al., 2013; Liu et al., 2017). We calculated the Pearson correlation coefficients between the time coefficients of the leading EOF mode of the NELD and the zonal wind. The zonal wind between 45°N and 60°N shows a significant negative correlation with the time coefficients, and this feature ranges from 1,000 to 50 hPa in Asia (Figure 10c, d), which also suggests that the zonal westerly winds have intensified in the above region; one of the important reasons is the increase in the difference in geopotential height between mid-latitudes and high-latitudes. The Pearson correlation coefficients between the time coefficients of the leading EOF mode of the NELD and the meridional wind in the lower troposphere are negatively significant in Siberia (Figure 10e), which reveals that for the above atmospheric patterns, the transport of cold air originating from high latitude became less powerful. Similar results also have been reported in previous studies (Gong et al., 2001; Niu et al., 2010).

### Table 2 Arctic Oscillation index in the years with below-normal NELD and the years with above-normal NELD

| Years with above-normal NELD | AO  | Years with below-normal NELD | AO  |
|-----------------------------|-----|-----------------------------|-----|
| 1962                        | −1.91         | 1990                         | 0.37          |
| 1963                        | −0.46         | 1998                         | 0.65          |
| 1966                        | −0.27         | 2001                         | 0.45          |
| 1967                        | −0.97         | 2006                         | 1.00          |
| 1968                        | −2.23         | 2014                         | 0.85          |
| 1969                        | −1.84         | 2016                         | 1.02          |
| 1973                        | −0.15         |                              |               |
| 1975                        | 0.99          |                              |               |
| 1976                        | −2.62         |                              |               |
| 1983                        | 0.26          |                              |               |

### 4 SUMMARY

This study analyses variations in the NELD. The NELD mainly has a significant decreasing trend across China. The leading NELD EOF mode shows consistent change characteristics over China, and the MK test of its time coefficients indicates that the NELD abruptly changed in approximately 1980. The second EOF mode shows an inverse change in the NELD between Qinghai to the southeast coastal area and northeast China in the northern part of Xinjiang. The third EOF mode shows a reverse change in the NELD between the first and second ladders of China.

The impact of sea ice concentration in the Arctic Ocean on the NELD is investigated. Sea ice concentrations in the Barents Sea and the sea east of Greenland during the four seasons all have significant positive correlations with the NELD. In the above regions, with the increased sea ice melts in summer and autumn, more thermal energy is absorbed; higher sea surface temperatures are maintained, producing a greater release of heat into the atmosphere in the winter. Thus, surface temperature and upper air temperature increase in the Barents Sea and the sea east of Greenland, which weakens the intensity of cold air source in winter.

As the sea ice in the Barents Sea and the sea east of Greenland continues to decline, the subsequent action causes surface pressure to decrease in the northern Siberian region and the regions from the sea area east of Greenland to the Barents Sea and to increase in the mid-latitudes region.
FIGURE 8  Horizontal distributions of the composite atmosphere variable anomalies in winter between years with below-normal NELD and those with above-normal NELD: (a) latent heat net flux (units: W/m$^2$); (b) sensible heat net flux (units: W/m$^2$); (c) upwards longwave radiation flux (units: W/m$^2$); (d) surface temperature (units: K). Composite anomalies that are not significant at the 95% confidence level are masked. Statistical significance is evaluated based on two-tailed Student’s $t$ tests.
including the Aleutian region. An obvious feature is that the Arctic Oscillation has become more positive. Due to the reduction in the pressure gradients between the Siberia High and the Aleutian Low, the winter monsoon in East Asia is weaker. Previous studies have also found that when the Arctic Oscillation is positive, the winter monsoon in East Asia is weak, and temperatures increase across China (Qian and Liang, 2012). Furthermore, the difference in geopotential height in the upper atmosphere between the high latitudes and mid-latitudes in Asia is enlarged, and air temperature at upper atmosphere in the Barents Sea and the sea east of Greenland increases, and the atmospheric baroclinicity at

FIGURE 9  Distributions of the composite atmosphere variable anomalies in winter between years with below-normal NELD and those with above-normal NELD: (a) 10°E latitude-pressure air temperature (units: °C); (b) 850-hPa air temperature (units: °C) and wind field (units: m/s); (c) surface pressure (units: Pa); (d) 925-hPa air temperature (units: °C) and wind field (units: m/s). Composite anomalies that are not significant at the 95% confidence level are masked. Statistical significance is evaluated based on two-tailed Student's t tests.
FIGURE 10  Distributions of the composite geopotential height anomalies (units: m) in winter between years with below-normal NELD and those with above-normal NELD: (a) 500 hPa; (b) 105°E latitude pressure. Distribution of the correlation coefficients between the time coefficients of the leading NELD EOF mode and the winter zonal wind: (c) 300 hPa, (d) 52.5°N longitude pressure; (e) the winter 925-hPa meridional wind. The correlation coefficients that are not significant at the 95% confidence level are masked. Statistical significance is evaluated based on two-tailed Student’s *t* tests.
high latitudes has changed distinctly. The zonal westerly winds have intensified between 45°N and 60°N in Asia, and the northerly winds in the lower troposphere in Siberia are weakened. Under these atmosphere patterns, the transport of cold air originating from high latitudes became less powerful and the NELD during winter over China tends to decrease.

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ORCID

Feifan Ge https://orcid.org/0000-0002-1517-3655

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