Relationship between the East Atlantic teleconnection pattern and the spring dust storm in northern China

Part-I: Impacts of components of the atmospheric circulation over Eurasia on dust storm dynamic power—Spring gales

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Abstract
Spring gale is a dynamic power for DSs (DSs), which presents a close connection with the DSs of northern China. Both display declining trends during the past 68 years (1954–2021). In this study, the influencing factors of spring gales and DSs around northern China and possible adjustment functions of the East Atlantic (EA) teleconnection pattern have been investigated. It was found that the major systems controlling spring gales include the North Polar vortex (NPV), mid–high-latitude blocking highs (BHs), air pressure status of the Tibetan Plateau (TP) over the Eurasian continent, India–Burma trough (IBT) and western Pacific subtropical high (WPSH). Under synthetic atmospheric circulation conditions of an enlarged NPV, lower air pressure over the TP, a strong IBT, and a southeastward-retreated WPSH, spring gales increase, and the frequency of DS occurrence is increased, and vice versa. Additionally, spring gales are also negatively affected by BHs. The most important is the Bai-kal BH, which has influence not only in previous seasons but also in the contemporary spring. Furthermore, the NPV and IBT have close negative correlation with the EA pattern, whereas the TP and WPSH have positive correlation with the EA pattern both in previous seasons and in the contemporary spring. A high-pitched EA pattern results in a strong western current north of Lake Baikal, which may prohibit the expansion of the NPV in the sector of northern China. A shrunk NPV means infrequent cold air attacks and decreased gales and DSs.

KEYWORDS
atmospheric circulation component, dust storm, EA teleconnection pattern, northern China, spring gale

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The Ural, Baikal, and Okhotsk blocking highs (BHs) are three warm high-pressure centres that occur over the mid-high latitudes of the NH as a consequence of enhanced longwave radiation. They are quasi-stationary longwave bridges containing closed high-pressure centres that can persist for reasonable durations. The BH is the most prevalent atmospheric system in the large region that extends from the eastern Atlantic Ocean through Europe to central Asia. Extremely strong anomaly of the Ural blocking high and a record-breaking anomaly of the surface Siberian high (SH) are major influence factors for the East Asian extreme cold-wave-related atmospheric circulation regime. The occurrence of extreme anomalies of Ural BH and SH have respectively increased by 58% and 57% during 1961–2016 (Ma & Zhu, 2019). The mean annual cycle of blocking is complex; it runs continuously throughout the year over most areas of Europe, with maximum intensity in autumn and winter. In the western Atlantic and Asia, there are two periods annually with a high frequency of occurrence of blocking (Tyrlis & Hoskins, 2008). The westerly currents and synoptic systems are very probably obstructed when a BH becomes established over the Eurasian continent. A previous study revealed that such blocking circumstances and even the BHs are the primary influencing components of precipitation and the wet–arid status in China during the rainy season (Zhao, 1999). Furthermore, other research assessed the linkages between the Ural BH over Siberia and the East Asian winter monsoon. A strong Ural BH enhances cold advection to the downstream region, and its frequent appearance can potentially promote a cold phase of the East Asian winter monsoon, and vice versa (Cheung et al., 2012). In this research, we investigated the impact of BHs on springtime strong winds (hereafter referred to as gales) in northern China and the related influencing systems.

It has been found that the decrease in surface wind speed was primarily caused by a strong wind decrease of ~8% decade−1 from 1960 to 2017 over China (Z. T. Zhang & Wang, 2020). The DSs present a declining trend during the past 48 years (1961–2008) with the decreased wind speed, except in the region of the Hunshad Sandy Lands in Inner Mongolia, where DSs have increased obviously during 2001–2008 due to reduced precipitation, the arid climatic regime, and deterioration of the condition of surface vegetation. Moreover, in comparison with the 30-year (hereafter referred to as 30-year) mean wind speed (1971–2000) observed during DS events, the mean velocity during 2001–2008 has reduced by 3.0 m s−1, indicating that the occurrence of DSs remains prominent despite the weaker winds (Gao et al., 2012). Natural factors probably have been confirmed to have the greatest impact on DSs (Kourgialas & Karatzas, 2015). Results of other
studies suggest that unfavourable moisture transportation, reduced precipitation, increased temperature, high evaporation, drought, and unfriendly underlying surface conditions combine to make DS source areas in North-west China more favourable for raising sand and dust particles (Cheng et al., 2004; Gao et al., 2006, 2009; Gao & Han, 2010). Moreover, it has also been found that spring DSs have a strong positive correlation with the upwind wind velocity and strong negative correlations with previous summer precipitation, soil moisture anomalies, and vegetation conditions (Liu et al., 2004; X. K. Xu et al., 2006).

There is no commonly recognized definition for DS (DS) or severe dust storm (SDS) events for specific regions, although meteorological organizations and research groups have proposed definitions for floating dust, DS, and SDS weather at specific observation stations. For example, a DS is simply defined as horizontal visibility of <1000 m with wind speed of >10.8 m s\(^{-1}\) observed in four daily observation registrations (China Central Meteorological Bureau [CCMB], 1979; Fang et al., 1993). In some areas, for example, the Hunshdak Sandy Lands, the dust-emitting wind speed at 1-m height has been measured at 5.6 m s\(^{-1}\) (Yue et al., 2008), which is well below the defined wind speed mentioned above. Statistical analyses conducted by Kurosaki and Mikami (2003) confirmed that frequent dust events are mainly caused by frequent strong winds. They also identified strong correlation between year-to-year variations in dust outbreaks and strong winds with a defined threshold of 6.5 m s\(^{-1}\). The wind speed required for floating dust depends on the surface conditions of the sand and dust source regions. Different source regions with dissimilar surface circumstances should have different dust-raising wind speeds. Therefore, in this study, we examined events with different wind speeds (i.e., 5, 6, 7, 10, and 12 m s\(^{-1}\)) to investigate the correlation between the spring gales and DSs in northern China.

Despite confirmation that DS occurrence is related to many influencing factors such as the underlying surface conditions, precipitation, and aridity situation, it is evident that a strong wind is the crucial dynamic power required for raising a DS. Moreover, the spring EA pattern exhibits contemporary or lag correlations with the spring gales directly. Correlation coefficients between them reaches –0.406 (at 0.01 significant levels) at Z500 for spring season. The previous winter EA pattern presents close connections with the spring gales at the lower levels. For instance, the coefficients for the surface and Z850 reach –0.317 (at 0.05 significant levels) and –0.367 (at 0.01 significant levels), respectively. Therefore, this study considered the factors that influence spring gales in exploring the relationships among the components of the atmospheric circulation around northern China (i.e., the EA pattern, mid–high-latitude BHs, NPV, WPSH, Tibetan Plateau [TP], and India–Burma trough [IBT]), not only for the contemporary season but also for previous terms. Determination of the lagged impact of such relationships could be helpful for improving forecasts of spring gales and DS.

This study intends to explore the correlations between the atmospheric circulation systems around the study domain and the spring gales that are highly connected to the DS in northern China. In addition, we explore the possible influence of the EA pattern on the circulation systems that mainly affected the frequency of the spring gales and DS.

2 | DATA, DEFINITION, AND METHODOLOGY

2.1 | Data source

Daily horizontal visibility (from 1 January 1954 to 31 May 2021) observations recorded at four regular monitoring times (i.e., 0000, 0600, 1200, and 1800 UTC) at the 65 stations (Figure 1a) in our region of interest were selected from ‘the China Severe DS Supporting Dataset’, which is issued by the Data Service Center of the China Meteorological Administration, and used to determine the number of DS and severe DS events that occurred in northern China during the study period. Monthly index sets (from January 1951 to May 2021) of atmospheric circulation components, which include the WPSH, NPV, TP, and IBT indexes, are issued by the National Climate Center of the China Meteorological Administration (http://ncc.cma.gov.cn/Website/index.php?ChannelID=5). The meanings of these indexes and the major components are explained in Table 1 (Fang et al., 1993; Z. B. Sun, 2010; Yan, 2003; Zhao, 1999). Our domain of focus and the locations of the surrounding atmospheric circulation components of interest are shown in Figure 1b.

The used data sets (2.5° × 2.5° grid) from January 1950 to May 2021 included monthly 500-hPa geopotential height, daily mean U- and V-wind speeds at the surface and 1000, 925, 850, 700, 600, and 500 hPa (hereafter, referred to as Sur, Z1000, Z925, Z850, Z700, Z600, and Z500, respectively), and the NOAA Extended Reconstructed SST V5 (ERSST; 2.0° × 2.0° grid), issued by and downloadable from the National Centers for Environmental Prediction/National Center for Atmospheric Research, United States (http://www.esrl.noaa.gov/psd).

The EA teleconnection pattern was defined as the third, sixth, eighth, and ninth principal components of a rotated principal component analysis of the monthly
Z500 height anomalies in the NH (poleward of 20° N), the monthly index of which can be downloaded from the website of the Climate Prediction Center, United States (http://www.cpc.ncep.noaa.gov/data).

2.2 | Definition and methodology

Seasonal means are averages of data relating to boreal spring (March–May), summer (June–August), autumn (September–November), and winter (December–February).

The occurrence of a DS or SDS at a single station can be determined on the basis of horizontal visibility of <1000 and <500 m, respectively (CCMB, 1979). In this study, a station could be assigned a DS or SDS score if visibility was recorded as <1000 or <500 m, respectively, at one or more of the four regular monitoring times during a day. A DS (SDS) day was defined as an event in which three or more stations in the domain of interest were assigned a DS (SDS) score.

The gridded U- and V-wind speed data sets were employed for determining the number of gale days in the region of northern China that is frequently affected by DS. The wind direction was not of concern in this study. We calculated the daily wind speed at the 28 key grids in

**FIGURE 1** Diagram of studied domain (northern China), 65 dust storm observation stations, used wind speed crucial grids and locations of the atmospheric circulation components around northern China.
TABLE 1  The major atmospheric circulation indices for Eurasia and Pacific regions

| Circulation components index | Brief explanation |
|-----------------------------|-------------------|
| Subtropical high (West Pacific: 110°E–180°E) | Area Total grids with geopotential height ≥588 gpdm in the range 10°–60° N of a specific longitude sector in 5° × 10° horizontal resolution of the monthly mean geopotential height at 500 hPa |
|  | Intensity Average of numbered grids with geopotential height ≥588 gpdm in the range 10°–60° N of a specific longitude sector in 5° × 10° horizontal resolution of the monthly mean geopotential height at 500 hPa. (588 gpdm numbered 1; 589 gpdm numbered 2; 590 gpdm numbered 3, etc.) |
| North Polar vortex (Asia: 60°–150°E) | Area Northern area confined by featured isohyke which mostly approaches to the maximum westerly axes between specific range of two longitudes in 500 hPa monthly mean weather chart |
|  | Intensity Air mass between two geopotential heights of 500 hPa mean isohyke and the featured isobaric surface mentioned above |
| Tibetan Plateau index | Accumulated number of geopotential high differences minus 5000 gpm and plus its grid area at all grids in a rectangle of 75°–105° E and 30°–40° N at 500 hPa |
| Intensity of India–Burma trough | Accumulated number of geopotential high differences minus 5800 gpm and plus its grid area at all grids in a rectangle of 80°–100° E and 15°–20° N at 500 hPa |
| Blocking high (anticyclone) | Ural SD of regional mean geopotential high anomaly at 500 hPa in a grid rectangle area of 40°–50° N; 40°–70° E |
|  | Baikal SD of regional mean geopotential high anomaly at 500 hPa in a grid rectangle area of 50°–60° N; 80°–110° E |
|  | Okhotsk SD of regional mean geopotential high anomaly at 500 hPa in a grid rectangle area of 50°–60° N; 120°–150° E |

our studied domain (Figure 1a) by using the following formula:

\[
\text{Wind speed} = \sqrt{Uwind^2 + Vwind^2}
\]

In the study domain, 65 observation stations were selected by determining the area affected most frequently by DSs (Figure 1a). We simply assigned a gale score to a grid in the domain when the wind speed at that grid was ≥5 m s⁻¹ (Kurosaki & Mikami, 2003; Yue et al., 2008). Moreover, gale days were distinguished depending on the wind speed. A day marked with a gale score could be categorized further depending on whether more than a certain proportion of the 28 key grids (Figure 1a) had wind speed equal to or greater than a specified threshold, for example, 5, 6, 7, 10, or 12 m s⁻¹. For example, a gale day marked with the sign of 5 m s⁻¹ (50%) for Sur level indicated that more than 50% of the 28 key grids had a daily mean wind speed of ≥5 m s⁻¹. Thus, it could be defined as a gale day at 5 m s⁻¹ wind speed on the surface. The same statistical approach was implemented for the Z925, Z850, Z700, and Z500 gale days. Moreover, the monthly occurrence frequency of gale days identified at different geopotential heights could be determined on the basis of the outcomes derived using the above approach.

This study also considered the three primary BHs in the mid–high latitudes of the Eurasian continent. Monthly anomalies of Z500 geopotential height at every grid were counted by removing the 30-year (1991–2020) mean monthly cycles. The monthly indexes of the Ural, Baikal, and Okhotsk BHs were obtained from the monthly SDs of regional mean geopotential height anomalies at Z500 in the rectangular areas of 40°–50° N and 40°–70° E, 50°–60° N and 80°–110° E, and 50°–60° N and 120°–150° E, respectively (Figure 1b). A BH is considered established if the index is ≥1.0, and a higher value of the BH index indicates more favourable blocking conditions (Z. B. Sun, 2010; Yan, 2003; Zhao, 1999).

For comparison and analysis of the evolutionary characteristics of the influential components of the atmospheric circulation (i.e., NPV area, WPSH area, TP intensity, IBT intensity, BHs, the EA pattern indices, the U- and V-wind speeds) from the previous summer to the following spring, by using the mean values of the indices from 1954 to 2019, anomalies of each atmospheric circulation components were calculated separately. Sixty-six year samples of the anomaly atmospheric circulation indices were divided objectively into three groups after ordering the index series from high to low values, where each group comprised 22 samples. Hereafter, we refer to
the first and last groups of 22 samples as the high group and the low group, respectively.

To elucidate the influence and lagged impact of the major atmospheric circulation components on the occurrence of spring gales in the studied domain, the lag-regression method was employed between specific components and the frequency of occurrence of gales on several levels (i.e., Sur, Z925, Z850, Z700, and Z500). For each pressure level, the dependent variable was the component index from the prior June to May, and the independent variable was the occurrence of spring gales during 1954–2020. The Student's t-test was used to determine the statistical significance of any relationship. Furthermore, to obtain a clear perspective of the influencing processes, and according to the lag-regression outcomes, profile figures with a statistical confidence of over 90% were drawn using GrADS software (http://grads.iges.org/grads/).

By regressing the EA pattern indexes (1950–2020) onto the Z500 geopotential height anomalies (used 30-year climate mean from 1991 to 2010) of the NH, the spatial structures, statistically significant areas, and positive and negative active centres of the EA pattern for winter and summer could be elucidated, where the monthly SDs reflect their characteristics of monthly activity. The EA annual mean indexes were used to inspect the annual and decadal variations during the past 71-year period (1950–2020). A decadal trend of the EA pattern was determined by counting the SDs of 11-year running indexes.

3 | SPRING GALES AND DSs

Gales are evidently the dynamic power behind the occurrence of DSs, especially during springtime drought in

FIGURE 2  Frequencies of spring dust storms (DSs) and gales at a velocity of 6 m s\(^{-1}\) in northern China from 1954 to 2021, (a) DS, (b) spring gale. SDS, severe dust storm
northern China. For the studied domain, the frequency of occurrence of springtime DSs, SDSs, and gales has been investigated in detail. The frequency of occurrence of both DSs and gales during the past 68-year period (1954–2021) has shown a trend of decline (Figure 2a,b). The years with the highest frequency of occurrence of springtime DSs were 1976, 1966, and 2021 with 30, 28, and 27 DS days, respectively. During the same period, the years with the lowest frequency of occurrence of springtime DSs (i.e., fewer than three DS days) were 1992, 1997, 1999, and 2013. For springtime SDSs, the years with the highest frequency of occurrence were 1976, 1966, and 1969 with 23, 22, and 21 severe DS days, respectively. Springtime SDSs did not occur in 1989, 1997, 2003, and 2013.

It can be seen that the 68-year (1954–2021) decadal mean frequencies of DSs and gales presented in Table 2 vary to differing degrees. Two periods with frequent occurrence of both DSs and gales are evident: one spanning the 27-year period of 1954–1980 and the other comprising the decades from the 2000s to the 2010s. A period with relatively low frequency of occurrence extended from the 1980s to the 1990s, that is, the values are below the 1954–2020 averaged frequencies of 19.7 and 6.2 DS and SDS days, respectively. Furthermore, the period of low frequency of occurrence of gales corresponds to this period of infrequent DS occurrence. Conversely, the DS of spring 2021 increased significantly in northern China. However, this spring is just the third DS that has frequently attacked spring during the past 68 years. Both DSs and SDSs occurred 14.5 and 1.1 times more than the 67-year historical means (1954–2020), respectively. Correspondingly, the frequency of occurrence of gales at the Sur and Z925 levels was 0.7 and 2.7 times more than the 67-year historical mean frequencies, respectively. Compared with the recent 10-year (2011–2020) mean frequencies, the study domain was affected more frequently by DSs, SDSs, and gales in 2021 (Table 2).

Our examination revealed a strong positive correlation between springtime DSs and gales. Gale frequencies at the different geopotential levels were calculated for wind speeds of 5, 6, 7, 10, and 12 m s$^{-1}$. The correlation coefficients for the wind speed scales at 6 m s$^{-1}$ (below Z700) and 10 m s$^{-1}$ (at Z500) are listed in Table 3. For the same wind speed, the correlations between the two elements were more significant at lower levels (i.e., Sur, Z925, and Z850) than at higher levels (i.e., Z700 and Z500), which indicates that spring gales at lower levels are more important to DS occurrence than those at higher levels. A comparison of DSs and SDSs revealed that the correlation of SDSs to gales is stronger than that of DSs.

### Table 2

| Decade       | DSs (day) | Gale frequency (day) at 6 m s$^{-1}$ UV-wind speed |
|--------------|-----------|---------------------------------------------------|
|              | DS        | SDS      | Sur      | Z925     | Z850     |
| 1954–1960    | 17.1      | 13.3     | 34.7     | 28.9     | 49.7     |
| 1961–1970    | 16.7      | 13.8     | 30.4     | 25.8     | 43.7     |
| 1971–1980    | 18.8      | 15.6     | 28.2     | 26.0     | 46.8     |
| 1981–1990    | 9.7       | 3.7      | 19.3     | 15.7     | 33.9     |
| 1991–2000    | 4.9       | 1.9      | 16.1     | 14.4     | 31.7     |
| 2001–2010    | 10.3      | 4.1      | 22.2     | 19.5     | 39.1     |
| 2011–2020    | 10.2      | 4.1      | 15.9     | 14.1     | 30.6     |
| Mean (1954–2020) | 12.3  | 7.8      | 23.3     | 20.3     | 38.9     |
| Mean (2011–2020) | 10.2 | 4.1      | 15.9     | 14.1     | 30.6     |
| 2021        | 27.0      | 13.0     | 24.0     | 23.0     | 38.0     |

Abbreviation: SDS, severe dust storm.
Because gales represent the dynamic power of DSs, few components of the atmospheric circulation will have direct impact on the occurrence of DSs. Instead, most will exert influence indirectly via impact on local climatic and/or synoptic conditions. Therefore, we focused our attention on strong wind events (gales) and the corresponding dynamic processes of the influencing components of the atmospheric circulation.

4 | COMPONENTS OF ATMOSPHERIC CIRCULATION THAT INFLUENCE SPRING GALES

Because gales represent the dynamic power of DSs, few components of the atmospheric circulation will have direct impact on the occurrence of DSs. Instead, most will exert influence indirectly via impact on local climatic and/or synoptic conditions. Therefore, we focused our attention on strong wind events (gales) and the corresponding dynamic processes of the influencing components of the atmospheric circulation.

4.1 | North Polar vortex

The NPV is a low-pressure system that is one of the most important influencing factors for mid–high-latitude regions of the NH (J. W. Zhang et al., 2014). Expansion and contraction of the NPV increase and diminish the extent of the area affected by cold outbreaks moving southward from the northern polar region. Declining trends in the indexes of the area and the intensity of the spring NPV during the 68-year period of 1954–2021, which reflect gradual contraction of the NPV area, correspond to the decreasing tendencies in the frequency of occurrence of springtime gales and DS storms (Figure 3a). The NPV might expand southward if cold air accumulating in the Novaya Zemlya archipelago region (Russia) amasses sufficiently to break out. Strong positive correlation exists between the indexes of the intensity and the area of the NPV. Significant correlation coefficients (at the 0.01 statistical significance level) indicate that the NPV might expand when it weakens from spring to winter. A comparison of the variations of the NPV mean area indexes for the high and low groups from the previous June to the following spring revealed that the high group keeps higher than the low group, which means that the NPV from the prior June to the following spring remains relatively large for the high group in comparison with the low group. A big amplitude of the NPV area curves for both the high and low group appears from the previous June to September, which indicates significant changes existing in both the high and low groups during this term. There is a small difference between the high and low groups from the prior October to the following February, which indicates the NPV keeps almost the same areas in this period, especially during January. Moreover, when spring comes, the differences between the two groups enlarge again (Figure 4a).

Strong cold outbreaks in northern China generally result in strong winds, which can cause DSs if the
underlying surface rich in sand and dust particles is sufficiently dry. It can be identified from Table 4 that the NPV indexes for the previous summer, autumn, and contemporary spring are closely connected to the occurrence of spring gales with different wind speeds. The correlations between the prior summer–autumn and spring gales at lower geopotential levels are stronger than those at higher geopotential levels (i.e., Z700 and Z500). In spring, a statistically significant correlation exists between the NPV indexes and gales at lower geopotential levels. An expanded NPV means that the region affected by invading cold air is large. During the prior summer–autumn and spring, a large NPV generally corresponds to increased occurrence of spring gales and DSs. Winter appears to act as a period of adjustment from warm to cold seasons for the NPV, and the wintertime NPV does not show any significant correlation with spring gales. Furthermore, the intensity index displays a negative correlation with spring gales.

Performing lag regression of the NPV area index on spring gales at different geopotential levels elucidated the lagged impact of the NPV on spring gales. For the period...
from the prior June to May, the most influential months can be determined by consideration of the significant areas over the 95% confidence levels. From the previous June to December, and to April and May, the NPV area displays significant correlations with spring gales, especially at the lower levels (i.e., below Z850), which means the spring gales at the lower levels (mainly below Z850) may increase significantly while the NPV at the Z500 enlarged during the previous summer and autumn, which connected with the spring gale frequency more closely than that of the contemporary spring season. Therefore, the NPV area index for the primary months mentioned above might provide seasonal forecast signals with sufficient lead time for forecasting spring gales and DSs in northern China (Figure 5a).

The variation curves and contrary trends of the previous autumn WPSH and spring gales at the surface can be observed in Figure 3b. Correlation analysis identified strong negative connections between the WPSH and spring gales at the lower geopotential levels (i.e., below Z850). It has been found that spring gales are affected more significantly by the prior summer and autumn WPSH than by that of the previous winter and contemporary spring (Table 4). In addition, we found that the WPSH area indices for both the high and low groups present almost similar amplitude with an opposite trend from the previous June to May. A big difference can be viewed for both groups from the previous June to December. The quietest months are January and February, and there are small differences between the WPSH areas of the high and low group. The WPSH enlarged or shrunk again for the high or low group in the following April (Figure 4b). Because the results of the lag-regression analysis present significant correlations between the WPSH from the prior June to December and the spring gales, it may be concluded that the WPSH in the previous warm season could provide a signal for predicting spring gales and DSs. The closest connections are shown for geopotential levels mainly below Z850 (Figure 5b).

### 4.2 Western Pacific subtropical high

The WPSH is a crucial atmospheric component of the weather and climate of China, especially in relation to the transportation of moisture from the ocean to interior areas. Regions under the control of the WPSH are most often affected by heat waves during the warm season.

| Level         | Prior summer | Prior autumn | Prior winter | Spring | Prior summer | Prior autumn | Prior winter | Spring |
|---------------|--------------|--------------|--------------|--------|--------------|--------------|--------------|--------|
| Sur           | 0.554        | 0.526        | 0.005<sup>a</sup> | 0.599  | 0.423        | 0.319<sup>b</sup> | 0.008<sup>a</sup> | 0.520  |
| Z925          | 0.519        | 0.504        | 0.063<sup>a</sup> | 0.554  | 0.425        | 0.337<sup>b</sup> | 0.066  | 0.442  |
| Z850          | 0.441        | 0.436        | 0.143<sup>a</sup> | 0.567  | 0.352<sup>b</sup> | 0.318<sup>b</sup> | 0.103  | 0.444  |
| Z700          | 0.328<sup>b</sup> | 0.286<sup>b</sup> | 0.174<sup>a</sup> | 0.476  | 0.230<sup>a</sup> | 0.242<sup>a</sup> | 0.094  | 0.344<sup>b</sup> |
| Z500          | 0.328<sup>b</sup> | 0.307<sup>b</sup> | 0.171<sup>a</sup> | 0.510  | 0.296<sup>b</sup> | 0.229<sup>a</sup> | 0.029  | 0.286<sup>b</sup> |

Note: The left are >99% statistical confidence level. The gale frequencies (day) are at UV-wind speed 6 m s<sup>-1</sup> except Z500 at 10 m s<sup>-1</sup>.<br>
<sup>a</sup>&lt;90% statistical confidence level.<br>
<sup>b</sup>&gt;95% statistical confidence level.
4.3 Influence of the Tibetan Plateau

The TP exerts both dynamic and thermal effects on regional atmospheric circulation patterns. Due to the special topographic characteristics, air currents can be diverted around the TP in two separate branches called the northern and southern branch jet streams (Yuan, 1983). The northern branch mainly affects...
atmospheric circulations at mid–lower geopotential levels, and it controls the average pattern of ridges and troughs in the NH to the north of 35° N. The TP also acts as a thermal source that instantly conveys thermal impact into the atmospheric circulation. On average, the air mass over the TP acts as a heat source from summer to winter; however, for the surrounding atmosphere, this air represents a cold source during wintertime (Gu et al., 1994).

The TP index expresses the status of air pressure in the mid-troposphere. It is closely connected with the frequency of occurrence of spring gales from the previous summer to the contemporary spring. All the correlation coefficients revealed an opposite correlation between the TP and spring gales. Its negative effect in the previous summer and autumn is bigger than that in the other two seasons and also for the lower geopotential levels (i.e., below Z850) (Table 4). Contrary trends between the TP index and spring gales at the Sur level can also be detected in Figure 3c. Furthermore, the variations of the TP anomaly indices for the high and low groups display an indistinctive trend from the prior June to May, but the low group presents lower values compared with the high group for all months, which means the air pressure over the TP for the low group always keeps a lower pressure condition than that of the high group (Figure 4c). Results of the lag-regression analysis of the monthly TP index on spring gales revealed the effects of the TP from the prior June to the following spring (Figure 5c). For lower levels, significant signals filled most of the rectangle below Z850 from the previous June to January, which means that the effect of the TP dominates the frequency of occurrence of spring gales during those months. The TP has little impact on the gales from February to April, but in May its effect is also significant at levels below Z850. The air pressure status of the TP during the period of the previous June to January might contain some useful signals for forecasting spring gales and DSs.

### 4.4 | Indian–Burma trough

The IBT is a westerly trough formed primarily as a dynamic function of the TP. It is a component of the southern branch jet stream, and it represents an important element regarding the forecasting of moisture transport and precipitation in southern China (Gu et al., 1994). Despite the above impacts of the IBT, our correlation analyses indicated that the IBT might also influence spring gales from the prior summer to the contemporary spring. Stronger connections exist at the lower levels than at the higher levels (Table 4). The annual variation curves of the IBT and the spring gales are correspondingly opposite. A spring with frequent occurrence of gales is usually accompanied by a strengthened IBT. Contrarily, it is the opposite (Figure 3d). Monthly changes of the IBT display the opposite variation features from the previous June to May for both the high group and the low group. The high group always performs weaker statue (shallower trough) than the low group for all months. Integrally, the IBT keeps shallow (weak) or deep (strong) with a slight declining or increasing trend for the high or low group from the previous summer to the next spring (Figure 4d). The IBT has significant links with spring gales, as confirmed by the lag-regression outcomes between it and the gales, especially at lower geopotential levels (i.e., below Z850) in all the months (Figure 5d). It means the spring gales would affect the study domain frequently if the IBT were to maintain its strengthened status from the previous June to the following spring.

### 4.5 | Blocking highs

The Ural, Baikal, and Okhotsk BHs are warm high-pressure systems that appear over the mid–high latitudes in the mid–high troposphere of the NH, which are

| BHs                | Gales (day)                      | Sur  | Z925 | Z850 | Z700 | Z500 |
|--------------------|----------------------------------|------|------|------|------|------|
| Baikal (pre-summer)| –0.595                           | –0.533 | –0.488 | –0.335 | –0.289 |
| Baikal (pre-autumn)| –0.374                           | –0.429 | –0.367 | –0.220 | –0.263 |
| Baikal (spring)    | –0.574                           | –0.520 | –0.594 | –0.648 | –0.625 |
| Ural (pre-summer)  | –0.522                           | –0.491 | –0.438 | –0.263 | –0.178 |
| Okhotsk (pre-summer)| –0.319a                         | –0.333a | –0.250b | –0.276a | –0.389 |
| Okhotsk (spring)   | –0.357a                          | –0.311 | –0.367 | –0.390 | –0.428 |

Note: The left are >99% statistical confidence level. The gale frequencies (day) are at UV-wind speed 6 m s⁻¹ except Z500 at 10 m s⁻¹.

a>95% statistical confidence level.
b<90% statistical confidence level.
commonly quasi-stationary over periods of several days. Generally, the establishment and breakdown of these BHs induce major adjustments in the atmospheric circulations of the NH. For example, the atmospheric circulation would typically change from a zonal to meridional pattern during the stage of establishment of these

### Table 6

Correlations between the North Polar vortex (NPV) area and the western Pacific subtropical high (WPSH), Tibetan Plateau (TP), and India–Burma trough (IBT)

| Atmospheric circulation components | Area of NPV in Euro-Asian sector (60°–150° E) | Season     | Spring | Summer | Autumn | Winter | Following spring |
|-----------------------------------|---------------------------------------------|------------|--------|--------|--------|--------|------------------|
| WPSH                              |                                             |            |        |        |        |        |                  |
| Area                              |                                             | Spring     | -0.462 | -0.540 | -0.478 | -0.214 | -0.496          |
|                                  |                                             | Summer     |        | -0.588 | -0.486 | -0.308 | -0.479          |
|                                  |                                             | Autumn     |        |        | -0.492 | -0.320 | -0.503          |
|                                  |                                             | Winter     |        |        |        | -0.280 | -0.374          |
| Intensity                         |                                             | Spring     | -0.441 | -0.516 | -0.413 | -0.222 | -0.448          |
|                                  |                                             | Summer     |        | -0.571 | -0.447 | -0.314 | -0.455          |
|                                  |                                             | Autumn     |        |        | -0.459 | -0.297 | -0.504          |
|                                  |                                             | Winter     |        |        |        | -0.291 | -0.330          |
| TP                                |                                             | Spring     | -0.515 | -0.593 | -0.638 | -0.044 | -0.564          |
|                                  |                                             | Summer     |        | -0.770 | -0.736 | -0.065 | -0.662          |
|                                  |                                             | Autumn     |        |        | -0.716 | -0.172 | -0.601          |
|                                  |                                             | Winter     |        |        |        | -0.498 | -0.332          |
| IBT                               |                                             | Spring     | -0.495 | -0.613 | -0.608 | -0.192 | -0.488          |
|                                  |                                             | Summer     |        | -0.624 | -0.651 | -0.084 | -0.573          |
|                                  |                                             | Autumn     |        |        | -0.630 | -0.133 | -0.587          |
|                                  |                                             | Winter     |        |        |        | -0.188 | -0.554          |

**Note:** The left are >99% statistical confidence level.

*a* <90% statistical confidence level.

*b* >95% statistical confidence level.

**Figure 6** Regression East Atlantic pattern index on the geopotential height at Z500, (a) winter, (b) spring
BHs, and then change back to a zonal circulation as they break down (Zhao, 1999).

Different variations can be found by comparing the high group and the low group with regard to the Baikal and Ural BHs. The high and low groups exhibit opposite varying trends from the previous June to May. For example, the curve of the Baikal high group starts at a high value in June (meaning that the blocking situation was strong), decreases until November, and then increases from December to May. Conversely, the trend for the low group is the opposite (Figure 4e). Similar variations are evident for the Ural BH; however, it has more turning points than that of the Baikal BH, that is, its two major turning points are in the previous October and the following February for the high group (Figure 4f).

The Baikal BH from the prior summer to spring is closely connected to spring gales below Z850. The most significant correlation between them appears in springtime. The occurrence of gales decreases if the Baikal BH becomes established. This is because southward movement of cold air from the northern polar region is prevented by the Baikal BH, which generally forms directly upstream of our study region. Thus, without cold outbreaks, the occurrence of spring gales and DS in northern China is reduced (Table 5). Moreover, the Ural BH is also an important component regarding the occurrence of spring gales, mainly at low levels below Z850. It is special for its two-season lagged impact through autumn and winter, that is, it might induce an increase in the occurrence of spring gales if it breaks down in the previous summer. In this circumstance, the atmospheric circulation would change from a meridional type to a zonal pattern, and the northwestern current would become strengthened, bringing increased occurrence of strong winds and DS to the study area.

**FIGURE 7** Differences of spring UV-wind at Z500 corresponding to East Atlantic (EA) high and low index groups, (a) EA high, (b) EA low.
FIGURE 8  Spring geopotential height anomalies at Z500 for the East Atlantic pattern index high and low groups of spring plus above 90% significant areas (a, high, b, low; contour interval 4 gpdm)

FIGURE 9  Monthly SD of the East Atlantic pattern
Different from the Ural BH, the summer Okhotsk BH mainly affects the wind speeds at high levels. In spring, it presents significant connections with gales at levels below the mid-troposphere (Table 5).

The results of the lag regression of the BHs revealed their lag influences during different months. For example, the prior July and October of the Baikal BH impact spring gales mainly at the lower levels, whereas the spring Baikal BH affects gales primarily at higher levels above Z850 (Figure 5e). Moreover, the lagged effects of the Ural BH chiefly appear from the previous June to October, most obviously at levels below Z850 (Figure 5f). The Ural and Baikal BHs could possibly be used as seasonal signals for forecasting DS in northern China, given the significant correlations between the BHs in the prior term and the springtime gales.

### 4.6 Relationships among the atmospheric components

To a certain degree, the spatial extent of the area of the NPV controls cold outbreaks. Generally, a cold outbreak generates strong winds and causes more DS in northern China. Given the close correlation between the NPV area and spring gales, the connections between the WPSH, TP, and IBT and the NPV area were examined. An antiphase relationship has been identified between the NPV and subtropical areas of high pressure such as the WPSH, the TP, and a low pressure of the IBT. Their interconnections are complex, and they have certain lagged effects on different time scales. All of the WPSH, TP, and IBT component indexes present negative correlation with the NPV area index from spring to the following spring. Most of the correlation coefficients are significant (at the 0.01 statistical significance level), and all the subtropical systems have an evident impact on the NPV area, not only in the contemporary season but also in the following seasons (except winter). The winter acts as a south–north period of adjustment of the atmospheric circulations from the prior spring, summer, and autumn to the following spring (Table 6). Therefore, certain seasonal forecast signals could be extracted from previous seasons regarding direct impact on the spring NPV and indirect impact on springtime gales and DS.

### TABLE 7 Correlations between the East Atlantic (EA) pattern and the North Polar vortex (NPV), western Pacific subtropical high (WPSH), Tibetan Plateau (TP) and India–Burma trough (IBT) during the contemporary and following seasons

| EA pattern | Area of WPSH | Intensity of WPSH | Area of NPV | Intensity of NPV | TP | IBT |
|------------|--------------|------------------|------------|-----------------|----|-----|
| Summer     |              |                  |            |                 |    |     |
| Pre-summer | 0.538        | 0.541            | −0.429     | −0.488          | 0.434<sup>a</sup> | 0.383<sup>a</sup> |
| Pre-autumn | 0.506        | 0.503            | −0.452     | −0.313<sup>a</sup> | 0.476 | 0.473 |
| Pre-winter | 0.537        | 0.544            | −0.324<sup>a</sup> | −0.267<sup>a</sup> | 0.481 | 0.542 |
| Pre-spring | 0.425        | 0.409            | −0.335<sup>a</sup> | −0.306<sup>a</sup> | 0.446 | 0.452 |
| Summer     | 0.583        | 0.583            | −0.564     | −0.510          | 0.581 | 0.470 |
| Autumn     |              |                  |            |                 |    |     |
| Pre-summer | 0.630        | 0.642            | −0.235<sup>b</sup> | −0.478          | 0.397<sup>a</sup> | 0.457 |
| Pre-autumn | 0.481        | 0.470            | −0.307<sup>a</sup> | −0.442          | 0.418<sup>a</sup> | 0.379<sup>a</sup> |
| Pre-winter | 0.468        | 0.490            | −0.425     | −0.151<sup>b</sup> | 0.477 | 0.418 |
| Spring     | 0.431        | 0.412            | −0.286<sup>a</sup> | −0.334          | 0.510 | 0.396 |
| Summer     | 0.559        | 0.574            | −0.423     | −0.538          | 0.520 | 0.490 |
| Autumn     | 0.566        | 0.578            | −0.254<sup>b</sup> | −0.375          | 0.498 | 0.567 |

**Note:** The left are >99% statistical confidence level.

<sup>a</sup> >95% statistical confidence level.

<sup>b</sup> <90% statistical confidence level.
4.7 | EA pattern and atmospheric circulation components

The winter and spring EA patterns are similar in terms of the positions of their active positive and negative centres (Figure 6a,b). Active centres of the spring EA pattern are relatively weaker when comparing them with the winter EA pattern. Three significant negative centres can be viewed in the winter model. Two large centres remain over the North Atlantic Ocean and the area to the north of the Lake Baikal. The third smaller centre is located over the south region of the Bering Strait. There are two significant negative centres over the mid–high latitude of the northeastern Atlantic and the Eurasian continent in spring EA pattern, while most tropical and subtropical regions, especially the large area of East Asia, are covered by significant positive values. It indicates that the EA pattern displays a positive influence on the air pressure field during the winter and spring seasons.

To examine the effects of the EA pattern on contemporary spring wind fields, two groups of spring wind speed charts (average of 22 samples) corresponding to the EA high and low groups were prepared (Figure 7a,b). It can be viewed that a strong southeast current went through our study region for the EA high group, while a strong western jet controlled the mid–high latitude of the central and east Eurasia, which obstructs direct southward movement of cold air from the polar region, forcing it in the northeastern direction instead. Thus, the study domain was affected to a lesser extent by cold attacks, and correspondingly the spring gales and DS decreased (Figure 7a). A large region in the wind filed for the EA low group was controlled by southeast currents over the northwest of Lake Baikal, while northern China was influenced by strong northwestern flow, meaning more cold air can be transferred to our study region, and then the spring gales and DS increased accordingly (Figure 7b). In addition, significant differences can be found in the averaged geopotential height anomaly charts at Z500 between the EA high and low groups during spring season (Figure 8a,b). There is a big negative anomaly covering most East Asia with 99 per cent statistical
confident level. Our study domain is under the control of a strong west current along the south edge of the low-pressure body (Figure 8b). The WPSH is weak when compared with the Z500 anomaly chart for the EA high group (Figure 8a). Strong western flow and a shrunken WPSH general lead to a frequent strong wind spring, and then frequent DSs in northern China.

The most and second-most active months of the EA pattern are December and April, respectively, as can be recognized from the monthly SDs. The least active months are June and July (Figure 9). The EA pattern has notable lagged impacts on the WPSH, NPV, TP, and IBT on the seasonal scale (Table 7). During the seasons from the previous to the following summer, the EA pattern implements its influence on the circulation components, not only within the same season but also in the following seasons. It can be seen from Table 7 that the WPSH and TP are strengthened, and the IBT is weakened if the EA pattern is in its positive phase, while the NPV is weakened markedly.

Most years since 1997 show positive values for the annual mean EA index, whereas the values of most years previous to 1997 are negative (Figure 10a). Overall, the EA pattern has shown a trend of increase during the past 71-year period (1950–2020), and according to the 11-year running curve of SDs, that reveals a decadal trend of the EA pattern. We selected December and July to elucidate the year-by-year variations for an active month and a quiet month, respectively, and both showed trends of increase in the past seven decades (Figure 10b), which are contrary to the trends of decrease observed in the occurrence of both spring gales and DSs in northern China (Figure 2a,b).

5 | CONCLUSIONS

5.1 | Summary

A significant positive correlation between spring gales at levels below Z500 and dust storms (DSs) proves that strong wind represents the crucial dynamic power for DS occurrence in northern China. However, the occurrence frequencies of gales and DSs display trends of decline during the past 68-year period (1954–2021).

The components of the atmospheric circulation that surround the study domain show a significant correlation with the occurrence of spring gales. These components exhibit influence and lagged impact on the occurrence of spring gales to differing degrees. The most influential system is the North Polar vortex (NPV), for which the area index is positively correlated to gale frequency at different geopotential levels during all seasons except winter. Spring gales become frequent when the spatial extent of the NPV is enlarged. Conversely, spring gales become less frequent, and the corresponding occurrence of DSs decreases when the extent of the NPV is contracted towards the north polar region.

The atmospheric circulation systems in subtropical regions of eastern Asia, for example, the western Pacific subtropical high (WPSH) and Tibetan Plateau (TP), exhibit negative influence, and the India–Burma trough (IBT) displays a positive effect and lagged impact on the occurrence of spring gales in the study domain. The connections between these atmospheric components and spring gales are stronger at low levels (i.e., below Z850) than at high levels (i.e., Z700 and Z500). Moreover, it was confirmed that the frequency of occurrence of spring gales is negatively controlled by the status of the Baikal, Ural, and Okhotsk blocking highs (BHs) over the mid-high latitudes of the Northern Hemisphere. The BHs present lagged influence on spring gales. The Baikal BH has greater influence than the other two BHs, not only in previous seasons but also in the contemporary spring. The multilateral connections among the influential atmospheric components over mid-eastern Asia mainly reflect two types of circulation systems. One includes the WPSH, TP, and IBT over subtropical regions, which are significantly and originally controlled by sea surface temperature variations. The other is the NPV over the northern polar region. An antiphase relationship exists between those two types of circulation systems. The NPV contracts northward if the subtropical circulation components become strengthened, and vice versa. A small NPV results in reduced cold outbreaks and consequently less frequent gales and DSs in northern China.

Significant differences indicate that the high- and low-pitched East Atlantic (EA) pattern may result in dissimilar wind fields over the Eurasian continent, especially in the study region. For the high-pitched EA pattern, a strong western current north of Lake Baikal may prohibit the expansion of the NPV; a shrunken NPV means an infrequent cold air attacked spring, leading to decreased gales and DS attacks in northern China. On the contrary, a frequent cold air outbreaking spring may appear when the EA pattern is at its low-pitched status, which means increased gales and DSs.

The annual index of the EA pattern shows a gradual increase during the past 71-year period (1950–2020). Its most active month is December and the most inactive months are June and July. It has been proven that the EA pattern indicates adjustment of the circulation components both for the contemporary term and for following seasons. Generally, a low-pitched EA pattern corresponds to a weakened WPSH, low air pressure over the TP, and a strong IBT, which correlate with obvious
expansion of the NPV. Under these circulation regimes, the frequencies of occurrence of spring gales and DSs in northern China are increased.

5.2 | Discussion

This study explored the impact of atmospheric circulation components on the occurrence of spring gales and DSs in northern China, and the related adjustment functions of the EA pattern. However, some questions are still left for further exploration. On the one hand, there are several atmospheric circulation systems that directly influence the spring gales and DSs, and they are proven to be impacted by the EA pattern to different degrees in this study, in which the main component affected by the EA pattern needs to be deeply studied. On the other hand, the EA pattern presents lag-influence on the circulation components; for the crucial circulation component, how long the EA pattern impacts the period on it in the previous term is left to be answered, which is very important for designing an efficient seasonal DS forecast scheme for our focused region.

A strong wind is required to raise surface sand and dust into the air, but the underlying conditions of the sand and dust source regions represent another important influencing factor of DSs. Different sources can have dissimilar underlying conditions. Variation of the underlying conditions generally depends on the characteristics of the local climatic regime, drought, precipitation, temperature, evaporation, relative humidity, local eco-environmental protection policies, and human activities. The previous and contemporary precipitation and temperature are very important for surface plants reviving in spring in Northwest China. Favourable surface vegetation conditions evidently limit the rising of the sand and dust particles. The annual precipitation exhibited an increasing trend, and the same tendency presented in summer precipitation over Northeast China and the Pearl River basin in Guangdong Province (Q. Zhang et al., 2009). Furthermore, some studies investigate the associated atmospheric circulation influence factors on China precipitations, such as the interseasonal oscillation over the tropical western Pacific and the South China Sea, Antarctic Oscillation, Northwestern Pacific High, the SST, etc. (Li & Li, 1997; Nan & Li, 2005; Qin et al., 2005; Wang, 1994; J. J. Xu & Johnny Chan, 2002).

Therefore, which element is the most critical impacting factor for the increase of DSs and how to estimate and confirm the influence degrees of human activities is a crucial question related to the local developing policies? It was found that the major influential element of the significantly increased spring DSs in Hunshdak Sandy Lands of northern China during 2001–2008 is drought, which is closely related to the lack of local precipitation, higher temperature, and strong evaporation in those 8 years. The unfavourable climate conditions deteriorated the local surface condition, which is verified by the reduction of vegetation cover (NDVI), soil moisture, and relative humidity. There are almost no people living in the sandy lands, because of the extreme lack of drinking water that can be found in the deserted region. Therefore, the impact of human activities is not the main influencing factor of the increased DSs in the sandy lands during 2001–2008 (Gao et al., 2012). In addition, ecosystem improvement represents systematic engineering projects that require long-term implementation of favourable policies and substantial investment. Therefore, to support such projects, further data on the effects of underlying conditions on the occurrence of DSs over different time scales should be collected and analysed comprehensively.

AUTHOR CONTRIBUTIONS

Tao Gao: Conceptualization (lead); data curation (lead); formal analysis (lead); funding acquisition (lead); investigation (lead); methodology (lead); resources (lead); software (lead). An Chang: Project administration (equal).

Mei Yong: Data curation (equal); project administration (equal).

Zelong Yang: Writing – review and editing (equal).

Xiaoyu Lu: Investigation (equal); methodology (equal).

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