Spatiotemporal Variability of Surface Wind Speed during 1961–2017 in the Jing–Jin–Ji Region, China

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ABSTRACT

Wind speed variations are influenced by both natural climate and human activities. It is important to understand the spatial and temporal distributions of wind speed and to analyze the cause of its changes. In this study, data from 26 meteorological stations in the Jing–Jin–Ji region of North China from 1961 to 2017 are analyzed by using the Mann–Kendall (MK) test. Over the study period, wind speed first decreased by $-0.028$ m s$^{-1}$ yr$^{-1}$ ($p < 0.01$) in 1961–1991, and then increased by $0.002$ m s$^{-1}$ yr$^{-1}$ ($p < 0.05$) in 1992–2017. Wind speed was the highest in spring ($2.98$ m s$^{-1}$), followed by winter, summer, and autumn. The largest wind speed changes for 1961–1991 and 1992–2017 occurred in winter ($-0.0392$ and $0.0065$ m s$^{-1}$ yr$^{-1}$, respectively); these values represented 36% and 58% of the annual wind speed changes. More than 90.4% of the wind speed was concentrated in the range of 1–5 m s$^{-1}$, according to the variation in the number of days with wind speed of different grades. Specifically, the decrease in wind speed in 1961–1991 was due to the decrease in days with wind speed of 3–5 m s$^{-1}$, while the increase in wind speed in 1992–2017 was mainly due to the increase in days with wind speed of 2–4 m s$^{-1}$. In terms of driving factors, variations in wind speed were closely correlated with temperature and atmospheric pressure, whereas elevation and underlying surface also influenced these changes.

Key words: climate change, Jing–Jin–Ji region, Mann–Kendall (MK) trend test, wind speed, driving factors

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1. Introduction

As a meteorological factor, wind greatly influences life on the earth, both directly and indirectly (Liao et al., 2018). First, in the context of climate change, wind-related natural disasters have occurred more frequently in recent years (Carlton, 2017). Second, as an intermediate medium connecting the surface and the lower atmosphere, it has an important impact on weather and climate, and it can alter evaporation by changing the aerodynamic driver of the evaporative demand (Wang et al., 2016), which inevitably affects the water cycle process (Azorin-Molina et al., 2014; Zhao et al., 2019). Meanwhile, as people’s awareness of ecological and environmental protection increases, their appreciation of the role of wind is becoming increasingly prominent (Jin et al., 2016). On the one hand, wind speed variation affects air quality, and the stronger the wind speed in winter, the better the air condition (Bottema, 1999; Fan et al., 2017). On the other hand, the use of conventional fossil energy sources (coal and oil) can generate greenhouse gases such as CO$_2$ and other environmental problems. As a renewable clean energy source, wind has become one of the fastest growing energy sources in the world (Huang et al., 2015). Moreover, the change in surface wind directly affects the development and utilization of wind energy. Therefore, understanding wind variations is very important.

Based on the above background, in recent decades, the research on wind has been increasing globally. For ex-
ample, over the past 50 years, wind speed has been found to exhibit a decreasing trend in North America, East Asia, Europe, and Oceania, with average values of −0.07, −0.08, −0.09, and −0.16 m s⁻¹ decade⁻¹, respectively (Torres et al., 2005; McVicar et al., 2008; Lin et al., 2013). However, in the past two decades, this trend of declining wind speed has slowed down significantly, and in many areas, a slightly increasing trend has been observed, such as in Italy (Pirazzoli and Tomasin, 2003), Korea (Kim and Paik, 2015), Saudi Arabia (Azorin-Molina et al., 2018), and the Aleutian Islands (Buxton et al., 2013). In China, wind speeds typically follow the globally observed decreasing trend. For example, Zhang et al. (2019) reported that, during 1958–2015, the wind speed dropped at a rate of −0.109 m s⁻¹ decade⁻¹, a trend that stabilized after 2000. Li et al. (2018) found that wind speed in Northwest China dropped sharply at a rate of 0.036 m s⁻¹ yr⁻¹ from 1969 to 1992; however, since 1993, the wind speed trend has recovered slightly to a positive value of 0.004 m s⁻¹ yr⁻¹. In general, wind speed changes around the world suggested a decrease starting in the 1950s or 1960s, followed by an increase starting in the 1990s or 2000s (Young et al., 2011). Furthermore, although spatial trends of wind speed are approximately consistent across the globe, spatial differences remain very conspicuous.

Thus, a question arises: What factors affect the temporal and spatial variations in wind speed? Past research has shown that it is influenced by both natural and human factors. Natural factors include latitude, elevation, season, temperature, and air pressure (Cheboxarov and Cheboxarov, 2008; Yang et al., 2012; Dadaser-Celik and Cengiz, 2014). McVicar et al. (2012) found that the declining trend at high latitudes is more pronounced than that at low latitudes, i.e., under the same conditions, wind speeds at high latitudes change more dramatically (McVicar et al., 2010). On the other hand, Li et al. (2018) reported that under the same climatic conditions, wind speed is more likely to change in the mountains or in winter. The increase of solar radiation on the earth’s surface caused the earth to brighten over the past decades, which would result in turbulence and atmospheric pressure instability, leading to changes in wind speed (Ferrari et al., 2012; Gupta et al., 2015; Zha et al., 2019). In addition, urbanization also plays an important role in wind speed changes (Wu et al., 2016). In Beijing, as urbanization increases by 10%, the wind speed decreases by 0.12 m s⁻¹ (Zha et al., 2017).

The Jing–Jin–Ji region, located in the North China Plain, is the region most severely affected by human activities in China (Han et al., 2018). Because this area is limited by its local shortage of water resources, many studies have been carried out on evapotranspiration and the water cycle process (Qiu et al., 2008; Yao, 2017), wherein the wind speed was one of the main factors affecting changes in these processes. However, little research has focused solely on wind trends. As such, this study analyzes wind speed trends in the Jing–Jin–Ji region, North China from 1961 to 2017 by using data from 26 meteorological stations. In addition to analyzing the conditions underlying changes in the wind speed, we also identify the main factors that affect the change in wind speed. These findings will be valuable to the study of evaporation and water cycle processes.

2. Study area and methods

2.1 Study area

The Jing–Jin–Ji region is located in 36°05′–42°40′N, 113°27′–119°50′E. It includes Beijing, Tianjin, and Hebei Province, and has a total area of 2.18 × 10⁶ km² (Fig. 1). It accounts for 2.2% of the country’s land area, 8.0% of the population, and 11.0% of the country’s gross domestic product (Li et al., 2013).

2.2 Data

We selected wind speed data from 26 national meteorological stations from 1961 to 2017 (Table 1). The daily data were downloaded from the National Meteorological Information Center (http://data.cma.cn). In addition, we used the 55-yr reanalysis data (JRA-55) of temperature and pressure from the Japan Meteorological Agency (JMA) for the period of 1961–2017 (Kobayashi et al., 2015), which were annual data on the 0.5625° latitude and longitude grid. The annual population data of Jing–Jin–Ji were obtained from the National Bureau of Statistics of China (http://data.stats.gov.cn).

2.3 Methods

The Mann–Kendall (MK) test is often employed for mutation testing and significance analysis (Liu et al., 2008; Olsson et al., 2010; Dinpashoh et al., 2011), where it is used to evaluate the monotonicity or mutations in a time series. The statistical value (S) and standardized test statistics (Z) are calculated as follows:

\[
S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i),
\]

\[
\text{sgn}(x_j - x_i) = \begin{cases} 
1, & \text{if } x_j - x_i > 0 \\
0, & \text{if } x_j - x_i = 0 \\
-1, & \text{if } x_j - x_i < 0
\end{cases}
\]
Table 1. Basic information of meteorological stations in the Jing–Jin–Ji region from 1961 to 2017

| Station code | Longitude (°E) | Latitude (°N) | Elevation (m) | Land type (plain or mountain/urban, rural, or natural) |
|--------------|----------------|---------------|---------------|---------------------------------------------------|
| 53399        | 114.70         | 41.15         | 1392          | Mountain/rural                                    |
| 53593        | 114.57         | 39.83         | 907           | Mountain/rural                                    |
| 53698        | 114.35         | 38.07         | 101           | Mountain/urban                                    |
| 53798        | 114.37         | 37.18         | 157           | Mountain/urban                                    |
| 54308        | 116.63         | 41.20         | 722           | Mountain/natural                                  |
| 54311        | 117.77         | 41.97         | 893           | Mountain/natural                                  |
| 54401        | 114.92         | 40.77         | 764           | Mountain/urban                                    |
| 54405        | 115.50         | 40.42         | 569           | Mountain/rural                                    |
| 54406        | 115.97         | 40.45         | 482           | Mountain/natural                                  |
| 54416        | 116.87         | 40.38         | 73            | Plain/natural                                     |
| 54423        | 117.92         | 40.97         | 370           | Mountain/natural                                  |
| 54429        | 117.95         | 40.20         | 40            | Plain/urban                                       |
| 54436        | 118.95         | 40.42         | 254           | Mountain/natural                                  |
| 54449        | 119.52         | 39.85         | 5             | Plain/urban                                       |
| 54511        | 116.47         | 39.80         | 25            | Plain/urban                                       |
| 54518        | 116.40         | 39.17         | 2             | Plain/rural                                       |
| 54525        | 117.28         | 39.73         | 6             | Plain/natural                                     |
| 54527        | 117.05         | 39.08         | 6             | Plain/urban                                       |
| 54534        | 118.10         | 39.65         | 16            | Plain/urban                                       |
| 54539        | 118.88         | 39.43         | 9             | Plain/rural                                       |
| 54602        | 115.48         | 38.73         | 11            | Plain/urban                                       |
| 54606        | 115.73         | 38.23         | 16            | Plain/rural                                       |
| 54618        | 116.55         | 38.08         | −3            | Plain/natural                                     |
| 54623        | 117.72         | 39.05         | 5             | Plain/urban                                       |
| 54624        | 117.32         | 38.40         | 4             | Plain/rural                                       |
| 54705        | 115.38         | 37.37         | 20            | Plain/rural                                       |

Fig. 1. Location of the Jing–Jin–Ji region and distribution of meteorological stations.
\[ \text{VAR}(S) = \frac{n(n-1)(2n+5)}{18} \sum_{p=1}^{q} t_p (t_p - 1)(2t_p + 5), \quad (3) \]

\[ Z = \begin{cases} 
\frac{S - 1}{\sqrt{\text{VAR}(S)}}, & \text{if } S > 0 \\
0, & \text{if } S = 0 \\
\frac{S + 1}{\sqrt{\text{VAR}(S)}}, & \text{if } S < 0
\end{cases}, \quad (4) \]

where \( x_i \) and \( x_k \) are the values in years or seasons \( i \) and \( k \), respectively. If we have \( n \) values of \( x_i \) in the time series, we will have \( N = n(n-1)/2 \) slopes of \( Q_i \). The Sen’s estimator of the slope is the median of these \( N \) values of \( Q_i \). The \( N \) values of \( Q_i \) are arranged from smallest to largest, and the Sen’s estimator is

\[ Q = \begin{cases} 
Q_{(N+1)/2}, & \text{if } N \text{ is odd}; \\
Q_{N/2} + Q_{(N+2)/2}, & \text{if } N \text{ is even.} 
\end{cases}, \quad (6) \]

In addition, in order to determine the degree of contribution of a certain season to the annual wind speed variation, we use the following calculation formula (Li et al., 2012):

\[ C_i = \frac{|P_{i,1961-1991} - P_{i,1992-2017}|}{\sum |P_{i,1961-1991} - P_{i,1992-2017}|}. \quad (7) \]

where \( C_i \) is the degree of contribution per season, \( P_i \) is the wind speed in each season, \( P_{i,1961-1991} \) and \( P_{i,1992-2017} \) denotes the years from 1961 to 1991 (from 1992 to 2017).

3. Results

3.1 Temporal and spatial variations in wind speed

Figure 2 shows the results of Cramer’s test for detecting the mutation of the annual wind speed series. The inflection point was in 1991, the significance was \( \pm 3.35 (p < 0.01) \), and combined with the results of potential evapotranspiration (ET\(_{p}\)) in the Jing–Jin–Ji region reported by Han et al. (2018), 1991 was also determined to be a mutation. Therefore, 1991 was selected as the inflection point and the study period was divided into two parts: 1961–1991 and 1992–2017. Figures 3 and 4 show the spatial–temporal variations in wind speed in the Jing–Jin–Ji region from 1961 to 2017. The overall trend was a decrease of wind speed with an annual average of 2.39 m s\(^{-1}\) and a significant declining rate of 0.0154 m s\(^{-1}\) yr\(^{-1}\). However, a clear decreasing trend was observed for wind speed from 1961 to 1991 whereas a small increase was apparent from 1991 to 2017, with change rates of −0.028 and 0.002 m s\(^{-1}\) yr\(^{-1}\), respectively.

During 1961–1991, the wind speed dropped significantly, and 25 of the 26 sites (96%) showed a downward trend, among which 23 stations showed statistically significant changes at the \( \alpha = 0.01 \) level (Table 2). Significant decreases were concentrated in the region of Tianjin (−0.0733 m s\(^{-1}\) yr\(^{-1}\)), followed by the center of Cangzhou (−0.052 m s\(^{-1}\) yr\(^{-1}\)), indicating that regions with high wind speeds were those that experienced the most rapid decreases. However, an increasing trend emerged in 1992–2017, with 11 of the 26 sites (42%) showing a rising trend, 8 of which were statistically significant at the \( \alpha = 0.05 \) level (Table 2). Wind speed increases were concentrated in the west (0.065 m s\(^{-1}\) yr\(^{-1}\)) and north (0.051 m s\(^{-1}\) yr\(^{-1}\)) of the study area and were most pronounced in Chengde.

3.2 Seasonal variations in wind speed

Seasonal variations in wind speed were also observed. Over the entire study period, spring had the highest wind speed (2.98 m s\(^{-1}\)), followed by winter (2.37 m s\(^{-1}\)), summer (2.10 m s\(^{-1}\)), and autumn (2.08 m s\(^{-1}\)). During 1961–1991, the fastest decline was in winter (−0.0392 m s\(^{-1}\) yr\(^{-1}\)), followed by spring (−0.0335 m s\(^{-1}\) yr\(^{-1}\)). All stations showed statistically significant differences at the \( \alpha = 0.05 \) level. Furthermore, 96%, 81%, 85%, and 100% of stations exhibited decreasing trends in spring, summer, autumn, and winter, respectively, except in a small part of Shijiazhuang. During 1992–2017, all seasons exhibited an increasing trend, except autumn (−0.0029 m s\(^{-1}\) yr\(^{-1}\)), although it exhibited a slower decrease than the
previous period. The wind speed increased the fastest in winter (0.0065 m s$^{-1}$ yr$^{-1}$), followed by summer (0.0014 m s$^{-1}$ yr$^{-1}$). The number of stations exhibiting an increasing trend accounted for approximately 46%, 42%, 35%, and 50% in spring, summer, autumn, and winter, respectively (Table 2). Areas with increasing wind speed were predominantly concentrated in Hebei Province, with the exception of Hengshui and Cangzhou.

In addition, in order to determine the impact of different seasons on wind speed, we calculated the contribution of each season to the overall wind speed trend (Fig. 5). During 1961–1991, spring and winter wind speeds had the greatest effect on the overall trend for the entire period, at 29% and 36%, respectively. During 1992–2017, winter represented the largest contributions at 58%.

### 3.3 Frequency of different wind speed ranges

Figure 6 shows the number of days with different wind speed ranges from 1961 to 2017. More than 330 days per year exhibited wind speeds of 1–5 m s$^{-1}$ regardless of the time period. During 1961–1991, the number of days per year with wind speeds of 1–2 m s$^{-1}$ exhibited the greatest increase (3.492 day yr$^{-1}$). Conversely, the number of days with wind speeds above 3 m s$^{-1}$ decreased significantly. The number of days with wind speeds of 3–4 and 4–5 m s$^{-1}$ decreased the most, at rates of −1.68 and −1.236 day yr$^{-1}$ (Table 3), respectively. Thus, the overall wind speed decreased during this period. The opposite occurred during 1992–2017, although the overall trend was less dramatic than that during 1961–1991. The number of days with wind speeds of 2–3 and 3–4 m s$^{-1}$ increased substantially by 0.558 and 0.079 day yr$^{-1}$. By comparing these trends in different seasons, we found that wind speeds less than 2 m s$^{-1}$ increased whereas wind speeds more than 3 m s$^{-1}$ decreased. This explains why wind speed exhibited the most rapid decrease in Tianjin and Cangzhou and the most rapid increase in Chengde. Moreover, the number of days with different wind speeds changed the most in winter, which explains why winter contributes to such a large proportion of the overall wind speed changes.
4. Discussion

Several natural and human factors can lead to changes in wind speed, such as elevation, the underlying surface, and climate change. In terms of elevation, we analyze the differences between plain and mountain stations, while in terms of the underlying surface, we analyze the differences between urban and rural stations. Finally, in terms of climate change, we analyze atmospheric circulation and temperature data in mid- and high-latitude stations.

4.1 Reliability analysis

Before analyzing the factors driving wind speed changes, we verify the reliability of the results. In this study, data from the China Meteorological Administration were used to calculate the temporal and spatial variations of wind speed, as well as the variation in the number of days with different wind speeds and the seasonal contributions to overall wind speed trends. Our calculation results are in good agreement with previous studies. For example, Guo et al. (2011) calculated that the wind speed change rate in China from 1969 to 2005 was $-0.018$ m s$^{-1}$ yr$^{-1}$, while our result was $-0.015$ m s$^{-1}$ yr$^{-1}$. However, our time series is longer and wind speeds have increased within the last 10 years. Nevertheless, our results agree with global change rates between $-0.004$ and $-0.017$ m s$^{-1}$ yr$^{-1}$ (Roderick et al., 2007).

In 1961–2017, the wind speed decreased by 0.028 m s$^{-1}$ yr$^{-1}$ from 1961 to 1991 then increased by 0.002 m s$^{-1}$ yr$^{-1}$ from 1992 to 2017. Meanwhile, 90.4% of the wind speeds are concentrated between 1 and 5 m s$^{-1}$. Furthermore, the number of days with wind speeds of 3–4 and 4–5 m s$^{-1}$ decreased the most, at rates of $-1.68$ and $-1.236$ day yr$^{-1}$ in 1961–1991, respectively, while the number of days with wind speeds of 1–3 and 5–7 m s$^{-1}$ increased the most, at rates of $0.016$ and $0.012$ day yr$^{-1}$ in 1992–2017.

### Table 2. Number of meteorological stations showing a decrease or increase in wind speed for different seasons

| Period     | Decrease/significant decrease | Increase/significant increase |
|------------|-------------------------------|------------------------------|
| Annual     | 1961–1991                    | 25/23                        | 1/0 |
|            | 1992–2017                    | 15/12                        | 11/8 |
| Spring     | 1961–1991                    | 25/23                        | 1/0 |
|            | 1992–2017                    | 14/10                        | 12/6 |
| Summer     | 1961–1991                    | 21/17                        | 5/1 |
|            | 1992–2017                    | 15/8                         | 11/7 |
| Autumn     | 1961–1991                    | 22/21                        | 4/0 |
|            | 1992–2017                    | 17/10                        | 9/8 |
| Winter     | 1961–1991                    | 26/24                        | 0/0 |
|            | 1992–2017                    | 13/6                         | 13/9 |
number of days with wind speeds of 2–3 and 3–4 m s$^{-1}$ increased substantially by 0.558 and 0.079 day yr$^{-1}$, respectively, in 1992–2017. This indicates that the number of days with the dominant wind speed has a dominant effect on the overall wind speed trend from 1961 to 2017. This conclusion is consistent with those of McInnes et al. (2011) and Rasmussen et al. (2011).

4.2 Relationship between elevation and wind speed

Figure 7 compares the wind speed variations at different elevations in different seasons. Between 1961 and 1991, wind speeds at all elevations show a decreasing trend regardless of the season, at rates of 0.021–0.037 m s$^{-1}$ yr$^{-1}$, which is consistent with our previous results. Interestingly, from 1992 to 2017, stations with elevations below 100 m and above 1000 m continued to show decreases, while elevations between 100 and 1000 m show an upward trend. For the whole year, the fastest decrease in wind speed was in areas with altitudes greater than 1000 m, and the rate of decline was $-0.037$ m s$^{-1}$ yr$^{-1}$, while the fastest increase in wind speed was in areas with altitudes between 500 and 1000 m, increasing at 0.033 m s$^{-1}$ yr$^{-1}$.

In 1961–1991, the wind speed trends in spring, summer, and autumn decreased with the increasing elevation in areas with elevations below 1000 m, while the areas
above 1000 m have fewer stations, and thus these trends are not representative. In winter, the rate of wind speed decline is between 0.035 and 0.057 m s\(^{-1}\) yr\(^{-1}\), which is the biggest decline in four seasons. Therefore, winter is the main season causing the overall wind speed decline (Zhang et al., 2014). In 1992–2017, although the wind speed in the area with elevations less than 100 m continues to decline, its downward trend is obviously less than that in 1961–1991. Meanwhile, in the area with elevations between 100 and 1000 m, the wind speed shows an obvious upward trend, and by further increasing elevation, the rate of wind speed recovery is gradually increasing. Therefore, we can conclude that below 1000 m, the wind speed gradually increases with the increasing altitude.

### 4.3 Relationship between the underlying surface and wind speed

Previous research results show that a change in the underlying surface may in turn change the wind speed (Wu et al., 2016, 2017). In Croatia, when urbanization expansion reaches 12.5% and 37.5%, the wind speed is predicted to decrease by 8% and 18%, respectively (Klaić et al., 2002). Moreover, in the past few decades, owing to increasing urbanization, the wind speed in Beijing has decreased at an average rate of \(-0.05\) m s\(^{-1}\), with the

| Table 3: Changes in the number of days per year (day yr\(^{-1}\)) for different daily mean wind speed ranges (m s\(^{-1}\)) |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Period          | 0–1    | 1–2    | 2–3    | 3–4    | 4–5    | 5–6    | 6–7    | 7–8    | 8–9    |
| Annual 1961–1991 | 0.110  | 3.492  | −0.050 | −1.680 | −1.236 | −0.395 | −0.163 | −0.055 | −0.024 |
| 1992–2017        | −0.343 | −0.087 | 0.558  | 0.079  | −0.114 | −0.093 | −0.002 | 0.000  | 0.000  |
| Spring 1961–1991 | 0.000  | 0.444  | 0.852  | −0.406 | −0.611 | −0.136 | −0.112 | −0.018 | −0.013 |
| 1992–2017        | −0.004 | −0.294 | 0.375  | 0.052  | −0.067 | −0.059 | −0.002 | 0.000  | 0.000  |
| Summer 1961–1991 | −0.015 | 0.819  | −0.198 | −0.446 | −0.146 | −0.012 | −0.004 | 0.000  | 0.000  |
| 1992–2017        | −0.023 | 0.101  | −0.052 | −0.023 | −0.003 | 0.000  | 0.000  | 0.000  | 0.000  |
| Autumn 1961–1991 | 0.038  | 0.966  | −0.454 | −0.314 | −0.142 | −0.058 | −0.013 | −0.020 | −0.003 |
| 1992–2017        | −0.153 | 0.346  | −0.085 | −0.093 | −0.013 | −0.002 | 0.000  | 0.000  | 0.000  |
| Winter 1961–1991 | 0.088  | 1.263  | −0.250 | −0.514 | −0.337 | −0.189 | −0.035 | −0.017 | −0.008 |
| 1992–2017        | −0.163 | −0.240 | 0.320  | 0.143  | −0.031 | −0.031 | 0.000  | 0.000  | 0.000  |

Fig. 7. Trends of wind speed for different elevation ranges during 1961–1991 and 1992–2017.
greatest decrease in urban areas, followed by suburban areas, and finally rural parts (Li et al., 2011). Based on the work of Han et al. (2019), stations were categorized according to the land use within 5 km around the station. Specifically, the stations with water, forest, and grass-land accounting for more than 50% are categorized as being in natural areas. Meanwhile, the stations with cultivated land accounting for more than 50% are considered rural. Finally, the stations with residents and industry accounting for more than 50% of the land use are considered urban. The wind speed changes under different types of underlying surface were then compared (Fig. 8a). Evidently, for different underlying surfaces, the wind speed changes are different. Regarding the average wind speed, it is higher in rural areas (2.72 m s$^{-1}$) than in urban areas (2.36 m s$^{-1}$) and natural areas (1.76 m s$^{-1}$). The difference between the average wind speed in rural and urban areas is approximately 0.6 m s$^{-1}$ and gradually decreases over time, which is consistent with previous studies (Guo et al., 2011; Gryning et al., 2014).

In 1961–1991, the downward trend was consistent with the average wind speed, which was also greater in rural areas (0.031 m s$^{-1}$ yr$^{-1}$) and urban areas (0.021 m s$^{-1}$ yr$^{-1}$) than in natural areas (0.016 m s$^{-1}$ yr$^{-1}$). This can be attributed to the fact that urbanization increases surface roughness and reduces wind speed variations (Vautard et al., 2010). However, in 1992–2017, this trend was different, wherein the average wind speed in natural areas (0.052 m s$^{-1}$ yr$^{-1}$) was increasing, while the rate of decline has slowed down in rural areas and changed to an increase in urban areas. Previous research has shown that China has seen a rapid increase in construction since the early 1990s, and thus urbanization would weaken the downward trend of wind speed, which is approximately in line with the actual situation in the Jing–Jin–Ji region (Xu et al., 2006).

In order to determine the relationship between urbanization and wind speed, we used a regression analysis to calculate the correlation between urbanization rate and wind speed. The urbanization rate represents the trend of urbanization, which is defined as the population of an area divided by the total population (Zhu et al., 2007). Figure 8b shows that the urbanization rate and wind speed exhibit a significant negative correlation. Thus, as the urbanization rate increases, the wind speed gradually decreases. Specifically, for every 1% increase in the urbanization rate, the wind speed will drop by 0.0061 m s$^{-1}$.

### 4.4 Atmospheric circulation and temperature

Atmospheric pressure is crucial for air circulation, whereas temperature is the main driving force for atmospheric pressure (Qiao et al., 2008). Here, we test whether these factors cause long-term wind speed changes by using JRA-55 from the JMA to analyze the temperature and atmospheric pressure in the study area (midlatitude region) and the area to the north of the study area (high latitudes).

Figure 9 reveals that, during 1961–1991, the temperature in the study area rose at a rate of 0.008°C yr$^{-1}$, while it was 0.035°C yr$^{-1}$ at higher latitudes. This asymmetric temperature change would lead to an overall increase in atmospheric pressure (Wu et al., 2018). Moreover, a negative correlation has been reported between changes in temperature and atmospheric pressure (Fujibe, 2011). Because of the rapid temperature rise at high latitudes, the pressure increase is slow. Conversely, the study area exhibits the opposite scenario. The average pressure at high latitude is higher than that in the study area, but the trend in the atmospheric pressure at high latitude (−0.97 Pa yr$^{-1}$) is lower than that in the study area (2.06 Pa yr$^{-1}$). The resulting variations in pressure are unequal, which will change the difference between the atmospheric pressure in high- and midlatitude areas; as this difference decreases, the wind speed will decrease accordingly. However, the results for 1992–2017 are the opposite to those in 1961–1991, i.e., the temperature trend changes more rapidly at midlatit-
udes, which can increase pressure gradients, resulting in a slight increase in wind speed. Previous research has proven that an increase in air temperature may decrease the atmospheric pressure, which further decreases the regional wind speed (Zhang et al., 2006; Chen et al., 2010). Although temperature can affect air pressure changes, the key driving factor for wind speed changes is still atmospheric circulation.

5. Summary

This study analyzed the temporal and spatial variations in wind speed in the Jing–Jin–Ji region of North China from 1961 to 2017 as well as the key driving factors behind these changes. The main conclusions are as follows.

(1) During 1961–2017, the wind speed decreased by \(-0.028 \text{ m s}^{-1} \text{ yr}^{-1}\) from 1961 to 1991 and then increased by 0.002 m s\(^{-1}\) yr\(^{-1}\) from 1992 to 2017. The regions with the greatest decrease and increase were Tianjin (\(-0.073 \text{ m s}^{-1} \text{ yr}^{-1}\)) and Chengde (0.065 m s\(^{-1}\) yr\(^{-1}\)), respectively.

(2) Winter showed the greatest decreases and increases in wind speed (\(-0.0392\) and 0.0065 m s\(^{-1}\) yr\(^{-1}\) in 1961–1991 and 1992–2017, respectively). These values represented 36% and 58% of the annual wind speed changes during the two time periods, respectively.

(3) More than 90.4% of the wind speeds were concentrated in the range of 1–5 m s\(^{-1}\). During 1961–1991, the number of days with wind speeds of 3–4 and 4–5 m s\(^{-1}\) decreased by \(-1.68\) and \(-1.236 \text{ day yr}^{-1}\), respectively; whereas in 1992–2017, the number of days with wind speeds of 2–3 and 3–4 m s\(^{-1}\) increased by 0.558 and 0.079 day yr\(^{-1}\), respectively. These changes in the distributions of days with certain wind speeds explain the observed overall decreasing and increasing trends during 1961–1991 and 1992–2017, respectively.

(4) A temperature change will lead to a change in atmospheric pressure, and a corresponding change in wind speed. However, the key factor affecting wind speed changes is atmospheric circulation. Moreover, urbanization and elevation will also affect wind speed.

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