Changes in surface wind speed and its different grades over China during 1961–2020 based on a high-resolution dataset

Jie Wu | Ying Shi

1School of Geography and Environmental Engineering, Gannan Normal University, Ganzhou, China
2National Climate Center, China
Meteorological Administration, Beijing, China

Correspondence
Ying Shi, National Climate Center, China
Meteorological Administration, Beijing, China.
Email: shiying@cma.gov.cn

Funding information
National Key Research and Development Program of China, Grant/Award Number: 2017YFA0605002; National Natural Science Foundation of China, Grant/Award Number: 41805063

Abstract
Changes in surface wind speed are important for wind energy planning, especially in China, which has the highest new and total wind power capacities globally. In this article, based on a daily high-resolution observation dataset for the period of 1961–2020, changes in the surface wind speed and its different grades over China were analysed. The results showed that following significant declines from 1961 to 2002, the annual and seasonal mean surface wind speeds began to increase over China and most of its subregions (all subregions except for East China) after 2002. Opposite trends were found in the probabilities for most different grades of surface wind speed from 1961 to 2002 and from 2002 to 2020. In addition, we compared the results with those from NCEP-1, JRA-55, and ERA5, which showed that all of the reanalysis data could reasonably reproduce the observed spatial distributions of the surface wind speed and its different grades, although with bias in values and smaller interannual variabilities. The wind reversal over China was closely related to changes in the trends of the sea level pressure gradient. Moreover, the variation in the Pacific Decadal Oscillation (PDO) has a significantly negative correlation coefficient with the surface wind speed over East, Central, and South China.

KEYWORDS
China, surface wind speed, wind grade, wind reversal

1 | INTRODUCTION

Changes in surface wind speed have great impacts on climate and human life, as they are linked with many aspects, including wind energy (Tian et al., 2019; Zeng et al., 2019; Ding et al., 2020), water cycles (Roderick et al., 2007; McVicar et al., 2012), air pollution (Cai et al., 2017; Han et al., 2017), wind-related natural disasters (Tamura and Cao, 2012; Cao and Wang, 2013), and human-perceived temperature (Wu et al., 2017; Gao et al., 2018). Thus, the investigation of surface wind speed changes is important, especially in China, which has had severe air pollution problems in recent years and the highest new and total wind power capacities globally (Global Wind Energy Council, 2019; Renewables, 2019; Sönnichsen, 2020).

Previous studies have reported declines in the surface wind speed over many parts of the world, such as Australia (Roderick et al., 2007; McVicar et al., 2008), Canada (Tuller, 2004; Wan et al., 2010), the United States (Pryor et al., 2009; Pryor and Ledolter, 2010), and Turkey (Dadaser-Celik and Cengiz, 2014). The ‘stilling’ phenomenon of the
surface wind speed over China (Xu et al., 2006; Jiang et al., 2009; Guo et al., 2011; Chen et al., 2013) and its subregions (You et al., 2010; Wu et al., 2015; Cui et al., 2020; Wu et al., 2020a) has also been reported.

Different from the decreasing trend from the mid-twentieth century to the beginning of the 21st century, increasing surface wind speed trends have been found in recent years. For example, Kim and Paik (2015) examined the observed surface wind speed over South Korea from 1954 to 2013, and found a decreasing trend in the period of 1954–2003. Zeng et al. (2019) reported surface wind speed trend reverses around 2010 by evaluating station data worldwide.

In recent years, the surface wind speed over China and its subregions has also reversed. Based on data from meteorological stations from 1961 to 2007, Fu et al. (2011) found a significant decline stage from 1974 to the 1990s, followed by a relatively steady phase from the 1990s to 2007. Guo et al. (2011) found that the decreasing trend of the annual and seasonal mean surface wind speeds over China from 1969 to 2005 has weakened since the early 1990s. Lin et al. (2013) reported positive trends in surface and upper-air wind speeds from 2002 to 2009. Zhang and Wang (2020) also found a weak wind speed recovery in China from 2005 to 2017. Yang et al. (2021) reported a reversal of the annual mean surface wind speed in China around 2014, and the reversal varied according to the regions and seasons. Such surface wind speed recovery phenomena were also observed over northwestern China from 1993 to 2015 (Li et al., 2020) and southwestern China from 2001 to 2009 (Yang et al., 2012). However, previous studies on the surface wind speed over China have usually focused on the period from the 1960s to approximately 2010, and few studies have analysed the changes in surface wind speed in recent years. Since large-scale transformations from manual observations to automatic observations occurred in the 2004–2011 period over China (Cao et al., 2016), it is necessary to evaluate the changes in surface wind speed in the time period until now.

In addition to the mean surface wind speed, changes in the probability distribution of wind speed are important. Knowledge of surface wind speed probability distributions is vital for surface flux estimation, wind risk assessments, and many applications in wind power climatology (He et al., 2010, 2012). Furthermore, strong winds can cause damage to structures and traffic, while low-speed winds are conducive to the accumulation of air pollutants. Zha et al. (2017) investigated the changes in the probabilities of different surface wind speed grades in China from 1970 to 2011 and concluded that these changes may have been influenced by urbanization and climate characteristics. Zhang and Wang (2020) found decreasing trends in strong and weak surface winds from 1960 to 2017 and a weak recovery of the surface wind speed over China from 2005 to 2017. However, few studies have explored the changes in the probability distribution within different wind ranges over China and its subregions in the time period of 1961–2020.

Due to the shortage of observations (gradual urbanization around weather stations, instrument changes, etc.), various reanalysis products have been used to investigate surface wind speed in China. For example, Chen et al. (2013) found that the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis outperformed the European Center for Medium-Range Weather Forecasts 40 years Re-Analysis (ERA-40). Yu et al. (2019) evaluated the performances of five sets of reanalysis products and found that Modern-ERA Retrospective Analysis for Research and Applications (MERRA) had the highest skill in reproducing the climatology and trends, while the Japanese Meteorological Agency 55-Year Reanalysis (JRA-55) showed the highest temporal correlation coefficients of the annual, summer and winter surface wind speed over China. Zhang and Wang (2020) reported that among five reanalysis datasets, JRA-55 had the highest correlations with observations over most of China and was the unique dataset that successfully depicted the recent surface wind speed recovery. Miao et al. (2020) found that JRA-55 had a high consistency with observations in most of China for reproducing the percentage difference of surface wind speed climatology. Liu et al. (2021) showed that ERA5 had a high performance in simulating the surface wind speed climatology over China, with a spatial correlation coefficient of 0.66. However, for the different wind grades over China and its subregions, few studies are based on reanalysis products.

In this article, the changes in surface wind speed and its different grades were provided by using a high-resolution observation dataset for the period of 1961–2020 from China. The remainder of this article is organized as follows. The datasets and methods are described in Section 2. The changes in surface wind speed and its different grades are analysed in Section 3. The possible dynamic mechanisms of surface wind change are discussed in Section 4, and key conclusions and a discussion are provided in Section 5.

## 2 | DATA AND METHODS

### 2.1 | Data

The daily 10-m wind speed observation dataset used in this study is CN05.1 (Wu and Gao, 2013), which covers
the period from 1961 to 2020, with a horizontal resolution of 0.25° × 0.25° (latitude × longitude). The dataset used in this article is available from https://doi.org/10.5281/zenodo.5630326. This dataset is constructed based on observations from 2,416 meteorological stations in China through basic quality control methods (Wu et al., 2017). Compared to the dense observation stations over eastern China, stations over western China, especially over the Tibetan Plateau and northwestern China, are sparse, which leads to great uncertainty in these regions. Compared with the data before 1960, there were more stations in the observations from 1961 to 2020 with fewer gawps and missing values (Fu et al., 2011). The interpolation method from station to grid used in CN05.1 is the ‘anomaly approach’ interpolation, which is the same as that in the Climatic Research Unit dataset (CRU; New et al., 2002). Specifically, the first step of the ‘anomaly approach’ interpolation is to calculate a gridded climatology by using thin-plate smoothing splines. Then, with an angular weight method, the daily anomalies at stations are interpolated to grids. The final gridded data are produced by adding daily anomalies to the climatology (Shi et al., 2018). CN05.1 is widely used in the validation of the surface wind speed over China (e.g., Yu et al., 2019; Chen et al., 2020; Wu et al., 2020b) and shows similar spatial patterns and time series to other wind observations (Wu et al., 2020b).

NCEP-1 (Kalnay et al., 1996), JRA-55 (Kobayashi et al., 2015), and ERA5 (Hersbach et al., 2020) were selected for a comparison with the observations because of their ample timespan that covers from 1961–2020.

The monthly mean sea level pressure from NCEP-1 (Kalnay et al., 1996; available at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.surface.html) from 1961 to 2020 was used to analyse the large-scale circulation. In addition, the monthly Pacific Decadal Oscillation (PDO) index from 1961 to 2020 is available at https://www.esrl.noaa.gov/psd/data/correlation/pdo.data.

2.2 Methods

Following the criteria suggested by Zha et al. (2016) and Zha et al. (2017), we divided the daily mean surface wind speed from the observations and three reanalysis datasets into the following six grades: calm (0–0.2 m s⁻¹); light air (0.3–1.5 m s⁻¹; LA); light breeze (1.6–3.3 m s⁻¹; LB); gentle breeze (3.4–5.4 m s⁻¹; GB); moderate breeze (5.5–7.9 m s⁻¹; MB); and a wind speed greater than or equal to 8 m s⁻¹ (≥8.0 m s⁻¹; WSGE8). The probabilities of different wind grades were calculated based on the following equation:

\[ P_{g,t} = \left( \frac{f(g, t)}{n_t} \right) \times 100\% \]

where \( g \) represents each wind grade, \( t \) represents each year and ranges from 1961 to 2020, \( f(g, t) \) represents the number of days in the \( g \) wind grade in year \( t \), and \( n_t \) represents the total number of days in year \( t \).

Since there are different horizontal resolutions in CN05.1, NCEP1, JRA55, and ERA5, we interpolated NCEP1 and JRA55 to a common 0.25° × 0.25° (latitude × longitude) grid, which is the same as that of CN05.1 and ERA5, by using a bilinear interpolation algorithm. In addition, the nonparametric Mann–Kendall test with Sen’s slope estimates (Sen, 1968), which has been widely used in wind studies, was employed to detect trends and to estimate their magnitude and significance (You et al., 2014; Li et al., 2020; Wu et al., 2020b). Both nonparametric methods are robust against outliers and do not assume a particular data distribution.

Finally, affected by the complex topography, land surface conditions, and monsoon circulations, the climate in China shows large regional differences. Therefore, in this study, we divided China into the following eight subregions (Figure 2a) based on societal and geographical conditions and administrative boundaries (National Report Committee, 2007): Northeast China (NEC; 39–54°N, 119–134°E); North China (NC; 36–46°N, 111–119°E); East China (EC; 27–36°N, 116–122°E); Central China (CC; 27–36°N, 106–116°E); South China (SC; 20–27°N, 106–120°E); the Tibetan Plateau (SWC1; 27–36°N, 77–106°E); Southwest China (SWC2; 22–27°N, 98–106°E); and Northwest China (NWC; 36–46°N, 75–111°E).

3 | CHANGES IN SURFACE WIND SPEED AND ITS DIFFERENT GRADES

3.1 Surface wind speed and its different grades based on observations

Figure 1 represents the time series of the annual and seasonal mean surface wind speeds over China from 1961 to 2020. As shown in the figure, the surface wind speed in spring (March–April–May, MAM) was the strongest, with a median of 3.39 m s⁻¹, and the surface wind speed in autumn (September–October–November, SON) was the weakest, with a median of 2.67 m s⁻¹, which is consistent with Guo et al. (2011) and Zhang and Wang (2020). Regarding the annual mean surface wind speed, a significant transition occurred in 2002, which is in line with the results of Yang et al. (2012) and Lin et al. (2013). There
was a significant decrease at a rate of $-0.22 \text{ m} \cdot \text{s}^{-1} \cdot \text{decade}^{-1}$ until 2002, and this trend reversed to an increasing trend at a rate of $0.10 \text{ m} \cdot \text{s}^{-1} \cdot \text{decade}^{-1}$ from 2002–2020. The significance of the trends and means from 1961 to 2002 and from 2002 to 2020 were tested with $p < 0.05$ by using the Mann–Kendall test and Student’s $t$-test, respectively. The surface wind speed in all seasons also recovered after 2002, with decreases and increases before and after 2002, respectively. The spatial distributions of the annual and seasonal mean trends of the surface wind speed from 1961 to 2002 and from 2002 to 2020 are presented in Figure 2. Significant decreasing trends were observed in the annual mean surface wind speed in most regions of China from 1961 to 2002 (Figure 2a); the trends reversed after 2002, and the significant increasing trends were in most regions of China, except for the eastern and central parts of northeastern China, the North China Plain, and the eastern and northern of northwestern China (Figure 2b). The reversals of the trends in the surface wind speed between the two periods were also observed in all seasons over most parts of China (Figures 2c–j), with large decreasing trends ($\leq -0.3 \text{ m} \cdot \text{s}^{-1} \cdot \text{decade}^{-1}$) in spring and winter (December–January–February, DJF) over northern China (Figures 2c, i) and increasing trends in all seasons over most regions of China (Figures 2d, f, h, j). Regarding the trends of the annual mean surface wind speed averaged over the eight subregions, decreasing and increasing trends were found over most subregions (seven out of eight) in the two periods of 1961–2002 and 2002–2020, respectively (Table 1). Specifically, the largest decreasing trend was found over North China (NC, $-0.27 \text{ m} \cdot \text{s}^{-1} \cdot \text{decade}^{-1}$), while the greatest increasing trend was observed over South China (SC, $0.20 \text{ m} \cdot \text{s}^{-1} \cdot \text{decade}^{-1}$). However, for East China (EC), the trends decreased in both periods.

The annual and seasonal mean surface wind speeds in different grades averaged over China from 1961 to 2020 are presented in Figure 3. Among the medians of all wind grades, the probabilities of LB were the highest annually and in all seasons, while the medians of calm were the lowest (all close to zero). The lowest probabilities in LA and LB were found in spring, with values of 10% and 43%, respectively, while their maximum probabilities (23% and 52%, respectively) were observed in winter and summer (June–July–August, JJA), respectively. The maximum probabilities of GB, MB, and WSGE8 in spring were 31%, 11%, and 2%, respectively. The median annual and summer GB values were both 24%, while those in autumn and winter were 21% and 20%.
respectively. In MB, the median values in summer, autumn, and winter were close to one another and ranged from 5% to 7%. Therefore, the maximum wind speed should be in spring, which is in line with the result of Figure 1b. Similar conclusions were shown by Chen et al. (2013) and Zha et al. (2017), who reported a
maximum wind speed in April. The interquartile annual/seasonal spreads (boxes) were close in each wind grade, except for those in LB. The spreads of LB were the largest in spring and the smallest in autumn, with comparable annual and winter values.

Before and after 2002, the trends of the probabilities in different grades of surface wind speed also showed adverse signs over most parts of China (Figure 4). The trend in the probabilities of LA increased significantly from 1961 to 2002 over most regions of China, except for the Tibetan Plateau and eastern part of northwestern China (Figure 4c), while it decreased significantly from 2002–2020 over most parts of China, except for the North China Plain and the lower reaches of the Yangtze River Basin (Figure 4d). From 1961 to 2002, the significant increase in the trend in the probabilities of LB was mainly over most parts of northeastern China, the North China Plain, and most regions of western China, while a significant decrease was found along the Qinling Mountains and over the areas to the south of the Yangtze River and the Tarim Basin (Figure 4e). From 2002 to 2020, opposite signs of the trends in LB were found over most parts of China (Figure 4f). The probabilities of GB and MB from 1961 to 2002 showed significant decreasing trends over most of China (Figures 4g, i) and reversed to increasing trends mainly over the Tibetan Plateau after 2002 (Figures 4h, j). For WSGE8, a significant decrease from 1961 to 2002 was found north of 35°E and on the Tibetan Plateau (Figure 4k), and the decrease from 2002 to 2020 mainly occurred over the northern border of China and the central Tibetan Plateau (Figure 4l).

The trends of the annual mean surface wind speed probabilities averaged over the eight subregions of China for the periods of 1961–2002 and 2002–2020 are listed in Table 2. Significant increasing trends in calm were found over Northeast China (NEC), Central China (CC), and Northwest China (NWC) from 1961 to 2002, with negative values in the second period after 2002. Over all subregions, the probabilities of LA showed significant increasing trends from 1961 to 2002, while decreasing trends were found from 2002 to 2020. For LB, significant increasing trends were found in both periods of 1961–2002 and 2002–2020 over NEC, NC, EC and NWC; decreasing and increasing trends were found in the periods of 1961–2002 and 2002–2020 over CC, SC and Southwest China (SWC2), respectively, with opposite trends of increasing and decreasing in the two periods over the Tibetan Plateau (SWC1). Different from the wind grades mentioned above, the probabilities of GB decreased (increased) in the period of 1961–2002 (2002–2020) over most parts of China except for EC and CC (decreasing trends in both periods). Decreasing trends from 1961–2002 and 2002–2020 in MB were found over most parts of China, except SWC1. For WSGE8, decreasing trends from 1961 to 2002 over all subregions were found, with increasing or no trends from 2002 to 2020 over most parts of China except for NEC, SWC1, and NWC (decreasing trends in both periods). Overall, the probabilities of calm, LA and GB, showed the opposite trends during the two periods over most parts of China.

| Region                  | 1961–2002 | 2002–2020 |
|-------------------------|-----------|-----------|
| Northeast China (NEC)   | −0.22*    | 0.05      |
| North China (NC)        | −0.27*    | 0.09*     |
| East China (EC)         | −0.24*    | −0.04*    |
| Central China (CC)      | −0.19*    | 0.12*     |
| South China (SC)        | −0.15*    | 0.20*     |
| The Tibetan Plateau (SWC1) | −0.18*  | 0.14*    |
| Southwest China (SWC2)  | −0.09*    | 0.08*     |
| Northwest China (NWC)   | −0.24*    | 0.06*     |

*Significant trends at $p <0.05$. 

![Figure 3](wileyonlinelibrary.com)
3.2 | Surface wind speed and its different grades from the reanalysis datasets

The climatology of the surface wind speed from the observations and the three reanalysis datasets are provided in Figure 5. All reanalysis datasets successfully reproduced the spatial patterns of the surface wind speed medians, which are characterized by low values in eastern China and high values on the Tibetan Plateau. Compared to CN05.1, NCEP-1, and ERA5 overestimated the surface wind speed over most parts of China with regional means of 3.19 and 3.50 m·s⁻¹, respectively (Figures 5b, g), while JRA-55 underestimated the value with a regional mean of 1.26 m·s⁻¹ (Figure 5c). The overestimation of NCEP-1 and ERA5 may be due to the interpolation of the data based on Monin-Obhukhov similarity theory, without assimilating the observed...
surface wind over land (Kalnay et al., 1996; Torralba et al., 2017; Ramon et al., 2019). In JRA-55, the assimilation of the observed surface wind speed over land was merely used for a screen-level analysis, not for an atmospheric analysis (Kobayashi et al., 2015), and the surface wind speed was interpolated based on a univariate two-dimensional optimal process that considered neutral stability at the lowermost level (Torralba et al., 2017; Zhang and Wang, 2020). Although systematic negative biases were found in JRA-55, it performed better in the spatial distribution of wind speed with a high pattern correlation coefficient (0.75) compared to that of NCEP-1 (0.56) and ERA5 (0.36).

To remove the system biases in each dataset, we compared the anomalies of surface wind speed and their probabilities in different grades averaged over China from CN05.1, NCEP-1, JRA-55, and ERA5 (Figure 6). The time series of the surface wind speed in all reanalysis datasets agreed well with that in the observations from 1961 to 2002, with the three Pearson correlation coefficients being greater than 0.47 with \( p < 0.05 \) (Table 3). Moreover, all reanalysis datasets reproduced the observed wind trends from 1961 to 2002 and from 2002 to 2020, although with smaller magnitudes (Table 3). However, compared to the observations, the reanalysis datasets showed lower interannual variabilities (Figure 6a), and this phenomenon also existed in the probabilities of surface wind in different grades (Figures 6b-g). Comparing the three reanalysis datasets, NCEP-1 and JRA-55 performed well in calm, LA, GB and MB due to the same signs in the trends as in the observations (Table 4).

The trends in the surface wind speed probabilities in different grades from NCEP-1, JRA-55, and ERA5 from 1961 to 2002 and from 2002 to 2020 had smaller magnitudes than those from the observations (figures not shown). Among them, NCEP-1 and JRA-55 performed well in reproducing the trends of the six grade probabilities, with similar spatial distributions and the same signs averaged over China in most grades of probabilities (Table 4). The performance of ERA5 was the worst, with much smaller magnitudes of the trends and zero values over a wider area than those from the observations (Table 4).

4 | POSSIBLE PHYSICAL CAUSES OF SURFACE WIND CHANGES

Previous studies have presented a variety of theories to explain the surface wind change over China, many of which have focused on the horizontal pressure gradient force (Xu et al., 2006; Guo et al., 2011; Li et al., 2020; Zhang and Wang, 2020), upper-air wind speed (Vautard et al., 2010; Lin et al., 2013) and circulation indices (Jiang et al., 2009; Fu et al., 2011; Chen et al., 2013; Zeng et al., 2019; Li et al., 2020; Zhang and Wang, 2020; Wu
et al., 2020a). For example, Lin et al. (2013) reported that surface wind speed is influenced by upper-air wind since the momentum at the surface is transported from the upper free atmosphere. Chen et al. (2013) reported that the AO and ENSO phases have strong influences on the wind speed over China. Li et al. (2020) indicated that the surface wind speed in northwestern China is closely related to the Eurasian Meridional Circulation and the Tibetan Plateau Index_B. Fu et al. (2011) suggested that the downward trend of the surface wind speed in China is associated with a positive-phase interdecadal Pacific oscillation (IPO)/PDO. This result was opposite to the findings of Zeng et al. (2019) who reported that the temperature gradient generates a westerly surface wind.

**Table 3** Correlation coefficients of the annual mean surface wind speed anomaly averaged over China between the three reanalysis datasets and CN05.1 and trends of the annual mean surface wind speed (units: m·s⁻¹·decade⁻¹) from CN05.1, NCEP-1, JRA-55, and ERA5 for the periods of 1961–2002 and 2002–2020.

| Data     | 1961–2002 Cor. | 2002–2020 Cor. | 1961–2002 Trend | 2002–2020 Trend |
|----------|----------------|----------------|----------------|----------------|---|
|          | 1961–2002      | 1961–2002 Trend | 2002–2020 Trend | 2002–2020 Trend |
| CN05.1   | —              | —              | —0.22*         | 0.10*          |
| NCEP-1   | 0.63*          | 0.39           | −0.07*         | 0.05           |
| JRA-55   | 0.62*          | 0.48*          | −0.05*         | 0.02           |
| ERA5     | 0.47*          | 0.00           | −0.01*         | 0.01           |

*Correlation coefficients/significant trends at p <0.05.
TABLE 4  Trends of the annual mean surface wind speed probabilities (units: %·decade⁻¹) averaged over China from CN05.1, NCEP-1, JRA-55, and ERA5 for the periods of 1961–2002 and 2002–2020

| Data   | Calm 1961–2002 | 2002–2020 | LA 1961–2002 | 2002–2020 | LB 1961–2002 | 2002–2020 | GB 1961–2002 | 2002–2020 | MB 1961–2002 | 2002–2020 | WSGE8 1961–2002 | 2002–2020 |
|--------|--------------|-----------|-------------|-----------|-------------|-----------|-------------|-----------|-------------|-----------|-----------------|-----------|
| CN05.1 | 0.02*       | −0.05*    | 3.02*       | −5.32*    | 1.22*       | 4.11*     | −2.46*      | 0.90      | −1.72*      | 0.34*     | −0.52*           | −0.08*    |
| NCEP-1 | 0.05*       | −0.02     | 1.26*       | −0.85     | 0.02        | 0.18      | −0.60*      | 0.20      | −0.36*      | 0.32      | −0.21*           | 0.19      |
| JRA-55 | 0.01*       | −0.02*    | 1.90*       | −1.69*    | −0.06*      | 0.56      | −1.17*      | 0.65*     | −0.52*      | 0.07      | −0.11*           | −0.10     |
| ERA5   | 0.00*       | 0.00      | 0.14        | 0.21      | 0.03        | −0.11     | −0.10       | −0.01     | −0.07       | −0.02*    | −0.02*           | −0.06*    |

*Significant trends at p < 0.05.

FIGURE 7  Spatial distributions of the sea level pressure trends (units: Pa·decade⁻¹) for the periods of (a) 1961–2002 and (b) 2002–2020, where ‘*’ indicates a significant trend with p<0.05. The purple boxes indicate the locations of the regions of interest, the values of the regional-mean trend are listed in each subregion, and significant trends with p<0.05 are marked with * [Colour figure can be viewed at wileyonlinelibrary.com]

under a positive-phase PDO, thus increasing the prevailing westerlies in the mid-latitudes. According to previous studies, the impacts of sea level pressure and large-circulation indices were selected in this article to illustrate the changes in the surface wind speed over the subregions of China in this section.

Figure 7 shows the trends of sea level pressure in the periods of 1961–2002 and 2002–2020. From 1961 to 2002, significantly increasing trends of sea level pressure were found over most of the continent south of 60°N, while decreasing trends were found over the high latitudes and east of Japan (Figure 7a). In contrast, from 2002 to 2020, the trends of sea level pressure increased over most parts of the high-latitude continent and the ocean but decreased over northwestern China and southern China (Figure 7b). A significant decrease from 1961 to 2002 and a significant increase from 2002 to 2020 in the regional mean surface wind speed were found over NC and NWC, respectively (Table 1). To clearly show the relationship between the sea level pressure and the surface wind speed, regional mean sea level pressure trends were calculated over high latitudes (50°–70°N, 75°–119°E) and low latitudes (36°–50°N, 75°–119°E), as shown in Figure 7. From 1961 to 2002, low-latitude sea level pressure increased significantly at a rate of 95.96 Pa·decade⁻¹, while high-latitude sea level pressure decreased slightly (−7.82 Pa·decade⁻¹). As the high mean sea level pressure was located at high latitudes, the asymmetric trends of sea level pressure reduced the latitudinal pressure gradients, which led to the annual decline in the mean surface wind speed (Figure 2a and Table 1). From 2002 to 2020, the trends of sea level pressure at high and low latitudes increased at a rate of 26.48 and 4.84 Pa·decade⁻¹, respectively. The weaker increase in the low latitudes compared to the high latitudes could lead to increased latitudinal pressure gradients and result in the surface wind speed reversal over NC and NWC (Figure 2b and Table 1).

As previously mentioned, changes in the surface wind speed over China were strongly influenced by the PDO. The PDO is a measure of sea level pressure, which is often defined by using the sea surface temperatures (SSTs) within a core region (110°E−100°W, 20°N−70°N) (Mantua et al., 1997). The correlation coefficients between the annual mean PDO index and the surface
wind speed over the eight subregions of China are shown in Table 5. The surface wind speeds were negatively correlated with the PDO over most subregions of China, except for SWC2. The surface wind speeds over EC, CC, and SC were significantly correlated with the PDO, which indicates that the annual surface wind speeds in these regions are affected by the Pacific SST.

### 5 | CONCLUSIONS AND DISCUSSION

This article investigated changes in the surface wind speed and its different grades over China by using an updated version of the high-resolution observation dataset (CN05.1) from 1961 to 2020. Our main conclusions and considerations can be summarized as follows.

1. Decreasing and increasing trends of the annual and seasonal mean surface wind speeds over China were found before and after 2002, respectively. Wind reversal was also found around 2002 in most parts of China, except East China.
2. The spatial patterns of the surface wind speed in different grades also showed the opposite signs in the trends over most parts of China before and after 2002. Specifically, the probabilities of calm and LA increased from 1961 to 2002, while they decreased from 2002 to 2020. For GB, significant decreases and increases were found in the periods of 1961–2002 and 2002–2020, respectively.
3. NCEP-1, JRA-55, and ERA5 reproduced the observed climatology of the surface wind speed and its different grades from 1961 to 2020, but with smaller interannual variabilities than the observations. Among the three reanalysis datasets, NCEP1 and JRA55 showed the best performances in terms of reproducing the surface wind speed and its different grades over China.
4. The recovery in the surface wind speed over North and Northwest China could be explained by the high-latitude sea level pressure gradient variations. Moreover, the surface wind speeds over East, Central, and South China were significantly negatively correlated with the PDO.

Due to the sparse distribution of meteorological stations over western China, the quality of the surface wind speed from the CN05.1 dataset was relatively poor in this region. In addition, previous studies have reported that the effect of urbanization has a considerable influence on surface wind speed and its different grades (Jiang et al., 2009; Zha et al., 2016; Li et al., 2020). Thus, the impact of urbanization on the recovery of surface wind speed and its different grades needs further investigation.

The main uncertainty for the observed surface wind speed is linked to the relocation of meteorological stations, and observation instrument changes (Zhang and Wang, 2020; Yang et al., 2021). Most meteorological stations in China (75.8% of all stations until 2011) were relocated at least once (Cao et al., 2016). Moreover, the anemometers have been replaced twice nationwide: from Wilde anemometers to EL or EN electric wind anemometers during the late1960s and then, to automatic observations during the 2001–2011 period (Cao et al., 2016). EL or EN electric wind anemometers and automatic instruments are more sensitive to surface wind speed changes than their predecessors (Zhang and Wang, 2020). For example, the starting wind speed in EL or EN electric wind anemometers is less than 1.5 m s$^{-1}$, while that in automatic instruments is less than 0.3 m s$^{-1}$. Anemometer replacement may also have had some impact on the surface wind speed and its different grades, which is worth further investigation.

### ACKNOWLEDGEMENTS

The authors appreciate four anonymous reviewers for their valuable comments. The research was jointly supported by the National Natural Science Foundation of China (41805063) and the National Key Research and Development Program of China (No. 2017YFA0605002).

### AUTHOR CONTRIBUTIONS

Jie Wu: Methodology; visualization. Ying Shi: Conceptualization; supervision.

### ORCID

Ying Shi https://orcid.org/0000-0002-4929-8739

### REFERENCES

Cai, W., Li, K., Liao, H., Wang, H. and Wu, L. (2017) Weather conditions conducive to Beijing severe haze more frequent under
climate change. Nature Climate Change, 7(4), 257–262. https://doi.org/10.1038/nclimate3249.
Cao, L., Zhu, Y., Tang, G., Yuan, F. and Yan, Z. (2016) Climatic warming in China according to a homogenized data set from 2419 stations. International Journal of Climatology, 36(13), 4384–4392. https://doi.org/10.1002/joc.4639.
Cao, S.Y. and Wang, J. (2013) Statistical summary and case studies of strong wind damage in China. Journal of Disaster Research, 8(6), 1096–1102. https://doi.org/10.20965/jdr.2013.p1096.
Chen, L., Li, D. and Pryor, S.C. (2013) Wind speed trends over Dadaser-Celik, F. and Cengiz, E. (2014) Wind speed trends over Turkey from 1975 to 2006. https://doi.org/10.1175/jcli-d-11-013979.
Cui, X., Dong, Z., Sun, H., Li, C., Xiao, F., Liu, Z., Song, S., Li, X., Xiao, N. and Xiao, W. (2020) Spatial and temporal variation of the near-surface wind environment in the dune fields of northern China. International Journal of Climatology, 38(5), 2333–2351. https://doi.org/10.1002/joc.5338.
Chen, Z., Li, W., Guo, J., Bao, Z., Pan, Z. and Hou, B. (2020) Projection of wind energy potential over Northern China using a regional climate model. Sustainability, 12(10), 3979. https://doi.org/10.3390/su12103979.
Dadaer-Celik, F. and Cengiz, E. (2014) Wind speed trends over Turkey from 1975 to 2006. International Journal of Climatology, 34(6), 1913–1927. https://doi.org/10.1002/joc.3810.
Ding, Y., Li, X. and Li, Q. (2020) Advances of surface wind speed changes over China under global warming (in Chinese). Journal of Applied Meteorological Science, 31(1), 1–12. https://doi.org/10.11898/1001-7313.20200101.
Fu, G., Yu, J., Zhang, Y., Hu, S., Ouyang, R. and Liu, W. (2011) Temporal variation of wind speed in China for 1961–2007. Theoretical and Applied Climatology, 104(3–4), 313–324. https://doi.org/10.1007/s00704-010-0348-x.
Gao, X.J., Wu, J., Shi, Y., Wu, J., Han, Z.Y., Zhang, D.F., Tong, Y., Li, R.-K., Xu, Y. and Giorgi, F. (2018) Future changes in thermal comfort conditions over China based on multi-RegCM4 simulations. Atmospheric and Oceanic Science Letters, 11(4), 291–299. https://doi.org/10.1002/asl.3284
Global Wind Energy Council (2019). Global wind report 2019. Available at: https://gwecc.net/wp-content/uploads/2020/08/Annual-Wind-Report_2019_digital_final_2r.pdf.
Guo, H., Xu, M. and Hu, Q. (2011) Changes in near-surface wind speed in China: 1969-2005. International Journal of Climatology, 31(3), 349–358. https://doi.org/10.1002/joc.2091.
Han, Z., Zhou, B., Xu, Y., Wu, J. and Shi, Y. (2017) Projected changes in haze pollution potential in China: an ensemble of regional climate model simulations. Atmospheric Chemistry and Physics, 17(16), 10109–10123. https://doi.org/10.5194/acp-17-10109-2017.
He, Y., McFarlane, N.A. and Monahan, A.H. (2012) The influence of boundary layer processes on the diurnal variation of the climatological near-surface wind speed probability distribution over land. Journal of Climate, 25(18), 6441–6458. https://doi.org/10.1175/jcli-d-11-00321.1.
He, Y., Monahan, A.H., Jones, C.G., Dai, A., Biner, S., Caya, D. and Winger, K. (2010) Probability distributions of land surface wind speeds over North America. Journal of Geophysical Research, 115(D4), D04103. https://doi.org/10.1029/2008jd010708.
Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peube, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Holm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Vaultume, S. and Thépaut, J.N. (2020) The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146, 1999–2049. https://doi.org/10.1002/qj.3803.
Jiang, Y., Luo, Y., Zhao, S. and Tuo, S. (2009) Changes in wind speed over China during 1956–2004. Theoretical and Applied Climatology, 99(3–4), 421–430. https://doi.org/10.1007/s00704-009-0152-7.
Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. and Joseph, D. (1996) The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society, 77(3), 437–471. https://doi.org/10.1175/1520-0477(1996)077<0437:Threpp>2.0.CO;2.
Kim, J. and Paik, K. (2015) Recent recovery of surface wind speed after decadal decrease: a focus on South Korea. Climate Dynamics, 45(5–6), 1699–1712. https://doi.org/10.1007/s00382-015-2456-9.
Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., Miyaoaka, K. and Takahashi, K. (2015) The JRA-55 reanalysis: general speciﬁcations and basic characteristics. Journal of the Meteorological Society of Japan. Series II, 93(1), 5–48. https://doi.org/10.2151/jmsj.2015-001.
Li, Y., Chen, Y., Li, Z. and Fang, G. (2020) Recent recovery of surface wind speed in Northwest China. International Journal of Climatology, 38(12), 4445–4458. https://doi.org/10.1002/joc.5679.
Lin, C., Yang, K., Qin, J. and Fu, R. (2013) Observed coherent trends of surface and upper-air wind speed over China since 1960. Journal of Climate, 26(9), 2891–2903. https://doi.org/10.1175/jcli-d-12-00093.1.
Liu, H., Dong, L., Yan, R., Zhang, X., Guo, C., Liang, S., Tu, J., Feng, X. and Wang, X. (2021) Evaluation of near-surface wind speed climatology and long-term trend over China's mainland region based on ERA5 reanalysis (in Chinese). Climatic and Environmental Research, 26(3), 299–311. https://doi.org/10.3878/jissn.1006-9585.2021.20101.
Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C. (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society, 78(6), 1069–1079. https://doi.org/10.1175/1520-0477(1997)078<1069:Apicowm>2.0.CO;2.
McVicar, T.R., Roderick, M.L., Donohue, R.J., Li, L.T., Van Niel, T.G., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., Mahowald, N.M., Mescherskaya, A.V., Kruger, A.C., Rehman, S. and Dinpashoh, Y. (2012) Global review and synthesis of trends in observed terrestrial near-surface wind
based on five reanalysis datasets. *Atmosphere*, 10(12), 804. https://doi.org/10.3390/atmos10120804.

Zeng, Z., Ziegler, A.D., Searchinger, T., Yang, L., Chen, A., Ju, K., Piao, S., Li, L.Z.X., Ciais, P., Chen, D., Liu, J., Azorin-Molina, C., Chappell, A., Medvigy, D. and Wood, E.F. (2019) A reversal in global terrestrial stilling and its implications for wind energy production. *Nature Climate Change*, 9(12), 979–985. https://doi.org/10.1038/s41558-019-0622-6.

Zha, J., Wu, J. and Zhao, D. (2016) Changes of probabilities in different wind grades induced by land use and cover change in eastern ChinaPlain during 1980-2011. *Atmospheric Science Letters*, 17(4), 264–269. https://doi.org/10.1002/asl.653.

Zha, J., Wu, J., Zhao, D. and Yang, Q. (2017) Changes of the probabilities in different ranges of near-surface wind speed in China during the period for 1970–2011. *Journal of Wind Engineering and Industrial Aerodynamics*, 169, 156–167. https://doi.org/10.1016/j.jweia.2017.07.019.

Zhang, Z. and Wang, K. (2020) Stilling and recovery of the surface wind speed based on observation, reanalysis, and geostrophic wind theory over China from 1960 to 2017. *Journal of Climate*, 33(10), 3989–4008. https://doi.org/10.1175/jcli-d-19-0281.1.

How to cite this article: Wu, J., & Shi, Y. (2022). Changes in surface wind speed and its different grades over China during 1961–2020 based on a high-resolution dataset. *International Journal of Climatology*, 42(7), 3954–3967. https://doi.org/10.1002/joc.7453.