The analysis of the spatiotemporal variations and mechanisms for the near-surface wind speed over China in the last 40 years

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Received: 23 September 2021 / Accepted: 18 February 2022 / Published online: 3 March 2022
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Abstract
This study mainly presents the spatiotemporal characteristics and changes of near-surface wind speed with observations from 679 stations over China for 1979–2019. Furthermore, mechanisms of the wind speed changes are also investigated. Major results show that the larger near-surface wind speed mainly occur in northern and eastern regions, Tibetan Plateau and the coastal zones in China. The wind speed in spring is larger than the other seasons with mean value of 2.57 m s\(^{-1}\). Significantly decreased near-surface wind speed trend in China is detected during 1979–2019, particularly in 1979–1996. The mean rates of decrease in 1979–2019 and 1979–1996 are \(-0.06\) m s\(^{-1}\) (10a\(^{-1}\)) and \(-0.19\) m s\(^{-1}\) (10a\(^{-1}\)), respectively. The decreased trends of the high wind speed percentiles are more significant than the low, especially in 1979–1996. The change rate of the 95th wind speed percentile in 1979–1996 even reaches to \(-0.48\) m s\(^{-1}\) (10a\(^{-1}\)) and passes the significance test at \(p < 0.05\). However, the wind speed trend reversed after 1997. The lowest 5th wind speed percentile has the most significant reversal trend. Therefore, the decreased wind speed trend before 1997 is mainly caused by the significant reduction of strong wind, while the reversal trend after 1997 results from weak wind. The variations of the wind speed over China attributed to both the U and V wind components. The significantly declined trend of the surface wind speed is closely related to the weakened upper westerly wind field. In addition, the uneven warming between high and low latitudes may also contribute to the surface wind speed changes through thermal adaption.

1 Introduction
Near-surface wind speed changes will have important effects on many aspects of human production and life, such as surface energy balance, wind energy, pollutant dispersion, and hydrological cycle (Azorin-Molina et al. 2014; Li et al. 2018a). The wind speed, particularly the upper percentiles of the wind speed, is closely related to the wind energy, a rapidly growing alternative energy source (Pryor et al. 2006; Liu et al. 2019). The reductions in global near-surface wind speed have threatened the wind power over the past few decades (Burton et al. 2001; Tian et al. 2019; Zeng et al. 2019). Tong and Leung (2012) clarified that the wind speed was also responsible for the diffusion of O\(_3\) concentration. Lin et al. (2015) reported that wind stilling could suppress the dispersion of aerosols and amplify the impacts of aerosol emissions on solar dimming. The decreasing wind speed had also caused the reduction in potential evapotranspiration in many regions over the last several decades (Roderick et al. 2007; McVicar et al. 2012; Xie and Zhu 2013; Chu et al. 2019). Sugita et al. (2020) demonstrated that the spatial variability of turbulent fluxes was mainly caused by the wind speed differences. In addition, the near surface wind speed plays a key role in wind erosion dynamics (Zhang et al. 2019a), which could eventually result in the occurrences of desertification and sandstorm.

In the past few decades, the near-surface wind speed declined over most regions around the world (McVicar et al. 2012; Wu et al. 2018a; Tian et al. 2019), including North America (Pryor and Ledolter 2010; Wan et al. 2010), Europe (Walter et al. 2006; Najac et al. 2011; Papaioannou et al. 2011; Birsan et al. 2020), Africa (Soulouknga et al. 2018), and Asia (Bandyopadhyay et al. 2009; Fujibe 2009; Kim and Paik 2015). China is a large agricultural country; the wind speed could have important impacts on agricultural production through affecting the evapotranspiration (Shi...
et al. 2017; Sun et al. 2017). In addition, to achieve sustainable socioeconomic development as part of the global community, China had set ambitious goals for developing wind power within its national energy security framework (Liu et al. 2019). Therefore, the near-surface wind speed changes in China had also received increasing attentions. The near-surface wind speed in most areas of China had also decreased significantly over the past decades, in line with the rest of the world (Jiang et al. 2010; Guo et al. 2011; Zha et al. 2017b; Li et al. 2018b; Zheng et al. 2018; Ben et al. 2020). The main possible causes of the near-surface wind speed reductions include the decreased trend of the spatial variance in both atmospheric pressure and air temperature (Kim and Paik 2015), the weakened East Asian trough, which has shifted eastward and northward (Jiang et al. 2010), the decreasing East Asian winter and summer monsoons (Jiang et al. 2010), the weakening of the pressure gradient force (Wu et al. 2018b), the urbanization effect (Guo et al. 2011), and the effects of land use and land cover changes (Zha et al. 2017a).

Additionally, it should be noted that the near-surface wind speed in some regions in the world have reversed in recent years (Kim and Paik 2015; Azorin-Molina et al. 2018; Blunden et al. 2018; Zeng et al. 2019). This may bring new opportunities for wind energy industry development and air pollution control. Li et al. (2018a) reported that the near-surface wind speed in northwest China also began to decrease significantly since 1992. Therefore, it remains to be studied whether the reversal near-surface wind speed trend only appears in only some regions of China or in the whole and what caused the reversal trend.

Most of the previous studies were mainly focused on the mean near-surface wind speed trend and the possible mechanisms in wind speed changes. In fact, in addition to the importance of mean near-surface wind speed, extreme wind speed changes could have more significant impacts on human lives sometimes (Zhang and Wang 2020). For example, the weak wind can increase the residence time of PM2.5 and other aerosol particles (Wang et al. 2016, 2018), which poses a serious threat to air quality and human health. However, strong winds such as wind storms can blow dust (Cowie et al. 2013), damage buildings and drops. Therefore, it is also of great significance to study different levels of near-surface wind speed. Wu and Shi (2021) and Zha et al. (2016, 2017b) analyzed the wind speed over China based on observation and reanalysis datasets through dividing the wind speed into different grades according to the criteria of CMA. The paper will also analyze the spatiotemporal variation characters of different grades wind speed in China, but with different classification method.

This study extends upon previous analyses and intends to analyze the spatial and temporal variations for the near-surface wind speed with observations at 679 stations in China during the last 40 years (1979–2019). In addition, the possible mechanisms of the wind speed variations are further analyzed. Because different levels of wind speed may have different effects on human production and life, the near-surface wind speed is divided into different percentiles during the analysis. The paper is structured as follows: Section 2 describes the data and methodology. The near-surface wind speed climatology, variations, and possible mechanisms are presented in Section 3. Section 4 shows the discussion. Lastly, the summary and conclusions are shown in Section 5.

2 Data and methods

2.1 Data

The observed near-surface wind speed and wind direction of maximum wind speed data are from ground daily dataset of China (V3.0), which is provided by the China Meteorological Data Service Center (https://data.cma.cn/). The dataset contains daily mean near-surface wind speed and wind direction of maximum wind speed at 824 observation stations across China from 1951 to present. Because of the different establishment time of the observation stations and some stations with long-term missing measurements, especially in the regions with relatively harsh environment, such as the surface observing stations in the western Tibetan Plateau began providing operational observations since the late 1970s (Si and Ding 2013), we firstly selected the study period (1979–2019) that with more observation stations. Then, we excluded those observation stations with a continuous lack of measurement for more than 90 days. Finally, for compatibility in the observation data for all stations, the near-surface wind speed and wind direction of maximum wind speed from 679 out of 824 observation stations in 1979–2019 are used in this study.

The surface air temperature, surface air pressure, geopotential height at 500 hPa, and the wind components at 200 hPa, 500 hPa, and 850 hPa from ERA-Interim are used to analyze the mechanisms of the near-surface wind speed variations in China. ERA-Interim is an improved version of ERA-40 and is a global atmospheric reanalysis, which is available from January 1, 1979, to August 31, 2019. The data assimilation system used to produce ERA-Interim is based on a 2006 release of the IFS (Cy3r12). The system includes a 4-dimensional variational analysis (4D-Var) with a 12-h analysis window. The vertical spatial resolution of the dataset is approximately 80 km (T255 spectral) with 60 levels from the surface up to 0.1 hPa (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim). Aside from the improved resolution over ERA-40, ERA-Interim also uses mostly the sets of observations acquired for ERA-40,
supplemented by data for later years from ECMWF’s operational archive. In addition, ERA-Interim makes extensive use of radiances such as altimeter wave heights and radio occultation measurements (Gao et al. 2015). As the ERA-Interim datasets are not updated after August, 2019, we select the corresponding variables from 1979 to 2018 for analysis.

2.2 Methods

The Pearson correlation coefficients were applied to study the relationship between the surface temperature, pressure gradients and geopotential height gradients and the near-surface wind speed. The t-test was used to test the significance of the correlation coefficients. The variation rates of the climatic variables were obtained through linear regression between the variables and time series. We also calculated the different wind speed percentiles (95th, 75th, 50th, 25th, and 5th percentiles) at each observation station according to time series of the near-surface wind speed for every single year in 1979–2019. Over China, the 95th percentile of daily mean near-surface wind speed corresponds to the wind speed of 5 m s$^{-1}$, which is as a reference to define strong wind. Consistently, the 5th wind speed percentile is used to define weak wind (Zhang and Wang 2020). Additionally, in order to examine how the near-surface wind speed at different levels changed at the last 40 years, we also calculated the 75th, 50th, and 25th wind speed percentiles. The sliding t-test was used to detect the abrupt change in near-surface wind speed; this method was widely used in climatological and hydrological trend analyses (Jin et al. 2016). The step length about the sliding t-test was set to 3 years in this study.

In addition, station relocation, anemometer height and type changes, and anemometer aging may produce the discontinuity of wind speed series (Wan et al. 2010; Azorin-molina et al. 2018; Zhang et al. 2020). Therefore, the R package Climatol that was broadly used to homogenize observed climatic variable series (Azorin-Molina et al. 2016, 2019; Zhang et al. 2020) was further used to quality control, homogenization, and infilling of the missing data in the selected wind speed observation series. The Homogen function in the R package Climatol version 3.1.2 (http://www.climatol.eu/) uses the well-established relative Alexandersson’s standard normal homogeneity test (SNHT) to detect sudden points (Alexandersson 1986). Homogen provides a default threshold value of SNHT = 25 to split the series into two at the shift point. The SNHT thresholds may be different depending on the variability of the series, which in turn is linked to the climatic element and time resolution analyzed (Azorin-Molina et al. 2016). Therefore, we can perform a first exploratory analysis with Homogen and use the provided SNHT histograms to help choosing an appropriate value to discriminate inhomogeneous series (Azorin-Molina et al. 2016). In this study, we choose the SNHT thresholds of 300 and 500 for the overlapping windows and whole series applications, respectively, according to the exploratory analysis of the near-surface wind speed series.

3 Results

3.1 The climatology of the near-surface wind speed

Figure 1 shows the spatial distributions of the annual and seasonal mean near-surface wind speed in 1979–2019. Annually, the larger wind speeds mainly occur in Tibetan Plateau, the northern and eastern parts of China where the mean wind speeds are basically above 2 m s$^{-1}$, while the wind speeds in southwestern and central China are relatively weak (Fig. 1a). Additionally, the high wind speed are also observed in coastal areas, which may be caused by the tropical cyclones and sea-land-breeze circulations (Jiang et al. 2013; Huang et al. 2016). The mean annual wind speed averaged over 679 observation stations in China is 2.21 m s$^{-1}$ (Table 1). The spatial distribution patterns of the seasonal mean wind speed are similar to the annual (Fig. 1b–e). Significantly, the wind speed in spring when the wind speed values at most of stations are above 2 m s$^{-1}$ (Fig. 1b) is larger than the other seasons when the wind speeds at most of the stations are below 2 m s$^{-1}$ (Fig. 1c–e). The mean wind speed averaged over 679 observation stations in spring is 2.57 m s$^{-1}$ and the smallest value appears in autumn, which is 2.04 m s$^{-1}$ (Table 1). Therefore, the observed near-surface wind speed in China exhibits a distinct seasonal cycle.

Figure 2 is the box plot of the annual and seasonal mean near-surface wind speed for 679 observation stations. Consistent with Fig. 1 and Table 1, it can be seen that the maximum wind speed, minimum wind speed, median wind speed, mean wind speed, and 75th and 25th wind speed percentiles in spring are all larger than the annual and the other seasonal results. Moreover, Fig. 2 also shows the interquartile range (25th and 75th percentiles) of the near-surface wind speed. As shown, the wind speed in spring exhibits the highest interquartile range, denoting the highest spatial dispersion in spring. The wind speed in winter and autumn show moderate interquartile ranges and summer presents the lowest.

In order to study the dispersion degrees of the near-surface wind speed time series at each observation station, we also calculated the standard deviations of the near-surface wind speed (Fig. 3). The standard deviations are larger in northern China than in southern, which is similar to the spatial patterns of the wind speed both annually and seasonally. That is to say the regions with larger wind speed correspond to the regions with larger standard deviations. The dispersion degrees of the near-surface wind speed in spring and winter are higher than that in summer and autumn. This may be correlated with Siberian high and North Pacific index.
which were the factors influencing surface wind speed decadal variabilities (Zhang and Wang 2020).

### 3.2 Trends of the near-surface wind speed

The spatial distribution of the linear trend for the annual mean near-surface wind speed is shown in Fig. 4. It can be seen that the wind speed in most areas of China decreased in 1979–2019. In more detail, 487 out of 679 observation stations have decreased wind speed and the trends at 273 stations are significant at $p < 0.01$. The stations with significant decreased trend mainly distribute in Tibetan Plateau, northeastern and eastern regions, while the stations with increased trends mainly in Northwest China except Qinghai province, Southwest China except Tibet Autonomous region and South China, but the increased trends at most of the stations fail the significance test. Zheng et al. (2018) suggested that the increased wind speed is correlated with the enhancement of the Asian Meridional Circulation (AMC). The mean wind speed averaged over all of the 679 observation stations in China decreased at a rate of $-0.06$ m s$^{-1}$ (10a)$^{-1}$ in 1979–2019, which passed the significance test (Fig. 5b). Zeng et al. (2019) showed that the near-surface wind speed in Southeast Asia has increased since 2000. In order to investigate whether the wind speed in China has a turning point, we conducted the sliding $t$-test on the mean wind speed averaged over 679 stations with the step length setting to 3, and the result shows that there is a turning point.
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near 1996 (Fig. 5a). Therefore, in the following analysis, we divided the study period into two segments, one of which is from 1979 to 1996 and the other is from 1997 to 2019. It can be seen from Fig. 5b that the mean wind speed before 1997 present significantly decreased trend at a rate of $-0.19 \text{ m s}^{-1} (10\text{a})^{-1}$, which is obviously larger than that in 1979–2019. After 1997, the mean wind speed in China also presents increased trend, although the trend does not pass the significance test.

Spatially, the wind speed at 565 out of 679 of the observation stations presents decreased trend in 1979–1996 (Table 2) and the changing rates at most stations are more than $0.2 \text{ m s}^{-1} (10\text{a})^{-1}$ (Fig. 6a). In addition, the wind speed at most stations such as in Xinjiang, Tibetan Plateau, and Northeast China, etc. decreased with even larger rates and pass the significant test at $p<0.01$, which finally results in the more significant decreased wind speed trend averaged over 679 stations in 1979–1996 than that in 1979–2019. However, the wind speed in 1997–2019 show increased trend at more than half of the observation stations (Table 2) and the increasing rates at most stations are above $0.1 \text{ m s}^{-1} (10\text{a})^{-1}$ and pass the significant test (Fig. 6b). Finally, the mean wind speed averaged over 679 stations shows a reversal trend after 1997 (Fig. 5). Zhang et al. (2019b) showed the insignificantly increasing wind speed trend from 2000 to 2015. Our results further suggest that the near-surface wind speed in China reversed, although the turning point is not consistent with previous studies, which may be caused by the inconsistency of the study period.

Figures 1a and 4 also present that the regions with more significant wind speed trend correspond to the regions with larger wind speed. Therefore, the wind speed is divided into different percentiles including 95th percentile, 75th percentile, 50th percentile, 25th percentile, and 5th percentile to study the variations of wind speed in different levels. Figure 7 presents the variations of different wind speed percentiles averaged over 679 stations in 1979–2019, 1979–1996, and 1997–2019. It can be seen that the larger wind speed, the more significant wind speed reduction trend is from 1979 to 2019. The change rate of the 95th wind speed percentile reaches to $-0.18 \text{ m s}^{-1} (10\text{a})^{-1}$ and passes the significance test at $p<0.05$ (Fig. 7a). The change rates of the 75th ($-0.12 \text{ m s}^{-1} (10\text{a})^{-1}$) and 50th ($-0.06 \text{ m s}^{-1} (10\text{a})^{-1}$) wind speed percentile also pass the significance test, although the decreased trends are not as significant as the 95th wind speed percentile (Fig. 7b and c). The decreased trend of the 25th wind percentile is not significant (Fig. 7d). It should be noted that the 5th wind speed percentiles show increased trend in 1979–2019 and pass the significance test (Fig. 7e).

Through analyzing the variations of the wind speed percentiles before and after 1997, it is found that no matter the high or the low wind speed percentile show decreased trends in 1979–1996, and the trends are even more significant than that in 1979–2019. Similarly, the reduction rates of higher wind speed percentiles are also larger than that of lower wind speed percentiles in 1979–1996. After 1997, except for the 75th and 50th wind speed percentiles present nonsignificant decreased trend, the other wind speed percentiles all show increased trend. The 5th wind speed percentile has an increase rate that is close to $0.1 \text{ m s}^{-1} (10\text{a})^{-1}$, which passes the significance test at $p<0.05$ (Fig. 7e).

The spatial distributions of the linear trend for the different wind speed percentiles in 1979–1996 and 1997–2019 are shown in Fig. 8. In 1979–1996, the 95th wind speed percentile at about 87% of the observation stations (Table 2) show significantly decreased trend and the change rates at most of the stations reach to $-0.6 \text{ m s}^{-1} (10\text{a})^{-1}$ (Fig. 8a1). The number of stations with significantly decreased wind speed trend reduced gradually along with the wind speed percentiles go down, and the amplitude of the wind speed reduction also decreased gradually (Fig. 8a1–e1). The spatial distribution patterns of the trends for the 75th (Fig. 8b1) and 50th (Fig. 8c1) wind speed percentiles are similar to that of the annual mean wind speed (Fig. 6a). For the 25th and 5th wind speed percentiles, the number of stations with decreased wind speed trend reduced more significantly (Table 2) and the decreasing rates are basically below $-0.2 \text{ m s}^{-1} (10\text{a})^{-1}$, especially for the 5th percentile wind speed (Fig. 8e1). The change rates are positive at 280 out 679 observation stations for the 5th wind speed percentile as shown in Table 2.
ultimately leads to the decreased trend of the weak wind speed is not so significant compared with that of the stronger wind speed in 1979–1996 (Fig. 7).

In 1997–2019, the 95th and 75th wind speed percentiles at nearly half of the observation stations present increased trend (Table 2), but the trends at most of the stations do not pass the significant test at $p < 0.01$ (Fig. 8a2), which finally bring about the mean 95th wind speed percentile averaged over 679 stations increased insignificantly from 1997 to 2019 (Fig. 7a). The 75th and 50th wind speed percentiles at most of stations show insignificantly decreased trend in 1997–2019 (Fig. 8b2 and c2), which results in the slightly decreased trend for the mean 75th and 50th wind speed percentiles averaged over 679 stations (Fig. 7b and c). Figure 8d2 and e2 show that the 25th and 5th wind speed percentiles at the vast majority of the observation stations in China have significantly increased trend at
The significant decreased trend of the mean wind speed is mainly caused by the decreased strong wind, but the reversal trend of the mean wind speed after 1997 mainly due to the increase trend of weak wind. Zhang and Wang (2020) also showed that the decreased trend for the wind speed was primarily caused by strong wind. As for the more significant decreased trend for strong wind than weak, it maybe correlated with the surface roughness increases. Some studies showed that the surface roughness had a larger influence on strong winds than weak (Li et al. 2011; Zhang and Wang 2020).

3.3 The mechanism of the near-surface wind speed variations

The variations of the near-surface wind speed may be attributed to the changes of the upper wind fields and the uneven warming between high and low latitude zones. Therefore, the reasons for the near-surface wind speed changes in China are analyzed from the following two aspects.

3.3.1 The variation of the upper wind fields

Figure 9 shows the spatial distribution of the linear trends for the absolute near-surface U and V wind components in 1979–1996 and 1997–2019. Because wind speed is the root mean square of the sum of the squares for the U and V wind components, so the variations of the absolute value for the U and V wind components are analyzed. The absolute U wind component presents significantly decreased trend at majority of the observation stations (439 out of 679 stations) in 1979–1996, and the change rates at most stations reach to $-0.1 \text{ m s}^{-1}$ or more (Fig. 9a). In addition, the spatial distribution characteristic of the trend for the absolute U wind component is in good agreement with that of the wind speed as shown in Fig. 6a in 1979–1996. The spatial correlation coefficient between the two is 0.72, which passes the 99.9% significance test. Furthermore, the time correlation coefficients between the absolute U wind component and wind speed are larger than 0.6 that

### Table 2

| Year       | Mean | 95% | 75% | 50% | 25% | 5%  |
|------------|------|-----|-----|-----|-----|-----|
| 1979–1996  | Increased 114 | 88  | 110 | 147 | 214 | 280 |
|            | Decreased 565  | 591 | 569 | 532 | 465 | 399 |
| 1997–2019  | Increased 372  | 343 | 322 | 290 | 342 | 439 |
|            | Decreased 307  | 336 | 357 | 389 | 337 | 240 |
while the larger coefficients for the V wind component mainly occur in southern regions, indicating the U wind component contributes more to the wind speed variation in northern regions and the V wind component contributes more in southern regions. After 1997, both the U and V wind components present increased trend at nearly half of the stations (364 out of 679 stations for the U wind component and 332 out of 679 stations for the V wind component) (Fig. 9c and d) and pass the significance test at \( p < 0.01 \). The spatial correlation coefficients between the wind speed and U V wind components are 0.68 and 0.62, respectively, both of which pass the 99.9% significance test. As shown in Fig. 10c and d, the time correlation coefficients between the wind speed and wind components are above 0.6 and pass 99.9% significance test at about 43% and 39% of all the stations for U and V wind components, respectively. Thus, the reversal trend for the near-surface wind speed after 1997 is also jointly determined by the changes of the U and V wind components.

Further, the variations of the near-surface wind components may be affected by the changes of upper wind field through momentum down transport. Figure 11 shows the linear trends of the zonal winds at 850 hPa, 500 hPa, and 200 hPa in 1979–1996 and 1997–2018. The annual mean zonal wind at 200 hPa weakened in 1979–1996 over most regions above China and the weakened center is above the northern regions, where the weakening rate reaches to \(-1.0 \, \text{m s}^{-1} (10a)^{-1} \) and more (Fig. 11a). The zonal wind at 500 hPa and 850 hPa also present weakened trend, which pass the significant test at \( p < 0.05 \) for 850 hPa in most areas above China in 1979–1996 (Fig. 11c and e), even though the weakening magnitudes are not as larger as that at 200 hPa. Ultimately, we speculate that the significant decrease of the near-surface U wind component in China from 1979 to 1996 may be related to the weakened westerly wind at upper levels based on the momentum downward transfer principle. Figure 11b shows that the zonal wind at 200 hPa after 1997 present increased trend over most areas of China except for parts of the southern regions. Similarly, the zonal wind at 500 hPa also increased in 1997–2018 and the increase amplitude is also less than that at 200 hPa (Fig. 11d). Different from the spatial distribution patterns of the wind trends at 200 hPa and 500 hPa, the insignificantly increased and decreased wind trends of 850 hPa sporadically distributed over China after 1997 (Fig. 11f). This maybe the momentum in the upper levels does not fully transfer to the lower layers and the reasons need to be further studied, which finally may lead to the mean wind speed averaged over China after 1997 presents increased trend but is not significant.
In summary, the variations of the near-surface wind speed are caused by the changes for both the near-surface U and V wind components, and the variations of the near-surface U wind component is closely related to the changes of the upper wind fields. Zhang et al. (2019b) showed that the variations of v wind component are closely associated to the weakened Siberian High.

3.3.2 The uneven warming between high and low latitude zones

Horizontal surface pressure gradient force is the main driving for the horizontal air motion. However, the changes of the surface pressure gradient is driven by the changes of the horizontal temperature gradient (Li et al. 2018a). So, the analysis for the changes to the near-surface air temperature and pressure gradient and their effects on near-surface wind speed are of great significance.

Figure 12 shows the spatial distributions of the linear trends for the surface air temperature and pressure in 1979–1996 and 1997–2019. The annual surface air temperature shows significant warming trend at most regions except for the western and southern parts over China in 1979–1996 (Fig. 12a). It is worth noting that the warming trend in high latitude zone (45°N–50°N and 70°E–140°E, the mean trend is 0.32 °C (10a)^{-1}) is more significant than that in low latitude zone (20°N–25°N and 70°E–140°E, the mean trend is 0.01 °C (10a)^{-1}). Generally speaking, the annual mean surface air temperature at higher latitude is lower than that at lower latitude (Zhang et al. 2021). However, because the warming rates in the high latitude zone is significantly larger than that in the low latitude zone, the surface temperature gradient between the high latitude and low latitude zones become smaller and smaller with time in 1979–1996 as shown in Fig. 13a. The surface pressure at most areas also presents increased trend in 1979–1996. The high latitude zone presents more significantly increased trend with mean value of 0.50 hPa (10a)^{-1}) than the low latitude zone with 0.19 hPa (10a)^{-1}) (Fig. 12c), which finally resulting the negative trend in the surface pressure gradient (Fig. 13c). Table 3 shows that the mean near-surface wind speed and wind speed percentiles all significantly correlated with the surface air temperature and surface pressure gradients at the 90% confidence level. Therefore, the significantly decreased near-surface wind speed in 1979–1996 is closely related to the decreased pressure gradient force, the latter is further corresponding to the reductions in surface air temperature gradient.
In addition, the decreased geopotential height gradient at 500 hPa is also found as shown in Fig. 13e. The geopotential height gradient is also significantly correlated with the mean wind speed and wind speed percentiles in 1979–1996. Therefore, the difference in the surface warming rate may modify the gradient of geopotential height through thermal adaption, and this change in free atmospheric circulation will further modify larger-scale pressure gradient and finally influence the surface wind speed through the momentum downward transport from free atmosphere to the atmospheric boundary layer (Lin et al. 2013; Zhang et al. 2020). Zhang et al. (2021) clarified that the declining near-surface wind speed in northern China is likely attributed to the uneven warming. Ge et al. (2021) also suggests that the spatially inhomogeneous variations in surface air temperature in Eurasia’s mid-high latitudes may be the main reason for the near-surface wind speed variations in Northwest China. Our study shows the similar results to theirs.

The surface air temperature continues to rise in most areas in China except for some regions in northern since 1997 (Fig. 12b). The mean warming rates in the low latitude zone (0.16 °C (10a)−1) is larger than that in the high latitude (0.004 °C (10a)−1), but the difference is not so significant, which is different from that in 1979–1996. This makes temperature gradient between the higher and lower latitude zones increase gradually (Fig. 13b). Correspondingly, the geopotential height gradient at 500 hPa also presents increased trend. However, the mean wind speed and wind speed percentiles are not significantly consistent with the surface temperature gradient and geopotential height gradient at 500 hPa after 1997 (Table 3). Different from 1979–1996, the surface pressure in 1997–2018 presents decreased trend at most areas over China except for the Tibetan Plateau and parts regions in northeastern China with a mean change rate of 0.06 hPa (10a)−1 in high latitude zone and −0.06 hPa (10a)−1 in low latitude zone (Fig. 12d). The pressure gradients between the high and low latitude zone present insignificantly decreased trend finally (Fig. 13d) and is insignificantly correlated to the wind speed (Table 3). On the one hand, this may be the difference of the warming rates between the high and low latitude in 1997–2018 is small that caused a slight change in geopotential height gradient at 500 hPa through thermal adaption, but this does not cause a significant change...
in larger-scale surface pressure gradient due to the little momentum downward transport from free atmosphere to the atmospheric boundary layer. The mean wind speed in 1997–2018 present increased trend but not so significant eventually (Fig. 5b). On the other hand, the variations of the wind speed in 1997–2019 may be also influenced by other factors besides the uneven warming. Zhang and Wang (2020) indicated that atmospheric circulation was the main cause of near-surface wind speed recovery over China since the early twenty-first century. Deng et al. (2021b) showed that the recent reversal of the wind speed trend is most likely a multi-decadal fluctuation related to the Pacific and Atlantic climate variations. In addition, researchers had also shown that the decadal strengthening of the East Asian winter monsoon (EAWM) may have resulted in an upward trend of the near-surface wind speed in Northwest China after the early 2000s by strengthening the Siberian High.

4 Discussions

We investigated the trend and change mechanisms for the near-surface wind speed during 1979–2019 using the homogenized observations at 679 stations in China. What is noteworthy is that observation stations are of scarcity and uneven distributed in the vast northwestern regions of China, especially in Xinjiang and the Tibetan Plateau, where most of the observations located in the valleys that with lower altitude and easily accessible to humans. These make our research have certain insufficiency on the near-surface wind speed based only on the station observations. Studying near-surface wind speed with high coverage dataset is crucial to understand the wind speed comprehensively. At present, the commonly used grid datasets mainly include reanalysis and climate model simulations. However, many studies have shown that the reanalysis and model simulations had larger error in simulating the trend of near-surface wind speed compared to the observations and the results were largely diverse among themselves (Li et al. 2017; Torralba et al. 2017; Yu et al. 2019; Miao et al. 2020; Wu et al. 2020). Therefore, it is necessary to make a further analysis of the near-surface wind speed characteristics in China with high resolution grid data that with better performance in describing the trend. The near-surface wind speed and its variation characteristics are analyzed on annual and monthly time scales in this study. In the future, it is very necessary to research the wind speed on daily, hourly and even smaller time scale to catch more wind speed variation information.
In this paper, the wind speed change mechanisms in China are analyzed from two aspects: upper wind fields and uneven warming between high and low latitude zones. In addition to the above two aspects, the variation of near-surface wind speed may be closely related to the aerosol forcing and land use changes (Deng et al. 2021a), urbanization (Wang et al. 2020), larger-scale ocean–atmosphere circulations (Zha et al. 2021), Arctic Oscillation (AO) (Ge et al. 2021), etc. In the future, it would be of great significance to study the variation mechanisms of near-surface wind speed in China from various aspects, and to quantitatively identify the main influencing factors of near-surface wind speed variations in different periods and regions.

5 Summary and conclusions

The wind speed is the key for the wind power industry developing. Changes for the near-surface wind speed could have some profound influences on environment and socioeconomic. Therefore, the study of the near-surface wind speed and its variations is of great significance. In this study, the spatial and temporal characteristics and variation mechanisms of the near-surface wind speed in 1979–2019 are analyzed using the homogenized observations at 679 observation stations in China and ERA-Interim datasets. The followings are obtained:

1. The annual mean wind speeds in northern and eastern parts, Tibetan Plateau and the coastal zone are larger than that in the other regions of China. The
wind speed at most of the stations in those regions are above 2 $\text{m s}^{-1}$. Seasonally, the wind speed in spring is significantly larger than the other seasons, and the mean wind speed averaged over 679 stations reaches to 2.57 $\text{m s}^{-1}$. In addition, the dispersion degree of the wind speed in spring is also larger than that in the other seasons both spatially and temporarily.

2. The wind speed in China shows decreased trends at 487 out of 679 observation stations during 1979 and 2019. The stations with significantly decreased trend mainly distributed in the Tibetan Plateau, northeastern and eastern regions of China, where the wind speed is commonly larger than in the other regions. In 1979–1996, the decreased trend of the wind speed is particularly significant and the change rate of the annual mean wind speed reaches to $-0.19$ $\text{m s}^{-1}$ ($10\text{a})^{-1}$. Consistent with other studies, the wind speed in China also shows reversal trend after 1997. This could create new opportunities for the development of the wind energy industry in China.

3. The regions with larger wind speed generally correspond to the regions with significantly decreasing wind speed. After dividing the wind speed into different percentiles, we find that the decreased trend of the high wind speed percentiles (95th and 75th percentile) are more significant than that of the low wind speed percentiles, especially in 1979–1996. The change rate of the 95th wind speed percentile in 1979–1996 even reaches to $-0.48$ $\text{m s}^{-1}$ ($10\text{a})^{-1}$ and passes the significance test at $p < 0.05$. The lowest wind speed percentile has the most significant reversal trend since 1997. Therefore, the rapidly mean wind speed decrease is mainly caused by the significant reduction of strong wind, while the reversal trend of the mean wind speed since 1997 mainly results from the variation of weak wind.

4. The variations of the near-surface wind speed in China during 1979 and 2019 are caused by the changes of both the near-surface U and V components. On the one hand, the variations of the near-surface zonal wind are mainly due to the weakening of the upper westerlies, which finally results the variations of the near-surface wind speed through the momentum downward transport. On the other hand, the significant decreased trend of the wind speed is closely related to the difference in the surface warming rate, which may modify the gradient of geopotential height through thermal adaption and further modify larger-scale pressure gradient.
Fig. 13 The interannual variations for surface air temperature gradients (a and b), surface pressure gradients (c and d) and geopotential height gradients at 500 hPa (e and f) between the high (45°N–50°N) and low (20°N–25°N) latitudes in 1979–1996 (a, c, and e) and 1997–2018 (b, d, and f).

Table 3 The time correlation coefficients between the surface temperature (TG), surface pressure (PG) and geopotential height (GG) gradients and the mean near-surface wind speed and wind speed percentiles in 1979–1996 and 1997–2018. The bold fonts indicate that the correlation coefficients that have passed significance test at the 90% confidence level.

|                  | Mean | 95% | 75% | 50% | 25% | 5%  |
|------------------|------|-----|-----|-----|-----|-----|
| (45°N–50°N) – (20°N–25°N) |      |     |     |     |     |     |
| 1979–1996        | TG   | 0.41| 0.38| 0.41| 0.39| 0.45| 0.48|
|                  | PG   | 0.41| 0.39| 0.39| 0.39| 0.41| 0.38|
|                  | GG   | 0.44| 0.39| 0.44| 0.44| 0.50| 0.58|
| 1997–2018        | TG   | 0.12| 0.18| 0.14| -0.03| -0.10| 0.05|
|                  | PG   | 0.24| 0.12| 0.30| 0.35| 0.24| -0.08|
|                  | GG   | 0.28| 0.35| 0.24| 0.00| 0.04| 0.23|

The bold entries indicate the correlation coefficients have passed significance test at the 90% confidence level.
Acknowledgements We wish to acknowledge the Editor and the anonymous reviewers for their detailed and helpful comments to the original manuscript. We also acknowledge China Meteorological Administration and European Centre for Medium-Range Weather Forecasts for providing the datasets.

Author contributions Xia Li analyzed the data and wrote the manuscript. Yongjie Pan provided guidance and revised the manuscript. Yingsha Jiang revised the manuscript and improved grammar.

Funding This work is jointly supported by the Strategic Priority Research Program of Chinese Academy of Sciences (XDA2006010202) and the Second Tibetan Plateau Scientific Expedition and Research (STEP) program (2019QZKK010314).

Data availability Wind speed data from station observations can be accessed at China Meteorological Administration (https://data.cma.cn/), and ERA-Interim Reanalysis was downloaded from ECMWF (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim).

Code availability Code is available on request.

Declarations

Ethics approval The authors confirm that this article is an original research.

Consent to participate The authors confirm that this article has not been published previously in any journal.

Consent for publication The authors have agreed to submit this manuscript in its current form for publication in the journal.

Conflicts of interest The authors declare no competing interests.

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