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**Contrasting Trend of Wintertime Wind Speed Between Near-surface and Upper Air in China During 1979–2021**

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**Abstract:** The long-term height-resolved wind trend in China under global warming still needs to be discovered. To fill this gap, in this paper we examined the climatology and long-term (1979–2021) trends of the wintertime wind speed at the near-surface and upper atmosphere in China based on long-term radiosonde measurements. At 700, 500, and 400 hPa, much higher wind speed was found over eastern China, compared with western China. At 300, 200, and 100 hPa, maximum wind speed was observed in the latitude zone of around 25–35°N. Furthermore, westerly winds dominated most parts of China between 20°N and 50°N at altitudes from 700 hPa to 100 hPa. A stilling was revealed for the near-surface wind from 1979–2003. From 2004 onward, the near-surface wind speed reversed from decreasing to increasing. This could be largely due to the joint impact of reduced surface roughness length, aerosol optical depth (AOD), and increased sensible heat flux in the ground surface. The decrease of AOD tended to reduce aerosol radiative forcing, thereby destabilizing the planetary boundary layer (PBL). By comparison, the wintertime wind in the upper atmosphere exhibited a significant monotonic upward trend, albeit with varying magnitude for different altitudes. In the upper troposphere, the wintertime maximum wind was observed along a westerly jet stream, with a pronounced upward trend within the zone approximately bounded by latitudes of 25–50°N, particularly above 500 hPa. This accelerating wind observed in the upper troposphere and lower stratosphere could be closely associated with the large planetary-scale meridional temperature trend gradient. Besides, the direction for the wind at the near-surface and lower troposphere (925 and 850 hPa) exhibited a larger variance over the period 1979–2021, which could be associated with the strong turbulence of PBL caused by the heterogeneous land surface. For those pressure levels higher than 850 hPa, large wind directional variance was merely found to the south of 25°N. The findings from long-term radiosonde measurements in winter over China shed light on the changes in wind speed on the ground and upper atmosphere under global warming from an observational perspective.

**Key words:** radiosonde; wind speed; long-term trend; thermal wind balance; China

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1 INTRODUCTION

Under the influences of global warming and intense anthropogenic activities, significant changes in atmospheric circulation have been well documented through both observational and modeling studies (Held [1], Francis and Vavrus [2], Berrisford et al. [3]). The variation in wind speed is a useful indicator of atmospheric circulation changes in the atmosphere (Troccoli et al. [4]), consequently, the changes in large-scale near-surface wind flow in the planetary boundary layer (PBL) are closely linked to convection initiation (Peters et al. [5]), cloud formation (Wirth et al. [6]) and air quality (Zhang and Wang [7]). Besides, the climatological variation of near-surface wind speed is of importance for industries that are affected or dependent on winds, such as forestry fire, air quality, renewable energy and insurance (Beer [8], Wang et al. [9], Tian et al. [10]). Likewise, the climatic mean state and its variation of wind speed in the upper air have broader implications for civil aviation (Lee et al. [11], Lv et al. [12]).

The changes in near-surface wind have drawn increasing attention (Guo et al. [13]). Before the 2010s, there was a growing consensus within the scientific community that the slowdown of near-surface winds had dominated global and regional wind climatology since the 1960s (Azorin-Molina et al. [14], Zeng et al. [15]). For instance, near-surface wind speeds were declining in the tropics and the mid-latitudes of the Northern Hemisphere.
The decreasing trend in surface wind speed is ubiquitously observed from 1979 to 2016 over most regions of the Northern Hemisphere (Tian et al. [10]). Additionally, annual mean surface wind speed declined by 5–15% between 1979 and 2008 (Vautard et al. [13]). Long-term observations indicated a declining trend in surface wind over North America (Wan et al. [18]; Pryor and Ledolter [19]). The decrease in surface wind has been widely recorded across Europe (Tian et al. [10]), including Germany (Walter et al. [20]), the Czech Republic (Brazdil et al. [21]), Switzerland (McVicar et al. [22]), France (Najac et al. [21]) and Greece (Papaioannou et al. [24]). Similar decreasing trends were found in many Asia countries, such as India, Japan (Bandyopadhyay et al. [23]; Fujibe [26]), and China (Tian et al. [10]; Guo et al. [13]; Chen et al. [23]; Yin et al. [28]). However, recent studies have found a recovery in surface wind speed since the last decade (Azorin-Molina et al. [28]; Zhang et al. [32]; Zhang and Wang [1]). The global mean surface wind speed anomaly in 2020 showed a positive value with respect to 1981–2010 (Blunden and Boyer [10]).

Numerous efforts have been made to unravel the mechanism underlying the declining wind observed worldwide, but it still needs to be more conclusive. The atmospheric stalling near the ground surface observed in Northern Hemisphere was attributed to the increase in surface roughness, mainly induced by biomass and land-use change (Vautard et al. [13]). Furthermore, rapid and continuous large-scale urban expansion tends to result in significant increases in the roughness length of heterogeneous underlying surfaces, which has been found to be closely associated with this stalling (Weyer et al. [31]; Guo et al. [13]). Besides, the weakening of atmospheric circulation under global warming is another potential influential factor for this decline in near-surface winds (Lu et al. [12]).

Similar to near-surface winds, the interest in elucidating the long-term trend and underlying causes for upper-air winds has dramatically grown in the last decades. It is known that upper-air winds can significantly affect aviation safety and the efficiency of long-haul flights (Kim et al. [93]; Lee et al. [13]). The upper-air wind is found to be sensitive to climate change (Manney and Hegglin [64]; Hudson [65]) and thus is essential for estimating the changes in the general atmospheric circulation and even for explaining the changes in near-surface winds (Vautard et al. [17]). It is reported that under the global warming background, cooling in the lower stratosphere over polar areas (Held [1]; Thompson and Solomon [60]) and warming in the tropical upper troposphere are found (Allen and Sherwood [63]; Mitchell et al. [56]; Sherwood and Nishant [57]), which leads to intensified meridional temperature gradient and thus increase the upper-air wind speed (Lorenz and DeWeaver [40]). Furthermore, recent observational analysis based on a homogenized radiosonde dataset showed that the subtropical westerly jets on both hemispheres strengthened and moved poleward by a few degrees from 1979–2012 (Sherwood and Nishant [39]). In the lower troposphere, by comparison, the Arctic warms faster than other mid- and low-latitude regions due to global warming, which tends to make the meridional temperature gradient much weaker and thus slow down the wind speed (Francis and Vavrus [2]; Haarsma and Oldenborgh [44]; Francis and Vavrus [42]).

The long-term trend of upper-air wind speed exhibits large regional variability. For example, the wind speed in the lower and upper troposphere declined from 1980 to 2006 (Zhang et al. [41]). In contrast, during 1979–2008, the wind speed at 850 hPa exhibited a rising tendency in Europe and North America but a decreasing tendency in Central and East Asia (Vautard et al. [13]). More interestingly, sporadic abrupt changes in wind speed over China were recorded at the upper troposphere for the subperiods 1969–1974 and 2002–2009, coinciding with the negative Arctic Oscillation phase (Lin et al. [44]).

Nevertheless, the knowledge of wind speed change over time remains limited based on radiosonde measurements that provide in-situ observations of the atmospheric state, although radiosonde and pilot balloons have been used since the 1930s (Stickler et al. [62]). Fortunately, the temporal homogeneity issues in radiosonde wind records have been well addressed in recent years (Gruber and Haimberger [46]). In China, there are 120 radiosonde stations in operational mode, in which the radiosonde balloon is launched twice per day (00 and 12 UTC). Several previous studies have attempted to analyze the trends of upper-air wind speed, but most of them are limited to a specific place or short periods (Chen et al. [27]). The long-term radiosonde measurements released in 2017 by China Meteorological Administration (Guo et al. [47]) provide an unprecedented opportunity to gain insights into the long-term change of wind speed in the upper air.

More importantly, as of the time of writing, few studies have unraveled how the wind speed at the near-surface and upper air changes simultaneously in China in the context of climate change. This motivates us to elucidate the long-term wind variation trend using radiosonde measurements and figure out its underlying mechanism. The remainder of this manuscript proceeds as follows: Section 2 describes the data and methods used in this study. Section 3 presents the spatial and temporal variation trend of wind speed ranging from near-surface to upper air. The potential influential factors and mechanisms are discussed as well. It ends with several key findings summarized in Section 4.

2 DATA AND METHODS

2.1 Radiosonde data and ERA5 and MERRA-2 reanalysis

The newly released quality-controlled radiosonde data from China Meteorological Administration were used in this study, covering the period from 1979–2021 (Chen et al. [48]; Guo et al. [47]). The radiosonde dataset provides the fine resolution profiles of temperature,
pressure, relative humidity, wind speed and direction at both standard and “significant” pressure levels. The wind and temperature measurements at the surface, 925 hPa, 850 hPa, 700 hPa, 500 hPa, 400 hPa, 300 hPa, 200 hPa, and 100 hPa were used here. Unless otherwise noted, the soundings we used were acquired at 0800 Beijing Time (BJT, UTC+8) and conditioned on strict data quality control procedures, including basic parameter inspection, internal consistency check, and duplicate value check. The quality control methods included the homogeneous test, the extreme test, and the temporal consistent test.

ERA5, the fifth generation of global atmospheric reanalysis produced at the European Centre for Medium-Range Weather Forecasts (ECMWF), is the successor of ERA-interim. It exhibits significant improvements over previous reanalysis, largely due to the updated parameterization schemes and more observations assimilated, which lead to its capability of public access within five days behind real time in operational mode. Meanwhile, ERA5 reanalysis provides a spatial resolution of 0.25°×0.25° and a temporal resolution of 1-h. Notably, the accuracy and performance have been well demonstrated in reproducing the variation of temperature, rainfall, wind, and surface energy balance (Hersbach et al. [49]). It covers the period from 1950 to the present (Bell et al. [49]). Here we use the monthly temperature dataset at various pressure levels, surface roughness length and sensible heat flux datasets over China from 1979 to 2021.

MERRA-2 is the first long-term global reanalysis to assimilate space-based observations of aerosols and represent their interactions with other physical processes in the climate system. The MERRA-2 reanalysis has a spatial resolution of 0.5°×0.625° (zonal × meridian), a vertical range of 72 layers from ground to 78 km (1Pa), and a renewal period of 6 hours (Gelaro et al. [50]). The AOD dataset from MARRA-2 reanalysis is used here, covering the whole of China from 1979 to 2021.

2.2 Trend analysis

The wind speed trends were estimated of wind speed for 1979–2021 based on the method of least square regression. Linear trends and their attendant significance levels were estimated using the same methods as Weatherhead et al. [51]. Least squares regression typically assumed a Gaussian data distribution in the trend analysis. The time series of observations could be modeled by fitting the following relationship with the least square approximation:

\[ Y_t = a + bt + \epsilon \]  

where \( t \) is the time, \( Y_t \) represents the time series of variables, \( a \) is the intercept, \( b \) is the slope, and \( \epsilon \) denotes the noise term. The statistical significance of the trend is tested by the \( F \)-test method.

2.3 Estimation of wind directional variance

To fully understand the trend of wind vectors, the trend of wind direction has to be estimated over 120 radiosonde stations in China from 1979–2021. The wind directional variance has been previously used to characterize the trend of wind direction. Here, following the methods proposed by Klink [52], we calculated the wind directional variance \( \sigma^2_z \) for each pressure level using the following equivalent scalar equation:

\[ \sigma^2_z = \frac{1}{n} \sum_{j=1}^{n} (Z_j - \bar{Z}) \times (Z_j - \bar{Z}) \]  

where \( \bar{Z} = \frac{1}{n} \sum_{j=1}^{n} Z_j \) is the mean wind direction, and \( * \) represents the complex conjugate.

Directional variance is a dimensionless number that ranges between zero (all directions are the same) and one (directions lack a single mode of concentration).

2.4 Meridional temperature gradient as a proxy for wind

The upper atmosphere in winter over most regions of China is subject to the influence of westerly jet streams, which is closely associated with a planetary-scale meridional temperature gradient (Wallace and Hobbs [53], Lee et al. [54]). To get an insight into the underlying wind trend observed in the upper atmosphere, a meridional temperature gradient has been calculated using ERA5 reanalysis. The dynamical relationship commonly known as the thermal-wind equation (Holton [55]) is utilized here to connect the wind shear \( V_T \) with the meridional temperature gradient, which is formulated as follows:

\[ V_T = \frac{R}{f} \ln \frac{p_2}{p_1} \times \nabla T \]  

where \( R \) is the specific gas constant for dry air, \( f \) is the Coriolis parameter, and \( p \) is atmospheric pressure.

This equation holds only when the Coriolis and pressure gradient forces dominate, whereas inertia and frictional effects can be ignored, which is the case for the wintertime wind trend analysis in China, particularly for those winds in the upper troposphere (Sherwood et al. [56]) up to the lower stratosphere (Randel [57]).

3 RESULTS AND DISCUSSION

3.1 Spatial pattern of height-resolved wind in China

In this study, we analyzed the annual mean wind direction and speed in China during the wintertime for the period 1979–2021. The annual mean wintertime wind vector at 925, 850, 700, 500, 400, 300, 200, and 100 hPa over all available radiosonde stations in China from 1979 to 2021 are shown in Fig. 1. On average, southerly wind prevailed south of 35°N, which shifted to westerly winds to the north of 35°N at 925 and 850 hPa. At middle-pressure levels such as 700, 500, and 400 hPa, the spatial pattern of wind speed exhibited an east-to-west gradient, decreasing from eastern China to western China. Particularly at 300, 200, and 100 hPa pressure levels, the annual mean wintertime wind speed showed meridional variation, with the maximum speed seen around the zonal region from 25 to 35°N that exceeds 40 m s\(^{-1}\). At the regions around 20°N and 50°N, the wind speed dropped to 20 m s\(^{-1}\), less than half of the maximum value. The
Wintertime wind can reach up to more than 60 m s$^{-1}$ at 200 hPa in the latitude zone of 20 to 40°N, where the upper-subtropical jet stream was generally located. In the vertical, wind speed tended to increase monotonically from lower troposphere up to 200 hPa, at which the polar front jet stream oftentimes occurred.

Interestingly, zonal winds in the winter for the investigated period dominated at the pressure levels from 700 hPa to 100 hPa, where the wind direction between 20°N and 50°N was mostly westerly. Previous studies indicated that the air temperature showed a pronounced spatial pattern of “south high and north low”, irrespective of pressure levels (Lv et al.$^{[12]}$). This meridional temperature gradient generated westerly winds that tended to strengthen with height as a consequence of thermal wind balance (Wallace and Hobbs$^{[54]}$). The strongest westerly winds observed in the upper troposphere of mid-latitude region were probably linked to upper-tropospheric jet stream. The mid-latitude baroclinic zone of the atmosphere, in combination with Coriolis force, could lead to this planetary-scale meridional temperature gradient between the equator and

**Figure 1.** Spatial distribution of annual mean wind vector (units: m s$^{-1}$) over 120 radiosonde stations in China in winter (December-January-February) for the period 1979–2021 at a variety of pressure levels: (a) 925 hPa, (b) 850 hPa, (c) 700 hPa, (d) 500 hPa, (e) 400 hPa, (f) 300 hPa, (g) 200 hPa, and (h) 100 hPa.
the polar region. Afterwards, the wind tended to weaken gradually at lower stratosphere.

3.2 Long-term trend of near-surface wind speed in China

We analyzed long-term trend of near-surface wind speed during the winter of the period 1979–2021. Overall, the wintertime near-surface wind speed in China showed a declining trend before 2004, after which the wind recovery was observed (Fig. 2a). In the earlier subperiod 1979–2003, a negative linear trend of $-0.18 \text{ m s}^{-1}$ 10a$^{-1}$ was found. In contrast, an abrupt change occurred in 2004, after which a significant increasing trend in near-surface wind speed was observed at $0.65 \text{ m s}^{-1}$ 10a$^{-1}$. Albeit with quite different magnitudes, the timing of this trend reversal is in broad agreement with that found in Europe, in which the turning point was reported in 2003 (Zeng et al. [15]). As shown in Fig. 2b, the 5-year moving average near-surface wind trend analysis gave more detailed information of the wind trend reversal, which was based on the robust Theil-Sen estimator of trend. After the year of 2004, the near-surface wind speed was dominated by the positive trend. By comparison, the speed trend as calculated over short time window was negative before 2004, and when the time window became longer, the trend turned to positive again, most of which was statistically significant at the 95% confidence level. Not surprisingly, the speed trend showed pronounced interannual fluctuations.

The spatial distributions of the annual mean wintertime near-surface wind speed trend for both subperiods were given in Fig. 2c and Fig. 2d, respectively. During the earlier subperiod, a large number of stations showed a negative trend, indicative of the dominance of wind stilling. On the contrary, the majority of stations followed a rising trend from 2004 to 2021, suggesting the indeed occurrence of the recovery of near-surface wind speed. Our results of the wintertime wind trend reversal based on long-term radiosonde dataset is in good agreements with most previous literatures (e.g., Azorin-Molina et al. [29], Zeng et al. [15]), although their turning points happened in the years ranging from 2004 to 2010.

The spatial distributions of wind directional variance over China for both subperiods were given in Fig. 3. Overall, no pronounced shift or change was found for the directional variation. Nevertheless, some interesting spatial patterns emerged. For instance, in the eastern China, high variance of direction can be observed for both subperiods. The latter subperiod had a larger magnitude in terms of the directional variance than the earlier subperiod in the southwest of China.

3.3 Long-term trend of upper-air wind speed in China

Figure 4 showed the spatial distribution of wintertime

- **Figure 2.** (a) Time series of annual mean surface wind speed (black line) and 5-year moving average surface wind speed (blue line) over 120 radiosonde stations in China in winter (December-January-February) for the period 1979–2021. The red lines denote the least squares linear fitting trend; the turning point is marked by vertical dashed black line in 2004, respectively. Red shading areas and dash lines represent 95% confidence intervals. (b) Running window linear trends in annual mean surface wind speed during 1979–2021. The $x$ axis represents the start year of the analysis period, while the $y$ axis represents the length of the analysis period. Trends that are statistically significant at the 95% confidence level are indicated by black dots. Note that running windows with lengths less than 5 years are not considered. Also shown is the spatial distribution of the trend (color shaded dots) of annual mean surface wind speed over the radiosonde stations in China in winter for 1979–2003 (c) and 2004–2021 (d). The dots in warm colors refer to the stations with increasing trend in wind, and the dots in cool colors the stations with decreasing trend. The dots highlighted with black circles indicate that trends are statistically significant ($p<0.05$), and the overall value of trend is given for each panel as well.
wind speed trend at different pressure levels from 1979 to 2021 in China. It was noticeable that over most regions north of 25°N in China, a significant increasing trend was observed in upper-air wind speed from long-term radiosonde measurements, irrespective of pressure levels. On average, the rising trend of wind speed was more salient above the pressure level of 500 hPa, particularly in the region to the north of 30°N. The maximum magnitude reached up to more than 2.5 m s$^{-1}$ 10a$^{-1}$. The mean trend of wind speed at 500, 400, 300, 200 and 100 hPa was

Figure 3. The spatial distribution of the directional variance of near-surface wind over 120 radiosonde stations in China in winter for 1979–2003 (a) and 2004–2021 (b). Wind directional variance (color shaded dot) is a dimensionless number that ranges between zero that means all wind directions are the same and one that means the wind directions lack a single mode of concentration; see Klink [53].

Figure 4. The height-resolved spatial evolution of annual mean wintertime wind speed trend (color shaded dots, unit: m s$^{-1}$ 10a$^{-1}$) in China for the period of 1979–2021 at (a) 925 hPa, (b) 850 hPa, (c) 700 hPa, (d) 500 hPa, (e) 400 hPa, (f) 300 hPa, (g) 200 hPa, and (h) 100hPa pressure level. The dots in warm colors refer to the stations with increasing trend in wind speed, and the dots in cool colors are the stations with decreasing wind speed trend. The dots highlighted with black circles indicate that trends are statistically significant ($p<0.05$), and the overall mean values of trends are given for each panel as well (the number in the lower left corner of each panel).
positive, corresponding to the mean value of 0.02, 0.13, 0.08, 0.96 \text{ m s}^{-1} \text{ 10a}^{-1}, respectively. At 700 hPa, a rising trend was shown to the north of 40°N, and most stations south of 40°N exhibited decreasing trends, with the mean value of 0.02 m s\(^{-1}\) 10a\(^{-1}\). At 850 hPa, the wind speed at most stations showed no apparent trend, and a few stations indicated a declining trend, with the mean value of 0.03 m s\(^{-1}\) 10a\(^{-1}\). At 925 hPa, about half of the stations showed positive trend of wind speed, with the mean value of 0.02 m s\(^{-1}\) 10a\(^{-1}\). By comparison, a weakening wind speed was found in the region to the south of 25°N at 500, 400, 300, 200 and 100 hPa.

Furthermore, wind speed trend was analyzed by classifying into various percentiles, and the results were shown in Table 1. Weak wind speed at 5\(^{th}\) percentile showed an increasing trend from surface to 100 hPa except for 850 hPa. In contrast, high wind speed (ie., 95\(^{th}\) percentile wind) displayed an increasing trend except for 500 hPa and 400 hPa. At 925, 200 and 100 hPa, the wind speeds in lower to higher percentiles showed an upward trend. Median wind speed (50\(^{th}\) percentile) exhibited a downward trend at 850, 700 and 500 hPa. Meanwhile wind speed in lower percentiles (5\(^{th}\)–40\(^{th}\) percentile) at 500, 400 and 300 hPa displayed an upward trend.

As shown in Fig. 5a, we divided stations into three regions based on the altitude of radiosonde station: the region with altitude less than 1000 m, the region with altitude lying between 1000 m and 3500 m, and the region with altitude above 3500 m. In terms of the vertical profile of wintertime wind trend averaged over all stations in China, it did not present obvious positive trend below 500 hPa. For all pressure levels starting from 500 hPa, a dramatic rising trend was found (Fig. 5b).

The spatial distributions of wind directional variance at different pressure levels from 1979 to 2021 in China were shown in Fig. 6. Not surprising was that the directional variance exhibited interesting geographical dependence. On the whole, the wind direction in the lower troposphere such as 925 and 850 hPa showed much higher variance, compared with other higher pressure levels. This could be because the atmosphere in proximity to the PBL was easily subject to the influence of unregular and anisotropic turbulent eddies that caused by the

### Table 1

<table>
<thead>
<tr>
<th>Percentiles</th>
<th>925hPa</th>
<th>850hPa</th>
<th>700hPa</th>
<th>500 hPa</th>
<th>400hPa</th>
<th>300hPa</th>
<th>200hPa</th>
<th>100hPa</th>
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<td>95(^{th})</td>
<td>0.247*</td>
<td>0.109</td>
<td>0.011</td>
<td>-0.115</td>
<td>-0.044</td>
<td>0.043</td>
<td>0.317</td>
<td>0.694*</td>
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<tr>
<td>90(^{th})</td>
<td>0.140*</td>
<td>0.064</td>
<td>-0.026</td>
<td>-0.057</td>
<td>0.046</td>
<td>-0.005</td>
<td>0.265</td>
<td>0.878*</td>
</tr>
<tr>
<td>85(^{th})</td>
<td>0.078</td>
<td>0.013</td>
<td>0.006</td>
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<td>0.016</td>
<td>-0.028</td>
<td>0.403</td>
<td>0.861*</td>
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<td>80(^{th})</td>
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<td>-0.008</td>
<td>0.017</td>
<td>-0.047</td>
<td>0.000</td>
<td>-0.011</td>
<td>0.340</td>
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<td>-0.050</td>
<td>0.009</td>
<td>0.022</td>
<td>0.439</td>
<td>0.892*</td>
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<td>0.012</td>
<td>-0.018</td>
<td>-0.026</td>
<td>-0.046</td>
<td>0.042</td>
<td>0.105</td>
<td>0.455*</td>
<td>0.882*</td>
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<td>-0.048</td>
<td>0.016</td>
<td>0.068</td>
<td>0.086</td>
<td>0.481*</td>
<td>0.944*</td>
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<td>60(^{th})</td>
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<td>-0.030</td>
<td>0.043</td>
<td>0.120</td>
<td>0.119</td>
<td>0.489*</td>
<td>1.013*</td>
</tr>
<tr>
<td>55(^{th})</td>
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<td>-0.023</td>
<td>0.138</td>
<td>0.239</td>
<td>0.236</td>
<td>0.586*</td>
<td>1.054*</td>
</tr>
<tr>
<td>50(^{th})</td>
<td>0.023</td>
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<td>0.166</td>
<td>0.357</td>
<td>0.448</td>
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<td>0.857*</td>
</tr>
<tr>
<td>45(^{th})</td>
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<td>0.179</td>
<td>0.372</td>
<td>0.513</td>
<td>0.740*</td>
<td>0.854*</td>
</tr>
</tbody>
</table>

* represents the trend is statistically significant at 95% confidence level.
heterogenous land surface (Stull [58], Li et al. [59]). Besides, high variance of direction can also be observed in the region to the south of 25°N at 500, 400, 300, 200 and 100 hPa. This roughly corresponded to the region where wind speed was observed to decline simultaneously.

3.4 Influential factors for the reversal of near-surface wind speed

The long-term near-surface wind speed in winter over China showed a decreasing trend during 1979–2003, which was also termed stilling. During the subperiod of 2004–2021, a widespread recovery of wind speed across China was found. The stilling during the first subperiod could be most likely due to the changes in atmospheric circulation (Vautard et al. [17]). And the observed recovery of near-surface wind in China in the second subperiod could be attributed to intensity variation of Aleutian low pressure over North Pacific (Zhang and Wang [7]).

Here we further attempted to unveil the roles of the changes of surface roughness length ($R_{sfc}$), sensible heat flux ($H_c$) and aerosol loading. $R_{sfc}$ was usually used to express the aerodynamic surface roughness. The surface forcing, such as frictional drag and heat transfer, played a significant role in the reversal of wind speed.

![Figure 6](image-url). The spatial distribution of height-resolved directional variance of wintertime wind registered over 120 radiosonde stations in China for the period of 1979–2021: (a) 925 hPa, (b) 850 hPa, (c) 700 hPa, (d) 500 hPa, (e) 400 hPa, (f) 300 hPa, (g) 200 hPa, and (h) 100 hPa pressure level.
dominant role in turbulent exchange and transport of the energy and momentum between the surface and free atmosphere, thereby changing the wind vector. The wind speed was generally found to increase considerably with height in the surface layer by following the logarithmic wind profile under neutral stability conditions, and the strongest surface friction in the ground surface associated with the minimum wind speed was closely related to large Rsfc (Stull [58], Li et al. [59]). Fig. 7a showed the bar plots summarizing the percentage of radiosonde stations in China with increasing and decreasing trend in Rsfc values from ERA5 reanalysis, respectively. Compared to the first subperiod from 1979 to 2003, most of the radiosonde stations have experienced the decrease in Rsfc during the second subperiod from 2004 to 2021. As such, this indicated that increased number of stations with downward trend in Rsfc accounted for the recovery of near-surface wind speed during the second subperiod. Furthermore, it was found that more radiosonde stations have experienced the rising of Hc, especially for the number of stations with Hc increase larger than 5 W m⁻² (Fig. 7b). Previous studies (Raga and Abarca [60]) indicated that strong Hc was typically positively correlated with high wind speed, especially in the low wind speed regime less than 10 m s⁻¹. Coincidently, Fig. 2a showed that the mean speed of near-surface wind was lower than 3 m s⁻¹ in China. So, we assumed that the positive relationship was true between Hc and near-surface wind speed. Therefore, the rising in Hc at least explained in part the recovery of wintertime near-surface wind speed in China in recent years.

Aerosol loading was another key factor that received increasing attention in recent years for its significant direct and indirect effect on the weather and climate system, which was indeed a case for China (Guo et al. [61-62], Yang et al. [63], Li et al. [64]). Fig. 8 presented the relationship between the wintertime wind speed trend and AOD trend during both subperiods: 1979–2003 and 2004–2021. Interestingly, approximately 80% radiosonde stations experienced significant decreasing trend in AOD during
the second subperiod, likely due to the aerosol emission reduction. Concurrently, more than two thirds of stations witnessed rising wind speed (Fig. 8b). It was inferred that the recovery of wind speed after 2004 was closely associated with the decrease of AOD. The mechanism behind this phenomenon could be owing to the decreases in aerosol direct effect that tended to destabilize the PBL (Ding et al. [65]; Li et al. [66]; Su et al. [67]; Jacobson and Kaufman [68]). Aerosol particles and aerosol-enhanced clouds exert a stabilizing effect on the PBL. During the day, the absorption and scattering of aerosol particles enhance stability by diminishing solar radiation reaching the ground, thereby impeding the vertical transport of horizontal momentum and ultimately reducing wind speeds beneath them. Therefore, as the AOD decreases, the stability of PBL diminishes, thereby intensifying the vertical transport of horizontal momentum and increasing the near-surface wind speed.

3.5 Influential factors for the rising upper-air wind speed

In terms of the causes of upper-air wind speed trend, we resorted to the thermal wind theory. The thermal wind balance exerted a dominant effect on the winter wind speed trend in the upper air of north hemisphere. Global warming has been increasingly recognized to most likely scale up the spatial gradient of temperature, thereby dramatically altering the spatio-temporal variability of jet stream around the world, especially in the mid-latitudes (Williams [69]). Our wind speed analyses at multiple pressure levels indicated a distinctive upward trend in upper-troposphere in winter, especially in the latitude zone between 25 to 50°N (Fig. 4), where upper-troposphere jet streams were located.

Figure 9 showed the pressure–latitude cross-section of zonally averaged temperature trend in winter for the period 1979–2021 over China. By comparing the temperature trend at various pressure levels, cooling was found in the stratosphere—around above 150 hPa, whilst the troposphere showed a warming trend, especially to the south of 45°N. The maximum temperature rises (up to 0.5 °C decade⁻¹) was found in the 500–200 hPa range to the south of 40°N, in contrast to the cooling zone in the almost same altitude to the north of 45°N. This led to a strengthened meridional temperature gradient between 25°N and 50°N, and a weakened temperature gradient to the south of 25°N. This led to a tug-of-war effect, where the temperature changes in most parts of troposphere acted to speed the jet steam up, while the temperature changes higher than 100 hPa acted to slow it down, according to the thermal wind theory (Seidel et al. [66]). This roughly corroborated the results revealed in Fig. 4 and Fig. 5 and could be attributed to global warming (Vallis et al. [50]). The increasing trends of wind over the region between 25°N and 50°N were likely due to the strengthening and the poleward shift of the subtropical jet stream, which was in association with Hadley circulation intensification under global warming (Lorenz and DeWeaver [40]; Seidel et al. [69]). Our observational findings are well in line with the model simulated response to global warming, indicating that the impact of global warming on East Asian circulation during winter may have already emerged. For instance, with the planetary-scale shift of westerly winds, there was an increase (decrease) in westerly mass flux on the northern (southern) side of the Tibetan Plateau, which served to strengthen (weaken) the northern (southern) branch of the westerly jet over East Asia (He [71]).

4 CONCLUDING REMARKS

The climatological and long-term trend of wintertime wind speed from surface to upper level during the period from 1979 to 2021 across China were analyzed in this study based on the long-term radiosonde measurements. At pressure levels of 700, 500, and 400 hPa, the wind speed exhibited a spatial pattern of “East High–West Low”. In the upper troposphere, such as 300, 200, and 100 hPa pressure levels, the wind speed exhibited pronounced meridional variation with highest values found around 25–35°N. In the vertical direction, the wind speed increased monotonically from lower troposphere up to the altitudes of the polar front jet stream. Moreover, westerly winds dominated over most parts of China between 20°N and 50°N at the pressure levels from 700 hPa to 100 hPa.

The long term trend of wind speed at the near-surface and upper air exhibited a quite different pattern. Robust trend analyses on the near-surface wind speed revealed a significant reversal occurred in 2004, turning from stilling wind to rising wind in the subperiod of 2004–2021. The
wind recovery after 2004 could be most likely due to the joint impact of increasing sensible heat flux, reduced roughness length and decreased AOD. Meanwhile, no pronounced shift or change was found for the directional variation in China for both subperiods, except for that the latter subperiod witnessed a larger magnitude than the earlier subperiod in Southwest China.

The upper-air wind speed exhibited rising trends, particularly above the 500 hPa pressure level. The wintertime wind speed at pressure levels ranging from 500 hPa to 100 hPa showed upward trends in the latitudinal zone between 25°C and 50°C, whereas downward trends were observed south of 25°C, which could be most likely induced by the meridional variation of air temperature at the same altitude zones. Overall, the contrasting trend has been revealed for both wind speed at the near-surface and upper atmosphere. Nevertheless, the wind speed trend above 100 hPa has not been investigated here, due to the large uncertainties in the radiosonde therein. Besides, the variation in the trends of wind speed is considerably affected by a variety of complex factors, which can be roughly classified into natural variability and anthropogenic activities. Besides, the wind direction in the lower troposphere such as 925 and 850 hPa showed much higher variance, compared with other higher pressure levels.

In the present study, we only did some preliminary statistical analysis. In the future, sensitivity experiments by model simulations are warranted to better unravel the mechanisms, which will be done in a separate study.

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REFERENCES


[39] SHERWOOD S C, NISHANT N. Atmospheric changes through 2012 as shown by iteratively homogenized radiosonde temperature and wind data (IUKv2) [J]. Environmental Research Letters, 2015, 10, 054007.


