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Impact of Urbanization on Near-surface Wind Speed in Heilongjiang Province

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On the basis of the monthly wind speed data and land use data from 81 meteorological observation stations in Heilongjiang Province from 1971 to 2020, we used the urban and rural comparison method to quantitatively analyze the impact of urbanization on near-surface wind speed. The results showed the following: (1) The annual mean wind speed in Heilongjiang Province showed a decreasing trend with a rate of change of −0.23 m/s per 10 annum (10 a) in the most recent 50 years. The annual mean wind speed and its change rate showed a “high–low–high” spatial distribution from north to south. (2) The annual mean wind speed at the urban stations in Heilongjiang Province was slightly higher than that at rural stations, with a difference of 0.11 m/s. The annual mean wind speed at urban stations and rural stations decreased at a rate of −0.243 and −0.215 (m/s)/10 a, respectively. (3) The impact of urbanization on the decreasing trend of annual mean wind speed in Heilongjiang Province was −0.03 (m/s)/10 a, indicating that urbanization was responsible for 22.6% of the overall decrease.

1. Introduction

As a representative feature of atmospheric circulation, wind not only reflects the characteristics of atmospheric circulation but also controls the transfer of water, energy, and momentum between the surface and the lower atmosphere.(1) Changes in wind speed have a crucial impact on local climate, human health,(2) atmospheric environment, wind energy utilization, and many other aspects of urban life.(3) With the acceleration of urbanization, climatic conditions in urban and rural areas have changed, and changes in wind speed are significantly affected by urbanization. Therefore, it is important to explore and study the impact of urbanization on changes in wind speed.

Based on meteorological measurements, numerous studies in North America,(4,5) and Europe(6,7) as well as other regions have revealed a noticeable decrease in surface wind speeds

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(SWSs); the reported rates of decrease of SWSs have been between −0.16 and −0.07 m/s per decade.(8) Some scholars have conducted research on the changes in wind speed in China and have determined that the wind speed has decreased significantly in China,(9,10) in northwest China,(11) on the East China Plain (ECP),(12) in Northeast China,(13) and on the Qinghai–Tibet Plateau.(14) Scholars have also studied what factors affect surface wind speed. In addition to large-scale circulation,(15) the update of wind measuring instruments,(16) the relocation of observation stations, and changes in the surrounding environment of observation sites,(17) urbanization is an important factor leading to the decrease in wind speed. Using data from meteorological observations, ERA5 data, land use data, advanced land observing satellite phased array L-band synthetic aperture radar (ALOS PALSAR) data, night light index, and other data, researchers have studied the impact of urbanization on surface wind speed based on urban/rural wind speed ratios, observation-minus-reanalysis (OMR) methods, and other techniques, and the conclusions have been basically the same. Liu *et al.* calculated spatial morphological parameters such as building height, building density (BD), building standard deviation, floor area ratio (FAR), frontal area index (FAI), length of roughness, sky view factor (SVF), and fractal dimensions and pointed out that urbanization can reduce the wind speed in urban areas at different times by 3 to 27%.(18) Zhang *et al.* analyzed the effect of urbanization expansion in the Beijing–Tianjin–Hebei region on wind speed and found that the average north wind velocity in the southern cities, except seaside cities, has declined significantly, a trend that is caused by the rapid expansion of built-up areas in this region.(1) Wu *et al.* quantitatively estimated the effect of the Land-Use and Land-Cover Change (LUCC) on the SWS over the ECP during the period from 1980 to 2011. The increase in the drag coefficient induced by the LUCC may account for the long-term decrease in the SWS. (19) Li *et al.* used the Defense Meteorological Satellite Program/operational line scan system (DMSP/OLS) nighttime light data from 1992 to 2013 to analyze the effects of urbanization on surface wind change. The observed surface wind decline is mainly attributed to underlying surface changes in the stations' observational areas, which were primarily induced by the urbanization in East China, and the faster the urbanization, the more the wind speed weakens.(12) Xia *et al.* investigated the effects of urbanization on SWS in the Guangdong–Hong Kong–Macao Greater Bay Area (GBA) megalopolis, particularly in Zhuhai, and concluded that the increase in surface roughness was the main contributor to the decrease in SWS and, indeed, it may account for as much as 75.5% of the decrease.(3) Peng *et al.* used data on the changing three-dimensional urban morphology of Kowloon during the period from 1964 to 2010, and calculated that the overall mean wind speed in the urban area gradually decreased due to the continuous urban development and elevation in building heights.(20) Wang *et al.* also concluded that the development of urbanization was one of the reasons for the decrease in wind speed and wind energy resources in recent years.(21) However, most of these studies focused on qualitative analysis, whereas quantitative analysis was part of relatively few evaluations. In addition, the study areas were mainly concentrated in the comprehensive economic zones in China, which are experiencing rapid urban expansion, such as the eastern coastal region, the Beijing–Tianjin–Hebei region, and the GBA. It is not clear whether urbanization has an impact on wind speed changes in northeast China.

Heilongjiang Province is rich in wind energy resources and ranks in the forefront of all provinces in China in that regard. According to the “Heilongjiang Province New and Renewable Energy Industry Development Plan (2010–2020)”, the province was predicted to reach 7.2 million kW by 2020 and the actual wind energy generation exceeds 1004 million kW, thereby accounting for 30% of the predicted power generation in the province.(22) After the reform and opening-up policy of China started in 1978, the urban area of Heilongjiang Province continued to expand, and the increase in urban population and building area led to a decrease in wind speed, which further affected the development and utilization of wind energy resources. However, it is unclear how much urbanization affected the wind speed in the province. Therefore, using the surface wind speed data from 81 meteorological observation stations in Heilongjiang Province from 1971 to 2020, we compared and analyzed the trend of the annual average wind speed at urban and rural stations and quantitatively evaluated the effect of urbanization in Heilongjiang Province on the annual average wind speed. By providing a theoretical basis for a comprehensive understanding of the characteristics of changes in wind speed in typical areas in northern China, the results of this study provide scientific guidance for wind energy resource assessment and urban development planning in Heilongjiang Province.

2. Materials and Methods

2.1 Data sources

2.1.1 Meteorological observations

The monthly 10-meter wind speed data used in this paper were provided by the Climatic Data Center of Heilongjiang Province. The Heilongjiang Meteorological Observatory Station was first established in 1951, and 83 national base meteorological observation stations and general meteorological observation stations have been established successively since then. According to the requirements of data integrity, the number of stations required for analysis, and whether the observation stations were relocated, a group of 81 meteorological observation stations with continuous and complete observation data from 1971 to 2020 in Heilongjiang Province were selected (Fig. 1). Records show that, in 1971, Heilongjiang Province changed its wind measuring instrument from the Wild type to EL electric wind anemometers, and, in 2004, the EL electric wind anemometers were replaced with DYYZ II automatic weather stations. The wind speed data from a DYYZ II automatic weather station is based on the EC9-1 wind sensor. The EC9-1 wind sensor collected data on wind direction and wind speed using an outdoor wind speed sensor and displays the wind direction and wind speed data transmitted by the sensor indoors. The wind speed data obtained by the wind speed sensor is applicable to islands, ports, high-rise buildings, bridges, large industrial and mining enterprises, forest fire prevention areas, and other departments. The system error caused by different principles of sensing wind cannot be ignored. However, statistical tests found no obvious breakpoint in the differences between each station and the reference sequence, so no homogenization correction was made in this analysis.

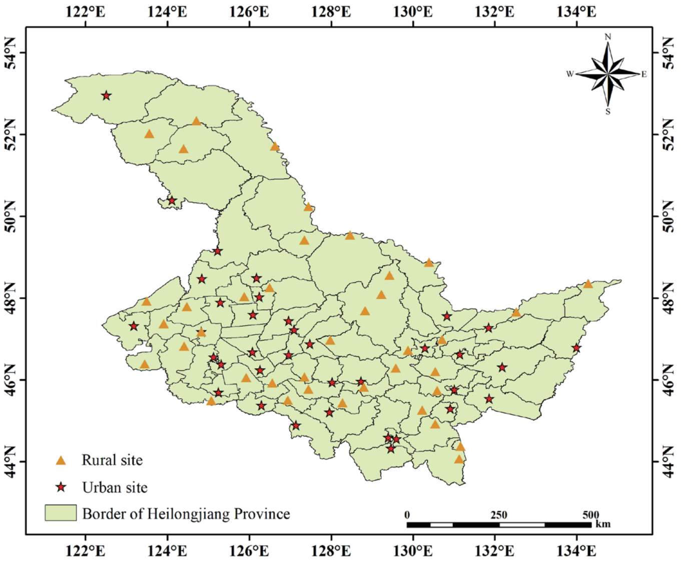


Fig. 1. (Color online) Distribution of meteorological stations in Heilongjiang Province, China.

2.1.2 China land-cover dataset (CLCD)

The annual CLCD is produced by Wuhan University, and it was the first fine-resolution annual land–cover dataset for China produced using observational images. The images contain land cover and its dynamic at a resolution of 30 m from 1985 to 2020.(23) This dataset was extracted from more than 300000 Landsat images on the Google Earth Engine (GEE) and contained nine land-cover types, including cropland, forest, shrub, grassland, water, snow or ice, barren, impervious, and wetland; the datasets are available free of charge at https://zenodo.org (accessed on 5 January 2022). A further assessment based on 5131 third-party test samples showed that the overall accuracy of CLCD (79.31%) outperformed those of MCD12Q1, ESACCI_LC, FROM_GLC, and GlobeLand30. In this study, we selected the proportion of impervious areas as a means of distinguishing the urban and rural sites.

2.2 Research methods

2.2.1 Classification of urban and rural stations

Currently, in both domestic and foreign studies on the impact of urbanization on wind speed, the classification criteria of urban and rural stations are established on the basis of the location of the station,(24) the population of the township where the station is located,(25) the night light index,(26) and the proportion of the urban area.(27) Among these, as the type and physical characteristics of the underlying surface of the stations and their surrounding areas are considered, the classification method of urban and rural stations by the proportion of urban area has been widely used.

A 5 km^2 circular buffer was generated with the meteorological stations as the center. First, the land use and cover data were superimposed every 5 years and extracted by a vector buffer, and an area tabulation tool was used to calculate the area and the proportion of each land type. Stations with more than 50% impervious surface area in the 5 km^2 buffer zone over a 5-year period were judged to be urban stations; otherwise, the stations are identified as rural. After quality control, Heilongjiang Province had a total of 38 urban stations and 43 rural stations (Fig. 1).

2.2.2 Trend analysis method

A univariate linear regression equation of the surface wind speed variable (y) and the corresponding time (x) was established:

$$y = ax + b \quad (i = 1, 2, ..., n), \tag{1}$$

where a is the linear regression coefficient indicating the rate of change in the surface wind speed. A positive or negative value of a indicates that the surface wind speed is increasing or decreasing over time, respectively.

2.2.3 Mann–Kendall (MK) test

The MK test is a technique for diagnosing and predicting climate. The non-parametric MK test is commonly employed to detect trends in climate and other data, with little interference from abnormal values. In addition to its simple and convenient calculation, another advantage of the MK test is that the samples are not required to follow a certain distribution. Using the MK test, we are able to know the exact time of an abrupt change.

The MK test is performed using the following equation, where n and x are the number of samples and the time sequence, respectively:

$$S_k = \sum_{i=1}^{k} r_i \quad (k = 2, 3 ..., n), \tag{2}$$

where

$$r_i = \begin{cases} +1 & \text{if } x_i > x_j \\ 0 & \text{if } x_i \le x_j \end{cases} \quad (j=1,2,...,i). \tag{3}$$

The order list S_k is the number of values that are greater at time i than at time j. The statistics of the MK test are defined using the following equation when the time series is assumed to be randomly independent.

$$UF_k = \frac{\left[S_k - E(S_k)\right]}{\sqrt{Var(S_k)}} \quad (k = 1,2,...,n) \tag{4}$$

Here, $UF_1 = 0$, $E(S_k)$, and $Var(S_k)$ are the average value and variance of S_k, respectively. If x_1, x_2, …, x_n are independent individuals with the same continuous distribution, $E(S_k)$ and $Var(S_k)$ are obtained using

$$E(S_k) = \frac{n(n+1)}{4}, \tag{5}$$

$$Var(S_k) = \frac{n(n-1)(2n+5)}{72}, \tag{6}$$

where UF_i is a standard normal distribution, which is calculated at time sequence x of x_1, x_2, …, x_n. Given a significance level α, we can examine the normal distribution table. If $UF_i > U_\alpha$, there exists an obvious change in the sequence. The above process is repeated for the reverse time sequence α of x_n, x_{n-1}, …, x_1 with the conditions of $UB_k = -UF_k$, $k = n$, n–1…1, $UB_1 = 0$.

Positive values of *UF* or *UB* indicate an increasing trend, and vice versa. If *UF* or *UB* is beyond the critical curve, then an obvious trend exists. The range beyond the critical curve stands for the period with an abrupt change. If *UB* and *UF* have a point of intersection with the critical curve, the year corresponding to the point is the start year of the abrupt change.

2.2.4 Variance analysis

One-way ANOVA is used to study whether different levels of a control variable have a significant impact on the observed variables. In this study, we compared whether there is a significant difference in wind speed changes between urban stations and rural stations and used an F-test to determine whether the difference is significant. The equation is

$$F = \frac{\frac{SS_A}{r-1}}{\frac{SS_E}{n-1}}, \tag{7}$$

where SS_A is the sum of squared deviations between groups. The term SS_E is the sum of squared deviations within the group. If $F > F\alpha/2\ (r-1,\ n-r)$, the difference is significant; otherwise, there is no significant difference.

2.2.5 Effect and contribution of urbanization

2.2.5.1 Effect of urbanization

This term refers to the change in the linear trend of the near-surface wind speed at stations around a city caused by factors such as urban heat island effect strengthening; it is expressed by ΔX_{ur}. The term X_u is the changing trend of the near-surface wind speed at urban stations, and X_r is the value at rural stations. The urbanization effect can be expressed as

$$\Delta X_{ur} = X_u - X_r. \tag{8}$$

When $\Delta X_{ur} > 0$, the urbanization effect increases the near-surface wind speed. When $\Delta X_{ur} = 0$, it means that urbanization has no impact. When $\Delta X_{ur} < 0$, it means that the urbanization effect decreases the surface wind speed. The results of this method are equivalent to the linear trend of the urban-rural difference series of surface wind speed, the value of which is equivalent to ΔX_{ur}.

2.2.5.2 Contribution of urbanization

This term refers to the percent of the contribution to the trend change of near-surface wind speed at stations near a city due to urbanization, which is the ratio of urbanization effect to the change in the trend of near-surface wind speed at stations near a city. It can be expressed as

$$E_u = \Delta X_{ur} / |X_u| \times 100\% = (X_u - X_r) / |X_u| \times 100\%. \tag{9}$$

For wind speed, a positive value of urbanization contribution (E_u) indicates that urbanization increases wind speed, and a negative value indicates that urbanization decreases wind speed.

The average trend in wind speed changes for all urban and rural stations from 1971 to 2020 was calculated, and the effect of urbanization was calculated by subtracting the two [Eq. (8)]. The contribution of urbanization was calculated by dividing the result of the urbanization effect by the mean of the change in the trend of wind speed at urban stations [Eq. (9)].

3. Results

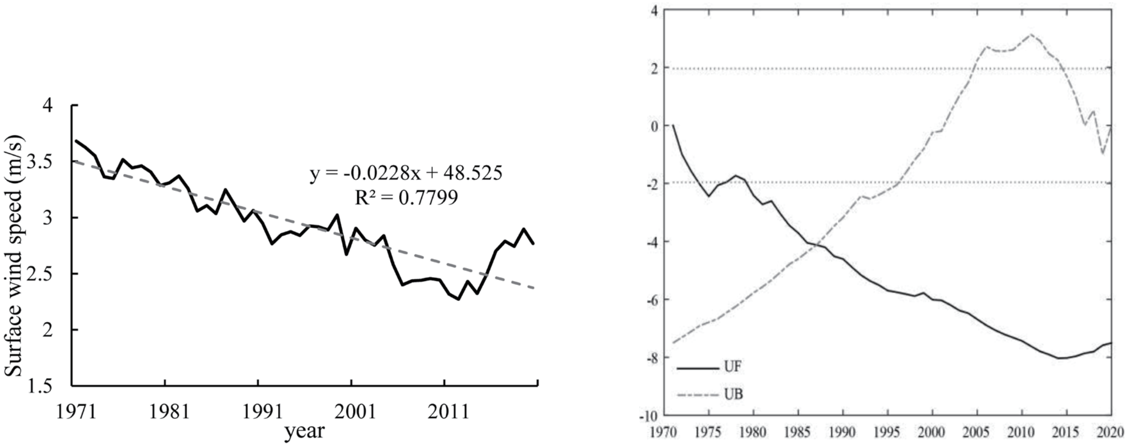
3.1 Characteristics of the spatial-temporal variation of 10-m-height wind speed in Heilongjiang Province from 1971 to 2020

The near-surface wind speed evaluated herein is the 10-m-height monthly wind speed provided by the Heilongjiang Climatic Data Center. The annual average 10-m-height monthly wind speed throughout the year was calculated and defined as the annual average near-surface wind speed in Heilongjiang Province.

The mean annual wind speed in Heilongjiang Province from 1971 to 2020 was 2.93 m/s. The maximum mean annual wind speed was 3.68 m/s in 1971 and the minimum was 2.27 m/s in

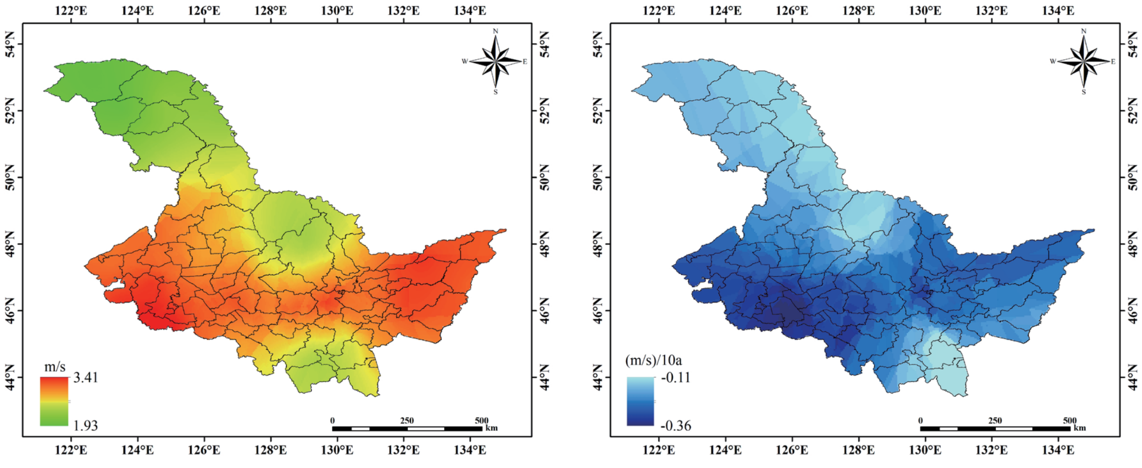
2012, with the coefficient of variation of 12.86%. The mean annual wind speed in Heilongjiang Province during the same period showed a highly significant downward trend with a change rate of −0.23 m/s per 10 annum (10 a), during which, 1.15 m/s was the mean annual wind speed decrease [Fig. 2(a)]. MK tests showed that the mean annual wind speed in Heilongjiang Province changed abruptly in 1987, from a relatively strong wind speed to a relatively weak wind speed [Fig. 2(b)]. On the one hand, the reason for the weakening of the wind speed in Heilongjiang Province is that, under the influence of climate warming, the temperature rise in high latitudes has changed the large-scale circulation field,(28) resulting in the weakening of the Siberian High in the cold season,(29) a reduction in the frequency of strong winds,(30) and a reduction in the mean wind speed near the surface. On the other hand, with the acceleration of urbanization and the increase in the number of urban buildings, the change in the surface roughness has a certain blocking effect on the wind, reducing the wind speed near the surface.

From 1971 to 2020, the mean annual wind speed in Heilongjiang Province showed obvious regional differences. From south to north, it increased first and then decreased, and the value range was 1.93–3.41 m/s, with a difference of 1.48 m/s [Fig. 3(a)]. The area with high values was mainly distributed in the Songnen and Sanjiang Plains, and the mean wind speed in Tonghe county was the highest. The low-value areas were mainly located in the small and big Xingan Mountains and the southern Zhangguangcai Mountains, and the mean wind speed in the Huzhong district was the smallest. The distribution of high and low values is related to topography and surface roughness. The plain area has flat and open terrain, small underlying surface roughness, and relatively high wind speed. The spatial distribution of annual mean wind speed in Heilongjiang Province during the period of the study is shown in Fig. 3(b). The annual mean wind speed in Heilongjiang Province during that time showed a downward trend with a decreasing range of −0.11 to −0.36 (m/s)/10 a. The high- and low-value areas of the annual mean wind speed reduction rate were consistent with the high- and low-value areas of the mean distribution. A significant decreasing trend ($p < 0.05$) was shown in 87.66% of the sites.



(a) (b)

Fig. 2. (a) Mean annual wind speed changes and (b) results of MK tests in Heilongjiang Province from 1971 to 2020.



(a) (b)

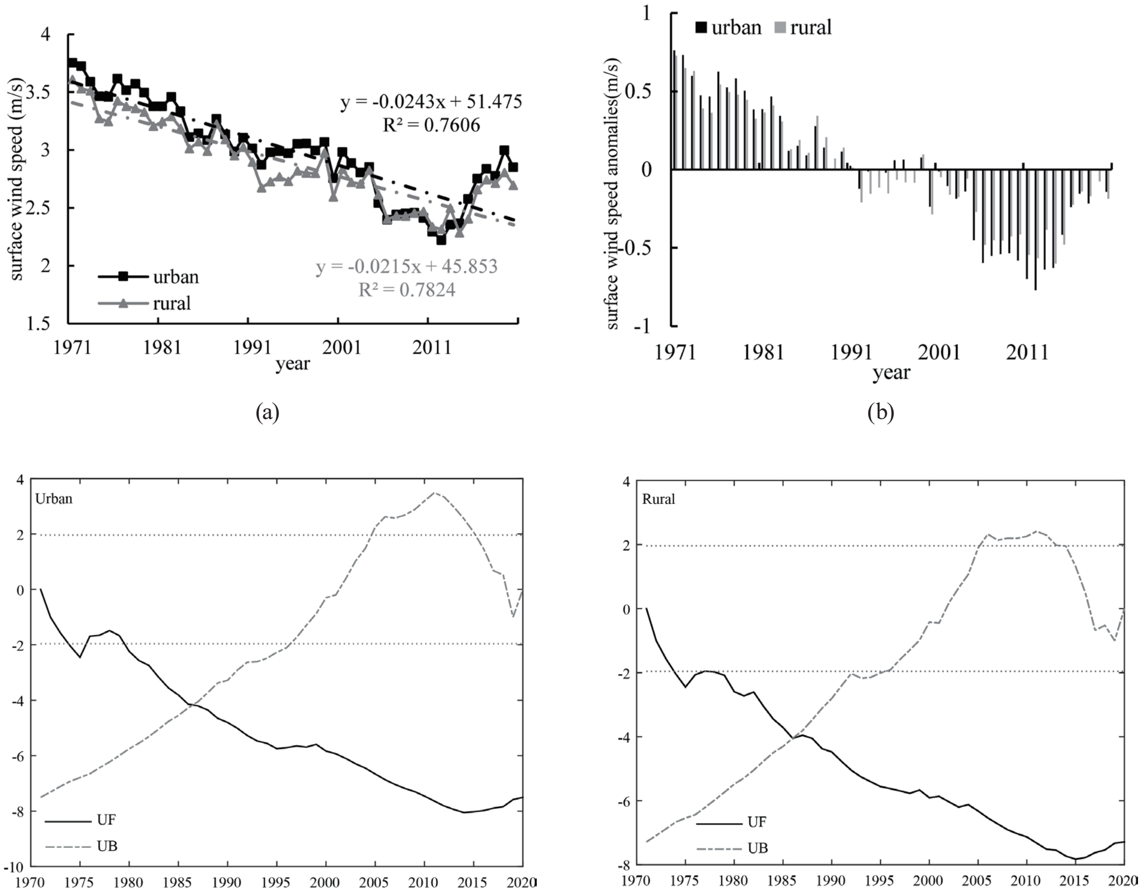
Fig. 3. (Color online) (a) Spatial distribution and (b) variations of mean annual wind speed in Heilongjiang Province from 1971 to 2020.

3.2 Wind speed variation characteristics of urban and rural stations in Heilongjiang Province from 1971 to 2020

The annual mean wind speed at urban and rural stations in Heilongjiang Province from 1971 to 2020 was 2.99 m/s and 2.88 m/s, as shown in Figs. 4(a) and 4(b), respectively. The wind speed at urban and rural stations showed a very significant decreasing trend, with change rates of −0.243 and −0.215 (m/s)/10 a, respectively. From 1971 to 2020, the annual mean wind speed at urban and rural stations decreased by 1.215 and 1.075 m/s, respectively, although the annual mean wind speed at urban stations was higher than that at rural stations. From 1971 to 2020, the wind speed of both urban and rural stations decreased, and the mean wind speed at urban stations decreased by 0.14 m/s more than that at rural stations. The results of MK mutations showed that both urban and rural stations mutated in 1987 [Figs. 4(c) and 4(d)]. According to the anomaly diagram for annual mean wind speed, the annual mean wind speed in Heilongjiang Province changed from positive to negative in the late 1980s, indicating that the annual mean wind speed changed from relatively strong to relatively weak.

Figure 5 shows the spatial distribution and variation of the annual mean wind speed of urban and rural stations in Heilongjiang Province from 1971 to 2020. There are obvious differences in the spatial distribution of annual average wind speed between urban and rural stations. The annual average wind speed of urban and rural stations in the western region of Heilongjiang Province was significantly higher than that in the eastern region. The annual mean wind speed at urban stations in Heilongjiang Province ranged from 1.74 to 3.77 m/s, whereas that at rural stations ranged from 1.56 to 3.76 m/s. The annual average wind speed at urban stations was significantly higher than that at rural stations, with an average difference of 0.11 m/s.

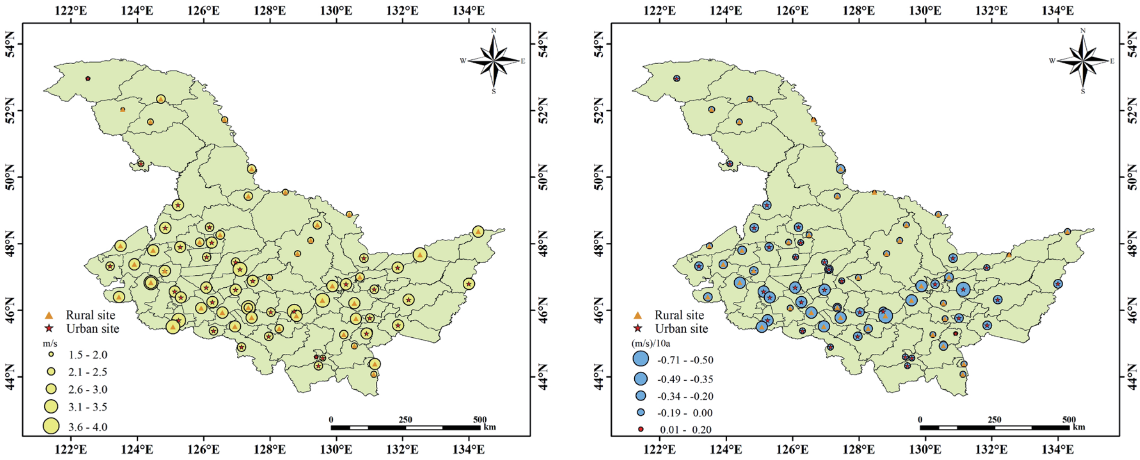
From the perspective of spatial variation, the annual mean wind speed at urban and rural stations increased first and then decreased from north to south but overall showed a decreasing trend. The annual average wind speed at urban stations was significantly higher than that of



(a) (b)

(c) (d)

Fig. 4. (a) Temporal variation, (b) anomalies, and results of MK test of surface wind speed at (c) urban and (d) rural stations in Heilongjiang Province from 1971 to 2020.



(a) (b)

Fig. 5. (Color online) (a) Spatial distribution and (b) variation of mean annual wind speed at urban and rural stations in Heilongjiang Province from 1971 to 2020.

rural stations, with a difference of 0.03 (m/s)/10 a. In 85.36% of urban stations, the annual average wind speed showed a significant decreasing trend, and the high-value areas were mainly located in the Beilin, Anda, and Shuangyashan areas, whereas 78.26% of the rural stations showed a significant trend of decreasing annual average wind speed; the high-value areas were mainly distributed in the areas of Fangzheng, Jixian, and Wangkui.

3.3 Urbanization effect

Further analysis of the annual mean wind speed and its rate of change at urban and rural stations showed that there were no significant differences in the annual mean wind speed ($p > 0.05$), but there were significant differences in the trend of annual mean wind speed changes between urban and rural stations ($p < 0.05$). Under the same background of atmospheric circulation, the trend change coefficient for the difference between urban and rural stations can be considered as an indicator of the urbanization effect.

During the years from 1971 to 2020, the annual mean wind speed difference at urban and rural stations in Heilongjiang Province was positive, indicating that the annual mean wind speed was higher at urban stations than at rural stations (Fig. 6). Before 2004, the annual mean wind speed difference between urban and rural areas was positive; it began to turn negative from 2005 to 2014 and reached its lowest value (−0.14 m/s) in 2013. It then turned positive after 2014, indicating that the annual mean wind speed difference between urban and rural stations in Heilongjiang Province had a "positive-negative-positive" change over 50 years. From 1971 to 2020, the difference in annual mean wind speed between urban and rural stations showed a highly significant decreasing trend, with a change rate of −0.03 (m/s)/10 a, indicating that urbanization in Heilongjiang Province resulted in the weakening of near-surface wind speeds. The contribution rate of urbanization accounted for 22.6% of this value, indicating that the weakening of annual average wind speed in Heilongjiang Province is partly caused by urbanization.

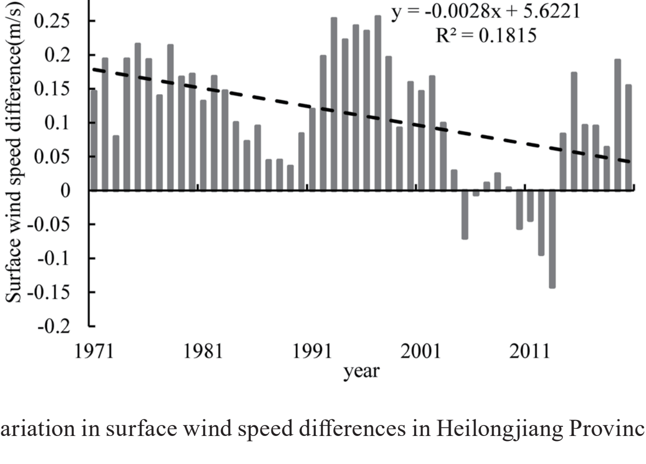


Fig. 6. Temporal variation in surface wind speed differences in Heilongjiang Province from 1971 to 2020.

4. Discussion

Currently, much research is being carried out on wind speed variations in China, covering the entire country, including northern China, the northern wind erosion area, Liaoning Province, Inner Mongolia, the northwestern area, the Xinjiang region, the Qinghai–Tibet Plateau region, and the Guangdong–Hong Kong–Macao Greater Bay area. The results showed that the near-surface wind speed in some regions shows a decreasing trend with a rate between 0.065–0.53 (m/s)/10 a (Table 1). The results of this study show that the annual mean wind speed in Heilongjiang Province is experiencing a highly significantly decreasing trend at a speed of −0.23 (m/s)/10 a. The rate of variation is within the range of variance of the national average annual wind speed, which provides evidence for the authenticity of the results of this study. Yu *et al.* studied the change in annual average wind speed in Heilongjiang Province from 1971 to 2004 and showed that the annual average wind speed showed a weakening trend with a change rate of −0.26 (m/s)/10 a.(22) The results reported herein are slightly smaller than those of Yu *et al.* The main reason is that the time scale of this paper is from 1971 to 2020, which is a longer time span than that studied by Yu *et al.* Moreover, the annual average wind speed shows an upward trend after 2010, which reduces the overall change rate.

The results show that urbanization is one of the main factors affecting the reduction of annual average wind speed in Heilongjiang Province; it is responsible for 22.6% of the total amount of the reduction. Existing studies on the impact of urbanization on wind speed show that urbanization is an important factor affecting regional near-surface wind speed variation. For example, Liu *et al.* pointed out that urbanization had a 25% impact on the reduction of mean surface wind speed in Hebei Province from 1975 to 2004.(43) Tao *et al.* analyzed the impact of urbanization on wind speed in Anhui Province, and the results showed that the contribution of urbanization to the reduction of annual mean wind speed was 40% from 1981 to 2010.(27) The contribution rate of urbanization to the annual average wind speed in Heilongjiang Province is slightly smaller than that in other regions, which may be related to the speed of the development

Table 1
Recent studies of surface wind speed variability in China during the past decades.

Reference	Study area	Time	Rate [(m/s)/10 a]
Wang *et al.*(31)	China	1979–2014	−0.142
Han *et al.*(32)	Wind erosion region of northern China	1971–2015	−0.17
Li *et al.*(33)	Beijing	1993–2011	−0.19
Fan *et al.*(34)	Liaoning Province	1964–2019	−0.13
Wang *et al.*(21)	Shenyang	1971–2020	−0.18
Xie *et al.*(35)	Jilin Province	1975–2012	−0.21
Xing *et al.*(36)	Inner Mongolia	1961–2018	−0.21
Fu *et al.*(37)	Qilian Mountains	1960–2017	−0.07
Shi *et al.*(38)	Longdong of Gansu Province	1960–2014	−0.09
Xu *et al.*(49)	Yili Area	1961–2016	−1.71
Li *et al.*(40)	Altay Prefecture	1962–2016	−0.211
Li *et al.*(41)	Yangtze River Basin	1960–2015	−0.065
Tang *et al.*(42)	Qinghai-Tibet Plateau	1970–2020	−0.1
Xia *et al.*(3)	Guangdong-Hongkong-Macao Greater Bay Area	2006–2019	−0.53
Peng *et al.*(20)	Hongkong	1996–2017	−0.16

of urbanization in Heilongjiang Province, and, to a certain extent, it may also be related to different research areas, research periods, and different methods of distinguishing urban and rural stations.

Although previous studies have shown a weakening trend in near-surface wind speed at global or regional scales, this analysis found that the near-surface wind speed has shown an increasing trend since the 2000s. On the global scale, Dunn *et al.* pointed out that the global land near-surface wind speed showed a weak but strengthening trend after 2000, mainly due to the moderate wind speeds (> 3 m/s).(44) In terms of regional scope, Kim and Paik pointed out that the near-surface wind speed in South Korea has been increasing since 2003, at a rate of 0.08 (m/s)/10a.(45) Zeng *et al.* found that the average wind speed in the United States has increased rapidly since 2010, and the increasing rate of wind speed from 2010 to 2017 was 3 times that of the decreasing rate from 1978 to 2010.(46) Liu *et al.* used the surface climate data daily data set (version 3.0) of China to analyze the recovery of wind speeds since 2012 and pointed out that the wind speed in China has significantly increased at a rate of 0.223 (m/s)/10 a since 2012.(47) Xing *et al.* analyzed the change in wind speed in Inner Mongolia from 1961 to 2018 and reported that the wind speed in Inner Mongolia picked up after 2010.(36) Five kinds of wind speed data observed and reanalyzed by Wu *et al.* from 1961 to 2020 were used to analyze the variations in surface wind speed over the Qinghai–Tibet Plateau. CN05.1, station data, and National Centers for Environmental Prediction (NCEP) annual mean wind speed all showed a significant increasing trend from 2002 to 2020; (48) the rates were 0.12, 0.11, and 0.16 (m/s)/10 a respectively. The results in this study lead to the same conclusions as the previous studies, showing that the annual average wind speed in Heilongjiang Province has been increasing since 2012, and the rate of change is 0.76 (m/s)/10 a. Although previous studies have shown that the global wind speed and some regional wind speeds have recovered since 2000, analysis of the reasons for the wind speed enhancement has rarely been offered. A few scholars have pointed out that the increase in wind speed is potentially a result of changing atmospheric circulation.(46) For example, the West Pacific Index (WPI) shows a more negative pattern when wind speed recovers.(49) Negative phases of WPI mean that more Western North Pacific tropical cyclones move into southern China and bring wind.(50) The recovery of Southern Oscillation Index (SOI) positive phases since 2000 has been followed by decreases in wind speed. The reasons for the increase in wind speed in Heilongjiang Province since 2012 have yet to be studied.

The characteristic variations in annual mean temperature and their correlation with annual mean wind speed in Heilongjiang Province were analyzed. The results showed that the annual mean temperature increased from 1971 to 2020 at a rate of 0.48℃/10 a. An abrupt change occurred in 1987, which was consistent with the abrupt change in wind speed. The correlation coefficient between annual mean temperature and annual mean wind speed was −0.523 ($p < 0.01$), which is a significant negative correlation; the annual mean temperature increased by 1 ℃ and the annual mean wind speed decreased by 0.523 m/s. The correlation between air temperature and wind speed at stations in Heilongjiang Province was further evaluated. Most (96.3%) of the stations showed a negative correlation, and 70.37% of the stations showed a significant negative correlation. These results show that the decrease in annual mean wind speed in Heilongjiang Province may be affected by the increase in the annual mean temperature.

5. Conclusions

On the basis of observations of wind speed at 81 meteorological stations of Heilongjiang Province during 1971–2020 combined with land use data, and by comparing the urban and rural stations, the spatial-temporal variations of annual mean wind speed of the Heilongjiang Province at urban and rural stations were analyzed to identify the effect of urbanization on the surface wind speed. The conclusions are as follows:

(1) During the years from 1971 to 2020, the annual mean wind speed was 2.93 m/s. Over this 50-year period, the annual mean wind speed in Heilongjiang Province showed a significant decreasing trend with a change rate of −0.23 (m/s)/10 a, and the wind speed decreased by 1.15 m/s. The annual mean wind speed changed abruptly in the mid-1980s.

(2) Obvious spatial differences are evident in the annual mean wind speed in Heilongjiang Province, which were primarily manifested as high annual mean wind speed in the Songnen and Sanjiang Plains and low wind speed in Xingan and Zhangguangcai Mountains. From 1971 to 2020, the annual mean wind speed at 81 stations in Heilongjiang Province decreased significantly, and the rate of change ranged from −0.11 to −0.36 (m/s)/10 a.

(3) The annual mean wind speed of urban stations in Heilongjiang Province was higher than that of rural stations, and the difference between them was 0.11 m/s. From 1971 to 2020, the annual mean wind speed of urban and rural stations showed a significant decreasing trend, and the rates of change were −0.243 and −0.215(m/s)/10 a, respectively. The annual mean wind speed of both urban and rural stations changed from relatively strong to relatively weak wind speeds in 1987.

(4) From 1971 to 2020, the difference in annual mean wind speed between urban and rural stations showed a very significant decreasing trend, with a change rate of −0.03 (m/s)/10 a, indicating that urbanization resulted in the weakening of near-surface wind speeds. The contribution of urbanization to the amount of overall change was 22.6%, indicating that the weakening of annual mean wind speed in Heilongjiang Province is partly caused by urbanization.

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