Spatiotemporal characteristics of wind energy resources from 1960 to 2016 over China

FENG Yucheng, QUE Linjing and FENG Jinming

*School of Information Engineering, China University of Geosciences in Beijing, Beijing, China; "Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China; "Heilongjiang Province Meteorological Service Center, Heilongjiang Province Meteorological Bureau, Harbin, China

ABSTRACT

In the paper, daily near-surface wind speed data from 462 stations are used to study the spatiotemporal characteristics of the annual and seasonal mean wind speed (MWS) and effective wind energy density (EWED) from 1960 to 2016, through the methods of kriging interpolation, least-squares, correlation coefficient testing, and empirical orthogonal function (EOF) analysis. The results show that the annual MWS is larger than 3 m s\(^{-1}\) and the EWED is larger than 75 W m\(^{-2}\) in northern China and parts of coastal areas. However, the MWS and EWED values in southern China are all smaller than in northern China. Over the past 50 years, the annual and seasonal MWS in China has shown a significant decreasing trend, with the largest rate of decline in spring for northern China and winter for coastal areas. The annual MWS in some areas of Guangdong has an increasing trend, but it shows little change in southwestern China, South China, and west of Central China. Where the MWS is high, the rate of decline is also high. The main spatial distributions of the annual MWS and the annual EWED show high consistency, with a decreasing trend year by year. The decreasing trend of wind speed and wind energy resources in China is mainly related to global warming and land use/cover change.

1. Introduction

Wind energy is a sustainable, ubiquitous, and innumerable pollution-free renewable resource. By 2050, as the population and the economies of each country grow, the demand for wind energy will double or triple (Nelson and Starcher 2009). China has a vast territory and abundant wind energy resources. The total storage capacity is 32.26 × 10\(^{11}\) W, and the actual exploitable amount is 2.53 × 10\(^{11}\) W (Xue et al. 2001). To fully utilize and develop wind energy resources, it is necessary to conduct in-depth research on the spatiotemporal characteristics of wind speed and wind energy resources. Small changes in wind speed will have a greater impact on wind energy resources, so the analysis of wind speed changes is the prerequisite and important basis for understanding wind energy resources and changes. Research on wind energy for China has involved the regionalization of wind energy (Zhu and Xue 1983), assessment of the value of wind energy resources (Wu and Fang 2009), assessment of the storage of wind energy resources (Zhu and Xue 1983), analysis of the wind speed and wind energy resources for an area (Huang et al. 2007; Wang and Zhang 2006), and so on. Regarding the spatiotemporal characteristics of wind speed, Li, Wang, and Tang (2007) showed that North China, Northeast China, and eastern coastal areas are rich in wind energy resources, based on analyzing a dataset consisting of 186 stations from 1960 to 1999. Liao, Liu, and Li (2008) analyzed wind speed data of 395 stations for the period 1991–2000 and found that the areas rich in wind energy resources are northern...
Xinjiang, most parts of Northeast China, coastal areas, and the central Tibetan Plateau. There have been many studies on wind speed and its changes in China. Liu, Qiu, and Mo (2009) analyzed the daily mean wind speed (MWS) of 104 stations on the North China Plain from 1951 to 2006 and found that the wind speed showed a decreasing trend, and the rate of change was about $-0.016 \text{ m s}^{-1} \text{ yr}^{-1}$. The decreasing trend of wind speed was most significant in winter and weakest in summer. Rong and Liang (2008) analyzed the wind speeds measured at 104 stations in North China from 1957 to 2006 and found that the northwest and southeast of North China had high wind speeds, and the low-wind-speed areas were basically northeast–southwest-oriented with a decreasing trend of wind speed. Guo, Xu, and Hu (2011) analyzed the near-surface wind speed change in 1969–2005 of 652 stations in China and its monsoon region, and the main conclusion was that the majority of stations showed significantly reduced annual and seasonal wind speed. The rate of decline in the annual MWS was $-0.018 \text{ m s}^{-1} \text{ yr}^{-1}$, and that of spring was the largest at $-0.021 \text{ m s}^{-1} \text{ yr}^{-1}$. Spatially, northern China, the Tibetan Plateau, eastern China, and southeast coastal areas had the largest rate of decline, but little change was detected for central and south-central areas. Wang et al. (2004) analyzed the changes of wind speed in China from 1954 to 2000 and showed a clear wind speed reduction in China in the past 50 years, with winter being the most obvious among the four seasons. Regionally, western Northwest China had the most obvious trend, with a rate of decline of $-1.7 \text{ m s}^{-1}/100 \text{ yr}$.

Most previous studies have been carried out on wind speed and its changes in China. Research on the effective wind energy density (EWED), meanwhile, is more scarce; plus, the data used are now quite old and the length of time used for studies was relatively short. In this study, based on the latest site-scale daily wind speed data available in China, we analyze the last 50 years of wind speed and wind energy resources distribution data and their variation. Using empirical orthogonal function (EOF) analysis, the spatiotemporal characteristics of the annual MWS and EWED are studied. At the same time, the possible causes of changes in wind speed and wind energy resources are discussed.

2. Data and methods

2.1. Source and preprocessing of data

The wind speed and wind direction are included in the observations of wind. The dataset of daily MWS at 10 m above the surface used in this study is from the National Meteorological Information Center. In order to ensure the retention of as many stations as possible, we use the data from 1960–2016, because early stations have more missing values.

The dataset used still has many missing values, however, and so it is necessary to preprocess the raw data. The stations with missing values for three consecutive days or more are eliminated. After that, there are 462 stations that meet the requirements. After preprocessing, the maximum percentage of missing data at each station is 0.32%, and the maximum percentage of missing data at all stations in the total data of that year is less than 0.52‰.

Therefore, the 10-m daily MWS at 462 stations from 1960 to 2016 in China is used in this study. When analyzing the spatiotemporal characteristics of seasonal MWS, spring is from March to May, summer is from June to August, autumn is from September to November, and winter is from December to January and February of the next year.

2.2. Methods

The ordinary kriging interpolation method is used for spatial interpolation, and all the variogram models are spherical models. EOF analysis of the normalized anomalies of the annual MWS and the annual EWED for a total of 57 years from 1960 to 2016 is carried out. First, we calculate the output of its standardized eigenvector and time series, i.e., eigenvalues are multiplied by the square-root of the eigenvalues and the time series is divided by the square-root of the eigenvalue. Then, the main spatial distribution modes of the MWS and EWED are obtained.

For wind energy, generally only wind speeds of 3–20 m s$^{-1}$ can be used by the fan of the wind turbine. Low wind speeds cannot start the fan turning, and high wind speeds can damage it. Thus, wind speeds is 3–20 m s$^{-1}$ are required, which is termed the ‘available wind speed’. The wind energy density obtained from the available wind speed is called the EWED, and the formula for calculating it is as follows:

$$W_e = \int_{v_1}^{v_2} \frac{1}{2} \rho v^3 P(v) dv,$$

where $W_e$ is the EWED; $v_1$ is the starting wind speed; $v_2$ is the stopping wind speed; $\rho$ is the mean density of the air, taken to be 1.29 kg m$^{-3}$; and $P(v)$ is the probability distribution density function of the available wind speed. The distribution of wind speed can be described by the Weibull distribution using the following formula:

$$P(v) = \frac{p(v)}{p(v_1 \leq v \leq v_2)} = \frac{(\frac{v}{\lambda})^{k-1} \exp\left[-\left(\frac{v}{\lambda}\right)^k\right]}{\exp\left[-\left(\frac{v_1}{\lambda}\right)^k\right] - \exp\left[-\left(\frac{v_2}{\lambda}\right)^k\right]}.$$


where $p(v)$ is the Weibull probability distribution density function, $v$ is the wind speed, $k$ is the shape parameter, and $c$ is the scale parameter. The parameters $k$ and $c$ of the Weibull distribution can be calculated from the mean and standard deviation of the wind speed. The formulas are as follows:

$$k = \left(\frac{\text{mean}(v)}{\text{std}(v)}\right)^{1.086},$$

$$c = \frac{\text{mean}(v)}{\Gamma\left(1 + \frac{1}{k}\right)}.$$

where mean $(v)$ is the average of the wind speed, std $(v)$ is the standard deviation of the wind speed, and $\Gamma$ is a gamma function.

### 3. Results

#### 3.1. Spatial distribution of annual and seasonal MWS and EWED

The spatial distribution of the annual MWS (Figure 1(a)) and EWED (Figure 2(a)) are similar, with large-value areas in northern China and parts of coastal areas, including the north of Xinjiang, Mongolia, most parts of Northeast

![Figure 1](image-url). Spatial distribution of the (a) annual and (b–e) seasonal MWS in China in 1960–2016.
China, and parts of the coastal areas, where the annual MWS is above 3 m s$^{-1}$ and the EWED is above 75 W m$^{-2}$. The small-value areas include parts of the coastal areas of Jilin and Liaoning (annual MWS of 2.5 m s$^{-1}$ or less), the southwest of Xinjiang (2 m s$^{-1}$ or less; 50 W m$^{-2}$ or less), and southern China (2.5 m s$^{-1}$ or less; 50 W m$^{-2}$ or less), wherein the minimum MWS (in Chongqing) is about 1 m s$^{-1}$ and the EWED is 25 W m$^{-2}$ or less. In southern China, the southwest of Yunnan is a center of small annual MWS, with values below 1.5 m s$^{-1}$.

The spatial distribution of the seasonal MWS (Figure 1(b–e)) is similar to that of the annual MWS, with large-value areas in northern China and parts of coastal areas, but with Xinjiang showing as a small-value area in winter. The spatial distribution of the seasonal EWED (Figure 2(b–e)) is also similar to that of the annual EWED, with large-value areas in North China and parts of coastal areas; however, the EWED in autumn and winter in Northeast China is relatively small. Comparing the MWS and EWED in each season, in northern China, spring has the largest MWS (3.5 m s$^{-1}$ or more) and largest EWED (100 W m$^{-2}$ or more). In parts of coastal areas, there is no obvious MWS variation among the four seasons, but parts of coastal areas in Shandong have the largest MWS (above 3 m s$^{-1}$) and largest EWED (above 100 W m$^{-2}$) in spring. The EWED along the Fujian coast is relatively large in autumn, at 75 W m$^{-2}$ or more. The MWS and EWED of each season in southern China are almost the same.
3.2. Temporal change of annual and seasonal MWS

The least-squares linear fitting algorithm is applied to detect the wind speed change and its trend. The statistical significance of wind speed changes is tested by the Pearson correlation coefficient test. The annual and seasonal MWS of stations with a significance level of 0.05 and a correlation coefficient of >0.4 are shown in Figure 3. From the beginning to the end of almost the entire 50 years of the study period, the majority of stations show a significant reduction in annual and seasonal MWS. The number of stations with a rate of decline of less than −0.01 m s$^{-1}$ yr$^{-1}$ (i.e., absolute value greater than 0.01) accounts for more than 75% of the total number of stations passing the significance test, with the largest proportion in spring (86.5%).

In terms of the trend for the annual MWS with time (Figure 3(a)), there is a significant trend of decline in wind speed in North, West, and East China, but especially in northern China and parts of the coastal areas. Apart from the trend of increasing annual MWS in some parts of Guangdong, the annual MWS in southern China shows little change. The trend of seasonal MWS changing with time (Figure 3(b–e)) is similar to that of the annual MWS. The rate of decline in North and East China is relatively large, with spring being the largest, followed by winter and finally autumn and summer.

3.3. Regional MWS change

China is divided into four regions according to the spatial distribution of MWS and the geographical location of

![Image of Figure 3](image-url)
each province, as shown in Figure 4. The north includes Mongolia and Northeast China, as region 1, where the MWS is relatively high. The northwest includes northern Xinjiang, Qinghai, and Gansu, as region 2; and the eastern coastal cities of Shandong, Jiangsu, Zhejiang, Shanghai, and Fujian also have relatively high MWS, as region 3. The remaining areas all have the smallest wind speeds and are grouped into region 4. Table 1 presents statistics on the rates of decline for each region, from which it can be seen that the regions with a large MWS also have a large rate of decline. The MWS of the four seasons in region 4 is the minimum, while spring in region 1 is the maximum and winter in region 3 is the maximum. In addition, the rate of decline in the MWS in the three seasons of spring, summer, and autumn is the largest in region 1, followed by region 3, and finally, regions 2 and 4, while the rate of decline is the largest in the eastern coastal region 3 in winter.

### 3.4. EOF analysis of annual MWS and EWED

EOF decomposition is used to analyze the main modes of the change in MWS and EWED. The error ranges of the first two eigenvectors of the EOF decomposition of annual MWS and annual EWED do not overlap, and all of them pass North’s significance test (after calculating the eigenvalues’ error range, if the error ranges of adjacent eigenvalues do not overlap then the two modes are considered to be independent of each other).
percentage variance contributions are shown in Table 2, from which we can see that the first two modes of the annual MWS and annual EWED account for 50.18% and 68% of the total variance, respectively.

The first mode of MWS reflects the main spatial pattern of annual MWS change (Figure 5(a)), and the percentage variance contribution reaches 35.73%. The first eigenvector (EV1) reveals that there is high consistency over all areas in China from 1960 to 2016 in terms of the rate of change in the annual MWS. The large-value centers are in Mongolia, Northeast China, northwest central China, and East China, with large variability; while the small-value centers are in Chongqing and coastal areas of Southwest China, with small variability. The corresponding time series of the mode 1 (TS1) (Figure 5(b)) decreases with time, indicating a reduction in the annual MWS.

The percentage variance contribution of the second mode of the annual MWS (Figure 5(c)) is 14.45%. In the second mode eigenvector (EV2), the large negative-value areas are over the three great plains of China (the Northeast Plain, North China Plain, and Middle-lower Yangtze Plain) and the west of the Great Bend of the Yellow River; while the large positive-value areas are over the Yanshan Mountains, west of the Hexi Corridor, and near the Yunnan-Guizhou Plateau. The Sichuan Basin, Tarim Basin, and Junggar Basin are also positive, which may be related to the local atmospheric circulation. The corresponding time series of the mode 2 (TS2) (Figure 5(d)) shows a slow decrease and then a sharp increase, and this mode of annual MWS has a large variability in 2003–04.

The percentage variance contribution of the first mode of annual EWED reaches 60%, and the EV1 for EWED shows that all of China is positive (Figure 5(e)), indicating that the trend of change in EWED for China from 1960 to 2016 is highly consistent, similar to the situation for MWS. The large-value areas are in North and East China, while the small-value areas are in southern Tibet and northeastern Xinjiang. In terms of the TS1 for EWED, the change of EWED with time is consistent with the annual MWS, decreasing year by year.

The percentage variance contribution of mode 2 is 8%. The EV2 for EWED shows that western China is dominated by positive values, with a large area over the Tibetan Plateau. On the contrary, East China is dominated by negative values. That is, the east and west of China show opposite changes. The TS2 for EWED shows a sharp increase and then a slow decrease. By comparing the second mode of MWS and EWED, it can be seen that the spatial distributions are similar. However, the time series show opposite change.

3.5. Possible causes of annual and seasonal MWS changes

Wind speed is an uncertain variable and the factors impacting it are complex. The background of climate change in the form of global warming and the associated land use/cover change at regional scales may be the main cause of reductions in wind speed and wind energy resources in recent decades. Li et al. (2008) showed that wind speeds have weakened due to the destruction of forest resources, urbanization, and agricultural irrigation, amongst other factors. Xiong (2015) found that wind speeds in Northeast China, Mongolia, eastern China, and southeast coastal areas are significantly and positively correlated with the area of the Arctic vortex and negatively correlated with the area, ridgeline, and intensity of the subtropical high. Huang et al. (2011) studied the relationship between the MWS and temperature in Northwest China and found that the decline in wind speed had a certain relationship with the increase in the mean maximum temperature. The main cause of the weakening of the wind speed was the change in atmospheric circulation. Under the background of global warming, the difference in sea level pressure and temperature between the Asian continent and the Pacific has significantly reduced, in turn significantly reducing the meridional circulation, enhancing the zonal circulation, and reducing the East Asian winter monsoon and summer monsoon. All of these factors have led to a decrease in MWS (Jiang et al. 2010).

The temperature is rising significantly in northern China where the MWS and the rate of decline are also high. However, the opposite is true in southern China (figure omitted). In winter, the increase in temperature is most obvious in northern China, which is

| Variable | Mode | Eigenvalue | Variance contribution | Cumulative variance contribution | Eigenvalue error range |
|----------|------|------------|-----------------------|----------------------------------|------------------------|
| MWS      | 1    | 162.16     | 35.73%                | 35.73%                           | 131.78                 |
|          | 2    | 65.61      | 14.45%                | 50.18%                           | 53.32                 |
| EWED     | 1    | 271.59     | 60%                   | 60%                              | 220.72                |
|          | 2    | 36.43      | 8%                    | 68%                              | 29.60                 |

Table 2. Statistics of the first two EOF modes of annual MWS and EWED based on data from 462 stations in China.
consistent with the frequent occurrence of warm winter events since global warming. As the temperature increases, the thermal contrast between land and sea decreases, which in turn reduces the wind speed.

It is also worth briefly discussing the normalized difference vegetation index (NDVI) and the East Asian summer monsoon index (EASMI). For this purpose, NDVI data from GIMMS NDVI3g and the EASMI downloaded from the website of Professor LI Jianping (http://ljp.gess.cn/dct/page/65577) are used. This index is defined as an area-averaged seasonally (June–July–August) dynamic normalized seasonality at 850 hPa within the East Asian monsoon domain (10°–40°N, 110°–140°E). The EASMI (Figure 6(a)) shows a decreasing trend, and global warming is the main cause of the decline in the East Asian summer monsoon. Both the spatial (Figure 7) and temporal (Figure 6(b–e)) characteristics of NDVI show an increasing trend, with the eastern coastal area having the greatest variability. This suggests that changes in the underlying surface have reduced the overall wind speed and wind energy in China.

The above analysis suggests that global and regional warming are the main reasons for the decline in wind speed and wind energy resources over China; meanwhile, changes in the underlying surface have also contributed.
4. Conclusion and discussion

Based on daily near-surface wind speed data from 462 meteorological stations from 1960 to 2016, the spatio-temporal characteristics of the annual MWS and EWED are analyzed using kriging spatial interpolation, the least-squares method, and EOF decomposition.

In the study period (1960–2016), the annual MWS is greater than 3 m s\(^{-1}\) and the EWED is greater than 75 W m\(^{-2}\) in northern China and parts of coastal areas. However, the MWS and EWED values in southern China are all smaller. The annual and seasonal MWS in China shows a significant decreasing trend, especially in northern China in spring and parts of coastal areas in winter. The annual MWS in some areas of Guangdong has an increasing trend, but it changes little in Southwest China, South China, and western central China. In areas with high wind speed, the rate of decline is also large.

The main modes of the annual MWS and EWED from the EOF analysis show that the changes in annual MWS and EWED reflect a high degree of consistency, both showing a decreasing trend. The percentage variance contribution of the annual EWED first mode reaches 60%. It can also be seen from the temperature distribution, EASMI and NDVI that global warming is the main reason for the decline in wind speed and wind energy resources over China, with changes to underlying surfaces also contributing.

Since the heights of the instruments gathering the data at the observation stations are all 10 m above the surface, the EWED calculated in this study also corresponds to that height. However, the height of the fans of wind turbines is higher, and so there will be some biases in terms of applying the findings of this study in a practical sense. Nonetheless, the results are still an important guide and reference for the wind energy sector. In addition, the stations used in this study are biased towards the east of China in terms of their spatial distribution. Therefore, the accuracy of the analysis in terms of wind speed and wind energy in western China is relatively lower than in the east.

Figure 6. The (a) EASMI and (b–e) comparison of annual MWS (units: m s\(^{-1}\)) and NDVI (units: yr\(^{-1}\)) in four regions (shown in Figure 5(a)).
Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Key R&D Program of China [grant numbers 2016YFA0600403 and 2016YFA0602501] and the General Project of the National Natural Science Foundation of China [grant number 41875134].

References

Guo, H., M. Xu, and Q. Hu. 2011. “Changes in Near-Surface Wind Speed in China: 1969–2005.” International Journal of Climatology 31 (3): 349–358. doi:10.1002/joc.2091.
Huang, S., A. Jiang, C. Liu, and B. Chen. 2007. “Reassessment and Study on Distribution of Wind Energy Resource in Jiangsu.” Scientia Meteorologica Sinica 27 (4): 407–412. doi:10.3969/j.issn.1009-0827.2007.04.008.
Huang, X., M. Zhang, S. Wang, H. Xin, and J. He. 2011. “Characteristics of Variation in Sunshine Duration and Wind Speed in the Last 50 Years in Northwest China.” Journal of Natural Resources 26 (5): 825–835. doi:10.11849/ zrzyxb.2011.05.010.
Jiang, Y., Y. Luo, Z. Zhao, and S. Tao. 2010. “Changes in Wind Speed over China during 1956–2004.” Theoretical Applied Climatology 99 (3–4): 421. doi:10.1007/s00704-009-0152-7.
Li, Y., Y. Wang, H. Chu, and J. Tang. 2008. “Influence of Climate Change and Underlying Anthropogenic Changes on Near-Surface Wind Energy Resources over China’s Land.” Chinese Science Bulletin 53 (21): 2646. doi:10.1360/csb2008-53-21-2646.
Li, Y., Y. Wang, and J. Tang. 2007. “Temporal and Spatial Variety Characteristics in near Surface Wind Energy in China.” Journal of Nanjing University (Natural Sciences) 43 (3): 280–291. doi:10.13232/j.cnki.jnju.2013.03.001.
Liao, S., K. Liu, and Z. Li. 2008. “Estimation of Grid Based Spatial Distribution of Wind Energy Resource in China.” Geo-Information Science 10 (5): 551–556. doi:10.3969/j.issn.1560-8999.2008.05.001.
Liu, S., J. Qiu, and X. Mo. 2009. “Wind Velocity Variation from 1951 to 2006 in the North China Plain.” Resources Science 31 (9): 1486–1492. doi:10.1016/S1003-6326(09)60084-4.
Nelson, V., and K. Starcher. 2009. Wind Energy: Renewable Energy and the Environment. Boca Raton: CRC press.
Rong, Y., and J. Liang. 2008. “Analysis of Variation of Wind Speed over North China.” Scientia Meteorologica Sinica 28 (6): 655–658. doi:10.3969/j.issn.1009-0827.2008.06.011.
Wang, Y., and C. Zhang. 2006. “Changes of Wind Speed and Wind Energy over Gansu Corridor.” Plateau Meteorology 25 (6): 1196–1202. doi:10.3321/j.issn.1000-0534.2006.06.030.
Wang, Z., Y. Ding, J. He, and J. Yu. 2004. “An Updating Analysis of the Climate Change in China in Recent 50 Years.” Acta Meteorologica Sinica 62 (2): 228–236. doi:10.3321/j.issn:0577-6619.2004.02.009.
Wu, F., and C. Fang. 2009. “Wind Power Resource Appraisal and Development Stage Regional Division of China.” Journal of Natural Resources 24 (8): 1412–1421. doi:10.11849/ zrzyxb.2009.08.010.
Xiong, M. 2015. “Climate Regionalization and Characteristics of Surface Winds over China in Recent 30 Years.” Plateau Meteorology 34 (1): 39–49. doi:10.7522/j.issn.1000-0534.2013.00159.
Xue, H., R. Zhu, Z. Yang, and C. Yuan. 2001. “Assessment of Wind Energy Reserves in China.” Acta Energiae Solaris Sinica 22 (2): 167–170. doi:10.3321/j.issn:0254-0096.2001.02.010.
Zhu, R., and H. Xue. 1983. “Division of Wind Energy in China.” Acta Energiae Solaris Sinica 4 (2): 123–132.