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Satellite-based re-examination of changes in terrestrial near-surface wind speed in the last 30 years

Wei Zhang[1], Lishui Zhang[2] and Jikai Liu[2]*

[1]College of Architecture, Anhui Science and Technology University, Chuzhou, China, [2]College of Resource and Environment, Anhui Science and Technology University, Chuzhou, China

Wind plays a crucial role in shaping climatic and environmental conditions; however, its spatial and temporal variabilities over land remain poorly understood. This study utilizes combined datasets from multiple satellite platforms to examine the spatial patterns and temporal trends of wind speed over land during the past 30 years (1988–2017). The results demonstrate a significantly increasing trend in global wind speed, with variations on both annual and monthly scales. Spatially, wind speeds are lower in low-latitude regions, particularly in the tropics. High wind speeds primarily occur in mid- to high-latitude regions, with the highest speeds observed in the Arctic. Temporally, wind speed trends are characterized by an increase in low-speed winds and decrease in high-speed winds. Overall, wind speed shows a significant correlation with temperature in the Amazon, northern Europe, and central Asia. Negative wind–temperature correlation is confined to small regions in central North America and northern Africa. The findings of this study help clarify wind trends, providing valuable insights for future research on global climate and environmental change.

KEYWORDS

wind speed, climate change, environment, satellite, terrestrial

1 Introduction

Wind is an important climate variable because it is one of the fundamental components of the Earth's climate system. It is responsible for transferring heat and energy across the Earth's surface and influencing climate patterns and weather events around the globe (Zhang et al., 2013). Changes in wind speed and direction can drive the development of and changes in weather systems, such as high and low pressure systems, which in turn influence precipitation patterns, temperatures, and storm formation (Yang et al., 2017). Furthermore, wind speed is a decisive factor in the potential of wind power generation, as higher wind speeds generally mean higher energy output and are critical to the growth of the wind industry (Wang et al., 2015). Understanding the wind and how it may be changing are important elements of projecting climatic adaptation and environmental management (Korhonen et al., 2010; Wang et al., 2015; Yang et al., 2017).

Several approaches have been developed to monitor wind speed which can be divided into *in situ* site methods, climate modeling, and satellite remote sensing. Weather stations usually measure wind speed through anemometers (Wilczak et al., 2001). Although accurate, the spatial representativeness of these stations is poor,

leaving great spatial uncertainty for capturing wind speed over a large region (Hobby et al., 2013). Climate models simulate wind based on the physical connection with climatic variables and can estimate the wind over different spatial scales with strong physical mechanism (Giannaros et al., 2017). However, the performance of models depends greatly on their assumptions and structure, causing uncertainty and weakening their application (Wang et al., 2011; Torralba et al., 2017). Alternatively, satellite remote sensing retrieves wind speed by measuring the correlation with brightness and temperature based on the radiative transfer function which helps to capture the wind accurately over large regions and has been increasing applied in recent decades (Wentz, 1992; Clarizia and Ruf, 2016). The main limitation of satellite wind data is its lifetime. To overcome this limitation, the integration of multi-satellite platforms has been proposed to produce long-range data sets of wind speed, which is showing great application (Wentz, 2015; Carr and Wu, 2018).

With the aid of the various datasets, wind speed has been analyzed over various regions. Young and colleagues have analyzed the wind over the ocean (Young et al., 2011; Young and Ribal, 2019) but not over the land. Terrestrial wind exerts a closer and more direct effect on humans, which has attracted increasing recent attention. Dadaser-Celik and Cengiz (2014) have examined the spatial and temporal dynamics of wind speeds over Turkey by analyzing data from 206 weather stations from 1975 to 2006. Laapas and Venäläinen (2017) analyzed monthly wind speed in Finland with the aid of 144 weather stations. Analyses of large regions (i.e., global or continent-wide) are relative rare. Azorin-Molina et al. (2018) examined wind speed trends at the land–ocean interface. Yin (2000) analyzed the spatial pattern of surface land wind with the aid of 1506 weather stations, although not temporal trends. The latest study of Jung (Jung et al., 2019) analyzed the long-term trends and inter-annual variability of global wind energy at a national scale, although the spatial details of the trend were still unclear. Most studies have declared the "stilling" of wind speed. However, great uncertainty has been aroused from different wind products (Torralba et al., 2017), triggering much controversy. For example, Li et al. (2018) found the recovery of surface wind speed in northwest China after decades of decrease from the 1960s. A similar trend has also been observed in South Korea (Kim and Paik, 2015). There is a strong need for a more direct and effective way to capture wind-speed change.

Given this overview, details of wind-speed trends over land are rare, which creates uncertainty for the investigation of global climate and environment change. The present study collects global wind speed observation data—including from ground weather stations, satellite remote sensing data, and climate model output—analyzes the changes of wind speed on different time scales, studies the spatial distribution and changes of wind speed in different geographical locations around the world, and explores the potential drivers of wind speed changes. It uses a cross-calibrated multi-platform grid surface vector wind dataset to assess wind patterns and trends. These datasets combine cross-calibrated satellite microwave wind observations with instrument observations using variational analysis. The goal of this study is to capture spatial patterns and temporal trends in global land-wind speeds and identify their potential drivers. To achieve this goal, spatial pattern analysis, temporal trend analysis, and potential driver identification are used. The methods and corresponding data sets are described in Section 2. The results are presented in Section 3. The conclusions and discussions are provided in Section 4. This study should be valuable for understanding patterns of global wind speed and supporting further research on global climate change.

2 Data and methods

2.1 Data sources and preprocessing

Several data sources, including the wind and relevantly correlated variables, are used for this investigation.

The data from the Cross-Calibrated Multi-Platform's (CCMP) gridded surface vector winds (www.remss.com/measurements/ccmp) is used to evaluate the pattern and trend of wind in this study. These datasets combine cross-calibrated satellite microwave winds and instrument observations using a variational analysis method (VAM) to produce high-resolution (0.25°) gridded analyses at a height of 10 m from 1988 to 2017. Satellite wind retrieval derived by remote sensing systems from a number of satellite-borne passive and active microwave instruments are used (Wentz, 2015). The data is validated against ocean moored buoys, which confirm that the measurements are in agreement (to within 0.8 m/s).

Besides wind speed data, temperature and vegetation datasets are also used in this analysis. Air temperature (Ta) data was taken from the GHCN_CAMS Gridded 2 m Temperature (Land) from 1948 to near present (https://www.esrl.noaa.gov/psd/data/gridded/data.ghcncams.html) at a spatial solution of 0.5°. These data use a combination of two large individual datasets of station observations collected from the Global Historical Climatology Network version 2 and the Climate Anomaly Monitoring System (GHCN + CAMS) by some unique interpolation methods, such as anomaly interpolation with spatially-temporally varying temperature lapse rates derived from observation-based reanalysis for topographic adjustment (Fan and Dool, 2008).

Normalized Difference Vegetation Index (NDVI) data is used to represent vegetation cover in this study. For the vegetation evaluation, the MODIS/Terra Vegetation Indices Monthly L3 Global 0.05Deg CMG (MODIS MOD13C2) was obtained from http://doi.org/10.5067/MODIS/MOD13C2.006. The data are cloud-free spatial composites of the gridded 16-day 1-km MOD13C2A2 from the year 2000 and are provided as a level-3 product projected on a 0.05° (5600-m) geographic climate modeling grid (CMG). Cloud-free global coverage is achieved by replacing clouds with the historical MODIS time-series climatology record (Didan et al., 2015).

All datasets are resampled at 1° to match the spatial resolution and then analyzed on monthly or annual scales.

2.2 Methods

The core objective of this study is to understand and describe the spatial distribution characteristics of global-land wind speed and its changes over time and to further explore the potential
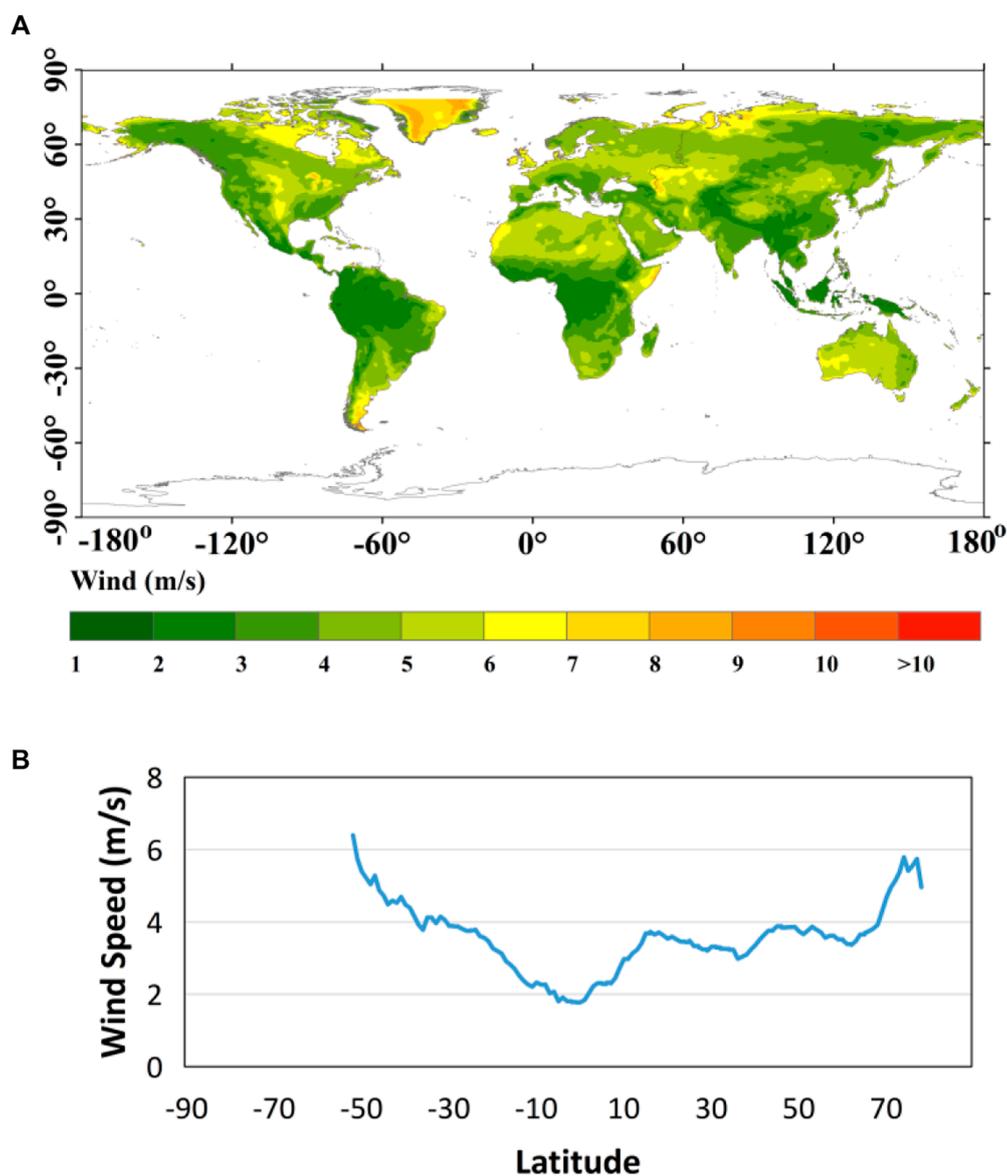
FIGURE 1
Spatial pattern of global wind speed **(A)** and spatial variability at latitude **(B)**. Blank in the statistics indicates no data for a region.

factors influencing these changes. In order to achieve this goal, the following methods were adopted. Mathematical statistics were used to analyze wind-speed data, including calculating annual average wind speed, standard difference, and other statistical indicators. Correlation analysis is applied to explore the relationship between wind speed and other environmental variables such as temperature, air pressure, and vegetation conditions. Geographic information system (GIS) technology was used to visualize and analyze the spatial distribution of wind speed. GIS tools are used for spatial interpolation to estimate and plot wind speed in areas without direct observational data. Trend analysis using a linear regression model to determine the trend of wind speed over time analyzed its slope and intercept. Trends are evaluated on different time and spatial scales. We explored, identified, and assessed potential drivers of wind-speed change, such as land-cover change, land-use change,

and climate change. The relationship between these factors and wind speed was quantified by mathematical statistics. Although simple, the methods have proved useful and effective in previous climatic and environmental studies (Jong et al., 2011; Young et al., 2011; McDonald et al., 2015; Young and Ribal, 2019).

(1) **Spatial pattern analysis**. The multiyear mean of wind speed is calculated at each pixel over land. GIS spatial analysis is used to describe the spatial pattern of the wind speed. Standard deviation is one of the most commonly used statistics to measure spatial variability, reflecting the dispersion of wind speed values around the mean. Furthermore, the indicator of "mean ± SD" (where $SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2}$ where the ith observation is the average and N is the total number of observations) is used to represent spatial variability.

FIGURE 2
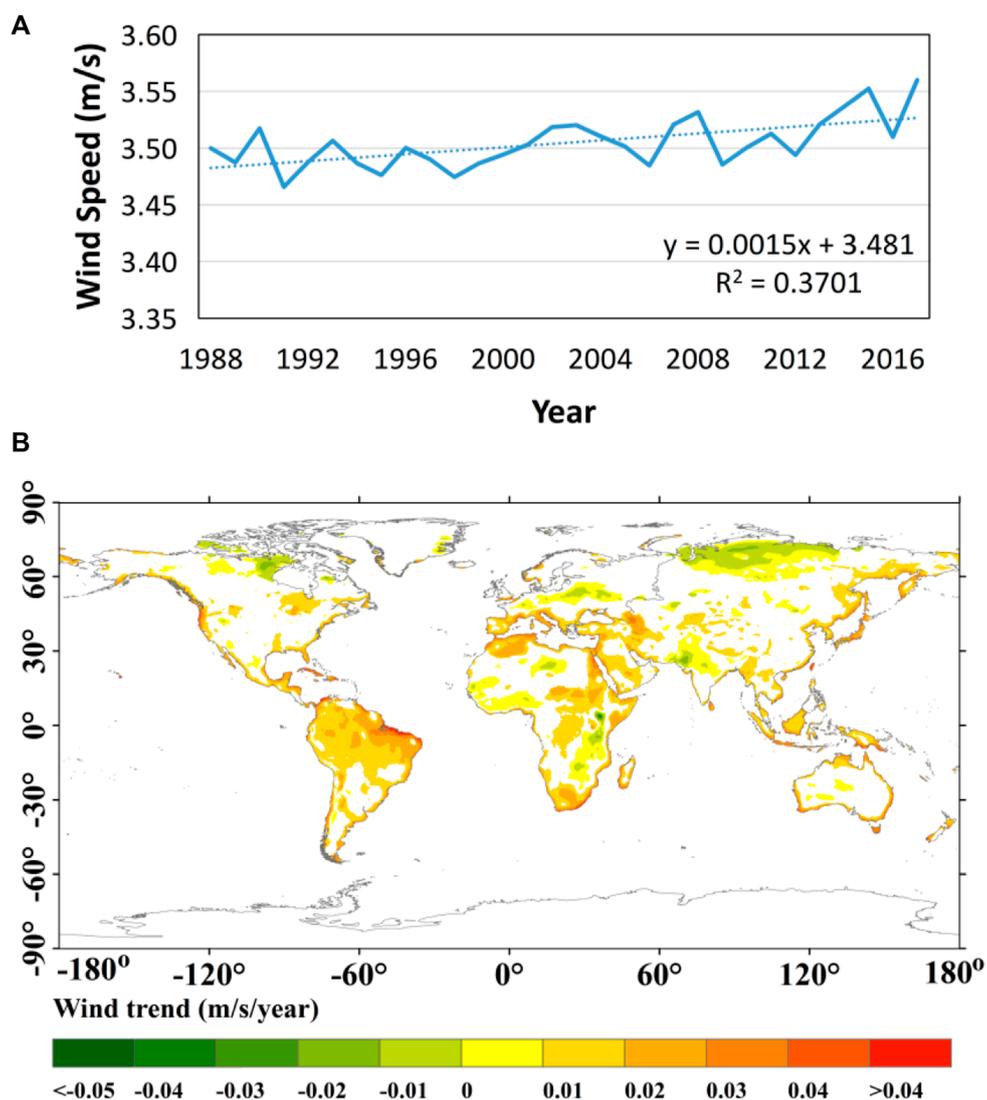Annual trend **(A)** and spatial pattern of wind change **(B)** in recent 30 years. Only trends that are significant at $p < 0.05$ are presented in **(B)**.
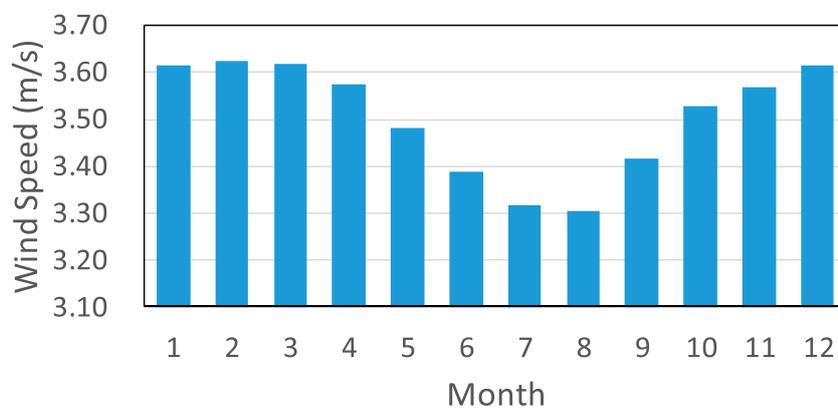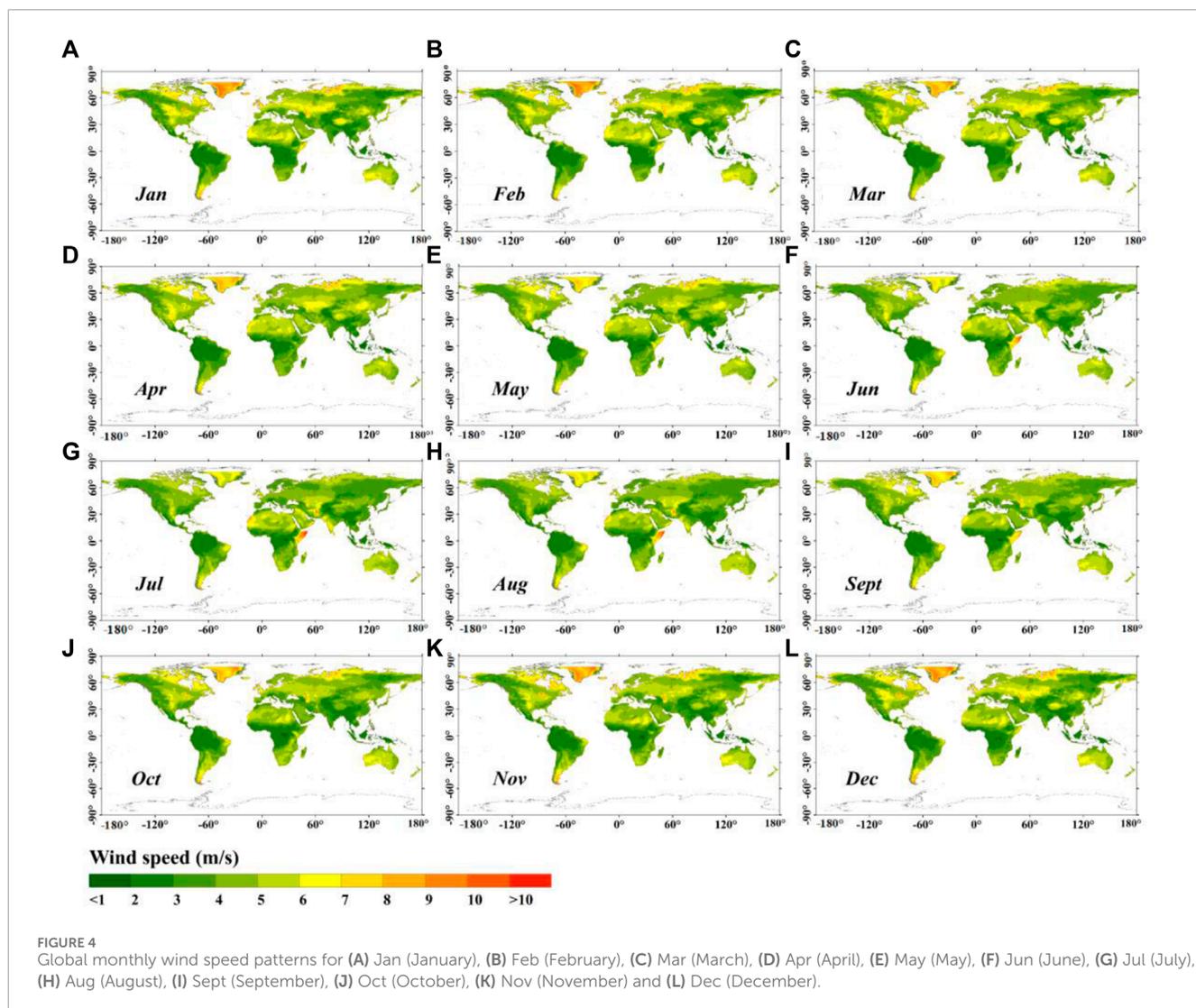

FIGURE 3
Monthly variation of global wind speed (m/s).

FIGURE 4
Global monthly wind speed patterns for **(A)** Jan (January), **(B)** Feb (February), **(C)** Mar (March), **(D)** Apr (April), **(E)** May (May), **(F)** Jun (June), **(G)** Jul (July), **(H)** Aug (August), **(I)** Sept (September), **(J)** Oct (October), **(K)** Nov (November) and **(L)** Dec (December).

(2) **Temporal trend analysis.** The trend is represented by the slope of linear regression, which can be written as (Eq. 1):

$$y = ax + b \qquad (1)$$

where y and x are the dependent (wind speed) and independent (time) variables, and a is the regression slope, which suggests temporal trend. b is the intercept. The trend is evaluated at various spatial and temporal scales. Spatially, the evaluation of global mean and pixel-wise are carried out. Temporally, the trend is capture on both annual and monthly scales. When using linear regression for wind trend analysis, it is important to ensure that the data satisfy the basic assumptions of the linear regression model, including linear relationships, independence, homoscedasticity, and normal distribution.

(3) **Potential driving factor identification.** Correlation analysis is used to identify the potential driving factors of the wind speed. Correlation analysis is an important method for this, and it can reveal statistical associations between different variables. Physically, wind originates from atmospheric pressure gradients and the earth's rotation (Yin, 2000) and is slowed by friction from surface irregularities (Bichet et al., 2012). The atmospheric pressure is further determined by temperature change. Therefore, we further evaluate the correlations of wind with near surface temperature and terrain and vegetation conditions.

3 Results

Global wind speed analysis is important for several fields for a number of reasons. In climate change research, wind speed is a key indicator of climate change. By analyzing changes in wind speed, scientists can better understand how the global climate system responds to changes in both natural and human factors. Wind energy is also one of the most important renewable energy sources. Understanding the distribution and trends of global wind speeds is essential for assessing wind energy resources and siting and designing wind farms. Furthermore, wind-speed data are critical for improving the accuracy of weather forecasts and the reliability of long-term climate predictions. Moreover, in environmental impact
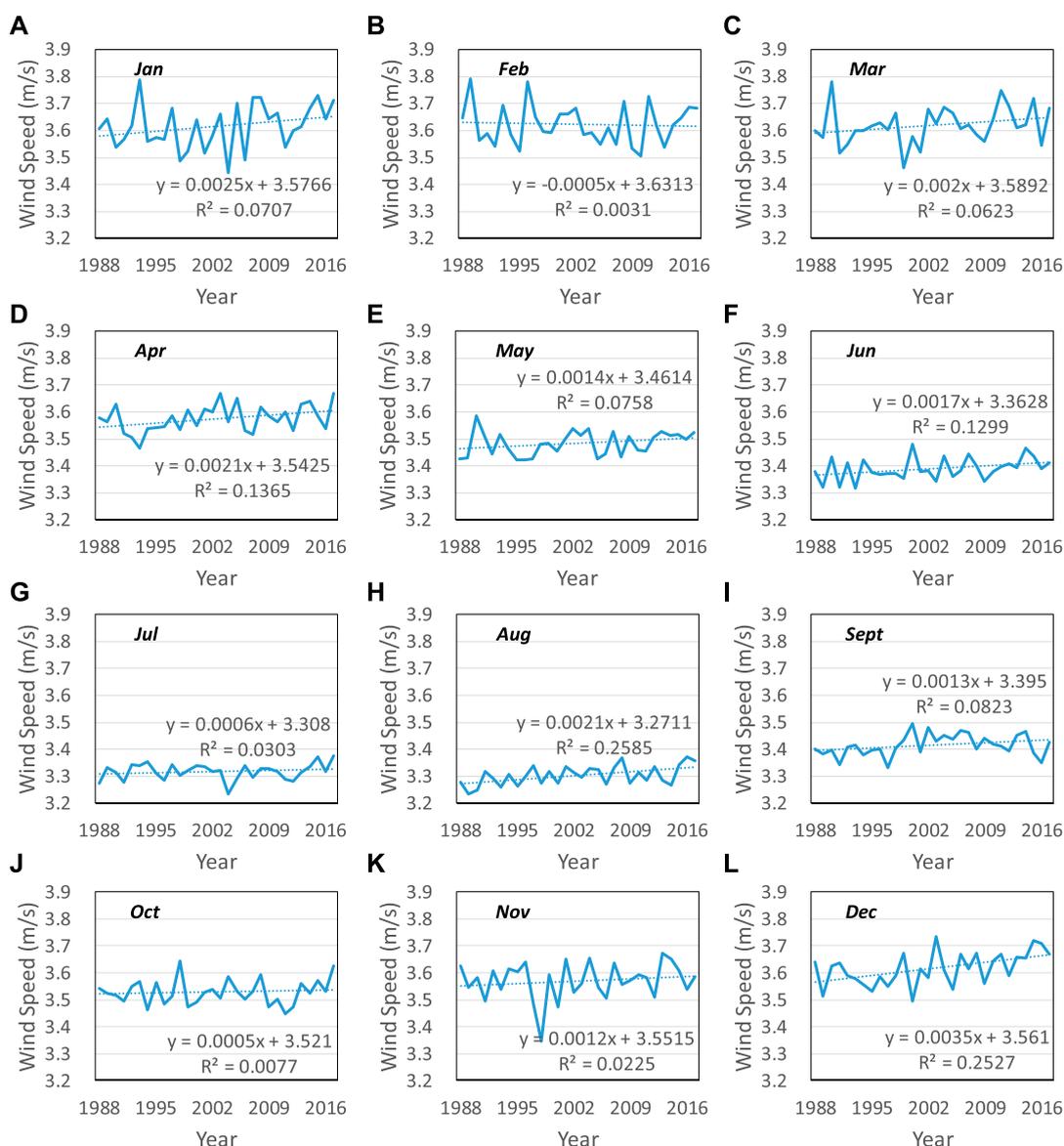
FIGURE 5
Nearly 30 years (1988–2017) from **(A)** Jan (January), **(B)** Feb (February), **(C)** Mar (March), **(D)** Apr (April), **(E)** May (May), **(F)** Jun (June), **(G)** Jul (July), **(H)** Aug (August), **(I)** Sept (September), **(J)** Oct (October), **(K)** Nov (November) and **(L)** Dec (December) time trend of monthly mean global wind speed.
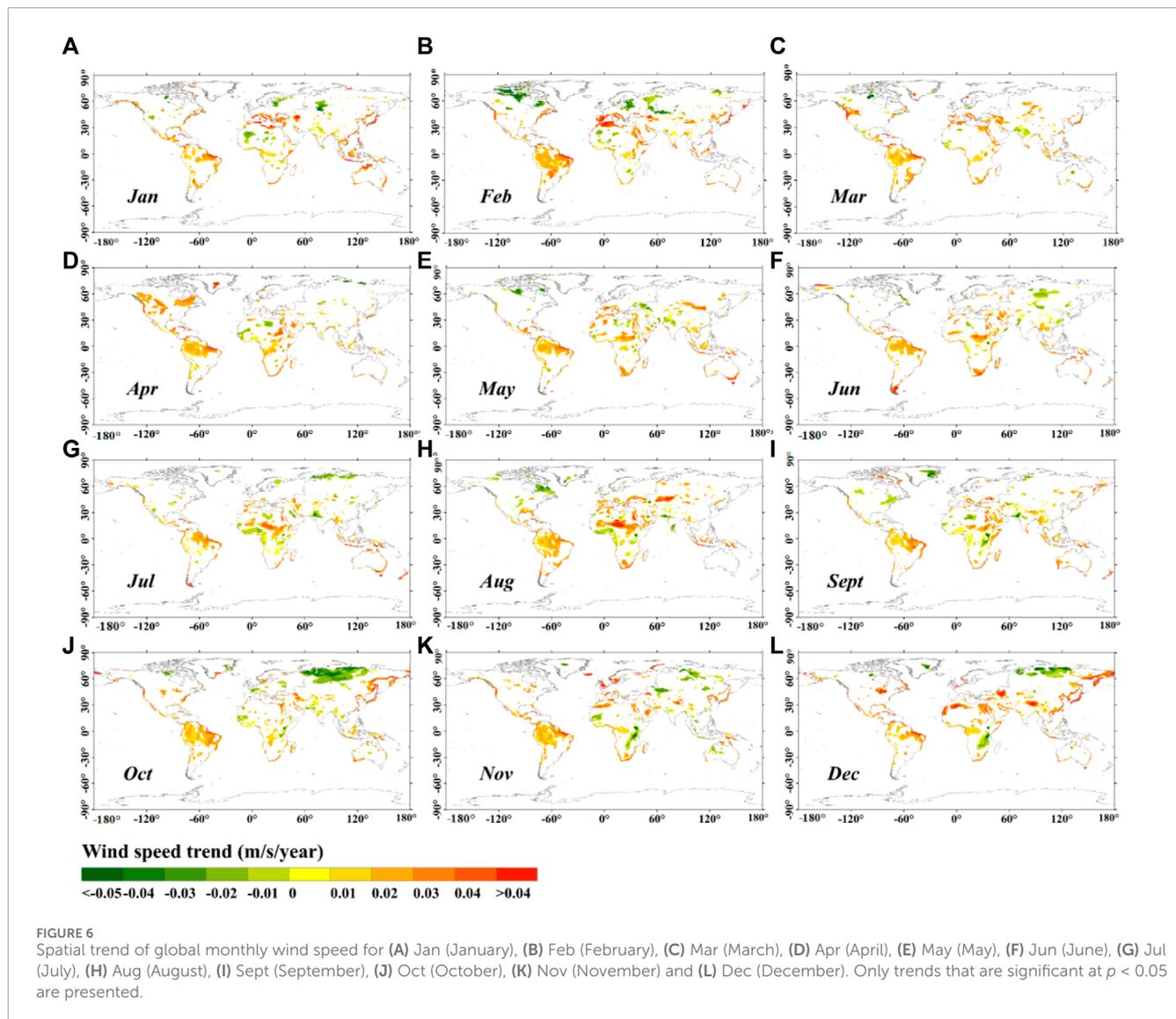
assessments, wind speed can affect air quality because it contributes to the dispersal of pollutants. Understanding wind speed patterns is important for assessing and managing environmental quality. Wind speed also has a direct impact on agricultural activities, such as the transpiration and irrigation needs of crops. Strong winds can also cause physical damage to crops. In transport, wind speed has a significant impact on modes of transport such as air, sea, and land transport, so understanding wind speed patterns can help optimize transport routes and improve safety. Lastly, for disaster prevention and mitigation, extreme wind speed events such as hurricanes and typhoons can lead to severe natural disasters. By analyzing wind speed trends, these events can be better predicted and prepared for.

In this section, the research methods of spatial pattern analysis, time trend analysis, and potential driving factor identification are

used. We performed spatial pattern and temporal trend analysis of wind speed and potential driving analysis of the factors.

3.1 Spatial pattern analysis of wind speed

Statistics show that the average multi-year wind speed on land is 3.50 m per second globally. Wind speed shows significant spatial variation between regions, with a standard deviation (SD) of 1.26 m per second. Wind speeds are generally lower at lower latitudes, especially in the tropics. Conversely, they are higher in middle or high latitudes, with the highest in the Arctic (Figure 1A). Because of solar radiation and the Earth's rotation, the theoretical pattern of wind direction (atmospheric circulation) is significantly dependent

FIGURE 6
Spatial trend of global monthly wind speed for **(A)** Jan (January), **(B)** Feb (February), **(C)** Mar (March), **(D)** Apr (April), **(E)** May (May), **(F)** Jun (June), **(G)** Jul (July), **(H)** Aug (August), **(I)** Sept (September), **(J)** Oct (October), **(K)** Nov (November) and **(L)** Dec (December). Only trends that are significant at $p < 0.05$ are presented.

on latitude (Barnston and Livezey, 1987), which also affects the variability of wind speed (Klink, 2005).

There is significant latitude variability of wind speed (Figure 1B). The overall patterns of variabilities are similar with that of theoretical work by Lambeck and Cazenave (1973) and Lambeck and Cazenave (1974), with wind speed increasing from the equator to the poles. However, the magnitude of variability is quite complex, suggesting complex interactions with potential driving factors. Moreover, wind speed is lowest at −10 °C. Areas with cooler temperatures may develop areas of high pressure, which can lead to lower wind speeds. At the same time, uneven distribution of temperature also affects wind speed and direction. Topographic features such as mountains, valleys, and plains can significantly affect wind speed. For example, mountains can block airflow, causing wind speeds to slow on the lee side. Different weather patterns, such as polar, temperate, and tropical climates, affect the distribution of wind speeds. In some climate models, wind speeds may be lower even if vegetation is sparse. Seasonal variations in wind speed may also influence this phenomenon. In some areas, wind speeds may be generally low in winter, which is

related to changes in temperature, barometric pressure, and seasonal winds. Local climate conditions, such as land, sea, and valley winds, may also lead to lower wind speeds in specific areas at specific temperatures. Human activities such as urbanization, deforestation, and land use change may also affect the distribution of wind speeds.

Besides spatial variability, global wind speed shows a significantly increasing trend over the land in the past 30 years (1988–2017), which can be written as $y = 0.0015 x + 3.48$ ($R2 = 0.37$, $p < 0.001$) (Figure 2A). The trend is consistent with results based on satellite observation (Young et al., 2011; Young and Ribal, 2019), which is opposite to those from *in situ* datasets (Guo et al., 2011; McVicar et al., 2012; Dadaser-Celik and Cengiz, 2014). Since spatial representativeness is limited, *in situ* observation may cause unavoidable uncertainty on the investigation at the large scale. This therefore suggests strategies for improving estimates of global wind speed, for new remote sensing, and for quantifying and reducing uncertainty. With the aid of satellite observation, spatial details of the trend can also be presented (Figure 2B). Wind has profoundly increased in the Amazon, which corresponds to the
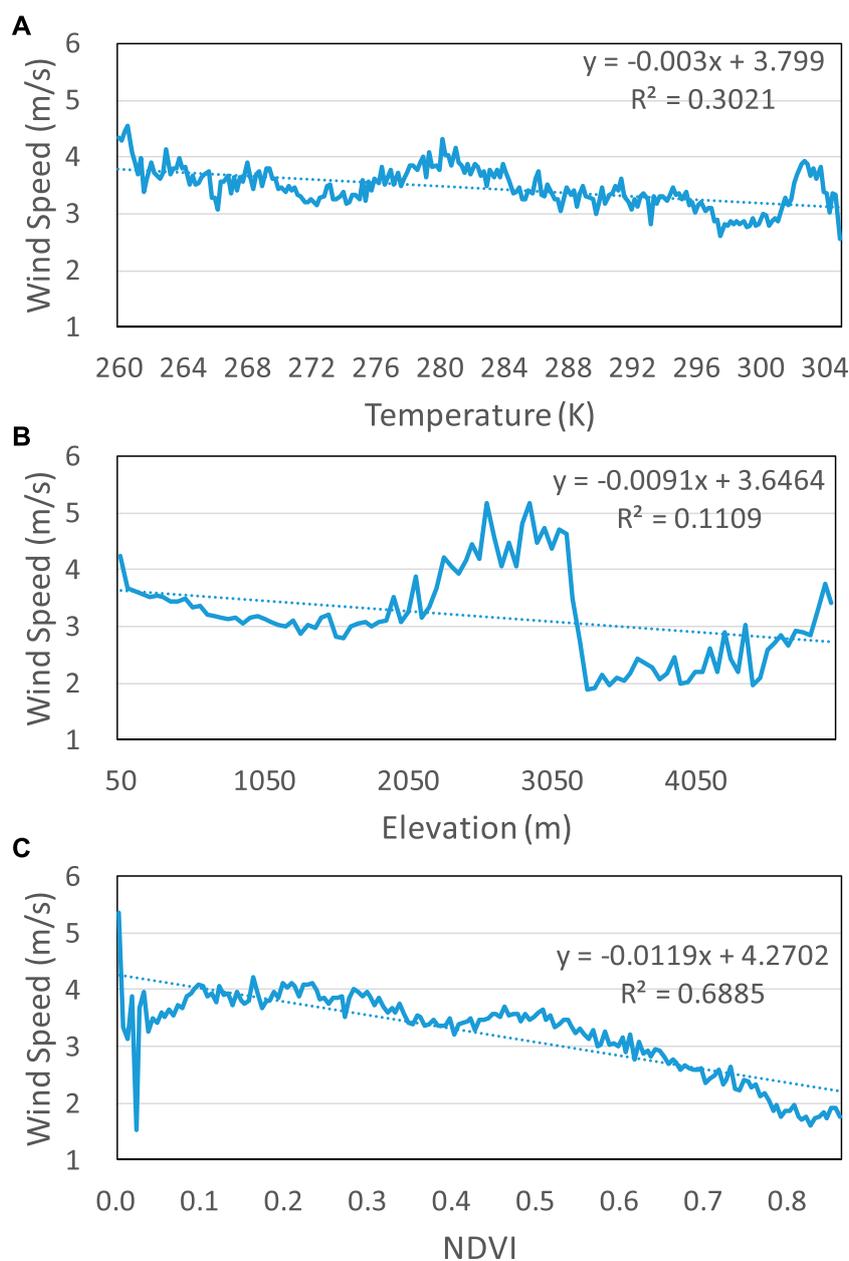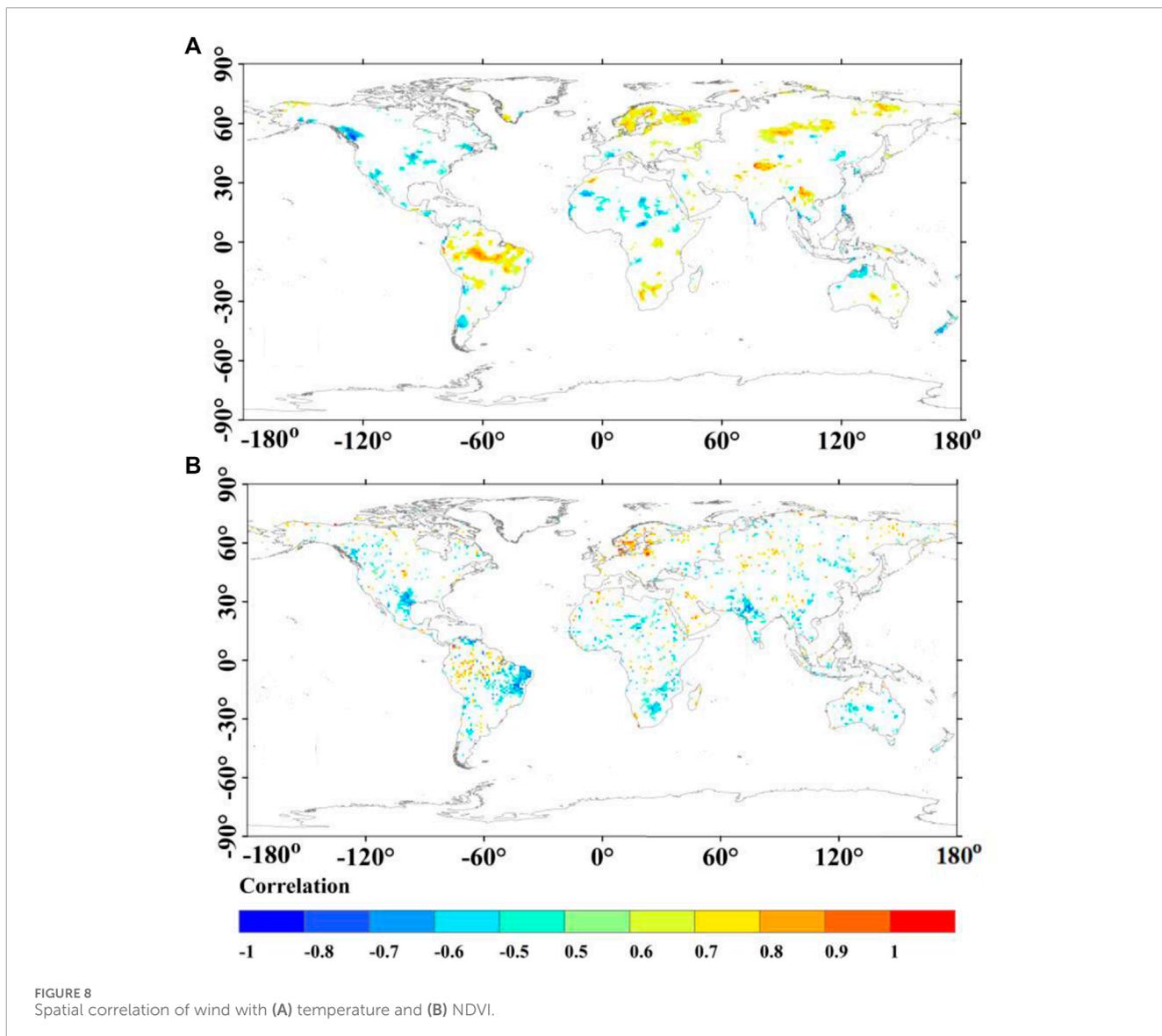
FIGURE 7
Correlation of wind speed with **(A)** near surface temperature, **(B)** elevation, and **(C)** vegetation.

lowest wind. On the other hand, the increasing trend is mainly in northern high latitudes, which correlates to the high speed in the spatial pattern. The wind trend can thus be characterized by "increase in slow speeds and decrease in high speeds." This may suggest that the spatial difference might be reduced in future, resulting in a homogeneous pattern of wind speed. The paradigm can be confirmed by the decreasing trend of global wind speed SD, written as $y = -0.001x + 1.28$ (R2 = 0.25, p = 0.004). Another noteworthy issue refers to the significantly increasing trend around many coastal regions, suggesting the continuous enhancement of land–ocean surface temperature differences due to greater warning over land than over the ocean (Hansen et al., 2006).

3.2 Temporal trend analysis of wind speed

To examine monthly variation, we analyzed the multiyear mean and trend of the wind in each month (Figure 3). It is low in summer and high in other seasons, with the slowest winds in August (3.30 m/s).

The spatial pattern of monthly wind speed is shown in Figures 4A–L. While there is significant variation between the global mean of wind speed at annual and monthly scales, the spatial patterns are highly similar. Wind speed is low in the Amazon and central Africa while it is high in northern and western Asia. Thus, the driving factors of the spatial pattern are similar on annual and monthly scales. The exception occurs in the Arctic: it is much higher in spring and winter, while the magnitude is relatively low in the summer and fall.

FIGURE 8
Spatial correlation of wind with **(A)** temperature and **(B)** NDVI.

Figures 5A–L shows the temporal trends for each month. Wind speed increases in most months, but the significances are relatively weak compared with the annual scale. The difference between annual and monthly trends suggests the hidden effect of temporal scale on wind speed. Generally, monthly wind can be captured as a sine function with the mean, amplitude, and peak of annual wind (Yin, 2000). The most significant increase occurs in August, which corresponds to the lowest speed at monthly scale. This indicates that the inner variability is expected to be reduced.

Figures 6A–L shows the spatial trend of monthly wind. In general, the patterns are similar at different months. The hotspots of the increasing wind speed are mainly located in the Amazon and northern Africa. The greatest difference is in the decreasing trend, which mainly occurs in spring and winter. However, the spatial aspects of the decrease are quite different. In spring, the decreasing trend is mainly in northern North America. In winter, however, the decreasing trend is located in northern Asia, which is spatially consistent with the pattern on an annual scale (Figure 2B).

3.3 Potential driving factors

As demonstrated in the previous studies, wind is controlled by temperature, terrain, and vegetation, which provides the clue for identifying its driving factors (Yin, 2000; Bichet et al., 2012). Figures 7A–C shows the variation of wind speed over different intervals of temperature, DEM, and NDVI. The results show that wind speed negatively correlates with all the variables, indicating that temperature and vegetation negatively control the spatial pattern of wind speed for the same period. The negative wind–DEM correlation reflects friction against the earth's surface (Yin, 2000; Vesala et al., 2008). This might be attributed to dense summer vegetation, which strengthens surface roughness (Wieringa, 1986). As estimated by Vautard et al. (2010), increases in biomass and land-use change could explain between 25% and 60% of atmospheric stilling in the Northern Hemisphere.

As well as the impact of spatial patterns, the relationship between temperature and vegetation also exerts great influence on wind

trends (Figures 8A, B). Generally, wind significantly correlates to temperature in the Amazon, northern Europe and central Asia. A negative wind–temperature correlation is only located in small areas of central North America and northern Africa. The warming climate weakens atmospheric stability, which tends to enhance the wind (Lee, 1979). By contrast, the wind presents weak and negative correlation in the eastern Amazon, southern Africa and southern India. A positive wind–vegetation correlation is rare and is mainly located in northern Europe. The combined effect of temperature and vegetation controls the sine and magnitude of wind trends. Considering the trend of increasing wind speed, it can be concluded that temperature may act as the predominant factor. Our previous studies have investigated the greening and warming world in the past decades (Feng et al., 2017; Feng and Zou, 2019). Consequently, increasing wind speeds are expected in the future.

4 Discussion and conclusion

In this study, the spatial pattern and temporal trend of global wind speed over land were re-examined with the aid of satellite observations in the last 30 years (1988–2017). Several conclusions can be drawn.

From 1988 to 2017, wind speeds showed a significant internal upward trend. The acceleration of wind speed has had a significant impact on the global environment and climate change. For example, wind enhances the dispersion of atmospheric pollutants and improves atmosphere quality. On the other hand, increasing wind speed might alter energy circulation, resulting in complex responses in global temperatures and precipitation (Long et al., 2023; Miao et al., 2023; Zhao et al., 2023). At the same time, wind speed also has shown a clear monthly variation, with a basin-like pattern between the months. Increased wind speed was most significant in August, when wind speeds are normally lowest. Spatially, global wind speed is low in low latitudes, particularly the tropics. High speeds mainly occur in mid or high latitudes, with the highest speed in the Arctic. Patterns of multiyear means were highly similar at annual and month scales.

Wind speed negatively correlates with all the variables, indicating that temperature and vegetation negatively control the spatial pattern of wind speed in the same period. A negative wind–temperature correlation is only present in small parts of central North America and northern Africa. The warming climate weakens atmospheric stability, which tends to enhance wind (Lee, 1979). By contrast, the wind presents a weak and negative correlation in the eastern Amazon, southern Africa, and southern India. Positive wind–vegetation correlation is rare and is mainly located in northern Europe. The combined effect of temperature and vegetation controls the sine and magnitude of the wind trend. Considering the trend of increasing wind speed, we can conclude that temperature may act as the predominant factor. Our previous studies depicted the greening and warming world in the past decades (Feng et al., 2017; Feng and Zou, 2019). Consequently, increasing wind speeds are expected in the future. However, unavoidable uncertainties remain due to the complexity of wind patterns and their corresponding driving factors. These uncertainties originate from the inherent complexity of wind speed, limitations in climate models, and the interactions between the driving factors. Furthermore, human activities (i.e., the urban development and land-use changes) would also generate uncertainties, aggravating the challenges in global wind investigation (Alsweiss et al., 2023; Li et al., 2024).

This study clarified the pattern and trend of global wind speed, which could provide background information for research on climate and environmental change. Several issues should be subject to future research. Firstly, this study examined the potential driving factors by analyzing the correlation of wind speed with temperature, terrain, and vegetation. The physical mechanism involved needs further clarification. Secondly, the impact of wind change on the climate and environment required full investigation regarding adaptation and management.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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