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ORIGINAL PAPER

Temporal variation of wind speed in China for 1961–2007

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Abstract Monthly observed wind speed data at 597 weather stations and NCEP wind speed data at 10 m above surface were used to explore the temporal variations of the wind speed for 1961–2007 in China. The results indicate that the temporal variation of annual wind speed in China has experienced four phases: two relatively steady periods from 1961 to 1968 and 1969 to 1974 with a sharp step change in 1969, a statistically significant decline stage from 1974 to 1990s, and another relatively steady period from 1990s to 2007. Except for the sharp step in 1969 being caused by the changes of observation instrument, other breakpoints correspond well with the positive and negative phases of the interdecadal Pacific oscillation. In addition, four different temporal variation patterns of annual wind speed in China have been identified by using cluster analysis and their spatial distributions were also explored.

1 Introduction

Wind speed is one important climate variable being ignored by most climatic change and variability studies in the literature, although complex changes in surface wind speeds could be expected as the greenhouse effects on general atmospheric circulations (Xu et al. 2006; McVicar et al. 2008; Fu et al. 2009a). This is maybe due to the quality of observed records of near-surface wind run being generally too poor for assessing changes in the wind climate (Smits et al. 2005). However, numerous studies have documented systematic changes in wind speed on the basis of station observations in Australia (Roderick et al. 2007; McVicar et al. 2008), China (Xu et al. 2006; Jiang et al. 2010), Europe (Pirazzoli and Tomasin 2003; Smits et al. 2005), and North America (Klink 1999; Tuller 2004; Pryor et al. 2007, 2009; Pryor and Ledolter 2010). For example, Schiesser et al. (1997) reported a significant negative trend in the number of winter storms in Switzerland, north of the Alps between 1864 and 1994. Pirazzoli and Tomasin (2003) reported a decrease in wind activity for the central Mediterranean and Adriatic region between 1951 and 1970 and an increase from 1970 onwards. Smits et al. (2005) indicated moderate wind events (that occur on average ten times per year) and strong wind events (that occur on average twice a year) had decreased between 5% and 10% for the Netherlands for the period 1962–2002. Tuller (2004) indicated three (Cape St James, Victoria International Airport, and Vancouver International Airport) out of four stations on the west coast of Canada showed a decline in mean annual and winter wind speeds during the later period of the 1940s or the 1950s to the early or mid-1990s. Groisman et al. (2004) indicated that there was a slight decrease in wind speed in the USA since 1960. Pryor et al. (2007) reported that over the contiguous USA, the annual median wind speed decreased significantly (P=0.1) for 118 out of 157 stations for 1973–2005. The Australian-averaged wind speed trend for 1975–2006 was −0.009 $\mathrm{m s^{-1} a^{-1}}$ with stilling over 88% of the land-

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surface (McVicar et al. 2008). The spatial differences and interannual fluctuations in temporal variability of surface pressure and wind speed on different timescales at 12 locations in the Canadian Arctic were also documented by Nawri and Stewart (2009). The overall observations of near-surface wind speed trends measured by terrestrial anemometers have shown declines between −0.004 $\mathrm{m\,s^{-1}\,a^{-1}}$and approximately −0.017 $\mathrm{m\,s^{-1}\,a^{-1}}$ (with an average of approximately −0.010 $\mathrm{m\,s^{-1}\,a^{-1}}$) over the last 30 to 50 years for a range of mid-latitude regions (Roderick et al. 2007; McVicar et al. 2008).

Several studies have documented the wind speed trends in the last 50 years for China. For example, Zhang and Ren (2003) have attributed the decrease of dust storm frequency in northern China for the last 50 years to the decline of wind speed and days with strong wind. Wang et al. (2004) and Ren et al. (2005) showed a magnitude −0.011 $\mathrm{m\,s^{-1}\,a^{-1}}$ of annual mean wind speed during 1954–2001 for mainland China as a whole by using a dataset of 740 national weather stations, and that wind speed trend magnitudes in winter and summer were larger than those in spring and fall seasons. In spatial distribution, north China had a relatively larger wind speed decreasing trend magnitude than south China, and west China had a relatively larger magnitude than east China. They further linked the decreasing wind trend to the winter and summer monsoons of China, and concluded that the decreasing wind speed in winter for China was related to global climate warming and the decreasing wind speed in summer was associated with the weakening East Asia monsoon since the 1970s. Xu et al. (2006) showed that the surface wind speed associated with the East Asian monsoon has significantly weakened in both winter and summer in the recent three decades. From 1969 to 2000, the annual mean wind speed over China has decreased steadily by 28%, and the prevalence of windy days (daily mean wind speed >5 m/s) has decreased by 58%. Significant winter warming in northern China may explain the decline of the winter monsoon, while the summer cooling in central south China and warming over the South China Sea and the western North Pacific Ocean maybe responsible for weakening the summer monsoon (Xu et al. 2006). They further concluded that the monsoon wind speed was also highly correlated with incoming solar radiation at the surface, and two mechanisms governed the decline of the East Asian winter and summer monsoons, both of which maybe related to human activities. The winter decline is associated with global-scale warming that maybe attributed to increased greenhouse gas emission, while the summer decline is associated with local cooling over south-central China that may result from air pollution. Jiang et al. (2010) have reported the decreasing trends for annual mean wind speed, days of strong wind, and maximum wind over broad areas of China from 1956 to 2004, based on two observational datasets. They have concluded that the decline wind speed in China resulted from four main reasons: changes of weather stations location and anemometers, effects of urbanization, changes and adjustments of atmospheric circulation, and extreme events and weather phenomena (e.g., dust storms and cold waves).

However, these existing studies of China have focused on trend analysis only, and have not explored the possible linkage between temporal variation of wind speed in China and large-scale circulation, such as interdecadal Pacific oscillation (IPO), which was the primary objective of this research. This topic was chosen because previous studies have shown that wind speed was associated with large-scale circulation. For example, Suselj et al. (2010) have investigated the North Sea near-surface wind climate and its relation to the large-scale circulation patterns, and reported that the dominant mode of 10-m wind speed (WS10) explained coherent variability of WS10 over the North Sea and was related to a sea level pressure (SLP) pattern similar to the North Atlantic oscillation (NAO). The increase of the magnitude of the dominant WS10 pattern was related to the increase of the magnitude of the NAO-like SLP pattern from 1960s to mid-1990s. The spatial distributions of different patterns of temporal variation from cluster analysis results were also investigated.

2 Data and methods

2.1 Dataset

Although the dataset supplied by China Meteorological Administration (CMA) spans from 1951 to 2007, we excluded wind speed data before 1960 in the current study because there were not enough stations, and data from the early years contain more gaps and missing values (Liu et al. 2004; Xu et al. 2006). The wind speed was measured with anemometers 10 m above the ground following the WMO's Guide to the Global Observing System and CMA's Technical Regulations on Weather Observations (Xu et al. 2006). If one station has more than 5% missing value months, the specific station was removed from our study. Finally, 597 among 752 available stations providing monthly means of daily wind speed were used for the current study (Fig. 1). The weather stations are not evenly distributed across the country, with more stations located in central and eastern China and fewer stations in western China, especially on the Tibetan Plateau (Liu et al. 2004; Xu et al. 2006). To estimate the mean value over the entire country, the wind speed was spatially averaged according to an area-based weighting factor for each station (Fig. 1). The area that each station controls was determined by a

Fig. 1 Spatial distribution of stations used in this study and their Thiessen polygons

Thiessen polygon (Thiessen 1911), which was created using ArcGIS software. One potential problem is that Thiessen polygon only takes the geometric configuration into account and does not make use of information regarding typical surface structure and orography. However, surface wind speed is essentially controlled by the general weather patterns, so its impacts are neglected in this study, but it needs further investigations.

In addition to the observed data, the US National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) wind speed at 10 m above surface data were also used as a reference. The NCEP/NCAR reanalysis uses a frozen state-of-the-art global data assimilation system and a database as complete as possible (Kalnay et al. 1996). The database has been enhanced with many sources of observations not available in real time for operations, provided by different countries and organizations (Kalnay et al. 1996).

2.2 Methods

The simple linear regression method was used in this study to report the linear trend magnitude and to test whether this trend magnitude was statistically significant. The significant level α=0.05 was adopted.

Cluster analysis, a numerical technique which tries to allocate objects into groups, or clusters, was used in this study to categorize the temporal patterns of annual wind speed in China. It generally follows some kind of similarity criterion based on the definition of a distance metric measure between two objects and an aggregation algorithm, such that a couple of objects in the same cluster can be considered more similar than a couple of objects belonging to distinct clusters (Everitt 1977; Burlando 2009).

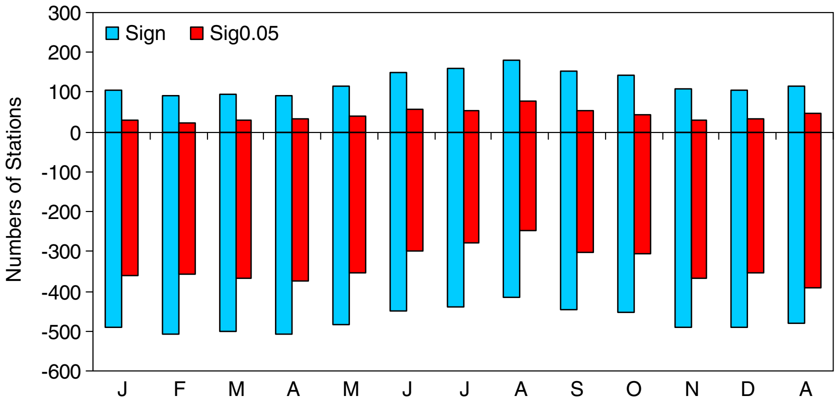
3 Results and discussion

3.1 Wind speed trend and spatial and seasonal distributions

There were 481 out of 597 stations, or 81%, showing a decreasing trend of annual wind speed in China from 1961 to 2007, while the decreasing trends for 392 stations (or 66%), were statistically significant at α=0.05 level (Fig. 2). In contrast, there were 116 stations showing an increasing trend of annual wind speed, and 47 of which (41%) were statistically significant at α=0.05 level (Fig. 2). Summer–early autumn months, such as June, July, August, September, and October, had relatively smaller numbers of decreasing monthly wind speed stations than other months and annual value. For example, the numbers of stations with a decreasing trend of monthly wind speed were 448, 439, 416, 445, and 453 for June, July, August, September, and October, respectively, which were 84—96% of annual number (Fig. 2). These summer–early autumn months accordingly had relatively larger numbers of increasing wind speed stations than other months and annual value. For example, the numbers of stations with an increasing trend of wind speed were 149, 158, 181, 152, and 144 for June, July, August, September, and October, respectively, which were 124–156% of annual number (Fig. 2).

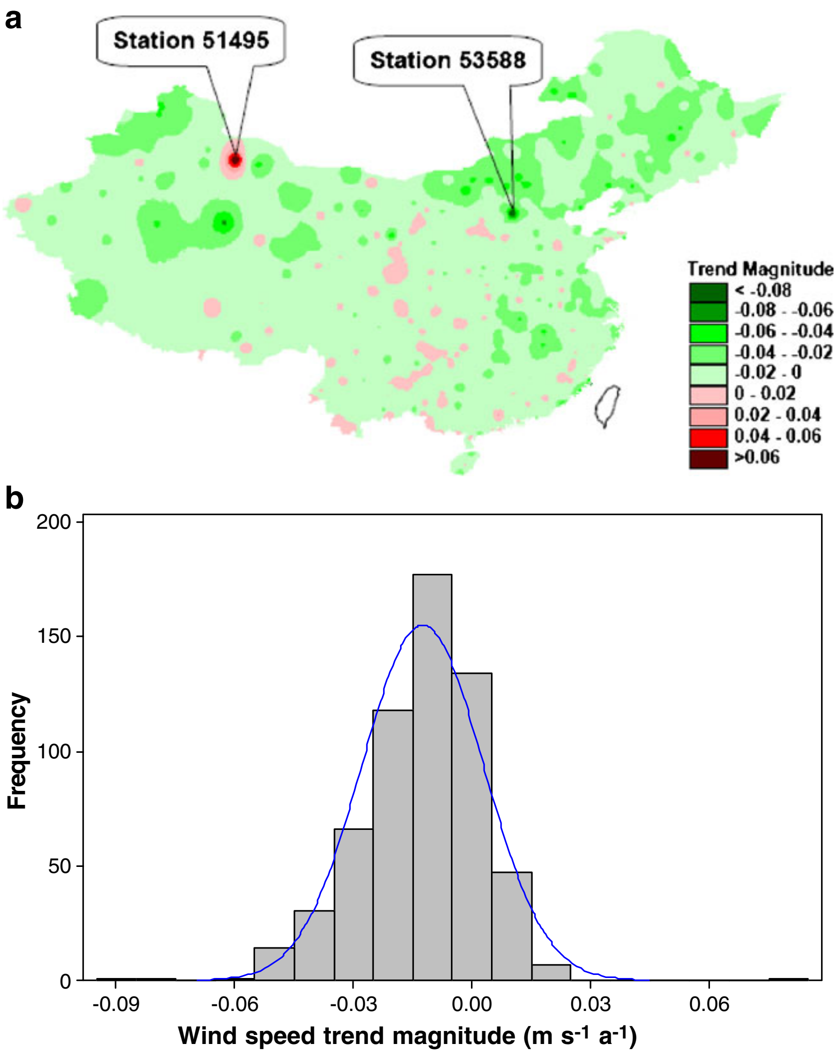
The average annual trend of −0.013 $\mathrm{ms^{-1}a^{-1}}$ was consistent with results of Wang et al. (2004) of −0.011 $\mathrm{ms^{-1}a^{-1}}$ for 1954–2001 and of Jiang et al. (2010) of −0.0124 $\mathrm{ms^{-1}a^{-1}}$ for 1956–2004, and as well as global studies of between −0.004 and −0.017 $\mathrm{ms^{-1}a^{-1}}$ (Roderick et al. 2007; McVicar et al. 2008), but smaller than that (−0.022 $\mathrm{ms^{-1}a^{-1}}$) estimated by Xu et al. (2006) by averaging 305 weather stations for 1969–2000. However, the range of wind speed trend magnitude for these 597 stations varied from −0.093 to +0.077 $\mathrm{ms^{-1}a^{-1}}$, which implied the heterogeneity of wind speed trend

Fig. 2 The numbers of stations with positive and negative trend (*Sign*), and the numbers of stations for which these trend are statistically significant at α= 0.05 (*Sig0.05*)



magnitudes from station to station (Fig. 3). The histogram accordingly showed an unsymmetrical distribution with more negative annual wind speed trend stations (Fig. 3b). The annual wind speed linear trend magnitude of −0.015 to −0.005 $\mathrm{m s^{-1} a^{-1}}$ had the largest number of stations, about 29.7%. There were 134 and 118 stations showing a wind speed trend magnitude of −0.005 to 0.005 $\mathrm{m s^{-1} a^{-1}}$ and −0.025 to −0.020 $\mathrm{m s^{-1} a^{-1}}$, respectively, making them the second and third largest groups (Fig. 3b).

Fig. 3 Spatial distribution (**a**) and histogram (**b**) of annual wind speed trend magnitude of China for 1961–2007



However, the observational wind speed dataset from CMA have not been revised for its changes of anemometers, relocation of stations, or the urbanization impact. There were the changes of the anemometers in China for several times, and the auto-observation stations had been used since the 21st century. It has caused the changes of the wind speeds in China significantly. Many meteorological sites have moved during the period of record, with moves from town centres to airports being particularly common (Trewin and Collins 2005; Fu et al. 2009a), and the influence of urbanization on climate records, as well as influences of changes in the local ground surface or local shelter, has been happened in many parts of world in the last 50 years. Therefore, there are uncertainties associated with this result, especially for the largest and smallest of wind trend magnitudes. For example, annual mean wind speed jumped from 4.7 m/s in 1998 to 8.7 m/s in 1999 at Station 51495 (Fig. 4). For similar reasons, annual wind speed at Station 53588 decreased from 8.8 m/s in 1995 to 6.0 m/s in 1998 (Fig. 4). These observations cannot be physically explained and there must be an anemometer or station changes and/or other reasons. These unusual observations resulted in the largest and smallest wind speed magnitudes being identified at these two stations (Fig. 3a). However, it seems that there are only a very small number of stations with this kind of unusual observation in term of trend analysis (Fig. 3). This justifies the use of this dataset and its associated results, although one research priority in the future would be corrections and homogenization of wind data, which are imperative for climate studies and other applications, especially for the assessment of observed wind speed trends (Wan et al. 2010).

The spatial patterns of annual wind speed trend magnitude showed (Fig. 3a) that the northern China (including northwest, north, and northeast) displayed a relatively larger decline magnitude and southern China a relatively smaller decline magnitude. The increasing trend area, located in the central regions of China from north to south, was about 5% of the entire China and was spatially scattered spots without a continuous bulky area. This spatial distribution of wind speed trend was consistent with previous studies, e.g., Wang et al. (2004), Ren et al. (2005), Xu et al. (2006), and Jiang et al. (2010).

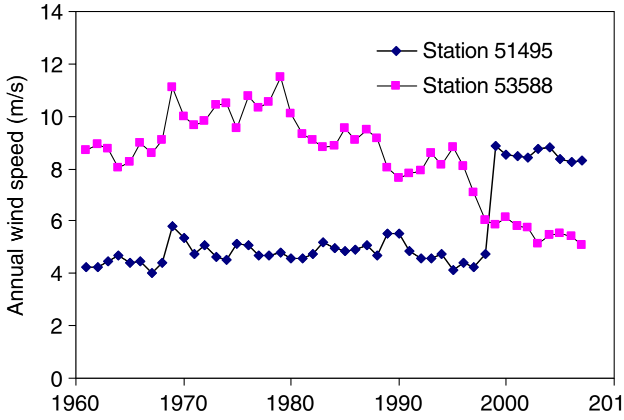


Fig. 4 Time series of annual average wind speed for Stations 51495 (the largest trend magnitude) and 53588 (the smallest trend magnitude) for 1961–2007

The monthly and seasonal wind speed trend magnitudes indicated that summer (June–August) and autumn (Sep–Nov) seasons had slightly smaller trend magnitudes and spring (March–May) season had a slightly larger magnitude than the annual value (Fig. 5). The monthly wind speed trend magnitude in August was the smallest with a magnitude of −0.0092 $\mathrm{ms}^{-1}\mathrm{a}^{-1}$, or about 72.4% of the annual value, while April has the largest magnitude of −0.0158 $\mathrm{ms}^{-1}\mathrm{a}^{-1}$, or about 124.2% of the annual value (Fig. 5). June, July, August, September, and October had a wind speed trend magnitude being less than the annual value, while the other months had a larger magnitude than the annual value.

3.2 Temporal variation of annual wind speed

The time series of China-weighted-average annual wind speed showed four phases: two relative steady periods from 1961 to 1968 and 1969 to 1974 with a sharp step change in 1969, followed by a long-term statistically significant decline phase from 1974 to 1990s, and another relatively steady phase for 1990s–2007 (Fig. 6a). This may partly explain the difference of our results with those of Xu et al. (2006), which focused on the study period of 1969–2000, but consistency with results of other studies with staring periods in 1950s and early 1960s, such as Wang et al. (2004), Ren et al. (2005), Xu et al. (2006), and Jiang et al. (2010).

The sharp step change of annual wind speed in 1969 may attribute to the change of wind speed observation instrument in China (Wang et al. 2004; Ren et al. 2005; Jiang et al. 2010). A comparison of overall wind speed change for two consecutive years at 597 stations used in this study indicated that the mean annual wind speed changes were 0.028 m/s (1.2%), 0.267 m/s (12.4%), and −0.091 ms (−2.9%), for 1968–1967, 1969–1968, and 1970–1969, respectively. There is an obvious biennial oscillation of surface wind (Fig. 6a), but the abnormal value of wind speed change magnitude for 1969–1968 confirms that this sharp step change in 1969 resulted from the observation instrument change in China. If a station was considered as an "outlier" when its annual mean wind speed in 1969 was 20% greater than that in 1968, then there were 137 stations falling into this category. The average annual wind speed trend magnitude for this 137 station was −0.0089 $\mathrm{ms}^{-1}\mathrm{a}^{-1}$ due to this sharp change, while

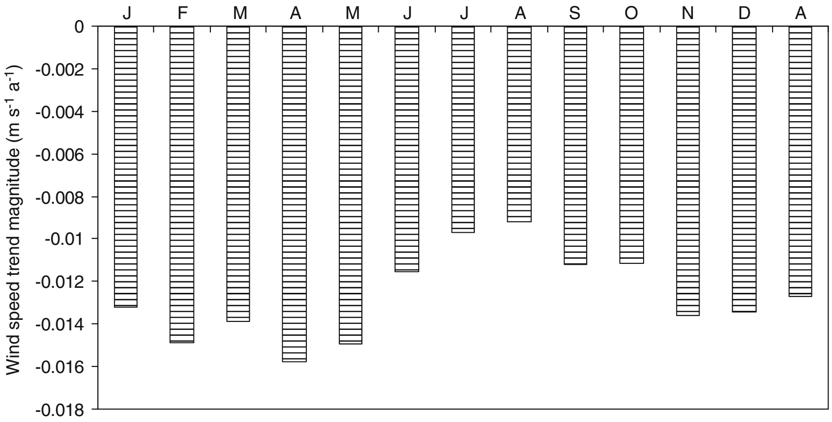


Fig. 5 Monthly distribution of wind speed trend magnitude of 1961–2007 for China

the average wind speed trend magnitude for the rest 460 stations was $-0.0150\ \text{ms}^{-1}\text{a}^{-1}$, or 68.5% larger.

The magnitude of China-weighted-average wind speed trend for 1961–2007 could increase into $-0.017\ \text{ms}^{-1}\text{a}^{-1}$, if we assumed that the mean annual wind speed of 1961–1968 was equal to that of 1969–1974. This assumption was supported with NCEP/NCAR 10 m wind speed, whose average annual wind speeds for China were 2.32 and 2.28 m/s for 1961–1968 and 1969–1974, respectively, and statistical testing results indicated that we could not reject the hypothesis that the mean values for two periods were the same. If only 1974–1992 data were used, the annual wind trend magnitude in China could be as high as $-0.029\ \text{ms}^{-1}\text{a}^{-1}$, which was not only higher than the reported global studies of between $-0.004\ \text{ms}^{-1}\text{a}^{-1}$ and $-0.017\ \text{ms}^{-1}\text{a}^{-1}$ (Roderick et al. 2007; McVicar et al. 2008), but also higher than $-0.022\ \text{ms}^{-1}\text{a}^{-1}$ of Xu et al. (2006). Therefore, it could be concluded that the consistency of instrument used—as well as study period—was a really critical factor for wind speed trend analysis, and the wind speed studies with starting period before 1969 may underestimate the wind speed trend magnitudes.

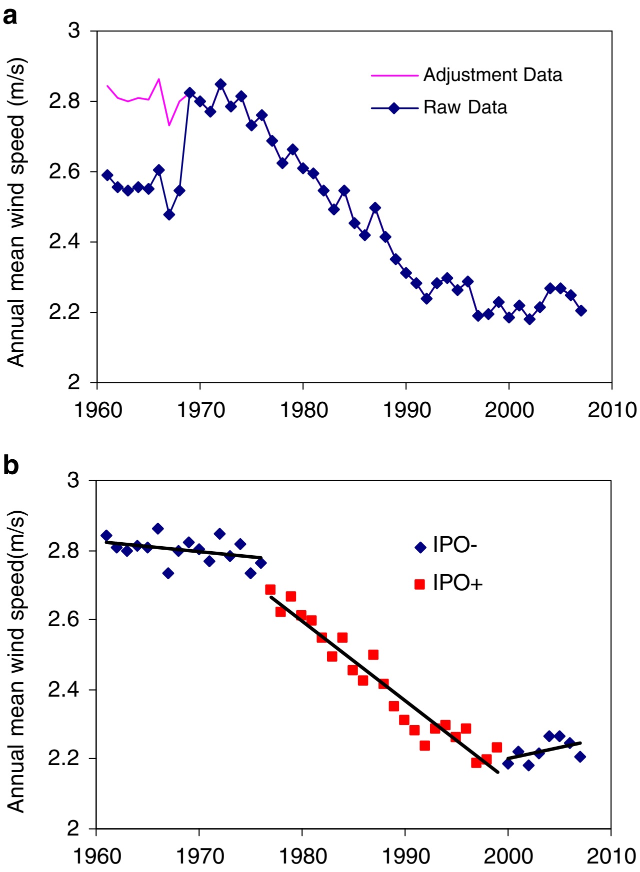


Fig. 6 **a** Time series of China-weighted-average wind speed and **b** trend magnitudes for IPO-positive and IPO-negative phases

3.3 Temporal variation and IPO

The relationship between China-weighted-average annual wind speed and IPO indicated that during a negative IPO phase, it usually did not show a wind speed decreasing trend; while a positive IPO phase was associated with a statistically significant wind speed decreasing trend (Fig 6b). The trend magnitude was much larger during a positive IPO phase than that during a negative IPO phase (Fig. 6b). The IPO (Folland et al. 1999, 2002) displays similar sea surface temperature (SST) and sea level pressure (SLP) patterns as the Pacific decadal oscillation (Mantua et al. 1997), but affects both the north and south Pacific. It is a pattern of Pacific climate variability that shifts phases on at least interdecadal time scales, usually about 15 to 30 years. During a "warm" or "positive" phase, the western Pacific becomes cool and part of the eastern Pacific warms; during a "cool" or "negative" phase, the opposite pattern occurs (Fu et al. 2009b). Since the changes of warm and cool phases of IPO are associated with SST and SLP patterns, it is understandable that it could affect the wind speed in China, which has a typical East Asia monsoon climate.

A wind speed trend magnitude comparison between IPO-positive and IPO-negative phases was made as below formula to further investigate the relationship between

IPO phase and wind speed in China spatially and seasonally:

$$
\begin{aligned}
\mathrm{TD} &= \mathrm{Trend}_{\mathrm{IPO}+} - \mathrm{Trend}_{\mathrm{IPO}-} \\
&= \mathrm{Trend}_{1977-1999} - \frac{\mathrm{Trend}_{1961-1976} + \mathrm{Trend}_{2000-2007}}{2}
\end{aligned}
$$

Spatial distribution of TD indicated that 76.4% of China showed a smaller wind speed trend magnitude during IPO-positive phase than during negative phases, i.e., a negative TD value; 74.6% of which, or 57.0% of the entire China, had a TD value within −0.05 $\mathrm{m\,s^{-1}a^{-1}}$ for (Fig. 7). On the other hand, 23.6% of China showed a larger wind speed trend magnitude during IPO-positive phase, which are mainly located in the eastern China (Fig. 7). This implies the complicated physical processes and mechanism how the IPO/PDO (Pacific decadal oscillation) influences the wind speed in China differ from region to region and this conclusion is consistent with results of previous studies. For example, Tuller (2004) has reported a similar relationship between IPO/PDO and wind speed in Canada. Parker et al. (2007) have noted that anomalous westerlies over the tropics and anomalous cyclonic circulation over the North Pacific when the IPO is positive, implying weakened easterly trades in the tropical Pacific and a deepened Aleutian low in the North Pacific. The associated subsurface temperature anomalies in the tropical Pacific are characterized by a warmer upper thermocline in the central and eastern tropical Pacific and a colder lower thermocline in the western and central tropical Pacific. Salinger et al. (2001) concluded that the IPO modulates regional temperature variability on a decadal time scale including the background of global warming trends and demonstrated that the IPO modulates decadal precipitation trends, and it modulates the interannual response of temperature and precipitation to ENSO over the South West Pacific region. The most recent phase of the IPO has enhanced teleconnections with ENSO in some parts, and weakens them in other parts of the region.

The seasonal wind speed trends have different signs for winter, spring, and summer during two IPO-negative phases of study periods, i.e., negative trends for 1961–1976 and positive ones for 2000–2007 (Fig. 8). The autumn is the only season when seasonal wind speed trend is consistent for these two IPO-negative phases (Fig. 8). The seasonal wind speed trends seem consistent during IPO-positive phase (1977–1999) with spring season having the largest negative trend magnitude and autumn season the smallest (Fig. 8).

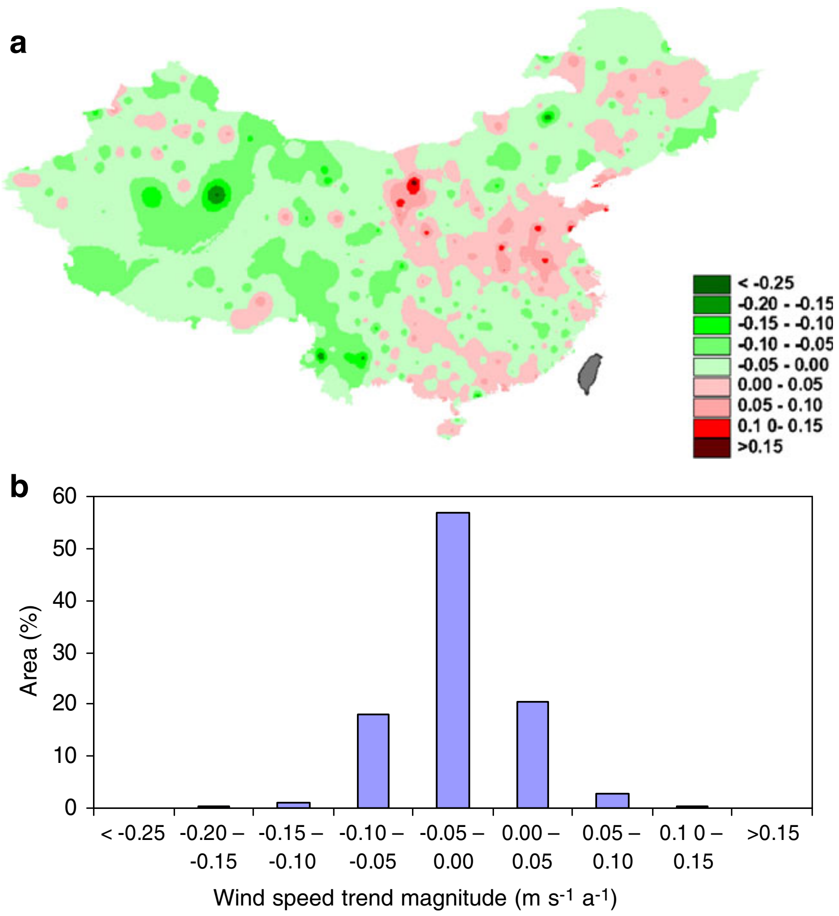
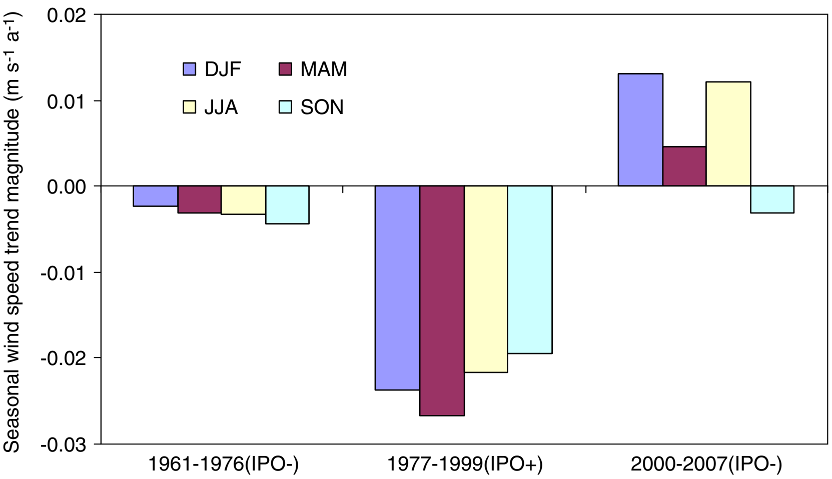


Fig. 7 Spatial distribution (**a**) and histogram (**b**) of annual wind speed trend magnitude difference between IPO-positive and IPO-negative phases

Fig. 8 Seasonal wind speed trend magnitudes during IPO-positive and IPO-negative phases



Besides the changes of IPO phases, another theory to explain why the annual mean wind speed of China has not shown a decreasing trend since early 1990s is the reversing global dimming. Global dimming is the reduction in the amount of global direct irradiance at the Earth's surface that was observed for a few decades after the start of measurements in 1950s. This trend reversed during the early 1990s. Since it happened simultaneously as the changing point of annual wind speed trend, it has also been used to explain the wind speed temporal variations. This conclusion is supported by Xu et al. (2006) and Yang et al. (2009) showing a positive relationship between the annual mean of wind speed in China and solar radiation, and a close correlation, temporally and spatially, between sunshine hours and wind speed in North China. However, the challenging concern for this hypothesis is that it cannot explain the spatial distribution of wind speed trend magnitudes. For example, the decreased solar irradiance trend rates were almost the same for northeast and southwest China (Liu et al. 2004), but their wind speed trend magnitude was different: The wind speed decreasing magnitude of northeast China was more than double that of southwest China (Fig. 3a).

3.4 Spatial similarity of temporal variation of wind speed

The clustering analysis results indicated that the temporal variations of annual wind speed in China for the last 50 years could be grouped into four categories (Figs. 9 and 10), which could be an indicator of complicated climate systems in China and regional differences:

Category I has a similar temporal variation with the overall China average: a sharp step change in 1969 and a continuous decreasing trend for 1969–2007 (Fig. 9a). There were 306 out of 597 (51.3%) stations in this category and it could locate at any part of China (Fig. 9a). The reversing global dimming process and the change phases of IPO in the late 1990s seem not to affect the wind speed trend in these stations. This observation could challenge the current hypothesis to explain the wind speed trend temporal variation in the last 50 years.

There are 53 stations, or 8.9%, in Category II. The breaking points in this category correspond well with IPO phase changes: one in 1970s and another one in 1990s (Fig. 9b). The fact that these stations do not show a sharp change during 1968–1969 implies that the instruments calibrated well in these stations and observations are relatively more reliable in these stations. There is a different principle among the anemometers which was used in China before or after 1968–1969, respectively. The main difference of these two types of the anemometers is the processing principle about both air density and inertia caused by wind speed. Therefore, it maybe entirely reasonable that the wind data at these stations could be used as benchmarks for wind speed data quality control studies. In spatial distribution, these stations locate mainly in the northeast and north portions of China (Fig. 10b).

Category III has 74 stations, or 12.4%, mainly in the east portion of China ranging from northeast, north, to south China (Fig. 10c). The temporal variation of this category was totally different with those of Category I, II, and overall China, and it had the largest number of the breakpoints: the sharpest step change from 1968 to 1969, a slope magnitude change in the late 1970s, another sharp increasing in the late 1980s, a relatively stable period with slightly decreasing trend from 1994 to 2001, and another decreasing period for 2002–2007 (Fig. 9c).

Category IV had a similar pattern with Category III (Fig. 9d), but a larger number of stations (164 stations) and a different spatial distribution pattern (Fig. 10d): they mainly locate in the south China and about 15 stations in the northwest China. It also had a step change in 1969, followed

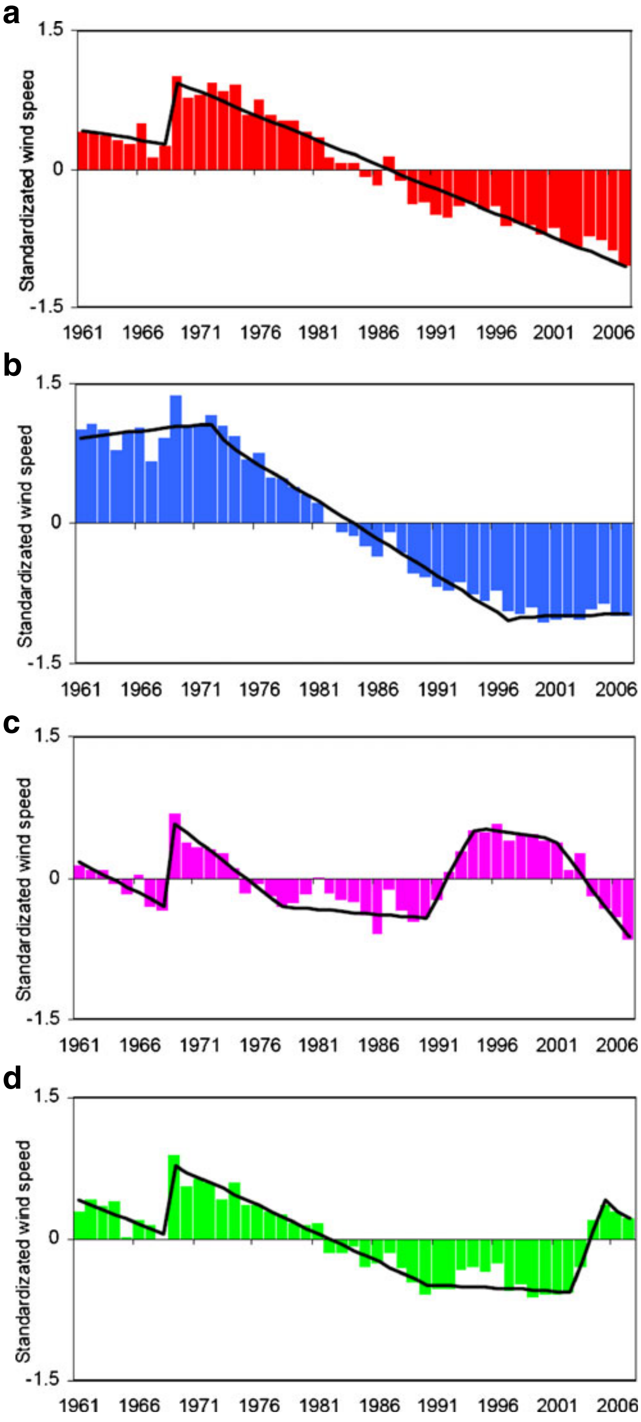


Fig. 9 Four different temporal variation patterns of annual wind speed in China (1961–2007) from cluster analysis

by a continuous decreasing trend until 2003 with a slope magnitude change around 1990 (Fig. 9d). During 2001–2005, these stations showed an increasing trend of annual wind speed, which was unique for this category stations. This could imply the existing of different temporal variations of annual wind speed for the southern and northern China, as their climate systems and mechanism are different.

The critical concern of cluster analysis results is the physical explanation, i.e., two stations, being spatially nearby each other, showed different patterns of temporal variations. The possible reasons include, but are not limit to, data quality control issue, inconsistent instruments/methods, land use and land cover change especially around the observation sites, change of stations locations, and automatic observation practices. There have been many systematic changes in instrumentation, including the general trend to automation of the observation network. A comparison of automatically and manually collected pan evaporation data indicated that daily pan evaporation amounts from the automated observations were generally less than the evaporation measurements from the manual observations (Bruton et al. 2000; Fu et al. 2009a).

3.5 Potential impacts of wind speed changes

The decline of wind speed was proposed to be the measurement evidence of the decline of East Asian monsoon, which may have changed the rainfall spatial patterns in China (Xu et al. 2006). The main source of this rainfall is the southerly transport of moisture from the ocean surface. The weakening of summer monsoon wind speed tends to produce more precipitation in southern China and less moisture transport to region further north, such as North China Plain (NCP), where historical observed data indicated that it had become warmer and drier over the last four decades (Fu et al. 2009b). Furthermore, Xu et al. (2006) have contributed this decline of wind speed, as well as East Asian monsoon, to the global-scale warming. This implies that the water shortage problem in NCP is likely to lead to exacerbated problems for agriculture, industry, urban communities, and the overall regional environment. Given the facts that NCP is one of the most water scarce regions in the world and that the water withdrawals for the three river basins in the NCP are 251.6%, 82.1%, and 88.1% of their respective internal water resources, this has produced a serious challenge for water resources management in the region (Fu et al. 2004, 2009b). Unfortunately, GCMs model outputs (Breslow and Sailor 2002; Hori and Ueda 2006) support this conclusion that the wind speed/East Asian monsoon would reduce in the future global warming scenarios.

Recently, while trying to explain the pan evaporation paradox, i.e., observations across the world show that the rate of pan evaporation at a regional scale has been steadily decreasing over the past 50 years in spite of the observed increases in global average temperature, Rayner (2007) and Roderick et al. (2007), using different Penman-style pan evaporation models, have concluded that trends of daily average wind speed were a dominant factor affecting pan evaporation trends in Australia. Whether these results are

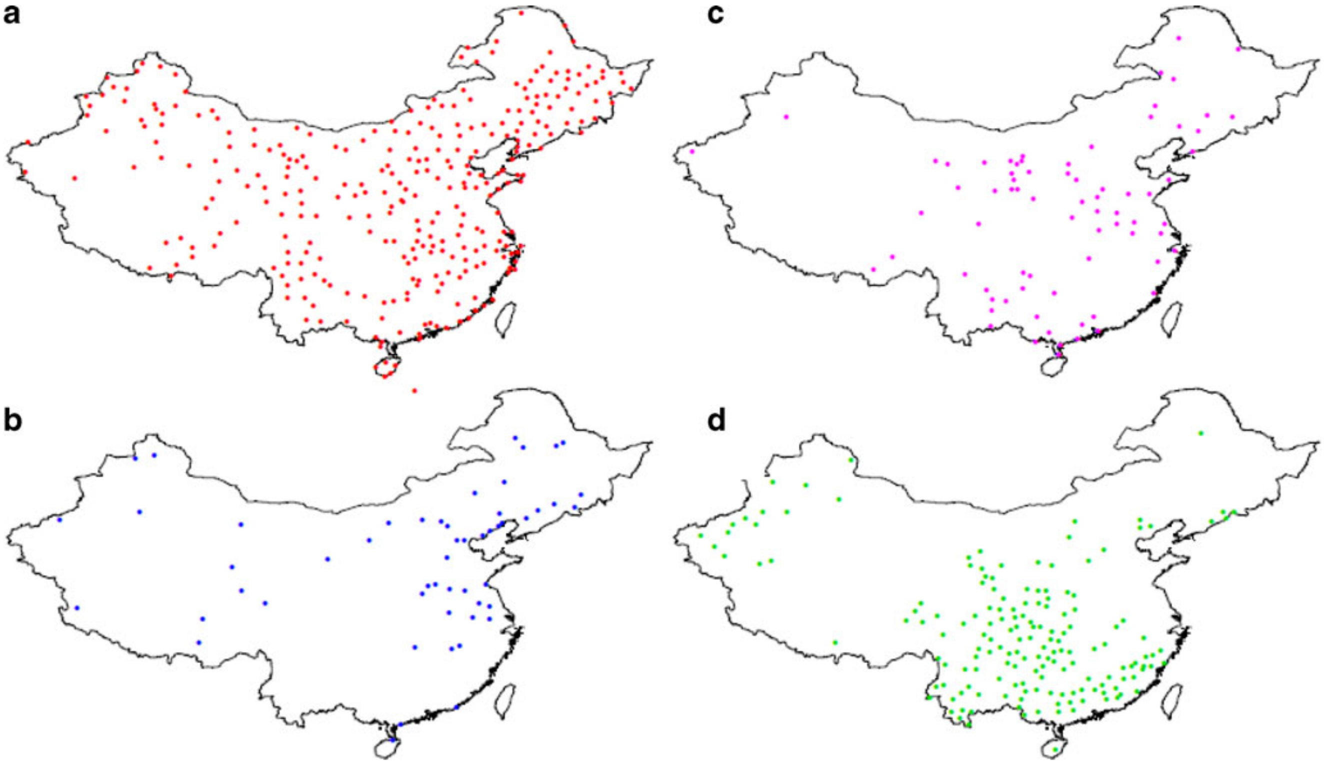


Fig. 10 The spatial distribution of four patterns of annual wind speed temporal variation from cluster analysis in China (1961–2007)

local is difficult to assess and needs further investigations, but it is no doubt that wind speed is an important factor often being ignored in current theoretical explanations of pan evaporation trends (Fu et al. 2009a). Several studies have partly attributed the decreasing trend of pan evaporation in China to the decline of wind speed in the last 50 years. For example, Zuo et al. (2005) have attributed the pan evaporation trend in China to changes of relative humidity, range of daily temperature, and wind speed, basing on regression analysis. Liu et al. (2009) reported that the range of daily temperature and wind speed were two most important factors resulting in pan evaporation trend in China and their relationships are statistically significant at α=0.05 level.

4 Conclusions

Wind speed in China showed a declining trend in the last 50 years: There were 481 out of 597 stations, or 81%, showing a decreasing trend of annual wind speed in China from 1961 to 2007, while the decreasing trends for 392 stations (or 66%), were statistically significant at α=0.05 level. The summer–early autumn months (e.g., June, July, August, September, and October) had relatively smaller numbers of decreasing monthly wind speed stations than other months and annual value, and the northern China (including northwest, north, and northeast) displayed a relatively larger decline magnitude than southern China did. The average annual wind speed trend magnitude of -0.013 m $s^{-1}a^{-1}$ was consistent with results in the literature.

The time series of China-weighted-average annual wind speed showed four phases from 1961 to 2007: two relatively steady periods from 1961 to 1968 and 1969 to 1974 with a sharp step change in 1969, followed by a long-term statistically significant decline phase from 1974 to 1990s, and another relatively steady period for 1990s–2007. Its relationship with IPO indicated that during a negative IPO phase it usually did not show a wind speed decreasing trend, while a positive IPO phase was associated with a statistically significant wind speed decreasing trend in China. The complicated physical processes and mechanisms need further investigation.

Four different temporal variation patterns were identified by using cluster analysis, and their spatial distributions indicated the complicated climate systems in China. The stations not showing a sharp change in 1968–1969 may have the instruments calibrated well and observations are relatively more reliable, and these stations could be potentially used as benchmarks for wind speed data quality control studies. The critical concern of cluster analysis results is the physical explanation, i.e., two stations, being spatially nearby each other, showed different patterns of temporal variations. The possible reasons include, but are not limited to, data quality control issue, inconsistent instruments/methods, land use and land cover change especially around the observation site, change of station locations, and automatic observation practices.

Previous studies have shown that the decreasing wind speed in China was a result of global warming and the decline of wind speed was proposed to be the measurement evidence of the decline of East Asian monsoon (Xu et al. 2006). Since the weakening of summer monsoon tends to produce less rainfall in NCP, the water shortage problem in NCP is likely to lead to exacerbated problems in the future global warming scenario.

Besides the sharp step change of annual wind speed in 1969 which has been identified as a change of observation instrument, there are other uncertainties associated with observed wind speed data, such as observational practice and movement of site locations. Many meteorological sites have moved during the period of record, with moves from town centres to airports being particularly common (Trewin and Collins 2005; Fu et al. 2009a). The influence of urbanization on climate records, as well as influences of changes in the local ground surface or local shelter, has been happened in many parts of the world in the last 50 years. The presence of obstacles near a site is particularly critical for wind and wind-influenced variables (such as evaporation). For example, annual mean wind speed jumped from 4.7 m/s in 1998 to 8.7 m/s in 1999 at Station 51495, and annual wind speed at Station 53588 decreased from 8.8 m/s in 1995 to 6.0 m/s in 1998 (Fig. 4). These observations cannot be physically explained and there must be an undisclosed reason. One research priority in the future would be to have a better data quality control, which is imperative for climate studies and other applications, especially for the assessment of observed wind speed trends.

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