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Changes in near-surface wind speed in China: 1969–2005

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ABSTRACT: This study extends upon previous analyses and details near-surface wind speed change in China and its monsoon regions from 1969 to 2005, using a new dataset consisting of 652 stations. Moreover, causes of wind speed changes are examined. Major results show that most stations in China have experienced significant weakening in annual and seasonal mean wind during the study period. The averaged rate of decrease in annual mean wind speed over China is -0.018 ms^{-1}a^{-1}. Decrease in seasonal mean wind differs. The largest rate of decline is in spring at -0.021 ms^{-1}a^{-1} and the least is in summer at -0.015 ms^{-1}a^{-1}. Spatially, large declines are found in northern China, the Tibetan Plateau and the coastal areas in east and southeast China, while central and south–central China have the least change in their wind speed. Significant weakening of wind speed has occurred primarily in strong wind categories. Decreases in light wind categories are trivial, and light wind has even increased slightly in parts of central China. These changes indicate reduced fluctuations in wind and wind storms in recent decades, contributing to decreased frequency and magnitude of dust storms. The trivial changes in summer winds in east and southeast China suggest fairly steady monsoon winds over the decades.

A main cause of the weakening wind is shown to be the weakening in the lower-tropospheric pressure-gradient force, a result pointing to climate variation as the primary source of the wind speed change. Superimposed on the climate effect is the urban effect. While analysis of winds between urban and rural stations reinstate the urban frictional effect, a peculiar stronger increase in wind at urban stations than at rural stations after the abrupt urbanization since 1990 indicates a new aspect of the urban effect on wind speed. Copyright © 2010 Royal Meteorological Society

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1. Introduction

Wind is an important indicator of the atmospheric circulation. Changes in wind speed are an indication of the circulation change due to either natural or anthropogenic processes. As part of the effort to understand the climate and related circulation changes, several recent studies have examined wind speed changes in regions around the world. For example, Pirazzoli and Tomasin (2003) show that the near-surface wind speeds at 17 coastal stations in Italy decreased considerably from 1951 to the mid-1970s, and the decrease has slowed down or leveled-off since 1980. Brazdil *et al*. (2009) reported more calm surface wind in most of the Czech Republic. Tuller (2004) found that the annual and winter mean winds at stations along the west coasts of Canada weakened during the period from the late 1940s to mid-1990s. Stilling winds also have been observed in the contiguous United States during 1973–2005 (Pryor *et al*., 2009). Reduction in wind speed was reported over 88% of the weather stations in Australia, with an average trend of -0.009 ms^{-1}a^{-1} over 1975–2006 (McVicar *et al*., 2008). In China, Wang *et al*. (2004a) examined wind speed change from 1951 to 2000 and also showed weakened wind speeds, especially in northwest China during winter. Additional details of these wind speed changes are documented by Xu *et al*. (2006a), who showed that the wind has weakened from 1969 to 2000 by 28% at an average rate of -0.021 ms^{-1}a^{-1} (Figure 1 in Xu *et al*. (2006a)). The decline occurred in both winter and summer. Weakening surface wind speed also has been referred to as a major factor causing decreases in surface evaporation (Liu *et al*., 2004; Chen *et al*., 2006; Shenbin *et al*., 2006; Xu *et al*., 2006b; Zhang *et al*., 2007) and dust storm frequency in China (Qian *et al*., 2002; Wang *et al*., 2004b; Liu *et al*., 2005; Huang *et al*., 2006; Yin and Wang, 2007).

The stilling wind was proposed to result partially from weakening pressure gradient between oceans and the major continents. The latter was attributed to temperature increase in land areas in the recent decades due to human-induced increase in aerosol/dust concentration in the atmospheric boundary layer and the subsequent effects on low-level cloud amount and radiation budget

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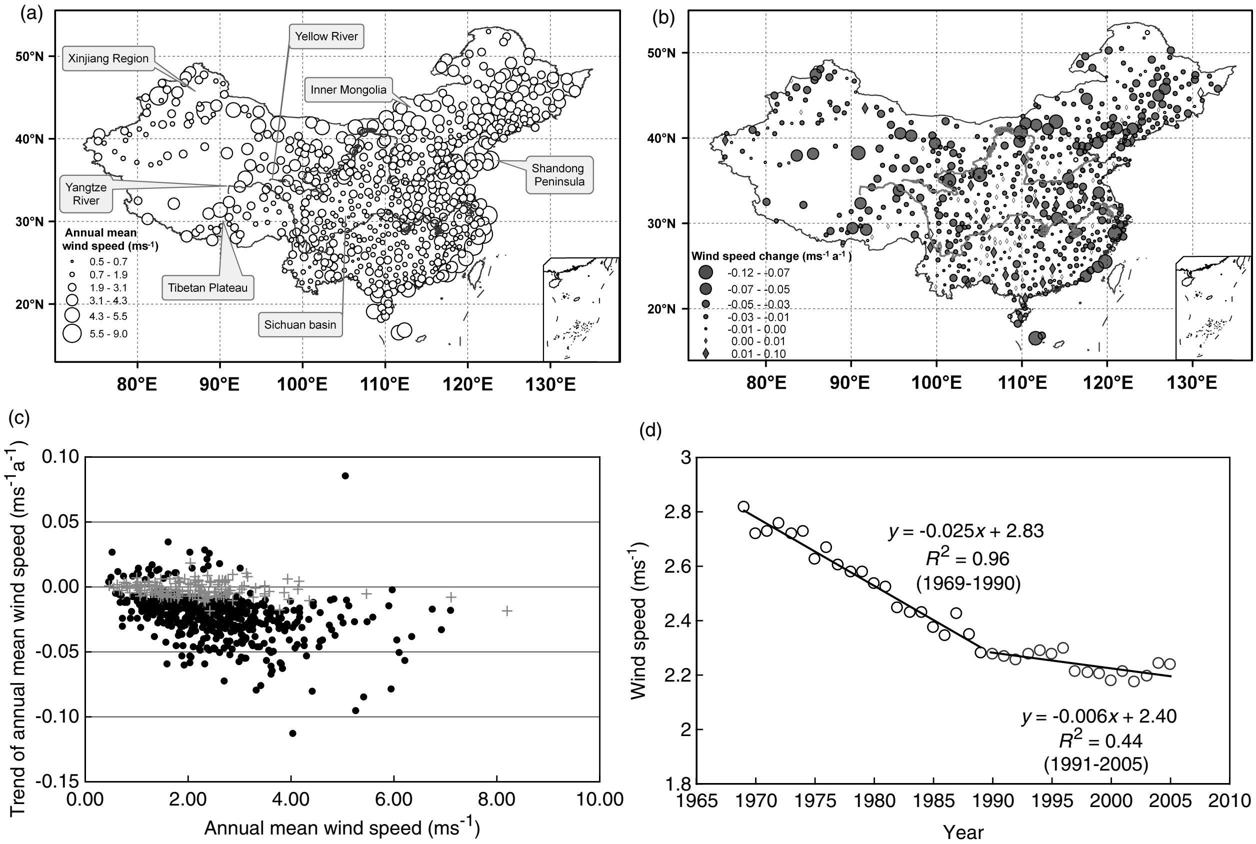

Figure 1. (a) Station annual mean surface wind speed in China. (b) Trend of stations' annual mean wind speed change from 1969 to 2005 (units: $ms^{-1}a^{-1}$). A circle indicates the station's wind speed has decreased; the bigger the circle the larger the decrease. A diamond indicates the station's wind speed has increased; the bigger diamond the larger the increase. A filled diamond or circle indicates that the increase or decrease of wind speed at the station is statistically significant at the 95% confidence level. (c) Trends in mean wind speed change at the 652 stations relative to their mean annual wind speeds (a cross means statistically insignificant and a filled diamond means statistically significant). (d) Temporal variation and trend (solid line) of annual mean wind speed averaged in China.

at the surface (Nazarenko and Menon, 2005; Huang *et al.*, 2006; Trenberth *et al.*, 2007; Lau *et al.*, 2008).

Changes in the near-surface wind speed could have some important environmental and socioeconomic consequences. Zhou *et al.* (2006) showed that the decline of wind speed has resulted in reduction in energy supplies from wind power in China's Pearl River Delta. Liu *et al.* (2005) showed that the expending arid areas in Ordos Plateau of China may have been largely exacerbated by wind speed and direction changes in recent years. Investigating the wind changes can thus improve our understanding of climate change and its impacts on environmental, ecological and socioeconomic systems in China and other nations/regions.

This current study expands on the previous analyses of wind changes in China by using an improved dataset with 652 weather stations, compared with 305 or fewer stations in previous studies (e.g. Xu *et al.*, 2006a). The study period from 1969 to 2005 also is longer than in previous studies. From examining the extended wind records, we provide more comprehensive results describing wind changes across China and its monsoon regions. In addition to providing detailed changes in wind speed at seasonal and annual timescales during 1969–2005, we propose a major cause for the wind speed changes in the past decades. The urban effect on the wind speed changes and its importance relative to the climate change effect also are examined and discussed.

2. Data and methods

Daily wind speed data in China from 1969 to 2005 were originally from the Chinese National Meteorological Center (CNMC). Feng *et al.* (2004) examined these data from 726 stations, testing the spatial and temporal consistency, marking the questionable data and giving suggestions on how to adjust/use them. In their quality-control procedure, Feng *et al.* (2004) evaluated the effects of station move/relocation, among other sources of bias, on data continuity. Available metadata and data consistency check were used to minimize such effects. Based on this quality-controlled daily wind dataset of Feng *et al.* (2004), we further evaluated the stations' winds, which were measured 10 m above the ground, and made additional quality checks on these wind data. Because of strong inhomogeneity, 19 of the 726 stations were excluded from this analysis. In addition, stations containing less than 30 years of data were removed from the dataset. After applying these additional quality restraints we obtained higher-quality data series of daily wind speed at 652 stations for the period from 1969 to 2005 (37 years). Among the 652 stations, the mean and standard deviation of the 'number of years' are 36.6 years and 1.3 years, respectively. These parameters indicate a rich and quality dataset for this analysis.

This improved wind dataset was used to analyse wind speed changes. We applied linear regression, combination of cumulative sum charts (CUSUM) and bootstrapping method (Taylor, 2000) to detect wind speed change and its trend. The statistical significance of wind speed changes was tested using the Student t-test and Mann–Kendall test. In addition, effects of urbanization on wind speed change were evaluated by comparing and contrasting wind speed change between large urban stations and rural stations over the study period. Changes in wind speed in different speed categories also were examined using the method described by Robeson (2004). In this method, daily wind speeds of the 37 years from 1969 to 2005 at a station or averaged over a region were used to calculate the trend of wind speed change for that day. The trend of wind speed change on each day in a month was then categorized, according to the daily mean wind speed of that month, into the 5th–95th mean wind percentiles. This analysis procedure was first applied to averaged wind speed over China and then to winds averaged in six sub-regions that have similar wind variation features. These results provide information regarding wind changes in different speed categories across various regions in China. These sub-regions were identified using a hierarchical clustering method with average linkage within groups; its details are described in Kaufman *et al.* (1990). Wind changes in these sub-regions help reveal monsoon wind variations in China from 1969 to 2005.

To address the question of what may have caused the observed wind speed change from 1969 to 2005, we examined changes in lower-troposphere pressure-gradient force over the same period using the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay *et al.*, 1996). The pressure-gradient force is the large-scale driver of the wind speed (Holton, 1979), and the force represented by the 850-hPa geostrophic wind was calculated to examine how large-scale circulation changes may have affected the surface wind speed variation from 1969 to 2005. Comparison of changes in the geostrophic wind and observed wind helps distinguish the large-scale forcing effect on observed changes in the wind speed. Differences between the observed and geostrophic winds may result from turbulent and eddy forcing on the surface wind. Downward atmospheric momentum transfer by turbulent and eddy mixing can often strengthen near-surface wind speed (e.g. Mahrt *et al.*, 1979; Stull, 1988). Owing to lack of data, the effect of the vertical eddy momentum mixing on surface wind change is not examined. Because this vertical mixing can affect surface wind speed, particularly in unstable stratification with small or negative Richardson number (Mahrt *et al.*, 1979), caution should be observed when using the 850-hPa geostrophic wind to interpret changes in the observed surface wind speed. In addition, the urban frictional force and local turbulence effects rising from terrain (Stull, 1988; McVicar *et al.*, 2007) and soil moisture heterogeneities (Stull, 1988; Ozdogan *et al.*, 2004, 2006) also act to alter the surface winds so that they differ from the pressure-gradient force. The urban effect is evaluated in this study from comparisons of surface wind speed changes between major urban stations and rural stations in China.

3. Results

3.1. Changes of annual mean wind speed in China

Figure 1(a) shows the annual mean wind speeds (1969–2005) at 652 stations in China. Strong winds are found in the south and southeast coastal regions and Shandong Peninsula with the annual mean wind speed ranging from 4.0 to 8.2 ms^{-1}. In inland areas, large annual mean wind speed, ranging from 2.0 to 6.3 ms^{-1}, are shown in northern China from the northeast to Inner Mongolia and to the stations in western China including northern part of the Xinjiang Autonomous Region and northern slope of the Tibetan Plateau. In contrast, weak annual mean winds are in the middle-reach of the Yangtze River basin, especially in the Sichuan Basin.

Changes in the annual mean wind speeds at individual stations are shown in Figure 1(b) by the linear trend of wind change over the period from 1969 to 2005. Inspecting Figure 1(b), we find significant decrease of wind speed in most areas in China over the study period. There are 469 stations showing significant decrease in wind speed (hereafter 'significant' refers to statistically significant at the 95% confidence level). Only 30 stations show significant increase in wind speed. The averaged rate of decrease in annual mean wind speed in China is $-0.018\ ms^{-1}a^{-1}$ for the study period. Comparison of Figure 1(a) and (b) indicates that significant decrease in wind speed has occurred at stations with strong mean wind. As further shown in Figure 1(c), decrease in wind speed at rates greater than $-0.07\ ms^{-1}a^{-1}$ occurred only at stations with annual mean wind speed greater than 2.0 ms^{-1}. Stations with weak mean wind ($<2.0\ ms^{-1}$), such as those in the Sichuan Basin, have smaller rates of decrease, around $-0.01\ ms^{-1}a^{-1}$.

The change in averaged wind speed over all the stations is summarized in Figure 1(d), showing decreasing wind at a nearly constant rate of $-0.025\ ms^{-1}a^{-1}$ from 1969 to about 1990. After 1990 (which is determined by the CUSUM and bootstrapping methods), the decrease in wind weakened. This recent leveling-off in wind speed is coherent with similar slow-down in decrease trend of solar radiation and pan evaporation found in many areas in China (e.g. Wild *et al.*, 2005; Liu *et al.*, 2004). Even with this consistency in check, cautions should be observed in interpreting this recent weakening in wind speed change as a possible indication of climate variation because of the rather short wind records from 1991 to 2005.

3.2. Urban effect on wind speed

Many factors may have affected these observed annual mean wind speed changes. One of them is the urbanization in China and associated massive housing constructions, which could modify local landscapes and influence the wind speed. To examine this effect, we selected 63 stations in urban areas of population >0.5 million and 100 stations in rural areas of population <10 000, based on the population survey in 2000, and compared and contrasted average wind speeds changes between these two groups of stations. To optimally evaluate the urban effect, these urban and rural stations were selected from stations in the same region (similar climate environment) in central part of China between 92° and 122 °E, where stations also are densely located (Figure 1(a)).

The changes in averaged wind speed at these urban and rural stations are shown in Figure 2. A similar rate of decrease in wind speed is shown in both the rural and urban stations from 1969 to 1990. These decreases are statistically significant at the 95% confidence level. Although the wind weakening has the same rate, the average speeds of the wind are quite different, with the rural wind stronger than the urban wind by an average of 0.3 ms^{-1}. Furthermore, different changes also emerged after 1990 between the rural and urban stations. The averaged wind at the urban stations broke the decrease trend and became strengthening from 1990 to 1995 and has since remained nearly steady around 2.3 ms^{-1}. On the other hand, wind at the rural stations has continued decreasing though at a much smaller rate. These differences in changes of wind speed between the urban and rural stations during 1990–2005 indicate a new aspect of urban effect on wind. If the wind speed change in rural stations could be regarded as the *natural* wind speed change, the strong strengthening in wind speed in urban stations since 1990 would indicate an urban effect on wind speed. This effect is however contrary to what we know about the urban frictional drag. As Xu *et al*. (2006a) indicated the urban constructions in China peaked in the late 1980s and early 1990s. If the urbanization had a strong drag effect to weaken the wind speed we should have had seen a larger decrease in wind speed in the urban stations since 1990. The observed strengthening wind at the urban stations, compared to the continuing decreasing wind at rural stations, suggests a new aspect of urban influences on their wind speed changes. This specific influence may be further examined and identified using detailed modelling studies and such work is beyond the scope of this study. It is interesting to point out that similar increase in wind speed also has been observed following the urbanization in southeast Queensland and northeast New South Wales in Australia (McVicar *et al*., 2008).

3.3. Seasonal wind speed change

Because wind varies considerably among seasons, it is necessary to examine seasonal wind changes and their difference. Such difference may shed light on changes in the monsoon climate in China. For example, large decrease in summer wind would indicate the weakening of the monsoons which strongly influence precipitation in southern and eastern China.

Seasonal wind changes in China are shown in Figure 3. Average wind speed of each of the four seasons has decreased from 1969 to 2005, and the decrease is statistically significant at the 95% confidence level. The largest decrease, at the rate of $-0.021\ ms^{-1}a^{-1}$, occurred in spring which also has the strongest wind among all seasons. The weaker winds in the other three seasons, with the weakest in autumn, have relatively weaker decreases. Summer wind has the smallest decrease at $-0.015\ ms^{-1}a^{-1}$, and the decrease in winter wind is $-0.019\ ms^{-1}a^{-1}$.

A comparison of the seasonal wind variations in Figure 3 with the annual mean wind speed change in Figure 1(d) indicates a similar weakening in decrease of wind speed since the early 1990s. This weakening is particularly strong in winter.

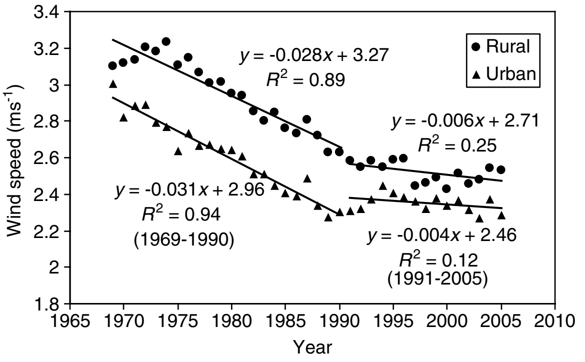

Figure 2. Variations of wind speed averaged over rural and large urban stations for 1969–2005. The rates of wind decrease and their R^2 values are shown in the margin.

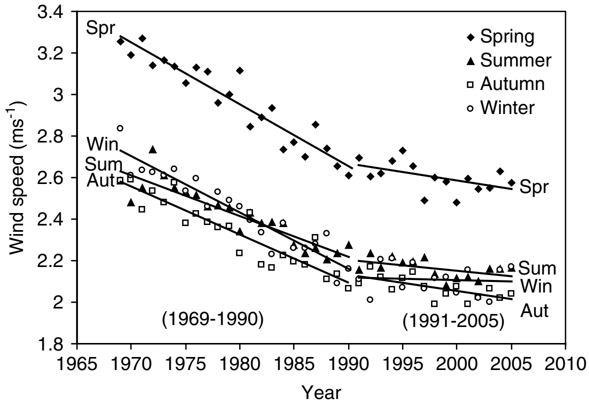

Figure 3. Temporal variations and trends (solid lines) of seasonal mean wind speed averaged in China, 1969–2005. The trends of seasonal wind speed change before and after 1990 are shown by separate lines (winter contains the months of December, January and February; spring has March, April and May; summer has June, July and August; and autumn has September, October and November).

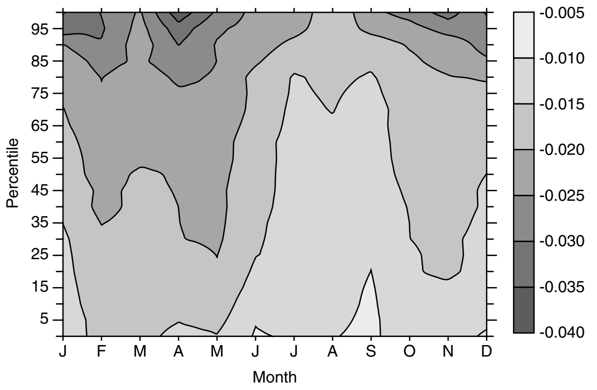

Figure 4. Trend of monthly mean wind speed change averaged in China in different wind speed percentiles, 1969–2005. Trend values are shown by the scale bar on the right, units: $ms^{-1}a^{-1}$.

3.4. Monthly wind speed change in different wind speed percentiles

The change in seasonal and annual mean wind speed is a collective effect of wind changes in various wind speed categories. It is important to examine wind speed change in different wind speed categories because of different implications of these changes. Weakening in strong wind category would suggest reduced wind storms and less-frequent dust storms. Stilling of wind in mid-strength wind categories could indicate more calm days which have impact on air quality and surface evaporation. To understand these details, we evaluated the changes of wind speed in different wind speed categories. Figure 4 shows the changes of monthly wind, averaged over China from 1969 to 2005, at different wind speed percentiles. Examining the variations in Figure 4 we find that wind has decreased in China in all categories of wind speed. Again, larger decreases are observed in stronger wind categories at rate ranging from −0.02 to −0.04 $ms^{-1}a^{-1}$. The largest decrease has occurred in strong wind categories in late winter and spring months, from September through May of the following year. Summer has the least decrease in wind speed in nearly all speed categories.

3.5. Wind speed change in different regions

Because of the complex topography and climate in China, its wind speed change has strong regional features. These features should be examined separately in order to gain better understanding of wind distribution and its variation. To examine these regional features, we first identified the regions in China of similar wind change in the study period using the method outlined in Section 2. Six regions were found from this analysis, and they are shown in Figure 5. We then examined wind speed changes in these different regions at different speed percentiles. The results are summarized in Figure 6.

By examining Figure 6(a)–(f), we find that region A (Figure 6(a)), which is in western part of Xinjiang Autonomous Region (Figure 5), has the largest decrease in wind speed in warm season months from April through September. In these months, winds in nearly all speed percentiles decreased at rates greater than −0.02 $ms^{-1}a^{-1}$. The largest decrease occurred in strongest wind category at rates ranging from −0.03 to −0.05 $ms^{-1}a^{-1}$. Wind speed also decreased in winter months (December–February) but at smaller rates. Unlike region A, region B (Figure 6(b)), in the Tibetan Plateau and the mountainous areas around its eastern fringe, shows the largest wind speed decrease in winter and spring months from January to April. In those months, winds in all speed percentiles weakened at rates greater than −0.02 $ms^{-1}a^{-1}$. Wind speed changed little in the second half of the year. Regions C (the Yellow River basin, Figure 6(c)) and D (northeastern China, Figure 6(d)) both have large decline of wind speed in spring and winter months, although weaker decline also was observed in the strong wind speed categories in the warm season months. A major difference in wind speed change between these two regions is the weakening at a much steeper rate (ranging from −0.02

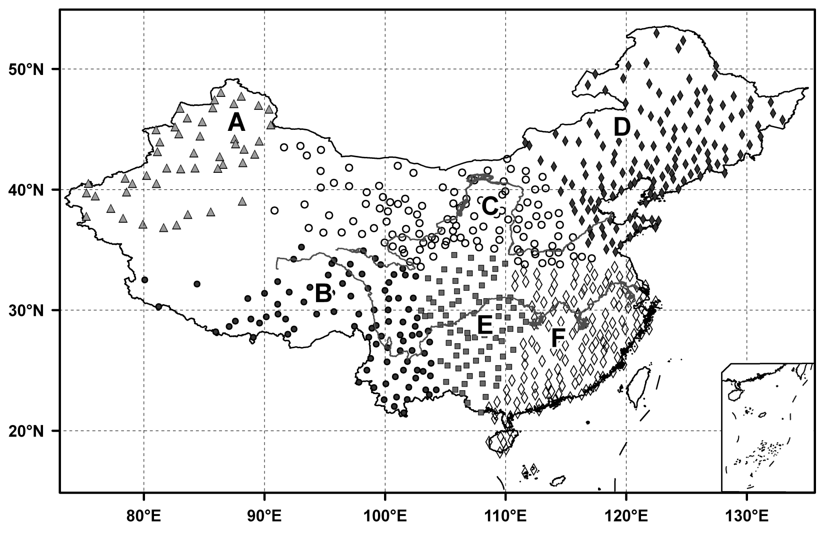

Figure 5. Six sub-regions (marked by different symbols for stations in the sub-regions) with similar wind speed change in China.

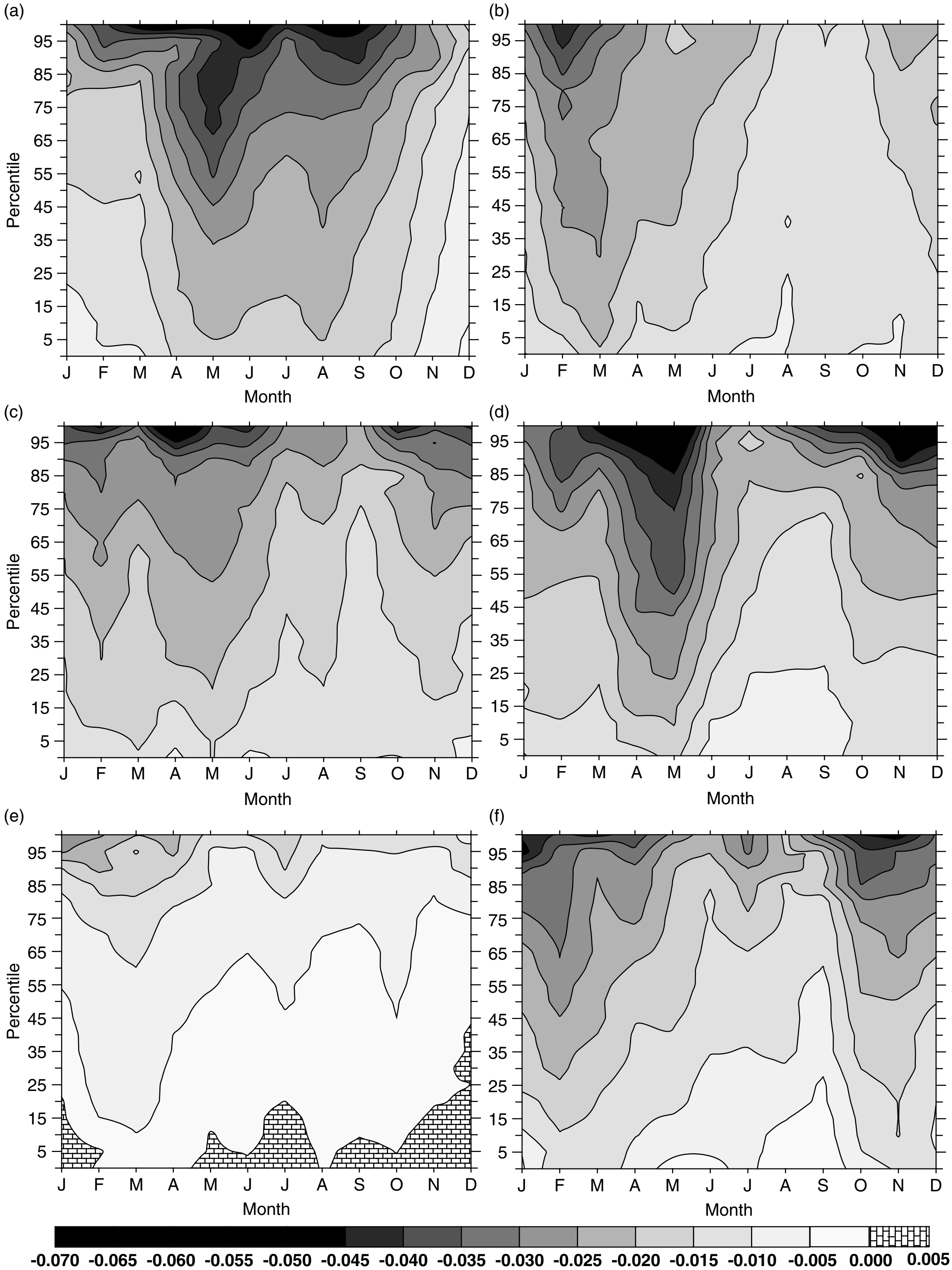

Figure 6. (a)–(f) shows, respectively, the trends of monthly mean wind speed change in different speed percentiles for sub-regions a, b, c, d, e and f, shown in Figure. 5, respectively. Trend values are shown by the scale bar on the bottom, units: $ms^{-1}a^{-1}$.

to -0.07 $ms^{-1}a^{-1}$) and a spread in nearly all speed categories in the spring wind in region D.

Region E (Figure 6(e)), in central China and the middle-reach of the Yangtze River basin, has the least change in wind speed (less than -0.01 $ms^{-1}a^{-1}$ in nearly all speed percentiles) in all seasons. In fact, the region's winds in weak speed categories have strengthened in the last 3 decades. Finally, region F (Figure 6(f)), in southeast China and the lower reach of the Yangtze River, shows larger decline in wind speed in high speed percentiles during the cold season months, opposite to the changes occurring in region A.

It is interesting to note that the wind change in regions C and D (Figure 6(c) and (d)) shows strong decrease in spring, though with different magnitudes between the regions. The stronger decrease in region D could be a result from earlier arrival of spring season with warmer temperatures, hence reducing temperature gradient with the regions in the south (e.g. Hu *et al.*, 2006). While depicting an aspect of regional climate change, the large decease in spring winds in these arid (region C) and semiarid (north of region D) regions may have partially contributed to the decrease of spring and early summer dust storms in these regions (Wang *et al.*, 2004b; Xu *et al.*, 2006b; Yin and Wang, 2007). In this regard, the recent change in climate may be alleviating the dust storm and their influence on major cities downwind in central and eastern China, and beyond (Duce *et al.*, 1980).

In region F (Figure 6(f)), except for some large decreases in very strong wind categories, the small change in summer wind speed suggests minor changes in monsoon wind intensities during the study period. This result suggests fairly steady Asian summer monsoon systems in the recent decades.

3.6. A cause of the wind speed change

A cause of the dominant trend of wind speed decrease across China may originate from continental-scale climate variations and may also be related to the temperature increases in China and the Eurasian continent in recent decades (e.g. Zhai *et al.*, 1999; Yan *et al.*, 2002; Ren *et al.*, 2005; Gadgil, 2007; Trenberth *et al.*, 2007). Increase of temperatures in land areas in winter, for example, could reduce the atmospheric pressure at near-surface levels and weaken the temperature and pressure gradients between the land and adjacent oceans. Weakened pressure-gradient force drives weaker winds, resulting in the observed wind speed decline, as shown in Figure 6. The weaker winter winds in the coastal areas of China (region F) could have been caused by weakening in the pressure gradient between the land and the oceans to the south and the east. Away from the coastal areas, the inland area of region E shares similar land-cover and climate with the region to the east and has the least change in spatial temperature as well as pressure-gradient variations. Thereby, it has the least change in wind speed of all seasons. As we will show next, in accordance to the warming temperatures in mid- and high-latitude land areas in China and the Eurasian continent the lower-troposphere as well as surface pressure-gradient forces have weakened. This weakening can explain a large portion of the observed weakening winds in China from 1969 to 2005. The weakening lower-tropospheric pressure-gradient force and (geostrophic) winds also cause downward eddy mixing to weaken horizontal momentum, compared with the strong lower-tropospheric wind situation. Thus, the eddy mixing is likely to contribute to weakening of the surface wind. On the other hand, more *localized* changes in surface temperature and therefore horizontal temperature gradient and thermal wind in the lower-troposphere, owing to terrain and land-cover heterogeneities, cause deviations of surface wind from the large-scale pressure-gradient force effect and may even increase the near-surface wind speed. Interactions of these competing processes result in rich variations in surface wind changes across geographical regions in China.

To examine changes in the pressure-gradient force, we used the NCEP–NCAR reanalysis of geopotential height and calculated 850-hPa geostrophic wind from 1969 to 2005. The geostrophic wind, $\vec{V}_g$, was used to describe the pressure-gradient force because (1) it is a direct function of the pressure-gradient force, i.e. $f\hat{k} \times \vec{V}_g = \nabla\Phi$, where $\hat{k}$ is the unit vector in the vertical direction, f the Coriolis' parameter in s^{-1}, Φ the geopotential height in m^2s^{-2}, and $\nabla\Phi$ is the pressure-gradient force in the pressure coordinates (Holton, 1979) and (2) $\vec{V}_g$ has a similar magnitude to the actual wind. The 850-hPa pressure-gradient force may be used as a proxy of the surface pressure-gradient force because it is above yet close to the surface in most of the regions in China (except for the Tibetan Plateau). The calculated $\vec{V}_g$ for each season from 1969 to 2005 was further used to compute the trend of $\vec{V}_g$, i.e. $\frac{\partial|\vec{V}_g|}{\partial t}$. These results are shown in Figure 7.

Figure 7(a)–(d) shows the trends of stations' spring and summer wind in China observed for the two periods, 1969–1990 and 1991–2005, when the surface winds have different rates of change (Figure 3). Figure 7(e)–(h) shows the trends of 850-hPa geostrophic wind speed in correspondence to Figure 7(a)–(d). Comparisons of these pairs of figures, i.e. Figure 7(a) *vs* (e), (b) *vs* (f), and so forth, show strong decrease in $|\vec{V}_g|_{850}$ in regions where the observed wind weakened significantly. For example, Figure 7(e) shows trend of weakening spring $|\vec{V}_g|_{850}$ in China from 1969 to 1990, except for the middle-reach of the Yangtze River and most of the Tibetan Plateau. The strongest decrease is in northern China from southern Xinjiang to Inner Mongolia and east–central China. These are also the regions where the strongest decrease in wind speed was observed in the same period (Figure 7(a)). The leveling-off or weakening in decrease of spring wind from 1991 to 2005 shown in Figure 7(b) (compared to Figure 7(a)) is also supported by increase in spring $|\vec{V}_g|_{850}$, particularly in northeastern China.

In summer, strong trend of decreasing $|\vec{V}_g|_{850}$ during 1969–1990 is shown in north and east–central China (Figure 7(g)), similar to that in spring for the same period (Figure 7(e)). In accordance with these trends in $|\vec{V}_g|_{850}$, the observed winds in these regions (Figure 7(c)) show large rates of decrease in wind speed. Similar consistent and comparable trends between Figure 7(h) and (d) also suggests a strong role of the lower-tropospheric pressure-gradient force in the observed surface wind speed changes.

In autumn and winter seasons, changes in sign and spatial pattern of $|\vec{V}_g|_{850}$ also are consistent with the sign and pattern of the trends of observed wind speed changes. Quantitatively, the average trend of $|\vec{V}_g|_{850}$ in China is -0.0059 ms^{-1}a^{-1} for autumn and is -0.0098 ms^{-1}a^{-1} for winter during 1969–1990, smaller but comparable to the observed average trend (Figure 3). These coherent changes in $|\vec{V}_g|_{850}$ and the observed wind speed support the notion that weakening in the lower-tropospheric pressure-gradient force has been a primary cause of the decrease of observed surface winds in recent decades.

4. Summary and concluding remarks

We improved a quality dataset of near-surface wind from 652 stations in China based on the work of Feng *et al*. (2004), and examined variations of the wind speed change from 1969 to 2005. Our results show that most stations in mainland China have experienced statistically significant decline of annual mean wind in this study period, except for some stations in central China. The average rate of decrease in annual mean wind speed over China is -0.018 ms^{-1}a^{-1}, and greater decrease occurred at stations with stronger winds. The decrease was at a much faster rate from 1969 to 1990 and weakened after 1990. While some of these results are consistent with the finding by Xu *et al*. (2006a), who used 305 stations in their analysis, our in-depth analyses of this new wind dataset and the NCEP-NCAR reanalysis data provide more comprehensive understandings of the wind speed changes and a cause of such changes.

The wind speed averaged for each season also has decreased significantly from 1969 to 2005. The largest decrease rate is in spring season at -0.021 ms^{-1}a^{-1}, followed by winter at -0.019 ms^{-1}a^{-1}. Summer and autumn have smaller decrease rates at -0.015 ms^{-1}a^{-1} and -0.016 ms^{-1}a^{-1}, respectively. Wind change also has distinct regional features. In western and northern Xinjiang Autonomous Region, strong decrease in wind speed occurred in the warm season months from April through October. Over the Tibetan Plateau, significant decrease was found in late winter and early spring. Relatively mild weakening in wind occurred in winter and spring months in north–central China, while northeast China has the largest decrease in wind speed in China with strongest weakening in winter and spring winds. The areas across the middle-reach of the Yangtze River and the Sichuan Basin have the least change in wind speed in China. Moreover, in all these regions, larger decreases have always occurred in the stronger wind categories. Large decrease in strong wind categories

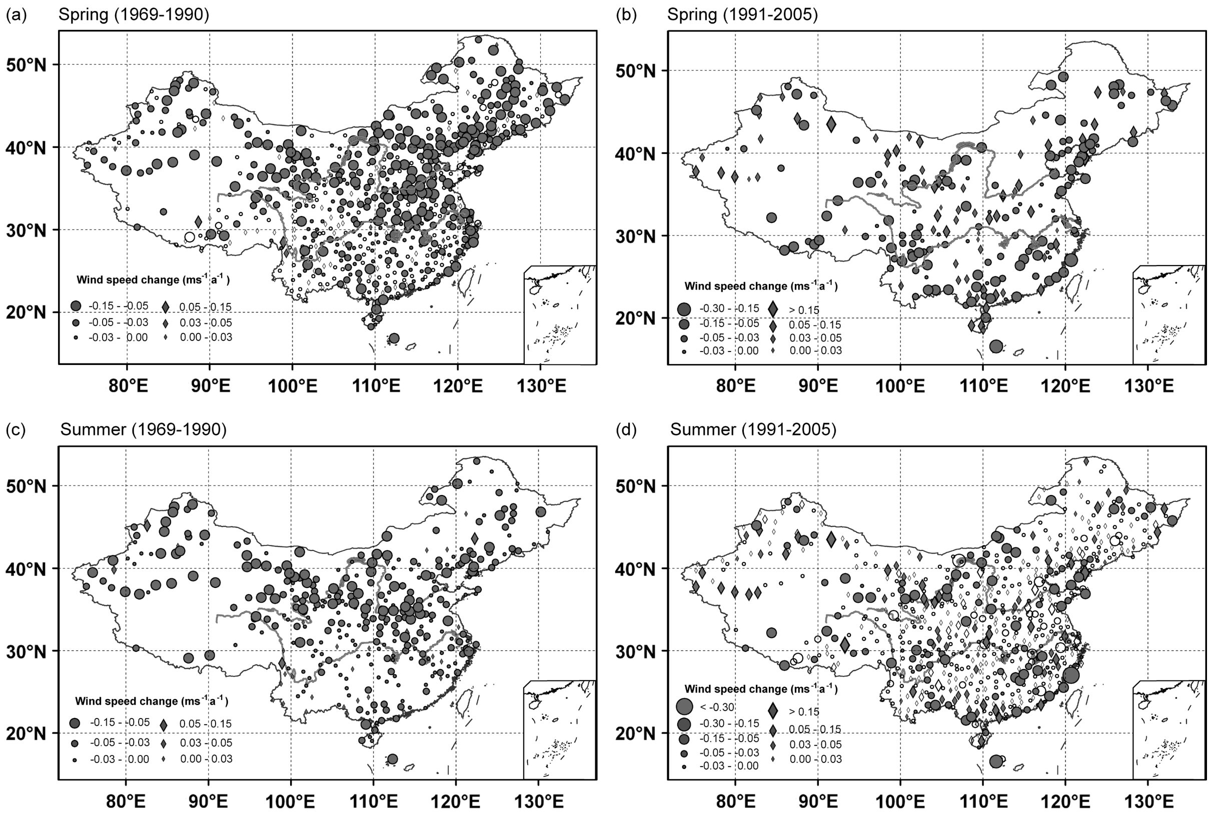

Figure 7. Trends of seasonal mean wind speed changes at stations for (a) spring of 1969–1990, (b) spring of 1991–2005, (c) summer of 1969–1990 and (d) summer of 1991–2005 (units: ms^{-1}a^{-1}). Filled circles or diamonds show trends significant at the 95% confidence level. Trends of seasonal mean geostrophic wind speed change for (e) spring of 1969–1990, (f) spring of 1991–2005, (g) summer of 1969–1990 and (h) summer of 1991–2005 (units: ms^{-1}a^{-1}). Shading indicates decreasing wind speed, and darker shading indicates decrease significant at the 95% confidence level. Blank indicates increasing wind speed, and stippled areas have increasing wind speed significant at the 95% confidence level.

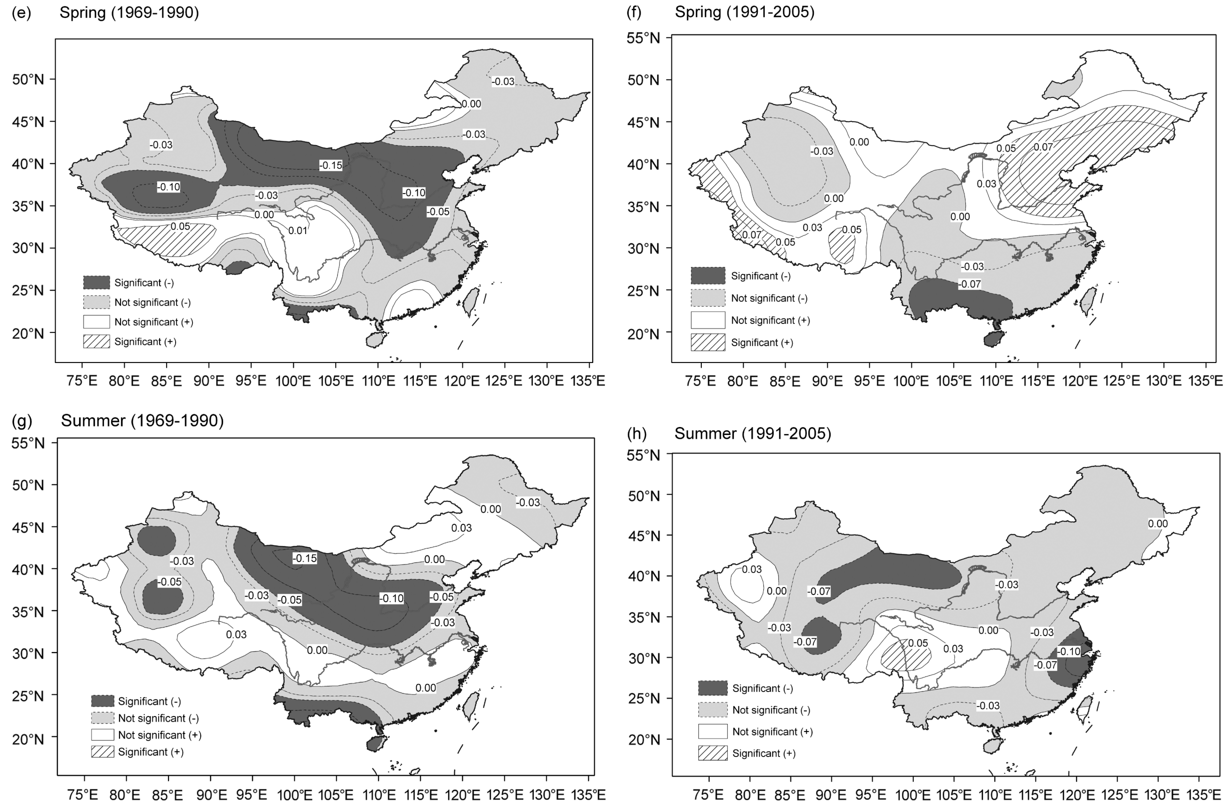

Figure 7. (*Continued*).

and small decrease or increase in light wind categories indicate that the wind speed fluctuations at monthly to seasonal timescales have reduced during the study period.

The large decrease in strong winds of spring months in north and northeast China is consistent with and may have contributed to the recent decline in the number of dust storms in China. Yet, this decrease in strong winds also may lower the potential for wind energy harvest in China. From climate perspective, the small decrease in wind speed in the warm season months in southeast as well as southern part of northeast China would suggest that both the Indian and East Asian summer monsoon winds only changed (weakened) slightly in the past 3 decades.

A physical process contributing to the observed weakening winds is the change in the large-scale atmospheric circulation in China and surrounding regions in the Eurasian continent. This notion is tested and supported by the results from our analysis of the lower-troposphere pressure-gradient force in the past 3 decades. Significant decreases in pressure-gradient force at 850 hPa, a proxy for the near-surface gradient force, are found from 1969 to 1990, and a 'slowing down' of this weakening trend also emerged after 1990. While the large-scale circulation is certainly a primary cause of these pressure-gradient changes, the strong increase in surface temperature, particularly in high-latitude regions, may have influenced the circulation and contributed to weakening the pressure-gradient force. Weakened lower-tropospheric pressure-gradient force further reduces downward momentum transport by vertical eddy mixing, also weakening the surface winds. Identifying these sources helps us comprehend the regional climate variations in the context of the global change.

Superimposed on the circulation and climate effects on the changing wind speed is the human-induced urban effect. It is intriguing that while the urban winds are much weaker than the rural winds their difference narrowed substantially from 1991 to 2005 by much stronger weakening decrease rate of surface wind in urban stations than in rural stations when the urbanization actually boomed in China. This observation which cannot be interpreted by the urban frictional effect on wind suggests a new effect from fast urban development on wind change and deserves further investigation.

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