Impact of Air Pollution on Summer Surface Winds in Xi'an*

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ABSTRACT

By analysis of observation data, this paper demonstrates that pollution particles could reduce surface wind speed through blocking solar radiation to the ground. The comparation between temperature at the lowland meteorological station Xi'an and that over the nearby highland station Mt. Hua suggests that surface solar radiation at Xi'an is reduced due to the increasing anthropogenic aerosols. The reduced surface energy suppresses the atmospheric instability and convective flows, and thus the downward transfer of faster winds aloft is reduced. Consequently, wind speeds near surface are weakened. This reduction of surface winds is shown by the significant reverse trends of wind speeds over the two stations at different elevations. The aerosols' effects on winds are also manifested in the trends of radionsonde wind speed. The decreased surface winds in Xi'an have also reduced local pan evaporation.

Key words: surface wind reduction, air pollution, Xi'an

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1. Introduction

Air pollution aerosols are reported to reduce the surface energy directly by blocking the solar radiation reaching the surface (Che et al., 2005; Koren et al., 2004; Qian et al., 2006). In fact, the aerosol indirect effect also reduces the surface energy. Through this mechanism clouds develop in higher altitude and maintain longer time with more cloud condensation nuclei provided by aerosols (Rosenfeld, 2000; Williams et al., 2002). Consequently, both more frequent cloudy skies and thicker clouds result in less solar radiation reaching the surface. Thus, the atmospheric instability would decrease due to less surface energy caused by the aerosol direct and indirect effects. The local surface winds would decrease with weaker convective movement and vertical energy transfer. Recent studies show that aerosols heat up the atmospheric layer in which aerosol particles are suspending (Koren et al., 2004; Pilewskie, 2007; Ramanathan et al., 2007). The relative warmer air layer acts as the top of the atmospheric inversion, slows the vertical heat transfer, and enhances the stability below it. This is another way the great amount of anthropogenic aerosols suppress surface winds.

Perlwitz et al. (2001) calculated the impacts of dust aerosol radiative forcing on dust aerosol cycle. Their analysis showed that the dust aerosol radiative forcing reduces the downward mixing of momentum within the planetary boundary layer and the surface wind speed. The model experiments by Jacobson and Kaufman (2006) showed that surface winds can be reduced by aerosol particles and aerosol-enhanced clouds. In China, the surface wind speeds have decreased in the past decades (Wang and Zhai, 2004; Xu et al., 2006b). Analysis of radiosonde data in eastern China by Zhao et al. (2006) indicates that the tropospheric instability decreased during the past decades, and this decreasing trend was strongly associated with aerosol loading in this region. In the present study, we use the observed data to analyze the trends of temperature and wind speed at the lowland meteorological

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station Xi'an and the mountain top station Mt. Hua. Our results show that the increased anthropogenic aerosols are greatly responsible for the reduction of surface wind speed at Xi'an.

The concentration of anthropogenic aerosols is increasing during the past decades over Xi'an (Wang et al., 2000; Su, 1998). As expected, the impacts of aerosols would be more pronounced in this region. This study focuses on the reduction of surface wind speed by aerosols at Xi'an in summer (i.e., June, July, and August). First of all, the decrease of surface solar radiation at Xi'an is demonstrated by a contrast analysis of temperature at lowland station Xi'an and highland station Mt. Hua. Secondly, the trends of wind speed four times a day for Xi'an and Mt. Hua show the evident decrease of surface winds at Xi'an where the air pollution layer is much thicker. The wind speed at Mt. Hua increased significantly as compensation for the reduction of winds at Xi'an. As a result, the pan evaporation at Xi'an also exhibits a decreasing trend due to the reduced aerodynamic force.

2. Data

The data used in this study are regular synoptic data observed at the highland station Mt. Hua and the nearby lowland station Xi'an. The data include temperature and wind speed observed at the two stations four times daily at 0200, 0800, 1400, and 2000 BT (Beijing Time), radiosonde wind data at Xi'an at 0800 and 2000 BT obtained from the National Meteorological Information Center of China, and daily pan evaporation and humidity data at Xi'an.

3. Results

3.1 Surface cooling

The warming trend of temperature, the most evident climate change in the past decades, has been well documented at regional and global scales (Karl et al., 1993; Wang and Gong, 2000). Most of the previous studies focus on the long-lived greenhouse gas effect on the climate change. The radiative forcing of anthropogenic aerosols has been paid less attention. With the great amount of industry air pollution and biomass burning smoke releasing into the atmosphere, the effect of aerosol particles' absorbing and reflecting of solar radiation becomes more distinct. Several studies have pointed out the impacts of anthropogenic aerosols on the surface radiation and temperature (Pilewskie, 2007; Qian et al., 2006; Ramanathan et al., 2001; Rosenfeld, 2006). The latest IPCC report suggests that the net effect of aerosol radiative forcing may counteract as much as half of the global warming caused by greenhouse gases (Forster et al., 2007).

The cooling effect of aerosols occurs mostly in the daytime when there is intense solar radiation particularly in the early afternoon. This would result in the afternoon surface temperature decrease while temperatures at other times in the day are less affected. Therefore, temperature at 1400 BT would have a decreasing trend regardless of the influences of greenhouse gases (GHG) and urban heat island (UHI). One character of the GHG effect is that the GHG forcing is more spatially uniform, that is to say, the GHG influences at the lowland station Xi'an and the highland station Mt. Hua are the same. Another character is that the GHG effect changes daytime temperature little but increases nighttime temperature largely. In contrast to the GHG effect, the aerosol cooling effect would be greater at the lowland station Xi'an than at the highland station Mt. Hua due to the thinner aerosol layer over the mountain top. Therefore, the time series of temperature difference (lowland–highland) is employed to neutralize the GHG-induced trends in the daytime. As for the influence of UHI, it would not affect the temperature trend much in the daytime since it is much weaker in summer (Arnfield, 2003) and mainly occurs at night (Huang et al., 2008; Sarrat et al., 2006).

Figure 1a shows the linear trends of the four-time daily temperature for Xi'an in summer (June–August) during the period 1951–2005. As expected, the temperatures at 0200, 0800, and 2000 BT have increasing trends, and the statistical significance levels are $p =$ 0.004, 0.037, and 0.029, respectively. The increasing trends are mainly caused by the GHG effect and partially by the UHI effect. In contrast, the afternoon temperature presented here by 1400-BT observations

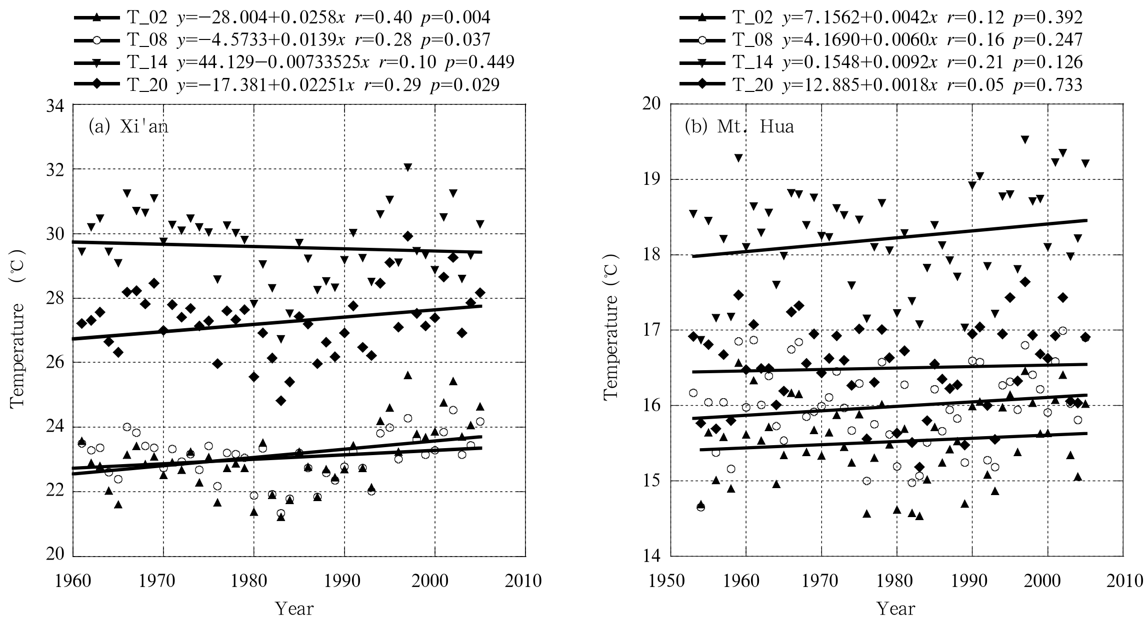

Fig. 1. The JJA surface temperature trends at (a) Xi'an for 1951–2005 and (b) Mt. Hua for 1953–2005. Upward triangles, circles, downward triangles, and squares represent data at 0200, 0800, 1400, and 2000 BT, respectively. Straight lines indicate the linear trends. The slope of the linear trend is denoted by p. Note in Xi'an the trend of afternoon temperature (1400 BT) is opposite to that of the other times mainly due to the aerosol cooling effect. The opposite increasing trend of afternoon temperature at Mt. Hua compared with that of Xi'an is mainly due to the absence of the aerosol cooling effect at high altitude.

has a little decreasing trend (statistically significant at $p = 0.449$). The nearly stable trend of afternoon temperature suggests that besides the aerosol cooling effect, there are other influences like the GHG effect and the marginal UHI nighttime warming. To isolate the GHG-induced trends, the time series of the difference between lowland and highland temperatures is employed, since the atmospheric circulations are almost the same for the two nearby stations with an approximate 120-km distance.

The summer temperature at Mt. Hua has an insignificant increasing trend for all the four observation times during the period 1953–2005 (Fig. 1b). The most salient difference between the temperatures at Xi'an and Mt. Hua is the opposite trends (although not significant) of temperature at 1400 BT. This difference is caused by different concentrations of aerosols at the two sites. For Mt. Hua, there is almost no aerosol cooling effect due to the much thinner aerosol layer at the 2064.9-m altitude. In addition, the significant level for the increasing trend of temperature at 0200 BT at Xi'an is far higher than that at Mt. Hua, suggesting the evident UHI warming effect.

The temperature difference in the afternoon (1400 BT) between Xi'an and Mt. Hua shows a decreasing trend significant at $p = 0.021$ (Fig. 2). The drop in the afternoon temperature difference suggests the aerosol cooling effect at Xi'an since the GHG effect has been eliminated and the UHI effect can be ignored in the daytime. The temperature difference in the late night (0200 BT) exhibits a highly significant increasing trend ($p = 0.0002$), suggesting the UHI nighttime warming in Xi'an. The stable temperature trend at 0800 BT might indicate a balance of the effects from both aerosols and UHI.

3.2 Surface wind reduction

The former section demonstrated that aerosols reduced surface solar radiation in Xi'an. Thus, the decrease of surface heating would induce less convective fluxes (Koren et al., 2004). The convection causes the air with low horizontal momentum to rise, and finally it is replaced by the air with greater momentum from the higher layers. This is the cause why winds

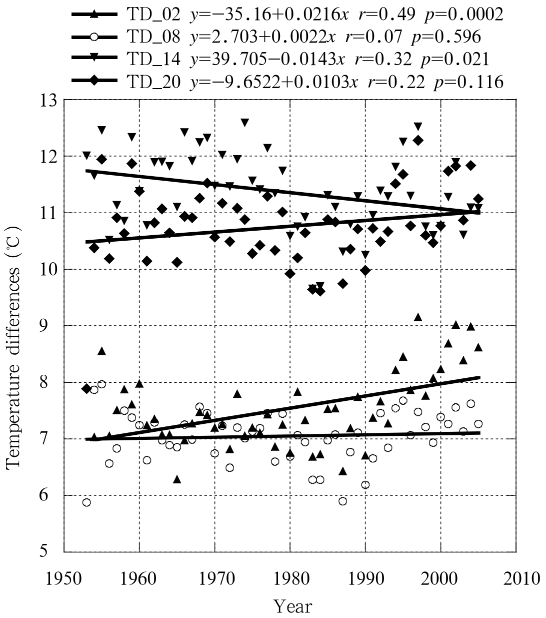

Fig. 2. The JJA trends of the temperature differences between Xi'an and Mt. Hua. Data symbol conventions are the same as in Fig. 1. Note the strong decrease at 1400 BT suggests the aerosol cooling effect while the increasing trend of the temperature difference at 0200 BT might indicate the UHI warming effect in Xi'an.

are usually stronger in daytime than in nighttime. A reduction in the surface wind speed would occur when the convective momentum attenuates. The simulation study by Jacobson and Kaufman (2006) suggests that aerosol particles may reduce near-surface wind speed by up to 8% locally.

The trends of wind speed over Xi'an and Mt. Hua at four observation times are shown in Fig. 3. It is seen that the trends of wind speed at 1400 BT in Xi'an and at the top of Mt. Hua indicate a decrease of 0.13 m s^{-1} per decade in Xi'an, balanced by an increase of the wind speed at the mountain top. This kind of compensation could also be seen in the following: the strongest wind in Xi'an occurs in the early afternoon whereas it appears during late night at Mt. Hua. The increasing trend of wind speed at the mountain top cannot be associated with synoptic causes, because the Xi'an radiosonde data show an opposite trend, i.e., a slight decreasing trend of wind speed at 700 hPa (at height of about 3000 m) (see Fig. 3c). The increasing trend of wind speed at the mountain top is an inevitable result of a decreasing trend in the convection that brings slower air from near the surface to upper levels. The above decreasing trend at the lowland station and increasing trend at the highland station of wind speed are the two sides of the same coin, that is, vertical energy exchanges have been suppressed due to the anthropogenic aerosol cooling effect.

The opposite trends in wind speed at the lowland station and at the mountain top peak in the afternoon as expected, but they also occur at other times of the day. This suggests that the suppression of convection caused by the aerosol surface cooling effect in daytime might persist into night. The decreasing trend of wind speed at Xi'an cannot be induced by changes in synoptic conditions because wind speed increases at all the four observation times at the nearby station Mt. Hua. The surroundings near the station Mt. Hua have not changed, so all the increasing trends of wind speed there cannot be aroused by landuse changes. Suppression of atmospheric instability by the aerosol cooling effect is the governing mechanism for the opposite trends of wind speed at the two nearby stations, considering that other possible factors such as the greenhouse gas effect and the atmospheric circulation change are usually spatially uniform.

3.3 Decline in pan evaporation

Aerosols decrease the surface wind speed through stabilizing the atmosphere. In consequence, the reduction of surface wind speed decreases the aerodynamic force and would bring about a shrink of pan evaporation.

The decreasing trend in summer pan evaporation in Xi'an (figure omitted) is consistent with the fact that pan evaporation decreases at most meteorological stations of China (Qian et al., 2006; Xu et al., 2006a). Evaporation is mainly influenced by temperature, relative humidity, and wind speed. The trends of annual temperature and relative humidity in the same period are opposite (figure omitted) although the changes are not significant and too small to exert influences. Thus, the decrease of wind speed might contribute a lot to the decline of evaporation. In fact, the trend of pan evaporation in Xi'an is highly correlated with the trend of mean wind speed in summer (figure omitted), with a correlation coefficient of 0.68

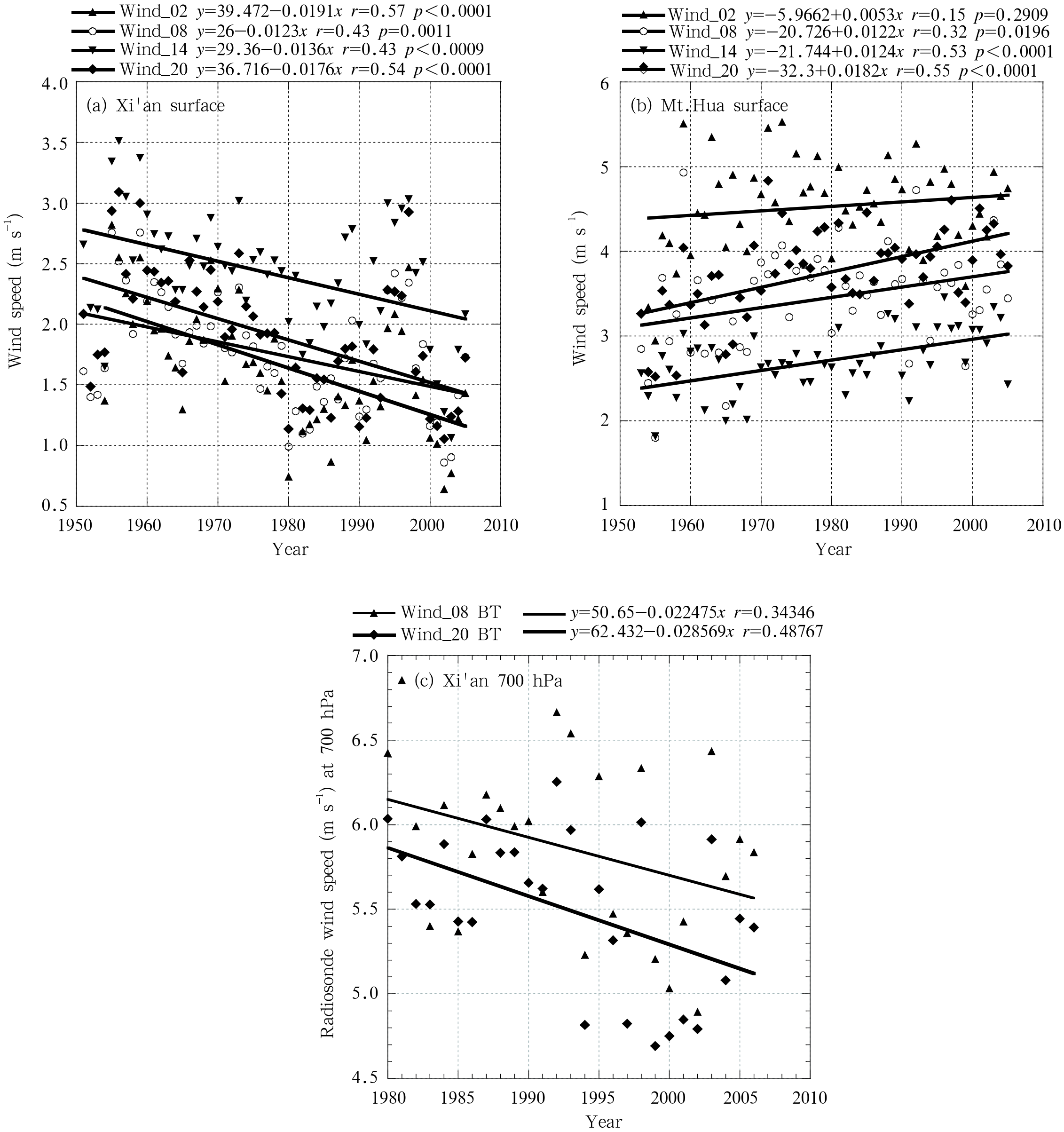

Fig. 3. The JJA trends of surface wind speed at (a) Xi'an for 1951–2005 and (b) Mt. Hua for 1953–2005. Conventions of data symbols are the same as in Fig. 1. The significant opposite trends between the two stations especially at 1400 BT show that the mountain winds increase at the expense of reduction of low-level winds, suggesting reduced vertical exchanges of air and momentum and suppressed convection. (c) The JJA trends of 700-hPa wind speed at Xi'an during 1980–2006. Upward triangles and squares represent data at 0800 and 2000 BT, respectively. The clear decreasing trend of 700-hPa wind speed is consistent with that of surface.

for the time series of the two variables (unfortunately pan evaporation was not observed for more than 20 yr in the early part of the series). The significant correlation indicates that the reduction of wind speed is highly likely a main reason for the decrease of pan evaporation. This consequence has also been found in many other regions (Rayner, 2007; Roderick et al., 2007; Shenbin et al., 2006; Xu et al., 2006a).

4. Summary and discussion

In this paper, the surface solar radiation reduction at Xi'an due to the increasing anthropogenic aerosols is demonstrated by the comparative temperature analysis between observations at Xi'an and the nearby mountain station Mt. Hua. The reduced surface heating induces less atmospheric instability. As a concomitant of surface energy change, the near surface winds also decrease because the reduced atmospheric convection declines the downward transport of faster winds. Analysis of surface wind speed at Xi'an and Mt. Hua and radiosonde wind speed at Xi'an justified the supposition that aerosols reduce local surface winds. The surface wind reduction results in a decrease of surface pan evaporation in Xi'an, explaining the conflicting trend of evaporation under a warming climate background. These variations indicate that human activity induced air pollution may greatly contribute to the regional and even global hydrologic cycle and climate changes.

One may argue if the surface wind reduction is natural variability or query how significant it is when compared to the natural fluctuation of wind speed. It is difficult to quantitatively detect the contribution of aerosols to the decrease of surface wind. However, the observation data at Xi'an and Mt. Hua validated the mechanism that aerosols decrease the surface wind speed by suppressing the convective instability. Our results indicate that changes of wind speed at the two stations are extremely unlikely to be manifestation of natural variability. To interpret the driving factors for the changes one by one is beyond the scope of this paper. Future studies using longer time series and other high quality data may supply more insights into this topic.

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