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ORIGINAL PAPER

New evidence of orographic precipitation suppression by aerosols in central China

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Abstract The correlation between light precipitation events and visibility at Mt. Hua, (Shannxi Province, China) and at the surrounding plains stations was analyzed. Trends and changes in visibility, precipitation, the precipitation difference between Mt. Hua and the plains stations (De) and wind speed over the study area during the years 1980–2009 were also investigated. The significant positive correlation between visibility and light precipitation throughout the study period indicates that light precipitation events, notably orographic precipitation, are suppressed by aerosol pollution in this region. The trend of increasing air pollution aerosols since 1980, represented by visibility at Mt. Hua, ended in 2002 with a decreasing trend observed in more recent years. These changes were mirrored by corresponding changes in De. However, the total precipitation trends at Mt. Hua and the plains stations are consistent in both frequency and amount during the two periods, suggesting that the suppressive effect of pollution aerosols on light and moderate precipitation is the most likely cause for the changes in orographic precipitation at Mt. Hua during this time. The analysis of wind strength suggests that the increase in winds at Mt. Hua is highly related to the aerosol radiative effects; this increase of mountain winds is therefore a potential cause for the reduction in precipitation at Mt. Hua. This research provides further support for the hypothesis that aerosol microphysical effects can reduce orographic precipitation and suggests that aerosol radiative effects might act to suppress orographic precipitation through changes in wind speed.

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1 Introduction

The impact of aerosols on cloud and precipitation has received increasing attention (Ramanathan et al. 2005; Rosenfeld et al. 2007; Li et al. 2011; Tao et al. 2012). Aerosols may affect precipitation through both direct radiative and indirect microphysical effects. Recent studies have suggested that pollution aerosols may act to suppress precipitation (Huang et al. 2007; Giorgi et al. 2003). For example, numerical simulations have hinted that anthropogenic aerosols were responsible for the decreasing trend in precipitation in eastern (Huang et al. 2007) and southern (Cheng et al. 2005) China. Ramanathan et al. (2005) further considered the reduction in monsoon rainfall due to absorbing aerosols and suggested that this effect could weaken the hydrological cycle and lead to a decrease in freshwater supplies in monsoon-dominated Asia. Observational and modeling studies in eastern China have also suggested that increasing aerosol concentrations caused a decrease in light rain in both frequency and amount (Qian et al. 2009), a phenomenon also documented by Liu et al. (2005). This reduction in precipitation could be caused by both aerosol microphysical and radiative effects as well as climate change (Qian et al. 2007). These studies provide a useful regional outlook on the potential negative effects of aerosols on precipitation patterns in Asia and provide valuable information concerning the issue of regional water resources. However, separating the direct and indirect effects of aerosols on precipitation and isolating aerosol effects from other trends in meteorology remain challenging.

Orographic precipitation is highly affected by aerosol microphysical effects because orographic clouds contain modest amounts of liquid water and have a relatively short lifetime (Levin and Cotton 2008). Remote sensing studies and in situ mountain-top measurements indicate that anthropogenic aerosols increase the concentration of cloud condensation nuclei (CCN) and therefore cloud drops (Borys et al. 2003). This alteration of cloud microphysics by aerosols could in turn result in temporal and spatial changes in mountain precipitation (Givati and Rosenfeld 2004). Studying changes in orographic precipitation is therefore a useful means by which to investigate the microphysical effects of aerosol on surface precipitation.

Mt. Hua (2,064.9 m) is located in the Shannxi Province, central China (Fig. 1), in the vicinity of the city of Xian, one of China's most densely populated cities. Local aerosol concentrations in this region are subject to many influences and vary greatly with time. As one of the biggest cities in central China, Xian is the main source of pollution aerosols for Mt. Hua. Coal combustion coupled with dust emission from construction activities and vehicles are the primary sources of pollution aerosols (Zhang et al. 2002). A particulate pollution control program has been underway since 1997 to reduce emissions (Zhang et al. 2007) and natural gas and liquefied petroleum have replaced coal as the main fuel (Zhai et al. 2009; Cheng et al. 2003). Consequently, pollution particulate emissions from this city are today greatly reduced, as evidenced by the notable improvement in air quality in the wider Guanzhong Basin (Zhai et al. 2009).

A recent modeling study by Zubler et al. (2011) has indicated that orographic precipitation processes were substantially affected by the microphysical effect of aerosols, notably for warm precipitation. Reductions in light mountain precipitation were found to occur extensively for seven mountains in eastern China, including Mt. Hua (Yang and Gong 2010). Due to the heavy pollution conditions affecting this region, the reduction in light mountain precipitation by anthropogenic aerosols is estimated to reach 30–50 % at Mt. Hua (Rosenfeld et al. 2007). In contrast, Yang and Gong (2010) attributed the reduction in light summer precipitation on those seven mountains primarily to decreasing wind speeds.

Observation and simulation results indicate that hilly precipitation is also inhibited by aerosol pollution (Lynn et al. 2007; Saleeby et al. 2009; Givati and Rosenfeld 2007; Rosenfeld and Givati 2006; Rosenfeld et al. 2008; Givati and Rosenfeld 2004; Jirak and Cotton 2006). It is therefore of interest to investigate the differences in aerosol effects on precipitation between mountain and plain stations.

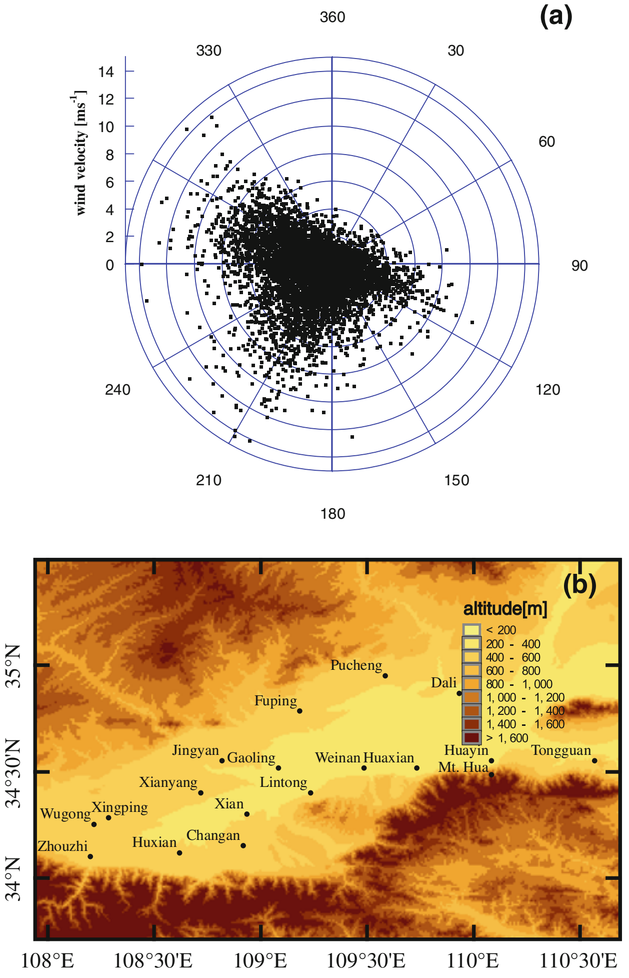

Fig. 1 **a** The distribution of wind speed (m s^{-1}) and direction (°azimuth) for rain days at the top of the Mt. Hua observatory. *Each point* represents the averaged wind vector for one rain day. The winds of all of the rain days from 1954 to 2009 are distributed on the *scatterplot*. **b** The topographic map of the study area and the location of the selected stations

In the present study, we investigate the influence of pollution aerosols on precipitation at Mt. Hua by analyzing the trends in precipitation and related meteorological variables, both at Mt. Hua itself and at nearby plains stations in the Guanzhong basin (Fig. 1b). Trends in wind speed at Mt. Hua and the basin stations were also evaluated. By analyzing: (1) the correlation between light precipitation events and visibility; (2) the trends and changes in visibility and precipitation; (3) the precipitation difference (De) between Mt. Hua and the plains stations; and (4) trends in wind speed, this study aims to investigate the impact of pollution aerosols on orographic precipitation at Mt Hua and understand the possible mechanisms causing the observed changes in precipitation at this site during the years 1980–2009. Particularly, we seek to investigate how changes in aerosol concentrations at Mt. Hua and its surrounding area have affected the suppression of orographic precipitation in this region.

2 Data and methods

Givati and Rosenfeld (2004) proposed a methodology that could reflect the influence of pollution aerosols on orographic precipitation, by analyzing the time series of the ratio (Ro) between mountain precipitation and that at upwind lowland meteorological stations. The underlying assumption of this method is that increasing aerosol emissions would result in a decrease in Ro. Due to the lesser effect of increasing aerosols on plain precipitation, the trend of Ro could reflect their influence on orographic precipitation. Orographic enhanced precipitation over mountain regions are therefore expected to display a long-term decreasing trend in conjunction with increasing aerosol concentrations.

This statistical method has been criticized for its mathematical limitation, namely that the trend in the ratio Ro is affected by the trends of both the numerator and denominator (Alpert et al. 2008). However, this would be a problem only when absolute increases in rainfall occur at both mountain and plain stations, which was not the case in the Mt. Hua region during the studied period (Rosenfeld et al. 2007).

Comparisons of the trends between De and Ro, and between Ro and De normalized to their respective arithmetic mean value, suggest that both series display similar changes, though the significance level for Ro is lower than for De. This may possibly be a result of the mathematical limitation of the ratio method (Alpert et al. 2008).

To avoid any possible concern, De was used in this study to analyze the effects of pollution aerosols on precipitation at Mt. Hua. Because of the moderate amount of precipitation in the study area, yearly rather than seasonal precipitation was used to ensure sufficient rainfall quantities for the analysis.

The trend in De indicates the relative change in precipitation between the mountain station and plains stations in the same climatic setting; that is, if mountain precipitation and plain precipitation both increase (decrease), the trend of their difference (De) would suggest a change in the orographic enhanced precipitation over the mountain. Analyzing this trend in precipitation amount is therefore also required to eliminate the exceptional situations in which the precipitation over the mountain and the plain changed in opposite directions, i.e., when precipitation increased (decreased) over the mountain while it decreased (increased) on the plain.

The primary insights into the effects of aerosols on orographic precipitation are obtained through the detection of change points in aerosol concentration and corresponding changes in the trend of De. Due to the lack of observational data of aerosol concentrations and the abundance of long-term records of visibility in China, visibility is frequently used as a proxy for the concentration of pollution aerosols (Wang et al. 2009; Rosenfeld et al. 2007). To reduce the influence of humidity on visibility, a correction formula is applied to the visibility data when the relative humidity is greater than 40 % and lower than 99 % (Rosenfeld et al. 2007). The influence of fog and precipitation is also taken into account by excluding any visibility records made in the presence of fog or precipitation.

Visibility data were recorded using different classification schemes before and after 1980: data are separated into 10 classes before 1980 but is presented as visibility ranges in units of km after this date. Although the classes for the early period can be transformed into the corresponding range distances, this transformation would lead to a systematic difference in visibility before and after 1980, which may affect the overall visibility trend. Moreover, aerosol emissions have continued to increase after 1980, following the rapid economic development that has occurred in China after this time, and data are complete at all stations. For these reasons, this study is limited to the period 1980–2009.

The timing of reversals in the visibility trend at Mt. Hua was detected using a nonparametric Mann–Whitney test (Tommaso et al. 2009; Kiely et al. 1998; Pettitt 1979). First, the time series of daily corrected visibility was divided into two time series at every data point. For each of the two newly produced time series, the rank sum and its significance were calculated according to the Mann–Whitney test. All of the possible change points were then selected based on these parameters and the corresponding years were chosen as the possible reversal years according to these change points. Second, for every possible reversal year, the time series of daily corrected visibility was further divided into two parts. The significance of the trend for the two parts was checked using a nonparametric Mann–Kendall test (Kendall 1975; Wilks 1995). If one of the two series had no significant trend, the corresponding year was eliminated from the list. Finally, the most significant year was selected as the year when aerosol concentrations began to decrease.

Pollution aerosols can have the effect of decreasing or increasing the onset of precipitation, depending on which side of the mountain they are located on and on the wind direction. To select the upwind lowland stations, we calculated the daily averaged wind vector based on four daily observations during the period 1954–2009. The distribution of these daily winds on rain days at Mt. Hua (Fig. 1a) shows the dominance of westerly winds, with a secondary maximum from the south and a third maximum from the east. The upwind stations are therefore located to the west, south and east of Mt. Hua. The presence of the Qinling Mountain Range to the south of Mt. Hua precludes the presence of many rain gauges and only the Tongguan station (556.6 m) is available to the east. Sixteen stations, all at altitudes below 500 m, are present to the west. These were selected along with the easterly Tongguan station to serve as lowland stations for our analysis, (see Fig. 1b).

The distributions of wind speed and wind direction for all of the plains stations were also analyzed. Distributions at all stations but Tongguan have similar patterns, characterized by prevailing southwesterly winds. At Tongguan, prevailing winds are southeasterly. The different prevailing winds on the two sides of Mt. Hua is a result of the influence of the Qingling Mountain (Fig. 1b). Furthermore, because the study area lies in the Asian monsoon region, the prevailing wind changes seasonally. The wind distributions at Tongguan and three stations in the central Xian valley are presented in Fig. 2a–d.

The percentage of seasonal precipitation and southwesterly and southeasterly winds at Mt. Hua for all rain days from 1954 to 2009 are given in Table 1. This period is long enough to reflect the patterns of daily wind direction at Mt. Hua. As shown in Table 1, the yearly precipitation at Mt. Hua occurs primarily in the summer (May to October) and to a lesser degree in winter (November to April). The

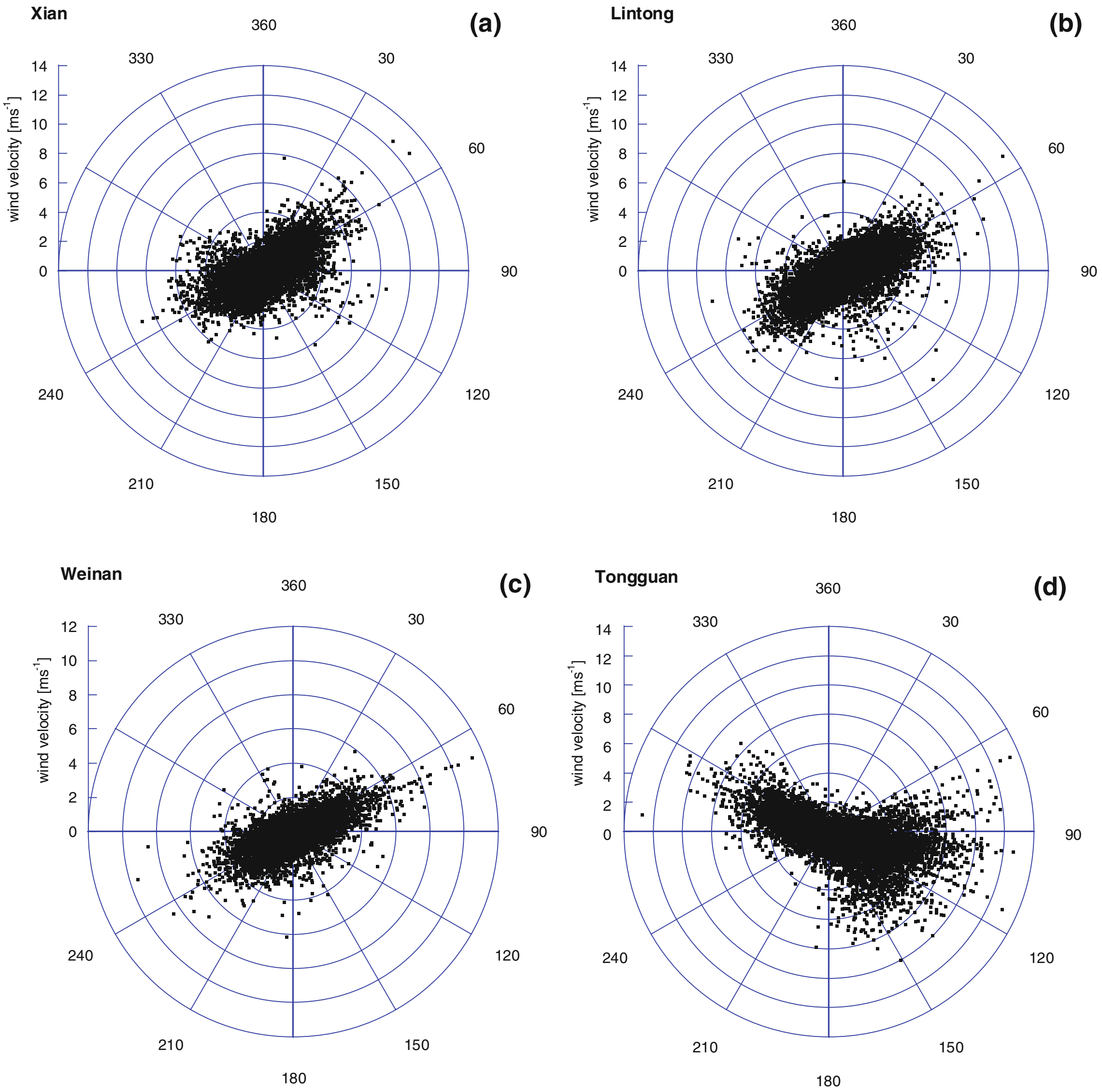

Fig. 2 The distribution of wind speed (m s^{-1}) and direction (°azimuth), from the installation of the station through to the end of 2009, for Xian (**a**), Lintong (**b**), Weinan (**c**), and Tongguan (**d**). As in Fig. 1a, each point in **a** through **d** represents the averaged wind vector for 1 day but data plotted here are not limited to rain days

Table 1 Percentage of seasonal precipitation and wind direction at Mt. Hua for all rain days from 1954 to 2009

	Summer (May–Oct.)	Winter (Nov.–Apr.)
Precipitation	78.4	21.6
Southwest wind	59.4	40.6
Southeast wind	69.3	30.7

southwesterly and southeasterly winds also occur in summer. Therefore, the lowland stations on both sides of Mt. Hua are located upwind from the mountain during the summer.

The dataset used in this study was composed of regular data observed at Mt. Hua and at the 17 lowland stations. The observations of surface winds, visibility and relative humidity are measured at four local times (LT): 02, 08, 14 and 20 LT. Radiosonde wind speed is observed at 08 and 20 LT. The quantity of precipitation was only observed once a day at 20 LT. The surface winds, visibility, relative humidity, and daily precipitation data were quality controlled and provided by the Meteorological Information Center of Shaanxi Province. The daily radiosonde wind speed data were obtained from the National Meteorological Information Centre of China and were only available for Xian.

3 Aerosol effects on orographic precipitation at Mt. Hua

3.1 Light precipitation suppressed by pollution aerosols

As mentioned previously, aerosols have been reported to suppress light rain through microphysical effects over large regions in China (Qian et al. 2009) and specifically over mountains (Rosenfeld and Givati 2006; Rosenfeld et al. 2007). Compared with precipitation over plains, orographic precipitation is more easily affected by aerosols, as demonstrated by the much larger precipitation events observed at mountain stations. In this study, we characterized light rain into 30 grades, based on precipitation amount (1 mm day^{-1} increments from 1 to 30 mm day^{-1}), for both Mt. Hua and the plains stations. Figure 3 presents the correlation between annual light rainfall rate, annual light rainfall amount (<25 mm day^{-1} at Mt. Hua and <2 mm day^{-1} for the plains stations) and averaged daily visibility from 1980 to 2009. The light rain days are significantly correlated with visibility for all of the grades at all stations, with a linear Pearson correlation coefficients larger than 0.6. The correlation coefficients of light rain amounts <25 mm day^{-1} at Mt. Hua and 2 mm day^{-1} for the plains stations average with visibility are 0.48854 and 0.41025, respectively. These coefficients between rain amounts and visibility are much lower for other grades (>25 mm day^{-1} at Mt. Hua and >2 mm day^{-1} for the plains stations).

As shown in Fig. 3a, the effects on orographic precipitation amount are primarily due to the reduction in the number of events in the grade less than 25 mm day^{-1} at Mt. Hua. Our finding is consistent with the results presented by Yang and Gong (2010), in which the reduction in light precipitation over mountains was intensified compared with that of plains stations from 1960 to 2007 in eastern China. Based on the much greater loss of contrast between orographic precipitation and the precipitation on the surrounding plains, Rosenfeld et al. (2007) assumed that plains precipitation was essentially not affected by the microphysical effects of aerosols.

Figure 3 directly reveals the reduction in the number of light rain days and the light rain amount with the decrease of visibility. Both the number of light rain days and the light rain amount are positively correlated with visibility. This may suggest that the reduction in the number of light rain events is closely linked with atmospheric aerosol loading. Therefore, the analysis of the 30-year measurements of light precipitation events and visibility from 1980 to 2009 indicates that light precipitation in the Guanzhong area, notably orographic precipitation at Mt. Hua, is suppressed by aerosols.

3.2 Changes in De and visibility

Visibility has been used as an indicator of aerosol concentration because it is directly associated with atmospheric pollution (Wang et al. 2009; Rosenfeld et al. 2007). At the top of Mt. Hua, the visibility is related to the surrounding aerosol concentration in the free atmosphere. However, the trends in visibility could also indicate that aerosols originate from the boundary layer, likely by detrainment from non-precipitating clouds, as documented in the Amazon (Andreae et al. 2004). To explore the variation in air pollution conditions over time in the study area, the daily average visibility at the top of Mt. Hua is shown in Fig. 4a. A Mann–Whitney analysis of trend changes suggests that visibility decreased from 1980 until 2002, followed by an increased until 2009. These decreasing then increasing trends are significant at a 99 % confidence level and the two periods (1980–2001 and 2002–2009) are hereafter referred to as the first and second period, respectively.

The De is calculated between Mt. Hua and each of the 17 plains stations and the average De represents the difference between Mt. Hua and the averaged precipitation of all plain stations. Because the distribution of all of the De

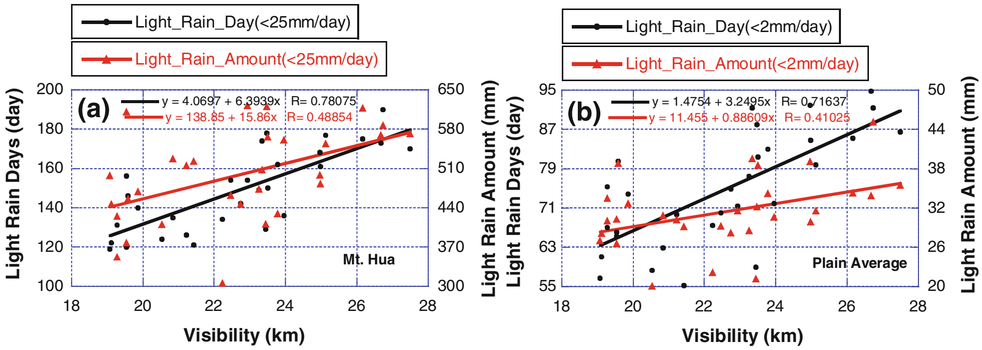

Fig. 3 Correlation between annual light rainfall rate, annual light rainfall amount and averaged daily visibility for **a** Mt. Hua and **b** the plains average from 1980 to 2009. Light rain days and amount are denoted by *dots* and *triangle*, respectively. The visibility is averaged from four corrected daily observations. The light rainfall rate and amount is calculated from each rain gauge station with a daily rainfall of less than 2 mm for the plains stations or 25 mm for Mt. Hua. The *lines* represent a linear regression through all the data

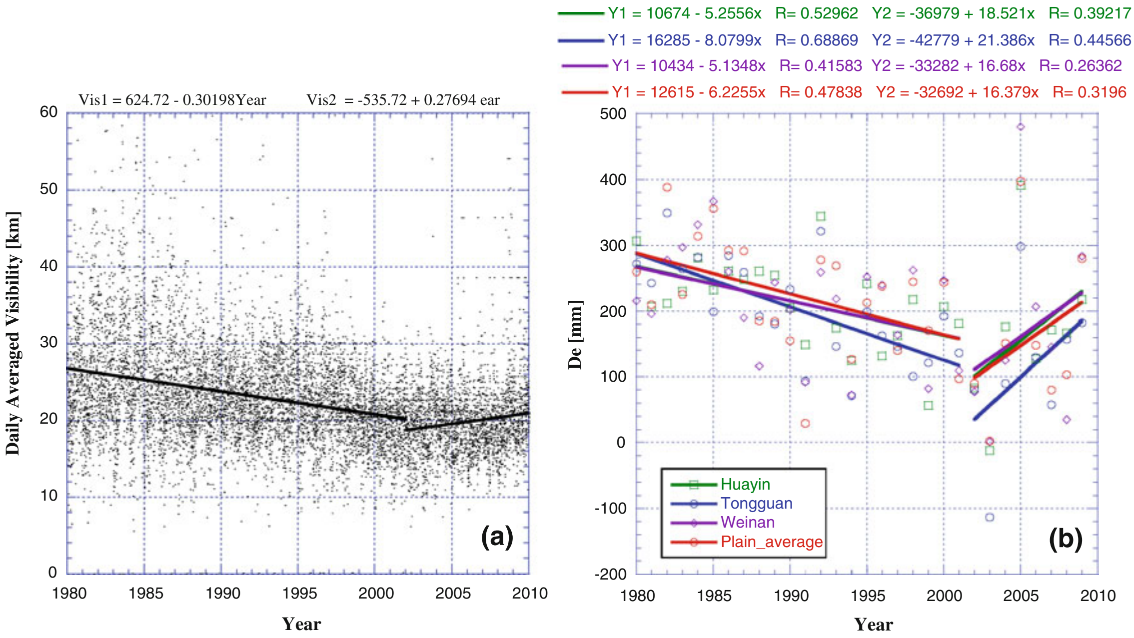

Fig. 4 **a** The daily corrected visibility at Mt. Hua for 1980–2009. *Each point* represents the averaged visibility for 1 day. The linear trends are calculated separately for the two sub-periods before and after 2002. **b** The trends in the precipitation difference between Mt. Hua and the plains stations (De) for the three closest stations to Mt. Hua (*blue* Tongguan, *purple* Weinan and *green* Huayin) and the average of all 17 plains stations. The linear trends are calculated separately for the periods before and after 2002 according to the equations shown. *R* denotes the correlation coefficient. The similar De at Huayin Weinan can be evidenced by the juxtaposition of the two trendlines (colour figure online)

values displays similar trends for both of the two periods, the three closest stations to Mt. Hua, Huayin, Tongguan, and Weinan, were selected and plotted in Fig. 4b, along with the average De. As shown in Fig. 4b, all of the De trends reversed around 2002. Apart from the Weinan station, the significance level of these decreasing trends is 5 %. After 2002, the trends become positive but the study period is too short for these to pass the 5 % confidence level significant test (Fig. 4b). Though this second trend clearly appears to be increasing, additional future data are required to enhance its significance level.

As suggested by Rosenfeld and Givati (2006), the decreasing trend in orographic enhancement is mostly due to the gradual reduction in precipitation at the mountain rain gauge in combination with a slight decreasing trend at the lowland gauges. In this study, the similar behavior of De reflects possible suppression of mountain precipitation. As shown in Fig. 4b, the decreasing trends in De during the first period suggest a reduction in orographic precipitation at Mt. Hua caused by increasing pollution aerosols.

Trends during the second period give further support to this hypothesis; as air pollution aerosol loading gradually decreased, the suppressed orographic precipitation begin to recover so that the mountain precipitation increased faster than the plains precipitation. The results from both subperiods suggest that pollution aerosols act to reduce the orographic precipitation at Mt. Hua.

3.3 Precipitation changes at Mt. Hua and the plains stations

To verify that the changes in De are the result of opposite trends in precipitation between Mt. Hua and the lowland stations, we analyzed the annual precipitation of the mountain and lowland stations.

All of the plains stations have similar changes in annual precipitation (Fig. 5). Figure 5a shows the annual precipitation from 1980 to 2009 for Mt. Hua, the three closest plains stations and the average of all of the plains stations. The change in the annual precipitation at Mt. Hua is consistent with that of the plains stations for the entire study period, with a decreasing trend from 1980 to 2002 and an increasing trend thereafter. The decreasing and increasing trends in De during the first and second periods, respectively (Fig. 4b), can therefore only be explained by the relative changes in precipitation at Mt. Hua. Furthermore, the abrupt increases in precipitation and De at Mt. Hua (Fig. 4b) coincide with the change to increasing visibility. This indicates that the suppression effect on orographic precipitation by pollution aerosols may be the possible cause of the precipitation pattern at Mt Hua.

As shown in Fig. 5b–d, the probability of light rain days decreases during the first period at both Mt. Hua and the plains stations. For example, the probability of light rain days (less than 2 mm) at Huayin show an evident decrease (Fig. 5b). However, the probability of rain days with more than 2 mm day^{-1} does not display any clear change. The situation is similar at Tongguan (Fig. 5c), although the loss of light rain days with less than 2 mm day^{-1} was smaller than that at Huayin. The clear reduction in light rain days is consistent with previous work (Qian et al. 2009; Yang and Gong 2010).

At Mt. Hua, both the probability of light rain days and the probability of moderate rain days with less than 25 mm decrease during the first decade (Fig. 5d). Indeed, the probability of light and moderate rain days with less than 25 mm decreased from approximately 31 % in the 1980s to 24 % in the 1990s. The greater loss of light and moderate rain days at Mt. Hua during the first period further supports the suppression effect on orographic precipitation by aerosols. Similarly to the increase in annual precipitation observed at Mt. Hua during the second period (Fig. 5a), the probability of light rain days from 2000 to 2009 displays an increasing trend and exceeds that of the 1990s for all stations from 2000 to 2009 (Fig. 5b–d). Once more, this increase is much stronger at Mt. Hua than at the surrounding stations.

Our study therefore suggests that hilly precipitation is more heavily suppressed by aerosols compared to precipitation at plains stations, in agreement with the results from Yang and Gong (2010). In their study, these authors observed a greater decrease in summer light rainfall ($\leq$2.5 mm day^{-1}) at seven mountains in eastern China, including Mt. Hua, than at surrounding plains stations between 1960 and 2007. However, our analysis does not support their conclusion that reduced plain wind speeds were responsible for such a reduction in orographic precipitation. Yang and Gong (2010) analyzed temporal trends in wind speed (including daily maximum surface wind speed, number of days with wind speed >5 m s^{-1} and daily averaged wind speed) for the same period and found decreasing trends in wind speeds at most stations, concluding that wind speed reduction was the main reason for the decrease in orographic precipitation. However, the loss of precipitation at Mt. Hua occurs mainly during light and moderate rain days (Fig. 5d), supporting the idea that aerosol microphysical effects are the primary drivers of changes in precipitation.

4 Aerosols increase winds at Mt. Hua

4.1 Reduction in plain winds and increase in winds at Mt. Hua

In order to investigate the effects of winds on orographic precipitation, we analyzed the surface and radiosonde winds to determine whether a decrease in mountain winds was observed during our study period.

Aerosols can reduce surface wind speed by weakening the vertical energy transport through radiative effects (Jacobson and Kaufman 2006). In our previous work, we observed that winds at Mt. Hua increased and surface winds at the nearby Xian plains station decreased due to aerosol radiative effects (Yang et al. 2011). Surface energy (as reflected by surface air temperature) at the Xian plain station was observed to be significantly reduced compared with that at Mt. Hua and this reduction in surface radiation was attributed to the radiative effect of aerosols. Reduced surface energy can suppress atmospheric instability and convective flows and hence the vertical flux of horizontal momentum. Our analysis of the winds at Mt. Hua and Xian in our previous work (Yang et al. 2011) and present study support this mechanism.

Generally, solar heating is strongest during the afternoon and weakest in the late night. Investigating the trends of all of four daily observations (02, 08, 14, 20 LT) also suggests that the difference in wind trend between Mt. Hua and the

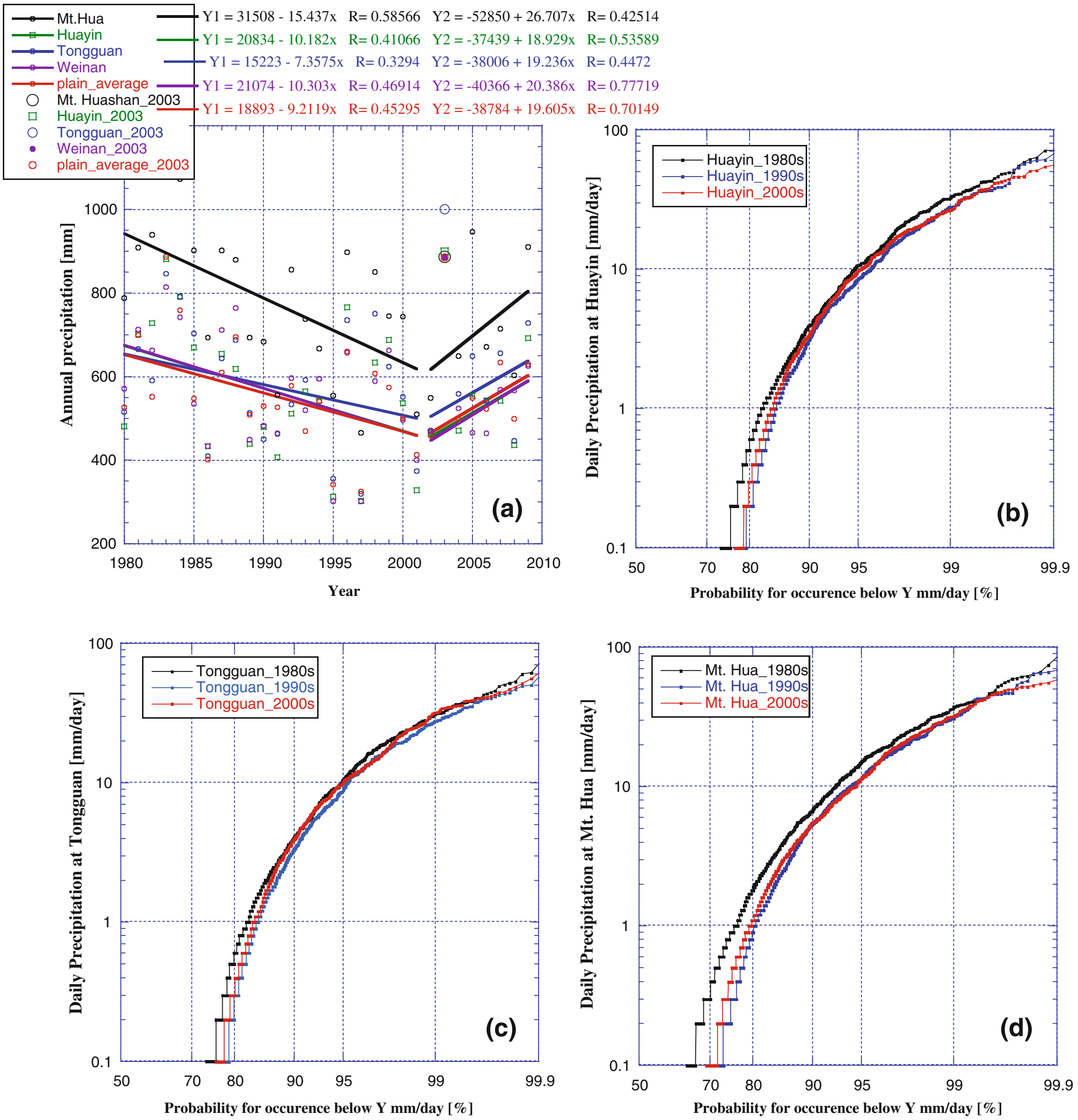

Fig. 5 **a** The annual precipitation for Mt. Hua (*black*) and the 3 nearby plains stations (*black* Mt. Hua, *blue* Tongguan, *purple* Weinan and *green* Huayin) from 1980 to 2009. The averaged annual precipitation for the plains stations is also shown (*red*) (**a**). The equations of the linear trends and the correlation coefficient *R* are shown. The trends in the latter period are calculated by excluding the data in 2003 because the data for this year are abruptly extremely high for all the stations. The trends for all stations are very similar in both periods, suggesting the precipitation changes are comparable for all of the stations. The probability of occurrence of daily precipitation does not exceed the amount shown in the ordinate (mm day^{-1}) at the **b** Huayin **c** Tongguan and **d** Mt. Hua rain gauges. *Black*, *blue* and *red* denote the periods 1980–1989, 1990–1999, 2000–2009, respectively. The probability for the decade of 1990–1999 decreased compared with the decade of 1980–1989, whereas the probability for the years 2000–2009 increased and exceeded that of the decade of 1990–1999, notably for the light rain (colour figure online)

plains stations is most evident at 14 LT and the weakest at 02 LT (Fig. 6). All trends during the first period are significant at the 5 % confidence level.

During the first period, the decreasing trend for the averaged plain surface wind speed at 14 LT is approximately 0.23 m s^{-1} per decade (Fig. 6a) balanced by a similar increasing trend in wind speed at Mt. Hua (approximately 0.26 m s^{-1} per decade). The balance of winds between the mountain and the plains for all days supports the hypothesis that the vertical energy transport was weakened by the aerosol radiative effect, in agreement with our previous work (Yang et al. 2011). Figure 6b further suggests that although the mountain and plain winds have opposite trends at both 14 and 02 LT, the slopes of the trends are smaller at 02 LT, when the aerosol radiative effect becomes the weakest, than 14 LT. The contrast in

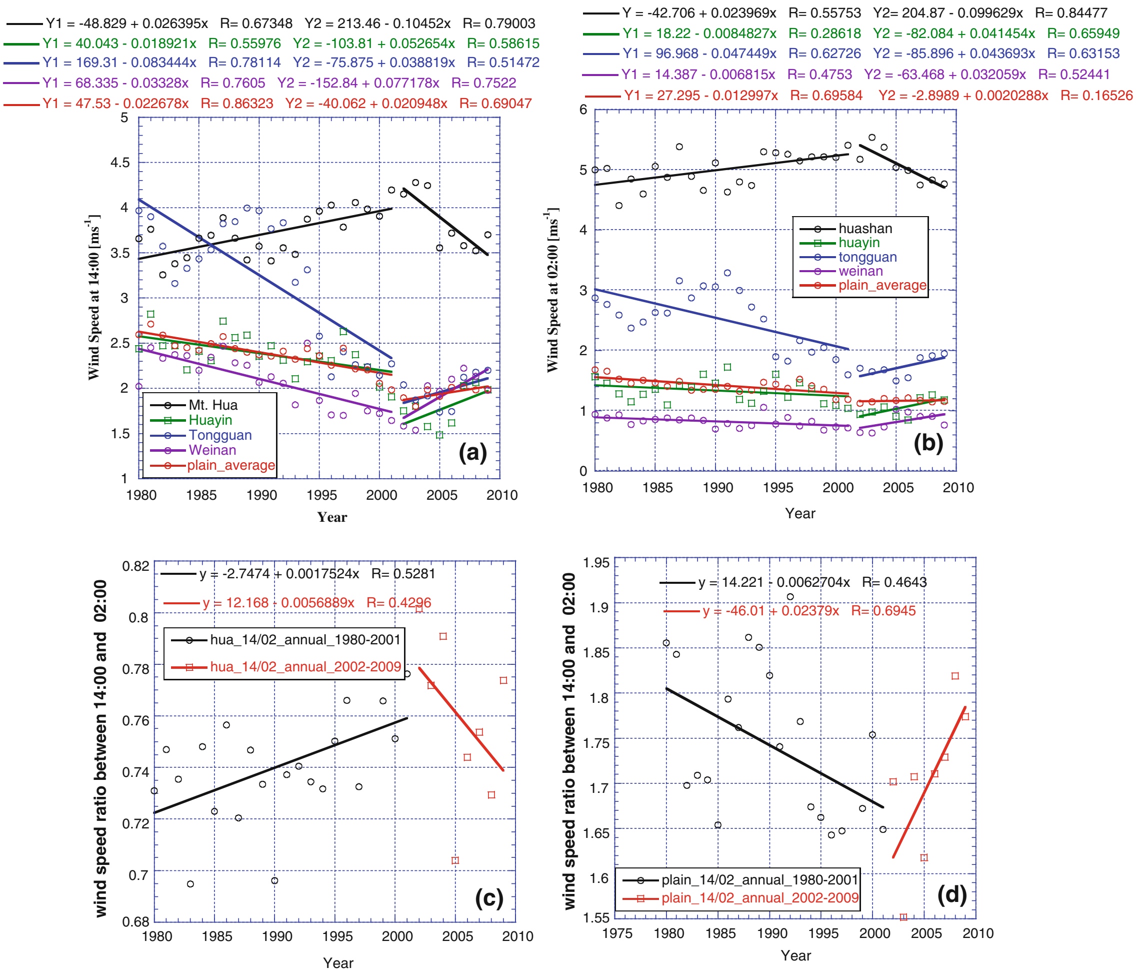

Fig. 6 The trend of surface-averaged wind speed at the top of Mt. Hua and for the plains stations at 14 LT (**a**) and at 02 LT (**b**): Mt. Hua (*black*), Tongguan (*blue*), Weinan (*purple*), Huayin (*green*) and the average of all 17 plains stations (*red*). The wind ratio between afternoon (14 LT) and late night (02 LT) for Mt. Hua and the plains are shown in **c** and **d**. The trends in **c** and **d** during the first period are significant at the 0.01 and 0.05 confidence level, respectively. The trends during the second period in **c** and **d** do not pass the 0.05 significant test for both Mt. Hua and the plains but have clear trend and reasonably high linear autocorrelation coefficients of 0.4296 and 0.6945, respectively. The correlation probabilities (*p* values, denoting the statistical significance level that the slope of the trend line does not equal zero) for the day–night wind ratio in the second period are 0.2881 and 0.0559 for Mt. Hua and the plain average, respectively. Smaller values of *p* suggest that the linear trend is more likely to be significant (colour figure online)

the slopes of the wind trends at 14 and 02 LT suggests that the vertical energy transfer is less affected by aerosols late at night. This diurnal contrast in the winds caused by the aerosol radiative effect is directly illustrated by Fig. 6c, d.

The relative increasing trend in the 14-LT winds compared with that seen at 02 LT at Mt. Hua during the first period (Fig. 6c) might indicate that afternoon mountain winds increased through decreased drag from the lower level due to aerosol radiative effects. Accordingly, the relative decreasing trend in the 14-LT winds compared with that seen at 02 LT in the plains during the first period (Fig. 6d) might suggest that afternoon plains winds decreased due to decreased downward transport of fast winds. During the second period, the changes in the winds also suggest that the aerosol radiative effect causes opposite trends between the mountain and plains (Fig. 6a, b) and the relative decrease (increase) in winds at 14 LT compared with that at 02 LT for Mt. Hua (for the plains) (Fig. 6d).

Figure 6 also indicates that the wind speed at Mt. Hua did not decrease during the first period, suggesting that the winds could not weaken the orographic lifting and reduce light precipitation over the mountain area, as claimed by Yang and Gong (2010). However, the increase in the wind speed at Mt. Hua could reduce the time during which an air mass can precipitate over the mountain, thereby decreasing the rainfall frequency or amount over the mountain. Thus, both the increase in the mountain winds and the decrease in the plain winds would cause a reduction of orographic precipitation at Mt. Hua.

4.2 Possible relationship between aerosol loading or 700 hPa winds and winds at Mt. Hua

Other studies have documented that aerosol radiative effects could reduce surface wind speeds through mechanisms other than the decrease in vertical energy exchange. Xu et al. (2006) attributed the reduction in winds to the weakened intensity of the Asian summer monsoon. Monsoonal winds weaken through a decrease in the land–sea thermal contrast in southeastern Asia caused by the radiative effect of aerosols (Qian et al. 2006). However, Mt. Hua is located in the margin of the Asian summer monsoon region and winds in this region are less affected by variations in monsoon intensity. Therefore, local factors such as changes in the vertical energy exchange affected by the cooling effect of aerosols are likely to dominate the winds at Mt. Hua.

To illustrate the possible cause-effect relationship between both plains winds and Mt. Hua winds, and 700 hPa winds and Mt. Hua winds, during the first period, we limited our analysis to the period 1980–2001 (Fig. 7). Figure 7a shows the annual trend of daily averaged winds at 700 hPa. The radiosonde wind data allow the comparison between the winds at Mt. Hua and at 700 hPa and the visualization of the changes in the winds on a large scale. The 700 hPa upper daily averaged winds clearly decreased throughout this interval, with a trend significant at the 5 % confidence level. The opposite wind trends between Mt. Hua and the 700 hPa pressure level indicate that the increasing trend during the first period at Mt. Hua (Fig. 6a) could not be the result of changes in the upper winds. Synoptic scale variability can therefore not explain the increasing trend in wind speed at Mt Hua. In fact, winds at Mt. Hua have a clear diurnal cycle (Fig. 7b), with a minimum in the afternoon at 14 LT, and the drag effect from the lower level is much more evident at Mt. Hua. Moreover, the significant inverse correlation between visibility and surface winds at Mt. Hua (−0.60397, Fig. 7b) suggests that the surface winds are closely linked to the changes in aerosol concentrations at ground level. Figure 7c further illustrates that the surface winds at Mt. Hua only correlate very weakly with the winds at 700 hPa (+0.0698). Therefore, the increase in winds at Mt. Hua is highly related with the vertical energy transfer caused by the aerosol radiative effect and is likely one of the causes for the reduction in mountain precipitation.

5 Summary and discussion

We analyzed the dependence of light precipitation days and precipitation amount on aerosol concentration (as determined by visibility at Mt. Hua) at both the mountain and plains stations. The significant positive correlation between light rain days for both Mt. Hua and the plains stations suggests that light precipitation events in the Guanzhong area, notably orographic rains at Mt. Hua, are suppressed by aerosols. For Mt. Hua, the decrease in precipitation further includes moderate events up to 25 mm day^{-1}.

The trends and changes in visibility, the precipitation difference between Mt. Hua and the average of the surrounding plains stations (De), the precipitation quantities and the wind speeds in the study area from 1980 to 2009 were also investigated. The results show that visibility at Mt. Hua decreased significantly until 2001 and subsequently increased from 2002 to 2009. The trends in De display similar changes. The changes in total precipitation at Mt. Hua and the plains stations are consistent in both probability and amount during the two periods, suggesting that changes in De are highly related to the amount of pollution aerosols, as determined by visibility at Mt. Hua. In other words, the suppression of orographic precipitation becomes stronger (i.e., De decreases) when there is more air pollution in the atmosphere. In a similar way, mountain precipitation recovers when pollution is reduced. The analysis of both surface winds and 700-hPa winds excludes the possibility that hilly precipitation reduction at Mt. Hua is a result of changes in winds.

However, there are many difficulties in performing observational studies of aerosol effects on precipitation, such as inadequate direct measurements of aerosol concentrations. As a result, visibility often serves as a proxy for pollution condition, as used in the present study. However, visibility may be influenced by many meteorological factors and is not solely dependent on the aerosol concentration. In the past decades, numerous studies have attempted to investigate air pollution aerosols by estimating the emission of fossil fuel combustion or the measurement of aerosol optical depth (AOD) (Stern 2006; Novakov et al. 2003; Qiu and Yang 2000; Li et al. 2007). Though these measurements can provide general descriptions of aerosols, they are limited to some aerosol types and can be heavily affected by cloud cover. Indirect estimates of aerosols concentration are highly uncertain due to the scattered distribution of the observation points and the coarse resolution of the retrieved data. Furthermore, aerosol distribution is not uniform and varies from location to location. Visibility integrates the aerosol effects along a path of several to tens of kilometers and therefore has a distinct advantage over the measurement of air pollution in specific locations. Though the top of the Mt. Hua station is often above the boundary layer, aerosols from this layer can extend to a much greater height through moist convection and there remains an abundance of aerosols above the atmospheric boundary layer (He et al. 2008). Visibility at Mt. Hua is therefore still a satisfactory proxy for aerosol concentration in this region.

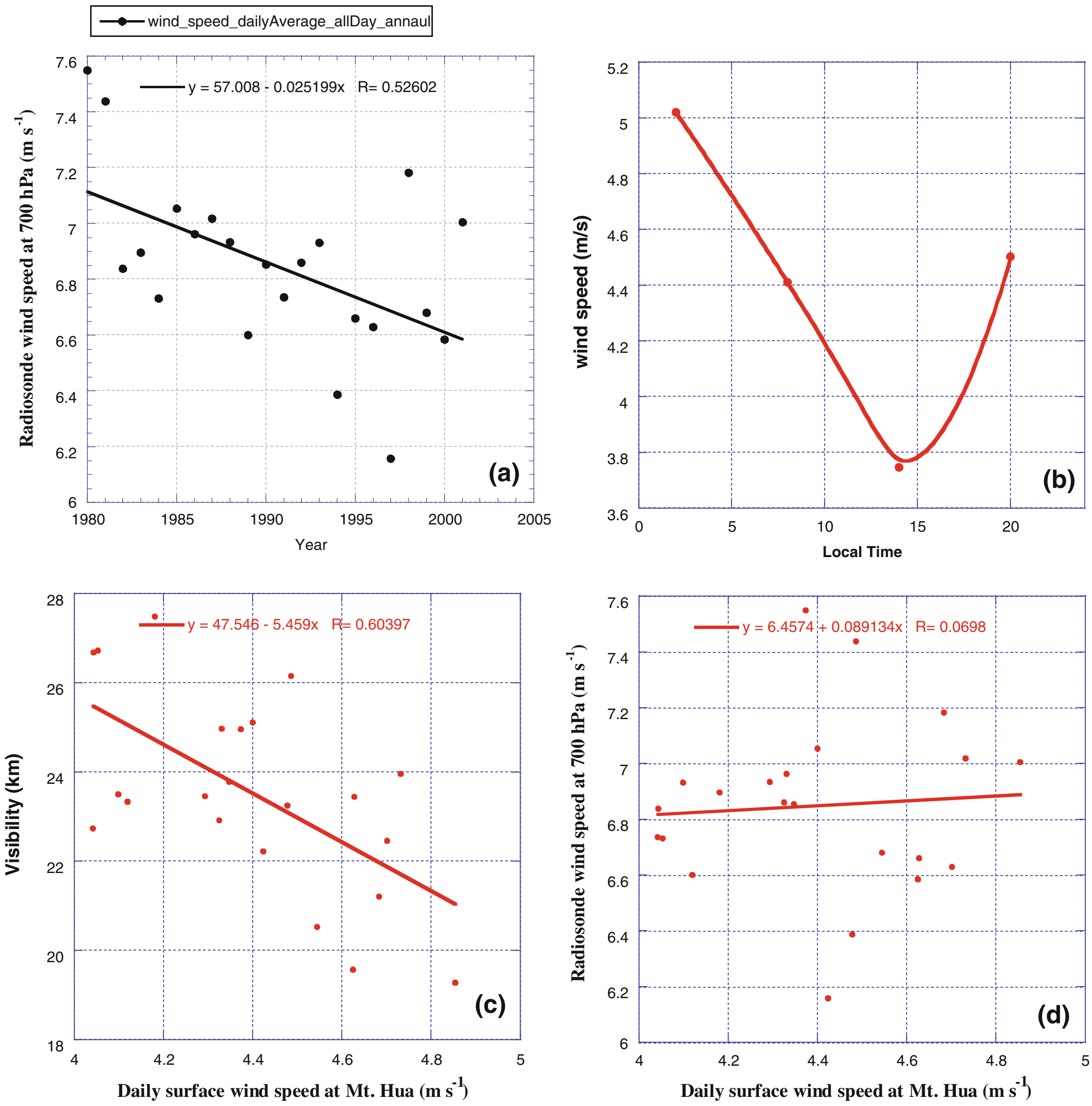

Fig. 7 **a** The annual trends of the 700 hPa daily wind speeds as measured by sounding at Xian. The equation for the linear trend and the correlation coefficient *R* are shown. **b** Diurnal cycle of wind speed at Mt. Hua The correlation between the daily surface wind speed and daily visibility (**c**) and 700 hPa winds (**d**) at Mt. Hua from 1980 to 2001. Both visibility and surface wind speed are averaged from the four daily observations. Daily 700 hPa winds are the average of two observations (08 and 20 LT)

One limitation of the present study is the short duration of the recent increase in visibility and De (second period, 2002–2009). Trends in De during this interval are fairly clear but the length of the time series precludes statistical significance. Nonetheless, results suggest that the recovery from the reduction of orographic precipitation at Mt. Hua is occurring with the gradual improvement in air quality. The consistency of the trends in both De and visibility during the two periods supports the suppression effect of aerosols on orographic precipitation. Further work and additional data are still needed to improve the confidence of these conclusions and diminish the uncertainty of the trend in De.

Wind speed reduction has been proposed as the main reason for the decrease in orographic precipitation in previous work (Yang and Gong 2010). Although aerosol radiative effects can reduce the land–ocean thermal contrast, the decrease of monsoon intensity cannot have a large effect on the winds at the inland station at Mt. Hua. The winds have also shown an increasing trend at the coastal station of Jiuxian Shan in Fujian Province (Yang and Gong 2010). Therefore, local winds are primarily influenced by other mechanisms. In this study, the analysis of both surface winds and radiosonde winds suggests that the vertical energy transport caused by the aerosol radiative effect is altering the winds at the mountain and plains stations.

Increasing winds at Mt. Hua are linked to decreasing winds at the plains stations, in agreement with Jacobson and Kaufman (2006). This opposite trend has also been recorded at Mt. Tai Shan and Jiuxian Shan (Yang and Gong 2010). This repeated opposite trend illustrates the aerosol radiative effects on winds through the suppression of convection. Both the increase in mountain winds and the decrease in plains winds could reduce the frequency and quantity of orographic precipitation. Therefore, aerosols can act to suppress orographic precipitation through both microphysical and radiative effects. Due to the limited available data and relatively shorter time scale, further study is needed to determine which of these two effects has the greatest influence on the reduction of hilly precipitation caused by air pollution.

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