Journal of Atmospheric and Solar-Terrestrial Physics 95–96 (2013) 28–40

Contents lists available at SciVerse ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Heavy air pollution suppresses summer thunderstorms in central China

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ARTICLE INFO

Article history:
Received 15 July 2011
Received in revised form
27 October 2012
Accepted 31 December 2012
Available online 17 January 2013

Keywords:
Aerosol
Precipitation suppression
Thunderstorm
China

ABSTRACT

Time series of rainfall, thunderstorms, temperatures, winds and aerosols of 50 years have been analyzed at the Xian valley (1951–2005, rain rates data are only available for the period of 1961–2000 for Xian) and the nearby Mount Hua (1951–2005) in central China, for assessing the impact of the increasing air pollution on convective precipitation. Adding aerosols to pristine air initially increases convective rainfall. However, aerosol amounts in the Xian valley (represented by large AOT and significant decreasing trend in visibility in the study area) have been shown to be sufficiently high so that added aerosols suppress convection and precipitation, by both radiative and microphysical effects, even at the starting of the analysis period in the 1950s.

It was found that the aerosol's negative radiative forcing stabilized the lowest troposphere. The stabilization resulted in less vertical exchanges of air, which caused reduction in the lowland (Xian) surface winds and increase in the highland (Mount Hua) wind speeds. The decreased instability caused a decrease in the frequency of the thunderstorm normalized by rainfall amount in the lowland due to the thick aerosol layer above, but not at the highland, above which the aerosol layer was much thinner. The indicated decreasing trend of highland precipitation was associated with a similar size decreasing trend in thunderstorm frequency. This decrease was contributed by light and moderate ($<25\ \mathrm{mm\ day^{-1}}$) rainy days. These patterns of rainfall changes at the highland are consistent with the microphysical suppressive effects of aerosols.

Despite the dramatic relative decrease in the already originally scarce thunderstorm activity in the Xian valley, the rainfall amount there appears to have little diurnal cycle, and shows little trend with the increasing aerosol amounts. Because only small fraction of the rainfall in Xian is generated by local instability, as indicated by the flat diurnal cycle, it appears to be a condition which is unsuitable for quantifying the impact of heavy aerosols on rainfall amounts. However, the dramatic relative decrease of the scarce thunderstorms in Xian suggests that aerosol's radiative effect can be substantial. Such study should be extended to other areas where local surface heating dominates rainfall amount.

1. Introduction

Aerosols can have both radiative and microphysical effects on clouds and precipitation. The effects are often conflicting and coexisting, making it very difficult to disentangle them and relate the co-variability of aerosol and precipitation in a physically meaningful way with each other. This study attempts to do that, benefiting from the unique data set available from Xian, China.

The radiative effects are summarized as follows: Aerosols reduce the surface energy by blocking solar radiation from reaching the surface (Charlson et al., 1992; Andreae et al., 2005; Forster et al., 2007; Pilewskie, 2007). The atmospheric instability would decrease since the surface heating has been reduced (Fan et al., 2008); as a result, the formation of boundary layer convectively forced clouds would be suppressed (Kaufman and Fraser, 1997; Ackerman et al., 2000; Koren et al., 2004; Qian et al., 2006). Ramanathan et al. (2001) also considered the reduction in surface evaporation due to the absorbing aerosols and suggested that this effect should weaken the hydrological cycle and lead to a decrease of fresh water. The increasing radiative effects caused by the greater amount of anthropogenic aerosols reduce vertical turbulence and horizontal compensatory movement simultaneously; therefore, the local surface wind would decrease with the weaker vertical energy transfer. The relatively warmer air layer formed by absorbing aerosols decreases the instability and slows the vertical heat transfer; this, in turn, reduces the

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http://dx.doi.org/10.1016/j.jastp.2012.12.023

downward transport of the horizontal momentum by the faster winds aloft. The simulations of Jacobson and Kaufman (2006) suggest that surface winds have been reduced by the aerosol's radiative effect. In this paper, our analysis is based on observational data that shows that the surface winds and the frequency of thunderstorms have been suppressed due to the aerosol radiative effects in very heavy aerosol loads.

The microphysical effects of the aerosols are even more complex (Tao et al., 2012). Enhanced concentrations of sub-micron cloud condensation nuclei (CCN) decrease cloud drop size, which decreases the rate at which they are converted into precipitate. Because drop size and the amount of cloud water increase with height above cloud base, smoke and pollution aerosols raise the minimum depth of clouds for onset of precipitation. In deep tropical and summer subtropical clouds this would prevent the precipitation from the clouds before their tops exceed the freezing level (Andreae et al., 2004). In CCN-rich tropical and subtropical convective clouds with warm bases, as proposed by D. Rosenfeld for this study and in previous papers (Williams et al., 2002; Andreae et al., 2004; Rosenfeld, 2006; Rosenfeld et al., 2008), warm rain is suppressed and liquid water from cloud ascends and freezes into ice hydrometeors, leading to the release of added latent heat of freezing; this additional release of freezing aloft implies stronger updrafts and larger depth of the mixed phase region, which are favorable for intense convective activity such as lightning activity. Observations and simulations support the suggestion that the aerosol microphysical effect strengthened convection in deep convective clouds (Andreae et al., 2004; Barry et al., 2005; Khain et al., 2005; Lin et al., 2006; Van Den Heever et al., 2006); this leads to a greater amount of precipitation and to an enhancement of monsoonal or Walker-like circulation cells (DeMaria, 1985; Bell et al., 2008). But for orographic clouds, the suppression of orographic rainfall caused by aerosol microphysical effects (Rosenfeld et al., 2007) is attributable to the short lifetime of the orographic clouds.

The aerosol microphysical effects do not conflict fundamentally with the reported suppression of orographic rainfall and the aerosol radiative effects (Yang, et al., 2013). While moderate addition of aerosols invigorates the convection through microphysical effects, large amounts of light absorbing aerosols can have the opposite effect via radiative effects. Previous studies suggested that these two opposing effects of aerosols on clouds and precipitation are superimposed and show the transition from the microphysical pathway to the radiative effects when aerosol concentration changed (Rosenfeld et al., 2008; Koren et al., 2008). In addition, the radiative effects of the aerosols become significant beyond this optimum concentration and suppress the precipitation by reducing the surface heating that energizes convection. Rosenfeld et al. (2008) suggested that this optimal aerosol concentration is about 1200 $CCN_{0.4}\,cm^{-3}$ (cloud condensation nuclei active at super saturation of 0.4%), which corresponds to an aerosol optical thickness of about 0.25–0.3. Koren et al. (2008) have observed the existence of a maximum of cloud cover and vertical development over the Amazon basin for this optimal aerosol optical thickness. During the biomass season, smoke aerosols due to fires in the Africa and Amazon reduced monthly mean surface solar radiation budget (SSRB) by 100 Wm^{-2} (Li, 1998), or $\sim$30% of the total.

Zhang et al. (2007) found a significant increase in deep convective clouds and thunderstorms over the Pacific Ocean and associated this increase with Asia pollution outflow via aerosol microphysical effects. Similar invigoration of mixed phase processes of clouds and storms by pollution is found in southeast U.S. (Bell et al., 2009). More recent observational study shows the high aerosol loading after volcanic activity invigorated the lightning activity through modification of cloud microphysics in Philippine (Yuan et al., 2011). Simulative studies suggested that aerosol increased intensity of precipitation and convection through invigoration of mixed phase processes of clouds in the South Great Plains (SGP) of U.S. (Li et al., 2011) and Pearl River Delta area in China (Li et al., 2009; Wang et al., 2011). All these increases in convection intensity under the influence of aerosols in the previous studies were ascribed to the changes in clouds microphysical processes. This is consistent with the hypothesis of Rosenfeld et al. (2008) that adding more aerosol in moist and convectively unstable environment would lead to more intense storms. Whereas in heavy aerosol loading and dry environment, the aerosol radiative effects may work preferentially and inhibit convection and clouds from the beginning (Koren et al., 2008; Rosenfeld et al., 2008). The simulation study by Fan et al. (2008) also suggested that the aerosol radiative effects significantly weakened atmosphere instability and hence the strength of deep convective clouds. One recent study also indicated that water vapor amount, slightly soluble organics and giant CCNs played important roles in aerosol impacts on cloud droplet effective radius (Yuan et al., 2008). Note that most previous studies on relationship between thunderstorms and anthropogenic pollution focused on the aerosol microphysical effects. To date, there are a few observational studies that investigated the impacts on thunderstorm activity by aerosol radiative effects. In this paper we report an investigation of possible aerosol radiative effects on summer afternoon thunderstorms at Xian valley and Mount Hua.

A unique set of measurements in Xian and the nearby Mount Hua in central China (Fig. 1) provides an opportunity to study the impact of the increasing aerosol load there during the last 50 years. In the past decades, anthropogenic pollution increased dramatically due to China's rapid economic growth. Novakov

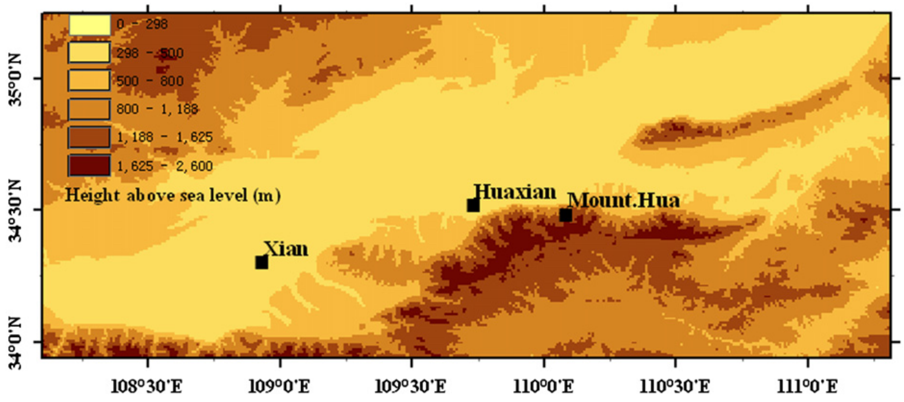

Fig. 1. Study area in central China.

et al. (2003) reported that significant increases of fossil fuel black carbon emissions were recorded in China over the period 1950–2000. Coinstantaneous, some parts of China, including Guangdong and Shaanxi Province, have reported a decreasing trend of thunderstorm frequency (Qin, 2000; Zhang et al., 2004; Li et al., 2005a, 2005b). Many researchers reported that eastern China is the most polluted region (Ansmann et al., 2005; Zhao et al., 2006; Liu et al., 2007); however, in central China, a large city like Xian also suffered intense aerosol loading from air pollution. Manifested by the decreasing trend of visibility at the top of Mount Hua near Xian, at the height of 2064.9 m, this serves as evidence that air pollution is not confined to cities but has become a problem at a regional scale and is extended into the free troposphere. The atmospheric aerosols come not only from traffic, industry, and dweller living activity (Su, 1998; Shi et al., 2000), but also from agricultural fires (e.g., to prepare for semination, every summer the wheat stalk is burned after harvest, and the cornstalk in every autumn) (Zhao, 2004, 2006; Chu, 2007). Moreover, the pollution aerosols in Xian would not be easily cleared off because of the surrounding terrain. The Xian city is surrounded by Qinling Mountain in the south and the east, and a higher plateau in the north. The continental monsoonal climate dominates the region of Xian; the prevailing winds are southeasterly during summer and northwesterly during winter.

2. Methodology

The large aerosol optical thickness (AOT) that is typical to the summer months in the study area of Xian, China (see Fig. 1), has increased from about 0.8 to 1.0 during the available record from 2000 to 2008 (see Fig. 2A). The AOT data were produced from MODIS Terra Monthly Level-3 Product with the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC). In the last 52 years averaged summer visibility of Mount Hua also decreased significantly. Due to the absence of long-term air pollution observation, visibility is often used as an indicator for aerosol concentration (Rosenfeld et al., 2007; Wang et al., 2009). The decreasing trend in summer visibility reflects the trend of increasing air pollution in the study area, shown in Fig. 2B. The recent AOT values for the study area are well beyond the critical value of about 0.25, where the suppressive effects of aerosols start to exceed the microphysical invigorating effects on convective clouds (Koren et al., 2008; Rosenfeld et al., 2008). We have previously indicated the aerosol's microphysical effects at Mount Hua, Shaanxi Province, show the suppression of orographic precipitation by air pollution (Rosenfeld et al., 2007). This work is the next step to reveal the aerosol's effects in Xian. Because most of the convective storms and precipitation occur during the summer in Xian (Li et al., 2005a), and the solar radiation is the most intense at that time, this study focuses on the summer months (June, July and August).

The first step is the documentation of the decreasing trend in the surface solar radiation as a result of the increasing air pollution aerosols. Qian et al. (2006, 2007) have indicated that surface radiation over most of China has decreased remarkably during the period 1960–1980 due to the air pollution aerosols and is still maintained at a low level after that period. In East Asia, aerosols surface radiative forcing is about $-30\ \mathrm{Wm}^{-2}$ in summer and spring (Yu et al., 2006). In China, heavy yet absorbing aerosols reduce the annual and diurnal means of SSRB by 16 Wm^{-2} across China, which is absorbed in the atmosphere (Li et al., 2010). This can drastically reduce surface and atmospheric temperatures and thus alter the stability of the atmosphere and convection. The trends in surface radiation should induce a trend in surface temperatures; however, the surface radiation data might be confounded by the small boundary layer clouds that decrease with increasing aerosols (Koren et al., 2004). Therefore, in this study, surface temperature data are used as the combining result of the overall aerosol direct and cloud mediated radiative effects in the Xian valley.

Although the general trend over most of China is already established (Qian et al., 2006), the specific diurnal variations of surface radiation modulated by aerosols have not been put forward. The negative surface radiative forcing occurs during daytime. The diurnal variation of surface radiation induces the daily temperature change. Specifically, the daily maximum temperature would decrease because a greater amount of surface heating is intercepted by the increasing aerosol amounts; however, the daily minimum temperature would be less affected, because IR cooling is not affected by pollution aerosols. These

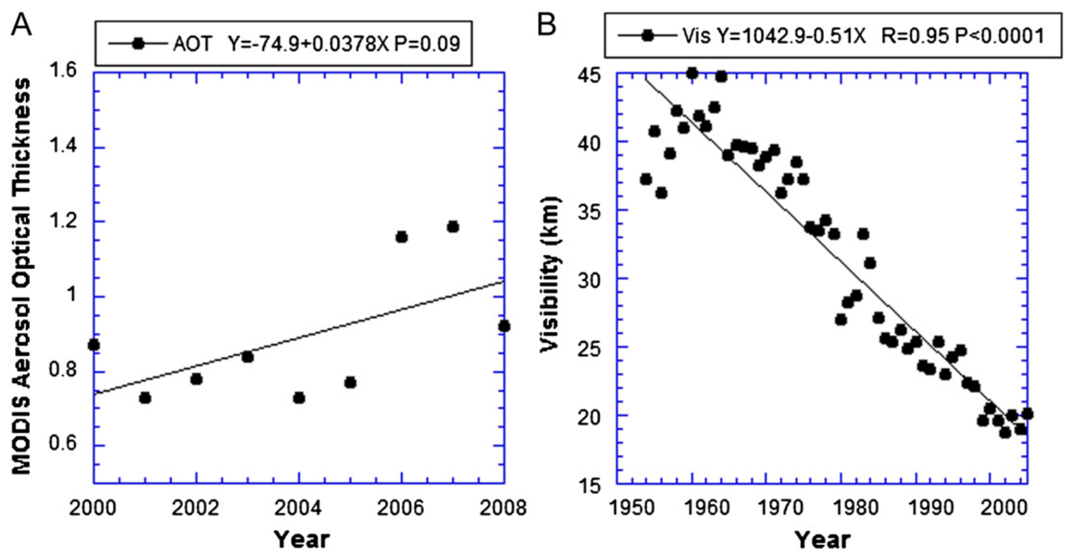

Fig. 2. (A) MODIS aerosol optical thickness for June–July–August of 2000–2008 over the 1×1 degree grid centered at 34.5N 108.5E, which covers Xian, China. The data were produced with the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC). (B) Trends of corrected visibility at Mt. Hua for June–July–August of 1954–2008. The correction is aimed to reduce the effect of relative humidity on visibility. Please refer to Rosenfeld et al. (2007) for a more detailed description of the RH correction process.

impacts originated from the aerosol's short-term effects within the day should cause a long-term decreasing trend in daily temperature range (DTR), regardless of the GHG (greenhouse gases)-induced trends and the urban heat island. Such decreasing trend at a rate of 2.5 °C per century has been observed over the polluted parts of China for the period of 1955–2000 (Liu et al., 2004). The effects of greenhouse gas and urban heat island should be separated from the aerosol's influence on surface temperature. The warming effect of greenhouse gases could also decrease the DTR by increasing the daily minimum temperature more than the daily maximum temperature increases. The other character of the greenhouse gas effect is that greenhouse gas forcing is more spatially uniform, i.e. the influence of greenhouse gases would be the same regardless of the location. In contrast with the greenhouse gas effect, the aerosol cooling effect would be greater at the lowland (Xian) than at the highland (Mount Hua) due to the thinner aerosol layer over the highland. Generally, aerosol's radiative effects could not significantly impact the temperature at Mount Hua because most aerosol particles are mixed in the boundary layer, whose height is similar to the height of Mount Hua (2064.9 m). Therefore, the time series of temperature difference (lowland–highland) is employed to neutralize the GHG-induced trends. Moreover, by using rural station of Huaxian as the contrast lowland station, the effects of urban heat island on temperature could be greatly reduced.

The surface cooling and respective lower tropospheric warming by the absorbing aerosols should result in decreasing low level atmospheric instability. The atmospheric stabilization due to the reduction of surface radiation occurs mainly during daytime (in particular, in the afternoon) and continues till evening. As a result, the surface winds as well as the frequencies of thunderstorms are expected to decrease, especially during the afternoon. The analysis of the trends of DTR and surface winds in Xian shows the impacts of aerosol's radiative effects.

Separation of the role of aerosols from other possible meteorological factors can be achieved by comparing trends of winds, precipitation and thunderstorms over the mountains and nearby lowland. This has been explored to some extent for the aerosol suppression effects on orograhic precipitation at Mount Hua (Rosenfeld et al., 2007). The difference in aerosol amounts above Xian and Mount Hua would determine the different behaviors in the trends of winds, rainfall and thunderstorms between the two locations. By using ratios of variables, much of the spurious trends caused by synoptic variability would be removed. Here the ratios are the number of thunderstorms per rainfall amount and the proportions of rainfall accumulation in different time periods in a day. Comparisons of the trends in surface winds and DTR between the mountain and lowland sites are also made.

The remaining of this paper is organized as follows. We describe the study area and datasets used for testing the hypothesis in Section 3. The temperature data are analyzed as the manifestation of surface radiative forcing in Section 4. It will be shown in Section 4 that there is a greater decreasing trend of DTR at Xian than that of Mount Hua caused by aerosol cooling effect, which indicates that the surface solar radiation has decreased due to the increasing particulate air pollution. In Section 5 we analyze the trends of surface winds in Xian and Mount Hua. The analysis of winds will show the reduction in surface winds and respective increase in mountain winds due to the reduced convection. The trends in thunderstorms and precipitation are analyzed in Section 6. The analysis in Section 6 will provide further support for the aerosol combined radiative and microphysical effects.

3. Study area and dataset

The dataset is composed of regular synoptic data observed at the highland station at the top of Mount Hua and the two lowland stations (see location in Fig. 1). The data of temperature, surface winds, visibility and humidity have four daily observations at 2, 8, 14, and 20 local times. The thunder data are only available for Xian and Mount Hua among the three stations. This dataset includes both thunder and lightning records with their occurrence time in the day. The code in the original file is 17, denoting thunder or lightning. Following the identifier of '17' is the start and the end time for the period during which thunder or lightning occurs. The rain barrel data from Xian and Mount Hua are the daily precipitation amount records. These thunderstorm records are conventional observed items and are served as the source of weather report. The digital data of 1-min precipitation intensity were originated from the recording pluviometer and available only for Xian. These data were the basis for the hourly and 1-min

Table 1
Data inventory.

Station	Temperature (T_{max}, T_{min})	Rain barrel data	Wind speed (four time observations in the day)	Thunderstorm and occurring time	Rain rates (digital rain gauge data)	Radiosonde wind data	Visibility (four time observations in the day)	Humidity (four time observations in the day)
Xian	1951–2005	1951–2005	1951–2005	1951–2005	1961–2000	1975–2005		
Mount Hua	1954–2005	1954–2005	1954–2005	1954–2005			1954–2005	1954–2005
Huaxian	1962–2005							

Table 2
Changes in the stations position.

Station	The beginning date	The ending date	Latitude	Longtitude	Altitude (m)	Surrounding environment
Xian	19,501,201	19,541,031	34°15′N	108°55′E	400.0	Suburb, airfield
	19,541,101	19,550,228	34°15′N	108°55′E	400.0	Suburban
	19,550,301	19,551,231	34°15′N	108°55′E	413.1	Suburban
	19,560,101	19,571,031	34°15′N	108°55′E	411.9	Suburban
	19,571,101	19,581,231	34°15′N	108°55′E	412.7	Suburban
	19,590,101	20,051,231	34°15′N	108°55′E	396.9	Suburban
Mount Hua	19,530,101	Till now	34°29′N	110°05′E	2064.9	Mountaintop
Huaxian	19,620,101	Till now	34°31′N	109°44′E	341.5	Farmland

rainfall analyses. The sounding data in the Guanzhong basin are also available only for Xian. Twice daily radiosonde winds at Xian were taken from the Department of Atmospheric Science, University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html). Wind speed at 08:00 local time and 20:00 local time on 700 hPa was used to investigate the trend of upper air compared to Mt. Hua. All the data we used are extracted from the original historical records of the meteorological stations and are summarized in Table 1. The changes in the location of these stations are described in Table 2.

Thunderstorm data (since the operation of the station till 2005) are the most important data to present the changes of intense convection in this study; therefore, we keep other data including temperature, winds, rain barrel data, visibility and humidity in the same time period. The digital data of 1-min precipitation intensity at Xian make an exception for the digitalization that has been done only for the recording pluviometer before 2000.

4. Temperature trends

The key point of aerosol–wind–thunderstorm hypothesis is that aerosol blocks the solar radiation from surface heating, so that the convective instability is decreased. The reduction of surface solar heating should be analyzed first because it is the primary response of the aerosols combining direct and cloud mediated radiative effects. However, the surface temperature was influenced not only by aerosols, but also by the increased greenhouse gases and by the buildup of the urban heat island of Xian. Therefore, the methodology of ratios between highland and lowland areas was applied to isolate the impacts of aerosols from these factors.

The increasing trend in aerosols is expected to decrease the daily temperature range (DTR) because aerosols absorb and reflect solar radiation and hence decrease the daily maximum temperature (T_{max}). The same aerosols are transparent to the terrestrial IR radiation and therefore not expected to affect the daily minimum temperature (T_{min}). Increased greenhouse gases reduce the DTR mainly via elevating T_{min}. The urban heat island should also reduce DTR, because it increases T_{min} more than it does T_{max}. This is clearly evident in the trends for Xian, shown in Fig. 3A, where the DTR decreased at a rate of 0.35 °C per decade during the period of 1951–2005. Most of that trend (0.30 °C decrease per decade) was contributed from an increase in T_{min}, and only 0.05 °C per decade was contributed by a slight cooling trend of T_{max}.

In Huaxian, a rural station outside the heat island effect of Xian, the DTR still decreased at a rate of 0.25 °C per decade during the period of 1962–2005 (this is the longest available record of this kind near Xian). Almost all of this trend was caused by cooling of T_{max}, with a slight positive change in T_{min} (see Fig. 3B) suggesting that the role of aerosols blocking the surface solar heating had a dominant role in this trend.

To test this hypothesis, observations should be taken from above the heavy aerosol layer. At an elevation of 2064.9 m above sea level, or 1723.4 m above the lowland station of Huaxian, the observatory at the top of Mount Hua provides an opportunity for this test. According to Fig. 3C, the DTR at Mount Hua has been stable (an indicated increasing trend of 0.02 °C per decade) during the period of 1953–2005. It was contributed by difference between the positive trends of T_{max} of 0.06 and T_{min} of 0.04 °C per decade. The aerosol effect can be therefore presented as the difference between the trends over the mountain and the lowland stations. The trends of the difference between Huaxian and Mount Hua temperatures, shown in Fig. 3D, suggest that aerosols have caused substantial cooling of the low troposphere with respect to the temperature at 1.7 km above the ground, mostly during daytime, but this cooling was also carried over to the nighttime.

5. Trends in convective overturning

The surface heating induces convection in the daytime when the solar radiation is the strongest. The convection causes air with low horizontal momentum to rise, and finally be replaced by air with greater momentum from the higher layers. That is the cause for winds in the daytime to be usually stronger than those in the nighttime. The aerosol induced stabilization should decrease the convection and the exchanges of momentum between the surface and higher elevations, which should cause a reduction in the wind speed near the surface. A simulation study by Jacobson and Kaufman (2006) suggests that the aerosol particles may reduce near-surface wind speeds by up to 8% locally. In China, the surface wind speeds have been already observed to decrease due to sandstorms in the past decades (Wang and Zhai, 2004), which could also be ascribed to pollution aerosols.

Trend analysis of the wind speeds at 14:00 local time in Xian and at the top of Mount Hua, shown in Fig. 4A, indicates a decreasing trend of 0.13 m s^{-1} per decade in Xian, balanced by a similar increasing trend of the wind speed at the mountain top. The increasing trend of the wind at the mountain top cannot be explained by intensification due to synoptic causes, because the Xian radiosonde data show the opposite trend, i.e., a significant decreasing trend of the wind speed at 700 hPa, which is at a height of about 3000 m (Fig. 4B). Therefore, Mount Hua is within the top of the mixed layer. When the aerosol layer blocks the turbulence from below, newly formed convection above aerosol layer forms and drags the upper winds, resulting in the decreasing trend in radiosonde winds at 700 hPa at Xian. The increasing trend at the mountain top is the inevitable result of a decreasing trend in the convection that brings slower air from near the surface and of more mixing of faster winds from further aloft. The indicated decreasing trend in lowland and increasing trend in highland are the two sides of the same coin; that is, vertical energy exchanges have been suppressed due to the anthropogenic aerosol's cooling effects. The opposite trends in the wind speed at the lowland and highland peak in the afternoon, as expected, but they also occur at other times of the day (not shown), suggesting that the suppression of convection caused by the aerosol's surface cooling effects in the daytime persists into the night.

The correlation between wind speed and visibility averaged over summer months (June, July and August) at Mt. Hua from 1954 to 2005 is displayed in a scatter plot (Fig. 4C). According to Fig. 4C, the summer wind speed at 14:00 LT is inversely correlated with visibility; the linear Pearson correlation coefficient is -0.48. In contrast, summer wind speed at 02:00 LT has almost no correlation with visibility, with a correlation coefficient of $+0.01$. The correlations between wind speed and visibility for Mt. Hua at 08:00 LT and 20:00 LT (not shown) are similar to but less clear than that at 02:00 LT and 14:00 LT, respectively. The contrast among correlations between wind speed and visibility at the four daily observation times indicates a daily cycle in the drag effects on mountain winds by lower winds. The daily cycle in the drag effects are mainly caused by the diurnal variation of boundary layer convection, which could be influenced by aerosol's surface cooling effects. The inverse relations between wind speed and visibility at 14:00 LT at Mt. Hua also show the close linkage between air pollution and the weakening of afternoon mountain winds directly. Consequently, time series of winds has opposite trends for Mt. Hua and Xian (Fig. 4A) with heavier aerosol loading. Therefore, the analysis of the 52-year wind speed from 1954 to 2005 may indicate that aerosol's radiative effects

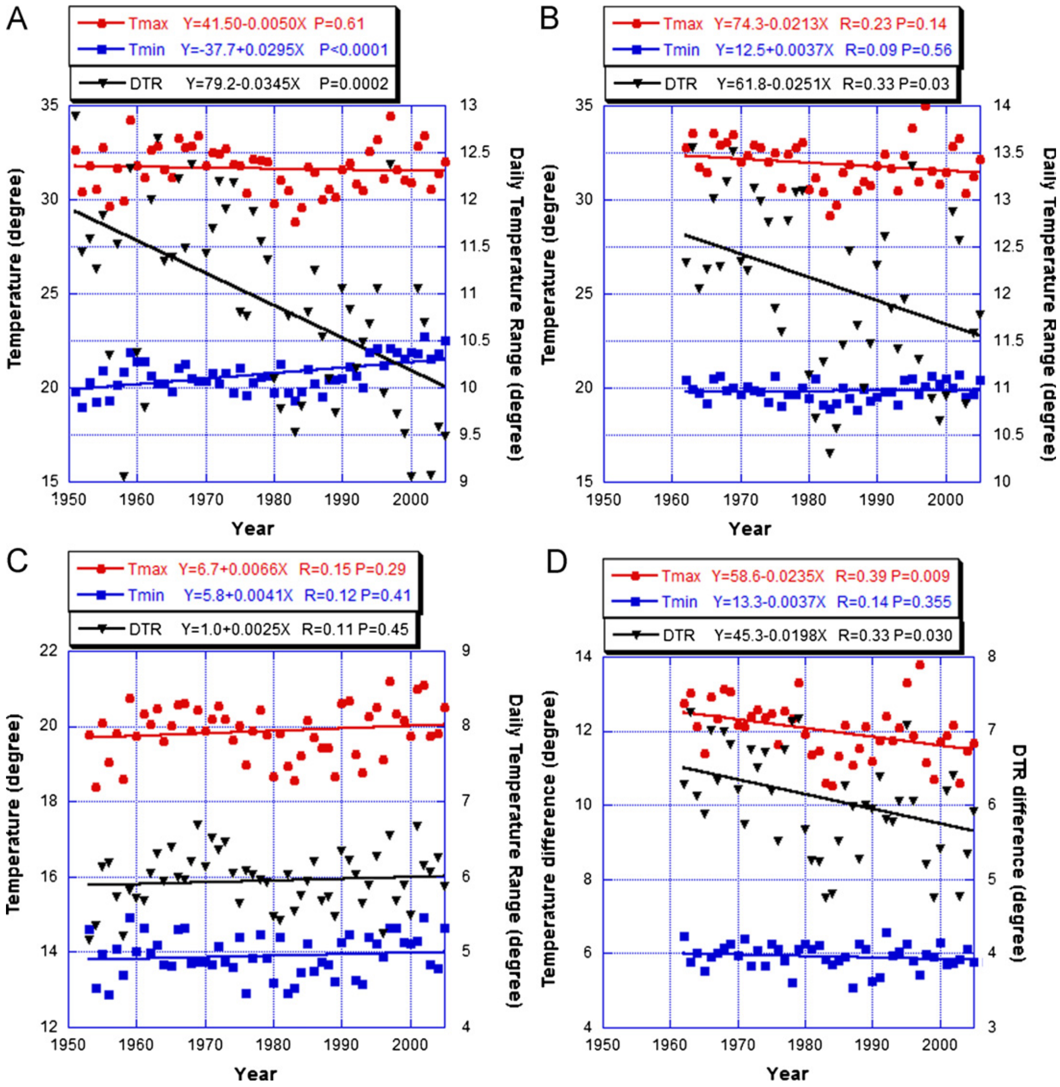

Fig. 3. (A) Surface temperature JJA trends in Xian. Shown are the trends of maximum (red ●), minimum (blue ■) and daily temperature range (black ▼). The *P* values denote the probability that the slope of the linear trend is not different than zero. Note the significant decreasing trend of DTR mainly due to increasing of nighttime minimum temperatures. (B) Surface temperature trends in the rural station of Huaxian, which is not affected by a heat island. Note the significant decreasing trend of DTR mainly due to the decreasing maximum temperatures. (C) Surface temperature trends at the top of Mount Hua, an elevation of 2064.9 m. Note the slight increasing trends of all temperatures. (D) The JJA trend of the temperature differences between the lowland rural station of Huaxian and the nearby highland station of Mount Hua. Note the strong relative decrease in the maximum temperature at the lowland with respect to the highland station, while keeping the difference between the minimum temperatures stable. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

suppressed daytime boundary layer convection hence surface winds in the Xian valley.

6. Trends of thunderstorms and precipitation

Summer precipitation depth in Xian has not changed significantly, whereas the relative decrease of mountain precipitation was ascribed to the microphysical effects of the pollution aerosols. The separation of the microphysical and radiative effects on the rainfall in the lowland from the synoptic causes for variability is even more challenging. This question is approached by testing the relative changes in rain intensities and by trends of frequency of thunderstorms normalized by rainfall amounts.

6.1. Precipitation

Aerosol's microphysical effects are expected to decrease the precipitation from shallow clouds. In contrast, the aerosol radiative effects are expected to decrease the instability and the probability of intense convection with thunderstorms. When both mechanisms are operative, it is conceivable that the combined effect of the contrasting impacts will result in little change in the overall rain intensities. Rain intensities are crudely approximated by the distributions of daily rainfall depths.

The probability of light rainy days decreased both at the high and low level rain gauges, although at the mountain station the loss was greater for rainier days. According to panel A of Fig. 5, at Xian, the probability for light rainy days with less than 1 mm day^{-1} was reduced from 19% at the decade centered at 1960 to 15% at the decade centered at 2000, or loss of about 20% of such light rainy days. However, the probability of rainy days with more than 5 mm day^{-1} did not change. Panel B of Fig. 5 shows a much stronger effect at Mount Hua. The probability of rainy days with 25 mm day^{-1} or less was reduced from 48% to 38%, i.e., to about 4/5 of what it was 50 years ago. Only the probability of rainy days with more than 30 mm day^{-1} was not changed. The probability for light and moderate rainy days has decreased gradually with the decades, with an enhanced pace during more recent decades, which is also supported by Fig. 6A and B. According to the time series in rainy days and rain amount, the

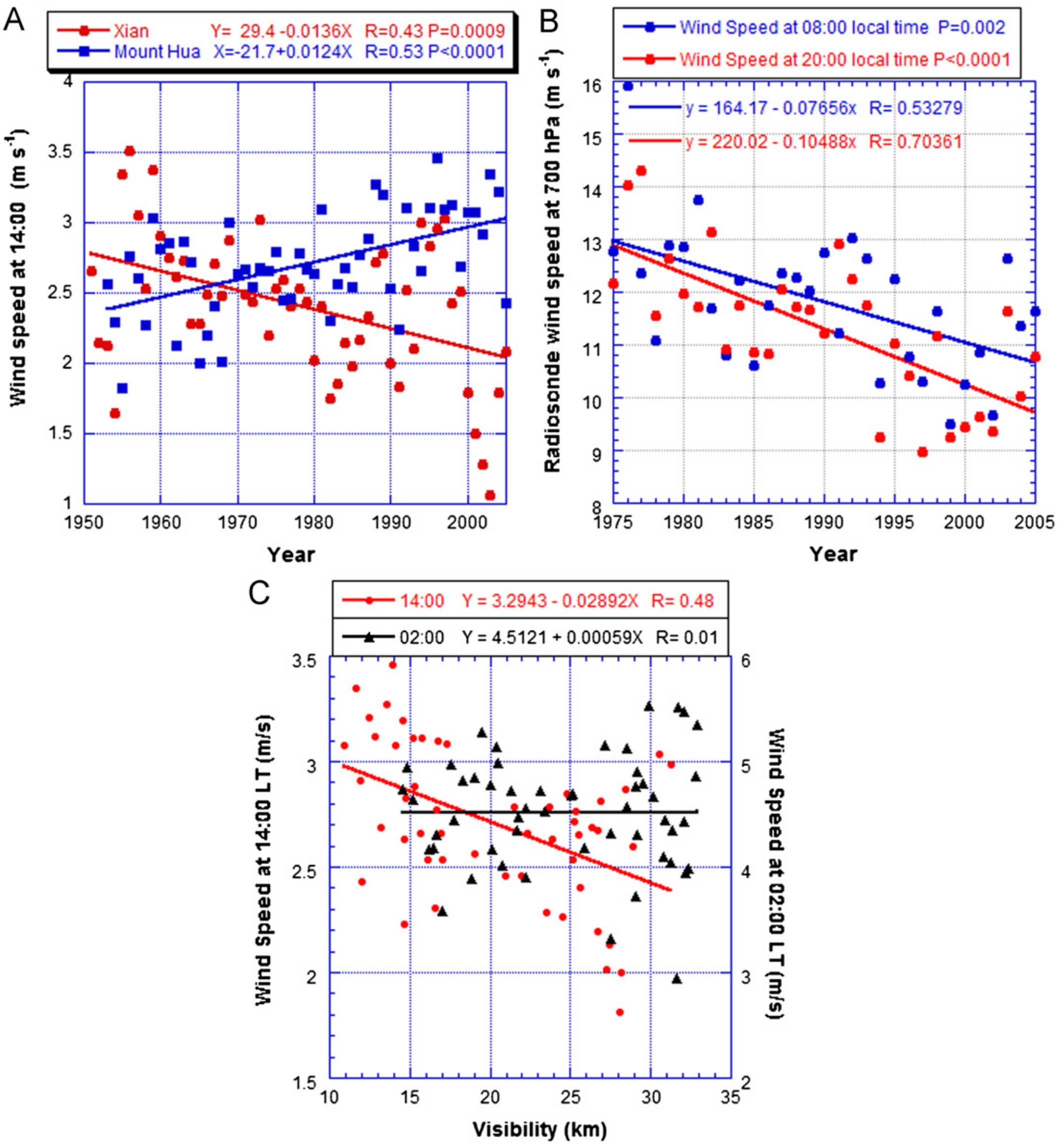

Fig. 4. (A) The JJA trend of surface wind speeds at 14:00 local time in Xian and at the top of Mount Hua. Note the significant opposite trends, where the mountain winds increase on expense of the low level winds. This suggests a trend of reduced vertical exchanges of air as a manifestation of suppressed convection. (B) The JJA trend of 700 hPa wind speeds. (C) Correlation between summer average wind speed and visibility at Mt. Hua from 1954 to 2005. Winds at 14:00 LT and 02:00 LT are denoted by dot and triangle, respectively. The visibility is from corresponding observation time and corrected to reduce the effect of relative humidity. The line represents a linear regression through all data.

decreasing trend of summer rain days are statistically significant for both Xian and Mount Hua (Fig. 6A), whereas the decreasing trend in summer rain amount is only discriminable for Mount Hua (Fig. 6B), suggesting that the suppression of precipitation at Mount Hua is relatively greater than that on Xian valley. The reduction of light rain events due to aerosol effects is consistent with previous studies (Choi et al., 2008; Qian et al., 2009).

It appears that the decreasing trend in the ratio of precipitation amount between Mount Hua and Xian or Huaxian in previous study (Rosenfeld et al., 2007) is contributed mainly by the preferential decrease of the probability of low and moderate precipitation days over the mountain in comparison to the plain gauges, as shown in Fig. 5. This is consistent with our expectations that the rainiest days occur from strongly forced synoptic situations where the clouds are deep and long lived, and therefore least susceptible to be affected by aerosols. This also means that the trends are not due to a few spurious large rainy days but rather due to the much larger numbers of small and moderate rainy days making the statistics more reliable and believable.

In addition, Fig. 6C and D presents the trends of rainfall amount during thunderstorm days and averaged rainfall amount for the thunderstorm days. The total rainfall amount during all thunderstorm days has no clear trend (Fig. 6C); however, the decreasing trends in the rainfall amount per thunderstorm day are clear and statistically significant for Mount Hua and Xian (see Fig. 6D), suggesting the decrease of convection intensity in this region. The evident decreasing trends in rainfall amount per thunderstorm day indicate the suppression of thunderstorm intensity and associated heavy precipitation in this region.

6.2. Thunderstorm

The surface solar heating atmospheric instability along with the surface winds in Xian is expected to suppress the intense convection such as that manifested in thunderstorms. The impacts of aerosols on thunderstorms should behave similar to the response of the temperature and winds in the diurnal variation. As expected, the thunderstorm frequency in the

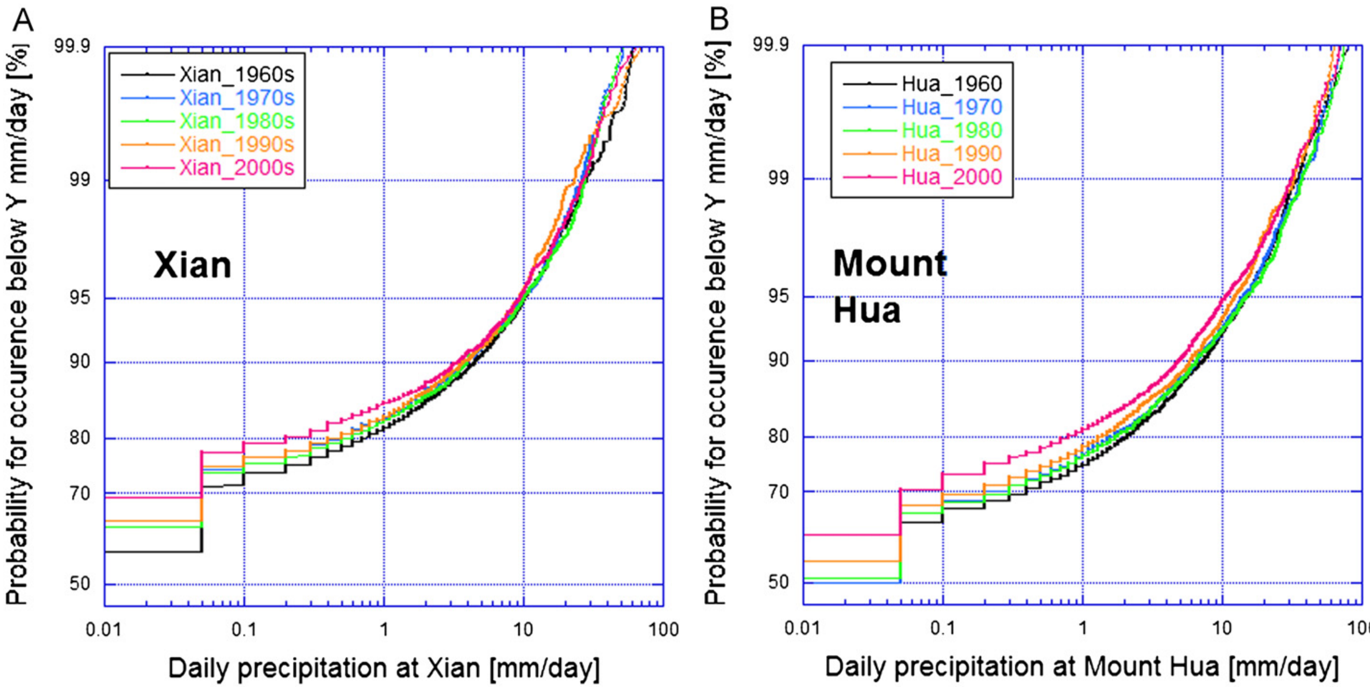

Fig. 5. Probability for occurrence of daily precipitation not exceeding the amount shown in the ordinate [mm day^{-1}], for Xian (A) and Mount Hua (B) rain gauges, for the decades of 1954–1964, 1965–1974, 1975–1984, 1985–1994, and 1995–2004. Note about 1/5 decrease of the probability of precipitation (up to 25 mm) days at Mount Hua (B) between the first and the last decades, whereas in Xian (A) only the probability of days with less than 5 mm was decreased.

afternoon at Xian shows a significant decrease by about half which persisted through the night (see Fig. 7A). Because rainfall at Xian showed little trend (see Fig. 7B), the decreasing trend in thunderstorm frequency in Fig. 7A can only be explained by the weakening of convective instability, which has likely been caused by the aerosol's radiative effects. The dominance of thunderstorms during afternoon (Fig. 7A) shows that solar heating dominates the occurrence of thunderstorms, despite the even distribution of rainfall amounts throughout the diurnal cycle. The role of aerosols in the indicated decreasing trend of thunderstorms (Fig. 7A) is supported by the observation that thunderstorm frequency was dramatically decreased during the afternoon with respect to the rest of the day at Xian, but not at Mount Hua (Fig. 7D). Although thunderstorm frequency is decreasing significantly in Xian, the rainfall amount does not appear to be significantly affected. This is in line with the diurnal change in the thunderstorm frequency that is not echoed by a similar change in the diurnal rainfall depth.

Although there is an overall decreasing trend in thunderstorm frequency at Mount Hua (Fig. 7C), the most important indicator is that the afternoon thunderstorm frequency at Mount Hua has no relative decreasing trend with respect to the rest of the day (Fig. 7D). Normalizing the thunderstorm trends by the rainfall amounts shows stability of normalized thunderstorm frequency in Mount Hua, whereas in Xian a substantial decreasing trend is noted (Fig. 9C). Finally, the ratio between the normalized thunderstorm trends of Xian over Mount Hua shows a relative decrease by a factor of two in the thunderstorms of Xian. This final figure is the closest that can be estimated to the net effect of the increasing pollution aerosols on the probability of thunderstorm in Xian.

7. Discussion

7.1. Conceptual considerations and implications of the heavy aerosol loading

The microphysical and radiative effects of pollution aerosols on precipitation properties in the Xian valley and the nearby mountains are evaluated in this study. Here we examine these effects in the view of the conceptual model presented by Rosenfeld et al. (2008). According to this model, the aerosol levels at the Xian region presently are far above the aerosol optical thickness (AOT) of 0.25, which is the point where added aerosols would have suppressive effects on convective precipitation. The AOT at 2005 was $\sim$0.8 according to satellite observations (Fig. 2A). Such observations have been available only since 2000, so that the estimation of the historical AOT must rely on trends in the measured horizontal visibility distance. The average summer visibility distance there decreased from $\sim$40 to $\sim$20 km during the period of 1954–2005 (see Fig. 2B). This implies an average AOT of $\sim$0.4 in the 1950s. The uncertainty in this over-simplified calculation is high, but even an AOT of 0.3 at that time would mean that the "clean" reference for the time series was already at the high-aerosol regime where added aerosols would suppress the precipitation by both radiative and microphysical considerations (Rosenfeld et al., 2008). The aerosols at these historical times could have come from agricultural fires and from uncontrolled burning of coal.

The trends of temperatures and winds have established that the aerosol radiative effects are substantial and have stabilized the lower troposphere and decreased the convection, at least within the boundary layer (Fig. 7). The top of Mount Hua is typically within the well mixed aerosol layer during summer afternoons, but under much smaller AOT as the lowland areas are some 1650 m lower. No measurements are available for the AOT at the mountain top; therefore, the aerosol's radiative effects on suppressing precipitation at the mountain top would be much smaller than those over the lowland.

7.2. The microphysical versus radiative aerosol effects

The microphysical effects on suppressing the orographic rainfall have already been documented in a previous study (Rosenfeld et al., 2007), showing a 20% reduction of annual rainfall compared to the reference of lowland rainfall. The relative trend for the

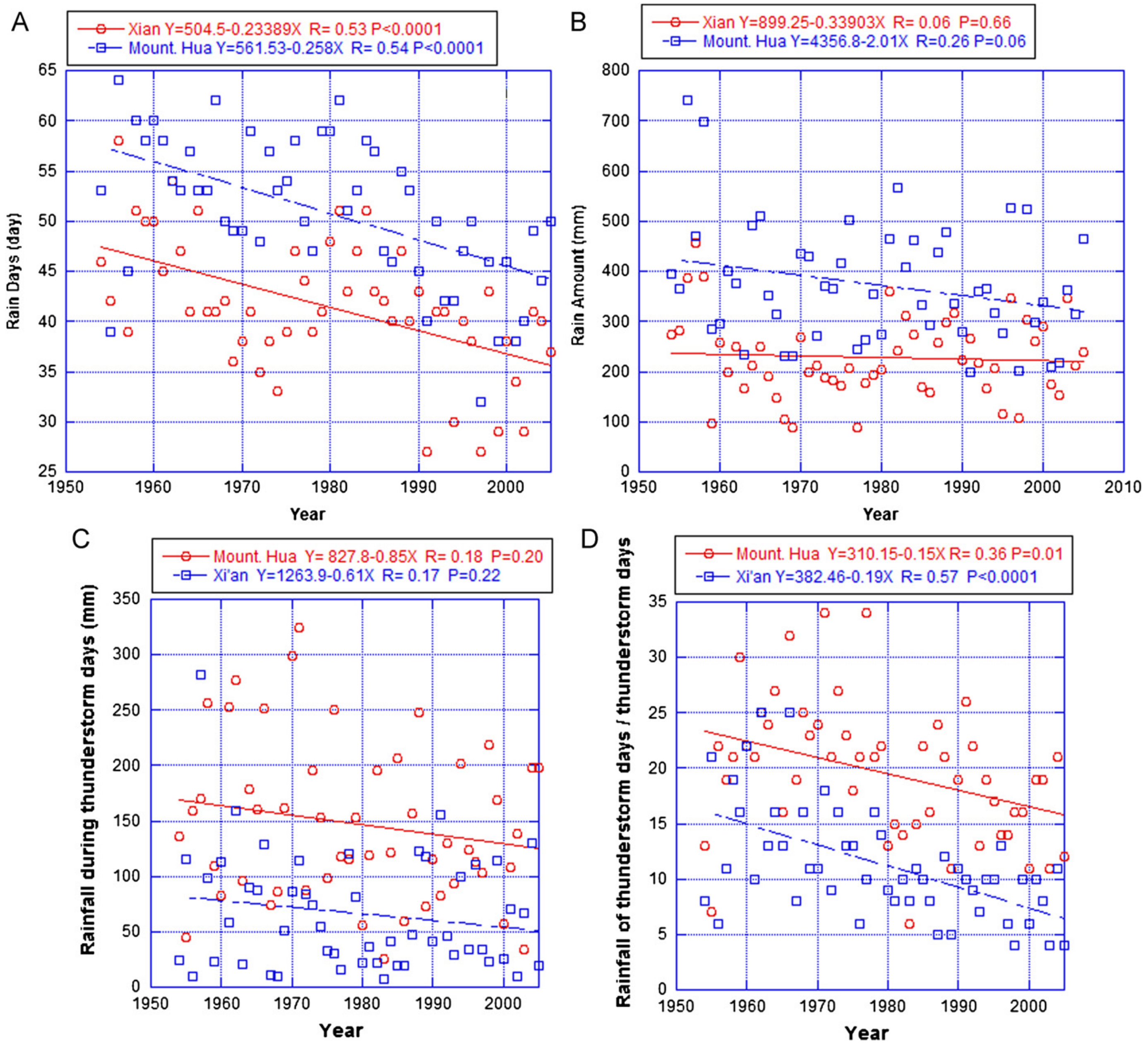

Fig. 6. JJA rain days trends (A) and rain amount trends (B) for Xian and Mount Hua from 1954 to 2005. JJA rainfall trends during thunderstorm days (C) and the relative trend of rainfall during thunderstorm days with respect to thunderstorm days (D) for Xian and Mount Hua. Note the significant decreasing trend of averaged rainfall amount for thunderstorm days.

summer months is replicated in this study (Fig. 9A). The decreasing trend of JJA thunderstorm days in Mount Hua (Fig. 9B) has the same magnitude of about 30% as the absolute trend of the rainfall amount there (Fig. 9A). The thunderstorm days normalized to rainfall amounts have been stable over Mount Hua during the years (Fig. 9C), meaning that decreasing rainfall was in line with the decreasing electrical activity. This association is consistent with the suggestion that the overburden of aerosols has been suppressing the mixed phase precipitation, in line with the conceptual model presented by thermodynamic track *a* in figure 3 of Rosenfeld et al. (2008). This suggestion is further supported by the observation that the frequency of days with light to moderate rainfall amount (<25 mm day^{-1}) was reduced by 1/3 during the 50 year study period (Fig. 5B).

In contrast to the lack of trend in Mount Hua, a sharp decreasing trend in the thunderstorm normalized by rainfall amount was observed in Xian (Fig. 9C). The frequency of normalized thunderstorms decreased in Xian by almost a factor of two relative to that of Mount Hua (Fig. 9D). Because the full microphysical effect is already taken into account by the normalized thunderstorm trends over Mount Hua, this dramatic additional decrease in thunderstorm activity in Xian relative to Mount Hua should represent the radiative effects that weaken the intensity of convection over the lowland.

In addition, the suppression of thunderstorm by aerosol's radiative effects in Xian region is not in conflict with the invigoration in thunderstorm activities by aerosol's microphysical effects as shown by some previous studies (Zhang et al., 2007; Yuan et al., 2011). There are significant distinctness for this study from previous papers. First, there is an abundant water vapor supply over the ocean surface or coastal area in previous studies, whereas the Xian valley is far away from oceans and the

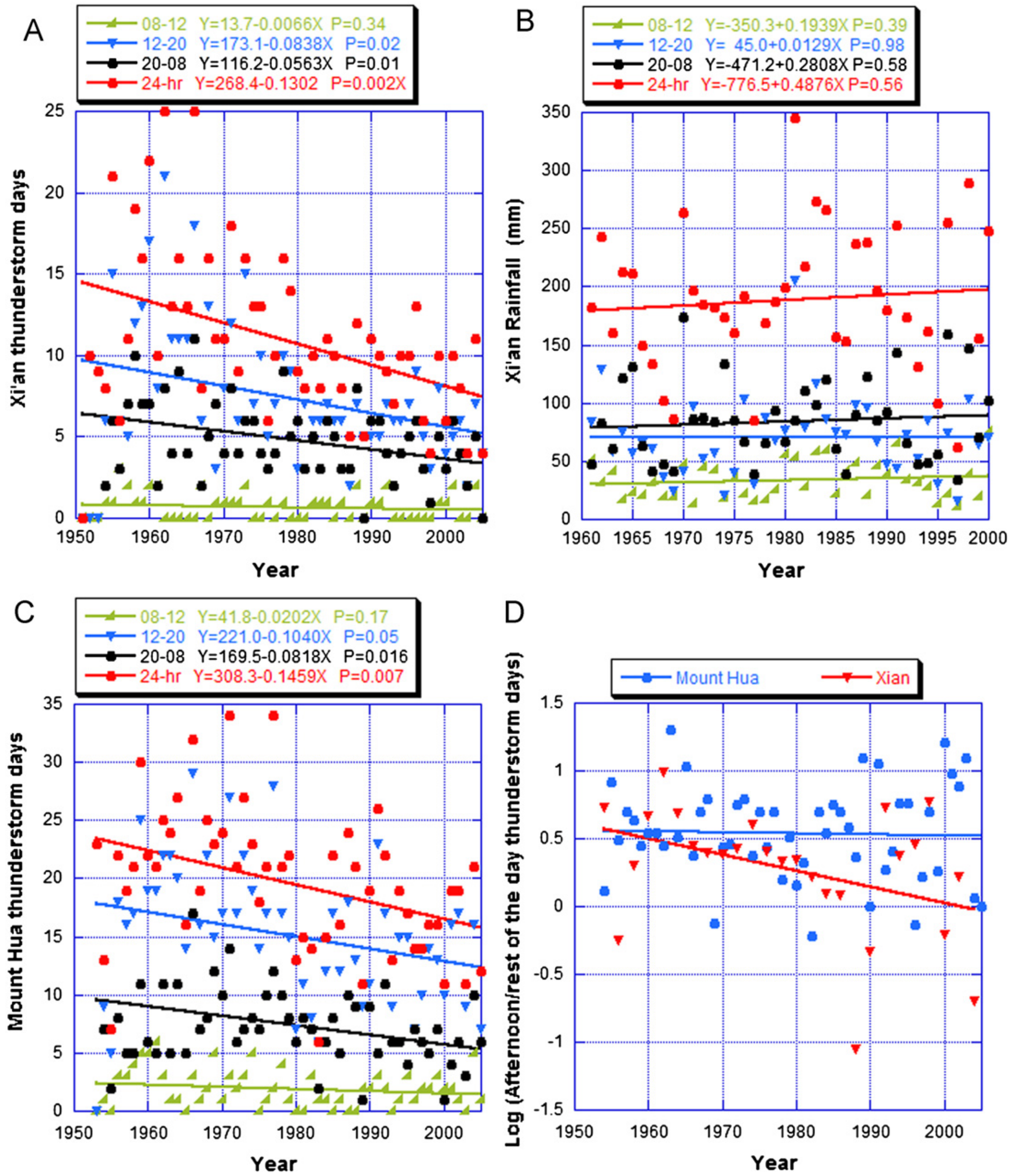

Fig. 7. (A) Trend of JJA thunderstorm events in Xian at different parts of the day. (B) The trend of JJA rainfall in Xian at different parts of the day. (C) The trend of JJA rainfall in Mount Hua at different parts of the day. (D) Trends of afternoon thunderstorms with respect to the rest of the day in Xian and in Mount Hua. Due to the large variations of the ratios, the log 10 transformation of the ratios is plotted. Note that the fraction of afternoon thunderstorms has remained constant in Mount Hua, while decreasing dramatically in Xian.

atmospheric water vapor is moderate. The content of precipitable water in atmosphere may decide whether the microphysical or the radiative effects dominate the development of clouds. A likely critical role of precipitable water in aerosol impacts on cloud droplet size was found in the study by Yuan et al. (2008). Second, the instability of environment and drive forcing are different evidently. The background environment is already instable in the previous studies with the encounter of Asia winter monsoon and warm and wet air mass from ocean surface, or with mesoscale squall line, while in Xian valley the most important energy source for atmosphere convection is the surface heating which has decreased due to aerosol's radiative cooling. Third, background aerosol loading is relatively low either over Pacific Ocean (Zhang et al., 2007) or in the contrast simulations (Yuan et al., 2008; Li et al., 2009). As suggested by Rosenfeld et al. (2008) and Koren et al. (2008), the two opposing but superimposed mechanisms would transfer the aerosol concentration. In this study aerosol loading in Xian valley is high enough to inhibit clouds from the beginning as shown in Section 2.

7.3. *The weak response of the rainfall at the lowland*

Despite the sharp decrease in thunderstorm activity in Xian, the rainfall depth in the lowland stations did not show any significant trend, both in Rosenfeld et al. (2007) and in this study. Furthermore, the frequency of light rainy days was decreased only slightly (Fig. 5A). This unexpected lack of relation between thunderstorm activity and surface rainfall is paralleled with the strong diurnal cycle of thunderstorm activity that is not matched by a similar diurnal cycle in the rainfall depth (Fig. 8A and C). This situation is different

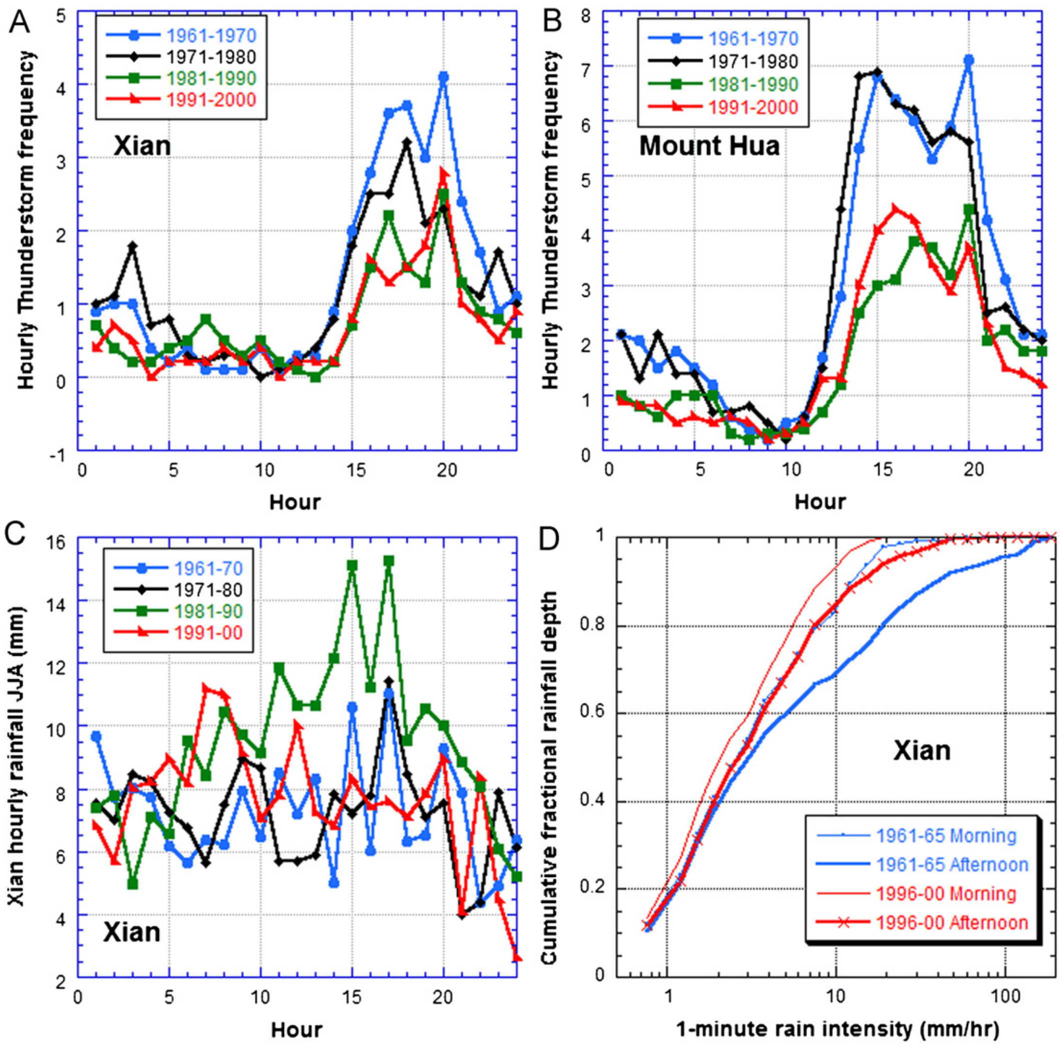

Fig. 8. JJA diurnal cycle of thunderstorms for 1961 – 70, 1971 – 80, 1981 – 90 and 1991 – 00 for, (A) Xian. (B) Mount Hua. (C) JJA diurnal accumulation of rainfall in Xian for 1961 – 70, 1971 – 80, 1981 – 90 and 1991 – 00. (D) Cumulative rain intensities in Xian for 1961 – 70 and 1991 – 00, and for morning and afternoon. Note the large diurnal cycle of thunderstorms and the dramatic decrease in afternoon thunderstorms (A). This trend is not paralleled in the rainfall amounts during most of the study period (C), and manifested only moderately in the rain intensities (D) at the early period.

from those in other regions with summer subtropical rainfall, such as the southeastern part of the USA (Bell et al., 2008; Li et al., 2011b). A possible explanation that resolves this apparent discrepancy is that most of the rainfall over Xian is not triggered by local low level instability, and the solar heating just adds a small convective component that is embedded within the other rainfall generating mechanisms in Xian, such as synoptic forcing and orographic triggering in the nearby high mountains (Fig. 8A and B). This could be displayed by Fig. 8C and quantified to some extent by Fig. 8D. The added convective rainfall depth during afternoon with respect to morning at the early cleaned period (1961 – 70) was only 14% of rain intensities >10 mm h^{-1}. This addition was reduced to a mere 8% during the latest decade (1991–2000).

This suggestion is supported by a small number of thunderstorm days in Xian—only ~7 for the three summer months of JJA (Fig. 7A) as compared to 16 in Mount Hua. This number was double in Xian in the 1950s, but even that is a small number for a climate in which most rainfall occurs in a continental summer monsoon.

The lack of decrease, and even some increase in rainfall over Xian may be caused by the documented synoptic changes that caused an upward shift in summer rainfall over the Yangtze River valley (Gong and Ho, 2002).

8. Conclusions

Aerosol levels in the Xian valley and the nearby mountains have been shown to be at levels where added aerosols suppress convection and precipitation, by both radiative and microphysical effects, even at the start of the analysis period in the 1950s. The main results are as follows:

- Aerosol's negative radiative forcing stabilized the lowest troposphere.
- The stabilization resulted in less vertical exchanges of air, which caused a reduction in the lowland surface winds and an increase in the highland wind speeds.
- The decreased instability caused a decrease in the frequency of the thunderstorms normalized by rainfall amount in the lowlands due to the thick aerosol layer above, but not at the highlands, above which the aerosol layer was much thinner.
- The decreasing trend of highland precipitation was associated with a similar decreasing trend in thunderstorm frequency.
- The decreasing trend of precipitation in the highlands was contributed from light and moderate rainy (<25 mm day^{-1}) days.

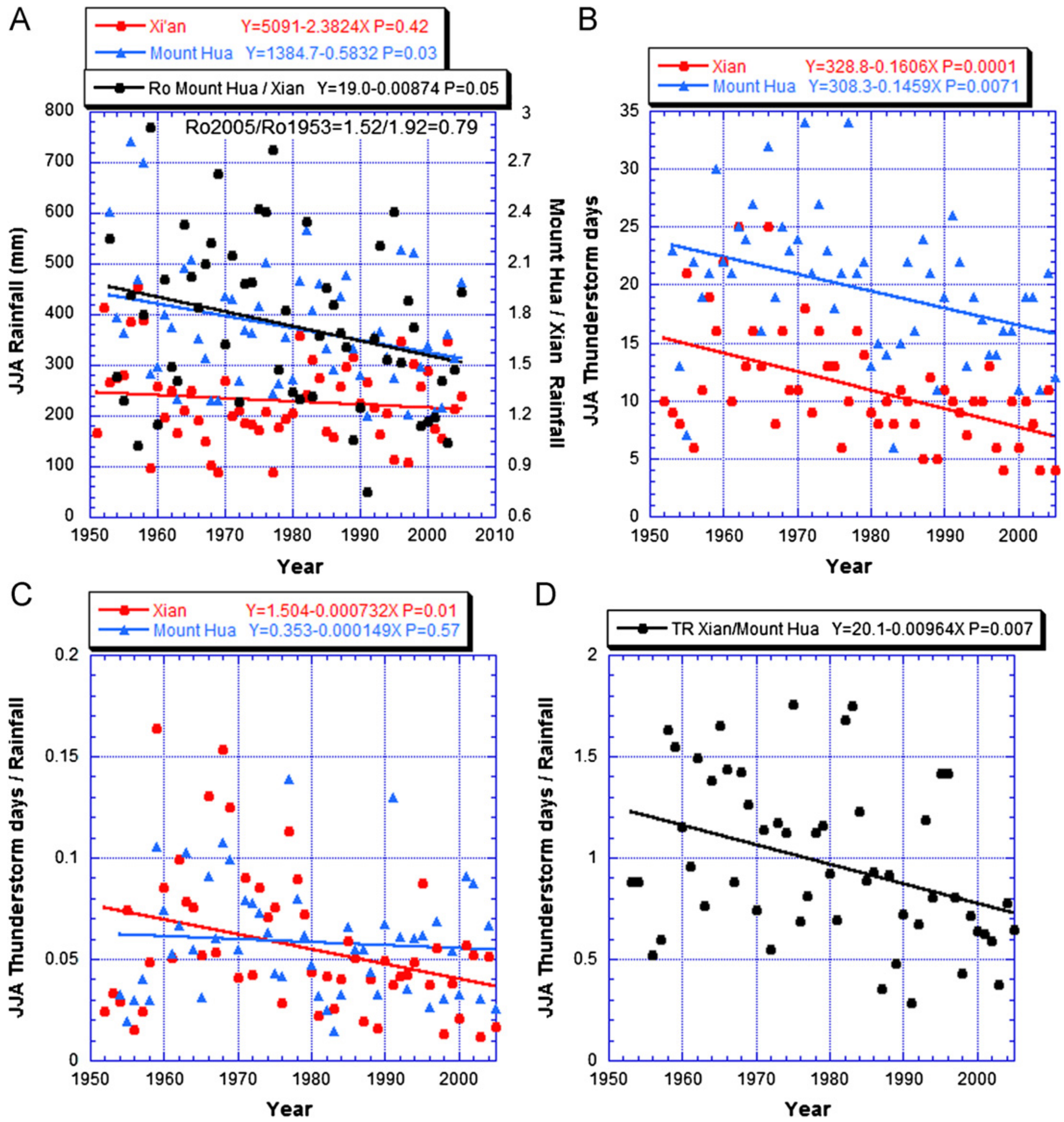

Fig. 9. (A) JJA rainfall trends in Mout Hua and Xian and the relative trend of Mount Hua with respect to Xian. (B) JJA trend of thunderstorm days in Mount Hua and Xian. (C) Trends of thunderstorm days/rainfall amounts in Mount Hua and Xian, i.e., B/A. (D) The thunderstorm/rainfall trend in Xian divided by thunderstorm/rainfall trend in Mount Hua, i.e., Xian/Mount Hua in C. Note the dramatic decreasing trend of thunderstorms normalized by rainfall amounts in Xian with respect to Mount Hua.

- The patterns of rainfall changes in the highlands (the previous two points) were consistent with the microphysical suppressive effects of aerosols.
- Despite the dramatic relative decrease in the already originally scarce thunderstorm activity in the Xian valley, the rainfall amount there appeared to have little diurnal cycle, and shows little trend with the increasing aerosol amounts.

Because only a small fraction of rainfall in Xian is generated by local instability, as indicated by the flat diurnal cycle, it appears to be a condition which is unsuitable for quantifying the impact of heavy aerosols on rainfall amounts. However, the dramatic relative decrease of the scarce thunderstorms in Xian suggests that such a study should be extended to other areas where the control of local surface heating dominates the rainfall amounts.

Acknowledgments

This research was supported by the Major State Basic Research Development Program of China (973 Program, Grant nos. 2013CB955804 and 2010CB950500). We are grateful to the Meteorological Information Center of Shaanxi Province for providing all data in this research. We thank D. Rosenfeld for the helpful discussion.

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