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Heavy air pollution suppresses summer thunderstorms in central China

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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 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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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 submicron 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 ~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

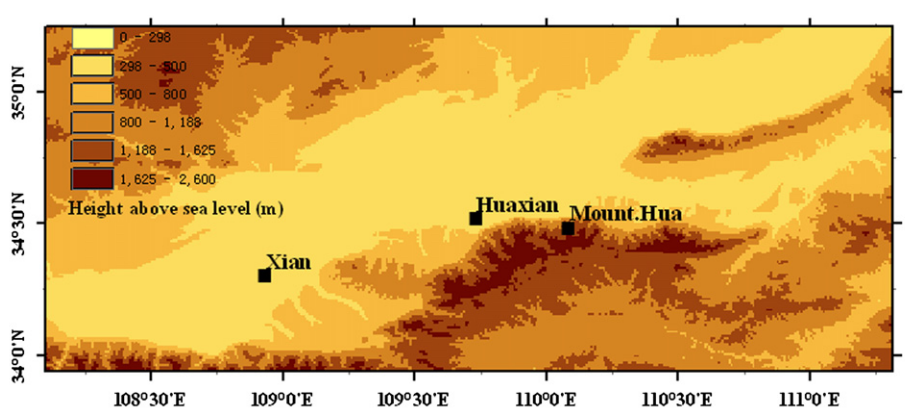

Fig. 1. Study area in central China.