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Advances in studying interactions between aerosols and monsoon in China

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Abstract Scientific issues relevant to interactions between aerosols and the Asian monsoon climate were discussed and evaluated at the 33rd "Forum of Science and Technology Frontiers" sponsored by the Department of Earth Sciences at the Chinese Academy of Sciences. Major results are summarized in this paper. The East Asian monsoon directly affects aerosol transport and provides a favorable background circulation for the occurrence and development of persistent fog-haze weather. Spatial features of aerosol transport and distribution are also influenced by the East Asian monsoon on seasonal, inter-annual, and decadal scales. High moisture levels in monsoon regions also affect aerosol optical and radiative properties. Observation analyses indicate that cloud physical properties and precipitation are significantly affected by aerosols in China with aerosols likely suppressing local light and moderate rainfall, and intensifying heavy rainfall in southeast coastal regions. However, the detailed mechanisms behind this pattern still need further exploration. The decadal variation in the East Asian monsoon strongly affects aerosol concentrations and their spatial patterns. The weakening monsoon circulation in recent decades has likely helped to increase regional aerosol concentrations. The substantial increase in Chinese air pollutants has likely decreased the temperature difference between land and sea, which favors intensification of the weakening monsoon circulation. Constructive suggestions regarding future studies on aerosols and monsoons were proposed in this forum and key uncertain issues were also discussed.

Keywords Aerosol, Monsoon, Interaction, Fog-haze

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1. Introduction

Climate change has been a great concern both to governments and people around the world since the 1980s. On the one hand, climate change is affected by natural factors in-

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cluding earth orbit parameters, solar activity, volcanic eruptions, and internal climate oscillations. On the other hand, climate is also influenced by the by-products of anthropogenic activities, such as greenhouse gases (GHGs) and aerosols, and land use practices. Presently, many regions suffer from floods or droughts, extremely high or low temperatures, high frequent precipitation, and other natural hazards. These hazards not only affect people's lives, but also endanger the sustainable development of global economics and societies. Of many influencing factors, the biggest uncertainty is from aerosols. For this reason, scientific issues regarding aerosols have been paid more attention in recent years (IPCC, 2013).

Aerosols are liquid or solid particles suspended in the air. Atmospheric aerosols come from direct emissions (primary sources) or gas-particle conversion processes (secondary sources). Aerosol primary sources include burning, dust, and biomass emissions, and its secondary formation is involved in the nucleation and growth of multiphase chemical processes (Zhang et al., 2004; Zhang, 2010; Zhang R Y et al., 2012, 2015). For example, many aerosol species are produced by anthropogenic activities, such as coal combustion, vehicular emissions, and residential cooking. Primary and secondary aerosols are subjected to physical and chemical ageing, interactions with cloud processes, and long-term transport (Zhang Y H et al., 2008).

Aerosols play great roles in the earth climate system through atmospheric radiation, cloud physics, and hydrologic cycle processes (IPCC, 2013). The interaction between aerosols and radiation, or the aerosol direct effect, is the mechanism by which aerosols absorb and scatter solar radiation, altering the radiation budget (Li et al., 2004; Forster et al., 2007; Myhre et al., 2013). The interaction between aerosols and clouds, or the aerosol indirect effect, is the mechanism by which aerosols modify cloud microphysical properties and lifetimes, producing changes in radiation and precipitation (Ramanathan et al., 2001; Rosenfeld, 2000; Rosenfeld et al., 2008; Li et al., 2011a; Tao et al., 2012). When the liquid water content is held fixed, an increase in the aerosol number concentration increases the cloud droplet number concentration, but cloud droplet sizes are smaller. This decreases solar radiation over cloudy areas and is called the "first aerosol indirect effect" (Twomey, 1977). An increase in aerosols could inhibit rainfall and prolong cloud lifetimes, leading to stronger cloud albedo effects. This is called the "second aerosol indirect effect" (Albrecht, 1989; Ackerman et al., 1995). Huang et al. (2006) pointed out that the daytime air temperature range has decreased by 0.7°C due to aerosol indirect effects. The aerosol effects mentioned above are likely intensified by feedbacks in general circulation. It is a challenging task for researchers to find observational aerosol effects, to simulate them, and to understand their mechanisms. Overall, if the aerosol number increases, cloud particle sizes tend to decrease, and rainfall caused by warm clouds is suppressed (Albrecht, 1989; Rosenfeld, 2000). On the other hand, aerosols postpone the occurrence of rainfall and make clouds develop higher into the atmosphere. The conversion of cloud phases releases latent heat and triggers convection, resulting in further cloud development and more rainfall (Andreae, 2004; Lin et al., 2006; Koren et al., 2008; Rosenfeld et al., 2008; Li et al., 2011a). The ultimate aerosol effect on clouds and precipitation depends on specific microphysics, and dynamic and thermal conditions (Khain et al., 2008; Fan et al., 2009).

A large amount of aerosols have been produced due to anthropogenic activities since the pre-industrial era. In past decades, with the rapid economic growth in China, India, and other booming countries, the amount of anthropogenic aerosols has quickly increased. As shown by observations (Zhang X Y et al., 2012, 2013), aerosol mass concentrations in eastern China cities are much higher and only lower than some of the South Asian cities on a world scale. Moreover, some anthropogenic species (e.g., sulfate, organic carbon, black carbon, and nitrate) comprise the bulk of total aerosols. Heavy regional aerosol loading not only causes serious environmental issues and threatens human health, but it also has an impact on weather and climate through aerosol-radiation-cloud interactions as noted above.

China is a major monsoon climate region. The temperature, precipitation, and atmospheric circulation in this region have distinct seasonal variations. Their changes on different time scales have a direct impact on regional changes in precipitation and temperature. Consequently, China has long been a key region in global climate change research. The monsoon circulation has a direct influence on the transfer of atmospheric matter such as water vapor and raindrops. Aerosol processes are also affected by atmospheric circulation and how they change in time is affected by the variation in monsoon circulation. Because of this, research on the interaction between aerosols and the East Asian monsoon (EAM) has become a hot topic in current atmospheric environment and climate change research.

Studies about the interaction between aerosols and monsoons were reviewed and summarized at the 33rd "Frontier Science and Technology Forum" sponsored by the Department of Earth Sciences at the Chinese Academy of Sciences. The forum brought together domestic and foreign research scientists who shared their insights into the topic at hand. Focusing on the importance and urgency of current environmental aerosol pollution and the problem of its effects on climate in China, this study reviews some of the progress made concerning the interaction between aerosols and weather-climate in the EAM region at home and abroad. Rather than being a comprehensive review, this paper summarizes the reports presented at the forum including the ensuing discussion.

2. Characteristics of aerosols and the monsoon climate in China

Unlike long-lived and spatially homogeneous GHGs, tropospheric aerosols have short lifetimes in the atmosphere, and stronger spatio-temporal features. China has the largest population in the world and the area over which anthropogenic aerosols are present is also the largest in the northern hemisphere. Over the past three decades, the economic development in China has grown rapidly. This has placed great pressure on the regional environment and natural resources. Chinese energy consumption mainly relies on coal. Wintertime heating in northern China produces large amounts of sulfate, nitrate, and carbonaceous emissions (Zhang Q et al., 2009). A wide range of agricultural industries in eastern China have led to emissions of many aerosol precursors, mainly ammonium. In central Asia, including northwestern China arid regions, mineral dust is transported eastward to downstream regions. Dust aerosols comprise the bulk of total aerosols there (Huang et al., 2008a, 2014). The industrial, agricultural, and natural activities mentioned above have deeply affected the distribution and climatic effects of Chinese aerosols.

To investigate aerosol climate effects in China, many large field campaigns have been carried out. Chinese aerosol network and international Aerosol Characterization Experiments-Asia observational experiments concerning aerosols have been done continuously since 2001 (Zhang et al., 2002a, 2003). The East Asian Study of Tropospheric Aerosols: an International Regional Experiment (EAST-AIRE) was conducted in 2005 and 2008 (Li Z Q et al., 2007a, 2007b, 2011a) and coordinated other existing observational projects. Some established aerosol observational networks include the Chinese Sun Hazemeter Network jointly established by the Chinese Academy of Sciences and University of Maryland (Xin et al., 2006, 2007), the Chinese Meteorological Administration Atmosphere Watch Network (CAWNET) (Zhang X Y et al., 2008a, 2008b, 2013), the China Aerosol Remote Sensing Network (Che et al., 2009) and operational sites for aerosol observations. Continuous observations of aerosols, clouds, and radiation have been made at some heavily instrumented sites, such as those in Beijing, Xianghe, Taihu, and Yuzhong (Li Z Q et al., 2007a; Huang et al., 2008b; Fan X H et al., 2013). In addition, there are several completed or ongoing National Basic Research Program of China campaigns, e.g., "Atmospheric Aerosols and Their Climate Effects", "Aerosol-cloud-radiation Feedbacks and Interactions with Asian Monsoon Studies", "Observational and Modeling Studies of Cloud, Aerosol and Their Climate Effects", "The Physical and Chemical Characteristics of Atmospheric Pollutants and Its Interaction with the Climate System", "Decadal Scale Global and China's Atmospheric Composition and Climate Change and Its Interactions", and "The Climate Effect of China's Eastern Coastal Urban Belt and Its Countermeasures". Many national and departmental projects include efforts to observe aerosols and to study their regional impacts. For example, the number of projects with "aerosol" in titles increased to 40 in 2013. This shows that studies about aerosols have become a new direction for Chinese climate research.

Through these comprehensive experiments, Chinese scientists have obtained a large number of aerosol datasets, which provide a good basis for studying aerosol climate effects. Based on observations, the composition and spatio-temporal characteristics of atmospheric aerosols are revealed in China. Observations show that some aerosol mass concentrations over eastern Chinese mega-cities are only lower than those in South Asia. Figure 1 shows that mineral, sulfate, organic carbon, nitrate, ammonium, and black carbon aerosols make up 35%, 16%, 15%, 7%, 5%, and 3%, respectively, of the bulk of total particles with diameters less than 10 mm (PM_{10}), resulting in scattering-cooling climate effects (Zhang X Y et al., 2012). Organic aerosols have a higher ratio in China than in Europe and North America. The ratios of secondary aerosols are about 55% and 60% in Chinese urban and rural regions, respectively. Other aerosol compositions are also similar in northern China and in Yangtze and Pearl River Delta (PRD) cities except for mineral aerosols (Zhang Y H et al., 2008; Zhang X Y et al., 2012). Heavy aerosol loading in China is also reflected in satellite retrievals of aerosol optical depth (AOD). Recent satellite datasets show that high AOD regions are mainly located in the North China Plain, the Sichuan Basin, central China, and the Yangtze and PRD regions. AOD over north China and the middle and lower reaches of the Yangtze River is much larger than over other regions in wintertime (Luo et al., 2014). Moreover, the AOD over eastern China is much larger than that over European and North American regions (Shindell et al., 2013). Observations further show that AOD heights can reach 2–3 km and that fine-mode aerosols are dominant (Li et al., 2009; Xia et al., 2013). High concentrations of aerosols are also behind the fog-haze episodes that frequently occur in eastern China cities (Ma et al., 2012; Sun et al., 2014). Thus, more attentions should be paid to aerosol issues.

Aerosols have clear regional features in terms of spatio-temporal characteristics. Their chemical and micro-physical characteristics are also strongly affected by local emissions and ambient factors. For the densely populated and highly industrial Beijing and Tianjin mega-city regions, 70% of aerosols are internally mixed with two or three other aerosol types (Li and Shao, 2009). The aerosol deliquescence point is shifted early after mixing, but its hygroscopic ability weakens (Shi et al., 2012).

The EAM system is not just a circulation system over the East Asian with distinct seasonal evolution, but rather a regional climate system involving the processions of ocean, land surface, snow and ice, as well as the Tibetan Plateau (Huang et al., 2007; Wu et al., 2012). Many nature factors and anthropogenic factors can exert influences on it. The EAM region is one of the most vulnerable areas to climate variability in the world. The frequent climate disasters (such as droughts and floods, severe cold spells, severe hot waves, precipitation extremes, etc.) have caused serious damage to human life and property together with social development in

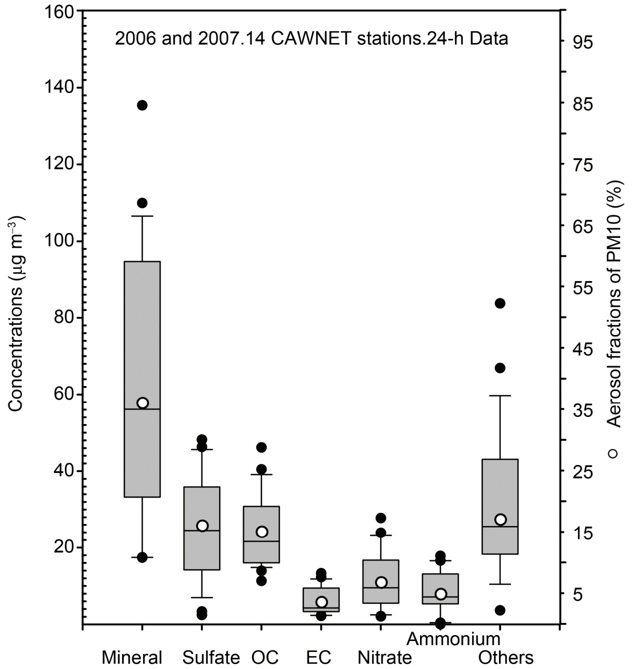


Figure 1 Annually-averaged mass concentrations (median of the box plot) of aerosol chemical species and their percentage (open circles) of PM_{10} in China. After Zhang X Y et al., 2012.

the East Asian. For example, the food loss in China can reach about 200×10^8 kg and the economic loss over 200 billion yuan each year due to these disasters (Huang, 2004). These disasters mentioned above have also caused a serial of social and environmental problems. All these are involved with the impact of climate change. The variation of aerosol over the East Asian region is an important factor affecting climate change. Therefore, the variation of aerosol over the East Asian region and its impact on the EAM climate are attracting more and more concerns.

3. The impacts of aerosols on weather and climate over China

Many studies have addressed the influence of aerosols on the Asian monsoon climate, especially over South Asia (e.g., Lau and Kim, 2006; Bollasina et al., 2011). However, due to the complexity of the factors affecting the EAM climate, there are many difficulties in simulating the long-term climate variation over China by current climate models. The present research on this influence is largely focused on the quantitative analysis of measurements and on numerical simulations based on climate models (Menon et al., 2002; Li L J et al., 2007; Niu et al., 2010; Li H M et al., 2010; Song et al., 2014), but no explicit conclusions have been reached yet. Since it is a huge challenge to quantify the influence of aerosols on weather and climate over China, this study briefly reviews relevant researches done at home and abroad from the two aspects of weather and climate, and points out some widely accepted results.

3.1 The impacts of aerosols on regional meteorological systems

Previous studies have revealed that clouds and precipitation are associated with aerosol concentrations, especially in regions polluted by aerosols throughout the year. Based on long-term observation-based aerosol and cloud datasets collected at the South Great Plains (SGP) site, Li et al. (2011a) have analyzed the effects of aerosols on cloud and precipitation under different meteorological conditions. In wet (dry) regions and seasons, the emission of aerosols could enhance (suppress) the development of clouds, thus increasing (decreasing) the frequency and intensity of precipitation and inducing more floods (droughts) (Figures 2 and 3). This conclusion is further confirmed by analyzing global satellite data (Niu and Li, 2012), which suggests that the conclusion is not confined to the SGP site, but can be applied to other regions in the world, especially tropical regions. For deep mixed-phase clouds, cloud-top temperatures are significantly negatively correlated with increasing aerosol loading, while no significant correlation is found for uniformly liquid clouds (Niu and Li, 2012). Ding et al. (2013) analyzed air pollution-weather interactions based on observational evidence and regional model results in the Yangtze River Delta area during May and June of 2012. They found that the presence of pollution aerosols can result in a decrease in solar radiation, sensible heat, and surface temperature, leading to changes in local short-term rainfall processes. In addition, the competition between direct and indirect effects of aerosols has been shown to affect clouds and precipitation (Fan et al., 2008).

Recent studies based on observations suggest that the increase in aerosol loading plays a role in changing cloud physical characteristics and thunderstorm activities. Aerosol effects on precipitation and thunderstorms in Shanxi Province, China have been investigated using long-term observational datasets from land stations. From this data, Yang et al. (2013a) found that aerosol microphysical effects could reduce orographic precipitation. When there is more pollution in the atmosphere, the suppressive effect of aerosols on light precipitation over the plains becomes stronger and the frequency of thunderstorms in the Guanzhong plain area is decreased (Yang et al., 2013a, 2013b). However, in southeast China, there is more orographic precipitation as air pollution increases (Yang and Li, 2014). These opposite responses to increasing air pollution levels may be due to the aerosol type dominant over the region in question. For example, concentrations of mineral and black carbon aerosols are higher in northwest China than in southeast China. Therefore, radiative and thermal effects dominate in northwest China, while the enhancement of deep convective clouds due to the cloud albedo effect dominates in southeast China.

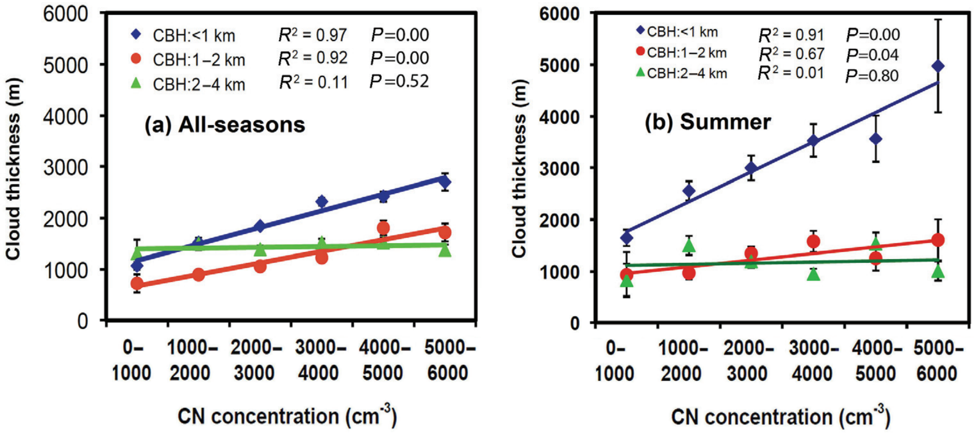


Figure 2 Changes in cloud thickness with concentration of condensation nuclei (CCN) in (a) all seasons and (b) summer. (After Li et al., 2011a).

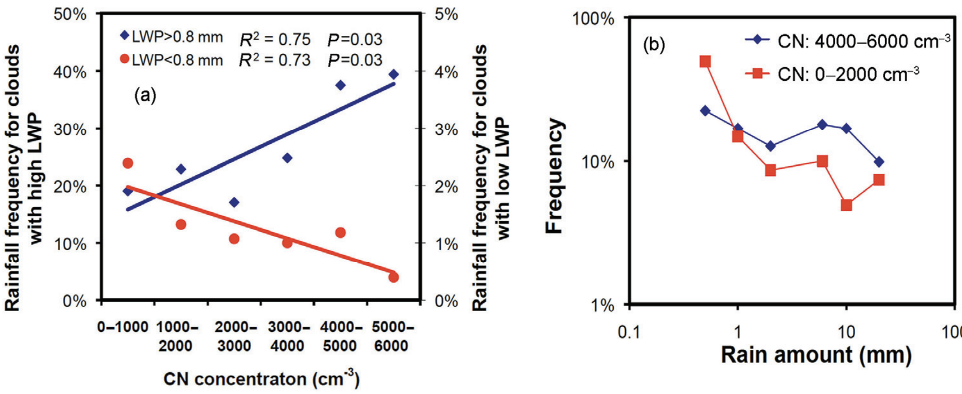


Figure 3 Changes in (a) rainfall frequency and (b) rain rate distribution with concentration of condensation nuclei (CCN). After Li et al., 2011a.

The impacts of aerosols on local cloud physical processes, precipitation, and lightning can be found in some heavily polluted regions. A seven-year analysis of precipitation, lightning flashes, and visibility from 2000 to 2006 has been carried out using data from the PRD region of China (Wang et al., 2011). The accumulated heavy rainfall (>25 mm per day) and frequency of lightning strikes are inversely correlated to visibility, and the spatial distributions of AOD and lightning are consistent (Wang et al., 2011). The Weather Research and Forecasting (WRF) model has been used to simulate a mesoscale convective system that occurred on March 28, 2009 in the PRD region (Wang et al., 2013a). Simulations suggest that precipitation and the lightning potential index are enhanced by about 16% and 50%, respectively, under polluted aerosol conditions (Wang et al., 2011). The elevated aerosol loading suppresses light and moderate precipitation (less than 25 mm per day), but enhances heavy precipitation (Figure 4). More intensified convection occurs under polluted aerosol conditions (Wang et al., 2013b).

3.2 The impacts of aerosols on regional climate features

From the 1960s to the late 1990s, the surface downwelling solar radiation over China has been significantly reduced (Luo et al., 2001; Shi et al., 2008), but the cloud amount has not changed much (Qian et al., 2007). Li Z Q et al. (2010) estimated the nationwide annual mean aerosol radiative forcing as 0.4 W m^{-2} at the top of the atmosphere, −15 W m^{-2} at the surface, and 15 W m^{-2} inside the atmosphere. Hence, the solar radiation change over China is likely due to the increase in aerosol loading. This is confirmed by the temperature changes observed over China, i.e., temperatures are generally increasing over China, but the magnitude of the warming is smallest in eastern China where the pollution level is higher. Strong atmospheric and surface aerosol radiative forcing can alter atmospheric stability and circulation significantly. An atmospheric model simulation has shown that the aerosol radiative forcing over China exerts large influences on the atmospheric circulation, surface pressure, temperature, humidity, and fog over China (Niu et al., 2010). Based on an observational analysis and long-term cloud-resolving model simulations, Fan J W et al. (2013) proposed a new theory that it is the combined microphysical and thermodynamic effects of aerosols that control the cloud development.

Based on a climate model simulation, He et al. (2013) have shown that the increase in aerosol loading contributes

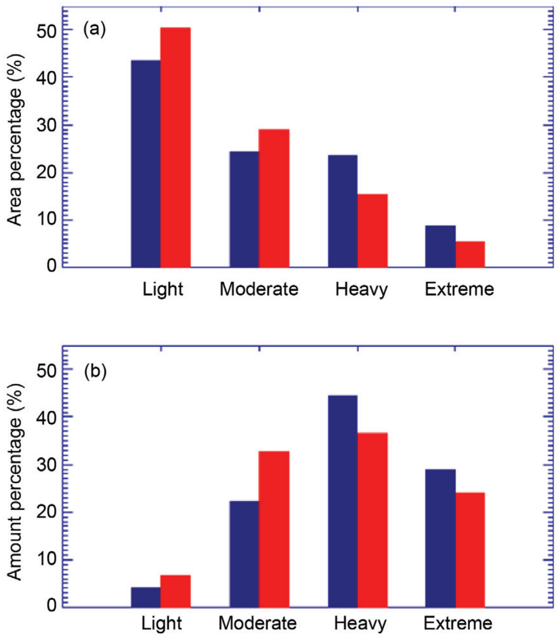


Figure 4 (a) Percentage of grid areas under each precipitation category over the entire model domain. (b) Percentage of the precipitation amount in each category over the total precipitation amount. Dark blue corresponds to the polluted atmosphere and red corresponds to the clean atmosphere. After Wang et al., 2013a.

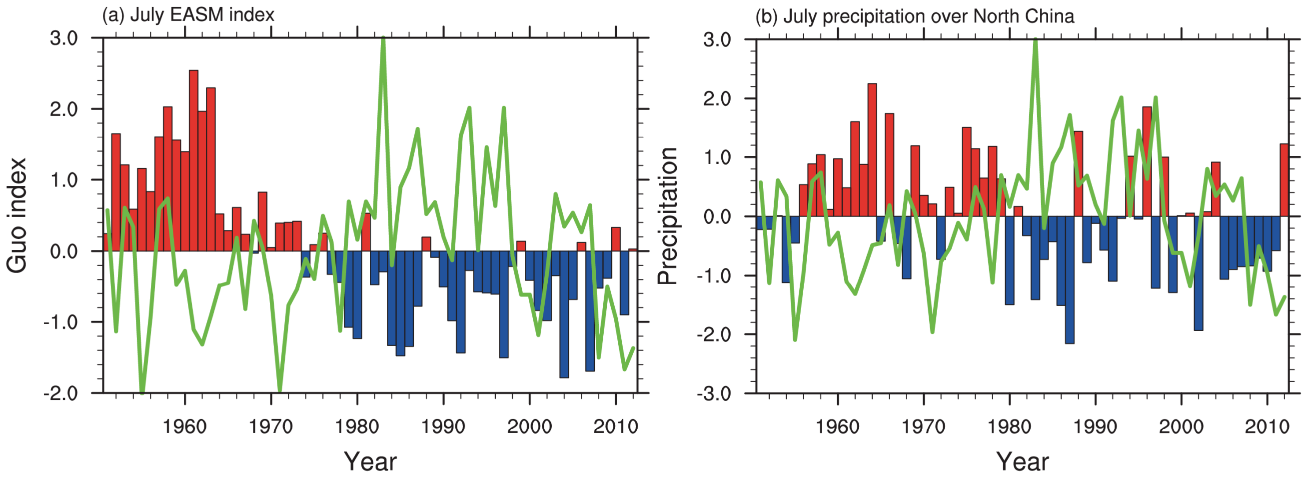
directly to the summer surface cooling over eastern China. Precipitation over China during the past few decades has shown a significant long-term trend, namely, that there is a "southern-flood-northern-drought" (SFND) pattern over eastern China where it is densely populated and where industrial and agricultural practices are highly developed, and a general "light rainfall decreases and heavy rainfall increases" trend over China. These changes may be due to many factors, including those involved with complex aerosol-cloud interactions (Li et al., 2011b; Qian et al., 2009). If these climate changes are related to aerosols, it will influence the future use of water resources and the sustainable development of the economy and society of this country.

3.3 The impacts of aerosols on atmospheric circulation

Many studies have revealed that aerosols have large influences on climate and atmospheric circulation. Influences on the climatology and long-term trends in cloud physics, temperature, and precipitation over China have increasingly become the focus of many studies.

The specific influences of aerosols on China are closely related to regional aerosol properties, weather, climate, and terrain, but are also largely controlled by the regional atmospheric circulation, namely, the monsoon circulation. In summer, along with the warm and moist air, strong surface heat fluxes and moist potential energy are favorable for the development of strong convection. Under these conditions, aerosols can likely reinforce convection and precipitation (Rosenfeld et al., 2008; Li et al., 2011b). By contrast, aerosols likely suppress convection and precipitation in winter. Wind shear is another factor that constrains the climate effect of aerosols. Weak wind shear is in favor of the aerosol effect, and strong wind shear hinders the aerosol effect (Fan et al., 2009). Wind shear may also be affected by the monsoon, forming the following feedback: surface wind is reduced by aerosols, but high-level wind remains almost unchanged, so that wind shear is enhanced and convection is suppressed by aerosols. The enhanced wind shear does not support the transfer and diffusion of aerosols from the surface to higher into the atmosphere. So, aerosol effects (including radiative and microphysical effects) will be intensified, further enhancing wind shear and suppressing convection (Fan et al., 2009).

The East Asian summer monsoon (EASM) has weakened during the late 1970s and 1990s, inducing the formation of the SFND precipitation pattern over eastern China (Hu, 1997; Wang, 2001; Yu et al., 2004, 2008; Yu and Zhou, 2007; Zhou et al., 2009a). Menon et al. (2002) have suggested that the increase in black carbon emissions contributes to the precipitation pattern. However, Meehl et al. (2008) have argued that the influence of black carbon on the Indian monsoon is significant, while its influence on the EASM is relatively weak because natural variability may play a dominant role. Zhou et al. (2008, 2013) have also supported the notion that the weakening of the EASM is mainly due to the tropical ocean's warming related to the phase shift of the Pacific Decadal Oscillation (PDO). Both the EASM index and North China precipitation are closely related to the PDO (Figure 5(a) and (b)). Corresponding to the weakening of the EASM, the SFND pattern is seen over eastern China (Figure 5(c)). In addition, Li H M et al. (2010) have found that the observed weakening of the EASM can be reasonably reproduced by an atmospheric general circulation model (AGCM) forced by the observed sea surface temperature (SST), which is mainly due to the tropical ocean's warming along with the positive phase of the PDO (Figure 6(a)–(c)). Li H M et al. (2010) have also suggested that the total effect of aerosols slightly enhances, rather than weakens, the EASM (Figure 6(d)). This conclusion is consistent with Li L J et al. (2007), which was based on the Institute of Atmospheric Physics/LASG AGCM, but different from Menon et al. (2002) who argued that the increase in black carbon aerosols favors the SFND precipitation pattern over eastern China. An important assumption is made by Menon et al. (2002) to explain these differences, namely, that the type of aerosol over China belongs to the "dark" aerosol category (aerosol single-scattering albedo (SSA)=0.85). However, according to satellite and surface observations, the aerosol SSA has large temporal and spatial variations over China. On average, aerosol absorption is weaker than that assumed by Menon et al. (2002). The national mean SSA is about 0.90 (Lee et al., 2007). Based on



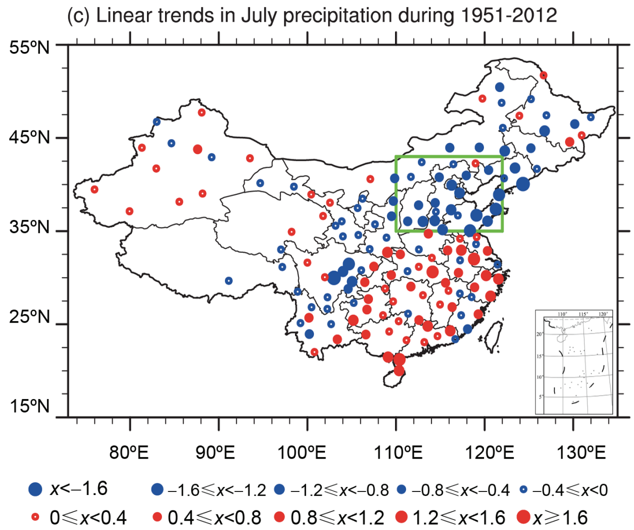


Figure 5 (a) Normalized July EASM index derived from NCEP/NCAR reanalysis based on Guo (1983). The green line shows the PDO index. (b) Normalized July precipitation amount averaged over North China (35°–43°N, 110°–122°E, 23 stations are included). The green line shows the PDO. (c) Linear trends in July precipitation during 1951–2012 (units: mm a^{-1}). The green box outlines the north China region (35°–43°N, 110°–122°E). PDO indices are obtained from http://jisao.washington.edu/pdo/PDO.latest. After Zhou et al., 2013.

sensitivity experiments using SSA=0.90, the SFND pattern cannot be reproduced. Zhang H et al. (2009) have found that the total direct effect of sulfate, organic carbon, and black carbon aerosols do not contribute to the SFND pattern, which is further confirmed by Zhang L et al. (2012) who used an updated emissions dataset and a climate model incorporating aerosol processes.

Zhang H et al. (2012) and Wang et al. (2014a) have suggested that the increase in aerosols weakens the EAM and suppresses convection along 30°N in China (Figure 7), favoring enhanced atmospheric stability. Jiang et al. (2013) have used a climate model to show that anthropogenic aerosols suppress precipitation over North China. Based on the latest Coupled Model Intercomparison Project Phase 5 (CMIP5) models, Song et al. (2014) have compared the different influences of natural forcing (solar activity and volcanic eruption) and anthropogenic forcing (GHGs and aerosols) on the decadal weakening of the EASM. The observed weakening of the EASM during 1958–2001 is partly reproduced in the all-forcing runs, but with much weaker magnitudes. Although the weakening of the EASM circulation can be reproduced, the SFND pattern cannot be captured in the all-forcing runs (Figure 8(a) and (b)). Comparisons of results from different forcing runs show that aerosols largely weaken the EASM circulation, while GHGs slightly enhance the EASM circulation (Figure 8(d) and (f)). Due to the heavy pollution over China, the surface cooling caused by aerosols is evident, leading to a weakened land-sea thermal contrast and a high sea-level pressure anomaly over North China (Figure 9). A decrease in cold air outbreaks and the weakening of northwesterly winds are also related to the increase in aerosols (Niu et al., 2010). Based on the above research conclusions, it is clear that there exist large uncertainties concerning the influence of aerosols on the EAM circulation. It is urgent to identify the influences of different types of aerosols and to overcome the influence of model uncertainties on the scientific conclusions.

The air pollution caused by aerosols over China not only affects regional weather systems, but also couples with convective systems downstream through long-range transport, and leads to intensified Pacific storm tracks (Zhang et al., 2007; Li et al., 2008). Wang et al. (2014b) have suggested that Asian (including China) pollution's

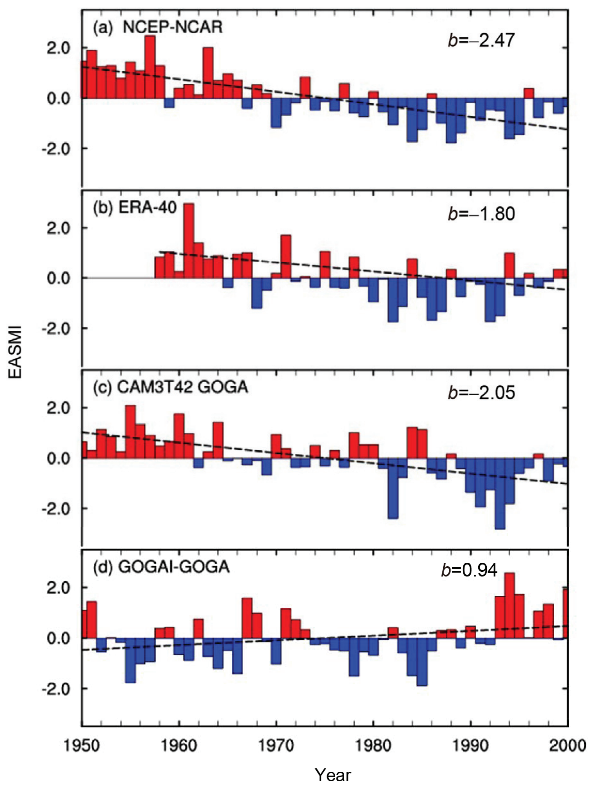


Figure 6 Time series of the EASM index (EASMI, bars) and its trend (dashed lines) from (a) the NCEP/NCAR reanalysis, (b) the ERA-40 reanalysis, (c) CAM3 GOGA runs forced by the global SST, and (d) CAM3 GOGAI minus GOGA runs, which represent GHG and aerosol forcing. The EASMI is defined as the normalized zonal wind shear between 850 and 200 hPa averaged over 20°–40°N and 110°–140°E. Also shown are the slopes of the trend ((b), change per 50 years). After Li H M et al., 2010.

long-range transport can intensify winter mid-latitude storm tracks, and further influence global atmospheric circulation and climate.

Another important route by which aerosols influence the China climate is through ocean feedbacks. For example, the Indian Ocean has warmed up during the past 50 years, which is correlated with the westward shift of the western North Pacific subtropical high, an important component of the EASM (Zhou et al., 2009b). The Indian Ocean warming is directly affected by anthropogenic aerosols mainly through their indirect effect, which significantly offsets the SST warming magnitude caused by GHGs (Dong et al., 2014; Dong and Zhou, 2014).

4 The impacts of the EAM on aerosols

The formation, distribution, maintenance, and change in local aerosols are influenced by meteorological conditions. Changes in the intensity of the EAM can directly affect the transport and lifetimes of a wide variety of aerosols.

4.1 The effects of the winter monsoon on the distribution of aerosols

High aerosol concentrations have led to heavy fog-haze pollution. After the year 2000, more haze days have occurred in most regions across the Chinese mainland due to increasing emissions of aerosols when compared to the 1970s and 1980s (Wu et al., 2010). The contributions of aerosol emissions and its precursor gases, as well as the population density, to reduced visibility because of hazy conditions in different regions of eastern China have been analyzed by Niu et al. (2010) and Zhang X Y et al. (2012). Increased emissions from human activities have resulted in more haze in eastern China (Zhang X Y et al., 2012). The EAM circulation could also play a potential role.

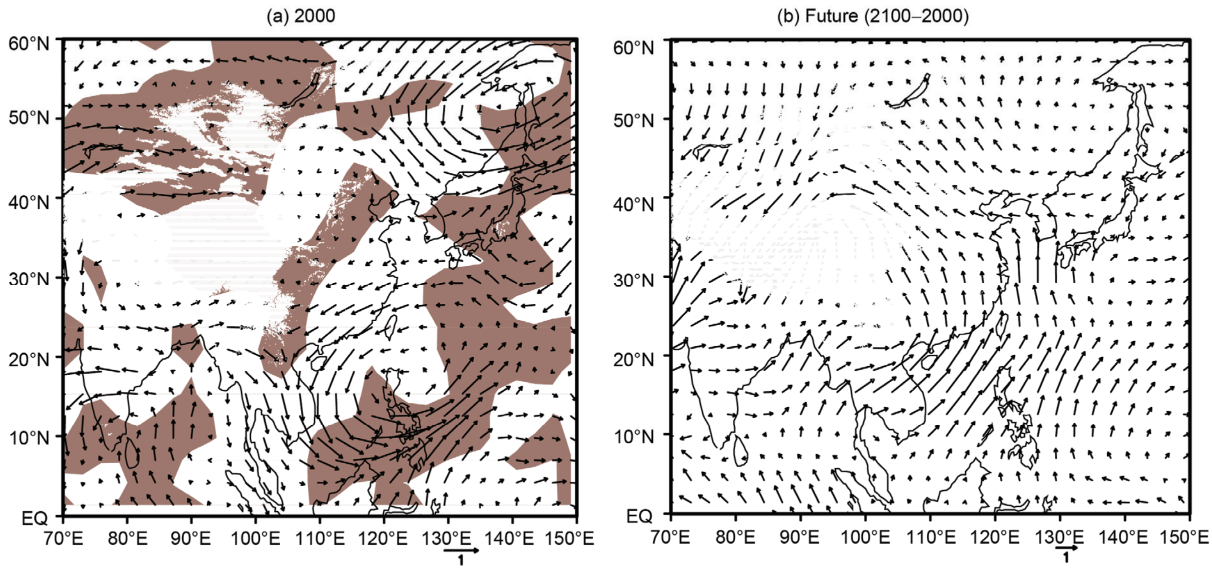


Figure 7 Simulated 850-hPa wind changes forced by (a) simulated aerosol increases in 2000. Shaded areas shows where differences in moisture flux divergence integrated from 850 to 700 hPa are negative (after Zhang H et al., 2012) and (b) the decrease in aerosols from 2000 to 2100 based upon the RCP45. After Wang et al., 2015.

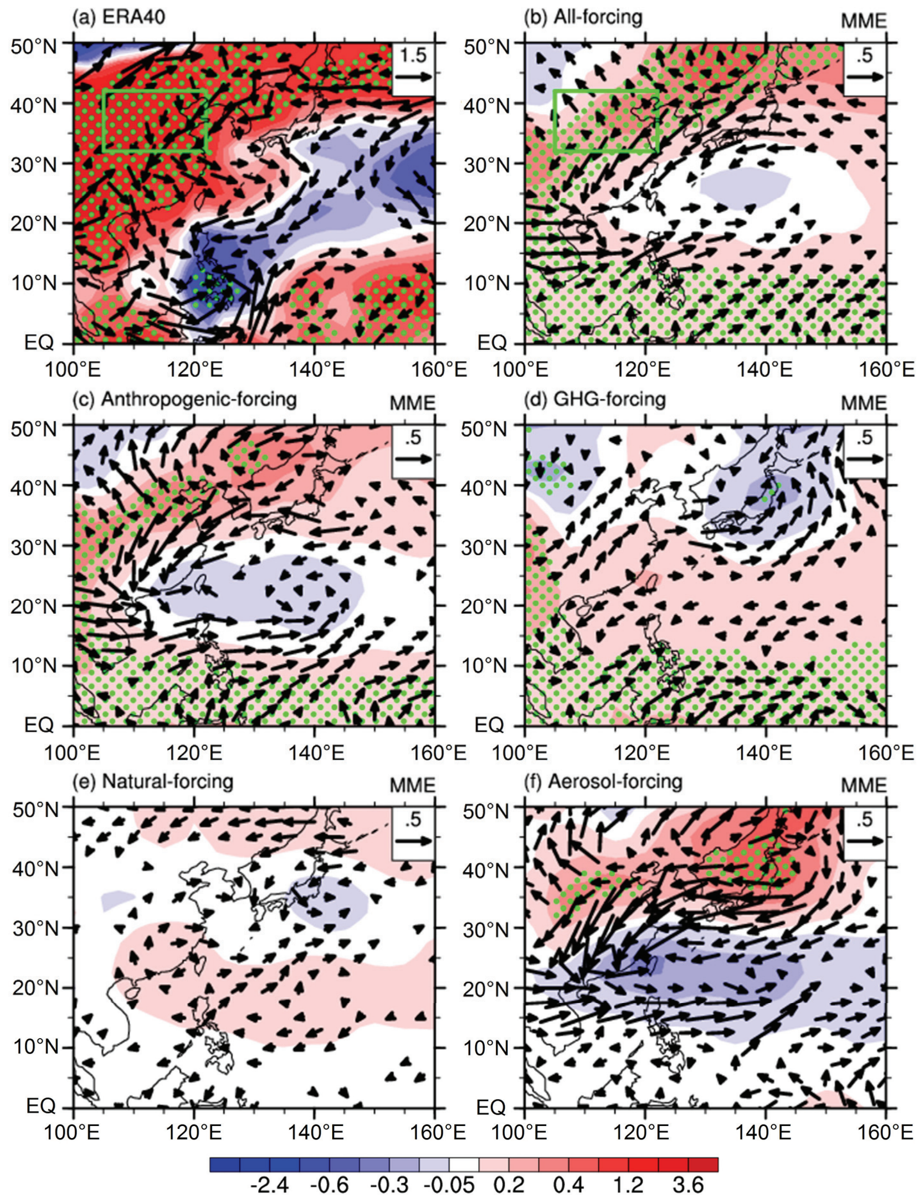


Figure 8 Linear trends in sea-level pressure (SLP) (shaded; hPa (44 year)$^{-1}$) and 850-hPa winds (vectors; m s^{-1} (44 year)$^{-1}$) in JJA during 1958–2001. (a) Observations (SLP and 850-hPa winds from ERA40), (b) all-forcing run, (c) anthropogenic-forcing run, (d) GHG-forcing run, (e) natural-forcing run, (f) aerosol-forcing run of the multi-model ensemble. The green boxes in (a) and (b) outline northern China (32°–42°N, 105°–122°E). The dotted areas indicate that the precipitation trends are statistically significant at the 10% level. After Song et al., 2014.

During recent years, heavy fog-haze events in the North China Plain during winter have been associated with a weak winter monsoon (Niu et al., 2010). Observations have shown that a large amount of local aerosols can reduce incoming solar radiation, which enhances regional atmospheric stability, and favors the accumulation and condensation of, and increase in aerosols (Li et al., 2010; Liu et al., 2012). The weaker East Asian winter monsoon (EAWM) reduces the transport of local aerosols from North China to other regions (Zhao et al., 2013; Zhang et al., 2013). A heavy fog-haze event of strong intensity, long duration, and extensive coverage occurred in eastern China in January 2013 (Zhang et al., 2014). The weak EAWM and the anomalous southerly winds in the middle and lower troposphere created conditions that were favorable for the transport of more water vapor to eastern China where fog and haze were concentrated (Zhang et al., 2014). In addition, the associated weaker upper westerly jet lead to the reduction of the vertical shear in horizontal winds, which weakened synoptic disturbances and the vertical mixing of the atmosphere, and increased the stability of surface air (Zhang et al., 2014). The anomalous southerly winds in the middle and lower troposphere made the transport of fog and haze outside of the affected region difficult. All these anomalous monsoon

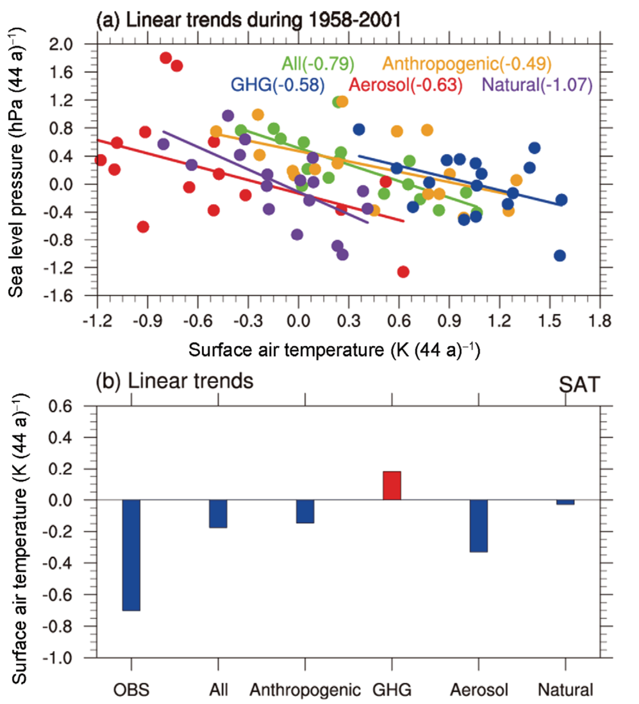


Figure 9 (a) Scatterplot of SLP averaged over northern China (32°–42°N, 105°–122°E) as a function of SAT averaged over eastern China (28°–38°N, 105°–122°E) in JJA during 1958–2001. Observations are from the GISS surface temperature analysis (GISTEMP). The domain average has been subtracted and is shown in the top right corner. (b) SAT trends averaged over eastern China (28°–38°N, 105°–122°E) from observations, the all-forcing run, the anthropogenic-forcing run, the GHG-forcing run, the aerosol-forcing run, and the natural-forcing run of the multi-model ensemble. After Song et al., 2014.

circulations are conducive to the maintenance and development of fog and haze over eastern China. Based on long-term observation data (1972–2014), Li et al. (2015) have found that the interannual variation in wintertime fog-haze days across central and eastern China is closely related to the EAWM. More (less) wintertime fog-haze days happen when the EAWM is weak (strong).

The increase in aerosols can also modulate the thermodynamic structure of the atmosphere and regulate atmospheric circulation through dynamic responses. For example, the extreme haze episodes that repeatedly shrouded Beijing during the winter of 2012–2013 is mainly attributed to the suitable meteorological conditions that were present at the time (Zheng et al., 2014). Guo et al. (2014) have further analyzed the evolution of organic aerosols during the haze episodes of 2013 in Beijing. They found that meteorological conditions such as wind speed and direction are the key factors controlling the periodic cycle of local fog-haze events. Northwesterly and northeasterly winds in winter directly contribute to the clearance of pollution in North China. These studies suggest that the EAWM is important for the transport, duration, and dissipation of local aerosols.

Dust episodes are also one of the severe kinds of weather phenomena that influence our country. Studies have shown that the intensity of the EAWM has a large impact on the transport of dust and the frequency of dust events that occur in the following spring (Zhang et al., 1993, 2005). High dust loadings decrease the thermal contrast between the Eurasian continent and the surrounding oceans, making dust storms subside (Zhang et al., 2002b). When dust is transported to the Pacific Ocean, it can enter the free troposphere and be transported by westerly winds. This transport across the Pacific Ocean is closely related to the large-scale variations in atmospheric circulation (Zhang et al., 1997).

4.2 The impacts of the EASM on aerosols

As an important component of the climate system, the EASM has a large influence on the long-range transport and distribution of aerosols. Moisture transport, along with the monsoon, also affects the climate effects of aerosols.

Liu et al. (2011) have reported that the Asian summer monsoon can affect the distribution of aerosols in China. Based on numerical and observational datasets, Yan et al. (2011) have found that under similar surface emission scenarios, the aerosol concentration and AOD are higher over southern China in the weaker monsoon years, but in the following stronger monsoon years, they expand to North China. The EASM is also accompanied by strong moisture transport, increasing the atmospheric humidity over eastern China in the summer. Compared to Europe and North America, the stronger summer atmospheric moisture conditions over East Asia enhance the aerosol hygroscopic effect and further increase AOD and strengthen direct radiative forcing (Li et al., 2012, 2014). As shown in Figure 10, the sulfate loading over Europe peaks in the 1970s and is higher than the projected maximum over East Asia; however, due to more abundant air moisture over East Asia and resulting stronger sulfate hydroscopic effect, AOD over East Asian is larger than Europe. Further, considering the dominance of sulfate in aerosol loading, anthropogenic aerosol direct radiative forcing at clear-sky TOA is also larger over East Asia than Europe. This suggests that the aerosol radiative forcing over East Asia is not only related to the aerosol amount, but also to the local moisture conditions.

The influence of the monsoon on aerosols is evident on seasonal, inter-annual, and decadal time scales, but published works about this are few. Zhang et al. (2010a) have used the global three-dimensional atmospheric chemistry transfer model called GEOS-Chem to investigate the influences of different Asian summer monsoon systems and strong/weak monsoons on Asian aerosol concentrations at seasonal and inter-annual time scales. Their results showed that the seasonal change in monsoons is important for the seasonal change in aerosol concentrations. The influence of the summer monsoon on aerosol concentrations is larger than the seasonal change in aerosol emissions, leading to higher aerosol concentrations in the winter than in the summer over China. This is contrary to the seasonal change in aerosols over eastern North America. The EASM was

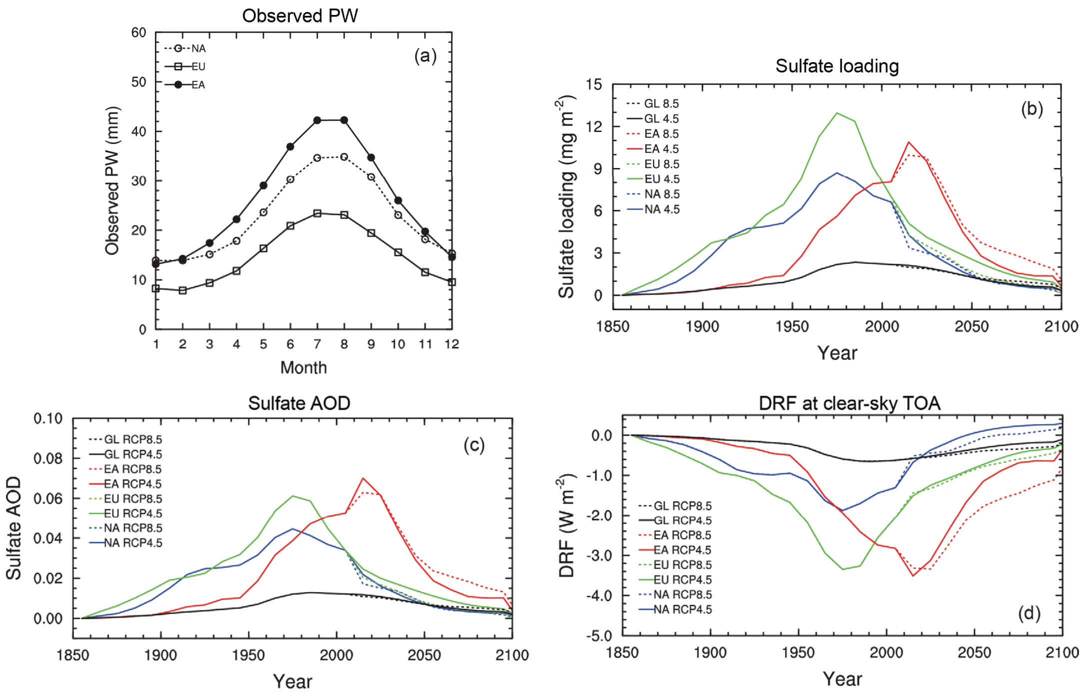


Figure 10 (a) Seasonal variation of observed climatological precipitable water (mm), time series of (b) sulfate atmospheric loading (mg m^{-2}), (c) sulfate aerosol optical depth (AOD) and (d) total anthropogenic aerosol direct radiative forcing (W m^{-2}) at clear-sky TOA relative to the PI (1850s) averaged over Europe (EU), East Asia (EA), North America (NA) and global domains. Here, long-term sulfate loading is from NCAR CAM-Chem model; the AOD and direct radiative forcing are calculated using LASG/IAP AGCM and the AOD is the averaged value for the shortwave band (0.50–0.625 μm); the anthropogenic aerosol species include black carbon, nitrate, sulfate and organic carbon; RCP4.5 and RCP8.5 denote middle and high emission scenarios in the future. After Li et al., 2014.

also found to be negatively correlated with aerosol concentration over eastern China. In the weak monsoon year of 1998, the aerosol concentration was significantly higher than in the strong monsoon year of 2002. The aerosol flux transport related to monsoon winds is stronger than the wet deposition induced by monsoon precipitation. Zhang et al. (2010b) have reported that the source of ~50%–70% of organic carbon above 700 hPa over eastern China in springtime is biomass burning in South Asia. Along with the transport effect of the South Asian summer monsoon, surface pollutants over South Asia are transported to high levels of the atmosphere. These pollutants will affect eastern China and even North America (Wang et al., 2014a, 2014b).

Previous studies commonly attribute the increase in aerosol concentrations in recent years to the large emissions generated by rapid economic growth. However, recent studies stress the importance of the monsoon's decadal variability. Using the GEOS-Chem model, Zhu et al. (2012) have shown that the weakening of the EASM contributed to the increase in aerosols over eastern China during recent decades. Even though anthropogenic emissions during the last 60 years are kept fixed, aerosol concentrations in eastern China can be about 20% higher in the weakest monsoon years than in the strongest monsoon years due to the decadal weakening of the EASM (Figure 11). These results provide a new way of understanding how aerosol concentrations can be so high in China (Chin, 2012).

5. Countermeasures to take and further research suggestions

In summary, interactions between air pollutants (aerosols) and monsoons is a major frontier scientific issue in the realm of atmosphere and global climate change research. The formation of atmospheric pollution and its intensity are tightly connected to meteorological conditions (Mu and Zhang, 2014). There are strong interactions between aerosols and monsoons. However, because observations and models have their limitations, large uncertainties still exist in understanding the above interaction studies. Further studies are therefore needed to reduce these uncertainties.

(1) In-depth understanding of aerosol physical and chemical properties, as well as formation processes, is needed. More understanding of how aerosols become cloud condensation nuclei (CCN) and ice nuclei, and what their optical and microphysical properties are, is also needed. Mu and Zhang (2014) proposed some countermeasures concerning fog-haze weather based on the study of the serious haze case that took place in January 2013. To better control air pollution, they pointed out that it would be useful if fog-haze predictions were based on operational weather forecasts and if more meteorological factors were taken into account. There is still a lack of comprehensive datasets of aerosol physical-chemical properties and long-term aerosol-

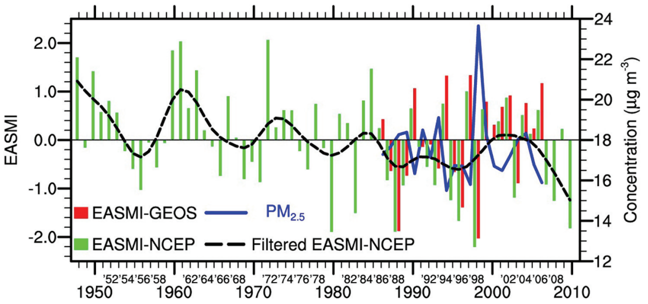


Figure 11 The normalized time series of EASMI (bars, left y-axis) and simulated JJA surface-layer $PM_{2.5}$ concentrations (i.e., mass concentration of particles with an equivalent aerodynamic diameter less than 2.5 μm) (blue line, right *y*-axis) averaged over eastern China (110°–125°E, 28°–45°N) from 1986–2006. The EASMI-GEOS from 1986–2006 (red bars) are calculated using GEOS-4 assimilated meteorological data, while the EASMI-NCEP from 1948–2010 (green bars) are calculated using NCEP/NCAR reanalysis data. The thick dashed line is the 9-year Gaussian-type filtered value of the EASMI-NCEP, which represent the decadal variation in the EASM. JJA aerosol concentrations averaged over eastern China are not in phase with changes in the EASMI (correlation coefficient is –0.65, statistically significant at the 5% level). After Zhu et al., 2012.

cloud observations. It behooves the community to strengthen fundamental research in making more observations and doing more experiments regarding aerosol physical and chemical processes in the monsoon region, as has been done in some past intensive field experiments (Li et al., 2007; 2011) and several ongoing 973 projects. Integrated observations of aerosol-cloud-radiation parameters could be strengthened if ground-based, aircraft, and remote sensing equipment was used. Three suggestions to accomplish this are: 1) integrate multi-source active and passive remote sensing and sampling techniques to obtain aerosol physical, optical, and chemical characteristics, CNN, cloud droplet spectra, and corresponding ambient parameters in typical regions; 2) investigate mechanisms behind conversions from different aerosols to CCN, the aerosol hydroscopic effect, and nucleating ability and rate; develop multi-wavelength laser radar and balloon sounding systems to get aerosol spectral profiles; develop parameterizations of aerosol and CCN spectral distributions to improve climate models; 3) develop a series of advanced techniques to analyze data obtained from ground, aircraft, and balloon-borne instruments; collect cloud micro- and macro-physical feature datasets, including cloud fraction, cloud-top height (temperature and pressure), cloud vertical structure, cloud-base height, cloud phase, cloud water and super-cooled water contents, cloud water optical depth, and effective radius.

(2) Numerical simulation research on the interactions between monsoons and aerosols should be enhanced. Results from different model simulations often have large discrepancies and even contradictions. The uncertainty of a model itself is also a major topic of research. Different models respond differently to external forcings such as GHGs and aerosols. They also treat indirect climatic effects of aerosols and aerosol-cloud-climate interactions differently, if at all. This directly influences the credibility of simulation results. Therefore, it is necessary to enhance numerical simulation research on the interactions between monsoons and aerosols, to improve the coupling of climate models with atmospheric chemistry models, and in particular, to strengthen bidirectional coupling simulation tests about interactions between the EAM climate and aerosols. The task of model development includes the consideration of models at different scales, such as large eddy models at a 1-m resolution, cloud-resolving models at a 1-km resolution, local single-column models, and global climate models.

(3) Interdisciplinary research among atmospheric physics, atmospheric chemistry, and monsoon climate dynamics groups should be strengthened. The impact and feedback of the Asian monsoon climate in different periods of the past as simulated by global and regional climate models which contain aerosol indirect, direct, and semi-direct effects, and in particular, the impact on monsoon precipitation, and the quantitative evaluation of aerosol-precipitation interactions in the long term by mesoscale models, needs to be further examined. The contributions of natural variability and variations in external forcings on long-term changes in the EAM should be quantitatively estimated. Aerosols can also have an influence on monsoon intra-seasonal phase transitions between oscillation active periods and interruption periods through the interaction between atmospheric radiation and cloud physical processes. The characteristics of monsoon-aerosol interactions at seasonal, interannual, and interdecadal scales should also be analyzed. A very important issue to address in future research is to better describe monsoon-aerosol interactions and their effect in climate models.

Until now, numerous studies have focused on the effects of aerosols on atmospheric circulation and meteorological factors, but little attention has been paid to the influence of monsoons on aerosols. Interactions between aerosols and monsoons are two-way and their relationships are complicated and interrelated, which make relevant studies scarce. The relative contributions of emissions and atmospheric conditions to aerosol pollution are also worth studying. This would require the use of a multi-model framework rather than cloud parameterization schemes in global climate models. Nested models are also a good way to examine interactions between aerosols and monsoons because cloud-resolved models with detailed microphysics are first used to do regional and seasonal simulations, and to produce the adiabatic forcing due to aerosols. This is then used as forcing input into climate models. Breakthroughs in this research field are expected in the near future only if cross-disciplinary efforts are made by researchers in the fields of atmospheric physics, chemistry, and monsoon climate dynamics.

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References

Ackerman A S, Toon O B, Hobbs P V. 1995. A model for particle microphysics, turbulent mixing, and radiative transfer in the stratocumulus-topped marine boundary layer and comparisons with measurements. J Atmos Sci, 52: 1204–1236

Albrecht B. 1989. Aerosols, cloud microphysics, and fractional cloudiness. Science, 245: 1227–1230

Andreae M O, Rosenfeld D, Artaxo P, Costa A A, Frank G P, Longo K M, Silva-Dias M A F. 2004. Smoking rain clouds over the Amazon. Science, 303: 1337–1341

Bollasina M A, Ming Y, Ramaswamy V. 2011. Anthropogenic aerosols and the weakening of the South Asian summer monsoon. Science, 334: 502–505

Che H Z, Zhang X Y, Chen H B, Damiri B, Goloub P, Li Z Q, Zhang X C, Wei Y, Zhou H G, Dong F, Li D P, Zhou T M. 2009. Instrument calibration and aerosol optical depth validation of the China Aerosol Remote Sensing Network. J Geophys Res, 114: D03206, doi: 10.1029/2008JD011030

Chin M. 2012. Dirtier air from a weaker monsoon. Nat Geosci, 5: 449–450

Ding A J, Fu C B, Yang X Q, Sun J N, Petäjä T, Kerminen V M, Wang T, Xie Y, Herrmann E, Zheng L F, Nie W, Liu Q, Wei X L, Kulmala M. 2013. Intense atmospheric pollution modifies weather: A case of mixed biomass burning wither fossil fuel combustion pollution in the eastern China. Atmos Chem Phys, 13: 10545–10554

Dong L, Zhou T J. 2014. The Indian Ocean sea surface temperature warming simulated by CMIP5 models during the 20th century: Competing forcing roles of GHGs and anthropogenic aerosols. J Clim, 27: 3348–3362

Dong L, Zhou T J, Wu B. 2014. Indian Ocean warming during 1958–2004 simulated by a climate system model and its mechanism. Clim Dyn, 42: 203–217

Fan J W, Zhang R Y, Tao W K, Mohr K I. 2008. Effects of aerosol optical properties on deep convective clouds and radiative forcing. J Geophys Res, 113: D08209, doi: 10.1029/2007JD009257

Fan J W, Yuan T L, Comstock J M, Ghan S, Khain A, Leung L R, Li Z Q, Martins V J, Ovchinnikov M. 2009. Dominant role by vertical wind shear in regulating aerosol effects on deep convective clouds. J Geophys Res, 114: D22206, doi: 10.1029/2009JD012352

Fan J W, Leung L R, Rosenfeld D, Chen Q, Li Z Q, Zhang J Q, Yan H R. 2013. Microphysical effects determine macrophysical response for aerosol impact on deep convective clouds. Proc Natl Acad Sci USA, 110: E4581–E4590

Fan X H, Chen H B, Xia X A. 2013. Progress in observation studies of atmospheric aerosol radiative properties in China (in Chinese). Chin J Atmos Sci, 37: 477–498

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey D W, Haywood J, Lean J, Lowe D C, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R. 2007. Changes in atmospheric constituents and in radiative forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press

Guo Q Y. 1983. The summer monsoon index in East Asia and its variation (in Chinese). Acta Geogr Sin, 38: 207–217

Guo S, Hu M, Zamora M L, Peng J F, Shang D J, Zheng J, Du Z F, Wu Z J, Shao M, Zeng L M, Molina M J, Zhang R Y. 2014. Elucidating severe urban haze formation in China. Proc Natl Acad Sci USA, 111: 17373–17378

He B, Bao Q, Li J D, Wu G X, Liu Y M, Wang X C, Sun Z B. 2013. Influences of external forcing changes on the summer cooling trend over East Asia. Clim Change, 117: 829–841

Hu Z Z. 1997. Interdecadal variability of summer climate over East Asia and its association with 500-hPa height and global sea surface temperature. J Geophys Res, 102: 19403–19412

Huang J P, Minnis R, Chen B, Huang Z W, Liu Z Y, Zhao Q Y, Yi Y H, Ayers J K. 2008a. Long-range transport and vertical structure of Asian dust from CALIPSO and surface measurements during PACDEX. J Geophys Res, 113: D23212, doi: 10.1029/2008JD010620

Huang J P, Zhang W, Zuo J Q, Bi J R, Shi J S, Wang X, Chang Z L, Huang Z W, Yang S, Zhang B D, Wang G Y, Feng G H, Yuan J Y, Zhang L, Zuo H C, Wang S G, Fu C B, Chou J F. 2008b. An overview of the semi-arid climate and environment research observatory over the Loess Plateau. Adv Atmos Sci, 25: 906–921

Huang J P, Wang T H, Wang W C, Li Z Q, Yan H R. 2014. Climate effect of dust aerosols over East Asian arid and semi-arid regions. J Geophys Res, 119: 11398–11416

Huang R H. 2004. Advances of the project of the formation mechanism and prediction theory of severe climatic disaster in China (in Chinese). China Basic Sci, 6: 6–16

Huang R H, Chen J L, Huang G. 2007. Characteristics and variations of the East Asian monsoon system and its impacts on climate disasters in China. Adv Atmos Sci, 24: 993–1023

Huang Y, Dickinson R E, Chameides W L. 2006. Impact of aerosol indirect effect on surface temperature over East Asia. Proc Natl Acad Sci USA, 103: 4371–4376

Intergovernmental Panel on Climate Change (IPCC). 2013. Climate Change 2013—The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press

Jiang Y Q, Liu X H, Yang X Q, Wang M H. 2013. A numerical study of the effect of different aerosol types on East Asian summer clouds and precipitation. Atmos Environ, 70: 51–63

Khain A P, BenMoshe N, Pokrovsky A. 2008. Factors determining the impact of aerosols on surface precipitation from clouds: An attempt at classification. J Atmos Sci, 65: 1721–1748

Koren I, Martins J V, Remer L A, Afargan H. 2008. Smoke invigoration versus inhibition of clouds over the Amazon. Science, 321: 946–949

Lau K M, Kim M K. 2006. Asian summer monsoon anomalies induced by aerosol direct forcing—The role of the Tibetan Plateau. Clim Dyn, 26: 855–864

Lee K H, Li Z Q, Wong M S, Xin J Y, Wang Y S, Hao W M, Zhao F S. 2007. Aerosol single scattering albedo estimated across China from a combination of ground and satellite measurements. J Geophys Res, 112: D22S15, doi: 10.1029/2007JD009077

Li G H, Wang Y, Lee K H, Diao Y W, Zhang R Y. 2008. Increased winter precipitation over the North Pacific from 1984–1994 to 1995–2005 inferred from the global precipitation climatology project. Geophys Res Lett, 35: L13821, doi: 10.1029/2008GL034668

Li H M, Dai A G, Zhou T J, Lu J. 2010. Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950–2000. Clim Dyn, 34: 501–514

Li J D, Sun Z A, Liu Y M, Li J N, Wang W C, Wu G X. 2012. A study on sulfate optical properties and direct radiative forcing using the LASG-IAP general circulation model. Adv Atmos Sci, 29: 1185–1199

Li J D, Wang W C, Sun Z A, Wu G X, Liao H, Liu Y M. 2014. Decadal variation of East Asian radiative forcing due to anthropogenic aerosols during 1850–2100 and the role of atmospheric moisture. Clim Res, 61: 241–257

Li L J, Wang B, Zhou T J. 2007. Contributions of natural and anthropogenic forcings to the summer cooling over eastern China: An AGCM study. Geophys Res Lett, 34: L18807, doi: 10.1029/2007GL030541

Li Q, Zhang R H, Wang Y. 2015. Interannual variation of the wintertime fog-haze days across central and eastern China and its relation with East Asian winter monsoon. Int J Climatol, doi: 10.1002/joc.4350

Li W J, Shao L Y. 2009. Transmission electron microscopy study of aerosol particles from the brown hazes in northern China. J Geophys Res, 114: D09302, doi: 10.1029/2008JD011285

Li Z Q. 2004. Aerosol and climate: A perspective from East Asia. In: Observation, Theory, and Modeling of the Atmospheric Variability. Singapore: World Scientific. 501–525

Li Z Q, Chen H, Cribb M, Dickerson R, Holben B, Li C, Lu D, Luo Y, Maring H, Shi G, Tsay S C, Wang P, Wang Y, Xia X, Zheng Y, Yuan T, Zhao F. 2007a. Preface to special section on East Asian Study of Tropospheric Aerosols: An International Regional Experiment (EAST-AIRE). J Geophys Res, 112: D22S00, doi: 10.1029/2007JD008853

Li Z Q, Niu F, Lee K H, Xin J Y, Hao W M, Nordgren B, Wang Y S, Wang P C. 2007b. Validation and understanding of Moderate Resolution Imaging Specteroradiometer aerosol products (C5) using ground-based measurements from the handheld Sun photometer network in China. J Geophys Res, 112: D22S07, doi: 10.1029/2007JD008479

Li Z Q, Zhao X P, Kahn R, Mishchenko M, Remer L, Lee K H, Wang M, Laszlo I, Nakajima T, Maring H. 2009. Uncertainties in satellite remote sensing of aerosols and impact on monitoring its long-term trend: A review and perspective. Ann Geophys, 27: 1–16

Li Z Q, Lee K H, Wang Y S, Xin J Y, Hao W M. 2010. First observation-based estimates of cloud-free aerosol radiative forcing across China. J Geophys Res, 115: D00K18, doi: 10.1029/2009JD013306

Li Z Q, Niu F, Fan J W, Liu Y G, Rosenfeld D, Ding Y N. 2011a. The long-term impacts of aerosols on the vertical development of clouds and precipitation. Nat Geosci, 4: 888–894

Li Z Q, Li C, Chen H, Tsay S C, Holben B, Huang J, Li B, Maring H, Qian Y, Shi G, Xia X, Yin Y, Zheng Y, Zhuang G. 2011b. East Asian Studies of Tropospheric Aerosols and their Impact on Regional Climate (EAST-AIRC): An overview. J Geophys Res, 116: D00K34, doi: 10.1029/2010JD015257

Lin J C, Matsui T, Pielke R A, Kummerow C. 2006. Effects of biomass-burning-derived aerosols on precipitation and clouds in the Amazon Basin: A satellite-based empirical study. J Geophys Res, 111: D19204, doi: 10.1029/2005JD006884

Liu J J, Zheng Y F, Li Z Q, Flynn C, Cribb M. 2012. Seasonal variations of aerosol optical properties, vertical distribution and associated radiative effects in the Yangtze Delta region of China. J Geophys Res, 117: D00K38, doi: 10.1029/2011JD016490.

Liu X D, Yan L B, Yang P, Yin Z Y, North G R. 2011. Influence of Indian summer monsoon on aerosol loading in East Asia. J Appl Meteor Clim, 50: 523–533

Luo Y F, Lu D R, Zhou X J, Li W L, He Q. 2001. Characteristics of the spatial distribution and yearly variation of aerosol optical depth over China in last 30 years. J Geophys Res, 106: 14501–14513

Luo Y X, Zheng X B, Zhao T L, Chen J. 2014. A climatology of aerosol optical depth over China from recent 10 years of MODIS remote sensing data. Int J Climatol, 34: 863–870

Ma J Z, Xu X B, Zhao C S, Yan P. 2012. A review of atmospheric chemistry research in China: Photochemical smog, haze pollution, and gas-aerosol interactions. Adv Atmos Sci, 29: 1006–1026

Meehl G A, Arblaster J M, Collins W D. 2008. Effects of black carbon aerosols on the Indian monsoon. J Clim, 21: 2869–2882

Menon S, Hansen J E, Nazarenko L, Luo Y F. 2002. Climate effects of black carbon aerosols in China and India. Science, 297: 2250–2253

Mu M, Zhang R H. 2014. Addressing the issue of fog and haze: A promising way of meteorological science and technology. Sci China Erath Sci, 57: 1–2

Myhre G, Shindell D, Bréon F M, Collins W, Fuglestvedt J, Huang J P, Koch D, Lamarque J F, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T, Zhang H. 2013. Anthropogenic and natural radiative forcing. In: Stocker T F, Qin D, Plattner G K, eds. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press

Niu F, Li Z Q, Li C, Lee K H, Wang M Y. 2010. Increase of wintertime fog in China: Potential impacts of weakening of the Eastern Asian monsoon circulation and increasing aerosol loading. J Geophys Res, 115: D00k20, doi: 10.1029/2009JD013484

Niu F, Li Z Q. 2012. Systematic variations of cloud top temperature and precipitation rate with aerosols over the global tropics. Atmos Chem Phys, 12, doi: 10.5194/acp-12-8491-2012

Qian Y, Wang W G, Leung L R, Kaiser D P. 2007. Variability of solar radiation under cloud-free skies in China: The role of aerosols. Geophys Res Lett, 34: L12804, doi: 10.1029/2006GL028800

Qian Y, Gong D Y, Fan J W, Leung L R, Bennartz R, Chen D L, Wang W G. 2009. Heavy pollution suppresses light rain in China: Observations and modeling. J Geophys Res, 114: D00K02, doi: 10.1029/2008JD011575

Ramanathan V C P J, Crutzen P J, Kiehl J T, Rosenfeld D. 2001. Aerosols, climate, and the hydrological cycle. Science, 294: 2119–2124

Rosenfeld D. 2000. Suppression of rain and snow by urban and industrial air pollution. Science, 287: 1793–1796

Rosenfeld D, Lohmann U, Raga G B, O'Dowd C D, Kulmala M, Fuzzi S, Reissell A, Andreae M O. 2008. Flood or drought: How do aerosols affect precipitation? Science, 321: 1309–1313

Shi G Y, Hayasaka T, Ohmura A, Chen Z H, Wang B, Zhao J Q, Che H Z, Xu L. 2008. Data quality assessment and the long-term trend of ground solar radiation in China. J Appl Meteorol, 47: 1006–1016

Shi Y J, Ge M F, Wang W G. 2012. Hygroscopicity of internally mixed aerosol particles containing benzoic acid and inorganic salts. Atmos Environ, 60: 9–17

Shindell D T, Lamarque J F, Schulz M, Flanner M, Jiao C, Chin M, Young P J, Lee Y H, Rotstayn L, Mahowald N, Milly G, Faluvegi G, Balkanski Y, Collins W J, Conley A J, Dalsoren S, Easter R, Ghan S, Horowitz L, Liu X, Myhre G, Nagashima T, Naik V, Rumbold S T, Skeie T, Sudo K, Szopa S, Takemura T, Voulgarakis A, Yoon J H, Lo F. 2013. Radiative forcing in the ACCMIP historical and future climate simulations. Atmos Chem Phys, 13: 2939–2974

Song F F, Zhou T J, Qian Y. 2014. Responses of East Asian summer monsoon to natural and anthropogenic forcings in the latest 17 CMIP5 models. Geophys Res Lett, 41: 596–603

Sun Y L, Jiang Q, Wang Z F, Fu P Q, Li J, Yang T, Yin Y. 2014. Investigation of the sources and evolution processes of severe haze pollution in Beijing in January 2013. J Geophys Res, 119: 4380–4398

Tao W K, Chen J P, Li Z Q, Wang C, Zhang C. 2012. Impact of aerosols on convective clouds and precipitation. Rev Geophys, 50, doi: 10.1029/2011RG000369

Twomey S. 1977. The influence of pollution on the shortwave albedo of clouds. J Atmos Sci, 34: 1149–1152

Wang H J. 2001. The weakening of Asian monsoon circulation after the end of 1970's. Adv Atmos Sci, 18: 376–386

Wang Y, Wan Q, Meng W, Liao F, Tan H, Zhang R. 2011. Long-term impacts of aerosols on precipitation and lightning over the Pearl River Delta megacity area in China. Atmos Chem Phys, 11: 12421–12436

Wang Y, Fan J W, Zhang R Y, Leung L R, Franklin C. 2013a. Improving bulk microphysics parameterizations in simulations of aerosol effects. J Geophys Res, 118: 5361–5379

Wang Y, Khalizov A, Levy M, Zhang R Y. 2013b. New Directions: Light absorbing aerosols and their atmospheric impacts. Atmos Environ, 81:

713–715

Wang Y, Zhang R Y, Saravanan R. 2014a. Asian pollution climatically modulates mid-latitude cyclones following hierarchical modelling and observational analysis. Nat Commun, 5: 3098, doi: 10.1038/ncomms4098

Wang Y, Wang M H, Zhang R Y, Ghan S J, Lin Y, Hu J X, Pan B W, Levy M, Jiang J H, Molina M J. 2014b. Assessing the impacts of anthropogenic aerosols on Pacific storm track using a multi-scale global climate model. Proc Natl Acad Sci USA, 111: 6894–6899

Wang Z L, Zhang H, Zhang X Y. 2015. Projected response of East Asian summer monsoon to future reductions in emissions of anthropogenic aerosols and their precursors. Clim Dyn, doi: 10.1007/s00382-015-2912-7

Wu D, Wu X J, Li F, Tan H B, Chen J, Cao Z Q, Sun X, Chen H H, Li H Y. 2010. Temporal and spatial variation of haze during 1951–2005 in Chinese mainland (in Chinese). Acta Meteorol Sin, 68: 680–688

Wu G X, Guan Y, Liu Y M, Yan J H, Mao J Y. 2012. Air-sea interaction and formation of the Asian summer monsoon onset vortex over the Bay of Bengal. Clim Dyn, 38: 261–279

Xia X A, Chen H B, Philippe G, Zong X M, Zhang W X, Wang P C. 2013. Climatological aspects of aerosol optical properties in North China Plain based on ground and satellite remote-sensing data. J Quant Spectrosc Ra, 127: 12–23

Xin J Y, Wang Y S, Li Z Q, Wang P C, Wang S G, Wen T X, Sun Y. 2006. Introduction and calibration of the Chinese sun hazemeter network (in Chinese). Environ Sci, 27: 1697–1702

Xin J Y, Wang Y S, Li Z Q, Wang P C, Hao W M, Nordgren B L, Wang S G, Liu G R, Wang L L, Wen T X, Sun Y, Hu B. 2007. Aerosol optical depth (AOD) and Angstrom exponent of aerosols observed by the Chinese Sun Hazemeter Network from August 2004 to September 2005. J Geophys Res, 112, doi: 10.1029/2006JD007075

Yan L B, Liu X D, Yang P, Yin Z , North G R. 2011. Study of the impact of summer monsoon circulation on spatial distribution of aerosols in east Asia based on numerical simulations. J Appl Meteor Climat, 50: 2270–2282

Yang X, Ferrat M, Li Z Q. 2013a. New evidence of orographic precipitation suppression by aerosols in central China. Meteor Atmos Phys, 119: 17–29

Yang X, Yao Z Y, Li Z Q, Fan T Y. 2013b. Heavy air pollution suppresses summer thunderstorms in central China. J Atmos Sol-Terr Phy, 95-96: 28–40

Yang X, Li Z Q. 2014. Increases in thunderstorm activity and relationships with air pollution in southeast China. J Geophys Res, 119: 1835–1844

Yu R C, Wang B, Zhou T J. 2004. Tropospheric cooling and summer monsoon weakening trend over East Asia. Geophys Res Lett, 31: L22212, doi: 10.1029/2004GL021270

Yu R C, Zhou T J. 2007. Seasonality and three dimensional structure of the interdecadal change in East Asian monsoon. J Clim, 20: 5344–5355

Yu R C, Zhou T J, Li J, Xin X G. 2008. Progress in the studies of three-dimensional structure of interdecadal climate change over eastern China (in Chinese). Chin J Atmos Sci, 32: 893–905

Zhang H, Wang Z L, Guo P W. 2009. A modeling study of the effects of direct radiative forcing due to carbonaceous aerosol on the climate in East Asia. Adv Atmos Sci, 26: 57–66

Zhang H, Wang Z L, Wang Z Z, Liu Q X, Gong S L, Zhang X Y, Shen Z P, Lu P, Wei X D, Che H Z, Li L. 2012. Simulation of direct radiative forcing of aerosols and their effects on east Asian climate using an interactive AGCM-aerosol coupled system. Clim Dyn, 38: 1675–1693

Zhang L, Ding Y H, Ren G Y. 2005. Variation of dust weather and its climatic attribution analysis in northern part of China (in Chinese). J Appl Meteorol Sci, 16: 583–592

Zhang L, Liao H, Li J P. 2010a. Impacts of Asian summer monsoon on seasonal and interannual variations of aerosols over eastern China. J Geophys Res, 115: D00K05, doi: 10.1029/2009JD012299

Zhang L, Liao H, Li J P. 2010b. Impact of the southeast Asian summer monsoon strength on the outflow of aerosols from South Asia. Ann Geophys, 28: 277–287

Zhang L, Henze D K, Grell G A, Carmichael G R. 2012. Assessment of the sources, distribution and climate impacts of black carbon aerosol over Asia using GEOS-Chem and WRF-Chem. 2012 AGU Fall Meeting

Zhang Q, Streets D G, Carmichael G R, He K B, Huo H, Kannari A, Klimont Z, Park I S, Reddy S, Fu J S, Chen D, Duan L, Lei Y, Wang L T, Yao Z L. 2009. Asian emissions in 2006 for the NASA INTEX-B mission. Atmos Chem Phys, 9: 5131–5153

Zhang R H, Li Q, Zhang R N. 2014. Meteorological conditions for the persistent severe fog and haze event over eastern China in January 2013. Sci China Earth Sci, 57: 26–35

Zhang R Y, Suh I, Zhao J, Zhang D, Fortner E C, Tie X X, Molina L T, Molina M J. 2004. Atmospheric new particle formation enhanced by organic acids. Science, 304: 1487–1490

Zhang R Y, Li G H, Fan J W, Wu D L, Molina M J. 2007. Intensification of Pacific storm track linked to Asian pollution. Proc Natl Acad Sci USA, 104: 5295–5299

Zhang R Y, Khalizov A F, Pagels J, Zhang D, Xue H X, McMurry P H. 2008. Variability in morphology, hygroscopic and optical properties of soot aerosols during internal mixing in the atmosphere. Proc Natl Acad Sci USA, 105: 10291–10296

Zhang R Y. 2010. Getting to the critical nucleus of aerosol formation. Science, 328: 1366–1367

Zhang R Y, Khalizov A, Wang L, Hu M, Xu W. 2012. Nucleation and growth of nanoparticles in the atmosphere. Chem Rev, 112: 1957–2011

Zhang X Y, Arimoto R, An Z S, Chen T, Zhang G Y, Zhu G H, Wang X F. 1993. Atmospheric trace elements over source regions for Chinese dust: Concentrations, sources and atmospheric deposition on the Loess Plateau. Atmos Environ, 27: 2051–2067

Zhang R Y. 2015. Formation of urban fine particulate matter. Chem Rev, 115: 3803–3855

Zhang X Y, Arimoto R, An Z S. 1997. Dust emission from Chinese desert sources linked to variations in atmospheric circulation. J Geophys Res, 102: 28041–28047

Zhang X Y, Cao J J, Li L M, Arimoto R, Cheng Y, Huebert B, Wang D. 2002a. Characterization of atmospheric aerosol over Xian in the South Margin of the Loess Plateau, China. Atmos Environ, 36: 4189–4199

Zhang X Y, Lu H Y, Arimoto R, Gong S L. 2002b. Atmospheric dust loadings and their relationship to rapid oscillations of the Asian winter monsoon climate: Two 250-kyr loess records. Earth Planet Sci Lett, 202: 637–643

Zhang X Y, Gong S L, Shen Z X, Mei F M, Xi X X, Liu L C, Zhou Z J, Wang D, Wang Y Q, Cheng Y. 2003. Characterization of soil dust aerosol in China and itstransport/distribution during 2001 ACE-Asia. 1. Network Observations. J Geophys Res, 108: 4261, doi: 10.1029/1004 2002JD002632

Zhang X Y, Wang Y Q, Zhang X C, Guo W, Gong S L. 2008a. Carbonaceous aerosol composition over various regions of China during 2006. J Geophys Res, 113: D14111, doi: 14110.11029/12007JD009525

Zhang X Y, Wang Y Q, Zhang X C, Guo W, Niu T, Gong S L, Yin Y, Zhao P, Jin J L, Yu M. 2008b. Aerosol monitoring at multiple locations in China: Contributions of EC and dust to aerosol light absorption. Tellus Ser B-Chem Phys Meteorol, 60: 647–656

Zhang X Y, Wang Y Q, Niu T, Zhang X C, Gong S L, Zhang Y M, Sun J Y. 2012. Atmospheric aerosol compositions in China: Spatial/temporal variability, chemical signature, regional haze distribution and comparisons with global aerosols. Atmos Chem Phys, 11: 26571–26615

Zhang X Y, Sun J Y, Wang Y Q, Li W J, Zhang Q, Wang W G, Quan J N, Cao G L, Wang J Z, Yang Y Q, Zhang Y M. 2013. Factors contributing to haze and fog in China. Chin Sci Bull, 58: 1178–1187

Zhang Y H, Hu M, Zhong L J, Wiedensohler A, Liu S C, Andreae M O, Wang W, Fan S J. 2008. Regional integrated experiments on air quality over Pearl River Delta 2004 (PRIDE-PRD2004): Overview. Atmos Environ, 42: 6157–6173

Zhao X J, Zhao P S, Xu J, Meng W, Pu W W, Dong F, He D, Shi Q F. 2013. Analysis of a winter regional haze event and its formation mechanism in the North China Plain. Atmos Chem Phys, 13: 5685–5696

Zheng G J, Duan F K, Su H, Ma Y L, Cheng Y, Zheng B, Zhang Q, Huang T, Kimoto T, Chang D, Pöschl U, Cheng Y F, He K B. 2014. Exploring the severe winter haze in Beijing: The impact of synoptic weather, regional transport and heterogeneous reactions. Atmos Chem Phys, 15: 2969–2983

Zhou T J, Yu R C, Li H M, Wang B. 2008. Ocean forcing to changes in global monsoon precipitation over the recent half-century. J Clim, 21: 3833–3852

Zhou T J, Gong D Y, Li J, Li B. 2009a. Detecting and understanding the multi-decadal variability of the East Asian Summer Monsoon-Recent progress and state of affairs. Meteorol Z, 18: 455–467

Zhou T J, Yu R C, Zhang J, Drange H, Cassou C, Deser C, Hodson D L R, Sanchez-Gomez E, Li J, Keenlyside N, Xin X G, Okumura Y. 2009b. Why the western Pacific subtropical high has extended westward since the late 1970s. J Clim, 22: 2199–2215

Zhou T J, Song F, Lin R, Chen X Chen X. 2013. The 2012 North China floods: Explaining an extreme rainfall event in the context of a long-term drying tendency [*in* "Explaining Extreme Events of 2012 from a Climate Perspective"]. Bull Amer Meteorol Soc, 94: S1–S74

Zhu J L, Liao H, Li J P. 2012. Increases in aerosol concentrations over eastern China due to the decadal-scale weakening of the East Asian summer monsoon. Geophys Res Lett, 39: L09809, doi: 10.1029/2012GL051428