

JGR Atmospheres

REVIEW ARTICLE

10.1029/2019JD030758

Key Points:

- East Asia has suffered heavy aerosol loading of diverse properties
- Strong absorbing aerosols lower the boundary layer, suppress convection, and worsens air pollution
- The joint effects of aerosol on radiation and clouds alter the development of clouds and precipitation and regional climate

Correspondence to:

Z. Li, Y. Wang, J. Guo and C. Zhao,
zli@atmos.umd.edu;
yuan.wang@caltech.edu;
jgguocams@gmail.com;
czhao@bnu.edu.cn

Citation:

Li, Z., Wang, Y., Guo, J., Cribb, M. C., Dong, X., Fan, J., et al. (2019). East Asian study of tropospheric aerosols and their impact on regional clouds, precipitation, and climate (EAST-AIR_{CPC}). *Journal of Geophysical Research: Atmospheres*, 124, 13,026–13,054. <https://doi.org/10.1029/2019JD030758>

Received 5 APR 2019

Accepted 6 SEP 2019

Accepted article online 23 OCT 2019

Published online 5 DEC 2019

East Asian Study of Tropospheric Aerosols and their Impact on Regional Clouds, Precipitation, and Climate (EAST-AIR_{CPC})

Zhanqing Li¹, Yuan Wang², Jianping Guo³, Chuanfeng Zhao⁴, Maureen C. Cribb¹, Xiquan Dong⁵, Jiwen Fan⁶, Daoyi Gong⁴, Jianping Huang⁷, Mengjiao Jiang⁸, Yiquan Jiang⁹, S.-S. Lee¹, Huan Li¹, Jiming Li⁷, Jianjun Liu¹⁰, Yun Qian⁶, Daniel Rosenfeld¹¹, Siyu Shan¹, Yele Sun¹², Huijun Wang¹³, Jinyuan Xin¹², Xin Yan¹⁴, Xin Yang¹⁴, Xiu-qun Yang⁹, Fang Zhang⁴, and Youtong Zheng¹

¹Department of Atmospheric and Oceanic Science and ESSIC, University of Maryland, College Park, Maryland, USA,

²Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, USA, ³State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China, ⁴State Key Laboratory of Earth Surface Processes and Resource Ecology, Chinese Academy of Meteorological Sciences, Beijing, 100875, China,

⁵Department of Hydrology and Atmospheric Sciences, University of Arizona, Tucson, Arizona, USA, ⁶Pacific Northwest National Laboratory, Richland, WA, USA, ⁷College of Atmospheric Sciences, Lanzhou University, Lanzhou, China,

⁸Sichuan Provincial Key Laboratory of Plateau Atmosphere and Environment, School of Atmospheric Sciences, Chengdu University of Information Technology, Chengdu, 610225, China, ⁹School of Atmospheric Sciences, Nanjing University, Nanjing, China, ¹⁰Laboratory of Environmental Model and Data Optima, Laurel, MD, USA, ¹¹Institute of Earth Sciences, Hebrew University, Jerusalem, Israel, ¹²Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 100029, China, ¹³Nanjing University of Information Science & Technology, Nanjing, 210044, China, ¹⁴State Key Laboratory of Remote Sensing Sciences, Beijing Normal University, Beijing, 100875, China

Abstract Aerosols have significant and complex impacts on regional climate in East Asia. Cloud-aerosol-precipitation interactions (CAPI) remain most challenging in climate studies. The quantitative understanding of CAPI requires good knowledge of aerosols, ranging from their formation, composition, transport, and their radiative, hygroscopic, and microphysical properties. A comprehensive review is presented here centered on the CAPI based chiefly, but not limited to, publications in the special section named EAST-AIR_{CPC} concerning (1) observations of aerosol loading and properties, (2) relationships between aerosols and meteorological variables affecting CAPI, (3) mechanisms behind CAPI, and (4) quantification of CAPI and their impact on climate. Heavy aerosol loading in East Asia has significant radiative effects by reducing surface radiation, increasing the air temperature, and lowering the boundary layer height. A key factor is aerosol absorption, which is particularly strong in central China. This absorption can have a wide range of impacts such as creating an imbalance of aerosol radiative forcing at the top and bottom of the atmosphere, leading to inconsistent retrievals of cloud variables from space-borne and ground-based instruments. Aerosol radiative forcing can delay or suppress the initiation and development of convective clouds whose microphysics can be further altered by the microphysical effect of aerosols. For the same cloud thickness, the likelihood of precipitation is influenced by aerosols: suppressing light rain and enhancing heavy rain, delaying but intensifying thunderstorms, and reducing the onset of isolated showers in most parts of China. Rainfall has become more inhomogeneous and more extreme in the heavily polluted urban regions.

1. Motivation and Background

As the most populated and fastest developing region of the world, East Asia has drawn much attention regarding the impact of human activities on the natural environment and climate. East Asia, especially China, suffers from severe dust storms and heavy air pollution from various emission sources (e.g., S. Chen et al., 2017; Guo, Deng, et al., 2016; Li, Guo, et al., 2017; Li, Liu, et al., 2017; Qian et al., 2003). With its sustained and steady economic growth, China's urbanization has stepped into the stage of full-scale acceleration. By the end of 2014, 55% of the total population lived in urban areas, a dramatic increase from 26% in 1990. Accompanied by the migration of people is rapid industrialization with dramatic increases in, for

example, the number of factories, power plants, roads, and vehicles. At such a fast pace of urbanization and industrialization, the potential impacts on the environment, including atmospheric composition, climate, and the hydrological cycle, are so strong and fast that the impacts must be understood in order to understand any anthropogenic impact on Earth's climate and environment over a wide range of spatial and temporal scales (Z. Li et al., 2016).

Aerosol particles, along with other pollutants in the gas phase and in water, have been primary environmental concerns in East Asia. Aerosols can cause respiratory and cardiovascular diseases (Brook et al., 2010) and reduce atmospheric visibility (Watson, 2002; Yang et al., 2016). The heavy loadings of sulfuric, carbonaceous, and mineral dust aerosols over East Asia further induce complicated effects on radiative fluxes and climate changes (Z. Li et al., 2007, Li et al., 2011, Li et al., 2016, Li, Guo, et al., 2017; Qian et al., 2006). Increases in aerosol concentration increase concentrations of cloud condensation nuclei (CCN) or ice nuclei (IN) upon which cloud droplets or ice particles form. More but smaller cloud droplets and more reflection of solar energy to space for a given amount of water vapor results. By reducing cloud droplet sizes, which feeds back into cloud thermodynamics and dynamics, aerosols modulate cloud microphysics and precipitation (Givati & Rosenfeld, 2004). The suppression of warm rain by aerosols causes more condensates to ascend and more latent heat to be released either through deposition or freezing or both. This may invigorate convection, resulting in increased cloud heights and thicknesses for deep convective clouds (DCCs; Li et al., 2008; Rosenfeld et al., 2008), which is the so-called "cold-phase" invigoration. The large number of ultrafine aerosol particles produced by industrialization can be activated in DCCs due to high supersaturation well above cloud base, enhancing condensation and invigorating convective intensity and precipitation in a more significant way than can the "cold-phase" invigoration (e.g., Sheffield et al., 2015; Fan et al., 2018; "warm-phase" invigoration). Aerosol microphysical effects on DCCs drastically enlarge cloud anvils (J. Fan et al., 2013; Yan et al., 2014). W. K. Tao et al. (2012), J. Fan et al. (2016), and Z. Li et al. (Li, Liu, et al., 2017) have comprehensively reviewed the influences of aerosols on radiation, clouds, and precipitation from different perspectives and scopes. Moreover, it was proposed that light-absorbing aerosols within the boundary layer can induce a thermodynamic invigoration of convective clouds by increasing the buoyancy near the cloud bottom and elevating convective available potential energy (CAPE) accordingly (Wang, Khalizov, et al., 2013). The effect of increased aerosols on cloud optical, microphysical, and macrophysical properties and associated radiative forcing is the most uncertain component of historical radiative forcing over the globe (IPCC, 2013).

As such, aerosol-related studies have increased nearly exponentially worldwide since the late 1980s (Figure 1). In 2017, the total number of aerosol-related publications exceeded 3,000, an increase by a factor of 10. In China, the wave of aerosol-related studies began much later but accelerated more quickly. Prior to 2000, the number of aerosol-related publications (limited to only Chinese journals) was less than 10. However, in 2017, the number of such publications jumped to 1,000, a nearly hundredfold increase in less than two decades. This explosive interest in aerosol science was and continues to be driven by concerns about climate change and the air pollution resulting from fast economic development.

Cloud-aerosol-precipitation interactions (CAPI) have been investigated intensively in an effort to reduce uncertainties in the prediction of climate changes. In recent years, many CAPI studies have focused on regional scales because of the impact on regional precipitation and weather extremes such as torrential rain (e.g., Fan et al., 2015; Lee et al., 2018; Z. Li et al., 2016). In particular, it is well known that East Asia has experienced dramatic changes in aerosol properties (e.g., loading) since industrialization began in that part of the world. It is thus expected that East Asia has experienced significant changes in clouds and precipitation, partially induced by the changing aerosol properties since industrialization. This merits the examination of CAPI in East Asia.

One major uncertainty of CAPI stems from the source of aerosols and CCN. The implementation of the "Atmospheric Pollution Prevention and Control Action Plan" in 2013 has led to significant improvement in air quality in the North China Plain (NCP) and Yangtze River Delta (YRD) regions of China. However, severe haze episodes characterized by high concentrations of fine particles ($PM_{2.5}$) still occur from time to time in both urban and rural areas during all seasons, though more frequently during wintertime (Liu, Chen, et al., 2016; Sun et al., 2014; Sun et al., 2016). While the composition, sources, and evolution processes of aerosol particles have been extensively studied for megacities in the NCP and the YRD, the level of

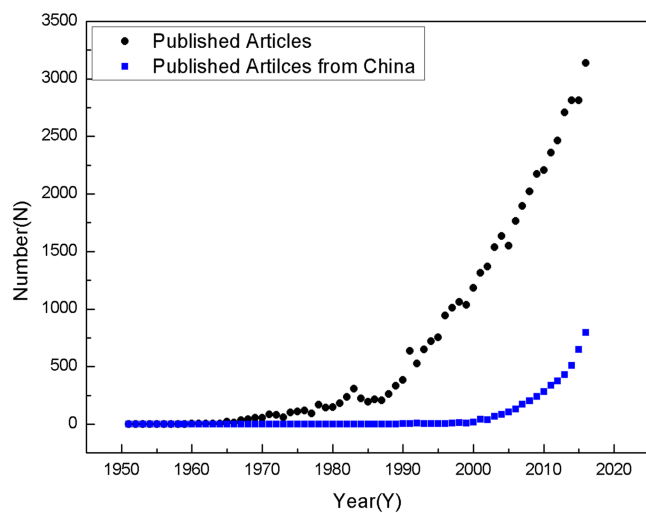


Figure 1. Number of publications about aerosols on a worldwide basis (black) and from China only (blue).

understanding of aerosol chemistry and new particle formation (NPF) in suburban and rural areas is low. Air pollution has proven to be a regional issue, and NPF is also recognized as a regional phenomenon. However, their influences may go far beyond local scales due to their transport and evolution along with large-scale atmospheric circulations.

East Asia is also an important monsoon area characterized by cold, dry winters and hot, humid summers with prevailing northerly and southerly winds in winter and summer, respectively. Analyses of long-term meteorological records have revealed that the East Asian monsoon (EAM) has experienced weakening trends in terms of both precipitation and circulation since the late 1970s (Ding et al., 2015). While the causes for the anomalies and trends of the EAM are diverse and highly uncertain, there appears to be a link with environmental changes, especially those induced by aerosols (Z. Li et al., 2016; Wu et al., 2016). Also under debate is whether greenhouse gases or aerosol forcing is responsible for the observed declining trend in light precipitation during the past few decades over eastern China (Wang, Guo, et al., 2015), besides natural variability. There is an urgent need to quantify the uncertainty of aerosol effects on climate in association with the uncertainties in aerosol emissions (external factors)

and in processes related to aerosol-cloud interactions (ACI; internal factors).

In light of the dramatic and rapid changes in the atmospheric environment and potential impact on regional climate in East Asia, especially China, as well as their interactions, numerous major research endeavors have been made in the region. Findings have been reported in a series of special collections in the *Journal of Geophysical Research: Atmospheres* entitled “East Asian Studies”: the East Asian Study of Tropospheric Aerosols: an International Regional Experiment (EAST-AIRE; Z. Li et al., 2007) and the East Asian Studies of Tropospheric Aerosols and their Impact on Regional Climate (EAST-AIRC; Li et al., 2011). Papers published in the current issue entitled “East Asian Study of Tropospheric Aerosols and Impact on Cloud and Precipitation (EAST-AIRcpc)” follow previous studies attempting to gain deeper insights into pertinent fronts but with a focus on the impact of aerosols on clouds and precipitation. Hence, the present review paper provides a synopsis of the new findings in those papers, centering on CAPI. The chemical formation and transformation of haze pollution, as well as the influence from emissions and meteorological conditions in East Asia, have recently been reviewed systematically by others (e.g., An et al., 2019; F. Zhang et al., 2014), so the present work is an important complement to them. This paper is structured as follows: section 2 summarizes the major methodologies employed in the papers of the current special issue, including ground-based, airborne, and spaceborne observations, as well as numerical models; section 3 reviews the studies pertaining to aerosol physicochemical properties; section 4 discusses the research about process-level understanding of aerosol effects on cloud and precipitation properties; section 5 reviews the large-scale effects of aerosols on the regional climate over East Asia; and section 6 summarizes the new findings in the current special issue and future challenges and directions.

2. Ground-Based, Airborne, and Spaceborne Observations and Modeling Studies

There is a wide range of observations and model simulations employed in the investigations published in this special section that are summarized as follows.

2.1. Ground-Based Observations

To understand formation mechanisms and sources of severe haze pollution, real-time measurements of sub-micron aerosol species and sizes, as well as precursor gases, were made using a suite of instruments deployed at five sites in China with different background aerosol sources and characteristics (Table 1).

The most comprehensive field experiment conducted was the Atmosphere-Aerosol-Boundary Layer-Cloud Interaction Joint Experiment held at a suburban site in Xingtai in Hebei Province. Xingtai is located near the western edge of the NCP (Figure 2).

These field experiments had the following objectives:

1. Investigation of aerosol and boundary-layer interactions using a variety of measurements of atmospheric profiles;
2. Investigation of cloud microphysical properties and development using aircraft in situ measurements and ground-based observations;
3. Investigation of ACI using coincident aerosol, cloud, and atmospheric observations.

To achieve these objectives, extensive measurements were made using a combination of ground-based, airborne, and spaceborne instruments. Five observation systems were deployed on the ground, each of which was composed of a suite of instruments to measure or infer (1) atmospheric profiles of temperature, humidity, wind using radiosondes, a Raman lidar, an infrared hyperspectral radiometer, and a microwave radiometer; (2) aerosol physical, chemical, optical, and hygroscopic properties, in combination with CCN; (3) cloud liquid water path (LWP), droplet size, and vertical profiles; (4) broadband and spectral radiative quantities; and (5) surface heat and turbulent fluxes. Ample measurements made in these experiments have been employed to conduct a wide range of studies toward achieving the above objectives whose findings are reviewed in the following sections.

2.2. Airborne and Spaceborne Studies

As a primary index of air pollution, fine-particle (i.e., $PM_{2.5}$) loading in China is particularly heavy and highly variable in time and space (Zhang & Cao, 2015). Although the number of ground monitoring stations has rapidly increased during the past five years, those at suburban, rural, and remote regions are still limited. As a result, characterization of the spatial distribution of $PM_{2.5}$, even with data assimilation, can have large uncertainties. The satellite-retrieved aerosol optical depth (AOD), a gross proxy of $PM_{2.5}$ loading, has advantages in studying the spatial and temporal variations of particulate pollutants (Xie et al., 2015). However, the accuracy of satellite retrievals of $PM_{2.5}$ strongly depends on the relationship between AOD and $PM_{2.5}$. Although AOD- $PM_{2.5}$ relationships have been established for the United States and Europe, it is far from completely understood in China, particularly before 2004 when there was no dedicated national monitoring network in place (Kong et al., 2016; Xin et al., 2007, 2014, 2016). It is, therefore, critical to investigate the relationships between AOD and $PM_{2.5}$ across different regions and seasons in China. The AOD- $PM_{2.5}$ relationship in China was for the first time elucidated using widely available satellite-retrieved AODs, combined with China Atmosphere Watch Network operated by China Meteorological Administration (Guo et al., 2009). Recently, Xin et al. (2016) analyzed $PM_{2.5}$ and AOD data from 23 stations as part of the “Campaign on atmospheric Aerosol REsearch network of China” (CARE-China; Xin et al., 2015). They found grossly consistent changes in AOD and $PM_{2.5}$ in three precipitable water vapor ranges. However, the linear regression functions ($PM_{2.5} = A \times AOD + B$) exhibited large differences in different regions and seasons. To tackle this problem, T. Su et al. (2018) examined the multiple relationships between AOD, the planetary boundary layer (PBL), $PM_{2.5}$, meteorological variables, and topography. Many of these quantities are intercorrelated and change with season and location. For example, there is a much stronger relationship between $PM_{2.5}$ and PBL in northern China in the winter than in southern China in the summer. Normalizing $PM_{2.5}$ by AOD generally leads to a stronger relationship with the PBL. Such findings help improve the estimation of $PM_{2.5}$ from remote sensing. More importantly, it has been recognized that the AOD of fine-mode aerosols retrieved from space is more useful in estimating surface $PM_{2.5}$. Note that it was not until recently that the fine-mode fraction could be estimated from satellites with reasonable accuracy (Yan, Li, et al., 2017; Yan, Shi, et al., 2017; Yan, et al., 2019). A higher accuracy ($R^2 \sim 0.85$ or higher) in the estimation of $PM_{2.5}$ was recently achieved by means of machine learning using the inputs of either satellite-derived AOD (Wei et al., 2019) or satellite-measured radiances (J. Liu et al., 2019), together with ancillary data such as meteorology and topography.

By applying two techniques widely used in computer science for image processing, Zhao et al. (2014) developed a new method to detect aerosol and cloud layers using the micropulse lidar (MPL). First, they used a semidiscretization processing technique to inhibit the impacts of increasing noise with distance from the MPL instrument. Second, they applied the value distribution equalization method to reduce the magnitude of signal variations with distance. Third, they defined threshold values to determine whether the signals originated from clouds or aerosols. Compared to empirical algorithms, this method can detect aerosols and clouds more accurately. The new method can identify more high-level clouds which were previously wrongly classified as aerosols by the standard method used by the U.S. Department of Energy Atmospheric Radiation

Table 1
Aerosol/Gas Composition Instruments Deployed at Five Sites in China

Instruments	Manufacturers/models	Measurements
1. Xianghe Atmospheric Observatory (39.798°N, 116.958°E), 1 June to 21 July 2013		
Aerosol chemical speciation monitor	Aerodyne Research Inc.	Organics, sulfate, nitrate, ammonium, and chloride
Aethalometer	Magee Scientific Corp./AE22	Black carbon
Photoacoustic soot spectrometer	Droplet Measurement Technologies/PASS-3	Absorption coefficients at 405, 532, and 781 nm
Scanning mobility particle sizer spectrometer	TSI Inc./DMA3081 and CPC3775	Particle number size distributions (14–736 nm)
Gas analyzers	Thermo Scientific/Models 45i, 43i, 42i, and 49i	CO, SO ₂ , NO/NO ₂ , and O ₃
Cloud condensation nuclei (CCN)	Droplet Measurement Technologies Inc.	CCN number concentration
2. Xinzhou (37.27°–38.25°N, 111.30°–113.09°E), 22 July to 26 August 2014		
Both ground and airborne instruments measuring full-fledged aerosol properties and precursor gases, CCN, together with meteorological and cloud variables. Key aerosol instruments include		
Aerosol chemical speciation monitor	Aerodyne Research Inc.	Organics, sulfate, nitrate, ammonium, and chloride
Aethalometer	Magee Scientific Corp./AE22	Black carbon
Scanning mobility particle sizer spectrometer	TSI Inc./DMA3081 and CPC3775	Particle number size distributions (14–736 nm)
Cloud condensation nuclei (CCN)	Droplet Measurement Technologies Inc.	CCN number concentration
Humidity Tandem Differential Mobility Analyzer	Custom-made	Hygroscopic growth factor
3. Xingtai (36°–40°N, 113°–117°E), 1 May 2016 to 5 January 2017 (Intensive Observation Period)		
Both ground and airborne instruments measuring full-fledged aerosol properties and precursor gases, CCN, together with meteorological and cloud variables. Key aerosol instruments include		
Aerosol chemical speciation monitor	Aerodyne Research Inc.	Organics, sulfate, nitrate, ammonium, and chloride
Aethalometer	Magee Scientific Corp./AE22	Black carbon
Scanning mobility particle sizer spectrometer	TSI Inc./DMA3081 and CPC3775	Particle number size distributions (14–736 nm)
Gas analyzers	Thermo Scientific/Models 45i, 43i, 42i, and 49i	CO, SO ₂ , NO/NO ₂ , and O ₃
Cloud condensation nuclei (CCN)	Droplet Measurement Technologies Inc.	CCN number concentration
Humidity Tandem Differential Mobility Analyzer (HV-TDMA)	TSI Inc./DMA3081 and CPC3775	Hygroscopic and volatility growth factor
4. Nanjing University of Information Science and Technology (32.30°N, 118.72°E), 25 October to 12 November 2015		
Scanning mobility particle sizer spectrometer	TSI Inc./DMA3085 and CPC3776	Particle number size distributions (4–70 nm)
Wide-range particle spectrometer	MSP Corp./WPS XP-1000	Particle number size distributions (70–750 nm)
Gas chromatograph	AMA Instruments GmbH/GC 5000	56 C2-C12 VOCs
Gas analyzers	Thermo Scientific (models 43i-TLE, 49i, 48i, and 42i)	SO ₂ , O ₃ , CO, NO ₂
Tapered element oscillating microbalance	Thermo Scientific/TEOM 1405	PM _{2.5}
5. Lake Gucheng (31.30°N, 118.93°E), 8–24 October 2015		
Scanning mobility particle sizer spectrometer	TSI Inc./DMA3085 and CPC3776	Particle number size distributions (3–64 nm)
Scanning mobility particle sizer spectrometer	TSI Inc./DMA3081 and CPC3775	Particle number size distributions (64–750 nm)
Gas analyzers	Thermo Environmental Instruments (models 43i-TLE, 49i, 48i, and 42i)	SO ₂ , O ₃ , CO, NO ₂
Tapered element oscillating microbalance	Thermo Scientific/TEOM 1405	PM _{2.5}

Measurement program. Moreover, the new method can accurately identify locations with sharp signal changes at cloud boundaries without smoothing, making the cloud bases not biased low and cloud tops not biased high as what happens with other methods. Without the ability to detect high-level ice clouds,

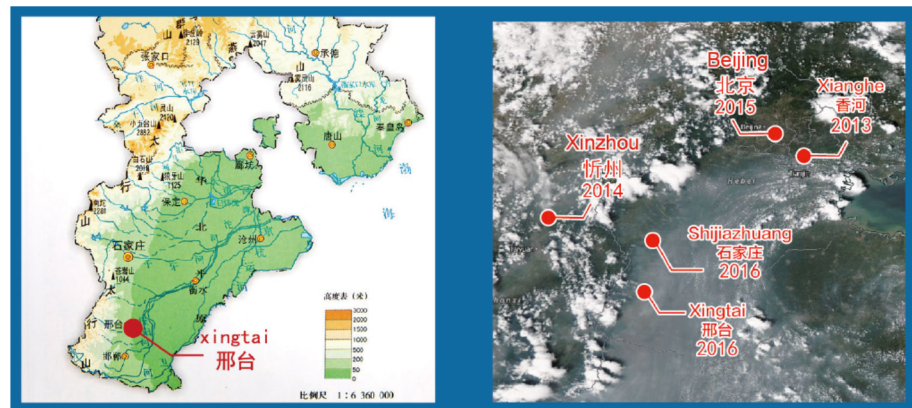


Figure 2. Locations of major field experiments conducted in the Northern China Plain from 2013–2016 led by Z. Li, focused on aerosol-cloud-precipitation interactions.

AOD retrievals from satellite and their radiative effects could be highly overestimated, creating issues with understanding the Earth's radiation budget. This is particularly important in urban areas where frequent haze events occur. Haze attenuates the lidar signal and makes distinguishing between aerosols and clouds difficult.

Shang et al. (2017) further proposed a new method to detect haze aerosols in the lower atmosphere in eastern China. Most current satellite-based cloud and aerosol detection algorithms make use of radiative properties and cloud geometrical textures to discriminate between cloudy and clear areas or between cloudy and hazy areas (Goodman & Henderson-Sellers, 1988; Remer et al., 2005). Shang et al. (2017) made use of digital elevation model data to adjust the threshold values of brightness temperatures used to detect aerosols and clouds, which can more accurately detect aerosols and clouds under heavy pollution conditions. The main idea proposed by Shang et al. (2007) is that haze occurs near the ground, whereas clouds typically exist at high altitudes.

The errors in aerosol retrievals come not only from the classification of aerosols and clouds but also from the impacts of particle optical properties and surface conditions. M. Tao et al. (2017) evaluated Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue (DB) Collection 6 aerosol retrievals in the desert regions of East Asia based on surface measurements from the China Aerosol Remote Sensing Network (CARSNET). They found that MODIS DB aerosol retrievals are low biased with most values falling outside the expected error envelope $\pm (0.05 + 20\% \text{ AOD}_{\text{CARSNET}})$. Two reasons for this were given: (1) the overestimated scattering ability of airborne dust over East Asia and (2) the overestimation of surface reflectance. The study by M. Tao et al. (2017) implies that MODIS DB retrievals can be improved by applying more realistic aerosol models and surface characterizations over East Asia based on more surface measurements.

The vertical structure of aerosols in China and their radiative properties, especially their absorbing capability, were assessed using long-term satellite observations from the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) and ground-based lidar observations and Aerosol Robotic Network data. P. Tian et al. (2017) reported that more than 80% of the column aerosols are distributed within 1.5 km above the ground in the winter when the aerosol extinction lapse rate exhibits a maximum seasonal average in most regions of China except for the Tibetan Plateau (TP). The aerosol extinction lapse rates in polluted regions are higher than those of less polluted regions, indicating a stabilized atmosphere due to absorptive aerosols in the polluted regions. Tian et al. (2018) also found a strong enhancement of absorption due to a mixing of dust (mineral absorbing) and anthropogenic pollution (black carbon, or BC, absorbing), as revealed by the spectral behavior of the absorbing AOD, single scattering albedo, and imaginary refractive index.

2.3. Modeling Studies

Comprehensive modeling studies were conducted using a variety of models as summarized in Table 2.

Traditionally, the aerosol effect is quantified in the climate modeling community by looking at the differences between two numerical simulations, one with present (higher) aerosol loading and the other with

Table 2
Model Simulations Done in This Special Issue

Model and key features	Experiment design	Paper(s)
WRF with spectral-bin cloud microphysics	Perturbing vertical wind shear; perturbing CCN concentration	Q. Chen et al. (2015) and Guo, Gao, et al. (2014)
WRF with two-moment bulk-bin cloud microphysics and aerosol radiative effect	Altering aerosol concentration	Lee et al. (2016)
WRF with CAM5 physics	Comparing two aerosol activation schemes and different treatments in the FN05 scheme	J. He et al. (2017), Lim et al. (2014); Wang et al. (2018), and Y. Zhang et al. (2015)
WRF-Chem	Switch on/off aerosol radiative effect; switching dust emission schemes	Fan et al. (2015), Su and Fung (2015), and Y. Yang et al. (2016)
WRF-Chem coupled with an Urban Canopy Model	Switch on/off aerosol direct and indirect effects and change land use	Zhong et al. (2015, 2017)
NCAR CAM5	Separately perturbing sulfate/BC/POM	Jiang, Yang, et al. (2017), Jiang et al. (2015), Jiang, Huo, et al. (2017)
NCAR CAM5 with in situ precipitation extreme diagnostics	Contrasting historically varying and fixed aerosol scenarios	Wang et al. (2016)
NCAR CAM5 with 256 simulations perturbing 26 cloud- and aerosol-related parameters	Contrasting simulations with different parameters	H. Yan et al. (2015)
A regional chemistry-climate model (RegCCMS)	Switch on/off aerosol direct and indirect effects	Wang, Guo, et al. (2015)

historical (lower) loading. However, this approach is not feasible for studying how aerosols impact the response to the gradual change in aerosol emissions from low to high. H. Yan et al. (2015) adopted a novel parametric sensitivity analysis framework that integrates the quasi-Monte Carlo parameter sampling approach and a surrogate model to examine aerosol effects on the EAM climate using the Community Atmosphere Model (CAM5). A total of 256 CAM5 simulations (Qian et al., 2015) were conducted to quantify the model responses to uncertain parameters associated with cloud microphysics parameterizations and aerosol (e.g., sulfate, BC, and dust) emission factors as well as their interactions (Figure 3). Interaction terms among parameters, which are usually ignored in modeling studies, are found to be important for quantifying the sensitivity of precipitation to the parameters. Their results also showed that sulfate, BC, and dust aerosols have very different impacts on the EAM climate through aerosol-cloud-radiation interactions. The climatic effects of aerosols do not always have a monotonic response to changes in emission factors. They also identified cloud microphysical parameters that have the most significant impacts on the climatic effect induced by different types of aerosols in East Asia.

3. Aerosol Formation, Nucleation, Optical Properties, and Radiative Effects

The importance of aerosol formation and transformation processes and their radiative effects in context with East Asia pollution have been identified and recognized in many previous studies. For example, NPF

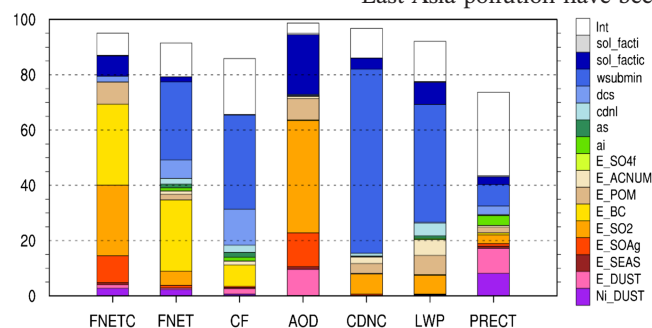


Figure 3. Fractional contributions of 16 parameters to the total variance estimated for summer mean net clear-sky radiative flux at the top of the atmosphere (FNETC), net all-sky radiative flux at the top of the atmosphere (FNET), cloud forcing (CF), aerosol optical depth (AOD), cloud droplet number concentration (CDNC), liquid water path (LWP), and total precipitation (PRECT) over East China. Adopted from H. Yan et al. (2015).

has been documented as a significant source of the aerosol population in China (Guo, Hu, et al., 2014; Zhang et al., 2015) and also an important source of CCN (Yue et al., 2011). The aerosol radiative effect, rapid aging, and enhanced absorption in polluted urban environments in China were characterized by chamber experiments (Peng, Hu, et al., 2016; Peng et al., 2017). Concerning aerosol growth, the formation of sulfate involving heterogeneous reactions (Wang et al., 2016; Wang et al., 2018) is crucial because these reactions largely regulate the aerosol hygroscopicity. These new findings from the EAST-AIRcpc are reviewed next.

3.1. Aerosol Formation and Growth

NPF is a ubiquitous phenomenon that has important implications in understanding the formation of secondary aerosols, air quality, and climate. However, NPF and particle growth in highly polluted environments remains less understood (Yu et al., 2017). Dai et al. (2017) made nearly two months of simultaneous measurements of particle number size

distributions (4–750 nm) at an urban site and a regional background site in the polluted YRD region. They found that the formation and growth rates at the polluted urban site were always lower than those at the regional background site during seven regional NPF events. This implies that regional NPF intensities are likely substantially underestimated if measurements are solely available from urban sites. Dai et al. (2017) also found a type of strong local nucleation event at the urban site where the formation rate of particles (e.g., J_5) was positively correlated with H_2SO_4 and enhanced by anthropogenic volatile organic compounds from nearby industrial emissions. This finding highlights that local NPF events might be an important contributor to CCN in polluted urban environments.

Sun et al. (2016) made real-time measurements of submicron aerosol species using an aerosol chemical speciation monitor in June 2013 at the suburban site Xianghe located ~50 km southeast of Beijing. There was an overall similarity between the aerosol composition at urban and rural sites in the NCP which are dominated by organics (35–40%) followed by nitrate (20–25%) and sulfate (18–25%; J. Sun et al., 2010; Y. Sun et al., 2012, Sun, Jiang, et al., 2016). This highlights the regional characteristics of air pollution. Y. Sun et al. (Sun, Jiang, et al., 2016) also found a significant impact of biomass burning (BB) on air quality in June. The average PM_{10} concentration was $126 \mu\text{g}/\text{m}^3$ during BB periods, which is more than twice that during non-BB periods ($61 \mu\text{g}/\text{m}^3$). In particular, BB organic aerosols (OA), which account for 21% of the total OA, show the largest increase (by a factor of 10) during BB periods. In addition to BB, Y. Sun et al. (Sun, Jiang, et al., 2016) also highlighted two major sources affecting air quality in the NCP: (1) regional transport dominated by secondary inorganic aerosols and secondary OA and (2) local source emissions dominated by organics and BC.

Particle growth plays a critical role in the deterioration of visibility for which aerosol hygroscopicity is a key factor. During field campaigns carried out in the NCP, this property has been investigated using in situ and remote sensing approaches (Wang et al., 2017). The former was achieved using the humidified tandem differential mobility analyzer and many collocated measurements, as shown in Table 1. The campaign in Beijing took place around the time of the 2015 China Victory Day Parade during which many drastic measures were implemented to reduce emissions in Beijing and surrounding regions. Comparisons before and after the parade (polluted and clean conditions, respectively) showed significant changes in aerosol species and associated aerosol properties, that is, hygroscopic growth. During the clean period, the dramatic reduction in inorganic gases and aerosols (especially secondary aerosols) rendered particles more hydrophobic and volatile, leading to a further improvement of air quality. Comparatively, measurements made at Xingtai, one of the most polluted regions in China, showed that aerosol particles are more hydrophilic and thus have a stronger swelling effect associated with the internal mixing of secondary aerosol species (Wang et al., 2018). By combining aerosol chemical composition measurements, Chen et al. (2019) further analyzed the roles of different aerosol species in affecting aerosol hygroscopic growth in Xingtai. However, most measurements of hygroscopicity are currently limited to the ground level. Until recently, Raman lidar retrievals were used to infer the hygroscopicity of aerosol particles aloft, as demonstrated by the campaign in Xinzhou (Lv et al., 2016).

3.2. CCN

By serving as CCN, aerosol particles play a key role in the formation of clouds and their evolution during which they alter both the water and energy cycles in the Earth's climate system. CCN is thus a dominant factor in ACI, which can further alter the energy balance of a cloud. To better understand ACI and their impact on precipitation and radiation, it is important to gain a good knowledge of the ability of aerosol particles to form CCN at the typical supersaturations found in the atmosphere. Due to the large spatial variability of aerosol types and compositions, the CCN activation efficiency varies greatly over different regions, especially in such a large and fast-developing country like China.

To this end, numerous field experiments have been conducted in China in recent years involving measurements of CCN, aimed at better characterizing CCN and its influential factors (e.g., Li, Zhang, et al., 2017; Ren et al., 2018; Wang, Li, Zhang, et al., 2018; F. Zhang et al., 2014, Zhang et al., 2016, 2017). These studies provide different perspectives on the influence of aerosol particle size and composition on CCN activity. For example, F. Zhang et al. (2014) demonstrated that the 30–40% uncertainties in the number of CCN (N_{CCN}) are mainly associated with changes in the particle composition. Also, the impacts of OA on CCN activity were investigated based on field measurements made at a suburban site in northern China. A strong dependence of N_{CCN} on the volume fraction of organic material and aerosol oxidation level was reported

(Zhang, Li, et al., 2016). NPF events were also found to enhance N_{CCN} during the “leveling-off” stage but restrain CCN activation at the “growth” stage during which larger particle diameters are needed to reach an activation diameter (Li, Zhang, et al., 2017). Using a comprehensive data set including size-resolved CCN activity, size-resolved hygroscopic growth factor, and chemical composition, F. Zhang et al. (2017) found that the effect of aging/coating on particle hygroscopicity for aged aerosols leads to an underestimation of $\sim 22\%$ of N_{CCN} . Such a coating effect has not been considered properly in most models. The underestimation of N_{CCN} is at par with the underestimation of aerosol hygroscopicity for aged aerosol particles (Wang, Li, Zhang, et al., 2018). For fresh aerosol particles, however, the CCN activity tends to be overestimated largely because of inaccurate assumptions about the particle mixing state and the variability in chemical composition over the particle size range of activation. A much better agreement between observed and model-predicted CCN can be achieved by accounting for size-resolved chemical compositions, as was done by Ren et al. (2018).

Despite the significant accomplishments of these studies, long-term measurements of those aerosol properties at more sites are needed to get more accurate CCN predictions under different atmospheric environments. This would improve the parameterization of N_{CCN} in models, which is critical for estimating ACI (Sotiropoulou et al., 2007). Novel remote sensing approaches that use clouds as cloud chambers (Rosenfeld et al., 2016), together with satellite-derived updraft speeds (e.g., Zheng et al., 2015), may help in this regard.

3.3. Visibility, Aerosol Optical Properties, and Radiative Effects

Visibility, a widely used proxy of air quality, has been measured as a standard meteorological variable at virtually all weather stations in China. Chen and Wang (2015) conducted a comprehensive analysis of the 1960–2012 visibility trend in northern China. They found that the poorest visibility tends to occur in the morning in wintertime. The most dramatic deterioration in visibility occurred from the 1960s to the 1970s and continued into the 2000s at a more moderate rate. Significant differences were noted between urban and rural areas, with the former being worse than the latter. Relative humidity, a key factor influencing visibility, is virtually identical between urban and nearby rural regions, signifying that the difference originates from the emissions of urban pollutants.

Bi et al. (2014) examined several serious atmospheric haze events that occurred over eastern and northern China in January 2013. They found that the volume size distribution and median radius of the fine-mode aerosol particles generally increased with AOD and discovered a significant amount of absorbing aerosols during these haze episodes. Correspondingly, they showed a strong influence of the aerosol direct radiative (ADR) effect on the atmospheric thermal structure: Up to half of the incident solar radiation was absorbed in aerosol layers, causing exceptionally strong heating of the atmosphere and cooling of the surface. The relationship between daily mean aerosol radiative forcing (ARF) and AOD at 500 nm at the surface and at the top of the atmosphere (TOA) was studied. The slopes of the best linear fittings were 11.02, 11.23, and 11.27 at the surface and 4.14, 3.57, and 2.56 at the TOA for three sites in Beijing. The ARF values at the surface are about twice those at the TOA. The daily mean heating rate in the aerosol layer over Beijing ranged from 0.12 to 0.81 K/day.

Liu et al. (2011) examined the aerosol optical properties and their associated radiative effects based on sky-radiometer and surface solar radiation data in the spring over the Loess Plateau in northwest China. Y. G. Liu et al. (2015) and Jia et al. (2018) examined aerosol transport to the TP and the dust-induced heating effect over the TP using satellite data, a radiative transfer model, and the Spectral Radiation-Transport Model for Aerosol Species. The aerosol index observed by the Ozone Monitoring Instrument shows that absorbing aerosols are distributed over the northern and southern slopes of the TP, corresponding to dust and carbonaceous aerosols, respectively. Model simulations show that high values of dust AOD are primarily distributed over the northern slope of the TP, whereas high AOD values due to anthropogenic aerosols, including carbonaceous and sulfate aerosols, are distributed over the southern slope and east of the TP. Dust aerosols significantly affect the radiative energy budget and thermodynamic structure of the air over the TP, mainly by altering the shortwave radiation budget. The instantaneous heating rate can be as high as 5.5 K/day depending on the density of the dust layers.

Wang, Zhang, et al. (2016) examined the effect of ADR on East Asian surface radiation and air quality using Weather Research and Forecasting model coupled with chemistry (WRF-Chem) simulations during the EAST-AIRE campaign. The ADR effect decreased surface downwelling radiation, the surface air temperature, the boundary layer height (BLH), and the temperature lapse rate. The $PM_{2.5}$ concentrations increased accordingly by 4.4%, 10%, 2.3%, and 9.6% in eastern China, southern China, western China, and the Sichuan Basin, respectively. Another observation-based estimation by Yang et al. (2016) found that the ADR effect can strengthen the total aerosol amount by $\sim 12\%$ and $\sim 15\%$ through reductions in the near-surface wind and BLH in Beijing, respectively, which are even larger than model simulation results. Yang et al. (2016) further analyzed the sensitivity of the ADR effect to aerosol type in China and found that the net effects of aerosols on the surface solar radiation and corresponding climatic effects are dependent on both the aerosol amount and optical properties. Note that the aforementioned studies are mostly of short duration. Interestingly, radiosonde-derived BLHs have shown a trend reversal (from increasing to decreasing) in recent decades in China. This is found, however, to be correlated more with increases in soil moisture than with the aerosol trend (Guo et al., 2019). Therefore, the long-term impact of ADR, especially on the PBL structure, remains inconclusive and merits further analyses by combining observations with model simulations where land-atmosphere coupling should be considered.

4. Impact of Aerosols on Clouds and Precipitation

4.1. Impact of Aerosols on Clouds

Ground-based and spaceborne remote sensing techniques have proven indispensable for learning more about the spatiotemporal variations of cloud and precipitation. Comparisons between cloud properties retrieved from the surface and spaceborne platforms are commonly made to validate satellite retrievals (e.g., Dong et al., 2002, 2008). It is important to understand and reconcile any systematic differences that arise before attributing any discrepancies to satellite retrieval errors. Comprehensive surface-based retrievals of cloud optical and microphysical properties were made at Taihu, a highly polluted site in the central YRD region, which were further compared to corresponding MODIS-Terra and MODIS-Aqua cloud property retrievals (J. Liu et al., 2013). Large discrepancies between surface- and satellite-retrieved cloud properties were found, suggesting that MODIS cloud products suffer from large uncertainties in this highly polluted region. The degradation in agreement likely stems from the influence of absorbing aerosols, which can also impinge on the retrieval of cloud properties (Coddington et al., 2010; Wilcox & Platnick, 2009). Z. Li et al. (2014) developed a ground-based retrieval algorithm for the simultaneous retrieval of cloud optical depth (COD) and cloud droplet effective radius over the same sites as that in J. Liu et al. (2013) to examine the influences of aerosols on both surface and satellite retrievals. They found stronger sensitivities in the retrieval of COD from spaceborne sensors to aerosol absorption and vertical distribution than that from ground-based retrievals. For absorbing aerosols mixed with clouds, COD tends to be underestimated from space, but overestimated from the ground, leading to a very poor agreement between ground-based and MODIS retrievals. This difference increases with increasing COD. Such a significant bias may be misconstrued as the semidirect effect of aerosols; that is, COD decreases with increasing AOD due to the cloud droplets undergoing evaporation by aerosol-induced absorption. Caution must thus be exercised when examining ACI using both satellite and ground retrievals over regions with an abundance of strongly absorbing aerosols.

Aerosols can alter cloud microphysics, which is concerned with the amount, phase, and size of cloud droplets and ice crystals. The first indirect effect (FIE) describes the reduction in cloud droplet effective radius with an increase in aerosol concentration under fixed LWP conditions (Feingold, 2003; Kim et al., 2008; Liu, Chen, et al., 2016). This implies an increase in the albedo of a cloud, resulting in enhanced reflection and a cooling effect (Twomey, 1977). Several studies using space-, surface-, and ship-based measurements have revealed the strong impact of aerosols on cloud droplet size, COD, and cloud reflection and emission (Feingold, 2003; Feingold et al., 2006; Kim et al., 2008; Liu, Chen, et al., 2016; Liu & Li, 2018a), indicating that the magnitude of the FIE differs drastically depending on aerosol properties, meteorological conditions, analysis methods, and so on (Liu & Li, 2018b; Liu, Chen, et al., 2016; Rosenfeld & Feingold, 2003; F. Wang et al., 2014). Under highly polluted conditions over eastern China, a positive FIE was observed; that is, cloud droplet effective radii increased with AOD (Liu et al., 2017; Tang et al., 2014; Wang, Guo, et al., 2014). Possible explanations included the

neglect of the overlapping status of aerosol and cloud layers in the vertical (J. Huang et al., 2015; Wang, Guo, et al., 2015) and the aerosol swelling effect (Liu & Li, 2018b), or both. Additional nucleation of cloud droplets aloft may also contribute because it decreases the effective radius with height. Meteorology plays a significant role in observational studies of the FIE. A positive relationship between the FIE and atmospheric stability was derived from surface-retrieved cloud and aerosol information, contradicting the negative relationship found from satellite data. This contrast originates from differences in the retrieved cloud microphysical properties at different levels from satellite and surface sensors, which likely explains some major discrepancies in many past studies concerning ACI (Liu, Li, & Cribb et al., 2016). The positive indicated FIE is likely unreal because the increase in AOD under moist conditions is not generally associated with an increase in CCN.

Aerosol particles like mineral dust, soot, organic matter, and biological aerosols can be efficient IN, helping to form ice crystals at temperatures below 0 °C. Increases in IN could lead to the so-called glaciation indirect effect for mixed-phase clouds (Ovchinnikov et al., 2011). Satellite observations have documented the relationships between aerosols and the glaciation temperature (T_g) in growing convective clouds over East Asia and adjacent oceans (Rosenfeld et al., 2011). They showed that the most important factor in the determination of T_g is the cloud droplet effective radius at the -5 °C isotherm. The effective radius is smaller with greater AOD, which leads to smaller T_g (see also Zhu et al., 2015). The cause for the increased T_g with less AOD is the larger droplets which freeze more quickly, mainly by the ice multiplication mechanism (Hallett & Mossop, 1974). For clouds with similar droplet effective radii at -5 °C, desert dust and urban air pollution cause higher T_g compared to other kinds of aerosols. Long-range transported dust particles from Asia were found to enhance snow precipitation in California orographic mixed-phase clouds (Fan et al., 2014, 2017). Nevertheless, studies of cloud thermodynamic phase changes and the vertical structures of mixed and ice-phase clouds over East Asia from both observations and model simulations are still sparse (Fan et al., 2012; J. Liu et al., 2013). The impacts of aerosols on cold-phase cloud thermodynamic phase changes over East Asia were studied using four years of combined measurements from the CloudSat radar and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) lidar (Zhang et al., 2015). Seasonal anomalies of glaciated and mixed-phase clouds correlate well with the seasonal variations in the frequency of dust occurrence. In addition, cold-phase clouds associated with mineral dust contain approximately 5%, 10%, and 20% larger glaciated (smaller mixed-phase) relative cloud fractions (CFs) than those associated with polluted dust, smoke, and background aerosols at any given cloud-top temperature (Zhang, Liu, et al., 2015). The study by Zhang, Liu, et al. (2015) illustrates the impact of dust on subfreezing clouds over East Asia by providing abundant effective IN to glaciate mixed-phase clouds.

Zhu et al. (2015) found that for convective clouds in the developing stage, the cloud droplet size increases with height, but the rate of change varies with aerosol loading, that is, faster under clean conditions than under dirty conditions. The cloud droplet size must reach a critical size of 13–14 μm for the initiation of the conversion of cloud droplets to raindrops and thus of precipitation (Freud & Rosenfeld, 2012). This leads to a positive correlation (with a correlation coefficient of 0.83) between AOD and cloud thickness, which is required to initiate precipitation. In a heavily polluted environment (e.g., AOD >0.6), clouds do not precipitate unless their thicknesses are on the order of a few kilometers. Clouds that are a few hundreds of meters thick can rain out if the AOD is less than 0.1. This was also measured directly in relation to cloud-base CCN and drop concentrations in India (Konwar et al., 2012) and in the Amazon (Braga et al., 2017). This finding has important implications for weather forecasting. Neglecting aerosol effects can lead to global rainfall forecast errors whose spatial pattern bears a close resemblance to the spatial pattern of aerosol loading (Jiang, Feng, et al., 2017).

The influence of aerosols on cloud droplets and ice crystals can induce changes in cloud lifetime and CF. Both positive and negative effects have been reported, arising from various mechanisms for different cloud regimes. A strong positive relationship between AOD and shallow CF has been widely observed over the Atlantic Ocean (e.g., Kaufman & Koren, 2006), the Amazon (e.g., Kaufman et al., 2005), the southeastern Pacific Ocean (e.g., X. Zheng et al., 2010), and eastern China (e.g., Wang, Guo, et al., 2014). This likely originates from aerosol microphysical and lifetime effects because the smaller cloud droplets resulting from more CCN are less likely to rain out and more likely to grow. Direct relationships between marine

boundary layer cloud-base droplet concentration, cloud cover, and cloud radiative effects show much stronger relationships than with AOD (Rosenfeld et al., 2019). This is so because clouds are most sensitive to changes in aerosols under clean conditions when AOD does not produce measurable signals at $\text{CCN} < 100 \text{ cm}^{-3}$ (Shinozuka et al., 2015). Meanwhile, the reduction in cloud droplet size may lead to increased evaporation and a reduction in CF (e.g., Small et al., 2009).

The aerosol microphysical effect also invigorates DCCs, elevates cloud tops, and induces increases in the anvil cloud cover of DCCs, leading to an overall warming effect in a polluted environment (e.g., Xu et al., 2017; H. Yan et al., 2014). Two main mechanisms have been proposed for the aerosol convective invigoration:

- a Enhanced latent heat induced from freezing of more condensates: Rosenfeld et al. (2008) have shown that the initiation of warm rain due to added CCN can lead to a greater amount of supercooled cloud water, which can freeze aloft and convert to ice hydrometeors, releasing more latent heat as a result of enhanced freezing and deposition. This would not happen if the same precipitation occurred as warm rain lower in the cloud. The added latent heating invigorates the clouds.
- b Enhanced latent heat of condensation: Fan et al. (2018) have shown that added ultrafine aerosol particles (UAP), which are generally too small to be activated at cloud base, can invigorate deep convection through being activated well above cloud base where in-cloud supersaturation is high because coalescence reduces the number of droplets for condensation. With a low concentrations of aerosols larger than 50 nm (such as several hundred cubic centimeter or less) and a humid condition in Amazon, the coalescence can lead to a vapor supersaturation exceeding 10% in strong updrafts when UAPs are scarce. When UAPs are present, they are activated and form much more additional cloud droplets, strengthening condensation and thereby latent heat release. As a result, the supersaturation can be lowered to 2–3% in the strong updrafts. This process can also occur at the supercooled levels and lead to nucleation of a larger number of smaller ice crystals, which form anvils with larger amounts of smaller ice crystals (Fan et al., 2013). This promotes the longevity of the anvils.

This aerosol convective invigoration increases cloud-top heights, thicknesses, or both, which is most significant for DCCs with warm cloud bases and relatively weak wind shear (e.g., Peng, Li, et al., 2016).

4.2. Impact of Aerosols on Precipitation

The initiation and development of convection are considerably affected by atmospheric dynamics and thermodynamics except for cloud microphysics. Aerosols, via the two main pathways of the radiative effect (i.e., aerosol-radiation interactions, or ARI) and the microphysical effect (i.e., ACI), can significantly change precipitation properties, including intensity, frequency, and initiation time. ARI tend to alter the atmospheric circulation by changing the thermodynamic profile of the atmosphere, which, in turn, changes the occurrence of clouds and precipitation. For example, BC is believed to account for the summertime “southern-flood-northern-drought” pattern over recent decades in China (Menon et al., 2002). The BC produced by biomass burning has proven to dramatically heat the atmosphere and stabilize air, making it difficult for clouds to form (Koren et al., 2004). The burning effect can also make clouds evaporate faster (Ackerman et al., 2000). By contrast, the quantification of the impact of ACI on precipitation appears challenging. The magnitude of ACI varies according to different cloud and precipitation regimes and depends on the large variation in meteorology. Even the sign of ACI changes or reverses abruptly, likely due to the buffered system embedded in the aerosol-cloud-meteorology system (Stevens & Feingold, 2009). The buffering effect explains the insensitivity to aerosols after system adjustment. The different signs of ACI are mainly due to different dynamics and thermodynamics.

As AOD increases, both rainfall amount and frequency from DCCs increase at first and then decrease, which was noted in numerous previous studies as reviewed by Z. Li et al. (2017a). To date, there have been many studies on the impact of aerosols on precipitation around the world and in China, as shown in Figures 4 and 5, respectively.

The rainfall suppression by aerosols has more to do with the aerosol radiative effect, whereas the enhancement is often fueled by the latent heat release due to both condensation and freezing (Li, Rosenfeld, et al., 2017). Downwelling solar radiative fluxes at the surface decrease as AOD increases. This decrease in solar radiation leads to a decrease in ground heat fluxes and CAPE, which is unfavorable for the development

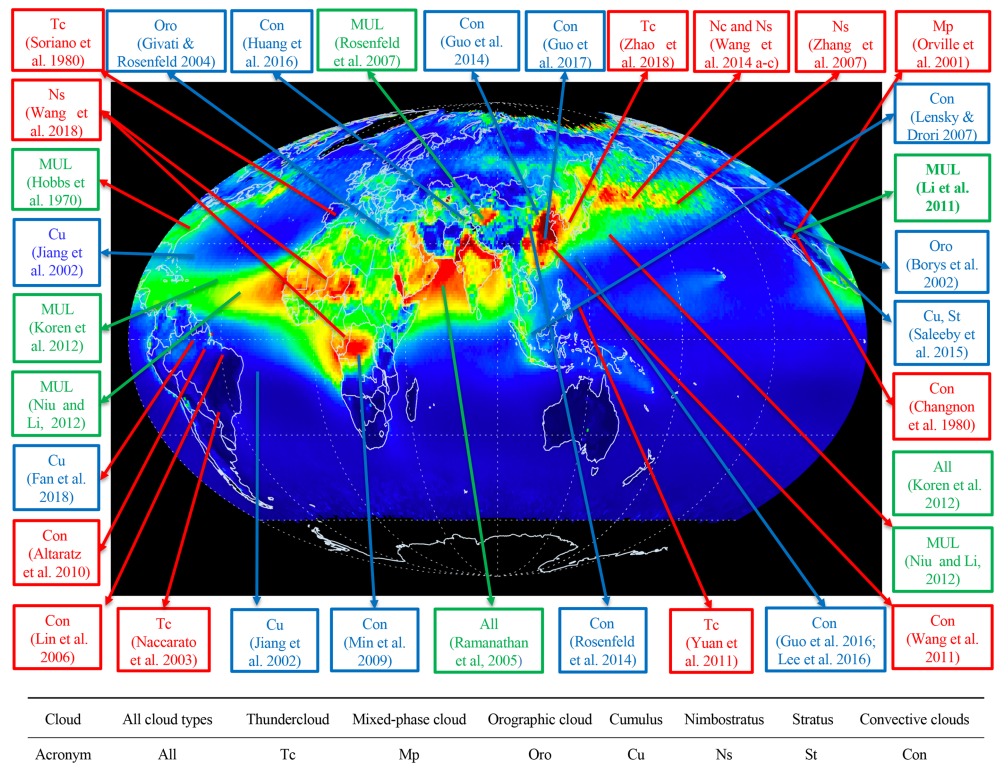


Figure 4. A global view of literature about the observed aerosol impact on precipitation around the world according to cloud or precipitation regime and the region of interest. Text in red denotes enhanced precipitation induced by aerosols, text in blue denotes inhibited precipitation induced by aerosols, and text in green represents either enhanced or inhibited precipitation by aerosols.

of convective clouds and precipitation (Guo, Deng, et al., 2016; Jiang et al., 2016). Cloud droplets tend to form more easily when aerosols increase due to increases in coalescence and collision induced by more CCN. By neglecting ACI, operational weather forecasts tend to overforecast light rain and underforecast heavy rain (Jiang, Feng, et al., 2017). This ACI effect leads to suppression of shallow liquid clouds and invigoration of warm-base mixed-phase clouds. The orography effect on precipitation cannot be ignored either (e.g., Dong et al., 2018; Fan et al., 2015; Guo, Deng, et al., 2014). In addition to changes in the prevailing circulation and moisture transport patterns, a decrease in precipitation over mountains has occurred mainly because increases in the local water vapor saturation capacity, which scales with temperature, have outpaced the available moisture supply. This reduces the relative humidity, suppressing precipitation (Dong et al., 2018). The coupling effect of aerosols and orographic lifting has proven to be crucial for precipitation forecasts (Fan et al., 2015; Rosenfeld et al., 2007).

Following previous pioneering studies (e.g., Qian et al., 2009; Zhao et al., 2006), intensive follow-up studies of the impact of aerosols on precipitation in China further confirmed that the increases in aerosol loading in recent decades are closely associated with changes in frequency and intensity of precipitation over the Guanzhong Plain of central-western China (Y. Wang et al., 2011; Wang, Allen, et al., 2016), the NCP (Guo, Deng, et al., 2014), and southeast China (Jiang, Feng, et al., 2017; Yang & Li, 2014). Typically, light rain has decreased, and heavy rain has increased, based on long-term contemporaneous aerosol and precipitation observations. No matter if rainfall is produced by orographic-forced shallow clouds or by mesoscale stratiform clouds, light rain is significantly inhibited, consistent with simultaneously observed increases in aerosol loading, which seems to be a testimony to the aerosol effect (Guo, Deng, et al., 2014).

From the perspective of precipitation diurnal variability, aerosol pollution is observed to suppress the initial convection over the Pearl River Delta region of China, leading to more frequent light rain prior to peak precipitation. This is followed by much delayed and considerably enhanced convection afterward (Guo, He, et

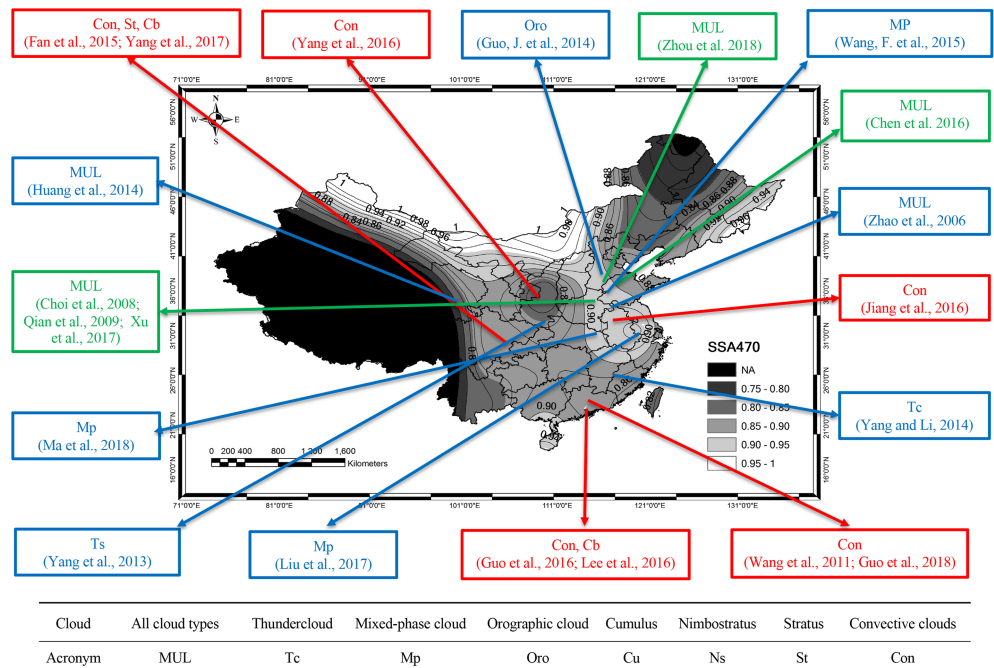


Figure 5. Same as Figure 4 but for studies focused on China.

al., 2016). Model simulations confirm this phenomenon, which is attributed to competing mechanisms induced by aerosol radiative and microphysical effects (Lee et al., 2016).

Analyses using hourly gauge data combined with long-term visibility measurements (Guo et al., 2017) point to the widespread declining trend in the frequency of summertime local-scale convective precipitation in eastern China. Its intensity, however, has increased, which can be due to the accelerated release of energy caused by the aerosol invigoration effect (Fan, Rosenfeld, et al., 2018; Rosenfeld et al., 2008). This effect was observed for the first time from the perspective of the spatial scale over which precipitation events occur. By contrast, the frequency of large-scale precipitation changed little, as opposed to the increasing trend in frontal precipitation (Day et al., 2018).

The advent of state-of-the-art satellites with active sensors (e.g., CloudSat, CALIPSO, and the Tropical Rainfall Measuring Mission satellite) allows us to take a closer look at the response of clouds or precipitation to aerosols from the vertical perspective (Wall et al., 2014). Chen et al. (2016) investigated the climatology of various cloud regimes in eastern China and connected relative changes in the vertical structures of clouds to aerosols. Among the cloud regimes, convective clouds were found to be significantly invigorated in the upper troposphere. By focusing on localized precipitation events, Guo et al. (2018) elucidated the responses of vertical precipitation structures to aerosols. One intriguing phenomenon is that the enhancement of convective precipitation was largely limited to the upper troposphere at the expense of lower tropospheric precipitation. Overall, the connection between changes in localized cloud or precipitation systems and aerosols seems to be more significant than that for large- or synoptic-scale systems. In the future, more focus will be placed on the initial stages of localized clouds or precipitation, which can only be accomplished through the combined use of geostationary observations and convection-permitting and -resolving model simulations.

Despite the increasing evidence of aerosol effects on precipitation, such effects seem to account more for rainfall variations than long-term trends in rainfall changes. Y. Wang et al. (2016) found that the accumulation of greenhouse gases, not the changes in aerosol properties since industrialization, is responsible for the shifts in precipitation intensity on a global scale. However, in East Asia, dramatic increases in anthropogenic aerosols appear to account for most of the observed light precipitation suppression since the 1950s. Under a warming climate induced by greenhouse gases, the enhanced ascending motions primarily lead to a decrease in the light precipitation frequency and increases in moderate and heavy precipitation frequencies over the tropics. There is no significant change in ascending motions over East Asia solely due to greenhouse gas forcing.

Mesoscale convective systems (MCSs) are responsible for the majority of precipitation. Hence, there is a very important implication in weather and climate by studying aerosol impacts on various forms of MCSs. However, there is limited work on this. Based on a summer convection event in East China, Q. Chen et al. (2015) found that the strong wind shear at different vertical levels changes the convective system organization, leading to the formation of different kinds of MCSs and total precipitation amounts over the domain. They found that aerosols induce stronger updrafts and downdrafts in all forms of MCSs. The stronger updrafts and enlarged convective core area contribute to larger vertical mass fluxes and enhance precipitation, indicating convective invigoration. The accumulated rainfall and mean rain rate are increased, with an increased occurrence frequency of heavy rain. This frequently involves decreases in the frequency of relatively weaker rain, leading to negligible changes in the rainfall amount. Both convective and stratiform regions show an increase in the rain rate with a more significant increase in the convective rain rate. The unanimous invigoration of MCSs by aerosols under various wind shear conditions revealed by this study has an important implication for weather and climate in warm and humid East Asia.

The impacts of the long-range transport of natural and anthropogenic aerosols on marine clouds and precipitation have received increasing attention. The long-range transport of anthropogenic aerosols from Asia in recent decades has been attributed to climatically significant changes in winter storm patterns over the Pacific. The observed increasing DCCs and precipitation, as well as a decadal variation in midlatitude cyclones, may be at least partially attributed to CAPI (G. Li et al., 2008; Wang, Wang, et al., 2014; Wang, Zhang, et al., 2014; Zhang et al., 2007). A recent observational analysis showed a significant correlation between enlarged rainfall areas of tropical cyclones over the northwestern Pacific with increasing anthropogenic aerosols (Zhao et al., 2018).

5. Impact of Aerosols on Regional Climate

It is important to detect and diagnose the regional climate impacts of aerosols (both anthropogenic and natural) for improving physical parameterizations and the validation of simulations. The impact of aerosols on the East Asian climate in the premonsoon season (spring) has attracted considerable attention. Previous studies (Deng et al., 2014; Hu & Liu, 2013; Jiang et al., 2015; Jiang, Yang, et al., 2017) have shown that an elevation in anthropogenic aerosols could lead to a significant reduction in precipitation in south China during spring. Jiang et al. (2015) further found that the distinct climatic background of East Asia could modulate aerosol effects. Large amounts of middle- and low-level clouds in cold seasons favor a strong aerosol indirect effect that leads to a significant spring drought in southern China. The summer monsoon circulation transports more aerosols to northern China, which explains why the summer drought takes place in northern China (Jiang et al., 2013).

5.1. Impact on Temperature and Its Diurnal Range

Temperature is an important climate indicator and important for human life owing to its physical links to the radiative and heat flux budgets. Aerosols may alter both temperature (Gong et al., 2014; Z. Li et al., 2016) and the diurnal temperature range (DTR) by the direct effect or by indirectly modulating clouds or both. Z. Li et al. (2016) argued that the cooling trend from the 1960s to the 1990s in central-eastern China in the midst of widespread warming across China (Ding et al., 2007) was caused at least partially by the rapid increase in air pollution, consistent with the long-term trends of changes in surface solar radiation (Luo et al., 2001) and visibility (Chen & Wang, 2015).

Note that the DTR is also affected by other factors such as clouds, the greenhouse effect, and the urbanization heat effect (X. Liu et al., 2016). A dominant feature of DTR changes in East Asia is its steady decreasing trend during the past five to six decades (L. Liu et al., 2018). Over heavily polluted northern China, the trend in DTR from 1960 to 2014 is -0.30 °C per decade, much faster than that under clear-sky conditions (-0.17 °C per decade; Xue et al., 2018). Over cloudy southeastern China, the observed DTR reduction under overcast conditions is even more significant (Xia, 2013). Previous observations and simulations have shown that both anthropogenic greenhouse gases and aerosols contribute to the decreasing DTR, especially over eastern Asia (Liu, Li, Yang, et al., 2016) and central China (Yang & Li, 2014). Through its direct effects, aerosols could dampen the DTR, which may explain the decreasing trend in DTR under clear-sky polluted conditions. In northern China, the DTR tends to decrease as the aerosol dry extinction for a given specific humidity increases (Xue et al., 2018). The sunshine duration, a proxy of solar radiation, likely plays a role in

modulating the maximum temperature seen in the weak DTR trend over eastern China since 1990 (Shen et al., 2014). Station surface incident solar radiation has consistently declined from 1994 to 2010 (-1.06 W/m^2 per decade; Wang & Wild, 2016). Such covariations between the DTR and solar radiation dimming/brightening are observed on monthly to decadal time scales (Wang & Dickinson, 2013). Recent efforts (e.g., L. Liu et al., 2018) suggest that changes in the large-scale circulation under global warming may at least partly account for the spatially uniform, declining pattern of the DTR.

5.2. Interactions Between Aerosols and Monsoon Climate and Circulation

Numerous studies have used global climate models to investigate anthropogenic aerosol effects on the East Asian monsoon climate (e.g., Jiang, Huo, et al., 2017; Tian et al., 2018). Anthropogenic aerosol effects on the East Asian summer monsoon (EASM) have been intensively investigated because the variation in summer monsoon precipitation has substantial impacts on agriculture, the economy, and human life (An et al., 2015). Numerous model results suggest that anthropogenic aerosols tend to reduce the land-sea thermal contrast, weaken the EASM, and thus decrease rainfall over land regions (Chen et al., 2016; Guo et al., 2013; Jiang et al., 2013; Li et al., 2016; X. Li et al., 2018; Wang et al., 2017). The decrease in land monsoon precipitation can reduce the upper tropospheric condensational heat release (cooling effect) and further weaken the EASM (dynamical feedback; Jiang et al., 2013). The EASM weakening could be directly induced by aerosol impacts on radiation and clouds (fast response) or indirectly by sea surface temperature (SST) adjustments (slow response). The fast response plays a dominant role in the land rainfall decrease (X. Li et al., 2018), while the slow response is more important in reducing the land-sea thermal contrast and weakening the monsoon circulation (Wang, Xie, et al., 2017).

In a modeling study of interactions between the EASM and anthropogenic aerosols, Wang, Zhuang, et al. (2015) used a coupled regional climate-chemistry model, a similar framework used by Qian and Giorgi (1999) and Qian et al. (2001). They found that aerosols emitted from East Asia reduced the sunlight reaching the surface and cooled the surface air over land, thus decreasing the land-ocean air temperature gradient and weakening the summer monsoon. This weakened monsoon circulation is unfavorable for the dispersion of aerosols, resulting in a further increase in aerosol loading over East Asia. However, the aerosol feedback in the study by Wang, Zhuang, et al. (2015) may be underestimated because the SST is fixed, and the external forcing is constrained by the lateral boundary condition in the limited-area model they used.

Compared with the summer monsoon, anthropogenic aerosol effects on the East Asian winter monsoon (EAWM) are rarely investigated. Niu et al. (2010) found that atmospheric aerosols tend to heat the atmosphere and generate a cyclonic circulation anomaly over eastern-central China during winter. By analyzing meteorological observations during holidays, J. Zhang et al. (2018) reported that following a significant reduction in air pollution, there tends to be anomalous cyclonic circulation over East Asia-northwestern Pacific. On holidays, the precipitation frequency and intensity, both tightly linked to the anomalous cyclone, decreased over southern China.

Jiang, Yang, et al. (2017) proposed a new mechanism responsible for anthropogenic aerosol effects on the EAWM, as illustrated in Figure 6. They found that BC-induced TP warming tends to intensify the northern mode of the EAWM (cooling in northern East Asia) by jet stream acceleration around 40°N and by the westward shifting of the East Asian major trough. Two positive feedback are underlined: the snow-albedo feedback over the TP and the transient eddy-mean flow feedback in the midlatitudes. Liu et al. (2017) investigated the dual effects of the EAWM on haze-fog variations in eastern China.

Aerosol concentrations are also strongly modulated by monsoon circulation through surface winds, rain scavenging, and stratification stability (Chen & Wang, 2015; Jeong & Park, 2017; Jia et al., 2018; Liu, Sheng, et al., 2017; Zhang et al., 2016). In summer, haze-fog events are related to the monsoon-induced changes in air flow transport and moisture convergence over eastern China (Liu, Sheng, et al., 2017; Wu et al., 2016). On a decadal time scale, a negative correlation between the summer monsoon strength and the aerosol pollution level in the Yangtze River valley was reported. The upper level westerlies and jets may impact the boundary layer pollutant concentration by dynamically modulating kinetic momentum and vertical motion (Chen & Wang, 2015; Zhang, Zhang, et al., 2016). Warmer tropical SSTs during El Niño–Southern Oscillation events lead to an anomalous anticyclonic circulation over the western Pacific. Discernable aerosol feedback in observations are reported. In northern China, the aerosol-wind covariation, which tends to strengthen air pollution, is observed in case studies (Yang, Fan, Leung, et al., 2016). The

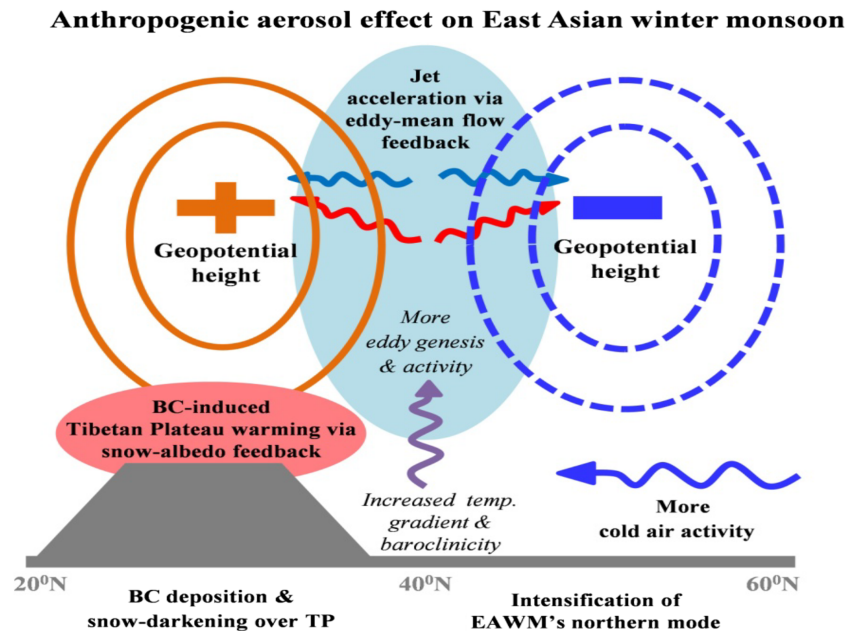


Figure 6. Schematic diagram of the role of anthropogenic black-carbon-induced Tibetan Plateau warming in the intensification of the East Asian winter monsoon's northern mode. Adopted from Jiang et al. (2017).

significant weakening of surface wind over eastern China during the past decades is likely related to the heavy air pollution there because such negative trends in wind speed cannot be found at mountain stations (X. Yang et al., 2013). The decrease in surface wind speeds over Asia may reduce dust aerosol emissions.

5.3. Impact of Combined Land Cover Change and Aerosols on Urban Climate

Urbanization is a worldwide trend that usually has two concurrent anthropogenic effects: (1) land cover change (e.g., Figure 7) and the associated urban heat island effect (UHI) and (2) air pollution or the urban aerosol effect. Zhong et al. (2015) conducted ensemble simulations with one-way three nested domains for the Greater Beijing Metropolitan Area using the WRF-Chem model coupled with a single-layer urban canopy



Figure 7. This nighttime image, taken by astronauts on the International Space Station, reveals the dramatic land development over one area of northeastern China. Research shows that large urban areas such as these can have dramatic impacts on regional weather and climate. Photo courtesy of the NASA Earth Observatory.

model. The model spatial resolution in the innermost domain is 4 km, which can resolve most clouds and partly considers cloud-aerosol interactions. Four sets of sensitivity experiments were performed to quantify the relative importance of UHI, ARI, and ACI. High-resolution urban area data were updated from NASA satellite nighttime light products. Their results show that ACI plays a dominant role in the region by modifying the rainfall pattern as aerosol particles suppress convection and rainfall in the upwind area and increase convection and rainfall in the downwind area. The findings from this study were derived from a single case study. The influence of aerosols on precipitation may be dependent on the environmental conditions of the atmosphere, such as cloud height and phase, and the geographical locations of cities. Further investigations are needed to gain an in-depth understanding of the impact of elevated aerosol concentrations on clouds and precipitation in other cases or other metropolitan areas with different weather conditions (Zhong et al., 2017). A relatively long-term simulation is also needed to understand and quantify the roles of both land-cover change and aerosols in modifying regional climate and air quality (Zhong et al., 2018) for various synoptic systems.

5.4. Impact of Dust Aerosols on Climate

Besides anthropogenic aerosols, natural aerosols like dust, which could be contaminated anthropogenically, can also have a significant impact on

climate. The Taklimakan desert is one of the largest global sources of atmospheric dust. Ge et al. (2014) combined data from the Multi-angle Imaging Spectroradiometer (MISR) and the CALIOP to investigate the three-dimensional distribution of dust over the Taklimakan desert and surrounding areas. They found that the dust extinction coefficient rapidly decreases in the vertical in the spring, while dust particles are relatively well mixed vertically in the summer. Using the daily AOD products from MISR and comparing low- and high-dust days, they also identified two meteorological conditions favorable for entrainment of dust from the dry desert surface: vertical lofting and horizontal transport, that is, a strong anticyclonic wind anomaly over the Taklimakan desert at 500 hPa and an enhanced easterly wind over the Tarim Basin at 850 hPa.

Huang et al. (2014) summarize the typical transport paths of East Asian dust, which affects regional and global climates, and discuss the numerous effects of dust aerosols on clouds and precipitation primarily over East Asian arid and semiarid regions. Compared with Saharan dust, East Asian dust absorbs more solar radiation, and its direct radiative forcing at the TOA is nearly positive or nil. This means that East Asian dust can influence cloud properties by not only acting as CCN and IN (via the first indirect, second indirect, and invigoration effects) but also through changing the relative humidity and stability of the atmosphere (via the semidirect effect). By converting visible light to thermal energy, dust aerosols can burn off cloud droplets, incurring a warming effect on climate, which is opposite to the first and second indirect effects of aerosols. The net dust aerosol radiative effects are still unclear. In addition, dust can inhibit or enhance precipitation under certain conditions, thus impacting the hydrological cycle. Over Asian arid and semiarid regions, the positive feedback loop in CAPI may aggravate drought in its interior.

Su and Fung (2015) studied the sensitivities of the WRF-Chem to the Air Force Weather Agency (AFWA) and Shao et al. (2011) (i.e., S11) dust emission schemes, and to various land surface properties generated from United States Geological Survey (USGS) and Beijing Normal University (BNU) soil data over East Asia for spring 2012. The dust emissions generated with the S11 scheme are 2–5 times that generated with the AFWA emission scheme, with emissions ranging from 0.2 to 1 T_g/day over East Asia during the study period. The AFWA emission scheme omits almost all of the Gobi desert and produces low dust emissions, whereas large dust emissions in this region are produced with the S11 emission scheme regardless of whether USGS or BNU soil data are used. The discrepancy between the performances of the AFWA and S11 emission schemes is mainly due to the underestimation of dust emissions over the Gobi desert by the AFWA scheme, which directly scales dust emissions based on the erodibility factor. This suggests that the erodibility factor for the Gobi desert is highly underestimated, highlighting an urgent need to improve the erodibility data set.

6. Concluding Remarks, Problems, and Future Directions

The changes in atmospheric composition, most notably the emissions of greenhouse gases and aerosols, have a significant impact on the climate system. Due to health concerns, the general public has increasingly paid more attention to severe pollution episodes and the degradation of air quality. Of importance is the strong coupling between the atmospheric environment and the climate system. Aerosols generally have a cooling effect, offsetting some of the warming induced by greenhouse gases. The former plays a much more complex role in the Earth's climate than does the latter. Radiative forcing by aerosols remains the largest source of uncertainties in simulating and predicting Earth's climate. To tackle this problem, studying the aerosol effects on climate in regions of the world characterized by heavy loadings of aerosols with diverse properties is critical. East Asia, especially China, is an ideal region for this effort. Three serial special sections focused on East Asian aerosols (Li et al., 2007, 2011, and the current special section) in the *Journal of Geophysical Research: Atmospheres* attest to this.

The papers collected in this special section represent some recent progress on aerosols and their impacts on clouds, precipitation, and climate through aerosol-radiation interactions and aerosol-cloud interactions in the region. Understanding the mechanisms and identifying and quantifying the impacts are the main thrusts for the current special section, which involves two major topics, that is, the formation of aerosol particles and CAPI. Understanding and accounting for CAPI in the context of the complex Asian climate system involves the coupling of emissions, atmospheric physics and chemistry, and the dynamics of the Asian monsoon climate system. Many painstaking efforts have been devoted to untangling CAPI from a wide range of factors,

leading to the identification and quantification of the roles of aerosols in changing surface temperature, clouds, precipitation, and monsoon circulation, among other factors. CAPI is found to be strongly contingent upon environmental conditions, that is, wind shear, stability, and humidity. Studies in this special section have revealed a wide range of climatic effects induced by aerosols through analyses of observational data acquired from both long-term meteorological observatories and short-term field experiments, and simulations by a hierarchy of models from cloud-resolving to global climate models.

Much effort has been made toward pollution abatement in China to improve air quality. As far as the aerosol direct radiative forcing is concerned, the improvement in air quality has tended to exacerbate the warming trend as the cooling effect of aerosols yields to global warming. During the twenty-first century, a higher frequency of hot summer days may ensue with accompanying changes in precipitation frequency and intensity, although the rainfall changes are much more uncertain than the temperature changes. As the rainfall variability increases, however, floods and prolonged droughts may increase. This would have a tremendous impact on properties and lives and on some critical sectors such as agriculture. Understanding the causes of these change and any connections between them are among the high priorities of environmental and climate sciences.

Uncertainties, Challenges, and Suggestions for Future Studies

Despite the tremendous progress made in our understanding of Asian aerosols and their climate effects, especially on clouds and precipitation, there still exist many uncertainties and challenges, from the observation of key variables to the better understanding of the complex CAPI processes. Understanding the true impact of aerosols on regional climate requires more thorough investigations as outlined here.

To make a leap in our understanding of CAPI and their broad impact on regional climate, it is important to obtain concurrent measurements of aerosol optical, physical, and chemical properties, CCN, cloud microphysical and dynamic properties, and their vertical profiles over a range of temporal and spatial scales. Aerosol properties have large spatiotemporal differences across Asia. With the dramatic development of industrialization and urbanization, aerosol emissions and properties have been changing quickly during the past 50 years in the region, which will continue in the foreseeable future. It is thus essential to build and maintain long-term observational networks for monitoring the spatiotemporal variation trends/patterns of aerosol optical properties, physical characteristics, chemical compositions, and aerosol gaseous precursors, as well as vertical distributions of aerosol and meteorological elements (e.g., Xin et al., 2015).

Major challenges in studying aerosol radiative effects are, among others, observing aerosol chemical compositions, which determines aerosol absorption, and water uptake, which modifies aerosol scattering. Measurements of aerosol size distributions are relatively easy to acquire. Changes in aerosol optical properties further make the quantification of aerosol radiative effects challenging. The response of air temperature to aerosol radiative effects is further complicated by the vertical distribution of aerosols, which is hard to measure. Air temperature is also affected by highly uncertain ACI. Elaborately designed field campaigns and numerical experiments are needed to identify the temperature changes caused by a specific type of aerosol and interaction mechanism. A key issue is to effectively distinguish the temperature response from the noisy, natural synoptic variability.

CCN and INP are essential to understanding CAPI. Despite the significant accomplishments achieved in studies regarding CCN, long-term measurements at more sites are needed to obtain more in situ CCN measurements and aerosol parameters used to estimate CCN in different atmospheric environments. This is because the ability for aerosols to serve as CCN and cloud droplets can vary greatly among regions with different atmospheric environments. For example, Fan, Liu, et al. (2018) have shown that ultrafine particles with diameters smaller than 50 nm can also serve as CCN in the Amazon region where the supersaturation is sometimes high enough to activate these very small particles, something once considered impossible to do. Currently, there is no single model that can predict CCN well under all environments. Models tend to underestimate the observed aerosol particle and CCN number concentrations (Fanourgakis et al., 2019). INP measurements in China are even less than CCN. A recent study indicated that anthropogenic aerosols in China may have enhanced ice formation by serving as INP and impacted cloud lifetime and radiative forcing (B. Zhao et al., 2019).

For any CAPI study, it is essential and most challenging to differentiate CAPI from other effects that are not physically related to aerosols but may covary with them (J. Fan et al., 2016; Li, Liu, et al., 2017; W. K. Tao et al., 2012). Separating the microphysical effects of aerosols from the dynamic effects of the atmosphere and surface is a general bottleneck, making the influence of aerosols on cloud properties particularly uncertain. Satellite-based retrievals of AOD have been widely used to study the influence of aerosols on clouds, but they have some inherent limitations such as large errors in estimating CCN from AOD (Andreae, 2009; Liu & Li, 2014). Comprehensive studies based on data from multiple platforms (surface, aircraft, and satellite; e.g., Liu et al., 2016) and model simulations are critically needed to investigate and differentiate the influences of various factors (e.g., CCN/INP, meteorology, swelling effects) for different types of aerosols and cloud regimes. Neglecting aerosol chemical composition and the ensuing swelling effect can lead to systematic biases in the estimate of ACI (Liu & Li, 2018b).

A possibility for disentangling meteorology and aerosol impacts on clouds is emerging with recently developed methodologies for retrieving cloud droplet number concentrations (Rosenfeld et al., 2014) and updrafts at the base of clouds (Zheng et al., 2015, 2016) from satellite observations. Having both cloud-base droplet number concentrations and updrafts allows calculating the cloud-base maximum supersaturation (S_{\max}). This has made it possible to retrieve CCN(S) from satellites (Rosenfeld et al., 2016). By applying the CCN and updraft retrievals over oceans, it is possible to disentangle the effects of aerosols and meteorology there (Rosenfeld et al., 2019). Application of these methodologies with additional in situ validation over both land and oceans has the best potential for advancement, especially at climate-relevant scales in space and time.

The advent of new-generation geostationary meteorological satellite makes it possible to identify the life cycle of clouds in Asian monsoon regions (Chen et al., 2019). This may lead to a major leap in our understanding of the aerosol impact on cloud lifetimes, which is the least understood aerosol-cloud-interaction process. More importantly, clouds in the initial stage (cumulus stage) are more susceptible to aerosol pollution in the PBL, largely due to the coupling of the land surface and the atmosphere (Houze, 2018). As such, one of the top priorities of future CAPI studies should be the identification of the status of coupling between clouds and the boundary layer, as done by Zheng et al. (2018), as well as unraveling how clouds in the initial or developing stage respond to aerosols, which makes more sense compared with the bulk cloud responses.

There are still large uncertainties in modeling studies of the impact of aerosols on the monsoon climate, although much progress has been made in recent years (Li et al., 2016). Current global climate models overestimate the indirect effect of aerosols, especially in highly polluted monsoon regions (e.g., East Asia and South Asia), which needs further examination using improved climate models and aerosol emission data sets. Furthermore, most current modeling studies are based on simulations with prescribed SSTs, where the slow response to aerosol forcing associated with SST changes is not considered. Fully coupled simulations are needed to include the air-sea coupling and feedback. To better understand the responses of the Asian monsoon climate to anthropogenic aerosols, the forcing-feedback paradigm needs to be accounted for in future investigations (Sherwood et al., 2014).

In Asia, there are some unique problems to tackle. First, aerosols are particularly inhomogeneous spatially, which may cause significant changes in precipitation by generating local circulations and associated changes in the spatiotemporal distributions of convective cells. It is necessary to account for interactions between aerosol advection and convective-cloud and precipitation processes in the process-level understanding of the effects of aerosol inhomogeneity on convective clouds and precipitation (W. K. Tao et al., 2012). High dust aerosol concentrations over East Asia lead to substantial effects on the energy budget and climate change through its interactions with clouds, radiation, and precipitation, a key process dictating the climate of semiarid regions in central Asia (Huang et al., 2017). However, the overall climatic effects of dust are still highly uncertain, particularly in its ice-nucleating effect. More investigations on dust transport, size distribution, wavelength-dependent dust refractive index, and droplet and ice nucleating capabilities are crucially needed to account for their impact on the Asian climate.

Appendix A.: List of Acronyms

ACI Aerosol-cloud interactions

ADR Aerosol direct radiative

AFWA Air Force Weather Agency
 AOD Aerosol optical depth
 ARI Aerosol-radiation interactions
 BB Biomass
 BC Black carbon
 BLH Boundary layer height
 BNU Beijing Normal University
 CALIOP Cloud–Aerosol Lidar with Orthogonal Polarization
 CALIPSO Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
 CAM5 Community Atmosphere Model
 CAPE Convective available potential energy
 CAPI Cloud-aerosol-precipitation interactions
 CARSNET China Aerosol Remote Sensing Network
 CCN Cloud condensation nuclei
 CFC cloud fraction
 COD Cloud optical depth
 DB Deep Blue
 DCC Deep convective cloud
 DTR Diurnal temperature range
 EAM East Asian monsoon
 EASM East Asian summer monsoon
 EAST-AIRC East Asian Studies of Tropospheric Aerosols and their Impact on Regional Climate
 EAST-AIR_{CPC} East Asian Study of Tropospheric Aerosols and their Impact on Regional
 Clouds, Precipitation, and Climate
 EAST-AIRE East Asian Study of Tropospheric Aerosols: an International Regional Experiment
 EAWM East Asian winter monsoon
 FIE First indirect effect
 IN Ice nuclei
 IPCC *Intergovernmental Panel on Climate Change*
 LWP Liquid water path
 MCS Mesoscale convective system
 MISR Multi-angle Imaging Spectroradiometer
 MODIS Moderate Resolution Imaging Spectroradiometer
 MPL Micropulse lidar
 NCAR *National Center for Atmospheric Research*
 N_{CCN} Number of CCN
 NCP North China Plain
 NPF New particle formation
 OA Organic aerosols
 PBL Planetary boundary layer

PM_{2.5} Particulate matter with diameters less than 2.5 μm
 POM Primary organic matter
 SST Sea surface temperature
 T_g Glaciation temperature
 TOA Top of the atmosphere
 TP Tibetan Plateau
 UAP Ultrafine aerosol particles
 UHI Urban heat island
 USGS United States Geological Survey
 WRF Weather Research and Forecasting model
 WRF-Chem Weather Research and Forecasting model coupled with chemistry
 YRD Yangtze River Delta

Acknowledgments

Acknowledgements The work reported here has been supported by a large number of grants that have been acknowledged in the cited references particularly. Listed here are those in support of a few authors who contributed most to this paper per se: the National Natural Science Foundation of China (91544217), the Ministry of Science and Technology of China (2017YFC1501702, 2017YFC1501401, 2013CB955804), the U.S. National Science Foundation (AGS1837811, 1700727), and the U.S. Department of Energy (DE-SC0018996, DE-AC05-76RL01830) and NASA (NNX16AN61G). J. Fan acknowledges the support of U.S. Department of Energy Office of Science Early Career Award Program.

References

- Ackerman, A. S., Toon, O. B., Taylor, J. P., Johnson, D. W., Hobbs, P. V., & Ferek, R. J. (2000). Effects of aerosols on cloud albedo: Evaluation of Twomey's parameterization of cloud susceptibility using measurements of ship tracks. *Journal of the Atmospheric Sciences*, *57*, 2684–2695. [https://doi.org/10.1175/1520-0469\(2000\)057<2684:EOAOCA>2.0.CO;2](https://doi.org/10.1175/1520-0469(2000)057<2684:EOAOCA>2.0.CO;2)
- An, Z., Huang, R. J., Zhang, R., Tie, X., Li, G., Cao, J., et al. (2019). Severe haze in Northern China: A synergy of anthropogenic emissions and atmospheric processes. *Proc. Natl. Acad. Sci. USA*, *116*(18), 8657–8666. <https://doi.org/10.1073/pnas.1900125116>
- An, Z., Wu, G., Li, J., Sun, Y., Liu, Y., Zhou, W., et al. (2015). Global monsoon dynamics and climate change. *Annual Review of Earth and Planetary Sciences*, *43*, 29–77. <https://doi.org/10.1146/annurev-earth-060313-054623>
- Andreae, M. O. (2009). Correlation between cloud condensation nuclei concentration and aerosol optical thickness in remote and polluted regions. *Atmospheric Chemistry and Physics*, *9*, 543–556. <https://doi.org/10.5194/acp-9-543-2009>
- Bi, J., Huang, J., Hu, Z., Holben, B. N., & Guo, Z. (2014). Investigating the aerosol optical and radiative characteristics of heavy haze episodes in Beijing during January of 2013. *Journal of Geophysical Research: Atmospheres*, *119*, 9884–9900. <https://doi.org/10.1002/2014JD021757>
- Braga, R. C., Rosenfeld, D., Weigel, R., Jurkat, T., Andreae, M. O., Wendisch, M., et al. (2017). Further evidence for CCN aerosol concentrations determining the height of warm rain and ice initiation in convective clouds over the Amazon basin. *Atmospheric Chemistry and Physics*, *17*, 14,433–14,456. <https://doi.org/10.5194/acp-17-14433-2017>
- Brook, R. D., Rajagopalan, S., Pope, C. A. III, Brook, J. R., Bhatnagar, A., Diez-Roux, A. V., et al., & American Heart Association Council on Epidemiology and Prevention, Council on the Kidney in Cardiovascular Disease, and Council on Nutrition, Physical Activity and Metabolism (2010). Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association. *Circulation*, *121*(21), 2331–2378. <https://doi.org/10.1161/CIR.0b013e3181d8e1>
- Chen, D., Guo, J., Yao, D., Lin, Y., Zhao, C., Min, M., et al. (2019). Mesoscale convective systems in East Asia from Advanced Himawari Imager: Algorithms and preliminary results. *Journal of Geophysical Research: Atmospheres*, *124*, 2210–2234. <https://doi.org/10.1029/2018JD029707>
- Chen, H., & Wang, H. (2015). Haze days in North China and the associated atmospheric circulations based on daily visibility data from 1960 to 2012. *Journal of Geophysical Research: Atmospheres*, *120*, 5895–5909. <https://doi.org/10.1002/2015JD023225>
- Chen, J., Chen, I., & Tsai, I. (2016). Dynamic feedback of aerosol effects on the East Asian summer monsoon. *Journal of Climate*, *29*(17), 6137–6149. <https://doi.org/10.1175/JCLI-D-15-0758.1>
- Chen, J., Li, Z., Lv, M., Wang, Y., Wang, W., Zhang, Y., et al. (2019). Aerosol hygroscopic growth, contributing factors and impact on haze events in a severely polluted region in northern China. *Atmospheric Chemistry and Physics*, *19*, 1–16. <https://doi.org/10.5194/acp-19-1-2019>
- Chen, Q., Fan, J., Hagos, S., Gustafson, W. I., & Berg, L. K. (2015). Roles of wind shear at different vertical levels: cloud system organization and properties. *Journal of Geophysical Research: Atmospheres*, *120*, 6551–6574. <https://doi.org/10.1002/2015JD023253>
- Chen, S., Huang, J., Qian, Y., Zhao, C., Kang, L., Yang, B., et al. (2017). An overview of mineral dust modeling over East Asia. *Journal of Meteorological Research*, *31*, 633–653. <https://doi.org/10.1007/s13351-017-6142-2>
- Chen, T., Guo, J., Li, Z., Zhao, C., Liu, H., Cribb, M., et al. (2016). A CloudSat perspective on the cloud climatology and its association with aerosol perturbation in the vertical over East China. *Journal of the Atmospheric Sciences*, *73*, 3599–3616. <https://doi.org/10.1175/JAS-D-15-0309.1>
- Coddington, O. M., Pilewskie, P., Redemann, J., Platnick, S., Russell, P. B., Schmidt, K. S., et al. (2010). Examining the impact of overlying aerosols on the retrieval of cloud optical properties from passive remote sensing. *Journal of Geophysical Research*, *115*, D10211. <https://doi.org/10.1029/2009JD012829>
- Dai, L., Wang, H., Zhou, L., An, J., Tang, L., Lu, C., et al. (2017). Regional and local new particle formation events observed in the Yangtze River Delta region, China. *Journal of Geophysical Research: Atmospheres*, *122*, 2389–2402. <https://doi.org/10.1002/2016JD026030>
- Day, J. A., Fung, I., & Liu, W. (2018). Changing character of rainfall in eastern China, 1951–2007. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 2016–2021. <https://doi.org/10.1073/pnas.1715386115>
- Deng, J., Xu, H., Ma, H., & Jiang, Z. (2014). Numerical study of the effect of anthropogenic aerosols on spring persistent rain over Eastern China. *Journal of Meteorological Research: Atmospheres*, *28*(3), 341–353. <https://doi.org/10.1007/s13351-014-3198-0>
- Ding, Y. H., Liu, Y., Song, Y., & Zhang, J. (2015). From MONEX to the global monsoon: a review of monsoon system research. *Advances in Atmospheric Sciences*, *32*(1), 10–31. <https://doi.org/10.1007/s00376-014-0008-7>

- Ding, Y. H., Ren, G., Zhao, Z., Xu, Y., Luo, Y., Li, Q., & Zhang, J. (2007). Detection, causes and projection of climate change over China: an overview of recent progress. *Advances in Atmospheric Sciences*, *24*, 954–971. <https://doi.org/10.1007/s00376-007-0954-4>
- Dong, W., Lin, Y., Wright, J. S., Xie, Y., Ming, Y., Zhang, H., et al. (2018). Regional disparities in warm season rainfall changes over arid eastern–central Asia. *Scientific Reports*, *8*(1), 13051. <https://doi.org/10.1038/s41598-018-31246-3>
- Dong, X., Minnis, P., Mace, G. G., Smith Jr, W. L., Poellot, M., Marchand, R., & Rapp, A. (2002). Comparison of stratus cloud properties deduced from surface, GOES, and aircraft data during the March 2000 ARM Cloud IOP. *Journal of Atmospheric Sciences*, *59*, 3265–3284. [https://doi.org/10.1175/1520-0469\(2002\)059<3265:COSCPD>2.0.CO;2](https://doi.org/10.1175/1520-0469(2002)059<3265:COSCPD>2.0.CO;2)
- Dong, X., Minnis, P., Xi, B., Sun-Mack, S., & Chen, Y. (2008). Validation of CERES-MODIS stratus cloud properties using ground-based measurements at the DOE ARM SGP site. *Journal of Geophysical Research*, *113*, D03204. <https://doi.org/10.1029/2007JD008438>
- Fan, J., Leung, L. R., DeMott, P. J., Comstock, J. M., Singh, B., Rosenfeld, D., et al. (2014). Aerosol impacts on California winter clouds and precipitation during CalWater 2011: local pollution versus long-range transported dust. *Atmospheric Chemistry and Physics*, *14*, 81–101. <https://doi.org/10.5194/acp-14-81-2014>
- Fan, J., Leung, L. R., Li, Z., Morrison, H., Chen, H., Zhou, Y., et al. (2012). Aerosol impacts on clouds and precipitation in eastern China: results from bin and bulk microphysics. *Journal of Geophysical Research*, *117*, D00K36. <https://doi.org/10.1029/2011JD016537>
- Fan, J., Leung, L. R., Rosenfeld, D., Chen, Q., Li, Z., Zhang, J., & Yan, H. (2013). Microphysical effects determine macrophysical response for aerosol impacts on deep convective clouds. *Proceedings from the National Academy of Science of the United States of America*, *110*, 581–590. <https://doi.org/10.1073/pnas.1316830110>
- Fan, J., Leung, L. R., Rosenfeld, D., & DeMott, P. J. (2017). Effects of cloud condensation nuclei and ice nucleating particles on precipitation processes and supercooled liquid in mixed-phase orographic clouds. *Atmospheric Chemistry and Physics*, *17*, 1017–1035. <https://doi.org/10.5194/acp-17-1017-2017>
- Fan, J., Rosenfeld, D., Yang, Y., Zhao, C., Leung, L. R., & Li, Z. (2015). Substantial contribution of anthropogenic air pollution to catastrophic floods in southwest China. *Geophysical Research Letters*, *42*, 6066–6075. <https://doi.org/10.1002/2015GL064479>
- Fan, J., Rosenfeld, D., Zhang, Y., Giangrande, S. E., Li, Z., Machado, L. A. T., et al. (2018). Substantial convection and precipitation enhancements by ultrafine aerosol particles. *Science*, *359*(6374), 411–418. <https://doi.org/10.1126/science.aan8461>
- Fan, J., Wang, Y., Rosenfeld, D., & Liu, X. (2016). Review of aerosol-cloud interactions: mechanisms, significance and challenges. *Journal of Atmospheric Sciences*, *73*, 4221–4252. <https://doi.org/10.1175/JAS-D-16-0037.1>
- Fan, T., Liu, X., Ma, P. L., Zhang, Q., Li, Z., Jiang, Y., et al. (2018). Emission or atmospheric processes? An attempt to attribute the source of large bias of aerosols in eastern China simulated by global climate models. *Atmospheric Chemistry and Physics*, *18*(2), 1395–1417. <https://doi.org/10.5194/acp-18-1395-2018>
- Fanourgakis, G. S., Kanakidou, M., Nenes, A., Bauer, S. E., Bergman, T., Carslaw, K. S., et al. (2019). Evaluation of global simulations of aerosol particle and cloud condensation nuclei number, with implications for cloud droplet formation. *Atmospheric Chemistry and Physics Discussions*, *19*, 8591–8617. <https://doi.org/10.5194/acp-19-8591-2019>
- Feingold, G. (2003). First measurements of the Twomey indirect effect using ground based remote sensors. *Geophysical Research Letters*, *30*(6), 1287. <https://doi.org/10.1029/2002GL016633>
- Feingold, G., Furrer, R., Pilewskie, P., Remer, L. A., Min, Q. L., & Jonsson, H. (2006). Aerosol indirect effect studies at Southern Great Plains during the May 2003 Intensive Operations Period. *Journal of Geophysical Research*, *111*, D05S14. <https://doi.org/10.1029/2004JD005648>
- Freud, E., & Rosenfeld, D. (2012). Linear relation between convective cloud drop number concentration and depth for rain initiation. *Journal of Geophysical Research*, *117*, D02207. <https://doi.org/10.1029/2011JD016457>
- Ge, J. M., Huang, J. P., Xu, C. P., Qi, Y. L., & Liu, H. Y. (2014). Characteristics of Taklimakan dust emission and distribution: a satellite and reanalysis field perspective. *Journal of Geophysical Research: Atmospheres*, *119*, 11,772–11,783. <https://doi.org/10.1002/2014JD022280>
- Givati, A., & Rosenfeld, D. (2004). Quantifying precipitation suppression due to air pollution. *Journal of Applied Meteorology*, *43*, 1038–1056. [https://doi.org/10.1175/1520-0450\(2004\)043<1038:QPSDTA>2.0.CO;2](https://doi.org/10.1175/1520-0450(2004)043<1038:QPSDTA>2.0.CO;2)
- Gong, D., Wang, W., Qian, Y., Bai, W., Guo, Y., & Mao, R. (2014). Observed holiday aerosol reduction and temperature cooling over East Asia. *Journal of Geophysical Research: Atmospheres*, *119*, 6306–6324. <https://doi.org/10.1002/2014JD021464>
- Goodman, A. H., & Henderson-Sellers, A. (1988). Cloud detection and analysis: a review of recent progress. *Atmospheric Research*, *21*, 203–228. [https://doi.org/10.1016/0169-8095\(88\)90027-0](https://doi.org/10.1016/0169-8095(88)90027-0)
- Guo, D., Gao, Y. Q., Bethke, I., Gong, D. Y., Johannessen, O. M., & Wang, H. J. (2014). Mechanism on how the spring Arctic sea ice impacts the East Asian summer monsoon. *Theoretical and Applied Climatology*, *115*, 107–119. <https://doi.org/10.1007/s00704-013-0872-6>
- Guo, J., Deng, M., Fan, J., Li, Z., Chen, Q., Zhai, P., et al. (2014). Precipitation and air pollution at mountain and plain stations in northern China: insights gained from observations and modeling. *Journal of Geophysical Research: Atmospheres*, *119*, 4793–4807. <https://doi.org/10.1002/2013JD021161>
- Guo, J., Deng, M., Lee, S. S., Wang, F., Li, Z., Zhai, P., et al. (2016). Delaying precipitation and lightning by air pollution over the Pearl River Delta. Part I: Observational analyses. *Journal of Geophysical Research: Atmospheres*, *121*, 6472–6488. <https://doi.org/10.1002/2015JD023257>
- Guo, J., He, J., Liu, H. L., Miao, Y., Liu, H., & Zhai, P. (2016). Impact of various emission control schemes on air quality using WRF-Chem during APEC China 2014. *Atmospheric Environment*, *140*, 311–319. <https://doi.org/10.1016/j.atmosenv.2016.05.046.s>
- Guo, J., Li, Y., Cohen, J., Li, J., Chen, D., Xu, H., et al. (2019). Shift in the temporal trend of boundary layer height trend in China using long-term (1979–2016) radiosonde data. *Geophysical Research Letters*, *46*(11), 6080–6089. <https://doi.org/10.1029/2019GL082666>
- Guo, J., Liu, H., Li, Z., Rosenfeld, D., Jiang, M., Xu, W., et al. (2018). Aerosol-induced changes in the vertical structure of precipitation: a perspective of TRMM precipitation radar. *Atmospheric Chemistry and Physics*, *18*(18), 13,329–13,343. <https://doi.org/10.5194/acp-2018-366>
- Guo, J., Su, T., Li, Z., Miao, Y., Li, J., Liu, H., et al. (2017). Declining frequency of summertime local-scale precipitation over eastern China from 1970 to 2010 and its potential link to aerosols. *Geophysical Research Letters*, *44*, 5700–5708. <https://doi.org/10.1002/2017GL073533>
- Guo, J., Zhang, X., Che, H., Gong, S., An, X., Cao, C., et al. (2009). Correlation between PM concentrations and aerosol optical depth in eastern China. *Atmospheric Environment*, *43*, 5876–5886. <https://doi.org/10.1016/j.atmosenv.2009.08.026>
- Guo, L., Highwood, E. J., Shaffrey, L. C., & Turner, A. G. (2013). The effect of regional changes in anthropogenic aerosols on rainfall of the East Asian Summer Monsoon. *Atmospheric Chemistry and Physics*, *13*(3), 1521–1534. <https://doi.org/10.5194/acp-13-1521-2013>
- Guo, S., Hu, M., Zamora, M. L., Peng, J., Shang, D., Zheng, J., et al. (2014). Elucidating severe urban haze formation in China. *Proceedings from the National Academy of Science of the United States of America*, *111*(17), 17373–17378. <https://doi.org/10.1073/pnas.1419604111>
- Hallett, J., & Mossop, S. C. (1974). Production of secondary ice particles during the riming process. *Nature*, *249*, 26–28. <https://doi.org/10.1038/249026a0>

- He, J., Zhang, Y., Wang, K., Chen, Y., Leung, L. R., Fan, J., et al. (2017). Multi-year application of WRF-CAM5 over East Asia. Part I: Comprehensive evaluation and formation regimes of O₃ and PM_{2.5}. *Atmospheric Environment*, *165*, 122–142. <https://doi.org/10.1016/j.atmosenv.2017.06.015>
- Houze Jr, R. A. (2018). 100 years of research on mesoscale convective systems. *Meteorological Monographs*, *59*, 17–1. <https://doi.org/https://doi.org/10.1175/AMSMONOGRAPHIS-D-18-0001.1>
- Hu, N., & Liu, X. (2013). Modeling study of the effect of anthropogenic aerosols on late spring drought in South China. *Acta Meteorologica Sinica*, *27*(5), 701–715. <https://doi.org/10.1007/s13351-013-0506-z>
- Huang, J., Guo, J., Wang, F., Liu, Z., Jeong, M.-J., Yu, H., & Zhang, Z. (2015). CALIPSO inferred most probable heights of global dust and smoke layers. *Journal of Geophysical Research: Atmospheres*, *120*, 5085–5100. <https://doi.org/10.1002/2014JD022898>
- Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A., et al. (2017). Dryland climate change: recent progress and challenges. *Reviews of Geophysics*, *55*, 719–778. <https://doi.org/10.1002/2016RG000550>
- Huang, J., Wang, T., Wang, W., Li, Z., & Yan, H. (2014). Climate effects of dust aerosols over East Asian arid and semiarid regions. *Journal of Geophysical Research: Atmospheres*, *119*, 11,398–11,416. <https://doi.org/10.1002/2014JD021796>
- Intergovernmental Panel on Climate Change (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, pp. 1535. Cambridge Univ. Press, Cambridge, U.K., and New York. [https://doi.org/10.1016/S0925-7721\(01\)00003-7](https://doi.org/10.1016/S0925-7721(01)00003-7)
- Jeong, J. I., & Park, R. J. (2017). Winter monsoon variability and its impact on aerosol concentrations in East Asia. *Environmental Pollution*, *221*, 285–292. <https://doi.org/10.1016/j.envpol.2016.11.075>
- Jia, R., Liu, Y., Hua, S., Zhu, Q., & Shao, T. (2018). Estimation of the aerosol radiative effect over the Tibetan Plateau based on the latest CALIPSO product. *Journal of Meteorological Research*, *32*(5), 707–722. <https://doi.org/10.1007/s13351-018-8060-3>
- Jiang, M., Feng, J., Li, Z., Sun, R., Hou, Y. T., Zhu, Y., et al. (2017). Potential influences of neglecting aerosol effects on the NCEP GFS precipitation forecast. *Atmospheric Chemistry and Physics*, *17*(22), 13,967–13,982. <https://doi.org/10.5194/acp-17-13967-2017>
- Jiang, M., Li, Z., Wan, B., & Cribb, M. C. (2016). Impact of aerosols on precipitation from deep convective clouds in eastern China. *Journal of Geophysical Research: Atmospheres*, *121*, 9607–9620. <https://doi.org/10.1002/2015JD024246>
- Jiang, Y., Liu, X., Yang, X. Q., & Wang, M. (2013). A numerical study of the effect of different aerosol types on East Asian summer clouds and precipitation. *Atmospheric Environment*, *70*, 51–63. <https://doi.org/10.1016/j.atmosenv.2012.12.039>
- Jiang, Y., Yang, X.-Q., & Liu, X. (2015). Seasonality in anthropogenic aerosol effects on East Asian climate simulated with CAM5. *Journal of Geophysical Research: Atmospheres*, *120*, 10,837–10,861. <https://doi.org/10.1002/2015JD023451>
- Jiang, Y., Yang, X.-Q., Liu, X., Yang, D., Sun, X., Wang, M., et al. (2017). Anthropogenic aerosol effects on East Asian winter monsoon: the role of black carbon-induced Tibetan Plateau warming. *Journal of Geophysical Research: Atmospheres*, *122*, 5883–5902. <https://doi.org/10.1002/2016JD026237>
- Jiang, Z., Huo, F., Ma, H., Song, J., & Dai, A. (2017). Impact of Chinese urbanization and aerosol emissions on the East Asian summer monsoon. *Journal of Climate*, *30*, 1019–1039. <https://doi.org/10.1175/JCLI-D-15-0593.1>
- Kaufman, Y. J., & Koren, I. (2006). Smoke and pollution aerosol effect on cloud cover. *Science*, *313*(5787), 655–658. <https://doi.org/10.1126/science.1126232>
- Kaufman, Y. J., Koren, I., Remer, L. A., Rosenfeld, D., & Rudich, Y. (2005). The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(32), 11207–11212. <https://doi.org/10.1073/pnas.0505191102>
- Kim, B. G., Miller, M. A., Schwartz, S. E., Liu, Y., & Min, Q. (2008). The role of adiabaticity in the aerosol first indirect effect. *Journal of Geophysical Research*, *113*, D05210. <https://doi.org/10.1029/2007jd008961>
- Kong, L., Xin, J., Zhang, W., & Wang, Y. (2016). The empirical correlations between PM_{2.5}, PM₁₀ and AOD in the Beijing metropolitan region and the PM_{2.5}, PM₁₀ distributions retrieved by MODIS. *Environmental Pollution*, *216*, 350–360. <https://doi.org/10.1016/j.envpol.2016.05.085>
- Konwar, M., Maheskumar, R. S., Kulkarni, J. R., Freud, E., Goswami, B. N., & Rosenfeld, D. (2012). Aerosol control on depth of warm rain in convective clouds. *Journal of Geophysical Research*, *117*, D13204. <https://doi.org/10.1029/2012JD017585>
- Koren, I., Kaufman, Y. J., Remer, L. A., & Martins, J. V. (2004). Measurement of the effect of Amazon smoke on inhibition of cloud formation. *Science*, *303*(5662), 1342–1345. <https://doi.org/10.1126/science.1089424>
- Lee, S. S., Guo, J., & Li, Z. (2016). Delaying precipitation and lightning by air pollution over the Pearl River Delta. Part 2: Model simulations. *Journal of Geophysical Research: Atmospheres*, *121*, 11,739–11,760. <https://doi.org/10.1002/2015JD024362>
- Lee, S. S., Kim, B. G., Li, Z., Choi, Y. S., Jung, C. H., Um, J., et al. (2018). Aerosol as a potential factor to control the increasing torrential rain events in urban areas over the last decades. *Atmospheric Chemistry and Physics*, *18*(16), 12,531–12,550. <https://doi.org/10.5194/acp-2018-126>
- Li, G., Wang, Y., & Zhang, R. (2008). Implementation of a two-moment bulk microphysics scheme to the WRF model to investigate aerosol-cloud interaction. *Journal of Geophysical Research*, *113*, D15211. <https://doi.org/10.1029/2007JD009361>
- Li, M., Liu, H., Geng, G., Hong, C., Liu, F., Song, Y., et al. (2017). Anthropogenic emission inventories in China: a review. *National Science Review*, *4*(6), 834–866. <https://doi.org/10.1093/nsr/nwx150>
- Li, X., Ting, M., & Lee, D. E. (2018). Fast adjustments of the Asian summer monsoon to anthropogenic aerosols. *Geophysical Research Letters*, *45*(2), 1001–1010. <https://doi.org/10.1002/2017GL076667>
- Li, Y., Zhang, F., Li, Z., Sun, L., Wang, Z., Li, P., et al. (2017). Influences of aerosol physiochemical properties and new particle formation on CCN activity from observation at a suburban site of China. *Atmospheric Research*, *188*, 80–89. <https://doi.org/10.1016/j.atmosres.2017.01.009>
- Li, Z., Chen, H., Cribb, M. C., Dickerson, R., Holben, B., Li, C., et al. (2007). Preface to special section on East Asian Studies of Tropospheric Aerosols: An International Regional Experiment (EAST-AIRE). *Journal of Geophysical Research*, *112*, D22S00. <https://doi.org/10.1029/2007JD008853>
- Li, Z., Guo, J., Ding, A., Liao, H., Liu, J., Sun, Y., et al. (2017). Aerosol and boundary-layer interactions and impact on air quality. *National Science Review*, *4*(6), 810–833. <https://doi.org/10.1093/nsr/nwx117>
- Li, Z., Lau, W. K.-M., Ramanathan, V., Wu, G., Ding, Y., Manoj, M. G., et al. (2016). Aerosol and monsoon climate interactions over Asia. *Reviews of Geophysics*, *54*, 866–929. <https://doi.org/10.1002/2015RG000500>
- Li, Z., Li, C., Chen, H., Tsay, S.-C., Holben, B., Huang, J., et al. (2011). East Asian Studies of Tropospheric Aerosols and their Impact on Regional Climate (EAST-AIRC): an overview. *Journal of Geophysical Research*, *116*, D00K34. <https://doi.org/10.1029/2010JD015257>
- Li, Z., Rosenfeld, D., & Fan, J. (2017). Aerosols and their impact on radiation, clouds, precipitation, and severe weather events. *Oxford Research Encyclopedia of Environmental Science*. <https://doi.org/10.1093/acrefore/9780199389414.013.126>

- Li, Z., Zhao, F., Liu, J., Jiang, M., Zhao, C., & Cribb, M. C. (2014). Opposite effects of absorbing aerosols on the retrievals of cloud optical depth from spaceborne and ground-based measurements. *Journal of Geophysical Research: Atmospheres*, *119*, 5104–5114. <https://doi.org/10.1002/2013JD021053>
- Lim, K.-S., Fan, J., Leung, L. R., Ma, P.-L., Singh, B., Zhao, C., et al. (2014). Investigation of aerosol indirect effects using a cumulus microphysics parameterization in a regional climate model. *Journal of Geophysical Research: Atmospheres*, *119*, 906–926. <https://doi.org/10.1002/2013JD020958>
- Liu, J., & Li, Z. (2014). Estimation of cloud condensation nuclei concentration from aerosol optical quantities: influential factors and uncertainties. *Atmospheric Chemistry and Physics*, *14*, 471–483. <https://doi.org/10.5194/acp-14-471-2014>
- Liu, J., & Li, Z. (2018a). First surface-based estimation of the aerosol indirect effect over a site in southeastern China. *Advances in Atmospheric Sciences*, *35*(2), 169–181. <https://doi.org/10.1007/s00376-017-7106-2>
- Liu, J., & Li, Z. (2018b). Significant underestimation in the optically based estimation of the aerosol indirect effect induced by the aerosol swelling effect. *Geophysical Research Letters*, *45*(11), 5690–5699. <https://doi.org/10.1029/2018GL077679>
- Liu, J., Li, Z., & Cribb, M. C. (2016). Response of marine boundary layer cloud properties to aerosol perturbations associated with meteorological conditions from the 19-Month AMF-Azores campaign. *Journal of the Atmospheric Sciences*, *73*(11), 4253–4268. <https://doi.org/10.1175/jas-d-15-0364.1>
- Liu, J., Li, Z., Zheng, Y., Chiu, J. C., Zhao, F., Cadetdu, M., et al. (2013). Cloud optical and microphysical properties derived from ground-based and satellite sensors over a site in the Yangtze Delta region. *Journal of Geophysical Research: Atmospheres*, *118*, 1–12. <https://doi.org/10.1002/jgrd.50648>
- Liu, J., Weng, F., & Li, Z. (2019). Satellite-based PM_{2.5} estimation directly from reflectance at the top of the atmosphere using a machine learning algorithm. *Atmospheric Environment*, *208*, 113–122. <https://doi.org/10.1016/j.atmosenv.2019.04.002>
- Liu, L., Guo, J., Chen, W., Wu, R., Wang, L., Gong, H., et al. (2018). Large-scale pattern of the diurnal temperature range changes over East Asia and Australia in boreal winter: a perspective of atmospheric circulation. *Journal of Climate*, *31*(7), 2715–2728. <https://doi.org/10.1175/JCLI-D-17-0608.1>
- Liu, L., Li, Z., Yang, X., Gong, H., Li, C., & Xiong, A. (2016). The long-term trend in the diurnal temperature range over Asia and its natural and anthropogenic causes. *Journal of Geophysical Research: Atmospheres*, *121*, 3519–3533. <https://doi.org/10.1002/2015JD024549>
- Liu, Q., Sheng, L., Cao, Z., Diao, Y., Wang, W., & Zhou, Y. (2017). Dual effects of the winter monsoon on haze-fog variations in eastern China. *Journal of Geophysical Research: Atmospheres*, *122*, 5857–5869. <https://doi.org/10.1002/2016JD026296>
- Liu, X., Chen, Q., Che, H., Zhang, R., Gui, K., Zhang, H., & Zhao, T. (2016). Spatial distribution and temporal variation of aerosol optical depth in the Sichuan basin, China, the recent ten years. *Atmospheric Environment*, *147*, 434–445. <https://doi.org/10.1016/j.atmosenv.2016.10.008>
- Liu, Y. G., Huang, J., Shi, G., Takamura, T., Khatri, P., Bi, J., Shi, J., et al. (2011). Aerosol optical properties and radiative effect determined from sky-radiometer over Loess Plateau of Northwest China. *Atmospheric Chemistry and Physics*, *11*, 11,455–11,463. <https://doi.org/10.5194/acp-11-11455-2011>
- Liu, Y. Q., de Leeuw, G., Kerminen, V.-M., Zhang, J., Zhou, P., Nie, W., et al. (2017). Analysis of aerosol effects on warm clouds over the Yangtze River Delta from multi-sensor satellite observations. *Atmospheric Chemistry and Physics*, *17*, 5623–5641. <https://doi.org/10.5194/acp-17-5623-2017>
- Luo, Y., Lu, D., Zhou, X., & Li, W. (2001). Characteristics of the spatial distribution and yearly variation of aerosol optical depth over China in last 30 years. *Journal of Geophysical Research*, *106*, 14,501–14,513. <https://doi.org/10.1029/2001JD900030>
- Lv, M., Liu, D., Li, Z., Mao, J., Sun, Y., Wang, Z., et al. (2016). Hygroscopic growth of atmospheric aerosol particles based on lidar, radiometer, and in situ measurements: case studies from the Xinzhou field campaign. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *188*, 60–70. <https://doi.org/10.1016/j.jqsrt.2015.12.029>
- Menon, S., Hansen, J., Nazarenko, L., & Luo, Y. (2002). Climate effects of black carbon aerosols in China and India. *Science*, *297*(5590), 2250–2253. <https://doi.org/10.1126/science.1075159>
- Niu, F., & Li, Z. (2012). Systematic variations of cloud top temperature and precipitation rate with aerosols over the global tropics. *Atmospheric Chemistry and Physics*, *12*, 8491–8498. <https://doi.org/10.5194/acp-12-8491-2012>
- Niu, F., Li, Z., Li, C., Lee, K. H., & Wang, M. (2010). Increase of wintertime fog in China: potential impacts of weakening of the Eastern Asian monsoon circulation and increasing aerosol loading. *Journal of Geophysical Research*, *115*, D00K20. <http://doi.org/10.1029/2009JD013484>
- Ovchinnikov, M., Korolev, A., & Fan, J. (2011). Effects of ice number concentration on dynamics of a shallow mixed-phase stratiform cloud. *Journal of Geophysical Research*, *116*, D00T06. <https://doi.org/10.1029/2011JD015888>
- Peng, J., Hu, M., Guo, S., Du, Z., Shang, D., Zheng, J., et al. (2017). Ageing and hygroscopicity variation of black carbon particles in Beijing measured by a quasi-atmospheric aerosol evolution study (QUALITY) chamber. *Atmospheric Chemistry and Physics*, *17*, 10,333–10,348. <https://doi.org/10.5194/acp-17-10333-2017>
- Peng, J., Hu, M., Guo, S., Du, Z., Zheng, J., Shang, D., et al. (2016). Markedly enhanced absorption and direct radiative forcing of black carbon under polluted urban environments. *Proceedings from the National Academy of Science of the United States of America*, *113*, 4266–4271. <https://doi.org/10.1073/pnas.1602310113>
- Peng, J., Li, Z., Zhang, H., Liu, J., & Cribb, M. C. (2016). Systematic changes in cloud radiative forcing with aerosol loading for deep clouds in the tropics. *Journal of the Atmospheric Sciences*, *73*, 231–249. <https://doi.org/10.1175/JAS-D-15-0080.1>
- Qian, Y., & Giorgi, F. (1999). Interactive coupling of regional climate and sulfate aerosol models over eastern Asia. *Journal of Geophysical Research*, *104*, 6477–6499. <https://doi.org/10.1029/98JD02347>
- Qian, Y., Giorgi, F., Huang, Y., Chameides, W., & Luo, C. (2001). Regional simulation of anthropogenic sulfur over East Asia and its sensitivity to model parameters. *Tellus B: Chemical and Physical Meteorology*, *53*(2), 171–191. <http://doi.org/10.1034/j.1600-0889.2001.d01-14.x>
- Qian, Y., Gong, D., Fan, J., Leung, L. R., Bennartz, R., Chen, D., & Wang, W. (2009). Heavy pollution suppresses light rain in China: observations and modeling. *Journal of Geophysical Research*, *114*, D00K02. <http://doi.org/10.1029/2008JD011575>
- Qian, Y., Kaiser, D. P., Leung, L. R., & Xu, M. (2006). More frequent cloud-free sky and less surface solar radiation in China from 1955 to 2000. *Geophysical Research Letters*, *33*, L01812. <http://doi.org/10.1029/2005GL024586>
- Qian, Y., Leung, L. R., Ghan, S. J., & Giorgi, F. (2003). Regional climate effects of aerosols over China: modeling and observation. *Tellus Series B - Chemical and Physical Meteorology*, *55*, 914–934. <http://doi.org/10.1046/j.1435-6935.2003.00070.x>
- Qian, Y., Yan, H., Hou, Z., Johannesson, G., Klein, S. A., Lucas, D., et al. (2015). Parametric sensitivity analysis of precipitation at global and local scales in the Community Atmosphere Model CAM5. *Journal of Advances in Modeling Earth Systems*, *7*, 382–411. <http://doi.org/10.1002/2014MS000354>

- Remer, L. A., Kaufman, Y. J., Tanré, D., Mattoo, S., Chu, D. A., Martins, J. V., & Holben, B. A. (2005). The MODIS algorithm, products, and validation. *Journal of the Atmospheric Sciences*, *62*, 947–973. <https://doi.org/10.1175/JAS3385.1>
- Ren, J., Zhang, F., Wang, Y., Collins, D., Fan, X., Jin, X., et al. (2018). Using different assumptions of aerosol mixing state and chemical composition to predict CCN concentrations based on field measurements in urban Beijing. *Atmospheric Chemistry and Physics*, *18*, 6907–6921. <https://doi.org/10.5194/acp-18-6907-2018>
- Rosenfeld, D., Dai, J., Yu, X., Yao, Z., Xu, X., Yang, X., & Du, C. (2007). Inverse relations between amounts of air pollution and orographic precipitation. *Science*, *315*(5817), 1396–1398. <https://doi.org/10.1126/science.1137949>
- Rosenfeld, D., & Feingold, G. (2003). Explanation of discrepancies among satellite observations of the aerosol indirect effects. *Geophysical Research Letters*, *30*(14), 1776. <https://doi.org/10.1029/2003GL017684>
- Rosenfeld, D., Liu, G., Yu, X., Zhu, Y., Dai, J., Xu, X., & Yue, Z. (2014). High-resolution (375 m) cloud microstructure as seen from the NPP/VIIRS satellite imager. *Atmospheric Chemistry and Physics*, *14*, 2479–2496. <https://doi.org/10.5194/acp-14-2479-2014>
- Rosenfeld, D., Lohmann, U., Raga, G. B., O'Dowd, C. D., Kulmala, M., Fuzzi, S., et al. (2008). Flood or drought: How do aerosols affect precipitation? *Science*, *321*(5894), 1309–1313. <https://doi.org/10.1126/science.1160606>
- Rosenfeld, D., Yu, X., Liu, G., Xu, X., Zhu, Y., Yue, Z., et al. (2011). Glaciation temperatures of convective clouds ingesting desert dust, air pollution and smoke from forest fires. *Geophysical Research Letters*, *38*, L21804. <https://doi.org/10.1029/2011GL049423>
- Rosenfeld, D., Zheng, Y., Hashimshoni, E., Pöhlker, M. L., Jefferson, A., Pöhlker, C., et al. (2016). Satellite retrieval of cloud condensation nuclei concentrations by using clouds as CCN chambers. *Proceedings of the National Academy of Sciences of the United States*, *113*, 5828–5834. <http://doi.org/10.1073/pnas.1514044113>
- Rosenfeld, D., Zhu, Y., Wang, M., Zheng, Y., Goren, T., & Yu, S. (2019). Aerosol-driven droplet concentrations dominate coverage and water of oceanic low level clouds. *Science*, *363*. <http://doi.org/10.1126/science.aav0566>
- Shang, H. Z., Chen, L. F., Letu, H. S., Zhao, M., Li, S. S., & Bao, S. H. (2017). Development of a daytime cloud and haze algorithm for Himawari-8 satellite measurements over central and eastern China. *Journal of Geophysical Research: Atmospheres*, *122*, 3528–3543. <https://doi.org/10.1002/2016JD025659>
- Shao, Y., Ishizuka, M., Mikami, M., & Leys, J. F. (2011). Parameterization of size-resolved dust emission and validation with measurements. *Journal of Geophysical Research*, *116*, D08203. <http://doi.org/10.1029/2010JD014527>
- Sheffield, A. M., Saleeby, S. M., & van den Heever, S. C. (2015). Aerosol-induced mechanisms for cumulus congestus growth. *J. Geophys. Res. Atmos.*, *120*, 8941–8952.
- Shen, X., Liu, B., Li, G., Wu, Z., Jin, Y., Yu, P., & Zhou, D. (2014). Spatiotemporal change of diurnal temperature range and its relationship with sunshine duration and precipitation in China. *Journal of Geophysical Research: Atmospheres*, *119*, 13,163–13,169. <https://doi.org/10.1002/2014JD022326>
- Sherwood, S. C., Bony, S., & Dufresne, J.-L. (2014). Spread in model climate sensitivity traced to atmospheric convective mixing. *Nature*, *505*(7481), 37–42. <https://doi.org/10.1038/nature12829>
- Shinozuka, Y., Clarke, A. D., Nenes, A., Jefferson, A., Wood, R., McNaughton, C. S., et al. (2015). The relationship between cloud condensation nuclei (CCN) concentration and light extinction of dried particles: indications of underlying aerosol processes and implications for satellite-based CCN estimates. *Atmospheric Chemistry and Physics*, *15*, 7585–7604. <https://doi.org/10.5194/acp-15-7585-2015>
- Small, J. D., Chuang, P. Y., Feingold, G., & Jiang, H. (2009). Can aerosol decrease cloud lifetime? *Geophysical Research Letters*, *36*, L16806. <https://doi.org/10.1029/2009GL038888>
- Sotiropoulou, R. E. P., Nenes, A., Adams, P. J., & Seinfeld, J. H. (2007). Cloud condensation nuclei prediction error from application of Köhler theory: importance for the aerosol indirect effect. *Journal of Geophysical Research*, *112*, D12202. <https://doi.org/10.1029/2006JD007834>
- Stevens, B., & Feingold, G. (2009). Untangling aerosol effects on clouds and precipitation in a buffered system. *Nature*, *461*(7264), 607–613. <https://doi.org/10.1038/nature08281>
- Su, L., & Fung, J. C. (2015). Sensitivities of WRF-Chem to dust emission schemes and land surface properties in simulating dust cycles during springtime over East Asia. *Journal of Geophysical Research: Atmospheres*, *120*, 11,215–11,230. <https://doi.org/10.1002/2015JD023446>
- Su, T., Li, Z., & Kahn, R. (2018). Relationships between the planetary boundary layer height and surface pollutants derived from lidar observations over China: regional pattern and influencing factors. *Atmospheric Chemistry and Physics*, *18*, 15,921–15,935. <https://doi.org/10.5194/acp-18-15921-2018>
- Sun, J., Zhang, Q., Canagaratna, M. R., Zhang, Y., Ng, N. L., Sun, Y., & Worsnop, D. R. (2010). Highly time- and size-resolved characterization of submicron aerosol particles in Beijing using an Aerodyne Aerosol Mass Spectrometer. *Atmospheric Environment*, *44*(1), 131–140. <https://doi.org/10.1016/j.atmosenv.2009.03.020>
- Sun, Y., Chen, C., Zhang, Y., Xu, W., Zhou, L., Cheng, X., & Fu, P. (2016). Rapid formation and evolution of an extreme haze episode in Northern China during winter 2015. *Scientific Reports*, *6*, 27151. <https://doi.org/10.1038/srep27151>
- Sun, Y., Jiang, Q., Wang, Z., Fu, P., Li, J., Yang, T., & Yin, Y. (2014). Investigation of the sources and evolution processes of severe haze pollution in Beijing in January 2013. *Journal of Geophysical Research: Atmospheres*, *119*, 4380–4398. <https://doi.org/10.1002/2014jd021641>
- Sun, Y., Jiang, Q., Xu, Y., Ma, Y., Zhang, Y., Liu, X., & Li, Z. (2016). Aerosol characterization over the North China Plain: haze life cycle and biomass burning impacts in summer. *Journal of Geophysical Research: Atmospheres*, *121*, 2508–2521. <https://doi.org/10.1002/2015JD024261>
- Sun, Y., Wang, Z., Dong, H., Yang, T., Li, J., Pan, X., & Jayne, J. T. (2012). Characterization of summer organic and inorganic aerosols in Beijing, China with an Aerosol Chemical Speciation Monitor. *Atmospheric Environment*, *51*, 250–259. <https://doi.org/10.1016/j.atmosenv.2012.01.013>
- Tang, J., Wang, P., Mickley, L. J., Xia, X., Liao, H., Yue, X., et al. (2014). Positive relationship between liquid cloud droplet effective radius and aerosol optical depth over Eastern China from satellite data. *Atmospheric Environment*, *84*, 244–253. <https://doi.org/10.1016/j.atmosenv.2013.08.024>
- Tao, M., Chen, L., Wang, Z., Wang, J., Che, H., Xu, X., et al. (2017). Evaluation of MODIS Deep Blue aerosol algorithm in desert region of East Asia: ground validation and intercomparison. *Journal of Geophysical Research: Atmospheres*, *122*(10), 10,357–10,368. <https://doi.org/10.1002/2017JD026976>
- Tao, W. K., Chen, J. P., Li, Z., Wang, C., & Zhang, C. (2012). Impact of aerosols on convective clouds and precipitation. *Reviews of Geophysics*, *50*, RG2001. <https://doi.org/10.1029/2011RG000369>

- Tian, F., Dong, B., Robson, J., & Sutton, R. (2018). Forced decadal changes in the East Asian summer monsoon: the roles of greenhouse gases and anthropogenic aerosols. *Climate Dynamics*, *51*(9-10), 3699–3715. <https://doi.org/10.1007/s00382-018-4105-7>
- Tian, P., Cao, X., Zhang, L., Sun, N., Sun, L., Logan, T., et al. (2017). Aerosol vertical distribution and optical properties over China from long-term satellite and ground-based remote sensing. *Atmospheric Chemistry And Physics*, *17*, 2509–2523. <https://doi.org/10.5194/acp-17-2509-2017>
- Tian, P., Zhang, L., Ma, J., Tang, K., Xu, L., Wang, Y., et al. (2018). Radiative absorption enhancement of dust mixed with anthropogenic pollution over East Asia. *Atmospheric Chemistry and Physics*, *18*, 7815–7825. <https://doi.org/10.5194/acp-18-7815-2018>
- Twomey, S. (1977). The influence of pollution on the shortwave albedo of clouds. *Journal of the Atmospheric Sciences*, *34*, 1149–1152. [https://doi.org/10.1175/1520-0469\(1977\)034<1149:TIOPOT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2)
- Wall, C., Zipser, E., & Liu, C. (2014). An investigation of the aerosol indirect effect on convective intensity using satellite observations. *Journal of the Atmospheric Sciences*, *71*(1), 430–447. <https://doi.org/10.1175/JAS-D-13-0158.1>
- Wang, F., Guo, J., Wu, Y., Zhang, X., Deng, M., Li, X., et al. (2014). Satellite observed aerosol-induced variability in warm cloud properties under different meteorological conditions over eastern China. *Atmospheric Environment*, *84*, 122–132. <https://doi.org/10.1016/j.atmosenv.2013.11.018>
- Wang, F., Guo, J., Zhang, J., Huang, J., Min, M., Chen, T., et al. (2015). Multi-sensor quantification of aerosol-induced variability in warm cloud properties over eastern China. *Atmospheric Environment*, *113*, 1–9. <https://doi.org/10.1016/j.atmosenv.2015.04.063>
- Wang, G., Zhang, F., Peng, J., Duan, L., Ji, Y., Marrero-Ortiz, W., et al. (2018). Particle acidity and sulfate production during severe haze events in China cannot be reliably inferred by assuming a mixture of inorganic salts. *Atmospheric Chemistry and Physics*, *18*, 10,123–10,132. <https://doi.org/10.5194/acp-18-10123-2018>
- Wang, G., Zhang, R., Gomez, M. E., Yang, L., Zamora, M. L., Hu, M., et al. (2016). Persistent sulfate formation from London Fog to Chinese haze. *Proceedings of the National Academy of Sciences of the United States*, *113*, 13,630–13,635. <https://doi.org/10.1073/pnas.1616540113>
- Wang, H., Xie, X., Yan, L., & Liu, X. (2017). Impact of East Asian summer monsoon circulation on the regional aerosol distribution in observations and models. *Theoretical and Applied Climatology*, *133*(1-2), 377–384. <https://doi.org/10.1007/s00704-017-2199-1>
- Wang, J., Allen, D. J., Pickering, K. E., Li, Z., & He, H. (2016). Impact of aerosol direct effect on East Asian air quality during the EAST-AIRE campaign. *Journal of Geophysical Research: Atmospheres*, *121*, 6534–6554. <https://doi.org/10.1002/2016JD025108>
- Wang, K., & Dickinson, R. E. (2013). Contribution of solar radiation to decadal temperature variability over land. *Proceedings of the National Academy of Sciences of the United States*, *110*, 14,877–14,882. <https://doi.org/10.1073/pnas.1311433110>
- Wang, K., Zhang, X., Fan, J., Leung, L. R., Zheng, B., Zhang, Q., & He, K. (2018). Fine-scale application of WRF-CAM5 during a dust storm episode over East Asia: sensitivity to grid resolutions and aerosol activation parameterizations. *Atmospheric Environment*, *176*, 1–20. <https://doi.org/10.1016/j.atmosenv.2017.12.014>
- Wang, T. J., Zhuang, B. L., Li, S., Liu, J., Xie, M., Yin, C. Q., & Han, Y. (2015). The interactions between anthropogenic aerosols and the East Asian summer monsoon using RegCCMS. *Journal of Geophysical Research: Atmospheres*, *120*, 5602–5621. <https://doi.org/10.1002/2014JD02287>
- Wang, Y., Khalizov, A., Levy, M., & Zhang, R. (2013). New directions: light absorbing aerosols and their atmospheric impacts. *Atmospheric Environment*, *81*, 713–715. <https://doi.org/https://doi.org/10.1016/j.atmosenv.2013.09.034>
- Wang, Y., Li, Z., Zhang, Y., Du, W., Zhang, F., Tan, H., et al. (2018). Characterization of aerosol hygroscopicity, mixing state, and CCN activity at a suburban site in the central North China Plain. *Atmospheric Chemistry and Physics*, *18*, 11,739–11,752. <https://doi.org/10.5194/acp-18-11739-2018>
- Wang, Y., Ma, P. L., Jiang, J. H., Su, H., & Rasch, P. J. (2016). Toward reconciling the influence of atmospheric aerosols and greenhouse gases on light precipitation changes in Eastern China. *Journal of Geophysical Research: Atmospheres*, *121*, 5878–5887. <https://doi.org/10.1002/2016JD024845>
- 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. *Atmospheric Chemistry and Physics*, *11*, 12,421–12,436. <https://doi.org/10.5194/acp-11-12421-2011>
- Wang, Y., Wang, M., Zhang, R., Ghan, S. J., Lin, Y., Hu, J., et al. (2014). Assessing the effects of anthropogenic aerosols on Pacific storm track using a multiscale global climate model. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 6894–6899. <https://doi.org/10.1073/pnas.1403364111>
- Wang, Y., & Wild, M. (2016). A new look at solar dimming and brightening in China. *Geophysical Research Letters*, *43*, 777–785. <https://doi.org/10.1002/2016GL071009>
- Wang, Y., Zhang, F., Li, Z., Tan, H., Xu, H., Ren, J., et al. (2017). Enhanced hydrophobicity and volatility of submicron aerosols under severe emission control conditions in Beijing. *Atmospheric Chemistry and Physics*, *17*. <https://doi.org/10.5194/acp-17-5239-2017>
- Wang, Y., Zhang, R., & Saravanan, R. (2014). Asian pollution climatically modulates mid-latitude cyclones following hierarchical modeling and observational analysis. *Nature Communications*, *5*, 3098. <https://doi.org/10.1038/ncomms4098>
- Watson, J. G. (2002). Visibility: science and regulation. *Journal of the Air and Waste Management Association*, *52*(6), 628–713. <https://doi.org/10.1080/10473289.2002.10470813>
- Wei, J., Huang, W., Li, Z., Xue, W., Peng, Y., Sun, L., & Cribb, M. (2019). Estimating 1-km-resolution PM_{2.5} concentrations across China using the space-time random forest approach. *Remote Sensing of Environment*, *231*, 111221. <https://doi.org/10.1016/j.rse.2019.111221>
- Wilcox, E. M., & Platnick, S. (2009). Estimate of the impact of absorbing aerosol over cloud on the MODIS retrievals of cloud optical thickness and effective radius using two independent retrievals of liquid water path. *Journal of Geophysical Research*, *114*, D05210. <https://doi.org/10.1029/2008JD010589>
- Wu, G., Li, Z., Fu, C., Zhang, X., Zhang, R., Zhang, R., & Wu, L. (2016). Advances in studying interactions between aerosols and monsoon in China. *Science China Earth Sciences*, *59*(1), 1–16. <https://doi.org/10.1007/s11430-015-5198-z>
- Xia, X. (2013). Variability and trend of diurnal temperature range in China and their relationship to total cloud cover and sunshine duration. *Annales Geophysicae*, *31*(5), 795–804. <https://doi.org/10.5194/angeo-31-795-2013>
- Xie, Y., Wang, Y., Zhang, K., Dong, W., Lv, B., & Bai, Y. (2015). Daily estimation of ground-level PM_{2.5} concentrations over Beijing using 3-km resolution MODIS AOD. *Environmental Science and Technology*, *49*(20), 12,280–12,288. <https://doi.org/10.1021/acs.est.5b01413>
- Xin, J., Gong, C., Liu, Z., Cong, Z., Gao, W., Song, T., & Tang, G. (2016). The observation-based relationships between PM_{2.5} and AOD over China. *Journal of Geophysical Research: Atmospheres*, *121*, 10,701–10,716. <https://doi.org/10.1002/2015JD024655>
- Xin, J., Wang, Y., Li, Z., Wang, P., Hao, W. M., Nordgren, B. L., & Sun, Y. (2007). Aerosol optical depth (AOD) and Ångström exponent of aerosols observed by the Chinese Sun Hazemeter Network from August 2004 to September 2005. *Journal of Geophysical Research*, *112*, D05203. <https://doi.org/10.1029/2006JD007075>

- Xin, J., Wang, Y., Pan, Y., Ji, D., Liu, Z., Wen, T., & Wang, P. (2015). The campaign on atmospheric aerosol research network of China: CARE-China. *Bulletin of the American Meteorological Society*, 96, 1137–1155. <https://doi.org/10.1175/BAMS-D-14-00039.1>
- Xin, J., Zhang, Q., Wang, L., Gong, C., Wang, Y., Liu, Z., & Gao, W. (2014). The empirical relationship between the PM_{2.5} concentration and aerosol optical depth over the background of North China from 2009 to 2011. *Atmospheric Research*, 138, 179–188. <https://doi.org/10.1016/j.atmosres.2013.11.001>
- Xu, H., Guo, J., Wang, Y., Zhao, C., Zhang, Z., Min, M., et al. (2017). Warming effect of dust aerosols modulated by overlapping clouds below. *Atmospheric Environment*, 166, 393–402. <https://doi.org/10.1016/j.atmosenv.2017.07.036>
- Xue, W., Guo, J., Zhang, Y., Zhou, S., Wang, Y., Miao, Y., & Liu, H. (2018). Declining diurnal temperature range in the North China Plain related to environmental changes. *Climate Dynamics*, 52(9–10), 6109–6119. <https://doi.org/10.1007/s00382-018-4505-8>
- Yan, H., Li, Z., Huang, J., Cribb, M. C., & Liu, J. (2014). Long-term aerosol-mediated changes in cloud radiative forcing of deep clouds at the top and bottom of the atmosphere over the Southern Great Plains. *Atmospheric Chemistry and Physics*, 14(14), 7113–7124. <https://doi.org/10.5194/acp-14-7113-2014>
- Yan, H., Qian, Y., Zhao, C., Wang, H., Wang, M., Yang, B., & Fu, Q. (2015). A new approach to modeling aerosol effects on East Asian climate: parametric uncertainties associated with emissions, cloud microphysics, and their interactions. *Journal of Geophysical Research: Atmospheres*, 120, 8905–8924. <https://doi.org/10.1002/2015JD023442>
- Yan, X., Li, Z., Shi, W., Luo, N., Shi, W., Zhao, W., et al. (2019). An improved algorithm for retrieving the fine-mode fraction of aerosol optical thickness. Part 2: application and validation in Asia. *Remote Sens. Environ.*, 222, 90–103. <https://doi.org/10.1016/j.rse.2018.12.012>
- Yan, X., Li, Z., Shi, W., Luo, N., Wu, T., & Zhao, W. (2017). An improved algorithm for retrieving the fine-mode fraction of aerosol optical thickness, part 1: Algorithm development. *Remote Sensing of Environment*, 192, 87–97. <https://doi.org/10.1016/j.rse.2017.02.005>
- Yan, X., Shi, W., Li, Z., Li, Z. Q., Luo, N., & Zhao, ... Yu, X. (2017). Satellite-based PM_{2.5} estimation using fine-mode aerosol optical depth thickness over China. *Atmospheric Environment*, 170, 290–302. <https://doi.org/10.1016/j.atmosenv.2017.09.023>
- Yang, X., & Li, Z. (2014). Increases in thunderstorm activity and relationships with air pollution in southeast China. *Journal of Geophysical Research: Atmospheres*, 119, 1835–1844. <https://doi.org/10.1002/2013JD021224>
- Yang, X., Yao, Z., Li, Z., & Fan, T. (2013). Heavy air pollution suppresses summer thunderstorms in central China. *Journal of Atmospheric and Solar-Terrestrial Physics*, 95–96, 28–40. <https://doi.org/https://doi.org/10.1016/j.jastp.2012.12.023>
- Yang, X., Zhao, C., Guo, J., & Wang, Y. (2016). Intensification of aerosol pollution associated with its feedback with surface solar radiation and winds in Beijing. *Journal of Geophysical Research: Atmospheres*, 121, 4093–4099. <https://doi.org/10.1002/2015JD024645>
- Yang, X., Zhao, C., Zhou, L., Wang, Y., & Liu, X. (2016). Distinct impact of different types of aerosols on surface solar radiation in China. *Journal of Geophysical Research: Atmospheres*, 121, 6459–6471. <https://doi.org/10.1002/2016JD024938>
- Yang, Y., Fan, J., Leung, L. R., Zhao, C., Li, Z., & Rosenfeld, D. (2016). Mechanisms contributing to suppressed precipitation in Mt. Hua of central China. Part I: Mountain valley circulation. *Journal of the Atmospheric Sciences*, 73(3), 1351–1366. <https://doi.org/10.1175/JAS-D-15-0233.1>
- Yu, H., Ren, L., & Kanawade, V. P. (2017). New particle formation and growth mechanisms in highly polluted environments. *Current Pollution Reports*, 3(4), 245–253. <https://doi.org/10.1007/s40726-017-0067-3>
- Yue, D., Hu, M., Zhang, R., Wu, Z., Su, H., Wang, Z. B., et al. (2011). Potential contribution of new particle formation to cloud condensation nuclei in Beijing. *Atmospheric Environment*, 45, 6070–6077. <https://doi.org/10.1016/j.atmosenv.2011.07.037>
- Zhang, D., Liu, D., Luo, T., Wang, Z., & Yin, Y. (2015). Aerosol impacts on cloud thermodynamic phase change over East Asia observed with CALIPSO and CloudSat measurements. *Journal of Geophysical Research: Atmospheres*, 120, 1490–1501. <http://doi.org/10.1002/2014JD022630>
- Zhang, F., Li, Z., Li, R., Sun, L., Zhao, C., Wang, P. C., et al. (2014). Aerosol hygroscopicity and cloud condensation nuclei activity during the AC3Exp campaign: implications for cloud condensation nuclei parameterization. *Atmospheric Chemistry and Physics*, 14, 13,423–13,437. <https://doi.org/10.5194/acp-14-13423-2014>
- Zhang, F., Li, Z., Li, Y., Sun, Y., Wang, Z., Li, P., et al. (2016). Impacts of organic aerosols and its oxidation level on CCN activity from measurement at a suburban site in China. *Atmospheric Chemistry and Physics*, 16, 5413–5425. <https://doi.org/10.5194/acp-16-5413-2016>
- Zhang, F., Wang, Y., Peng, J., Ren, J., Collins, D., Zhang, R., et al. (2017). Uncertainty in predicting CCN activity of aged and primary aerosols. *Journal of Geophysical Research: Atmospheres*, 122, 11,723–11,736. <https://doi.org/10.1002/2017JD027058>
- Zhang, J., Gong, D. Y., Mao, R., Yang, J., Zhang, Z., & Qian, Y. (2018). Anomalous holiday precipitation over southern China. *Atmospheric Chemistry and Physics*, 18(22), 16,775–16,791. <https://doi.org/10.5194/acp-2018-102>
- Zhang, R., Li, G., Fan, J., Wu, D. L., & Molina, M. J. (2007). Intensification of Pacific storm track linked to Asian pollution. *Proc. Natl. Acad. Sci. USA*, 104(13), 5295–5299. <https://doi.org/10.1073/pnas.0700618104>
- Zhang, R., Wang, G., Guo, S., Zamora, M. L., Ying, Q., Lin, Y., et al. (2015). Formation of urban fine particulate matter. *Chemical Reviews*, 115(10), 3803–3855. <https://doi.org/10.1021/acs.chemrev.5b00067>
- Zhang, Y., Zhang, X., Wang, K., He, J., Leung, L. R., Fan, J., & Nenes, A. (2015). Incorporating an advanced aerosol activation parameterization into WRF-CAM5: model evaluation and parameterization intercomparison. *Journal of Geophysical Research: Atmospheres*, 120, 6952–6979. <https://doi.org/10.1002/2014JD023051>
- Zhang, Y. L., & Cao, F. (2015). Fine particulate matter (PM_{2.5}) in China at a city level. *Scientific Reports*, 5, 14884. <https://doi.org/10.1038/srep14884>
- Zhang, Z., Zhang, X., Gong, D., Kim, S. J., Mao, R., & Zhao, X. (2016). Possible influence of atmospheric circulations on winter haze pollution in the Beijing-Tianjin-Hebei region, northern China. *Atmospheric Chemistry and Physics*, 16(2), 561–571. <https://doi.org/10.5194/acp-16-561-2016>
- Zhao, B., Wang, Y., Gu, Y., Liou, K. N., Jiang, J., Fan, J., et al. (2019). Ice nucleation by aerosols from anthropogenic pollution. *Nat. Geoscience*, 12, 602–607.
- Zhao, C., Lin, Y., Wu, F., Wang, Y., Li, Z., Roosenfeld, D., & Wang, Y. (2018). Enlarging rainfall area of tropical cyclones by atmospheric aerosols. *Geophysical Research Letters*, 45, 8604–8611. <https://doi.org/10.1029/2018GL079427>
- Zhao, C., Tie, X., & Lin, Y. (2006). A possible positive feedback of reduction of precipitation and increase in aerosols over eastern central China. *Geophysical Research Letters*, 33, L11814. <https://doi.org/10.1029/2006GL025959>
- Zhao, C., Wang, Y., Wang, Q., Li, Z., Wang, Z., & Liu, D. (2014). A new cloud and aerosol layer detection method based on micropulse lidar measurements. *Journal of Geophysical Research: Atmospheres*, 119. <https://doi.org/10.1002/2014JD021760>
- Zheng, X., Albrecht, B., Minnis, P., Ayers, K., & Jonson, H. H. (2010). Observed aerosol and liquid water path relationships in marine stratocumulus. *Geophysical Research Letters*, 37, L17803. <https://doi.org/10.1029/2010GL044095>
- Zheng, Y., Rosenfeld, D., & Li, Z. (2015). Satellite inference of thermals and cloud-base updraft speeds based on retrieved surface and cloud-base temperatures. *Journal of the Atmospheric Sciences*, 72(6), 2411–2428. <https://doi.org/10.1175/JAS-D-14-0283.1>

- Zheng, Y., Rosenfeld, D., & Li, Z. (2016). Quantifying cloud base updraft speeds of marine stratocumulus from cloud top radiative cooling. *Geophysical Research Letters*, 3, 11–407. <https://doi.org/10.1002/2016GL071185>
- Zheng, Y., Rosenfeld, D., & Li, Z. (2018). Estimating the decoupling degree of subtropical marine stratocumulus decks from satellite. *Geophysical Research Letters*, 45(22), 12–560. <https://doi.org/10.1029/2018GL078382>
- Zhong, S., Qian, Y., Sarangi, C., Zhao, C., Leung, R., Wang, H., & Yang, B. (2018). Urbanization effect on winter haze in the Yangtze River Delta region of China. *Geophysical Research Letters*, 45, 6710–6718. <https://doi.org/10.1029/2018GL077239>
- Zhong, S., Qian, Y., Zhao, C., Leung, R., Wang, H., Yang, B., & Liu, D. (2017). Urbanization-induced urban heat island and aerosol effects on climate extremes in the Yangtze River Delta region of China. *Atmospheric Chemistry and Physics*, 17(8), 5439–5457. <https://doi.org/10.5194/acp-17-5439-2017>
- Zhong, S., Qian, Y., Zhao, C., Leung, R., & Yang, X. Q. (2015). A case study of urbanization impact on summer precipitation in the Greater Beijing Metropolitan Area: urban heat island versus aerosol effects. *Journal of Geophysical Research: Atmospheres*, 120, 10,903–10,914. <https://doi.org/10.1002/2015JD023753>
- Zhu, Y., Rosenfeld, D., Yu, X., & Li, Z. (2015). Separating aerosol microphysical effects and satellite measurement artifacts of the relationships between warm rain onset height and aerosol optical depth. *Journal of Geophysical Research: Atmospheres*, 120, 7726–7736. <https://doi.org/10.1002/2015JD023547>