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Roles of Atmospheric Aerosols in Extreme Meteorological Events: a Systematic Review

Zilin Wang[1,2] · **Lian Xue**[1,2] · **Jingyi Liu**[1,2] · **Ke Ding**[1,2,3] · **Sijia Lou**[1,2,3] · **Aijun Ding**[1,2,3] · **Jiandong Wang**[4] · **Xin Huang**[1,2,3]

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Abstract

Purpose of Review Atmospheric aerosol from both natural and anthropogenic activities has long been acknowledged as one of the important factors influencing regional and global climate change. Many regions around the globe experienced high aerosol loadings because of intensive emissions, yet the roles of atmospheric aerosols in extreme meteorological and air pollution events have not been well demonstrated due mainly to the complexity of atmospheric physical and chemical interaction at mesoscale and even microscale. Here, we present a comprehensive review of current understanding on the role of atmospheric aerosols in the development and evolution of extreme meteorological events, including monsoon circulation, heat waves, extreme rainfall, tornadoes, and severe air pollution.

Recent Findings Aerosols could participate in the development of meteorological systems through direct and indirect effects. Large-scale precipitation from shallow stratiform clouds was found to be suppressed by aerosols, while invigoration effects contribute to deep convection and even catastrophic floods in local areas. The occurrence of high-impact weather such as tornadoes and tropical cyclone is also related to aerosol concentration and distribution. Moreover, a positive feedback between aerosols and boundary layer meteorology is proposed as an important factor conducive to heavy haze pollution over urban areas.

Summary The work underscores the great importance of aerosols' meteorological feedback in extreme weather events. Integrated observations and seamless coupling of meteorology and atmospheric chemistry in models are highlighted for future studies to fill the knowledge gap in current research.

Keywords Atmospheric aerosols · Meteorological feedback · Extreme weather events · Thermodynamic circulation · Precipitation · Boundary layer · Climate change

Introduction

Atmospheric pollutants consist of gaseous pollutants, such as greenhouse gases (GHGs), as well as particulate matters which are usually referred to as aerosols. As known, a wide variety of natural and anthropogenic sources are able to produce diverse pollutants, which have the potential to boost climate change, i.e., global warming, and ecosystem evolution [1••, 2, 3]. Such pollutants could also cause heart disease and respiratory disorders, posing a threat to human health [4, 5]. By interacting with solar and thermal infrared radiation, suspended aerosol could perturb the radiative energy balance of the Earth–atmosphere system in two different ways, namely, direct and indirect effects of aerosols [6••, 7•]. Unlike the long-lived greenhouse gases, which are distributed uniformly across the globe, lifetime of aerosols ranges

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✉ Xin Huang
xinhuang@nju.edu.cn

[1] School of Atmospheric Sciences, Nanjing University, Nanjing, China

[2] Jiangsu Provincial Collaborative Innovation Center for Climate Change, Nanjing, China

[3] Frontiers Science Center for Critical Earth Material Cycling, Nanjing University, Nanjing, China

[4] Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, School of Atmospheric Physics, Nanjing University of Information Science and Technology, Nanjing 210044, China

from minutes to weeks, resulting in substantial variations in space and time with peak concentrations near the emission sources [8].

Over the past decades, due to rapidly expanding economic and industrial developments, the energy consumption and pollutant emissions increase markedly, making air pollution one of the top environmental concerns in developing countries [9, 10]. For example, China experienced extremely severe and persistent haze pollution with a record-breaking daily $PM_{2.5}$ concentration of more than 700 $\mu g/m^3$ in 2013, January [11], far exceeding the air quality standards prescribed by World Health Organization (35 $\mu g/m^3$). As another pollution hotspot, India also suffered surprisingly high aerosol loading on account of intensive fossil fuel combustion and biomass burning [12, 13]. Such heterogeneity serves as an important factor contributing to weather anomalies and even extreme meteorological events.

Extreme meteorological events are occurrence of unusually severe weather or climate conditions that can cause devastating impacts on human beings as well as agricultural and natural ecosystems. Weather-related extreme events often exist in short term, including heat waves, freezes, floods, lightning, tornadoes, and tropical cyclones. Due to its destructive consequence, extreme events have drawn much attention and have been the active focus of atmospheric researches [14, 15, 16•]. For instance, the unprecedented warming and extreme drought over Amazonian rain forests is associated with the anomalies in large-scale circulation, e.g., anomalous El Niño–Southern Oscillation (ENSO) by Jimenez-Munoz et al. [17]. Cayan et al. [18] found that daily precipitation in the western United States exhibits strong and systematic responses to ENSO–phase differences. Moreover, the recent increase in hurricane activities is linked in part to higher sea surface temperature in the region where they formed in and moved through due to natural variability [19].

Emerging evidences have confirmed that the increasing frequency of extreme weather in recent decades are likely to be related to human activities, especially pollutant emissions [20•, 21]. Despite their small mass and volume fraction, specific gases and particles in the atmosphere strongly influence the transfer of radiant energy and the spatial distribution of latent heating, thereby influencing the formation and evolution of extreme weather system [22]. For instance, global warming caused by GHGs can contribute to the intensity of heat waves by increasing the chances of hot days and nights [23]. Warming air also boosts evaporation and early melting of snow, worsening the drought in snow-dominated regions [24]. By contrast, aerosol is usually associated with intensive convection and extreme downpours [25, 26].

As two important factors exerting great impact on health and well-being of human population in modern society, air pollution and extreme weather events are both frontal scientific topics and arouse wide scientific interest. Consisting of complex chemical and physical processes, interactions between atmospheric pollutants and extreme meteorological events are under fervent discussion [20•, 22, 27, 28]. However, comprehensive summary and review of their intimate relations are still lacking. In this paper, we review the major advances in how atmospheric pollutants, especially aerosols, affect the development and evolution of different extreme weather events, including their influence on circulation, hydrology, and heavy pollution, and highlight the priorities for future studies.

Impact on Atmospheric Thermal and Dynamical Fields

Global warming is one of the important environmental concerns and significant aspects of climate change. Long-lasting and intensive warming could result in heat waves or heat extremes, which pose enormous danger to human health and ecosystems. Numerous studies have found that GHGs are responsible for increasing frequency and intensity of heat waves observed during the past few decades [2, 29, 30]. By affecting the energy balance between incoming solar radiation and outgoing infrared radiation, anthropogenic GHGs can increase the Earth's energy budget, exerting a positive forcing on average, and ultimately leading to atmospheric warming [1••, 31]. Unlike GHGs, atmospheric aerosols intercept incoming insolation reaching the Earth surface through directly interact with radiation or indirectly serving as cloud condensation nuclei (CCN), exerting a cooling effect at the ground surface, which is also referred to as global dimming [32•, 33]. Globally, the radiative cooling caused by anthropogenic aerosols is estimated to be –0.8 W m^{-2} in total with large uncertainties [1••]. Long-term negative trends in surface solar irradiance have been observed by surface radiometers worldwide over land, although the observed changes may not be solely due to aerosols [32•, 34]. With parallel simulations considering the radiative effect of aerosol, extreme high temperatures and the number of days with temperature above the 90th percentile were found to decline over most of the United States [27]. Chen et al. [35] identified the recent increase in Asian anthropogenic aerosols as the driving factor of cooling trend over China, partly cancelling out the warming trend due to rising GHGs [36]. At a regional scale, the extinction of radiation by aerosols could also partially offset the urban heat island (UHI) effect, which arouses higher air temperature due to particular underlying surface along with anthropogenic heat and, therefore, alleviate heat waves over urban areas [37]. In fact, aerosol emissions were even proposed as an alternative solution for regional heat wave mitigation in geoengineering, which is a deliberate and large-scale intervention in Earth's climate system. [38]. In addition to surface cooling, absorbing aerosols such as black carbon (BC) and mineral dust also warm the atmosphere due to absorption of solar radiation, further complicating the atmospheric stratification [39].

The modification of atmospheric thermal structure induced by aerosols could also reshape dynamic fields (Fig. 1) especially monsoon circulation. As important parts of global-scale atmospheric circulation which exert great impact on agriculture, human health, and economics throughout Eurasian Continent, South and East Asian monsoon systems affected by aerosols are the focus of tremendous researches. By cooling the land surface through dimming effect and related precipitation change, aerosol forcing might play a significant role in weakening the land-sea thermal contrast, thereby deteriorating the low-level summer monsoon circulation over East and South Asia [40, 41•, 42]. For example, Song et al. [40] found out that the external forcing of aerosols from model simulations could partly explain the observational decreasing summer surface air temperature trends over eastern China. The reduction of temperature leads to a higher sea level pressure over northern China, thus exhibiting a weaker East Asia summer monsoon circulation. Additionally, monsoon circulation is found to modulate the magnitude and distribution of aerosols [43, 44], which further complicated the interaction between aerosol and atmospheric circulation.

For South Asia monsoon systems, considering the non-negligible influence of the Tibetan Plateau, “elevated heat pump” was put forward as a mechanism combining the aerosol forcing and topographical impact, where dust load and BC emissions may lead to an advance and intensification of Indian summer monsoon [45••, 46]. The adjusted circulation further modulates spatial–temporal distribution of monsoon precipitation variability via moisture transport and atmospheric stability, possibly related to regional flood or drought [47, 48]. In addition, biomass burning aerosols aloft that can strongly increase the low cloud coverage over southeastern Asia through semidirect effect have been revealed to induce aerosol–cloud–boundary layer interaction with monsoon circulation [49]. Furthermore, it has also been suggested that aerosols can also affect East Asia winter monsoon (EAWM) by radiative forcing, ocean–cloud feedback, transient eddy–mean flow feedback, and other processes [50–53]. Based on a global aerosol–climate model, Lou et al. [52] showed that BC transported to the oceans decelerated the EAWM wind by changing the cloud structure and land–sea thermal contrast and then led to the intensification of haze over North China Plain. However, Jiang et al. [51] investigated the effects of anthropogenic aerosols on EAWM modeling and identified the strengthening of the EAWM northern mode, indicating a colder winter in the northern East Asia [54].

Apart from monsoon circulation, many other large-scale atmospheric and oceanic patterns have also been reported to be influenced by aerosols and their precursor gases, such as the variability of El Niño–Southern Oscillation (ENSO), the latitudinal shift of the Intertropical Convergence Zone (ITCZ), the perturbation of the width of the tropical belt, and the equatorward shift of the Northern Hemisphere storm tracks. Most of these changes would further cause corresponding impact on atmospheric circulations, cloud, and precipitation, potentially leading to the changes in frequency and location of extreme events [55–58, 59•, 60, 61]. At a regional scale, severe convective fire storms are proved to be associated with the intensive emissions of heat and aerosols during the combustion process [62•, 63, 64]. Both

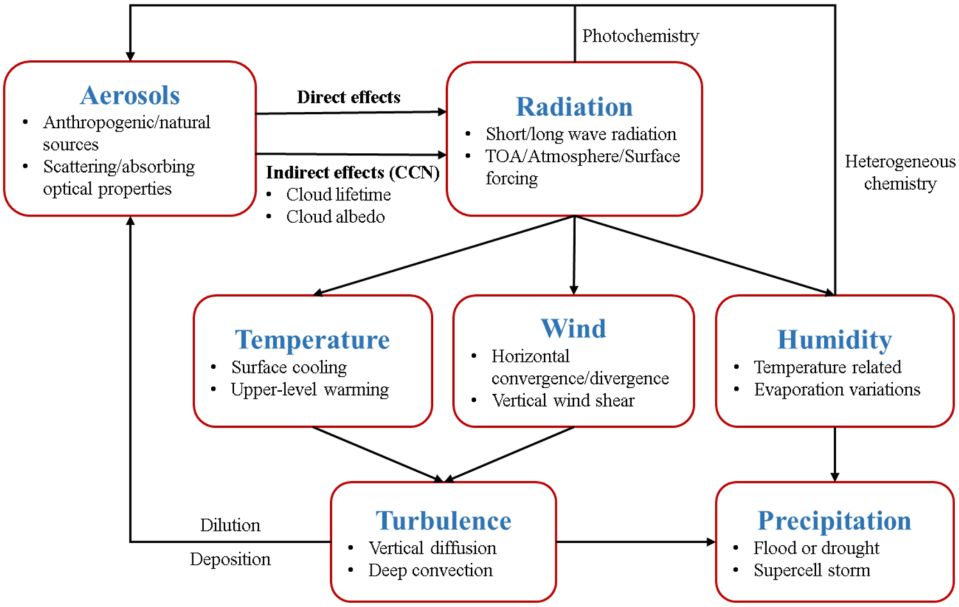

Fig. 1 Overall scheme of how atmospheric aerosols can interact with diverse atmospheric physical and chemical fields. Note: TOA represents top of the atmosphere and CCN represents cloud condensation nuclei

heat and aerosol tend to increase atmospheric temperature and mid-level air buoyancy, resulting in stronger updrafts and convective intensity [65].

To mitigate environmental pollution and the resulting impacts on human health, governments worldwide are urgent to take continuous and stringent measures to reduce the emissions of anthropogenic pollutants. Such movements will lead to sharp decrease in atmospheric aerosol concentration and relatively slow reduction of GHGs since the lifetime of aerosols is quite limited. Plenty of studies have pointed out that the reduction of aerosols would magnify the warming effect due to GHGs and give rise to more severe heat waves with minor contributions from future temperature variability changes, especially over the Northern Hemisphere [66, 67]. The global mean surface heating excluding the effect of aerosols is derived to reach 0.5–1.1 °C, and extreme weather indices also increase by the report [68]. Yet, studies conducted over northern Eurasia showed opposite results where warming due to aerosol reductions enhanced meridional temperature gradient, resulting in significantly suppression in winter extreme events [69]. With higher atmospheric temperature, lower relative humidity, and larger surface wind, the GHG emissions were shown to double extreme fire weather risks in some region [28]. Aerosol-forced cooling substantially compensated for such adverse conditions, reducing the wildfire risks and delaying the time of emergence. However, considering the descending trend of aerosols due to strict emission control measures, aerosols are projected to provide little to no relief for extreme fire–weather risk in the future.

Impact on Hydrological Cycle and Extreme Precipitation

Most of the current studies suggest that aerosols contribute to the delay and suppression of large-scale precipitation, leading to a weaker hydrological cycle which is closely related to availability and quality of fresh water [70••, 71, 72]. By examining the CMIP5 simulations for decades, Zhang et al. [73] revealed that the frequent occurrence of extreme summer droughts over North China is ascribed to anthropogenic aerosol forcing. The increasing aerosol optical depth (AOD), which represents light extinction due to the aerosol in the entire column of the atmosphere, is inversely related to Indian summer precipitation over Gangetic Plain, suggesting that increased load of aerosol is probably restricting the rainfall and leading to meteorological drought conditions [74, 75]. Using a regional coupled climate–chemistry–aerosol model, Huang et al. [76] demonstrated the influence of combined direct/first indirect effect of aerosols that could take responsibility for 10% reduction of precipitation. The decreasing trend of climatological precipitation over East Asia since the last century is geographically consistent with the distribution of the model-simulated precipitation reduction induced by anthropogenic aerosols. Previous studies have also revealed the clear impact of biomass burning aerosols (mainly BC) on local hydrological cycle. The atmospheric heating attributable to BC leads to a decrease in surface precipitation flux, accounting for the observed precipitation reduction in southern Africa [71]. Using an Earth system model, Tosca et al. [77] evaluated the climate response to the smoke forcing and also found a decline in precipitation over intensive biomass burning regions because of tropospheric heating from carbonaceous aerosols. In addition, aerosol's impact on hydrology also exhibit spatial heterogeneity. Menon et al. [78] concluded that anthropogenic aerosols have increased precipitation in Southeast China but suppressed precipitation over northeast region, intensifying flood in the south and drying in the north. Over the arid and semiarid areas including northwestern East Asia and West Africa, there exists positive feedback in dust aerosol–cloud–precipitation interactions [79–82]. Frequent occurrence of dust storms due to the deficit in soil moisture would result in elevated mineral dust loadings in the warm clouds, which decreases the low cloud cover and water vapor amount through the semidirect effect of aerosols, leading to declined rainfall. The drastic drop in precipitation further contributes to new dust storms. Despite the rainfall reduction due to aerosols, global warming caused by GHGs is shown to coincide with an increase in global precipitation by about 1 to 2% per Kelvin due to the increase in surface evaporation. Modeling studies have found that the spin-down effect of aerosols on the hydrological cycle may be large enough to reverse the effect of GHGs [83, 84].

To current knowledge, physical processes concerning how aerosols interfere with precipitation have been discussed in enormous studies and can be summarized as two main mechanisms. On the one hand, atmospheric aerosols tend to produce drier circulation systems that redistribute the precipitation [78, 85]. Since aerosols decrease the amount of solar radiation arriving at the land surface, less heat is available for evaporating water and energizing convective rain clouds [70••, 86]. In terms of absorbing particles such as BC and mineral dust, radiation is blocked within the atmosphere thus inducing extra heating of air above the surface, which stabilizes the low troposphere and suppresses the generation of convective clouds and precipitation [87, 88]. Another approach is more concerned with aerosols' microphysical effects providing cloud condensation nuclei (CCN) and ice nuclei. Assuming that aerosol concentration is growing while the condensed moisture inside the cloud remain constant, the droplet radius will decrease because of the increase in its number concentration, which results in a decrease in the raindrop coalescence and precipitation efficiency [8, 89]. Such impacts of aerosols is more significant in localized short-time precipitation response than rainfall on monthly to seasonal timescales, as proposed by Vinoj et al. [90] using satellite data and models.

Aerosols could suppress the large-scale precipitation from shallow stratiform clouds, yet invigorate rainfall from deep convection and even catastrophic floods in local areas [72]. Within idealized simulations, rain suppression occurs during the early stage of the polluted convective system, while enhancement is detected when the system grow into the mature stage [91]. Similarly, an observational analysis recorded that the heavy precipitation in polluted urban areas is first postponed, since the reduction of solar radiation reaching the surface delay the occurrence of strong convection, then enhanced when aerosol invigoration effect becomes dominant [92]. Sensitivity experiments show that aerosols tend to increase cloud liquid evaporation and produce stronger convergence line, which favors the formation of torrential rainfall [93, 94]. Tao et al. [91] also emphasize the evaporative cooling in the lower troposphere is a key process, which is associated with the strength of cold pool and low-level convergence. The distinct changes in spatial and temporal distribution of extreme precipitation are also documented in several studies. Due to heavy pollution trapped in the Sichuan Basin, increased atmospheric stability prohibits the convection and thus allows excess moist air to be transported to mountainous areas (Fig. 2). Under the influence of specific topography, the orographic lifting of humid air mass generates strong convection and extremely heavy rainfall [95•]. In addition, the nocturnal precipitation, which is supposed to take place over an urban city during daytime, shifted to the downwind areas of a biomass burning plume, as a result of increased convection as well as convergence caused by absorbing aerosols heating the upper level atmosphere [96]. Enhancement of rainfall downstream of major polluted metropolitan areas, including New York City and Houston, has also been documented for periods of time [97, 98]. However, the quantitative evaluation of aerosol effects on precipitation are still under debate and may depend on the specific meteorological environment such as air humidity, buoyancy, and wind shear [99].

In addition to extreme precipitation, catastrophic weather events that occurred over populated areas have also been revealed to be closely related to anthropogenic pollutants, especially aerosols [100••]. Although aerosols are not primary atmospheric driver of a certain weather system, they can modulate its evolution and intensity under specific conditions. A few observational studies indicated aerosols enhance the occurrence and strength of supercells and hailstones [101•, 102, 103] and even promote tornadogenesis through microphysical effects [104, 105]. As has been noted, elevated aerosol concentration makes cloud drops smaller and hydrometeor larger. The reduced evaporation from the larger hydrometeor produces weaker cold pools and then contributes to more hailstones and tornados [26, 106]. Less evaporative cooling and weaker cold pools are confirmed as important reasons in dusty simulations engendering larger raindrop and hailstone, indicating an positive effect of aerosols on tornadogenesis [105]. Smoke from biomass burning was also found to modify the environment conditions during a tornado outbreak case in southeastern United States, by producing more CCN and strengthening capping inversion above clouds, which is conducive for greater tornado intensity and longevity [101•].

Likewise, aerosols can modify the thermodynamic and microphysical conditions influencing tropical cyclones (TC) generation. On the one hand, by reducing the radiation reaching the sea surface, aerosol could perturb TC genesis

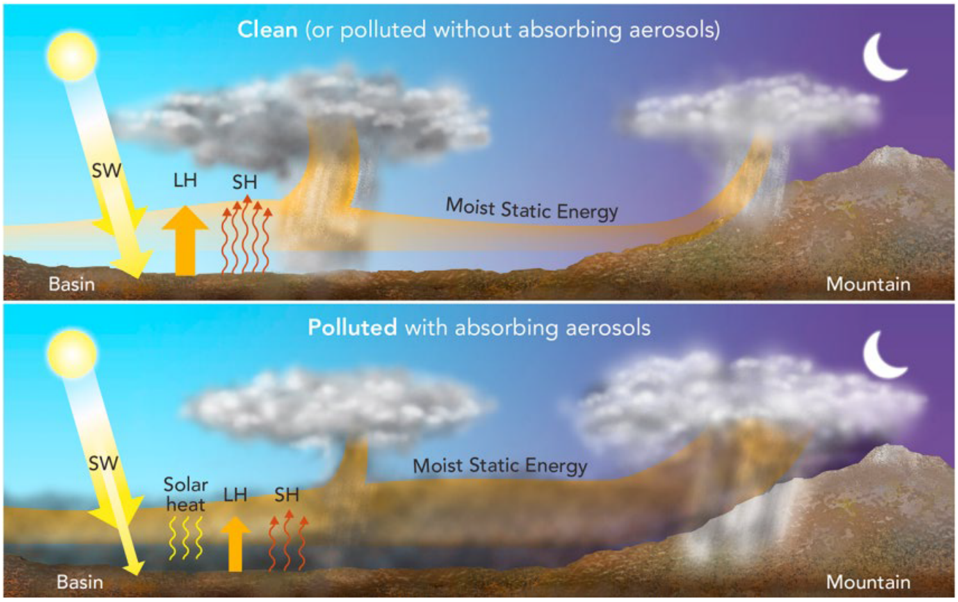

Fig. 2 An illustration of the mechanism of aerosol-induced catastrophic flood in the Sichuan Basin in summer 2013. Note: SW stands for shortwave radiation. SH is short for surface sensible heat flux, and LH is surface latent heat flux. Sourced from Fan et al. [95•]

and development, although dynamic factors play the leading role in most cases [107, 108]. On the other hand, an increase of CCN at the inner TC tends to magnify its intensity, while aerosol suspending at periphery leads to weakening of TC systems [109, 110]. Additionally, the plume complexes emitted from forest fires were found to favor the formation of pyrocumulonimbus clouds reaching the height of 15 km. Evaporation of moisture in pyrocumulonimbus clouds leads to descent and the release of suspended precipitation, which produce thunderstorms with the threat of downbursts and generate hundreds of lightning strokes, further increasing the risks of new fire ignitions [111, 112].

Impact on Planetary Boundary Layer and Haze Pollution

In addition to large-scale synoptic forcing, the growth of the PBL during daytime is mainly driven by surface heating and upper PBL entrainment [113••, 114], which are related to surface energy input and boundary layer stratification, respectively. Since aerosols could directly interact with solar radiation and perturb the Earth–atmosphere energy budget, the PBL evolution was greatly affected by aerosols in two ways. On the one hand, the incident solar energy is attenuated by atmospheric column extinction caused by radiative aerosols. The radiative forcing of aerosols exhibits tremendous heterogeneity in spatial distribution and variety for different aerosol species with various optical properties [115, 116]. High $PM_{2.5}$ concentration could cause over 50% decrease of surface solar radiation as well as a drastic surface temperature drop [117, 118•]. The deficient energy input resulted from less down-welling shortwave radiation at surface decrease the magnitude of turbulent latent and sensible heat flux, while the latter is in charge of the daytime development of PBL [119, 120]. On the other hand, the absorbing aerosols such as BC could warm the atmosphere above, altering the atmospheric thermodynamic structure. The impact of absorbing aerosols on stratification is closely related to its vertical distribution [121]. When located near the surface, aerosol absorbing radiation would heat near-surface layer and promote the PBL entrainment. On the contrary, absorbing aerosol plume at the upper PBL, which is more common during regional pollution episodes, is more efficient to strengthen the inversion layer, leading to an increasing stability [122, 123]. For instance, the turbulent kinetic energy in the surface mixing layer at the base of the atmosphere is observed to decrease concurrently with an increase in absorbing aerosols [124].

Both of the two processes mentioned before contribute to the decay of turbulence and mixing within PBL, through decreased surface heat flux and enhanced stability, resulting in a shallower boundary layer [118•, 125, 126•]. Combining *in situ* observations together with numerical simulations, Zhong et al. [127] and Ding et al. [128••] have revealed the surface cooling as well as upper level warming by $PM_{2.5}$ contribute to anomalous inversion which reduces turbulent diffusion and boundary layer height. Aerosol-induced reduction in PBL height is estimated by a statistical method, and

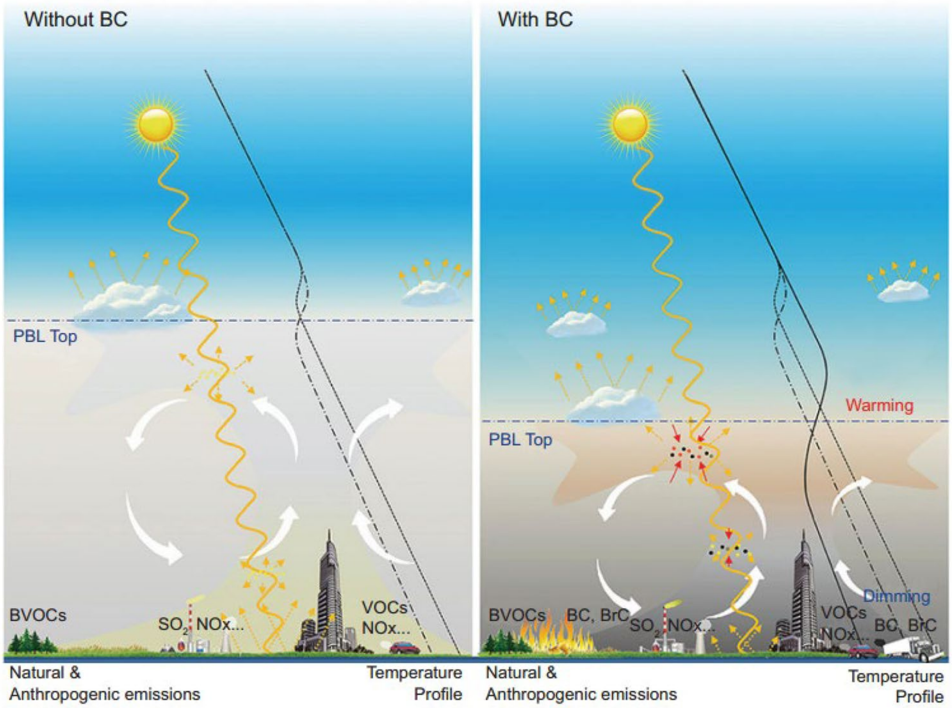

Fig. 3 A schematic figure showing the aerosol–boundary layer feedback loop for scenarios without and with black carbon (BC) emissions in a megacity. The black lines represent vertical temperature profiles. The yellow dashed lines with arrows denote the reflection of solar radiation by the ground surface, clouds, and aerosols. The red arrows show absorption of solar radiation by absorbing aerosols. The blue dash-dotted line indicates the top of the PBL. White arrows show the vertical ventilation of urban plumes induced by circulations or large eddies induced by the urban heat island effect. Sourced from Ding et al. [128••]

Zou et al. [120] found that PBL height decrease more rapidly with increasing aerosol loadings. Due to weakened vertical diffusion and turbulent mixing, wind speed in lower troposphere also shows a reduction under the influence of aerosols [129]. The visibility within PBL is also greatly deteriorated by light attenuation due to aerosol extinction [130]. During the pollution episodes, degradation of visibility is commonly observed accompanied with high aerosol concentration in an exponential relationship [131]. The hygroscopic growth of aerosol particles at high relative humidity leads to further reduction on atmospheric visibility [132, 133].

In turn, aerosols and other primary pollutants released from emission sources near the surface are to a large extent blocked within the PBL. Under relatively constant synoptic-scale weather conditions, the development and vertical structure of PBL represent an important factor modulating spatial–temporal distribution of local pollutants. A suppressed boundary layer height tends to increase locally emitted pollutant concentration due to much weakened dilution. Negative relationship between surface $PM_{2.5}$ concentration and convective PBL height was identified by studies combining theoretical analysis with observational data [117, 134•]. As shown in Fig. 3, the two-way feedback between PBL meteorology and aerosol particles exists over heavily polluted region during pollution transport and cumulative stages [128••, 135]. The positive feedback not only suppresses the development of daytime convective mixing layer but also modulates the nocturnal boundary layer. The increased air temperature in the residual layer at nighttime can also contribute to the formation of an inversion and increase the stability of a nocturnal stable boundary layer, favoring the accumulation of air pollutants in megacities [136].

Moreover, the reduction of solar radiation and air temperature within the boundary layer could weaken the photochemical reactions and thus ozone production. The surplus NO_x even tends to deplete ozone through its titration effect, exerting an impact on atmospheric oxidizing capacity [129, 137]. The surface cooling by $PM_{2.5}$ decreases near-ground saturation vapor pressure and significantly increases relative humidity. Simultaneously, it reduced vertical turbulence and PBL height trap primary pollutants and accumulates water vapor. Many studies have demonstrated that the formation of secondary PM is strongly linked to relative humidity [138, 139]. High moisture condition would further enhance aerosol hygroscopic growth and accelerate liquid phase and heterogeneous reactions, inducing additional secondary

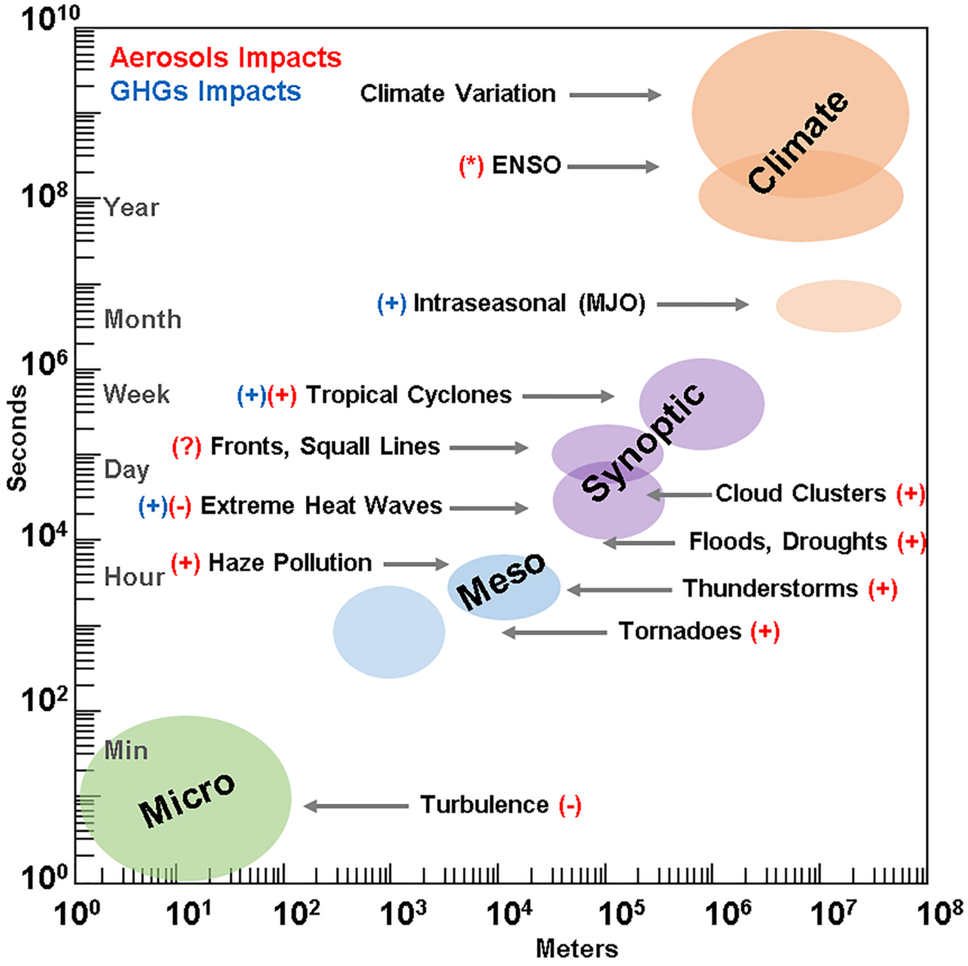

Fig. 4 Summary of aerosols and GHGs impact on weather phenomena at different spatial and temporal scales. Notation: the plus (+) indicates aerosols/GHGs generally exert a positive effect on such phenomenon, while minus (-) indicates negative effect. The asterisk (*) marks controversial effects which are still under debate and the question mark (?) indicates the current knowledge gap which requires further study

aerosol formation, which further enhance the feedback loop and deteriorate the air quality [127, 140•].

Concluding Remarks

Atmospheric aerosol from both natural and anthropogenic activities has long been acknowledged as one of the most important factors influencing global climate change. In this work, we present a comprehensive review of current understanding on the role of atmospheric aerosols in the development and evolution of extreme meteorological events, including monsoon circulation, heat waves, extreme rainfall, tornadoes, and severe air pollution (Fig. 4, Table S1). Overall, aerosols could influence the development of meteorological systems through direct and indirect effects. Surface dimming and cooling due to aerosol extinction can partly offset the global warming caused by GHGs, although such effect is weakening owing to strict emission control measurements. Large-scale precipitation from shallow stratiform clouds was found to be suppressed by aerosols, while invigoration effects contribute to deep convection and even catastrophic floods in local areas. The occurrence of severe weather events such as tornadoes and tropical cyclone is also related to aerosol concentration and distribution. Moreover, a positive feedback between aerosols and boundary layer meteorology is proposed as an important factor conducive to heavy haze pollution over urban areas.

However, there are still a wide range of fundamental characteristics and key processes that are poorly understood or neglected, which requires integrated observations and seamless coupling of atmospheric aerosol and meteorology in models. Studies have highlighted the significance of investigating the vertical structure of atmospheric processes in detail in the lower atmosphere, which is very important for improving the understanding of the interaction of atmospheric physics and chemistry. A dense network of both aerosol and meteorological measurements is needed to gain an explicit insight into the roles of aerosols played in large-scale and local-scale extreme meteorological events. In terms of numerical simulations, current climate and regional models show large uncertainties, and even opposite results of the indirect effect of aerosols. The discrepancy could be attributed to inaccurate parameterization of sub-grid processes as well as aerosol–cloud interactions that were poorly described in simulations with coarse grid resolution [141]. Moreover, existing models fail to forecast regional weather during extremely high episodes in China, since the mechanism described here is not included in a proper way in models. Therefore, it is crucial to include the feedback-loop in air quality and weather forecasts and as part of an early warning system for extreme air quality episodes. Furthermore, better understanding of aerosol's impact helps identify its proper role in solar radiation management of geoengineering, which requires accurate prediction of consequences.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

1.•• Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, et al. Climate Change 2021: the physical science basis Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Switzerland: IPCC; 2021. **This report comprehensively reviewed the climate forcing and effects of aerosols based on observational and simulation studies.**
2. Meehl GA, Tebaldi C. More intense more frequent and longer lasting heat waves in the 21st century. Science. 2004;305:994–7.
3. Piao S, Ciais P, Huang Y, Shen Z, Peng S, Li J, et al. The impacts of climate change on water resources and agriculture in China. Nature. 2010;467:43–51.
4. Pope CA 3rd, Dockery DW. Health effects of fine particulate air pollution: lines that connect. J Air Waste Manag Assoc. 2006;56:709–42.
5. Brunekreef B, Holgate ST. Air pollution and health. Lancet. 2002;360:1233–42.
6.•• Twomey S. Pollution and the planetary albedo. Atmos Environ. 1974;8:1251–6. **This study revealed the importance of indirect effect of aerosols serving as cloud condensation nuclei.**
7.• Hansen J, Sato M, Ruedy R. Radiative forcing and climate response. J Geophys Res Atmos. 1997;102:6831–64. **This article examined the sensitivity of climate models to radiative forcing of different atmospheric components.**
8. Haywood J, Boucher O. Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: a review. Rev Geophys. 2000;38:513–43.
9. Chan CK, Yao X. Air pollution in mega cities in China. Atmos Environ. 2008;42:1–42.
10. Huang RJ, Zhang Y, Bozzetti C, Ho KF, Cao JJ, Han Y, et al. High secondary aerosol contribution to particulate pollution during haze events in China. Nature. 2014;514:218–22.

11. Ji D, Li L, Wang Y, Zhang J, Cheng M, Sun Y, et al. The heaviest particulate air-pollution episodes occurred in northern China in January 2013: insights gained from observation. Atmos Environ. 2014;92:546–56.
12. Lelieveld J, Crutzen PJ, Ramanathan V, Andreae MO, Brenninkmeijer CAM, Campos T, et al. The Indian ocean experiment: widespread air pollution from South and Southeast Asia. Science. 2001;291:1031–6.
13. Ramanathan V, Crutzen PJ, Lelieveld J, Mitra AP, Althausen D, Anderson J, et al. Indian Ocean experiment: an integrated analysis of the climate forcing and effects of the great Indo-Asian haze. J Geophys Res Atmos. 2001;106:28371–98.
14. Duffy PB, Tebaldi C. Increasing prevalence of extreme summer temperatures in the US. Clim Change. 2012;111:487–95.
15. Ashley WS, Ashley ST. Flood fatalities in the United States. J Appl Meteorol Climatol. 2008;47:805–18.
16.• Mueller B, Seneviratne SI. Hot days induced by precipitation deficits at the global scale. Proc Natl Acad Sci USA. 2012;109:12398–403. **This article examined the strong linkage between hot extremes and moisture deficits, indicating widespread moisture-temperature coupling relationship.**
17. Jimenez-Munoz JC, Mattar C, Barichivich J, Santamaria-Artigas A, Takahashi K, Malhi Y, et al. Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Nino 2015–2016. Sci Rep. 2016;6:33130.
18. Cayan DR, Redmond KT, Riddle LG. ENSO and hydrologic extremes in the western United States. J Clim. 1999;12:2881–93.
19. Camargo SJ, Ting M, Kushnir Y. Influence of local and remote SST on North Atlantic tropical cyclone potential intensity. Clim Dyn. 2012;40:1515–29.
20.• Brown SJ, Stott PA, Christidis N. The role of human activity in the recent warming of extremely warm daytime temperatures. J Clim. 2011;24:1922–30. **This work showed evidence of a significant anthropogenic influences on the occurrence of extreme warm climate.**
21. Doocy S, Daniels A, Murray S, Kirsch TD. The human impact of floods: a historical review of events 1980–2009 and systematic literature review. PLoS Curr. 2013;5.
22. Mitchell JFB, Lowe J, Wood RA, Vellinga M. Extreme events due to human-induced climate change. Philos Trans R Soc A Math Phys Eng Sci. 2006;364:2117–33.
23. Cowan T, Undorf S, Hegerl GC, Harrington LJ, Otto FEL. Present-day greenhouse gases could cause more frequent and longer Dust Bowl heatwaves. Nat Clim Change. 2020;10:505–10.
24. Barnett TP, Adam JC, Lettenmaier DP. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature. 2005;438:303–9.
25. Gryspeerdt E, Stier P, Partridge DG. Links between satellite-retrieved aerosol and precipitation. Atmos Chem Phys. 2014;14:9677–94.
26. Khain AP, Ilotoviz E, Benmoshe N, Phillips VTJ, Ryzhkov AV. Effect of aerosols on freezing drops hail and precipitation in a midlatitude storm. J Atmos Sci. 2016;73:109–44.
27. Fiore AM, Mascioli NR, Previdi M, Correa G. Temperature and precipitation extremes in the United States: quantifying the responses to anthropogenic aerosols and greenhouse gases +. J Clim. 2016;29:2689–701.
28. Touma D, Stevenson S, Lehner F, Coats S. Human-driven greenhouse gas and aerosol emissions cause distinct regional impacts on extreme fire weather. Nat Commun. 2021;12:212.
29. Mora C, Spirandelli D, Franklin EC, Lynham J, Kantar MB, Miles W, et al. Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. Nat Clim Change. 2018;8:1062–71.
30. Stott PA, Allen M, Christidis N, Dole RM, Hoerling M, Huntingford C, et al. Attribution of weather and climate-related events. In: Asrar GR, Hurrell JW, editors., et al., Climate science for serving society: research modeling and prediction priorities. Dordrecht: Springer, Netherlands; 2013. p. 307–37.
31. Iacono MJ, Delamere JS, Mlawer EJ, Shephard MW, Clough SA, Collins WD. Radiative forcing by long-lived greenhouse gases: calculations with the AER radiative transfer models. J Geophys Res. 2008;113.
32.• Stanhill G, Cohen S. Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. Agric For Meteorol. 2001;107:255–78. **This article examined the reduction in solar radiation caused by anthropogenic aerosols using accurate measurements.**
33. Charlson R, Schwartz S, Hales J, Cess R, Coakley JA Jr, Hansen J, et al. Climate Forcing by Anthropogenic Aerosols. Science. 1992;255:423–30.
34. Gilgen H, Wild M, Ohmura A. Means and trends of shortwave irradiance at the surface estimated from global energy balance archive data. J Clim. 1998;11:2042–61.
35. Chen W, Dong B, Wilcox L, Luo F, Dunstone N, Highwood EJ. Attribution of recent trends in temperature extremes over China: role of changes in anthropogenic aerosol emissions over Asia. J Clim. 2019;32:7539–60.
36. Shiogama H, Christidis N, Caesar J, Yokohata T, Nozawa T, Emori S. Detection of greenhouse gas and aerosol influences on changes in temperature extremes. SOLA. 2006;2:152–5.
37. Zhong S, Qian Y, Zhao C, Leung R, Wang H, Yang B, et al. Urbanization-induced urban heat island and aerosol effects on climate extremes in the Yangtze River Delta region of China. Atmos Chem Phys. 2017;17:5439–57.
38. Bernstein DN, Neelin JD, Li QB, Chen D. Could aerosol emissions be used for regional heat wave mitigation? Atmos Chem Phys. 2013;13:6373–90.
39. Dave P, Bhushan M, Venkataraman C. Absorbing aerosol influence on temperature maxima: An observation based study over India. Atmos Environ. 2020;223:117237.
40. Song F, Zhou T, Qian Y. Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models. Geophys Res Lett. 2014;41:596–603.
41.• Bollasina MA, Ming Y, Ramaswamy V. Anthropogenic aerosols and the weakening of the South Asian summer monsoon. Science. 2011;334:502–5. **This work linked the summertime drying trend over South Asia to human influenced aerosol emissions by a series of climate model experiments.**
42. Sarangi C, Kanawade VP, Tripathi SN, Thomas A, Ganguly D. Aerosol-induced intensification of cooling effect of clouds during Indian summer monsoon. Nat Commun. 2018;9:3754.
43. Zhu J, Liao H, Li J. Increases in aerosol concentrations over eastern China due to the decadal-scale weakening of the East Asian summer monsoon. Geophys Res Lett. 2012;39.
44. Zhang L, Liao H, Li J. Impacts of Asian summer monsoon on seasonal and interannual variations of aerosols over eastern China. J Geophys Res. 2010;115.
45.•• Lau KM, Kim MK, Kim KM. Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau. Clim Dyn. 2006;26:855–64. **This article proposed the well-known "elevated heat pump" theory to explain the role of aerosols with the impact of Tibetan Plateau topography.**
46. Meehl GA, Arblaster JM, Collins WD. Effects of black carbon aerosols on the Indian monsoon. J Clim. 2008;21:2869–82.
47. Lau WKM, Kim KM, Shi JJ, Matsui T, Chin M, Tan Q, et al. Impacts of aerosol-monsoon interaction on rainfall and circulation over Northern India and the Himalaya Foothills. Clim Dyn. 2017;49:1945–60.
48. Zhao C, Liu X, Ruby Leung L, Hagos S. Radiative impact of mineral dust on monsoon precipitation variability over West Africa. Atmos Chem Phys. 2011;11:1879–93.

49. Ding K, Huang X, Ding A, Wang M, Su H, Kerminen VM, et al. Aerosol-boundary-layer-monsoon interactions amplify semi-direct effect of biomass smoke on low cloud formation in Southeast Asia. Nat Commun. 2021;12:6416.
50. Liu Y, Sun JR, Yang B. The effects of black carbon and sulphate aerosols in China regions on East Asia monsoons. Tellus B Chem Phys Meteorol. 2009;61:642–56.
51. Jiang Y, Yang X-Q, Liu X, Yang D, Sun X, Wang M, et al. Anthropogenic aerosol effects on East Asian winter monsoon: the role of black carbon-induced Tibetan Plateau warming. J Geophys Res Atmos. 2017;122:5883–902.
52. Lou SJ, Yang Y, Wang HL, Smith SJ, Qian Y, Rasch PJ. Black carbon amplifies haze over the North China Plain by weakening the East Asian winter monsoon. Geophys Res Lett. 2019;46:452–60.
53. Niu F, Li ZQ, Li C, Lee KH, Wang MY. Increase of wintertime fog in China: Potential impacts of weakening of the Eastern Asian monsoon circulation and increasing aerosol loading. J Geophys Res Atmos. 2010;115:12.
54. Wang B, Wu ZW, Chang CP, Liu J, Li JP, Zhou TJ. Another look at interannual-to-interdecadal variations of the East Asian winter monsoon: the northern and southern temperature modes. J Clim. 2010;23:1495–512.
55. Lou S, Yang Y, Wang H, Lu J, Smith SJ, Liu F, et al. Black carbon increases frequency of extreme ENSO events. J Clim. 2019;32:8323–33.
56. Allen RJ, Evan AT, Booth BBB. Interhemispheric aerosol radiative forcing and tropical precipitation shifts during the late twentieth century. J Clim. 2015;28:8219–46.
57. McGregor S, Timmermann A. The effect of explosive tropical volcanism on ENSO. J Clim. 2011;24:2178–91.
58. Khodri M, Izumo T, Vialard J, Janicot S, Cassou C, Lengaigne M, et al. Tropical explosive volcanic eruptions can trigger El Nino by cooling tropical Africa. Nat Commun. 2017;8:13.
59.• Yang Y, Russell LM, Lou S, Lamjiri MA, Liu Y, Singh B, et al. Changes in sea salt emissions enhance ENSO variability. J Clim. 2016;29:8575–88. **This article quantified the interactions between sea salt emissions and El Nino-Southern Oscillation.**
60. Allen RJ, Norris JR, Kovilakam M. Influence of anthropogenic aerosols and the Pacific decadal oscillation on tropical belt width. Nat Geosci. 2014;7:270–4.
61. Ming Y, Ramaswamy V. Nonlinear climate and hydrological responses to aerosol effects. J Clim. 2009;22:1329–39.
62.• Cunningham P, Reeder MJ. Severe convective storms initiated by intense wildfires: numerical simulations of pyro-convection and pyro-tornadogenesis. Geophys Res Lett. 2009;36. **This work reported and analyzed an intensive wildfire and the subsequent severe storm using large eddy simulation.**
63. Kablick G, Fromm M, Miller S, Partain P, Peterson D, Lee S, et al. The Great Slave Lake PyroCb of 5 August 2014: observations simulations comparisons with regular convection and impact on UTLS water vapor. J Geophys Res Atmos. 2018;123:12332–52.
64. Christian K, Wang J, Ge C, Peterson D, Hyer E, Yorks J, et al. Radiative forcing and stratospheric warming of pyrocumulonimbus smoke aerosols: first modeling results with multisensor (EPIC CALIPSO and CATS) views from space. Geophys Res Lett. 2019;46:10061–71.
65. Zhang Y, Fan J, Logan T, Li Z, Homeyer CR. Wildfire impact on environmental thermodynamics and severe convective storms. Geophys Res Lett. 2019;46:10082–93.
66. Wang Z, Lin L, Yang M, Xu Y. The effect of future reduction in aerosol emissions on climate extremes in China. Clim Dyn. 2016;47:2885–99.
67. Zhao A, Bollasina MA, Stevenson DS. Strong influence of aerosol reductions on future heatwaves. Geophys Res Lett. 2019;46:4913–23.
68. Samset BH, Sand M, Smith CJ, Bauer SE, Forster PM, Fuglestvedt JS, et al. Climate impacts from a removal of anthropogenic aerosol emissions. Geophys Res Lett. 2018;45:1020–9.
69. Wang Y, Le T, Chen G, Yung YL, Su H, Seinfeld JH, et al. Reduced European aerosol emissions suppress winter extremes over northern Eurasia. Nat Clim Change. 2020;10:225–30.
70.•• Ramanathan V, Crutzen PJ, Kiehl JT, Rosenfeld D. Aerosols climate and the hydrological cycle. Science. 2001;294:2119–24. **This work comprehensively introduced the effect aerosols on the earth energy budget and hydrological cycle.**
71. Hodnebrog O, Myhre G, Forster PM, Sillmann J, Samset BH. Local biomass burning is a dominant cause of the observed precipitation reduction in southern Africa. Nat Commun. 2016;7:11236.
72. Andreae MO, Rosenfeld D, Artaxo P, Costa AA, Frank GP, Longo KM, et al. Smoking rain clouds over the Amazon. Science. 2004;303:1337–42.
73. Zhang L, Wu P, Zhou T. Aerosol forcing of extreme summer drought over North China. Environ Res Lett. 2017;12:034020.
74. Baskar G, Gvt GK. Correlation of aerosol optical depth and spatial rainfall variability patterns for the assessment of meteorological drought. 2016.
75. Sarthi PP, Kumar S, Barat A, Kumar P, Sinha AK, Goswami V. Linkage of aerosol optical depth with rainfall and circulation parameters over the Eastern Gangetic Plains of India. J Earth Syst Sci. 2019;128.
76. Huang Y, Chameides WL, Dickinson RE. Direct and indirect effects of anthropogenic aerosols on regional precipitation over east Asia. J Geophys Res. 2007;112.
77. Tosca MG, Randerson JT, Zender CS. Global impact of smoke aerosols from landscape fires on climate and the Hadley circulation. Atmos Chem Phys. 2013;13:5227–41.
78. Menon S, Hansen J, Nazarenko L, Luo Y. Climate effects of black carbon aerosols in China and India. Science. 2002;297:2250–3.
79. Hui WJ, Cook BI, Ravi S, Fuentes JD, D'Odorico P. Dust-rainfall feedbacks in the West African sahel. Water Resour Res. 2008;44:6.
80. Min QL, Li R, Lin B, Joseph E, Wang S, Hu Y, et al. Evidence of mineral dust altering cloud microphysics and precipitation. Atmos Chem Phys. 2009;9:3223–31.
81. Yin Y, Chen L. The effects of heating by transported dust layers on cloud and precipitation: a numerical study. Atmos Chem Phys. 2007;7:3497–505.
82. Huang JP, Wang TH, Wang WC, Li ZQ, Yan HR. Climate effects of dust aerosols over East Asian arid and semiarid regions. J Geophys Res Atmos. 2014;119:11398–416.
83. Mitchell JFB, Johns TC. On modification of global warming by sulfate aerosols. J Clim. 1997;10:245–67.
84. Roeckner E, Bengtsson L, Feichter J, Lelieveld J, Rodhe H. Transient climate change simulations with a coupled atmosphere–ocean GCM including the tropospheric sulfur cycle. J Clim. 1999;12:3004–32.
85. Wang C. A modeling study on the climate impacts of black carbon aerosols. J Geophys Res Atmos. 2004;109.
86. Mukai M, Nakajima T. Potentiality of aerosols in changing the precipitation field in Asia. SOLA. 2009;5:97–100.
87. Koren I, Kaufman YJ, Remer LA, Martins JV. Measurement of the effect of Amazon smoke on inhibition of cloud formation. Science. 2004;303:1342–5.

88. Tao W-K, Chen J-P, Li Z, Wang C, Zhang C. Impact of aerosols on convective clouds and precipitation. Rev Geophys. 2012;50.
89. Rosenfeld D. Flood or Drought: How Do Aerosols Affect Precipitation? Science. 2008;321:1309.
90. Vinoj V, Rasch PJ, Wang H, Yoon J-H, Ma P-L, Landu K, et al. Short-term modulation of Indian summer monsoon rainfall by West Asian dust. Nat Geosci. 2014;7:308–13.
91. Tao W-K, Li X, Khain A, Matsui T, Lang S, Simpson J. Role of atmospheric aerosol concentration on deep convective precipitation: cloud-resolving model simulations. J Geophys Res. 2007;112.
92. Guo J, Deng M, Lee SS, Wang F, Li Z, Zhai P, et al. Delaying precipitation and lightning by air pollution over the Pearl River Delta Part I: observational analyses. J Geophys Res Atmos. 2016;121:6472–88.
93. Lee SS, Donner LJ, Phillips VTJ, Ming Y. Examination of aerosol effects on precipitation in deep convective clouds during the 1997 ARM summer experiment. Q J R Meteorol Soc. 2008;134:1201–20.
94. Khain A, Rosenfeld D, Pokrovsky A. Aerosol impact on the dynamics and microphysics of deep convective clouds. Q J R Meteorol Soc. 2005;131:2639–63.
95.● Fan J, Rosenfeld D, Yang Y, Zhao C, Leung LR, Li Z. Substantial contribution of anthropogenic air pollution to catastrophic floods in Southwest China. Geophys Res Lett. 2015;42:6066–75. **This work showed that aerosol pollution would contribute to suppressed convection and excess moist air transported to mountainous areas, which leads to extreme rainfall.**
96. Huang X, Ding A, Liu L, Liu Q, Ding K, Niu X, et al. Effects of aerosol–radiation interaction on precipitation during biomass-burning season in East China. Atmos Chem Phys. 2016;16:10063–82.
97. Jin M. Urban aerosols and their variations with clouds and rainfall: a case study for New York and Houston. J Geophys Res. 2005;110.
98. Shepherd JM, Burian SJ. Detection of urban-induced rainfall anomalies in a major coastal city. Earth Interact. 2003;7:1–17.
99. Khain AP. Notes on state-of-the-art investigations of aerosol effects on precipitation: a critical review. Environ Res Lett. 2009;4:015004.
100.●●Fan J, Wang Y, Rosenfeld D, Liu X. Review of aerosol–cloud interactions: mechanisms, significance, and challenges. J Atmos Sci. 2016;73:4221–52. **The article reviewed theoretical studies and important mechanisms on aerosol-cloud interactions and discussed the significances of aerosol impacts on radiative forcing and precipitation extremes.**
101.● Saide PE, Spak SN, Pierce RB, Otkin JA, Schaack TK, Heidinger AK, et al. Central American biomass burning smoke can increase tornado severity in the US. Geophys Res Lett. 2015;42:956–65. **This work suggested the presence of smoke leads to thickening of shallow clouds as well as enhance the capping inversion, favoring tornadogenesis and tornado intensity.**
102. Yang X, Li Z. Increases in thunderstorm activity and relationships with air pollution in southeast China. J Geophys Res Atmos. 2014;119:1835–44.
103. Bell TL, Rosenfeld D, Kim K-M, Yoo J-M, Lee M-I, Hahnenberger M. Midweek increase in U.S. summer rain and storm heights suggests air pollution invigorates rainstorms. J Geophys Res. 2008;113.
104. Lerach DG, Gaudet BJ, Cotton WR. Idealized simulations of aerosol influences on tornadogenesis. Geophys Res Lett. 2008;35.
105. Cotton WR, Lerach DG. Comparing aerosol and low-level moisture influences on supercell tornadogenesis: three-dimensional idealized simulations. J Atmos Sci. 2012;69:969–87.
106. Rosenfeld D, Bell TL. Why do tornados and hailstorms rest on weekends? J Geophys Res. 2011;116.
107. Rosenfeld D, Woodley WL, Khain A, Cotton WR, Carrió G, Ginis I, et al. Aerosol effects on microstructure and intensity of tropical cyclones. Bull Am Meteorol Soc. 2012;93:987–1001.
108. Wang Y, Lee K-H, Lin Y, Levy M, Zhang R. Distinct effects of anthropogenic aerosols on tropical cyclones. Nat Clim Change. 2014;4:368–73.
109. Benmoshe N, Shpund J, Rosenfeld D, Kelman G, Yuan T, Michelson SA, et al. The sensitivity of hurricane Irene to aerosols and ocean coupling: simulations with WRF spectral bin microphysics. J Atmos Sci. 2016;73:467–86.
110. Khain A, Lynn B, Shpund J. High resolution WRF simulations of Hurricane Irene: Ssensitivity to aerosols and choice of microphysical schemes. Atmos Res. 2016;167:129–45.
111. Dowdy AJ, Fromm MD, McCarthy N. Pyrocumulonimbus lightning and fire ignition on Black Saturday in southeast Australia. J Geophys Res Atmos. 2017;122:7342–54.
112. Rosenfeld D, Fromm M, Trentmann J, Luderer G, Andreae MO, Servranckx R. The Chisholm firestorm observed microstructure, precipitation and lightning. Atmos Chem Phys. 2007;7(3):645–59.
113.●●Stull RBE. An introduction to boundary layer meteorology. Dordrecht: Springer Netherlands; 1988. **This article systematically introduce the fundamental theory and basic physical processes of planetary boundary layer.**
114. Sühring M, Maronga B, Herbort F, Raasch S. On the effect of surface heat-flux heterogeneities on the mixed-layer-top entrainment. Bound Layer Meteorol. 2014;151:531–56.
115. Myhre G, Samset BH, Schulz M, Balkanski Y, Bauer S, Berntsen TK, et al. Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations. Atmos Chem Phys. 2013;13:1853–77.
116. Huang X, Song Y, Zhao C, Cai X, Zhang H, Zhu T. Direct radiative effect by multicomponent aerosol over China. J Clim. 2015;28:3472–95.
117. Wang J, Wang S, Jiang J, Ding A, Zheng M, Zhao B, et al. Impact of aerosol–meteorology interactions on fine particle pollution during China's severe haze episode in January 2013. Environ Res Lett. 2014;9:094002.
118.● Ding A, Fu C, Yang X, Sun J, Petäjä T, Kerminen VM, et al. Intense atmospheric pollution modifies weather: a case of mixed biomass burning with fossil fuel combustion pollution in eastern China. Atmos Chem Phys. 2013;13:10545–54. **This work quantify the impact of air pollution on boundary layer dynamics and aerosol-radiation-cloud feedbacks by comprehensive measurements.**
119. Petaja T, Jarvi L, Kerminen VM, Ding AJ, Sun JN, Nie W, et al. Enhanced air pollution via aerosol-boundary layer feedback in China. Sci Rep. 2016;6:18998.
120. Zou J, Sun J, Ding A, Wang M, Guo W, Fu C. Observation-based estimation of aerosol-induced reduction of planetary boundary layer height. Adv Atmos Sci. 2017;34:1057–68.
121. Yu H, Liu SC, Dickinson RE. Radiative effects of aerosols on the evolution of the atmospheric boundary layer. J Geophys Res. 2002;107.
122. Barbaro E, Vilà-Guerau de Arellano J, Krol MC, Holtslag AAM. Impacts of Aerosol shortwave radiation absorption on the dynamics of an idealized convective atmospheric boundary layer. Bound Layer Meteorol. 2013;148:31–49.
123. Wang Z, Huang X, Ding A. Dome effect of black carbon and its key influencing factors: a one-dimensional modelling study. Atmos Chem Phys. 2018;18:2821–34.
124. Wilcox EM, Thomas RM, Praveen PS, Pistone K, Bender FA, Ramanathan V. Black carbon solar absorption suppresses turbulence in the atmospheric boundary layer. Proc Natl Acad Sci USA. 2016;113:11794–9.

125. Li Z, Guo J, Ding A, Liao H, Liu J, Sun Y, et al. Aerosol and boundary-layer interactions and impact on air quality. Natl Sci Rev. 2017;4:810–33.

126.• Zhong J, Zhang X, Wang Y, Liu C, Dong Y. Heavy aerosol pollution episodes in winter Beijing enhanced by radiative cooling effects of aerosols. Atmos Res. 2018; 209:59–64. **This work emphasized the aerosol's radiative cooling effects could exert remarkable impacts on the local synoptic weather and further aggravates aerosol pollution.**

127. Zhong J, Zhang X, Dong Y, Wang Y, Liu C, Wang J, et al. Feedback effects of boundary-layer meteorological factors on cumulative explosive growth of PM2.5 during winter heavy pollution episodes in Beijing from 2013 to 2016. Atmos Chem Phys. 2018;18:247–58.

128.••Ding AJ, Huang X, Nie W, Sun JN, Kerminen VM, Petäjä T, et al. Enhanced haze pollution by black carbon in megacities in China. Geophys Res Lett. 2016; 43:2873–9. **This article showed that absorbing aerosols play the key role in modifying the boundary layer meteorology and hence enhancing the haze pollution.**

129. Zhang B, Wang Y, Hao J. Simulating aerosol–radiation–cloud feedbacks on meteorology and air quality over eastern China under severe haze conditionsin winter. Atmos Chem Phys. 2015;15:2387–404.

130. Qu WJ, Wang J, Zhang XY, Wang D, Sheng LF. Influence of relative humidity on aerosol composition: impacts on light extinction and visibility impairment at two sites in coastal area of China. Atmos Res. 2015;153:500–11.

131. Zhang Q, Quan J, Tie X, Li X, Liu Q, Gao Y, et al. Effects of meteorology and secondary particle formation on visibility during heavy haze events in Beijing China. Sci Total Environ. 2015;502:578–84.

132. Liu PF, Zhao CS, Göbel T, Hallbauer E, Nowak A, Ran L, et al. Hygroscopic properties of aerosol particles at high relative humidity and their diurnal variations in the North China Plain. Atmos Chem Phys. 2011;11:3479–94.

133. Quan J, Zhang Q, He H, Liu J, Huang M, Jin H. Analysis of the formation of fog and haze in North China Plain (NCP). Atmos Chem Phys. 2011;11:8205–14.

134.• Miao Y, Liu S. Linkages between aerosol pollution and planetary boundary layer structure in China. Sci Total Environ. 2019;650:288–96. **This article investigated the linkages between boundary layer and aerosols and found PBL structure greatly modulate pollution variabilities.**

135. Liu L, Zhang X, Zhong J, Wang J, Yang Y. The 'two-way feedback mechanism' between unfavorable meteorological conditions and cumulative PM2.5 mass existing in polluted areas south of Beijing. Atmos Environ. 2019;208:1–9.

136. Huang X, Huang J, Ren C, Wang J, Wang H, Wang J, et al. Chemical boundary layer and its impact on air pollution in Northern China. Environ Sci Technol Lett. 2020;7:826–32.

137. Forkel R, Werhahn J, Hansen AB, McKeen S, Peckham S, Grell G, et al. Effect of aerosol-radiation feedback on regional air quality – a case study with WRF/Chem. Atmos Environ. 2012;53:202–11.

138. He H, Wang Y, Ma Q, Ma J, Chu B, Ji D, et al. Mineral dust and NOx promote the conversion of SO2 to sulfate in heavy pollution days. Sci Rep. 2014;4:4172.

139. Zheng GJ, Duan FK, Su H, Ma YL, Cheng Y, Zheng B, et al. Exploring the severe winter haze in Beijing: the impact of synoptic weather, regional transport and heterogeneous reactions. Atmos Chem Phys. 2015;15:2969–83.

140.• Huang X, Ding A, Wang Z, Ding K, Gao J, Chai F, et al. Amplified transboundary transport of haze by aerosol–boundary layer interaction in China. Nat Geosci. 2020. **This work highlighted the interactions between long-range transport and aerosol-boundary layer feedback during regional haze pollution.**

141. Gao Y, Fu JS, Drake JB, et al. Projected changes of extreme weather events in the eastern United States based on a high resolution climate modeling system. Environ Res Lett. 2012;7:044025.