Oxford Research Encyclopedia of Environmental Science

Air Pollution and Weather Interaction in East Asia

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Subject: Environmental Processes and Systems

Online Publication Date: Apr 2017 DOI: 10.1093/acrefore/9780199389414.013.536

Summary and Keywords

Air pollution is one of the grand environmental challenges in developing countries, especially those with high population density like China. High concentrations of primary and secondary trace gases and particulate matter (PM) are frequently observed in the industrialized and urbanized regions, causing negative effectson the health of humans, plants, and the ecosystem.

Meteorological conditionsareamong the most important factors influencing day-to-day air quality. Synoptic weather and boundary layer dynamics control the dispersion capacity and transport of air pollutants, while themain meteorological parameters, such as air temperature, radiation, and relative humidity, influence the chemical transformation of secondary air pollutants at the same time. Intense air pollution, especially high concentration of radiatively important aerosols, can substantially influence meteorological parameters, boundary layer dynamics, synoptic weather, and even regional climate through their strong radiative effects.

As one of the main monsoon regions, with the most intense human activities in the world, East Asia is a region experiencing complex air pollution, with sources from anthropogenic fossil fuel combustion, biomass burning, dust storms, andbiogenic emissions. A mixture of these different plumes can cause substantial two-way interactions and feedbacks in the formation of air pollutants under variousweather conditions. Improving the understanding of such interactions needs more field measurements using integratedmultiprocess measurement platforms, as well asmore efforts in developing numerical models, especially for those with online coupled processes. All these efforts are very important for policymaking from the perspectives of environmental protection and mitigation of climate change.

Keywords: Air pollution, synoptic weather, climate change, meteorological processes, feedbacks, aerosols, planetary boundary layer, East Asia

Air pollution and weather are separate topics in the atmospheric sciences, but both have been known to strongly interact. Synoptic weather and the associated multiscale meteorological processes are important factors influencing day-to-day air quality. Many meteorological parameters caninfluence the processes related to the formation and evolution of air pollution, such as emission, chemical reactions, dispersion, transport, and deposition of air pollutants (Jacob & Winner, 2009; Zhang et al., 2015; Kulmala et al., 2016). At the same time, many air pollutants, such as particulate matter (PM, also called aerosol), in the atmosphere are radiatively active. Because of different chemical compositions, optical properties, and roles in cloud formation, PM is the most important andcomplicated pollutant influencing the meteorological parameters (Ding et al., 2013a; IPCC, 2013).

East Asia has been suffering from poor air quality for several decades because of intense emissions from a huge amount of energy consumption associated with rapid industrialization and urbanization. Episodes with extremely high concentrations of air pollutants, such as PM and ozone (O_3), are frequently observed in this region, especially in the megacities of eastern China, causing negative impacts on human health and the ecosystem sustainability (Tie & Cao, 2009; Huang et al., 2014a; Guo et al., 2014a; Ding et al., 2016a). The interaction between meteorological processes and air pollutants has been found to play important roles in the formation of these extreme pollution episodes and in the modification of synoptic weather, bringing great challenges to the current understanding of environmental and climate systems and to the capability of air quality forecast and weather prediction in this region (Ding et al., 2013a).

To meet this challenge, this article brings the readers some fundamental concepts of the characteristics and sources of air pollution in East Asia, a region with complicated pollution sources, and shows how air pollution and synoptic weather interact by presenting some case studies. This article is expected to provide some new insights into the understanding of air pollution, weather, and climate issues in East Asia and to help bridge the gap between the environmental and atmospheric sciences in this region.

General Characteristics of Air Pollution and Its Sources in East Asia

Air quality in East Asian countries has experienced different stages in the latest two decades because of different progresses of industrialization and urbanization, as well asthe change of the energy-consuming structure. In Japan and South Korea, air pollution is nota major environmental issue any longer because of their relatively few high-emission industries and earlier applications of clean technology. In these two developed countries, air pollution episodes appear only occasionally, in megacities and under specific meteorological conditions. However, China(especially the plain areas in northern and eastern China) still suffers from poor air quality due to intense emissions from fossil fuel combustion sources related to fast economic development (Fig.1). Mitigation of haze pollution has been considered as the top priority of environment protection in this country since 2012, and many scientific efforts have been concentrated in understanding the sources and origins, chemical formation, and long-range transport of fine particles (also known as PM with aerodynamic diameters up to 2.5 µm,i.e., the so-called $PM_{2.5}$), as well as their impacts on weather and regional climate.

The air quality in eastern China is mainly characterized by high concentrations of $PM_{2.5}$ and secondary trace gases (e.g., O_3). Satellite-retrieved $PM_{2.5}$ shows that the North China Plain (NCP), with$PM_{2.5}$ concentrationsof over 100 μg/m^3 during 2010–2012, has the highest haze pollution in the entire East Asia (Fig.1). This is consistent with the ground-based measurements by the air-quality-monitoring network in China for 2013 (Wang et al., 2017), in which it was shown that the annual mean concentrations of $PM_{2.5}$were 110, 70, and 48 μg/m^3in the cities in the Beijing-Tianjing- Hebei (JJJ) area in the NCP, the Yangtze River Delta (YRD), and the Pearl River Delta (PRD), respectively (Wang et al., 2017). It was also reported that the annual mean $PM_{2.5}$ concentration in the three regions in 2015 dropped to about 85, 55, and 34 μg/m^3, respectively, because of strict emissions control measures carried out in those developed regions (Wang et al., 2017). In northern and eastern China, $PM_{2.5}$ concentration generally peaks in winter(e.g., December and January) because of poor dispersion conditions and more emissions related to civil heating. Despite a decreasing trend of annual $PM_{2.5}$ concentration, extreme haze events with hourly $PM_{2.5}$ concentrations over 500 μg/$m^3$are still frequently observed in megacities in North and East China such as Beijing, Zhengzhou, Nanjing, and Shanghai (Zhang et al., 2013; Wang et al., 2014a; 2014b; Ding et al., 2016a).

As opposed to $PM_{2.5}$, O_3, another important secondary pollutant, showed an overall summer maximum in East China, but a double-peak pattern (spring and autumn) in South China (Ding, Wang, Thouret, Cammas, &Nédélec, 2008;Ding et al., 2013b; Wang et al., 2009). All the available long-term observations showed a positive trend of O_3 in the three developed regions in the latest fewdecades (Ding et al., 2008; Xu et al., 2008; Wang et al., 2009). Primary trace gases, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), show similar seasonal variation with $PM_{2.5}$, while a significant decrease has been observed from ground-based and satellite measurements. For example, SO_2 shows a decreasing trend since 2006 because of strict control measures for coal-fired power plants in China (Wang et al., 2015a). Satellite-retrieved tropospheric NO_2 column concentration also showed a decreasing trend since 2011 in East China(Parrish, Xu, Croes, &Shao, 2016).

The most important source of air pollutants in Asia is fossil fuel combustion, which mainly consists of categories like industry, power plants, transportation, and residential sources (a sum of residential biofuel, fossil fuel, and noncombustion sources). According to the Multiresolution Emission Inventory for China (MEIC) database (http://www.meicmodel.org), the contributions of the categories of industry, power plants, transportation, and residential sources of NOx to the total fossil fuel combustion sources in China in 2010 were 38.6%, 32.5%, 25%, and 3.9%, respectively.

Besides these anthropogenic emissions, East Asia is also influenced by other complex pollution sources. Biomass burning, from either natural burning of forests and grasses or human-made burning of agricultural straw, is another important pollution source in Asia (Fig.2B). In Asia, the main biomass burning sources include springtime (March–April) forest burning in South Asia (Zhou et al., 2013), springtime (April–May) wildfires in Siberia (Jaffe et al., 2004), and agricultural straw burning in late spring and early summer (May-June)in eastern China (Huang, Li, Li, &Song, 2012; Ding et al., 2013a). The total amount of annual emissions from agricultural straw burning in East China was relatively lessthan biomass-burning emissions in South Asia and Siberia (Fig.2B) and fossil fuel combustion sources in eastern China (Fig.2A). However, because these activities generally occur in a very short period [e.g., 1–2 weeks after the harvest (Ding et al., 2013a)], the intensity of the emission is generally much higher than the fossil fuel combustion from cities (Huang et al., 2016).

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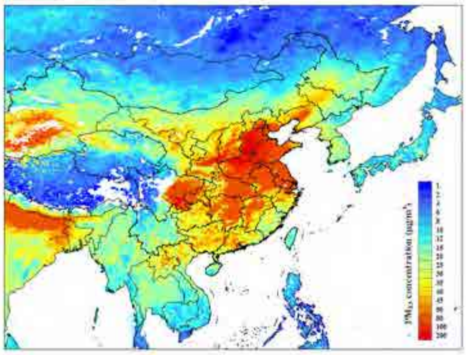

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*Figure 1.*Average satellite-retrieved $PM_{2.5}$ concentrations in East Asia (2010–2012).

Data from Socioeconomic Data and Applications Center (SEDAC) of NASA (van Donkelaar et al., 2015).

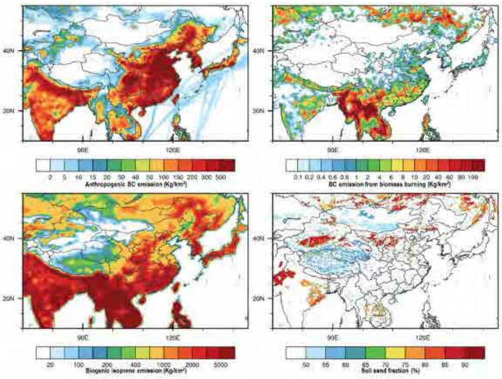

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Figure 2. Distributions of different emission sources in Asia in 2010. Black carbon annual emissions from (a) anthropogenic sources (Granier et al., 2011) and (b) biomass-burning sources (Kaiser et al., 2012);(c)isoprene emissions from biogenic sources (Sindelarova et al., 2014); and (d) soil and sand fraction (as the indicator of dust emission) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009).

Biogenic emissions from vegetation arean important natural source of reactive volatile organic components (VOCs), such as isoprene and monoterpene (Kesselmeier&Staudt, 1999), which are important precursors for ozone and secondary organic aerosols (Zhang, 2007a,2007b). Because of more forests and strong solar radiation, biogenic emissions of VOCs areparticularly strong in the lower latitudes of Asia, especially South Asia. The mountain areas of southern China, central northern China, and northeastern China, as well asNorth and South Korea and Japan,also have strong biogenic emissions because of a large coverage of forests (Fig.2C).

Another important seasonally varying natural pollution source in Asia is dust storms. The wind-blown dust, which originated from the Taklimakan and Gobi deserts in northwestern China in spring (Fig.2D), could be transported by large-scale circulation to East China, South China, and even wider regions in the Northern Hemisphere, such as the Pacific Ocean and North America (Zhang et al., 2003; Nie et al., 2012,2014; Huang, Wang, Wang, Li, &Yan,2014b). During the dust storms, PM concentration could rise to over 1,000μg/m^3 even after a long-range transport over a few thousand kilometers from the desert regions in Northwest China (Nie et al., 2014; Liu, Huang, Ding, &Fu, 2016a).

The unique distribution of different emission sources and the large-scale monsoon circulations results in a complex environment for the secondary formation of air pollutants in East Asia. Multiscale meteorological processes can cause a substantial mixing of different types of air pollutants and promote complicated chemical formation of secondary pollutants. It is worthwhile to point out that both dust and biomass-burning aerosols areradiatively active and could have strong radiative effects and play important roles in modifying meteorological parameters, making East Asia a unique region to study air pollution–weather interactions.

Main Synoptic Weather Influencing Air Pollution in East Asia

The formation of air pollution has been known to be influenced by multiple meteorological variables and processes (Jacob & Winner, 2009; Ding, Wang, Zhao, Wang, &Li, 2004,Ding et al., 2009). For example, air temperature is an important factor influencing emission and chemical reactions. In East Asian countries, because of very hot and humid summers and cold winters, the usage of electricity power related to air conditioners and heaters is strongly linked with ambient air temperature. Household emissions have even been found to be the major ambient pollution source in northern China in winter (Liu et al., 2016a). On the other hand, air temperature, humidity, and solar radiation are important factors influencing kinetic reaction rates and can promote the formation of secondary aerosols (Xie et al., 2015). The vertical structure of air temperature in the planetary boundary layer (PBL) is an important factor influencing turbulent mixing, which controls the dispersion of air pollutants around the sources, the development of daytime mixing layers, and the dry deposition velocity of many pollutants (Wesely& Hicks, 2000; Ding et al., 2004,2016a). Therefore, PBL dynamics is the most important factor for air quality near the ground surface. In addition tothese elements, precipitation and clouds can influence wet deposition(i.e., the wet removal) of water-soluble air pollutants, and winds and circulations are the important factors controlling the multiscale transport of air pollutants (Xu et al., 2006; Jacob & Winner, 2009).

Synoptic weather in East Asia is strongly influenced by the Asian monsoon system, which shows contrasting circulation patterns in cold and warm seasons (Ding & Chan, 2005; Fu, Ding, &Wu, 2017). The Siberian High and the Pacific High, dominant in cold and warm seasons respectively, are two of the most important anticyclonesin East Asia (Fig.3). In cold seasons, the strong Siberian High brings a massive collection of cold, dry air that accumulates on the northeastern part of the Eurasian continent and sweeps over East Asia to the lowlatitudes and the Pacific Ocean (Chen et al., 1991; Wong et al., 2007). In summer, South China and East China are dominated by thesouthwest summer monsoon and the Pacific High. The latter can cause extremely hot weather and less rainfall to these regions, except for the passage of the Northwest Pacific Typhoon (Ding et al., 2004; Ding & Chan, 2005). In late June to early July, the confrontation of the continental High withthe summer monsoon or the Pacific High tends to form a nearly stationary Meiyu front (also called theBeiu front in Japan) in the eastern part of China to South Japan, resulting in a persistent, heavy convective rainfall in this region, which is also called the plum rain season in China (Ding et al., 1992; Wang & Lin, 2002). Besides these large-scale weather systems, there are also smaller-scale weather processes in some specific regions caused by the forcing of large-scale topography. For example, the Southwestern LowVortex in the Sichuan Basin and the Lanzhou Small Anticyclone in Northwest China are two important weather phenomena induced by topographical effects of the Tibetan Plateau (Kuo et al., 1981; Li et al., 2006).

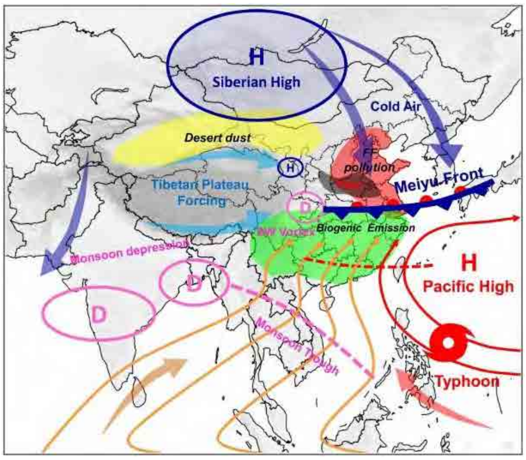

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*Figure 3.*The main synoptic weather systems and monsoon circulations in Asia.The main air pollution emission sources in China, such as fossil fuel (FF) pollution, desert dust, biogenic emission, and biomass burning, are marked indifferent colors. H and D indicate high-pressure (anticyclone) and low-pressure (cyclone), respectively.

Although there are various types of synoptic weather, their influences on air quality in a specific city or a region could be attributed into two aspects: (a) the impact oflocal air pollutant accumulation or removal process, and (b) the influence of long-range transport (Zhang et al., 2016). A cyclone (i.e., low pressure), associated with strong wind, more clouds and precipitation, less radiation, and cool air temperature, generally favors the removal of air pollutants and results in relatively good air quality. In contrast, an anticyclone generally favors the formation of air pollution because of strong solar radiation, high air temperature, weak (even calm) surface wind, and the associated large-scale subsidence. Cities often suffer from poor air quality (e.g., O_3 or $PM_{2.5}$ episodes) under the influence of an anticyclone, especially when they are continuously controlled by an anticyclone for several days (Zhang et al., 2016). The coldfront in the edge of an anticyclone, generally associated with strong wind, can cause long-range transport of air pollutants. Associated with cyclones and fronts, warm-conveyor belts (WCBs), with air originated at low levels in the warm sector and lifted by cold fronts and warm fronts in turn (Cooper,Moody, &Stohl,2001; Cooper et al., 2004), is one of the most efficient ways to lift large-scale surface air pollutants to the middle and even upper troposphere, where the air pollutants could experience substantial long-range transport by westerlies and jets (Cooper et al.,2001;Ding et al.,2009).

East Asia is theregion with the most frequent cyclogenesis in the world(Chen et al., 1991). Cyclones and anticyclones alternatively influence a region ona time scale of 3–7 days, which generally caused periodic strawlike air pollution in megacities (Guo et al., 2014a). In cold seasons, the passage of a cold front associated with the Siberian High could cause substantial equatorward and eastward long-range transport of air masses. The accumulated air pollutants in the front of cold fronts, mainly PM and its precursors, in the developed regions of East China(e.g., NCP and YRD) are easily transported to South China and even the North Pacific Ocean (Wang et al., 2003; Wong, Wang, Ding, Black, &Nam, 2007; Ding et al., 2008; Ding, Wang, & Fu,2013c).

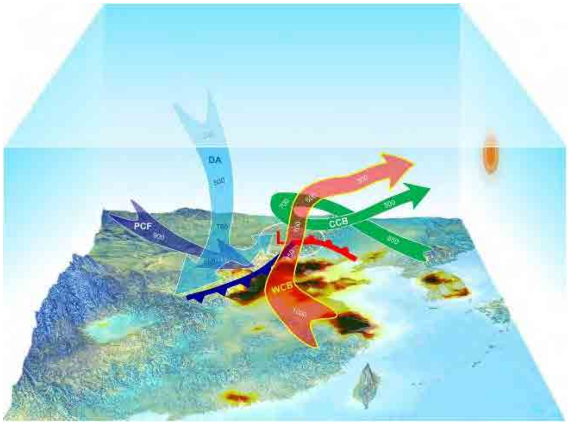

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Figure 4.A schematic figure for air pollution transport mechanism of different circulations of a cyclone. TheWCB-warm conveyor belt, which is the most efficient transport process for lifting surface air pollution to middle- and even upper-troposphere (Ding et al., 2009).Acronyms: CCB–cold conveyor belt, DA–dry airstream, PCF–post cold front airstream (Cooper et al.,2001). The numbers marked on these belts indicate the pressure level.

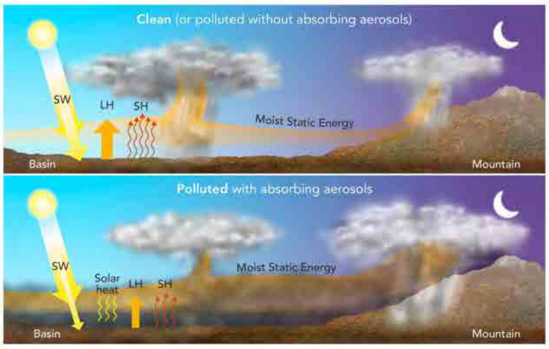

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Figure 5. An illustration of the mechanism of aerosol induced catastrophic flood in the Sichuan Basin in summer 2013.Acronyms: SW–shortwave radiation, SH–surface sensible heat flux and LH–surface latent heat flux.

Sourced from Fan et al.(2015).

In summer, the Pacific High is the dominant process influencing ozone pollution in East China (Ding et al., 2013b). When it dominates the land area, such as Southeast China or East China, the Pacific High brings strong solar radiation and hot weather, which favor the formation of ozone episodes by promoting photochemical reactions and by enhancing biogenic emissions from forests in South China (Ding et al., 2008,2013b). In the northern part of China, midlatitude cyclones have been found to be particularly frequent in summer (Chen, Kuo, Zhang, &Bai, 1991). The fronts and WCBs associated with these cyclones play an important role in lifting plumes from the PBL to the free troposphere. For example, based on aircraft measurements,Ding et al. (2009) captured aged plumes of $O_3$and SO_2 in the free troposphere (at an altitude of 2.6 km aboveground level) over Northeast China, and they also identified the origins of these plumes as the megacities Beijing and Tianjin based on mesoscale numerical modeling combined with Lagrangian backward dispersion simulations using WRF-FLEXPART (Ding et al., 2009). Some studies (e.g., Wang et al., 2014c; Ding et al., 2015) found that suchtransport processesarealso important in winter and spring, which could influence the chemical compositionsofthe middleand uppertroposphere of Northeast Asia and the Pacific Ocean.The schematic figure of the cyclone-related air pollution transport mechanism in East Asia is shown in Figure 4.

Another type of cyclone influencing air quality in Asia is the tropical cyclone(i.e., the Northwest Pacific typhoon). A typhoon, as a severe synoptic process with strong wind and heavy rain, surely is good for air quality in a city because of strong dispersion and wet removal conditions. However, the outer periphery of a typhoon easily causes poor air quality because of overall large-scale subsidence and calm/stagnant conditions. This phenomenon is particularly frequent and evident in PRD cities, such as Hong Kong and Guangzhou, in South China. In summer, most ozone and haze pollution episodes in these cities are related to an approaching typhoon, especially when it is located around Taiwan(i.e., with its center located 600–1,000 km away in the southeast). The continuous offshore synoptic wind and a delayed development of sea-land breezes have been attributed as the main contributors to the subregional air pollution transport and accumulation under such kindsof synoptic weather (Ding et al.,2004,2013c). Besides these large-scale high-pressure systems, air pollution episodes often occurred under some small and stagnant weather conditions. For example, in Nanjing inEast China, heavy ozone pollution episodes also occurred when a small anticyclone covered eastern China, causing a subregional transport of air pollutants from the city clusters of YRD to Nanjing (Ding et al., 2013b).

Impact of Air Pollutants on Synoptic Weather

Many pollutants, such asPM (i.e., aerosols) and reactive trace gases with greenhouse effects, are radiatively active in the atmosphere. Among all these pollutants, because of complex chemical compositions, optical properties, and different roles in cloud formation, aerosols are the most important andthe most complicated factors influencing the change of meteorological parameters. From the perspective of climate change, the impact of aerosolshas been widely studied in the past few decades, and it has been known that radiativelyactive aerosol species can change the climate by their direct effect on solar radiation transfer and by their indirect influence via modification of clouds and precipitation (IPCC, 2013).

In East Asia, the impacts of anthropogenic and natural atmospheric aerosols on regional climate change(e.g., solar radiation, surface air temperature, cloud, and precipitation patterns, and even large-scale circulations like the East Asian Monsoon) have been intensively studied based on data analysis and numerical modeling (Menon, Hansen, Nazarenko, &Luo, 2002; Qian, Leung, Ghan, &Giorgi, 2003; Huang et al., 2006; Li et al., 2011; Jiang, Liu, Yang, &Wang, 2013; Gong et al., 2014; Huang et al.,2014b,2015; Fu et al., 2017).Observational evidence of the influence of air pollution onclimate isbased primarily on long-term measurements at ground stations (including mountain sites) and satellite retrievals. For example, based on 50-year ground measurements, Qian et al. (2009) found that increased aerosol concentrations contributed to decreased light rain events in China, but heavy rain presented an increasing trend. Based on long-term observations in Mount Hua and Xi’an, Yang, Yao, Li, andFan(2013) found that air pollution reduced both light orographic precipitation and the frequency of thunderstorms. Yang andLi (2014) also found that thunderstorm and lightning activities have increased in both frequency and intensity over time in Southeast China, associated with decreased visibility over the past several decades. Modeling studies also showed that aerosols could contribute to the large-scale summertime “southernflood–northerndrought” precipitation pattern change in China in recent decades by modifying the land-sea thermal contrast and weakening the East Asia summer monsoon circulations (Menon et al., 2002; Jiang et al., 2013; Fu et al., 2017). Among all the aerosols, black carbon from anthropogenic fossil fuel combustion or biomass burning has been found to beone of the most important because of its strong absorption effect in the atmosphere and on snow or ice, especially in Asia (Wu,Fu, Xu, Wang, &Wang, 2008; Ramanathan & Carmichael, 2008; Huang et al., 2011; Bond et al., 2013).

On synoptic scales, our understanding of the impact of aerosols is even more limited because of relatively few observations and verycomplicated air pollution conditions in this region. In general, it needs a combined effort of measurement and modeling to quantify the roles of air pollution in synoptic weather modification forspecific episodes or events. Guo et al. (2014b) conducted a case study for a summer convective precipitation in the Beijing-Tijian area in July 2008, based on MODIS data and the WRF-Chem model. They found that the amount of precipitation during such a convective precipitation event was increased up to 17% by air pollutants. Zhong, Qian, Zhao, Leung, andYang(2015) conducted another case study to compare the impact of urban heat island versus aerosols on summer precipitation in the great Beijing Metropolitan Area, based on convection-resolving, ensemble WRF-Chem/UCM simulations. They found that aerosols played a more dominant role, leading to enhanced convection and more precipitation in the downstream. Fan et al. (2015) conducted WRF-Chem modeling for a heavy rainfall related to a catastrophic flood in the Sichuan Basin in July 2013. They found that aerosols played a substantial role in enhancing the nighttime convective precipitation in mountainous areas through the mechanisms of aerosol-enhanced conditional instability, together with an orographic lifting effect (Fig.5). In this event, the direct effect of strongly absorbing black carbon aerosol, also called soot, played a more important role than the aerosol indirect effect and caused an increased convection and precipitation downwind of the heavily polluted area in the Sichuan Basin in southwestern China.

Another “golden” case reported by Ding et al. (2013a) presented the twofold effect of air pollution to precipitation. On June 10, 2012, many cities in eastern China experienced a severe haze episode with a brownsky. Ground-based measurements at a flagship station, the Station for Observing Regional Processes of the Earth System (SORPES) (Ding et al., 2016b), in Nanjing reported an extreme air pollution event, with $PM_{2.5}$ concentration over 400 $\mu g/m^3$ lasting for about 36 h. Chemical tracers, satellite measurement, and air mass transport pathways show that this episode was influenced by agricultural straw burning in the northwest 300–500 km away. Comparisons of observations with several weather-forecast products, such as the European Centre for Medium-Range Weather Forecasts (ECMWF) product, WRF simulations, and NCEP FNL Operational Model Global Tropospheric Analyses data, suggested that inthis case,heavy air pollution caused a drop of air temperature of up to 10 K in the early afternoon of that day in Nanjing and adjacent cities. At the same time, the afternoon local convective precipitation around Nanjing was “burned off”, while the nighttime precipitation downwind of the biomass burning plume was enhanced (Ding et al., 2013a; Huang et al., 2016) and showed a similar result asthat reported by Fan et al. (2015) in the Sichuan Basin. Huang et al. (2016) quantified the twofold effect by conducting WRF-Chem simulations considering the emission from biomass burning estimated from satellite-retrieved fire counts. They found that agricultural straw burning was responsible for the majority of the observed regional haze pollution in East China, which played a substantial role in modifying air temperature and precipitation through its direct effect;i.e., significant cooling at the ground surface and warming above the boundary layer.

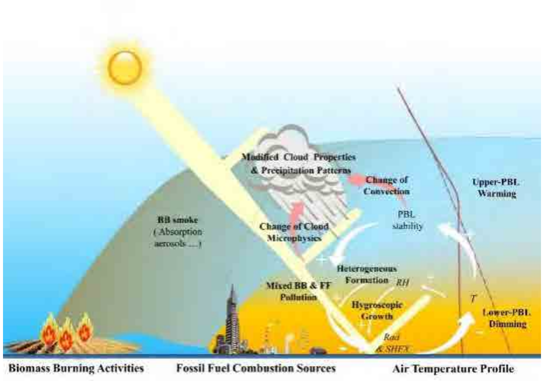

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Figure 6.A schematic figure for interactions of air pollution–PBL dynamics and aerosol–radiation–clouds for the mixed agriculture burning plumes and fossil fuel combustion pollutants.The yellow bands show the radiative transfer of solar radiation. The brown solid and dashed lines indicatethe air temperature profiles for episode and nonepisode cases, respectively. The black thin dashed line represents the top of a fossil fuel combustion plume ina nonepisode condition. The plus (+) and minus (−) signs mean the enhancement and reduction of a target process, respectively.Modified from Ding et al.(2013a).

Ding et al. (2013a) brought out a conceptual model to show the main processes of air pollution–weather interactions for this case (Fig.6). The considerable amount of light-absorbing aerosols in the fire plumes heated the atmosphere and cooled the ground surface, thereby suppressing the vertical mixing and dispersion of pollutants. Enhanced PBL stability in turn led to more anthropogenic pollutants in the lower boundary layer, mixed with the biomass burning plumes. Meanwhile, the cooling effect in the lower PBL resulted in an increase in relative humidity, which further amplified the feedback by increasing the aerosol scattering coefficient through hygroscopic effects and by enhancing secondary aerosol formation from heterogeneous reactions (Nie et al., 2015; Xie et al., 2015). The clouds and precipitation pattern was also influenced by the modified dynamics and changed microphysics.

Enhancement of Air Pollution by Two-Way Interactions

The conceptual scheme given in Figure 6 for the case reported by Ding et al. (2013a) shows not only how the air pollution-PBL feedback contributed to the modification of weather, but also how the substantially modified meteorological parameters or processes enhanced the formation of air pollution. It has been known that many meteorological parameters and processes are closely linked with the formation, transport, and removal of air pollutants in the atmosphere. Several other observational and modeling studies have also confirmed that aerosol-weather interactions contribute to an enhancement of ground-based air pollution in East Asia. For example, Quan et al. (2013) raised the point of an aerosol-boundary feedback loop by estimating the evolution of the PBL height in Tianjin based on wind profile radar, microwave radiometer, and Lidar measurement. Several modeling studies for the extreme haze pollution episode in Beijing and the NCP in January 2013, with multiple-day, severe $PM_{2.5}$ episodes and hourly maximum over 800 μg/m^3,also have highlighted the importance of considering aerosol-meteorology interactions in air-quality-forecast modeling. Most of the studies (e.g., Wang et al., 2014a,2014b; Gao et al., 2015) showed that with a consideration of aerosol-radiation-meteorology feedbacks, the numerical model could well reproduce the extreme $PM_{2.5}$ events and match better with field measurements, and the opposite is true for simulations without these feedbacks.

Boundary layer dynamics has been known to control the dispersion condition of air pollutants. Surface-emitted air pollutants are generally constrained within the PBL(i.e., the mixing layer from a perspective of air quality). The evolution of PBL height directly influencesground-level air pollution levels. The development ofPBL is mainly driven by thermal processes;i.e., the heating/dimming effects at the ground and in the atmosphere (Yu, Liu,&Dickinson, 2002; Sühring, Maronga, Herbort, &Raasch, 2014; Ding et al., 2016a).

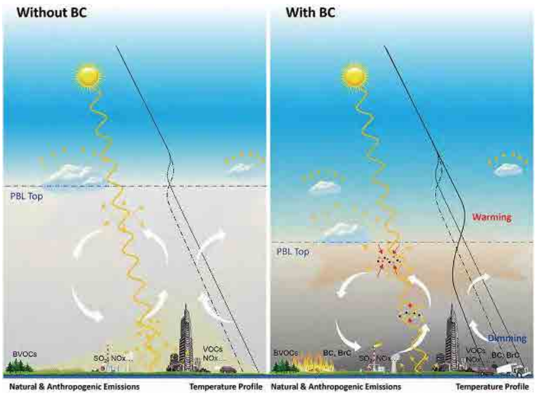

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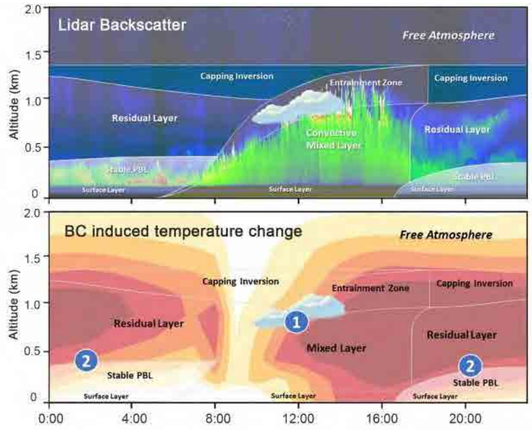
*Figure 7.*A schematic figure showing aerosol- PBL feedback loops for the scenarios with and without black carbon emission in a megacity. The black lines show vertical profile air temperatures for the scenarios with BC (solid), with aerosols except for BC (dash-dotted) and without aerosols (dotted), respectively. The yellow dashed arrows show the reflection of solar radiation. The red arrows show the absorption of solar radiation by absorbing aerosols. The blue dash-dotted line indicates the boundary layer height. The white arrows indicate the vertical ventilation of urban plumes induced by circulations or large eddies in the city. The difference in the color of urban plumes means different chemical compositions.

Sourced from Ding et al.(2016a).

The direct effect of aerosols influences the surface flux, one of the key drivers for PBL evolution. Scattering or absorption of PM in the atmosphere has been found to decrease the solar radiation reaching the ground surface (IPCC, 2013). For example, in the extreme event reported by Ding et al. (2013a), a reduction of solar radiation intensity by more than 70% and sensible heat by more than 85% was observed duringthe extreme episode day. Based on model simulations with different scenarios, Gao et al. (2015) found that during the fog-haze event during January 2013, air pollution could lead to a significant negative radiative forcing of 20–140 W/m^2, together with a daytime temperature decrease by 0.8–2.0 K and an increase of relative humidity about 4%–12% at the ground surface. Based on two experiments using the GRAPES/CUACE model for a haze episode in June 2008 over Beijing, Wang et al. (2015b) found that the mean solar radiation flux that reached the ground decreased by 20% to 25% in the region with the highest aerosol optical depth during the event.

Based on the theoretical analysis, the decreased surface flux certainly will result in a decrease of daytime turbulence mixing and a suppression of the daytime boundary layer height (Petäjä et al., 2016). However, the model-simulated change inPBL height depends not only on the change of surface flux, but on the heating in the atmosphere. Some pollutants, like black carbon and dust, which are particularly strong in East Asia, have been found to have very strong heating effects through absorbing solar radiation or long-wave radiation (Bond et al., 2013; Huang et al., 2014b). For black carbon, it is already wellaccepted that its warming effect in the atmosphere is quantitatively comparable to its dimming effect at the ground surface (Bond et al.,2013, Ramananthan&

Carmichael, 2008). In astudy of North China byGao et al. (2015), a positive radiative forcing (20–120 W/m^2) was found in the atmosphere, comparable with a negative forcing of 20–140 W/m^{2}at the surface.



Click to view larger

*Figure 8.*An illustration of diurnal variation of PBL structure and the impact of black carbon on daytime and nocturnal PBL.Definition of the terms here follows Stull (1988). The shaded figure in the upper panel shows Lidar-measured normalized relative backscatter at the SORPES station for a case in Nanjing, eastern China (Ding et al., 2016b). The shaded figure in the lower panel gives the modeled air temperature change due to heating of black carbon, based on WRF-Chem simulations for haze days in Nanjing (Ding et al.,2016a). (1)and(2) in the bottom panel represent the two key locations of the PBL feedback by black carbon(i.e., the suppression of convective mixing layer in daytime and the enhancement of nocturnal stable boundary layer at nighttime, respectively).

By using the meteorology-chemistry coupled regional model WRF-Chem (Grell et al., 2005), Ding et al. (2016a) further investigated the role of black carbon in the feedback in haze pollution extending from the NCP to YRD regions during December 2013. They found a quantitatively comparable but reversedradiative forcing of black carbon at the ground and in the atmosphere, andreported that with a samesurface-flux change, black carbon could reduce the PBL height more than other scattering aerosols because of the strong heating of black carbon in the upper PBL.The main reason for more efficient aerosol-PBL feedback is because of the heating in the atmosphere, with a relatively higher heating efficiency around the top of the boundary layer. Together with dimming at the surface, it favored a capping inversion in the upper PBL to suppress the development of the daytime convective mixing layer, followed by a concentrated PM at the ground surface. Ding et al. (2016a) named this effect thedome effectof black carbon (Fig.7). The dome effect of black carbon not only suppresses the development of daytime convective mixing layer, but also caninfluence the nocturnal boundary layer. The increased air temperature in the residual layer at nighttime also may enhance the formation of an inversion layer or increase the stability of a nocturnal stable boundary layer (Fig.8), which favors the accumulation of air pollutants and enhances air pollution in megacities. In Asia, not only black carbon, but also other absorption aerosols like dust aerosols, have such feedback in changing the PBL dynamics (Wang et al., 2010; Liu et al., 2016b).

The mechanisms of air pollution–weather interactions given in Figure 6 also show that the enhancement of air pollution by this feedback not only came from physical processes, but also were strongly related to chemical processes, especially the heterogeneous formation of secondary PM. It is well known that the relative humidity largely depends on the air temperature. The droppingof air temperature in the lower PBL by air pollution–radiative feedback will naturally increase relative humidity there. Many studies have demonstrated that the formation of secondary PM is strongly linked torelative humidity. For example, sulfate formation will be promoted under conditions of higher relative humidity (He et al., 2014; Zheng et al., 2015). Xie et al. (2015) also found that inconditions of high relative humidity, the concentration of HONO, one of the important sources of OH radical, was obviously increased and the sulfate formation significantly enhanced in the mixed dust plumes or biomass-burning plumes with fossil fuel–combustion plumes. The increase inrelative humidity induced by air pollution–weather interactions certainly enhances the secondary pollution, which further enhances the feedback loop. However, so far, a quantitative understanding of the impact of relative humidity change to the enhancement of secondary aerosols in China is very limited (Zhang et al., 2015; Kulmala et al., 2016).

Implications and Challenges

This article clearly demonstrates that air pollution is strongly linked with the weather and climate in East Asia from several aspects: (a) the influence of multiscale meteorological processes on the formation, transport, and removal of air pollutants; (b) the roles of air pollutants, especially radiativelyactive aerosols, in modifying meteorological parameters, regional climate, and even synoptic weather; and (c) the mechanism of enhanced air pollution in megacities through air pollution–PBL-weather interactions. These issues will potentially have strong implications forair quality forecasting and weather/climate forecasting and should be considered in policymaking for the mitigation of air pollution and climate change in this region.

Given the important role of air pollution–weather interactions in modifying weather and enhancing air pollution, such processes should be considered in operational air quality and weather forecasting models. Currently, most operational numerical models for air quality forecasting and weather forecasting havenot yet included fully-coupled meteorology and chemistry. To well capture the interactions between air pollution and weather, these models should have the capacity to address the change of complex sources other than anthropogenic sources, especially for those aerosols with strong radiative effects, such as biomass-burning aerosols and dust aerosols. Therefore,a real-time or quasi-real-time update or data assimilation based on satellite- or ground-based measurements is needed.

From the perspectives of air quality control policy, the air pollution–weather interactions also should be considered. As meteorological parameters and synoptic weather strongly influence air pollution, the change of monsoon climate and synoptic weather types should be considered in understanding the interannual variation and the long-term trend of air quality. Considering the role of black carbon in air pollution–weather interactions, more restricted control measures for reducing the emission of black carbon and other light-absorbing fine particles could be the most efficient way to mitigate extreme haze pollution in megacities in China, because reducing black carbon will give a nonlinearlyquick improvement of air quality through its effects on meteorological conditions (Ding et al., 2016a). Of course, this special, black carbon–focused control policy will certainly cobenefit the mitigation of climate change from regional to global scales and also will reduce excess mortality (Ding et al.,2016a; Xing et al., 2016).

However, the current understanding ofair pollution–weather interactions is still limited because of many uncertainties related to the interactions between chemical and physical processes. More studies are needed to identify the mixing and aging of black carbon aerosols in the complex atmospheric environment in East Asia, and a more quantified understanding of heterogeneous reactions related to air pollution–weather interactions is also needed. In East Asia, one of the main challenges for improving current understanding is that there are only limited observations, especially measurements from integrated stations with multiple physical and chemical processes. Ding et al. (2016b) demonstrated how an integrated measurement site, like the SORPES station in Nanjing, could help to improve understanding the unique chemical and physical mechanisms in such a complex environment in Asia. Besides the ground measurements, more vertical observations based on aircraft and sounding platforms are needed to give a clearer picture about the three-dimensional perspectives of air pollutants and to gain in-depth insight into the interaction of air pollution and meteorological processes above the ground surface.

Another key challenge comes from the developing of numerical models. Even though the current numerical models include complex physical and chemical processes, most of the parameters were obtained or built based on measurements from regions other than East Asia (e.g., the United States or Europe). Some of these mechanisms have been demonstrated to be different from the unique environment in East Asia, with much more complicated pollution sources. Future model development should be based on the new findings from field measurements and chamber studies under real environmental conditions at first (Zhang et al., 2015; Kulmala et al., 2016), and then on evaluations with various field measurements in this region (Liao, Zhang, Chen, Raes, &Seinfeld, 2009). Only with the joint effects of field measurement and numerical modeling can we gain a more holistic understanding of air pollution–weather interactions and reach a final solution toair pollution issues in this region. To achieve these, the community needs to meet the challenge of high level of interdisciplinary/cross-disciplinary research with more collaboration between environmental scientists and meteorologists.

Acknowledgments

The work was supported by National Science Foundation of China (NSFC)(91544231, 41422504), Ministry of Science and Technology of the People’s Republic of China (2016YFC0200506), Jiangsu Provincial Science Fund(BK20140021), and Jiangsu Provincial 2011 program (Collaborative Innovation Center of Climate Change).

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