Impacts of Anthropogenic Aerosols on Fog in North China Plain

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Abstract Fog poses a severe environmental problem in the North China Plain, China, which has been witnessing increases in anthropogenic emission since the early 1980s. This work first uses the WRF/Chem model coupled with the local anthropogenic emissions to simulate and evaluate a severe fog event occurring in North China Plain. Comparison of the simulations against observations shows that WRF/Chem well reproduces the general features of temporal evolution of PM2.5 mass concentration, fog spatial distribution, visibility, and vertical profiles of temperature, water vapor content, and relative humidity in the planetary boundary layer throughout the whole period of the fog event. Sensitivity studies are then performed with five different levels of anthropogenic emission as model inputs to systematically examine the comprehensive impacts of aerosols on fog microphysical, macrophysical, radiative, and dynamical properties. The results show that as aerosol concentration increases, fog droplet number concentration and liquid water content all increase nonlinearly; but effective radius decreases. Macrophysical properties (fog fraction, fog duration, fog height, and liquid water path) also increase nonlinearly with increasing aerosol concentration, with rates of changes smaller than microphysical properties. Further analysis reveals distinct aerosol effects on thermodynamic and dynamical conditions during different stages of fog evolution: increasing aerosols invigorate fog formation and development by enhancing longwave-induced instability, fog droplet condensation accompanying latent heat release, and thus turbulence, but delay fog dissipation by reducing surface solar radiation, surface sensible, and latent heat fluxes, and thus suppressing turbulence during the dissipation stage.

1. Introduction

Fog can significantly affect visibility, air quality, traffic, human health, and economy (Gultepe et al., 2007). Fog is more likely to occur in a stable planetary boundary layer (PBL) with low wind speed and high relative humidity (RH; Sachweh & Koepeke, 1995; S. Niu et al., 2010). The meteorological conditions favoring for fog occurrence are also conducive to accumulation of pollutants and aerosols in PBL. Globally, most aerosol particles are in PBL (typically lowest 1–3 km) where fog coincidently occurs (Li et al., 2017). Air pollution has become a major environmental concern in densely populated urban areas in China due to high emissions of air pollutants from anthropogenic activities (Q. Zhang et al., 2009; X. Zhang et al., 2015). Thus, more attentions have been drawn to the impacts of aerosols on fog.

Some previous studies have reported aerosol effects on fog properties. Shi et al. (2008) suggested, based on statistical analyses of daily meteorological observations during last 50 years, that increased air pollution and high aerosol loading resulting from urbanization and industrialization affected fog duration. F. Niu et al. (2010) also suggested that the winter fog events in east central China occurred more frequently over the past three decades because of increasing aerosol loading and weakening monsoon circulation. In polluted areas, fog droplet number concentration (Nc) can be larger than 1,000 cm−3, resulting in a small mean fog droplet radius (5–6 μm) and extremely low visibility (Li, 2001; S. Niu et al., 2010; Quan et al., 2011), whereas Nc is about 100 cm−3 and radius is larger in clean areas in Canada (Gultepe et al., 2009). Bott (1991) found that the different physical and chemical properties of urban, rural, and maritime aerosols result in different fog microstructures and life cycles. Gultepe and Isaac (1996, 1999) found that fog droplet number concentration can be obtained as a function of aerosol number concentration for air masses over the ocean based on the observation. These studies showed that aerosol particles could affect fog microphysics by serving as fog...
condensation nuclei, like the aerosol effect on cloud microphysical properties via cloud condensation nuclei (Albrecht, 1989; Gultepe et al., 2017; Twomey & Warner, 1967).

Despite the progress, our understanding and modeling of the fog processes are still limited. Particularly limited is our understanding of the relationships of aerosol particles from anthropogenic emission and the aerosol effects on fog properties in megacity areas. The problem is becoming especially acute in North China Plain (NCP), China, which is one of the most polluted regions in China with the highest aerosol loading (Chan & Yao, 2008; Quan et al., 2014; Sun et al., 2013). Although there have been many studies on aerosol effects on cloud and precipitation (Fan et al., 2015; Xue et al., 2012), studies on the aerosol effects on fog are rare and limited. Furthermore, fog is influenced by many factors (e.g., turbulence, radiation, microphysics, and topographical conditions) that often interact with one another in a complex way, posing great challenges to untangle the physical mechanisms underlying aerosol-fog interactions (Bott & Carmichael, 1993; Duynkerke, 1999; Gultepe et al., 2007; Lu et al., 2013; Muller et al., 2010; Zhou & Ferrier, 2008). Studies of aerosol effects on fog macrophysics and dynamics are still rare (Gultepe et al., 2016).

To address these challenges, here we use the WRF/Chem model coupled with anthropogenic emissions to perform a comprehensive investigation of various aerosol effects on the microphysical, macrophysical, radiative, and dynamical properties of fog occurring in NCP, China. The results have important implications for aerosol effects on fog and clouds in general. The rest of this paper is organized as follows. Section 2 describes the observational data, WRF/Chem model, and the design of numerical experiments. Section 3 first evaluates the numerical simulations against the observations, and then discusses the results of sensitivity experiments. The major finding and conclusions are summarized in sections 4 and 5.

2. Description of Observational Data, Model, and Experiment Design
   2.1. Observational Data

   Observational data from four different sources are used. The first set is from a comprehensive field experiment conducted to study fog characteristics in NCP from November to December in 2009 at the Wuqing (WQ) meteorological station (117°E, 39°24’N) jointly operated by Beijing Meteorology Bureau, WQ Meteorology Station, and Peking University. A microwave radiometer (MP-3000A) was used to retrieve the profiles of temperature, water vapor, and RH during the field experiment (Hewison & Gaffard, 2003). Visibility is observed by PARSIVEL-EF (PARticle SIze and VELocity-Eehanced Fog). Figure 1 shows the location of WQ site along with relevant information.

   The second set of data is the routine measurements of air pollutants at one urban site and one rural site. The urban site is located in Beijing (39°56’N, 116°17’E) and denoted by BJ hereafter and the rural site is at Shangdianzi (40°36’N, 117°24’E; SDZ), northeast of BJ. The mass concentrations of PM$_{2.5}$ particles (particle diameters ≤ 2.5 μm) and trace gases are measured with a set of commercial instruments from the Thermo Fisher Environmental Instrument, Inc., USA. The instruments at the BJ site are installed at the 2- and 80-m levels of a 325-m meteorological tower; the SDZ instruments are installed at the 8-m level of a 50-m meteorological tower. All the instruments are calibrated every 2 weeks. The third set of data is the fog product based on the polar-orbiting satellite NOAA-16 and surface visibility, which shows the fog spatial area (http://satellite.cma.gov.cn/PortalSite/Data/Satellite.aspx). The fourth set consists of the anthropogenic emissions derived from the Asian emission inventory in 2006 for the NASA INTEX-B mission, including SO$_2$, BC, OC, CO, NOx, NH$_3$, PM$_{10}$, PM$_{2.5}$, and volatile organic compounds (Q. Zhang et al., 2009). Previous studies have shown that these emission data represent the region well (Gao et al., 2015; Jiang et al., 2012). The original data are gridded with a horizontal resolution of 0.5° by 0.5°, which are interpolated onto the WRF/Chem domain and grids in this study.
2.2. Model Description

The WRF/Chem V3.5 developed by the National Center for Atmospheric Research and other collaborative agencies is used in this study (Grell et al., 2005). The air quality component of WRF/Chem is fully consistent with the meteorological component, having the same transport scheme, same horizontal and vertical grids, same subgrid-scale transport schemes, and same time steps for transport and vertical mixing (Grell et al., 2005). The model fully considers the interactions between aerosols, radiation, and clouds, including direct and indirect effects (Chapman et al., 2009; Fast et al., 2006).

The model domain (Figure 1) covers the urban clusters of northern and eastern China. Also shown in Figure 1 is the spatial distribution of CO (data from Asian Emission Inventory in 2006) to represent the intensity and distribution of pollution, since CO has a long lifetime and is mainly emitted from anthropogenic activities. The horizontal resolution is 5 km (200 × 200 grids). There are 33 vertical layers from the surface to 50 hPa, with 13 layers below 500 m in order to simulate the fog event well. The available data on land use, soil-type, topography, and other input variables with the high resolution (30 arc sec) are used. The meteorological initial and boundary conditions are from the NCEP Final analysis data on 1° by 1° grids. Table 1 summarizes the physical and chemical parameterization schemes used in this study. Briefly, the gas-phase scheme uses the Regional Acid Deposition Model (RADM2; Stockwell et al., 1990). The Modal Aerosol Dynamics model for Europe (MADE; Ackermann et al., 1998) with the Secondary organic aerosol model (SORGAM; Schell et al., 2001) uses three lognormal-distributed modes to simulate both interstitial and cloud-borne aerosols. Activation process of aerosol particles into fog droplets is based on the Abdul-Razzak and Ghan (2000) scheme (see also Yang et al., 2011). The Morrison two-moment microphysical scheme (Morrison et al., 2005) is used, which calculates mass and number concentration of the fog droplets as well. The Quasi-Normal Scale Elimination scheme (Sukoriansky et al., 2006) is selected for the PBL parameterization.

An event of large-scale dense fog occurred over the northern and eastern China from 30 November night to 1 December 2009, as the warm high ridge at 850 hPa and uniform pressure field at surface provided a good circulation condition for the wide spread dense fog. The WRF/Chem model is used to simulate this fog event and to study the impacts of anthropogenic aerosols on fog. The model is integrated for 54 hr from 00:00 LST, 29 November to 14:00 LST, 1 December 2009, while the first 24 hr is considered as “spin-up” time and is excluded in the analyses. The spin-up period allows enough time for aerosol concentrations to build up throughout the simulation domain and to minimize the effects of initial conditions in the analyses.

2.3. Design of Sensitivity Experiments

To investigate the effects of aerosols on fog, sensitivity experiments are performed with five different aerosol scenarios by reducing the emission intensity of David Streets’ 2006 emission inventory by multiplying 0.05(S1), 0.1(S2), 0.3(S3), 0.5(S4), and 1(S5). Figure 2 illustrates the differences in the PM$_{2.5}$ mass concentrations under the five emission scenarios over the simulation domain. The mean PM$_{2.5}$ concentrations under the S1 scenario is 2.53 μg/m$^3$, with 90% PM$_{2.5}$ concentrations less than 5 μg/m$^3$. This condition is close to that in the remote area in China and is used to represent the clean environment. The mean PM$_{2.5}$ concentration under S5 is 38.3 μg/m$^3$, with 80% values ranging from 5 to 75 μg/m$^3$, and is used to represent the typical polluted environment in NCP. The S2, S3, and S4 scenarios fall between the clean (S1) and polluted (S5) scenarios, with the mean PM$_{2.5}$ concentrations being 4.81, 13.1, 20.8 μg/m$^3$, respectively. To isolate the aerosol effects, the other model components, including model physics and chemistry, remain the same in all the five experiments.

![Box plots showing the PM$_{2.5}$ concentrations under the five different emission scenarios (S1 to S5). The results are the averages over the simulation domain. For each scenario, the whisker represents the range from 10% to 90% percentiles; the wide box represents the range from 25% to 75% percentiles; the square and center line represents the mean and median values, respectively.](image-url)
3. Model Evaluation Against Observations

To lend confidence to the model, this section evaluates the model in terms of its performance in simulating aerosol properties, meteorological parameters, and boundary conditions against the available observations. All evaluations are based on the results of emission inventory S5, since it is closest to the realistic situation.

3.1. Aerosol Concentration

First, the simulated aerosol properties are evaluated against the measurements collected at the two routine observational sites described in section 2.1 (BJ and SDZ). The model results are averaged over an area of 2 × 2 grid cells around each site in comparison with the measurements. Figure 3 compares the temporal variations of simulated PM$_{2.5}$ concentration with the measurements from 8:00 LST, 30 November to 14:00 LST, 1 December in 2009. At BJ site, the modeled PM$_{2.5}$ has a similar magnitude and trend as the observation at both 2 m (upper panel) and 80-m heights (middle panel). The PM$_{2.5}$ mass concentration at the 2-m level is higher than that at the 80-m level in both the simulation and observation. The 2-m PM$_{2.5}$ mass concentration peaks around 19:00 LST and 80-m PM$_{2.5}$ mass concentration peaks around 17:00 LST in both the simulation and observation. At the rural SDZ station (lower panel), PM$_{2.5}$ mass concentration is much lower (less than 40 μg/m$^3$) relative to the urban BJ site as expected, and the model captures this behavior as well. The model also reproduces the magnitude and trend of variations reasonably well. Note that the discrepancy between the modeled and measured PM$_{2.5}$ concentration at the SDZ site seems larger than that at the BJ site, and the model tends to underestimate the PM$_{2.5}$ concentration after 20:00 LST, because of overestimated wind speed. Other possible reasons for the differences between the observation and simulation include scale-mismatch (the observation is at a single point whereas the simulation represents average over an area of four grid cells) and model resolution. The anthropogenic emission may suffer from some uncertainty due to residential coal combustion and small industries in rural areas, which may result in errors in the spatial and temporal distribution of aerosol concentration (Matsui et al., 2009; Q. Zhang et al., 2009). Despite some detailed discrepancies, the overall agreement between the simulations and measurements at both the urban and rural sites and at the different altitudes suggests that the model is capable of capturing the essential features of fog-related aerosol properties.

3.2. PBL Structure

Figure 4 compares the simulated temporal changes of the vertical profiles of temperature, water vapor content, and RH in PBL against the measurements from the microwave radiometer at the WQ site. For comparison with the measurements, the model results are averaged over an area of 2 × 2 grid cells around the site. The simulations are in general agreement with the observations and capture the temporal evolution of fog. Specifically, as shown in Figure 4a, the microwave radiometer observed a temperature inversion layer from 18:00 LST 30 November to 12:00 LST 1 December, and the height of temperature inversion increased from tens of meters to hundreds of meters as the fog developed with time. The simulation not only captures this temporal change of temperature inversion but also the temperature magnitude. The water vapor content is highest near surface and decrease with height (Figures 4c and 4d). Water vapor was accumulated near the surface due to the temperature inversion, and then decreased sharply after 24:00 LST 30 November because of vapor condensation and then increased obviously after 10:00 LST due to fog dissipation. The observed visibility at WQ site is further used to evaluate the simulations (Figure 5). Two visibility parameterizations are used to calculate the fog visibility in simulation: the Kunkel expression (Kunkel, 1984) that estimates fog visibility as a function of liquid water content (LWC) and the more recent Gultepe et al. (2006) expression that estimates fog visibility in terms of both LWC and N$_c$. The evolution of simulated visibility has similar trend and magnitude with the observed visibility, starting to decrease sharply at 24:00 LST, 30 November, and
remaining around 100 m until 10:00 LST, 1 December. In comparison, the Gultepe et al. (2006) parameterization performs better than the Kunkel parameterization, suggesting the important role of $N_c$ in determining fog visibility. The model tends to underestimate the visibility, likely because LWC is underestimated. The underestimation of LWC and water vapor content during the fog period maybe related to simulated warm and dry biases, which mostly is related to systematic errors of the WRF/Chem, partly related to the bulk microphysical scheme used in the model (Khain et al., 2009; Morrison et al., 2005). It is interesting to note that the changes of visibility are consistent with that of the surface water vapor content. The model largely reproduces temporal evolution of water vapor content. The simulated RH agrees favorably with the observations at heights below 300 m (with RH being higher than 80% near the surface from 18:00 LST, 30 November to 12:00 LST, 1 December, and reached saturation during

Figure 4. Comparison of time-height distributions of (a, b) temperature (${^\circ}$C), (c, d) water vapor content (g/m$^3$), and (e, f) RH (%) between the model simulations and observations at the Wuqing station and from 08:00 LST 30 November to 14:00 LST 1 December 2009. RH = relative humidity.
24:00 LST, 30 November to 10:00 LST, 1 December) in Figures 4e and 4f, except for fog dissipation time during which simulated RH is much lower than observed RH.

3.3. Fog Spatial Distribution

Figure 6 compares the spatial distributions of simulated (right) and observed (left) fog areas. The simulated fog area was based on the liquid water path (LWP) threshold of LWP > 2 g/m² at 09:00 LST, 1 December. In calculation of simulated LWP, only the fog pixels defined as the fog LWC ≥ 0.01 g/kg (Zhou & Du, 2010) are used. The observed white fog area is determined by combining the satellite measurements with the surface visibility observations at 08:47 LST, 1 December. It is worth noting that the observed fog area appeared like the letter “C” and covered Tianjin, Shandong, northeast of Hebei, north of Jiangsu, and north of Anhui (Figure 6a). The model was able to reproduce such C-like spatial distribution. Also noteworthy is that the simulation underestimated the fog area compared to the observation. Note that we also compared the simulated result with the LWP threshold of 0.5 g/m² and found similar results.

4. Aerosol Effects on Fog Properties

The preceding comparisons between the numerical simulations and measurements show that the WRF/Chem model generally captures the temporal evolutions of PM₂.₅ concentration, PBL thermodynamic profiles, and fog spatial distribution, lending confidence to the WRF/Chem model in simulating aerosol and fog events. This section further investigates the aerosols effects on fog microphysical, macrophysical, radiative, thermodynamic, and dynamical properties and dissects the complex interactions and feedbacks among them.

Figure 6. (a) Multichannel RGB satellite image from NOAA-16 at 08:47 LST on 1 December 2009. The satellite image reflects the combined albedo of three wavelength bands: 1.58~1.64, 0.725~1.1, 0.55~0.68 (μm). The white fog area is determined by the National Satellite Meteorological Center of China by combining the satellite with the surface visibility observations at the relevant meteorological stations. The little darker gray area represents shallower and thinner fog area. (b) Simulated LWP (color, unit: g/m²) and wind vector (arrow, unit: m/s) at 10-m height at 09:00 LST, 1 December 2009. The black box shows the focus region discussed in section 4.2. LWP = liquid water path.
4.1. Event-Mean Fog Properties

The aerosol effects on fog microphysical properties can be seen from the relationships of the PM$_{2.5}$ concentration to the fog-event-averaged (all the foggy grids average during the whole fog event) $N_c$, LWC, and effective radius ($r_e$) under the five different emission scenarios (Figure 7). $N_c$ is obtained from Morrison scheme (Morrison et al., 2005). It is evident that $N_c$ increases non-linearly with increasing PM$_{2.5}$ concentration, with a high increasing rate when PM$_{2.5}$ concentration is less than 20 μg/m$^3$, and gradually leveling off afterward. The LWC exhibits a similar non-linear increasing trend, as PM$_{2.5}$ concentration increases from the S1 to S5 emission scenarios, but with a smaller rate of increase compared to $N_c$. The smaller increasing rate of LWC relative to $N_c$ still causes a decrease of $r_e$ with increasing PM$_{2.5}$ concentration. It is worth emphasizing that the increase of LWC with increasing aerosol loading leads to a decreasing rate of $r_e$ with increasing aerosol concentration smaller than that expected from assuming a constant LWC in most studies of the first indirect aerosol effect (Twomey, 1977). Like $N_c$ and LWC, $r_e$ exhibits a weaker dependence on aerosol concentration when aerosol concentration is high. These nonlinear relationships reflect the regime dependence of aerosol activation into droplets (Chen et al., 2016; Reutter et al., 2009) and other interactions to be detailed later. Similar nonlinear behaviors have been reported in previous studies. For example, F. Wang et al. (2015) found by analyzing remote sensing data that the increasing trend of cloud droplets radius gradually leveling off as aerosol optical depth increases beyond 0.3.

The key macrophysical properties (fog area fraction, fog top height, fog duration, and LWP) exhibit similar nonlinear dependence on PM$_{2.5}$ concentration (Figure 8). The fog area fraction is defined as the ratio of the number of fog grid cells to the total number of grid points; fog top is defined as the highest height of foggy grids average during the whole fog event). The smaller increasing rate of LWC relative to $N_c$ is actually the mean-volume radius as the monodisperse droplet size distribution is assumed in calculation of $r_e$ from LWC and $N_c$. The neglect of the dispersion effect may overestimate or underestimate the change in $r_e$ depending on the specific aerosol-fog interaction regimes (Chen et al., 2016; Liu & Daum, 2002). Similar differences exist between the measurements conducted over NCP and Ontario, Canada. When the two regions share similar fog LWC of 0.2 g/m$^3$, $N_c$ over NCP reaches about 1,000 cm$^{-3}$ and $r_e$ is almost smaller than 10 μm (Quan et al., 2011), whereas $N_c$ is about 100 cm$^{-3}$ and $r_e$ reaches 15 μm in Ontario, Canada (Gultepe et al., 2009). These simulated changes of fog microphysical properties are similar to the previous results of midlatitude clouds reported by Y. Wang et al. (2014) as well. The fog area, top height, fog duration, and LWP increase from the clean to polluted scenarios by 12%, 11%, 14%, and 70%, respectively. A comparison of these aerosol-induced changes shows that on average, the aerosol-induced relative changes in the macrophysical properties (duration [14%], area [12%], and top height [11%]) are smaller than those in the microphysical properties ($N_c$ [447%], LWC [38%], and $r_e$ [−39%]), except for LWP (70%). The larger change in LWP stems from the combined increases of microphysical properties can be indirectly influenced by aerosols as fog droplets nuclei, but macrophysical properties are combined results of microphysics, dynamics, and thermodynamics (Fan et al., 2016). Similar change rates caused by aerosols effects on stratiform and midlatitude clouds are founded in previous study (Fan et al., 2012, 2013; Li et al., 2011; Y. Wang et al., 2014). The overall smaller aerosol effect on fog macrophysical properties raise the difficulty of detecting the second aerosol indirect effect.
Higher-resolution simulations (1-km horizontal grid spacing over a domain of 250 × 250 grids) are also performed to check the potential effect of model resolution. Similar changing rates are found, comparing to the values in the 5-km resolution simulations. The details are given in the supporting information.

4.2. Temporal Evolution

The fog event experienced a complete cycle of evolution from formation to growth to dissipation, providing a unique opportunity to further investigate the aerosol effects during different stages of fog evolution. For this purpose, this subsection focuses on a subdomain denoted as "study region" (black box in Figure 6b). The study region is chosen because it contains most foggy grids based on the criteria discussed in section 3.2 and minimizes influences of boundary conditions and geography. Meanwhile, fog tops in these grids are higher, permitting better visualization of the variable changes in and below fog. From the temporal variations of vertical profiles of LWC in the polluted S5 scenario (figure ignored), it is found that the fog formed at surface at 22:00 LST due to longwave radiative cooling. 30 November, and the fog top gradually risen as it developed; around 9:00 LST 1 December, fog started to dissipate from the surface and the fog base gradually risen. Therefore, the whole fog event could be divided into two phases according to the unique behavior of fog base. Phase I was identified from 22:00 LST 30 November to 9:00 LST 1 December, during which fog bases were below 20 m for 80% grids in the study region. Phase II was from 10:00 to 13:00 LST 1 December, during which the fog bases of 80% grids in the study region are above 20 m.

To illustrate the aerosol effects during different stages of fog evolution, Figure 10 shows the height-time dependence of the differences between the two emission scenarios (S5–S1) of LWC (a), N_c (b), r_e (c), T (d), RH (e), Temperature Change caused by Long Wave radiation (f), and Turbulence Kinetic Energy (TKE; g). It can be seen that an increase in aerosols enhanced LWC, N_c, and RH throughout the fog event, with the maximum changed place moving from the lower part to the upper part as fog evolved. However, aerosol-induced differences in r_e, T, Temperature Change caused by Long Wave radiation, and TKE were clearly distinct between Phase I and II. Increased aerosols reduced r_e in the lower-to-middle part of the fog in Phase I but enhanced r_e in Phase II. The contrasts of aerosol-induced changes between the two phases stemmed from the different increasing rates of LWC and N_c as aerosol increased; the increase rate of LWC was smaller than that of N_c in Phase I but became larger in Phase II. It is interesting to note that the aerosol-induced change in T virtually mirrored that of r_e: temperature first increased in the lower-to-middle part but decreased in the upper part of fog in Phase I, and then decreased over the whole fog layer in Phase II. Further comparative inspection shows that the changes of temperature were closely related to longwave radiation: aerosols enhanced longwave radiative cooling in the middle-upper part of fog, and longwave radiative warming (Figure 10f) in the lower part of fog in Phase I. The vertical temperature gradient caused by the aerosol-induced longwave radiation further enhanced atmospheric instability lead to promote turbulence (Figure 10g) in Phase I. Moreover, the enhanced condensation process and latent heat release, which also strengthened the turbulence in the whole fog layer. As a result, the TKE increased by up to 0.05 J/kg in the upper part of fog in Phase I.

The differences and similarities in aerosol-induced changes between the different phases can be seen more clearly in Figure 11, which compares the vertical profiles of the key variables under the S1 and S5 scenarios at 7:00 and 11:00 LST, 1 December. The two specific times are used to represent Phase I and Phase II, respectively. In addition to the above-mentioned differences, three more differences between the two phases are noteworthy. First, the fog layer was much lower in Phase I than Phase II, consistent with the stronger TKE in Phase I (Figure 11). Although aerosols acted to reduce TKE in Phase II, turbulence was so much stronger in Phase II than in Phase I. Second, although increasing aerosols led to an increase in r_e in Phase II, the overall values of r_e in Phase II were much lower than those in Phase I, and lower than the threshold size for sizable role of autoconversion processes (Liu et al., 2005).

To further illustrate the physical mechanisms underlying the differences between different stages of fog evolution, Figure 12 compares the temporal variations of sensible heat flux, latent heat flux, shortwave
Figure 10. Differences ($S_5 - S_1$) as a function of time and height of (a) LWC (g/kg), (b) $N_c$ (cm$^{-3}$), (c) $r_e$ ($\mu$m), (d) $T$ ($^\circ$C), (e) RH (%), (f) TCLW (K/hr), (g) TKE ($\times 10^{-2}$ J/kg) between the clean ($S_1$) and polluted ($S_5$) scenarios over the study region described in the Figure 5. This period including Phase I and Phase II. LWC = liquid water content; RH = relative humidity; TCLW = Temperature Change caused by Long Wave radiation; TKE = Turbulence Kinetic Energy.
radiative flux, and longwave radiative flux at surface. In Phase I, shortwave, sensible heat, and latent heat latent were all small, and longwave radiation played the dominant role. On the contrary, in Phase II, although longwave radiation was still important, the roles of other three fluxes became more dominant. Increased aerosols thus reduced surface shortwave heating, and sensible and latent heat fluxes, consequently suppressing turbulence (Fan et al., 2015). The TKE decreased by up to 0.05 J/kg during the dissipation. According to the theory of Zhou and Ferrier (2008) and the simulation by Gao et al. (2015), aerosol-induced reduction in TKE delayed the fog dissipation in Phase II.

4.3. Further Discussion

The preceding analyses suggest that the aerosol effects on fog properties are materialized through a web of complex interactions among aerosols, fog microphysics, radiation, dynamics, and thermodynamics, with distinct influences in different stages of fog evolution. To facilitate understanding, Figure 13 schematically illustrated the major mechanism in Phase I and Phase II as revealed by this study. Briefly in Phase I, under the polluted scenario, more aerosols lead to more and smaller droplets similar to the first aerosol indirect effect on clouds suggested for clouds by Twomey (1977) and others, which further weaken droplet sedimentation, autoconversion processes, and thus higher LWC similar to the second aerosol indirect effect suggested by and others. Furthermore, there exists a positive feedback between condensation and longwave radiative cooling: a higher LWC leads to a stronger longwave radiative cooling in the upper part of fog, which in turn enhances RH, condensational growth, and thereby LWC. Another important positive feedback is between condensation and turbulence: enhanced condensation could release more latent heat and thereby the

Figure 11. Vertical profiles of fog LWC (g/kg), \(N_c\) (cm\(^{-3}\)), \(r_e\) (\(\mu\)m), \(T\) (°C), water vapor content (g/m\(^3\)), RH (%), TCLW (K/hr), TKE (×10\(^{-2}\) J/kg) under the clean (black) and polluted (red) scenarios in Phase I at 07:00 LST (solid line) and in Phase II at 11:00 LST (dash line) 1 December 2009. LWC = liquid water content; RH = relative humidity; TCLW = Temperature Change caused by Long Wave radiation; TKE = Turbulence Kinetic Energy.
turbulence invigoration, which, in turn, would further promote lifting condensation and increased LWC. Dynamically, a stronger radiative cooling in the upper part and weaker cooling (stronger warming) in lower-to-middle part conspire to enhance the fog layer instability and thus turbulence intensity. A stronger turbulence will further increase the fog top height and area.

In the Phase II, under the polluted scenario, increasing aerosols lead to significant increase of LWC and droplets number concentration, but result in larger \( r_e \). The positive interactions among condensation, longwave
radiative cooling, and turbulence still exist, but the shortwave radiation played the dominant role in Phase II. Under the polluted scenario, the larger LWC and $N_c$ lead to reduced surface shortwave radiation, which induces to temperature cooling, sensible heat flux, and latent heat flux reduction. In consequence, the turbulence is suppressed in Phase II. Furthermore, the lower $T$ in fog caused by less sensible and latent heat flux would weaken droplets evaporation. The aerosol-induced thermodynamic and microphysical changes conspire to delay fog dissipation and prolong duration.

These results highlight the critical importance of aerosol’s effects on different stages of fog and the need to understand the complex interactions/feedbacks among aerosols, fog microphysics, radiation, dynamics, and thermodynamics.

5. Conclusion

In order to examine the aerosol effects on fog properties, a heavy fog event from 30 November to 1 December in NCP, one of the most populated and polluted regions in China, is investigated by use of the WRF/Chem model. Comparison of the simulations against observations shows that WRF/Chem reproduces reasonably well the general features of temporal evolution of PM$_{2.5}$ concentration, fog spatial distribution, and vertical profiles of temperature, water vapor content, and RH in the PBL throughout the whole period of the fog event.

Further sensitivity experiments are performed with five different aerosol scenarios by reducing the emission intensity of 1, 0.5, 0.3, 0.1, and 0.05 times. Comparison of aerosol effects on mean microphysics and macrophysical properties under the five scenarios show that $N_c$, LWC, LWP, fog area, fog height, and fog duration all increase nonlinearly with increasing aerosol concentrations, with different increasing rates. Effective radius $r_e$ decreases nonlinearly with increasing aerosol concentrations, because $N_c$ increases faster than LWC. On average, the increasing or decreasing rates of microphysics and macrophysical properties are larger when the PM$_{2.5}$ concentration less than 20 $\mu$g/m$^3$ and become gradually smaller after PM$_{2.5}$ concentration larger than 20 $\mu$g/m$^3$. Further comparative analysis shows that when the emission scenario changes from the clean to polluted conditions, droplet number concentrations increase by 44%, and LWC by 38%, but $r_e$ decreases by 39%, for macroproperties, the fog area, top height, duration, and LWP increases by 12%, 11%, 14%, and 70%, respectively. The high increasing rate for LWP derives from the combined increases of LWC and fog height.

Contrasting anthropogenic aerosol effects on thermodynamic and dynamical conditions are found during different stages of fog evolution. In Phase I, increasing aerosols increase $N_c$ but decrease $r_e$, resulting in weaker sedimentation and autoconversion microphysical processes in polluted condition. The aerosol-induced longwave radiative enhancement invigorates the turbulence by increasing instability and latent heat released by condensation. Two important positive feedbacks conspire to increase LWC: (1) the feedback between condensation and longwave radiative cooling in upper fog; (2) feedback between condensation and turbulence. Consequently, these thermodynamic and dynamical effects caused by increasing aerosols lead to larger fog LWP and fog area in Phase I.

In Phase II, when fog starts to dissipate and shortwave radiation plays the dominant role, the large LWP and high aerosol concentration in polluted conditions reduce surface shortwave radiation, correspondingly decrease surface sensible and latent heat, which lead to cooler environment and inhibition of turbulence. The weakened turbulence delays the fog dissipation and increase fog duration. Therefore, increasing aerosols provides favorable thermodynamic and dynamical conditions for fog development and maintenance in different phases in polluted conditions.

The results suggest that anthropogenic aerosols enhance the fog intensity and prolong duration in polluted environments, generating long and severe fog events. Thus, reducing aerosol-related anthropogenic emission could effectively ease the fog-haze environmental situation in heavily polluted region such as NCP.

References


