Modelling the Effect of Aerosol Feedbacks on the Regional Meteorology Factors over China

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ABSTRACT

The fully coupled online air quality model WRF/chem was used to investigate the aerosol-radiation interaction and aerosol-cloud interaction on the regional meteorological factors over China in 2006. The aerosol-radiation interaction and aerosol-cloud interaction of aerosols influence the various regional meteorological factors in the worst aerosol-polluted regions of China. Domain-wide monthly-mean over all day and night hours incoming solar radiation decreased by –11.03 W/m², –9.84 W/m², –5.84 W/m² and –12.37 W/m²; temperature at 2 meters (T2) decreased by –0.22°C, –0.12°C, –0.06°C and –0.24°C; Planetary boundary layer (PBL) height decreased by –16.44 m, –15.90 m, –5.48 m and –31.59 m in January, April, July and October, respectively. The values of the monthly-mean incoming solar radiation, T2 and PBL height had greater decreases in east China. Due to aerosol feedbacks, a slight increase of the monthly-mean precipitation occurred in southern and south-eastern China. The aerosol-radiation interaction and aerosol-cloud interaction of aerosols were compared for the United States (U.S.) continent, Europe, India and this study. Due to the higher aerosol load in China, the monthly-mean incoming solar radiation, T2 and PBL height exhibited greater decreases in China than in the U.S. continent and in Europe. Aerosol extinction was the dominant effect on the incoming solar radiation for either cloudless or cloudy weather conditions in China, but aerosol extinction was only apparent during cloudless weather in Europe. In India, the incoming solar radiation decreased by –20 W/m² or more in the most aerosol polluted area, which is close to the value of decrease determined in China.

Keywords: Aerosol-radiation interaction; Aerosol-cloud interaction; Meteorological factors; WRF/chem.

INTRODUCTION

The aerosol-radiation interaction and aerosol-cloud interaction play an important role in both regional meteorological factors variation and climate change (Ramanathan et al., 2001a; Jacobson, 2002; IPCC, 2007a; Zhang, 2008). First, aerosol can scatter (i.e., sulphate aerosol) and absorb (i.e., Black Carbon (BC) aerosol) solar radiation, which will lead to a decrease of the incoming solar radiation at the surface and at the top of the atmosphere (TOA), this result represents the aerosol-radiation interaction of aerosols (Charlson et al., 1992). Second, because of the change of the incoming solar radiation, the surface temperature, wind speed, planetary boundary layer (PBL) height, relative humidity and atmospheric stability will be affected, which represents the semi-direct effect. Third, aerosols can serve as cloud condensation nuclei (CCN), which will increase the cloud droplet number concentration (CDNC) through the first aerosol-cloud interaction (also known as the cloud albedo effect). The cloud water content, cloud cover, cloud lifetime and precipitation will be changed due to the CCN produced through the aerosol-cloud interaction of aerosols (also known as the cloud life time effect).

Modelling studies and field experiments were conducted to understand the aerosol-radiation interaction and aerosol-cloud interaction influence of aerosols on regional and global climate change. Global anthropogenic contributions to the concentration of aerosols (primarily sulphate, organic carbon,
black carbon, nitrate and dust) together produce a cooling effect with a total (including atmosphere and surface) direct radiative forcing of ~0.5 W/m² and an indirect cloud albedo forcing of ~0.7 W/m² (IPCC, 2007b). The Atmospheric Brown Cloud (ABC) regional assessment report suggests that ABC has led to global scale dimming of ~4.4 W/m², with ~1.7 W/m² of BC radiative forcing and ~2.5 W/m² of other aerosol radiative forcing (Ramanathan et al., 2008). In the Indian Ocean Experiment (Ramanathan et al., 2001b) and the North Atlantic Regional Experiment (Liu et al., 1996), an obvious decrease of the incoming short wave solar radiation was found; this apparent decrease is largely caused by the aerosol-radiation interaction and aerosol-cloud interaction of aerosols. Ohmura et al. (2009) used decadal observed data to determine the relationship between the global dimming period (approximately from the 1960s to the 1980s) and the aerosol-radiation interaction and aerosol-cloud interaction of aerosols. The result demonstrated equal weights of the contributions of the aerosol-radiation interaction and aerosol-cloud interaction; this study also examined the sensitivity of temperature to aerosol feedbacks. Different particle sizes of aerosols acting as CCN will have different effects on the regional precipitation, i.e., small aerosols inhibit precipitation and large aerosols increase precipitation (Leaitch et al., 1996; Li et al., 1996). In the Amazon and Indonesian rainforests, soot and smoke form wildfires can suppress the warm rain-forming process by making CCN smaller and quantity (Warner, 1968; Kaufman and Fraser, 1997; Rosenfeld, 1999; Zhang et al., 2010). The significant formation of CCN by aerosols arriving downwind from urban and lager factories areas, especially paper mills, will increase precipitation (Cerveny et al., 1998; Zhang et al., 2010a).

Simulation of the aerosol-radiation interaction and aerosol-cloud interaction of aerosol feedbacks require on-line coupled models (Zhang, 2008). The time-dependent climate response to changing concentrations of greenhouse gases and sulphate aerosols is studied using a coupled general circulation model and the simulation results indicate that the intensity of the global hydrological cycle becomes weaker in a warmer climate if both aerosol-radiation interaction and aerosol-cloud interaction are included in addition to the effects of greenhouse gases (Roeckner et al., 1999). The results of a General Circulation Model (GCM) used to understand the role of ABC in climate change indicated that absorbing aerosols in ABC have played a major role in the observed regional climate and hydrological cycle changes and have masked as much as 50% of the surface warming due to the global increase in greenhouse gases (Ramanathan et al., 2005). A study of the climatic influence of BC within clouds using the Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, Ocean Model (GATOR-GCMOM) suggested that BC in cloud can increase water vapor, decrease precipitation and decrease cloud fraction (Jacobson et al., 2006a). A three-dimensional interactive aerosol-climate model has been developed and used to study the climatic impact of BC aerosols, which indicated that the significant global-scale changes caused by BC aerosols occurring in surface latent and sensible heat flux, the surface net long-wave radiative flux, the planetary boundary layer height, convective precipitation (all negative), and low-cloud coverage (positive) are all closely related to the hydrological cycle (Wang, 2004).

The aerosol-radiation interaction and aerosol-cloud interaction of aerosols on the regional meteorological factors in the short-term are important in the dispersion of pollutants and in secondary organic reactions. Among the previously described studies, field experiments have deficiencies in investigating the aerosol-radiation interaction and aerosol-cloud interaction of aerosols on regional meteorological factors and air quality over a large region and a long-term (years and decades) period. Although using general circulation models and climate models can focus on the regional and long-term period aerosol feedbacks, but it cannot fully reflect the short-term (hours and days) characteristic of aerosol feedbacks. On-line air quality models are designed for aerosol simulation, which include the accurate simulation of the aerosol concentration and the regional- to global-scale of the feedback between air pollutants and meteorological factors (Zhang, 2008). The Weather Research Forecasting Model with chemistry (WRF/chem) is a fully coupled on-line air quality model (Grell et al., 2005; Zhang, 2008), it contains comprehensive feedback components and processes, such as on-line pollutant feedback to heating rates to drive meteorology and on-line pollutant feedbacks to photolysis to drive photochemistry. WRF/chem includes a unified significantly coupled mesoscale meteorology chemistry aerosol radiation model, which represents the state-of-the-science online-coupled models that account for many types of feedbacks (Zhang, 2008). WRF/chem has been used in simulating the effect of elevated sources on aerosol forcing and cloud-aerosol interaction in summertime over northeastern North America (Chapman et al., 2009); the three days of studies revealed a domain-averaged reduction of 5 W/m² in the mean daytime incoming solar radiation, and the rainfall was increased by 31%. Another study focused on the chemistry-aerosol-cloud-radiation-climate feedbacks over the continental United States (Zhang et al., 2010a). The result of that study indicated a decrease of the incoming solar radiation, temperature and PBL height; increased amounts of small CCN that inhibit precipitation; and decreases and increases of NO2 photolysis in different places over the United States (U.S.). A five-day period study with Weather Research and Forecasting model with Chemistry (WRF/Chem) with the Model of Aerosol Dynamics, Reaction, Ionization, and Dissolution (MADRID) (referred to as WRF/chem-MADRID) of 2000 Texas Air Quality (TexAQS2000) found that the incoming solar radiation and near-surface temperature decreased due to aerosol-radiation interaction and aerosol-cloud interaction feedbacks, and aerosols led to excessive numbers of cloud condensation nuclei with too low saturation and reduced precipitation via these CCN (Zhang et al., 2010b). A summertime case study in Europe using WRF/chem examined aerosol-radiation feedback on the regional meteorology and air quality; the result indicated an obvious decrease of the solar radiation due to clouds, which changed the optical properties and lifetime and was affected by the aerosol-cloud interaction of aerosols, thereby resulting in precipitation changes from ~100% to 100% in comparison with different scenarios; the PM10 concentration increased
while the PBL height decreased due to the semi-direct effect, and the change in ozone is primarily related to the change of the cloud cover (Forkel et al., 2012). The global scale online air quality model Global-through-urban Weather Research Forecasting Model with chemistry (GU-WRF/Chem) has been developed and initially applied to the study of the global-through-urban aerosol-radiation interaction and aerosol-cloud interaction of aerosols on meteorological factors (Zhang et al., 2012).

China is the largest developing country; unfortunately, the air pollution is worsening as rapidly as the economic growth is increasing in China. East Asia, where China is located, is one of the five regional ABC hotspots around the world (Ramanathan et al., 2008); the yearly average PM$_{10}$ level during 2001–2006 is over 75 µg/m$^3$, which is much higher than the levels in the U.S. and in the European region (van Donkelaar et al., 2010). High concentrations of air pollutants and highly oxidising regional air pollution are poisoning China’s atmosphere. In particular, because the meteorological conditions are unfavourable for the spread of contaminants, extremely high aerosol concentrations are easily formed. In January 2013, the hourly PM$_{2.5}$ concentration once reached up to 800 µg/m$^3$ in east China. Such a high concentration of aerosol pollution will lead to significant differences of the long-term and short-term changes of meteorological factors due to aerosol feedback between China and the lower aerosol concentration regions.

Few studies have focused on aerosol feedback in China. A study that used the regional climate model (RegCM) coupled with a sulphate feedback mechanism (i.e., a chemistry mechanism coupled with the regional climate model (RegCM)) suggests that the aerosol-radiation interaction and aerosol-cloud interaction of anthropogenic sulphate over east Asia induce a negative radiative forcing that results in a cooling of the surface and a decrease of precipitation (Giorgi et al., 2003). To understand the aerosol-radiation interaction and aerosol-cloud interaction of black carbon in China, the regional climate chemistry model system (RegCCMS) coupled modelling system was used to investigate BC loading, SSA forcing, and its climatic responses; the results indicated that the annual mean aerosol-radiation interaction is primarily reflected in the areas with high BC loadings, with a regional mean decrease of 0.75 W/m$^2$; the single-scattering albedo (SSA) are high at the surface and the TOA in the regions with high BC concentration and cloud cover (Zhuang et al., 2010). The Regional Climate Chemistry Modeling System was used to investigate the direct, semi-direct and indirect of fossil fuel black carbon in China; the results indicated that the regional-averaged direct and indirect radiative forcing of BC in China was about +0.81 W/m$^2$ and –0.95 W/m$^2$, respectively, leading to a net radiative forcing of –0.15W/m$^2$ at the TOA (Zhuang et al., 2010, 2011). The effect of aerosols on surface temperature, clouds and precipitation were studied with different models (Huang et al., 2006; Liu et al., 2011). Only a single aerosol species or meteorological factor is discussed in the above studies over China, which cannot fully reflect the circumstances of aerosol feedback in China. The complete investigation of the aerosol-radiation interaction and aerosol-cloud interaction of aerosols (including sulphate, BC and other aerosols) requires further study. In this work, the fully coupled online air quality model WRF/chem is applied to evaluate the aerosol-radiation interaction and aerosol-cloud interaction of aerosols in four representative months (January, April, July and October) of the four seasons in 2006. Several meteorological parameters are analysed to explore the influence of aerosol feedbacks in China, and the effects of aerosol feedbacks in the U.S. continent, Europe and India are compared with this study.

**MODEL SETUP**

The version of WRF/chem V3.4 was used in this work. The physics options include the Lin microphysics scheme, the Goddard short wave scheme, the Rapid Radiative Transfer Model (RRTM) long wave scheme, the Yonsei University (YSU) PBL meteorology scheme, Noah-MP land surface model and the Grell-Devenyi cumulus parameterisation. Carbon Bond Mechanism version Z (CBM-Z) is used to calculate the gas phase chemistry, which consists of 67 prognostic species and 164 reactions. The aerosol module used was the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) (Zaveri et al., 2008). To work with CBM-Z, MOSAIC treats all the major aerosol species at the urban, regional, and global scales. It contains sulphate (SULF = SO$_4^{2-}$ + HSO$_4^-$), methanesulphonate (CH$_3$SO$_3^-$), nitrate (NO$_3^-$), chloride (Cl$^-$), carbonate, ammonium (NH$_4^+$), sodium, calcium, black carbon, primary organic mass, liquid water and other unspecified inorganic species. The secondary organic aerosol (SOA) is describe by the 2-bin version Volatility Basis Set Approach (VBS) coupled with MOSIAC (Shrivastava et al., 2010, 2011). The particle size distribution is simulated for 4 size bins between 39nm to10µm, each bin is assumed to be internally mixed, while particles in different bins are externally mixed (Zaveri et al., 2008). Aerosol optical properties calculated based upon volume approximation (Peckham et al., 2011). The aerosol-radiative feedback is simulated through coupling with the Goddard shortwave radiation parameterization using aerosol optical depth, single scattering albedo, and asymmetry factor derived from MOSAIC particulates and Mie theory (Ghan et al., 2001; Fast et al., 2006; Gustafson et al., 2007, Chapman et al., 2009) and the Lin et al. microphysics parameterization. The aerosol-cloud interaction is simulated through coupling with the Lin et al. microphysics parameterization (Gustafson et al., 2007; Chapman et al., 2009) that include prognostic treatments of cloud droplet number and activated (cloud-phase) aerosol species, aerosol activation and resuspension (Ghan et al., 2001; Zhang et al., 2002), bulk cloud chemistry (Fahey and Pandis, 2001), and in-cloud and below-cloud wet removal of particulates and trace gases (Easter et al., 2004).

The study area is divided into 92 × 78 horizontal grid cells with a 54-km grid spacing. The entire China continent, part of East China Sea and part of Southeast Asia are included. 27 logarithmic structure layers divide the modelling vertical zone, which range from the surface to a fixed pressure of 100 mb. The National Centers for Environmental Prediction (NECP) Final Analysis Reanalysis data are used to generate
the meteorology initial conditions and boundary conditions. The INTEX-B emission inventory for Asia in 2006 was used as the anthropogenic emission input, which is built by Zhang et al. (2009) in the Intercontinental Chemical Transport Experiment (INTEX-B). Natural emissions are calculated online based on the U.S. Geological Survey (USGS) land use data. The meteorological observed data come from the Meteorological Information Comprehensive Analysis and Process System (MICAPS). The PM$_{10}$ concentration observed data are calculated based on the API value, which published on China EPA website (http://datacenter.mep.gov.cn/report/air_daly/air_dairy.jsp). Three scenarios are set up in this study to calculate the aerosol-radiation interaction and aerosol-cloud interaction, with the description of each listed in Table 1. The DIF (aerosol-radiation interaction and aerosol-cloud interaction) scenario involves the calculation of both aerosol-radiation interaction and aerosol-cloud interaction processes. The DF (aerosol-radiation interaction) scenario involves the calculation of the aerosol-radiation interaction only. The NF (No aerosol Feedback) scenario does not calculate any aerosol feedback process. The difference between the DIF and NF responses is the co-influence of the aerosol-radiation interaction and aerosol-cloud interaction on the meteorological factors; the difference between the DF and NF response the influence of aerosol-radiation interaction on meteorological factors.

**MODEL EVALUATION**

According to the U.S. EPA model evaluation protocol (U.S. EPA, 2007), the mean bias (MB), normalised mean bias (NMB), normalised mean gross error (NME), mean normalised bias (MNB) and correlation coefficient (RC) are used to perform statistical analysis. The simulated temperature at 2 meters (T2), the wind speed at 10 meters (WSP10), the daily precipitation, the meteorological factors and the PM$_{10}$ concentration are compared with the available observational data to evaluate the accuracy of the WRF/chem simulation. The summarised performance statistics of the meteorology factors and the PM$_{10}$ concentration levels are listed in Table 2 to Table 4. Fig. 1 compares the simulated and observed hourly T2 at Beijing, Shanghai, Wuhan and Guangzhou, which are located in China in the north, south, central and east, respectively, WRF/chem well captured the variations of T2 at all sites in the four months with correlation coefficients (RC) between 0.78-0.93. Warm bias occurs in some periods, which represent –0.50℃ to 2.16℃ MB and –1.71% to 44.08% NMB of four sites in the four seasons.

**Table 1. Simulation scenarios set up.**

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIF</td>
<td>Aerosol-radiation interaction &amp; Aerosol-cloud interaction</td>
</tr>
<tr>
<td>DF</td>
<td>Aerosol-radiation interaction</td>
</tr>
<tr>
<td>NF</td>
<td>No aerosol feedback</td>
</tr>
</tbody>
</table>

**Table 2. Performance statistics of the hourly T2 of WRF-chem in January 2006 a.**

<table>
<thead>
<tr>
<th>Month</th>
<th>stations</th>
<th>MB</th>
<th>NMB</th>
<th>NME (%)</th>
<th>MNB (%)</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>Beijing</td>
<td>–0.02</td>
<td>1.23</td>
<td>–0.48%</td>
<td>–16.4%</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>0.41</td>
<td>5.93</td>
<td>0.19%</td>
<td>8.5%</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>1.82</td>
<td>44.08</td>
<td>0.21%</td>
<td>48.7%</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>0.87</td>
<td>5.66</td>
<td>0.05%</td>
<td>6.0%</td>
<td>0.94</td>
</tr>
<tr>
<td>April</td>
<td>Beijing</td>
<td>1.61</td>
<td>12.34</td>
<td>0.08%</td>
<td>14.6%</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>0.70</td>
<td>4.09</td>
<td>0.13%</td>
<td>4.5%</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>1.57</td>
<td>8.47</td>
<td>0.05%</td>
<td>11.7%</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>1.54</td>
<td>6.64</td>
<td>0.04%</td>
<td>7.7%</td>
<td>0.86</td>
</tr>
<tr>
<td>July</td>
<td>Beijing</td>
<td>2.16</td>
<td>8.49</td>
<td>0.04%</td>
<td>8.6%</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>–0.50</td>
<td>–1.71</td>
<td>0.05%</td>
<td>–1.5%</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>0.80</td>
<td>2.68</td>
<td>0.02%</td>
<td>2.8%</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>–0.85</td>
<td>–2.87</td>
<td>0.02%</td>
<td>–2.6%</td>
<td>0.78</td>
</tr>
<tr>
<td>October</td>
<td>Beijing</td>
<td>1.65</td>
<td>10.49</td>
<td>0.06%</td>
<td>13.1%</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>–0.18</td>
<td>–0.37</td>
<td>0.05%</td>
<td>–0.7%</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>1.35</td>
<td>6.49</td>
<td>0.04%</td>
<td>6.7%</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>–0.03</td>
<td>–0.10</td>
<td>0.02%</td>
<td>–0.1%</td>
<td>0.85</td>
</tr>
</tbody>
</table>

a. Model are value of model simulated value; Obs are value of the observed value; N are value of the number of data pairs. The units of MB, NMB and RC are same to each variable, for NME and MNB is in %. The definitions of the statistical measures are as follows: MB = \( \frac{1}{N} \sum_{i=1}^{N} (\text{Model}_i - \text{Obs}_i) \); NMB = \( \frac{1}{N} \sum_{i=1}^{N} (\text{Model}_i - \text{Obs}_i) / \sum_{i=1}^{N} (\text{Obs}_i) \); NME = \( \sum_{i=1}^{N} (\text{Model}_i - \text{Obs}_i) / \sum_{i=1}^{N} (\text{Obs}_i) \times 100\% \); MNB = \( \frac{1}{N} \sum_{i=1}^{N} (\text{Model}_i - \text{Obs}_i) / \sum_{i=1}^{N} (\text{Obs}_i) \times 100\% \); RC = \( \frac{\sum_{i=1}^{N} (\text{Model}_i - \text{Obs}_i) (\text{Obs}_i - \text{Obs})} {\sqrt{\sum_{i=1}^{N} (\text{Model}_i - \text{Model})^2 \sum_{i=1}^{N} (\text{Obs}_i - \text{Obs})^2}} \).
Table 3. Performance statistics of the hourly WSP10 of WRF-chem in January 2006a.

<table>
<thead>
<tr>
<th>Month</th>
<th>stations</th>
<th>MB</th>
<th>NMB</th>
<th>NME(%)</th>
<th>MNB(%)</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>Beijing</td>
<td>0.99</td>
<td>49.4</td>
<td>0.33 %</td>
<td>69.3%</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>2.84</td>
<td>169.5</td>
<td>1.92 %</td>
<td>156.2%</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>2.24</td>
<td>163.3</td>
<td>0.71 %</td>
<td>144.7%</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>2.74</td>
<td>176.5</td>
<td>0.78 %</td>
<td>163.7%</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Beijing</td>
<td>1.29</td>
<td>42.0</td>
<td>0.28 %</td>
<td>68.3%</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>3.09</td>
<td>151.9</td>
<td>1.72 %</td>
<td>173.2%</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>2.27</td>
<td>134.5</td>
<td>0.61 %</td>
<td>143.4%</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>2.24</td>
<td>136.9</td>
<td>0.64 %</td>
<td>149.8%</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Beijing</td>
<td>0.51</td>
<td>22.4</td>
<td>0.24 %</td>
<td>41.4%</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>2.73</td>
<td>147.1</td>
<td>1.76 %</td>
<td>147.0%</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>1.79</td>
<td>95.4</td>
<td>0.00 %</td>
<td>107.5%</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>1.61</td>
<td>93.1</td>
<td>0.45 %</td>
<td>118.2%</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>Beijing</td>
<td>1.19</td>
<td>63.4</td>
<td>0.34 %</td>
<td>81.8%</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>1.82</td>
<td>36.8</td>
<td>1.29 %</td>
<td>107.5%</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>0.90</td>
<td>77.7</td>
<td>0.44 %</td>
<td>66.7%</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>1.30</td>
<td>110.8</td>
<td>0.56 %</td>
<td>93.2%</td>
<td>0.21</td>
</tr>
</tbody>
</table>

a. Model are value of model simulated value; Obs are value of the observed value; N are value of the number of data pairs. The units of MB, NMB and RC are same to each variable, for NME and MNB is in %. The definitions of the statistical measures are as follows: MB = \( \frac{1}{N} \sum_{i=1}^{N} (Model - Obs) \); NMB = \( \frac{1}{N} \sum_{i=1}^{N} ((Model - Obs) / Obs) \times 100 \% \);

NME = \( \frac{\sum_{i=1}^{N} |Model - Obs|}{\sum_{i=1}^{N} (Obs) \times 100} \); MNB = \( \frac{1}{N} \sum_{i=1}^{N} ((Model - Obs) / Obs) \times 100 \% \);

RC = \( \sqrt{\frac{\sum_{i=1}^{N} (Model - Obs)}{\sum_{i=1}^{N} (Obs) - \overline{Obs}}} \).

Table 4. Performance statistics of 24-hour average PM10 of WRF-chem in January 2006a.

<table>
<thead>
<tr>
<th>Month</th>
<th>stations</th>
<th>MB</th>
<th>NMB</th>
<th>NME(%)</th>
<th>MNB(%)</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>Beijing</td>
<td>–48.16</td>
<td>–24.5</td>
<td>1.12 %</td>
<td>–20.9%</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>55.93</td>
<td>65.3</td>
<td>2.27 %</td>
<td>76.3%</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>31.34</td>
<td>21.2</td>
<td>1.05 %</td>
<td>25.5%</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>–2.91</td>
<td>–2.4</td>
<td>1.31 %</td>
<td>25.8%</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Beijing</td>
<td>–168.33</td>
<td>–67.9</td>
<td>2.36 %</td>
<td>–57.2%</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>–27.29</td>
<td>–24.6</td>
<td>1.36 %</td>
<td>–15.9%</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>2.41</td>
<td>2.1</td>
<td>1.27 %</td>
<td>8.9%</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>–1.76</td>
<td>–2.9</td>
<td>1.66 %</td>
<td>20.6%</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>Beijing</td>
<td>–5.90</td>
<td>–6.3</td>
<td>1.19 %</td>
<td>9.2%</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>–4.03</td>
<td>–6.9</td>
<td>0.99 %</td>
<td>1.3%</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>–17.97</td>
<td>–23.5</td>
<td>0.93 %</td>
<td>–23.4%</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>–6.15</td>
<td>–12.1</td>
<td>1.10 %</td>
<td>–4.7%</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Beijing</td>
<td>–8.95</td>
<td>–5.6</td>
<td>1.08 %</td>
<td>–4.2%</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>Shanghai</td>
<td>14.39</td>
<td>17.7</td>
<td>1.21 %</td>
<td>23.8%</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Wuhan</td>
<td>64.22</td>
<td>42.4</td>
<td>1.63 %</td>
<td>45.9%</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Guangzhou</td>
<td>28.67</td>
<td>33.6</td>
<td>1.53 %</td>
<td>29.1%</td>
<td>0.61</td>
</tr>
</tbody>
</table>

a. Model are value of model simulated value; Obs are value of the observed value; N are value of the number of data pairs. The units of MB, NMB and RC are same to each variable, for NME and MNB is in %. The definitions of the statistical measures are as follows: MB = \( \frac{1}{N} \sum_{i=1}^{N} (Model - Obs) \); NMB = \( \frac{1}{N} \sum_{i=1}^{N} ((Model - Obs) / Obs) \times 100 \% \);

NME = \( \frac{\sum_{i=1}^{N} |Model - Obs|}{\sum_{i=1}^{N} (Obs) \times 100} \); MNB = \( \frac{1}{N} \sum_{i=1}^{N} ((Model - Obs) / Obs) \times 100 \% \);

RC = \( \sqrt{\frac{\sum_{i=1}^{N} (Model - Obs)}{\sum_{i=1}^{N} (Obs) - \overline{Obs}}} \).
Fig. 1. Time series of the observed and simulated hourly Temperature at 2 meters (T2), during January, April, July and October 2006 in Beijing, Shanghai, Wuhan and Guangzhou.

especially in April. The warm bias is caused by the limitations in the PBL scheme, radiation schemes (Zhang et al., 2010; García-Díez et al., 2012) and the land-surface model (Lee et al., 2011). The moderate to large over-prediction occurred in the hourly WSP10 in all the sites, with a domain wide average bias are 0.77, 1.35, 0.41, 0.69 m/s in January, April, July and October, respectively, as shown in Table 3 and Fig. 2. The bias is caused by two points. First, analysis nudging (FDDA) was not applied to the meteorological factors to prevent the aerosol-radiation interaction and aerosol-cloud interaction of aerosols on meteorological factors are the suppressed (Forkel et al., 2012). Second, with a horizontal resolution of 54 km, the model has difficulties in capturing the wind properly. The hourly precipitation is well captured by WRF/chem, as shown in Fig. 3, but incorrect reports (which represent cases when rain did not occur, but the model reported it and vice versa) of precipitations are found in the north China sites, and under-predictions are found in the south China sites.

The time series of observed and simulated 24-hour average PM$_{2.5}$ concentration are shown in Fig. 4, and the performance statistics are listed in Table 4. The monthly variation of observed and simulated PM$_{2.5}$ exhibited good agreement, and the spatial distribution is well-captured by the model. The domain-wide average biases are 9.05 µg/m$^3$, −8.31 µg/m$^3$, −7.21 µg/m$^3$, 26.03 µg/m$^3$ in January, April, July and October, respectively. In autumn and winter, the PM$_{2.5}$ levels are over-predicted, it is due to the cold bias of temperature and the incorrect reporting of precipitation in some time periods. In spring and summer, the PM$_{2.5}$ levels are under-predicted, it is related to the positive deviation of the wind speed in the spring and summer, as well as the incorrect simulation of the
precipitation in July. A large under-prediction of PM$_{10}$ is found over Beijing in 15$^{th}$ to 16$^{th}$ January with −225 µg/m$^3$ MB. This bias is due to the large over-prediction of T$_2$, with a performance of 4.7°C MB. The over-simulated temperature leads to a higher PBL height and a better atmospheric diffusion capacity; thus, the PM$_{10}$ particles are not easily accumulated to form a heavy pollution. The same bias of the PM$_{10}$ level occurs in Shijiazhuang (figure not shown), the −2.2°C temperature MB cause −100 µg/m$^3$ MB of PM$_{10}$ in 25$^{th}$ January. The over-estimation of the wind speed cause the under-predicted of PM$_{10}$ levels in Beijing and Wuhan in some periods. The uncertainty of the anthropogenic emission inventory and the land-use data, the inadequate nature of PBL scheme are cause the inaccuracy of PM$_{10}$ concentration. The large negative deviation of PM$_{10}$ in Beijing in April is caused by a sand storm (Zhang et al., 2010), which is natural source and does not calculate by WRF-chem; the same bias occurs in Tianjin and Shijiazhuang (figure not shown) during the same time period.

RESULTS AND DISCUSSION

Effect on the Regional Meteorology Factors

Under the action of aerosol-radiation interaction, the incoming solar radiation, temperature at 2 m, planetary boundary layer height and precipitation are changed in the four seasons in 2006 over China. The yearly average incoming solar radiation reduced by −18.52 W/m$^2$, T$_2$ reduced by −0.15°C, the PBL height decreased by −17.35 m and precipitation increased by 0.09 mm. The worst affected areas appear in eastern China, where the monthly-mean particle concentrations are higher than the yearly average
of Chinese air quality standards for Grade II (the reference PM$_{10}$ concentration is 70 µg/m$^3$ and the reference PM$_{2.5}$ concentration is 35 µg/m$^3$, the Chinese air quality standard is not specified in terms of the monthly-average particle concentration, so we used the yearly-average standards instead). Changes of T2 and the PBL height are very similar to that of the incoming solar radiation in the monthly average result, with the largest decrease occurring in east China and the smallest decrease occurring in the west. The monthly average precipitation increase in southeast China, the Taiwan Strait and the South China Sea and only slightly change in the Outback. The changes in the monthly and hourly variations of each of the meteorological factors are discussed below.

**Incoming Solar Radiation**

The domain-wide monthly-mean reductions over all day and night hours of the incoming shortwave radiation are $-11.03$ W/m$^2$, $-9.84$ W/m$^2$, $-5.84$ W/m$^2$, and $-12.37$ W/m$^2$ in January, April, July and October, respectively, as shown in Fig. 5. The simulated result indicates a correlation between the incoming solar radiation and the PM$_{10}$ concentration. When the PM$_{10}$ concentration is over 70 µg/m$^3$, the monthly-average incoming solar radiation exhibits an obvious decrease of over $-20$ W/m$^2$ in Beijing-Tianjin-Hebei (BTH), the Yangtze River Delta (YRD) and the Pearl River Delta (PRD) region, and four urban agglomerations of Shandong, Wuhan and the surrounding areas, Chang-Zhu-Tan and Chengdu-Chongqing. These above-mentioned places are the key areas of air pollution control in the 12th Five Year Plan in China. In contrast to those places, the incoming solar radiation exhibits little change, with a decrease of less than $-3$ W/m$^2$, in west China (mainly in Xinjiang, Qinghai and Tibet), where the yearly PM$_{10}$ concentration is lower than 70 µg/m$^3$. In autumn and winter, the PM$_{10}$ concentration was over 70 µg/m$^3$ in most of east China, and the decrease in the monthly-mean incoming solar radiation was over 20 W/m$^2$. In spring and
Fig. 4. Time series of the observed and simulated 24-hour-average PM$_{10}$ concentration during January, April, July and October 2006 in Beijing, Shanghai, Wuhan and Guangzhou.

Summer, the decrease area of the incoming solar radiation is smaller due to the smaller PM$_{10}$ concentration than the levels of autumn and winter. The difference between the cold season (autumn and winter) and the warm season (spring and summer) is caused by the subtropical monsoon, it brings rain and wind to the southeast China continent during the warm season; the wet deposition and wet removal of particles are dynamic, which result in low concentrations of particulate matter and thus reduce the influence of the aerosol-radiation interaction. Even when the PM$_{10}$ concentration in a polluted region is lower than that in a clean region, the decrease of the incoming solar radiation in a polluted region is higher than that in a clean region. This is related to the difference of the aerosol component, i.e., a polluted region exhibits more scattering and absorbing aerosols due to anthropogenic emissions. Incoming solar radiation is affected more in spring and summer, which is dominated by the monsoon climate system. In monsoon season (including spring and summer), the high temperature, the abundant vapour from the maritime airstream and suitable meteorological conditions produce many clouds, which provide aerosols more opportunities to alter the optical properties and lifetime of clouds.
Comparing the DIF and DF monthly results in Fig. 5, incoming solar radiation further decreased due to only the effect of aerosol extinction. This reduction in solar radiation is related to the decline of cloud cover caused by aerosol feedback. The warm effects of the absorption of aerosols or the semi-direct effect of aerosols primarily suppress the formation and growth of clouds (Ten Hoeve et al., 2011). The evaporation of clouds within the aerosol layer may also occur due to the increase in the temperature and the decrease in the relative humidity caused by aerosol absorption of solar radiation (Yu et al., 2002; Jacobson, 2002, 2006b). As shown in Fig. 9, the hourly change of the incoming solar radiation in all day and night hours, the temperature at 2 meters and the PBL height in Beijing, Shanghai and Guangzhou, i.e., three megacities in China, are examined to investigate the aerosol-radiation interaction and aerosol-cloud interaction of aerosols on the regional meteorological factors. The decrease of the incoming solar radiation can be found in the hourly simulated results in the four months. In the four seasons, when the PM$_{10}$ concentration is over 150 µg/m$^3$ (the second level of the 24-hour-average PM$_{10}$ air quality standards in China; the Chinese air quality standards are not specified in terms of hourly PM$_{10}$ concentrations, so we use the 24-hour-average standards instead), the incoming solar radiation will be reduced by 50–120 W/m$^2$. This phenomenon often occurs in Beijing and Shanghai due to the high PM$_{10}$ concentration in winter. Although the PM$_{10}$ hourly concentration in Guangzhou is generally under 150 µg/m$^3$, the decrease of the incoming solar radiation can still be found, with the incoming solar radiation decreased by 25–60 W/m$^2$ when the PM$_{10}$ concentration is over 50 µg/m$^3$ (the first level of the 24-hour-average PM$_{10}$ air quality standards in China).

**Temperature and the PBL Height**

Temperature and PBL height are affected with the change of the incoming solar radiation. As shown in Fig. 6 and Fig. 7, the domain-wide monthly-average T2 decreases of –0.22°C, –0.12°C, –0.06°C, and –0.24°C occurred in January, April, July and October, respectively, and the PBL height decreases of –16.44 m, –15.90 m, –5.48 m and –31.59 m occurred in January, April, July and October, respectively. The aerosol-radiation interaction on the change of meteorological factors are dominated by the PM$_{10}$ concentration. The largest decline of the incoming solar radiation, T2 and the PBL height all appear in eastern China, where the monthly-average PM$_{10}$ concentration is the highest. Both the monthly-average T2 and PBL height exhibit a lower reduction in value in spring and summer than in autumn and winter in eastern China. In particular, in summer, monthly-average T2 decrease of less than only –0.1°C occurred. Both the T2 and PBL height exhibit greater changes in the DF simulation than in the DIF due to the warm effects of absorption aerosols.

Fig. 10 and Fig. 11 show the hourly change of T2 and PBL height and their relationship between hourly PM$_{10}$ in three cities. Beijing exhibits the worst hourly PM$_{10}$ pollution, with the greatest number of over 150 µg/m$^3$ PM$_{10}$ concentration days in the four months. The simulated results show that both the hourly T2 and PBL height decreased substantially, while the hourly PM$_{10}$ concentration changes rapidly in a short amount of time (one to two days) which often occurs in Beijing and Guangzhou. T2 and PBL height change little, while the PM$_{10}$ concentration remain at a low level; however, when the PM$_{10}$ level rises to higher concentrations, both T2 and PBL height sharply declined. When the PM$_{10}$ level returned to a low level, the T2 and the PBL height stopped decreasing. The hourly PM$_{10}$ concentration in Guangzhou is the lowest of the three cities. However, due to the rapid change of the PM$_{10}$ concentration, a substantial decrease of both T2 and PBL height often occurs. Although periods of high concentration of PM$_{10}$ pollution occur in Shanghai, but both the T2 and PBL height change more slowly than in Beijing and Guangzhou due to the slowly accumulation of PM$_{10}$.

**Precipitation**

As shown in Fig. 8, a slight change of precipitation occurs in the entire country due to the aerosol-radiation interaction and aerosol-cloud interaction of aerosols. The increases of precipitation occur in different places and with different volumes in the four seasons. In winter, the increase mainly occurs in Taiwan Island and the surrounding sea area with an increase of over 0.2 mm, while a slight decrease appears in the outback area with less than 1% precipitation (figure not shown). Different trends of change are found in autumn, when the precipitation increased in Beijing and southwest Sichuan Basin instead of the marine area. In spring and summer, the precipitation increased in the southeast China continent, East China Sea, Taiwan and the Himalayas. The amount of precipitation further increased in spring and summer, which is related to the monsoon rainfall climate in China. Abundant water vapour is brought in from the sea by monsoons, which provide enough vapour for the aerosol seved CCN to form precipitation. Compared to the DIF and DF, the aerosol-cloud interaction of aerosols dominate the change of the precipitation, whereas the aerosol-radiation interaction exhibits a notably minor influence.

**Comparison with the United States Europe and India**

China is one of the region most seriously affected by aerosol pollution in the world, where the influence of the aerosol-radiation interaction and aerosol-cloud interaction of aerosols is different compared to the low aerosol concentration regions. The difference of the change of the meteorological factors under the influence of aerosol feedback between the continental U.S., Europe and India this study are compared.

**Continental United States**

The aerosol-radiation interaction and aerosol-cloud interaction of aerosols in the continental United States in 2006 are compared to China. Zhang et al. (2010) investigated the aerosol-radiation interaction and aerosol-cloud interaction of aerosols over the continental United States based on the simulated result of WRF-chem. The result indicated that solar radiation, temperature at 2 meters, PBL height and precipitation are all reduced in most of the continental U.S.
Fig. 5. Simulated result of the monthly-mean incoming solar radiation (Insolation) in W/m² in January, April, July and October, 2006. DIF-NF (Left row) represent the difference between the scenarios including the aerosol-radiation interaction and aerosol-cloud interaction of aerosols and the scenarios of non-feedback. DF-NF (Right row) represent the difference between the scenarios including the aerosol-radiation interaction of aerosols and the non-feedback scenarios.
Fig. 6. Simulated result of the monthly-mean temperature at 2 meters (T2) in °C in January, April, July and October, 2006. DIF-NF (Left row) represent the difference between the scenarios including the aerosol-radiation interaction and aerosol-cloud interaction of aerosols and the non-feedback scenarios. DF-NF (Right row) represent the difference between the scenarios including the aerosol-radiation interaction of aerosols and the non-feedback scenarios.
Fig. 7. Simulated result of the monthly-mean planetary boundary layer (PBL) height in meters in January, April, July and October, 2006. DIF-NF (Left row) represent the scenarios including the aerosol-radiation interaction and aerosol-cloud interaction of aerosols and the non-feedback scenarios. DF-NF (Right row) represent the difference between the scenarios including the aerosol-radiation interaction of aerosols and the non-feedback scenarios.
Fig. 8. Simulated result of the monthly-mean precipitation (Precip) in millimetres in January, April, July and October, 2006. DIF-NF (Left row) represent the scenarios including the aerosol-radiation interaction and aerosol-cloud interaction of aerosols and the non-feedback scenarios. DF-NF (Right row) represent the difference between the scenarios including the aerosol-radiation interaction of aerosols and the non-feedback scenarios.
due to aerosol feedback, and the meteorological factors are affected most in July. There are several differences of meteorological factors in two regions, which are caused by the different levels of particle concentration. First, the incoming solar radiation, T2 and PBL height are further reduced in China. The U.S. and China suffer from different levels of aerosol pollution. The worst aerosol pollution area of the continental U.S. is located in the eastern U.S., where the five year (2001–2006) average PM$_{2.5}$ concentration is 10–15 µg/m$^3$ or higher. East China is the worst aerosol pollution region in China, with a yearly average PM$_{2.5}$ concentration of 50–80 µg/m$^3$ or higher (van Donkelaar et al., 2010) which is much higher than eastern U.S. In the east continental U.S., the monthly-average incoming solar radiation decrease is 10 W/m$^2$ or higher, and the peak decrease values in January and July are 11.3 W/m$^2$ and 39.5 W/m$^2$, respectively; the monthly-average T2 decrease is 0.1–0.3°C or higher, and the peak decrease value in January and July are 0.16°C and 0.37°C, respectively; the monthly-average PBL height decrease is 10–30 m or higher, and the peak decrease value in January and July are 22.4 m and 92.4 m, respectively. In eastern China, the incoming solar radiation decrease is 20 W/m$^2$ or higher, and the peak reduction values in the four seasons are over 90 W/m$^2$; the monthly-average T2 decrease is 0.17–0.3°C or higher, the peak reduction values in the four seasons are over –2°C; The monthly-average PBL height reduces by 20–30 m or higher, the peak decrease values in the four seasons are over 70 m. The comparison of the results of the change in the domain-wide monthly-average of the distribution of meteorological factors indicates that
Fig. 10. Effect of aerosol-radiation interaction and aerosol-cloud interaction on hourly temperature at 2 meters (T2) in °C in Beijing, Shanghai and Guangzhou in January, April, July and October, 2006. The plots represent the difference between the DIF scenarios and the aerosol-cloud interaction and NF scenarios. The red line represents the hourly incoming solar radiation reaching the ground surface in the three cities; the blue line represents the change of the hourly incoming solar radiation under the influence of aerosol feedback in the three cities; the black line represents the PM$_{10}$ concentration in the three cities in January, April, July and October, 2006; the lake blue line represents the Chinese air quality standards for Grade II of PM$_{10}$ concentration, 150μg/m$^3$.

The areas of decline of solar radiation, temperature at 2 meters and the PBL height in China are larger than in the continental U.S. Second, the changes of incoming solar radiation, T2 and PBL height in winter and summer are different in the two countries. In China, due to the emission of heating boilers and the adverse diffusion conditions, the aerosol concentration is higher in winter, which results in a higher value of reduction of the meteorological factors and a larger reduction in the affected area in winter than in summer. However, in the continental U.S., the meteorological factors are more sensitive to the aerosol-radiation interaction in summer. Third, the changes of precipitation are different for the different countries. A slight increase of precipitation, less than 0.5 mm, occurs in the four months over China. The precipitation changes slightly in winter, but significantly decreases in summer, with a peak value of 19.4 mm in the continental U.S.

Europe

Based on the work of van Donkelaar et al. (2010) the five year (2001–2006) average aerosol concentration is 10–20 μg/m$^3$ or higher in Europe, which is four times smaller than that in China. This difference in concentrations results in the different changes of meteorological factors. First, the aerosol-radiation interaction of aerosols on solar radiation are different. The WRF-chem simulation results of the aerosol-radiation interaction and aerosol-cloud interaction aerosols in summer 2006 over Europe (Forkel et al., 2012) indicates that the incoming solar radiation slightly changes when the aerosol-radiation interaction acted alone and strongly...
changes when both the aerosol-radiation interaction and aerosol-cloud interaction worked together. This behaviour is related to the low aerosol load in Europe, the higher extinction in clouds compared to aerosols, and the requirement for cloudless conditions for the scattering and absorption of aerosols to be apparent. In China, for either cloudless or cloudy conditions, aerosol extinction dominates the effect on incoming solar radiation in all seasons. Moreover, a greater increase of the incoming solar radiation occurs in the Atlantic and north-east Europe, which is not apparent in China. Second, under the action of the aerosol-radiation interaction, the T2 and PBL height reductions are different in the two countries. In Europe, an obvious decrease occurs in the Mediterranean Sea (Black Sea, Mediterranean Sea), the Inland sea (the Baltic Sea) and the coastal areas (Italy and Lithuania). In China, the large decline of both T2 and the PBL height only appear in land areas.

### India

India and China are two larger developing countries in Asia. The five year (2001–2006) average PM$_{2.5}$ of north India is 20–50 µg/m$^3$, which is two-times smaller than that of east China. Seethala et al. (2011) simulated the aerosol-radiation interaction of aerosols on incoming solar radiation over India in January 1999 by using WRF-chem. The obvious decrease of the incoming solar radiation occurs in the Indo-Gangetic basins, in the north-west and the Southern tip. The monthly-average decline is −20 W/m$^2$ or higher, which is close to
that of China. The incoming solar radiation China in January exhibits a regional trend of reduction, with a decline of over 20 W/m² in east China; however, this trend was not apparent in India because regional aerosol pollution did not form.

CONCLUSIONS

The fully coupled online air quality model WRF/chem was applied to investigate the aerosol-radiation interaction and aerosol-cloud interaction of aerosols on the regional meteorological factors. Four representative months (January, April, July and October) of the four seasons in 2006 were studied in China. The incoming solar radiation, temperature at 2 meters, planetary boundary layer (PBL) height and precipitation were analysed to explore the influence of aerosol feedbacks in China, and the differences among the continental United States (U.S.), Europe, India and this study were discussed. The model closely reproduced the surface chemical concentrations and the observed meteorological variables found in this study, despite problems in the WRF/Chem V3.4 treatments and the coarse horizontal resolution.

The simulation results indicate that the domain-wide monthly-mean reduction of the incoming shortwave radiation in January, April, July and October are -11.03 W/m², -9.84 W/m², -5.84 W/m², -12.37 W/m², respectively, and greater decreases occur in autumn and winter compared to spring and summer. In the areas where the PM_{10} concentration is over 70 µg/m³ (yearly average PM_{10} concentration of Chinese air quality standards for Grade II), the monthly-average incoming solar radiation was reduced by over -20 W/m². The hourly simulated results indicate that when the PM_{10} concentration is over 150 µg/m³ (24-hour-average PM_{10} concentration of Chinese air quality standards for Grade I), the incoming solar radiation reduces to the range of 50–120 W/m²; when the PM_{10} concentration is over 50 µg/m³ (24-hour-average PM_{10} concentration of Chinese air quality standards for Grade I), the incoming solar radiation reduces to the range of 25–60 W/m². Due to the warm effect of absorption of aerosols and the semi-direct effect, the incoming solar radiation decreases further when only the aerosol-radiation interaction was active compared to when both the aerosol-radiation interaction and aerosol-cloud interaction of aerosols and clouds were active.

Due to the semi-direct effect, the domain-wide monthly-average T2 reduced by -0.22°C, -0.12°C, -0.06°C, and -0.24°C in January, April, July and October respectively, and the PBL height reduced by -16.44 m, -15.90 m, -5.48 m, and -31.59 m in January, April, July and October, respectively. Similar to the behaviour of the incoming solar radiation, the largest reduction of both the monthly-average T2 and the PBL height occur in east China. The hourly simulated results indicate that both the T2 and the PBL height decreased substantially while the hourly PM_{10} concentration changed rapidly in a short time (1 to 2 days); this phenomenon often occurs in Beijing and Guangzhou, especially in winter. A slight increase of precipitation occurred in China. Under the action of the monsoon rainfall climate in China, the precipitation increased more in spring and summer than in autumn and winter. Due to the aerosol-cloud interaction, an increase of precipitation occurred in the outback area in autumn, and in Taiwan Island and the surroundings in winter.

To investigate the difference of the changes of the meteorological factors under the action of aerosol feedback between the other regions and China, three WRF-chem simulated studies were compared with this work: the result for the continental United States in January and July in 2006, the result for Europe in the summer in 2006 and the result for India in January in 1999. In both the continental U.S. and China, the meteorological factors reduced more in the regions with higher particle concentrations. However, the aerosol load is much higher in China than in U.S., which results in the higher decrease of the monthly-average incoming solar radiation. T2 and PBL height was greater in winter than in summer, and these changes are different in the two countries. The precipitation in the two countries are also different: in China, a slight increase of precipitation occurred in the two seasons; in the continental U.S., the precipitation changed slightly in winter and decreased significantly in summer. The difference between Europe and China is reflected in two points. First, the scattering and absorption of aerosols only are apparent in the cloudless condition, and the extinction by clouds was more effective than the aerosol extinction under the aerosol-radiation interaction and aerosol-cloud interaction of aerosols in Europe. However, in China, under either cloudless or cloudy condition, aerosol extinction was the dominant effect on the incoming solar radiation in all seasons due to the high aerosol load. Second, the monthly-average T2 and PBL height exhibited greater changes in the coastal and sea areas in Europe but exhibited greater changes in the land area in China. In India, the incoming solar radiation decrease was -20 W/m² or higher in the most aerosol polluted areas, which is comparable with the incoming solar radiation change in China. However, the incoming solar radiation in China in January exhibited a regional decreasing trend, which did not appear in India.

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