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Role of Black Carbon-Induced Changes in Snow Albedo in Predictions of Temperature and Precipitation during a Snowstorm

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Abstract In this study the authors apply the chemistry version of the Weather Research and Forecasting model (WRF-Chem) to examine the impacts of black carbon (BC)-induced changes in snow albedo on simulated temperature and precipitation during the severe snowstorm that occurred in southern China during 0800 26 January to 0800 29 January 2008 (Note that all times are local time except when otherwise stated). Black carbon aerosol was simulated online within the WRF-Chem. The model results showed that surface-albedo, averaged over 27–28 January, can be reduced by up to 10% by the deposition of BC. As a result, relative to a simulation that does not consider deposition of BC on snow/ice, the predicted surface air temperatures during 27–28 January can differ by −1.95 to 2.70 K, and the predicted accumulated precipitation over 27–28 January can differ by −2.91 to 3.10 mm over Areas A and B with large BC deposition. Different signs of changes are determined by the feedback of clouds and by the availability of water vapor in the atmosphere.

Keywords: Black carbon, snow albedo, weather

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1 Introduction

Black carbon (BC) aerosol is an air pollutant that absorbs solar radiation. The deposition of soot particles on snow can reduce snow albedo and affect snowmelt (Warren and Wiscombe, 1980, 1985; Hansen and Nazarenko, 2004; Jacobson, 2004; Flanner et al., 2007), leading to climate change on global and regional scales. Anthropogenic radiative forcing induced by “soot on snow” between 1750 and 2005 is estimated to be 0.1 W m^{-2} (Intergovernmental Panel on Climate Change (IPCC), 2007).

There are a number of studies that have examined the effect of BC deposition on climate. Using a global climate model, Hansen and Nazarenko (2004) assumed reductions in surface albedo of 1.5% in the Arctic and 3% in the landmasses of the Northern Hemisphere. They also obtained a climate forcing of 0.3 W m^{-2} in the Northern Hemisphere. Hansen et al. (2005) parameterized the changes in snow/ice albedo based on a simulated deposition of black carbon. They estimated a positive radiative forcing of 0.15 W m^{-2} and predicted a global warming of 0.24°C. Jacobson (2004) predicted that BC aerosol from fossil fuel and biomass burning reduces surface albedo by 0.4% globally and by 1% in the Northern Hemisphere, leading to a global warming of 0.06°C. Flanner et al. (2007) coupled a snow/ice model that can treat the aging process of snow with a general circulation model (GCM). They estimated a global annual mean radiative forcing of 0.05 W m^{-2} by deposition of BC on snow/ice and a corresponding increase in global-mean surface air temperature of 0.10–0.15°C. Few studies have examined impacts of BC on snow/ice on regional climate and weather. Recently, Qian et al. (2009) simulated the effects of BC-induced changes in snow albedo on snowpack and the hydrological cycle in the western United States using the chemistry version of the Weather Research and Forecasting model (WRF-Chem). They reported that the deposition of BC on snow/ice can increase surface air temperature by 0.1–1.0°C over the majority of the snow-covered areas in the western United States during late winter to early spring.

In this work, we explore the role BC-induced snow/ice albedo changes have in weather prediction, focusing on the severe snowstorm that hit southern China in January 2008. This snowstorm consisted of four short snowing periods (Wang et al., 2008), which lasted from 11 January to 2 February. We simulated the third snowing period (26–29 January 2008), which had the heaviest snow, using the WRF-Chem model with online simulation of BC aerosol, to see the strongest effect of BC deposition on meteorological parameters.

2 Model description and experiments

2.1 The WRF-Chem model

We examined the role of BC-induced albedo changes in weather prediction using the mesoscale model, WRF-Chem, described by Grell et al. (2005), Fast et al. (2006), Gustafson et al. (2007), and Chapman et al. (2008). The model was set to simulate the whole Asian domain, with a horizontal resolution of 60 km and 31 ver-

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tical layers that covered from surface to 10 hPa altitude.

The model simulated BC using the MOSAIC (the Model for Simulating Aerosol Interactions and Chemistry) sectional aerosol module with eight size bins (0.039–0.078, 0.078–0.156, 0.156–0.3125, 0.3125–0.625, 0.625–1.25, 1.25–2.5, 2.5–5.0, and 5.0–10 μm). Anthropogenic emissions of BC (including emissions from power, industrial, residential, and transportation sources) in the Asian domain were updated using data from the David Streets 2006 emission inventory (http://www.cgrer.uiowa.edu/EMISSION_DATA_new/index_16.html). Emissions of BC were put into fine (0.039–2.5 μm) and coarse (2.5–10 μm) modes by assuming a lognormal size distribution with a number median radius of 0.03 μm and a standard deviation of 1.59 (Stier et al., 2005). The emissions of BC in fine mode were distributed into the eight size bins, using fractions of 0.060, 0.045, 0.245, 0.400, 0.100, 0.150, 0.0, and 0.0, respectively. Those in the coarse mode were distributed into the eight size bins with fractions of 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.3, and 0.7, respectively. The annual emission of BC over the whole Asian domain was 2.9 Tg yr^{-1}.

2.2 Changes in snow/ice albedo by deposition of BC

Measurements have shown that deposition of BC on snow or ice can reduce surface albedo by 5%–70% when the mass ratios of BC to snow are in the range of 0.2–200 ppm (Zender et al., 2008) (http://www.sciencepoles.org/index.php?/articles/&uid=1254). We parameterized changes in snow and ice albedo based on the measurements of Zender et al. (2008):

$$y=\begin{cases}\dfrac{0.05}{0.2}x & (0.0-0.2\ \text{ppm})\\[2mm] \dfrac{(0.7-0.05)}{(200-0.2)}x-\dfrac{(0.7-0.05)}{(200-0.2)}\times 200+0.7 & (0.2-200\ \text{ppm})\end{cases}, \tag{1}$$

where x is the mass ratio of BC deposition (dry and wet) to snow mass accumulated at the surface in ppm; and y is the percentage change in snow albedo, with a maximum change set to 70%. In this scheme, we take into consideration the removal of deposited BC by melted water, but the snow aging process that leads to increases in the grain size of snow was not included.

2.3 Experimental design

In order to examine the effect of BC-induced changes in surface albedo on weather prediction, we performed two simulations. The first simulation is the control run without the impact of BC deposition (denoted as CTRL, hereafter). The second simulation accounts for changes in snow/ice albedo by deposition of BC (denoted as BCDEP, hereafter). The CTRL simulation was first integrated over 0800 25 January, to 0800 26 January, as model spin-up. The saved restart file was then used as the initial conditions for both the CTRL and BCDEP simulations that were integrated over 0800 26 January, to 0800 29 January 2008. The initial conditions for spin-up, as well as the boundary conditions, were taken from the NCEP (the National Center for Environmental Prediction) FNL (Final) Operational Analysis data. Model results of 0000 27 January to 2400 28 January are analyzed and presented in the following sections.

3 Model results

3.1 Simulated surface air temperature and precipitation

To simulate the impacts of BC-induced snow albedo change on meteorological parameters, it is important to realistically capture temperature and precipitation in the CTRL simulation. Figure 1 compares simulated temperature and precipitation with observations from weather stations for 27 and 28 January (http://10.28.17.59/micaps).

The predicted pattern of temperatures at 1400 27 January (Fig. 1a) was about the same as those on 28 January (Fig. 1c). Low temperatures of 270–275 K were predicted over the Hunan and Guizhou provinces, while warmer temperatures exceeding 275 K were found over eastern Sichuan and Yunnan provinces. The predicted distribution and magnitude of temperatures agreed reasonably well with observations from weather stations (Figs. 1b and 1d).

Figures 1e and 1g present simulated precipitation accumulated over 0800–1400 27 and 28 January, respectively. The strongest simulated rain belt was in southwestern China on 27 January. It strengthened as it stretched from southwestern to northeastern China on 28 January, which agrees well with the observations. The model underestimated the precipitation on 27 January, but captured reasonably well the precipitation on 28 January. The maximum precipitation of 24 mm was predicted over the Jiangxi Province (28°N, 114.5°E) on 28 January, which is close to the observed maximum precipitation of 20 mm located at 30.13°N and 116.7°E.

3.2 Simulated distributions of concentration and deposition of BC

Figure 2 shows the simulated emissions, surface-layer concentrations, and deposition of BC averaged over 0000 27 January to 2400 28 January. The distribution of BC surface concentrations generally mimics that of BC emissions, with the highest concentrations (above 18 μg m^{-3}) predicted over the Hebei and Henan provinces. The deposition of BC shown in Fig. 2c includes both dry and wet deposition, both of which lead to changes in surface albedo. The largest deposition was predicted over the provinces of Hebei, Hunan, and eastern Sichuan as a result of the large precipitation (wet deposition) in these areas.

Comparisons of simulated BC concentrations with measurements of BC are given in Table 1. The measurements of BC are the averages over 6–20 January 2003, which are taken from the study of Cao et al. (2007). Because of the lack of measurements for 2008, the purpose of the comparisons is simply to show that the predicted BC concentrations in our model have a reasonable magnitude. The model underestimated BC over the cities lo-

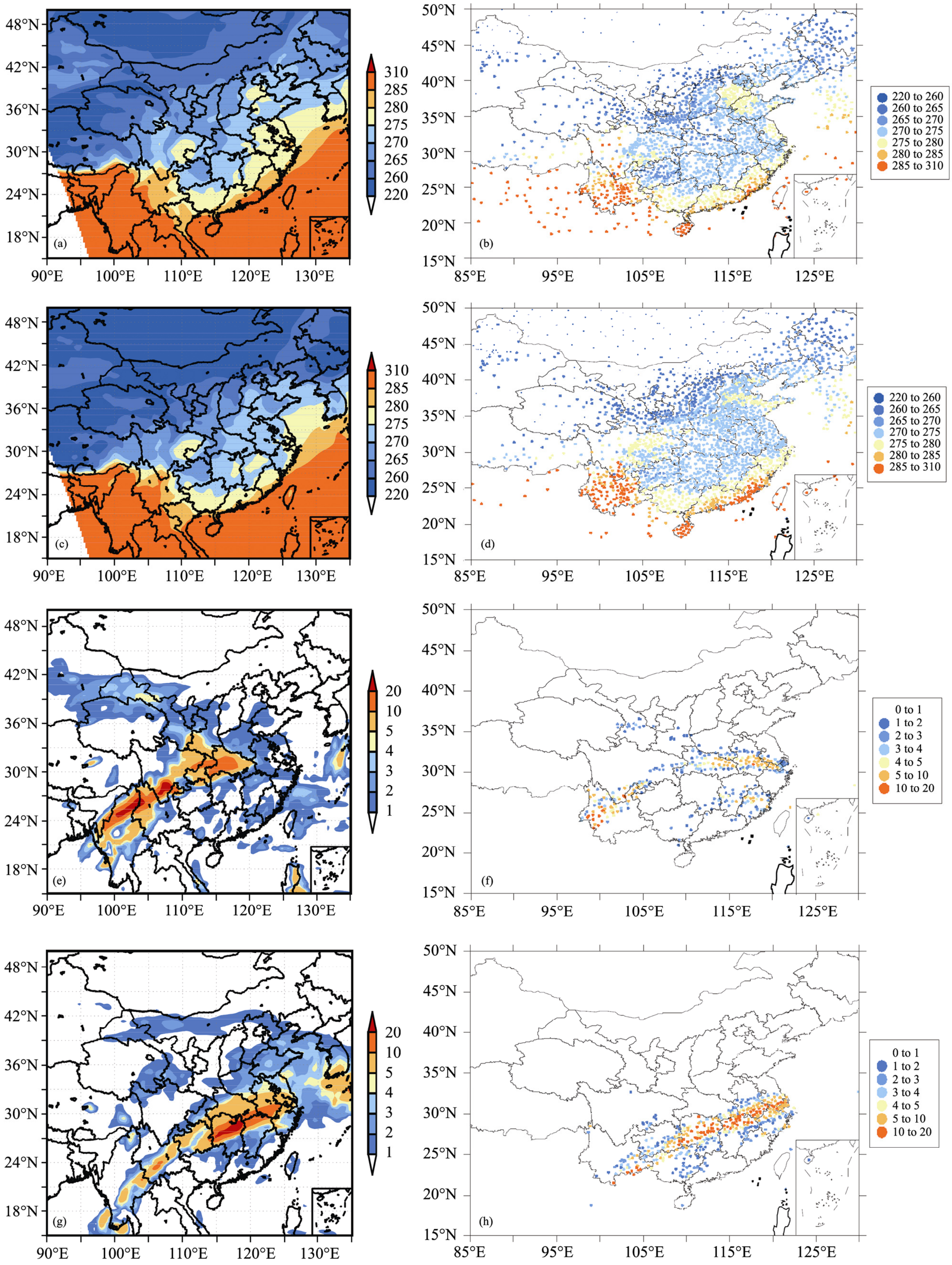

Figure 1 Comparisons of simulated temperature (K) and precipitation (mm) with observations from weather stations for 27 and 28 January. (a)–(b) temperatures at 1400 27 January; (c)–(d) temperatures at 1400 28 January; (e)–(f) precipitation accumulated over 0800–1400 27 January; (g)–(h) precipitation accumulated over 0800–1400 28 January. Left column shows model predictions and right column presents observations.

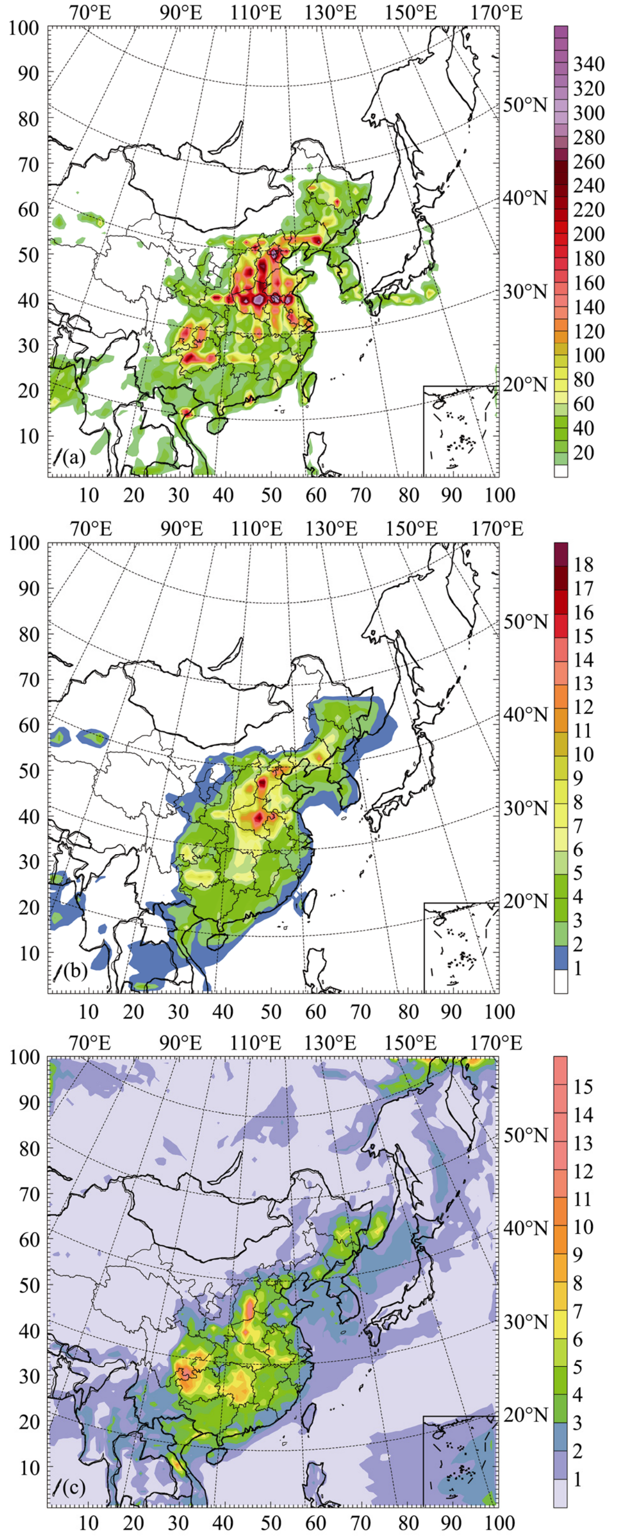

Figure 2 Simulated (a) emissions (μg m^{-2} hr^{-1}), (b) surface-layer concentrations (concentrations of BC in the lowest model layer in the atmosphere) (μg m^{-3}), and (c) deposition (μg m^{-2} hr^{-1}) of BC averaged over 0000 27 January to 2400 28 January.

cated in southern China (such as Chongqing, Shanghai, Hangzhou, Xiamen, Guangzhou, and Hong Kong), indicating that our estimated effect of BC deposition might be in the lower end of the perturbations of the snowstorm.

Table 1 Comparisons of simulated BC concentrations with measurements from 14 cities. Measurements were taken in January 2003 (Cao et al., 2007).

City	Observed (μg m^{-3})	Simulated (μg m^{-3})
Beijing	7.1±3.5	8.83
Changchun	13.5±2.9	5.28
Jinchang	5.0±1.2	1.8
Qingdao	6.3±2.4	4.59
Tianjin	8.5±3.5	10.69
Xi'an	21.6±5.4	8.63
Yulin	9.2±4.0	2.00
Chongqing	16.6±5.4	9.87
Guangzhou	14.5±9.9	6.09
Hong Kong	5.8±2.6	4.67
Hangzhou	9.3±2.1	3.69
Shanghai	8.3±5.4	2.62
Wuhan	8.4±2.9	9.42
Xiamen	5.0±1.4	2.20

3.3 BC-induced changes in surface albedo

Figure 3a shows the predicted changes in surface albedo (the differences in albedo between simulations BCDEP and CTRL) averaged over 27–28 January. Changes in surface albedo occurred only over snow/ice surfaces with deposition of BC. To examine the impacts of BC deposition in detail, we focused on three areas, which are marked by red, solid rectangles in Fig. 3a. Reductions of albedo were mostly in the range of 2%–6% over Area A. Area B had the largest deposition of BC, resulting in reductions in surface albedo of 6%–10% in northeastern Hunan and western Guizhou provinces. Area C had no snowfall and, hence, no changes in albedo. Our simulated changes in surface albedo are close to the measured changes of 5%–10% (Clarke and Noone, 1985) and the simulated changes of up to 13% by Flanner et al. (2007).

3.4 BC-induced changes in surface air temperature

Deposition of BC on ice/snow leads to reductions in surface albedo, which can increase net shortwave flux at the surface and, hence, increase surface temperature. Changes in surface air temperature are also influenced by the responses in clouds. Surface air temperatures in Area A were predicted to generally increase (Fig. 3b), with a maximum increase of about 0.24 K in southern Henan Province. In the absence of significant responses in clouds in Area A, deposition of BC on ice/snow reduced surface albedo, increased net surface shortwave flux, and, hence, increased temperature. Area A had an increase in temperature of 0.019 K, as model results were averaged over the 48 hours of 27 and 28 January (Table 2). Over Area B, with surface albedo reduced by about 10% in northeastern Hunan and western Guizhou, predicted surface temperatures mostly increased in the western half of the area, whereas temperatures were predicted to have an overall

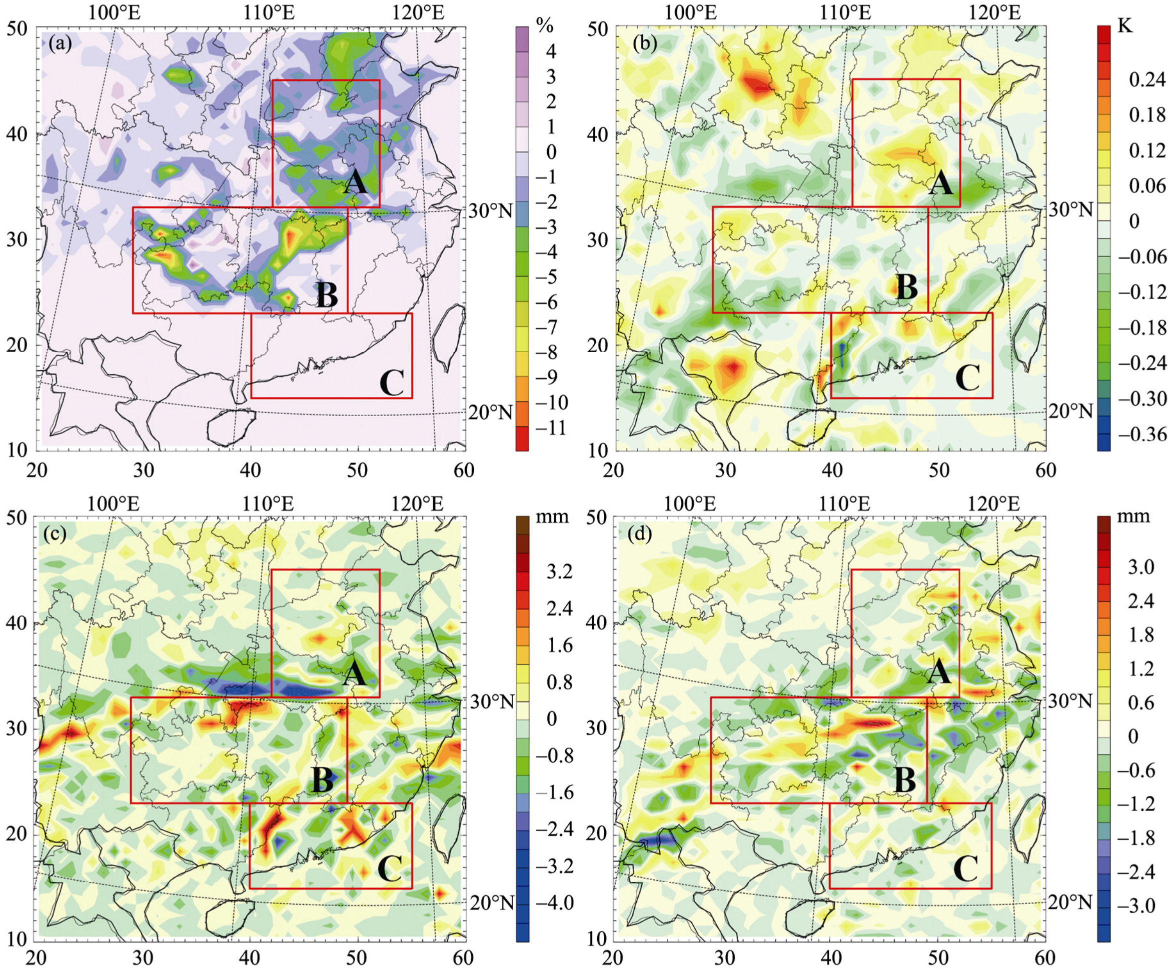

Figure 3 Predicted BC-induced changes (the differences between simulations BCDEP and CTRL) in (a) albedo (in percentage) and (b) surface air temperature averaged over 0000 27 January to 2400 28 January, (c) and (d) show the differences (values in BCDEP minus those in CTRL) in accumulated precipitation over the 24-hour period for 27 and 28 January, respectively.

decrease in eastern Area B. This is because the predicted increases in cloud cover shielded incoming solar radiation over 0800–2000 28 January. The 48-hour average in surface air temperature over Area B shows a decrease of 0.006 K. Area C is located to the south of the rain/snow belt (Fig. 1c) and has no changes in surface albedo. With clouds increasing on the northern edge, but decreasing on the southern edge of the rain/snow belt in the presence of BC deposition, temperatures over Area C decreased by 0.003 K, based on the 48-hour average. Because of the short-term feedback of clouds, the sign of predicted changes in temperature can be different from that in Qian et al. (2009). They have shown that, with BC deposition, surface temperatures increase by 0.1–1.0 K over the majority of the snow-covered areas in the western United States during late winter to early spring.

Although BC-induced average changes in temperature are small over the selected areas, predicted instantaneous changes in temperature can be perturbed by −1.27 to 1.14 K, −1.95 to 1.47 K, and −1.77 to 2.70 K over Areas A, B,

Table 2 BC-induced changes in surface air temperature averaged over 27, 28 and 27–28 January, , as well as BC-induced accumulated changes in precipitation over the same time periods. For temperature, the numbers in the parentheses indicate the maximum positive and negative changes found in the corresponding time period and the selected area. For precipitation, the numbers in the parentheses are the maximum positive and negative changes accumulated over the corresponding time period within the selected area.

	Date	Area A	Area B	Area C
T_{air} (K)	27	0.058 (−0.68, 1.14)	0.004 (−1.95, 1.47)	−0.046 (−1.40, 1.49)
	28	−0.019 (−1.27, 0.60)	−0.017 (−0.90, 1.45)	0.039 (−1.77, 2.70)
	27–28 avg	0.019 (−1.27, 1.14)	−0.006 (−1.95, 1.47)	−0.003 (−1.77, 2.70)
P (mm)	27	−0.164 (−4.33, 2.50)	−0.027 (−4.45, 3.73)	0.138 (−3.22, 4.30)
	28	0.114 (−3.09, 5.38)	−0.035 (−5.07, 5.38)	−0.152 (−7.73, 4.30)
	27–28 sum	−0.050 (−2.69, 2.42)	−0.062 (−2.91, 3.10)	−0.014 (−4.71, 2.90)

and C, respectively (Table 2). This indicates the potential importance of BC deposition in weather prediction.

3.5 BC-induced changes in precipitation

Predicted responses in precipitation to BC deposition are more complex than predicted responses in temperature. While the melting of snow/ice by BC deposition can increase water vapor in the atmosphere, the changes in precipitation are mainly dependent on the availability of water vapor associated with the weather system. Figures 3c and 3d show the differences (values in BCDEP minus those in CTRL) in accumulated precipitation over the 24-hour period for 27 and 28 January, respectively. On 27 January, the predicted increases in surface air temperature in southern Henan Province led to increases in evaporation (and, hence, clouds), which resulted in increased precipitation. Compared to the simulation CTRL, a maximum reduction of –2.1 mm in precipitation was predicted in the Hubei and eastern Sichuan provinces during 27 January because of the predicted decrease in water-vapor supply to this region in the BCDEP run. Large increases in precipitation, exceeding 1.8 mm, were predicted in a region that extends from northern Yunnan to southern Hubei. While BC deposition here led to increases in temperature and evaporation at the surface, the southerlies at the 850 hPa altitude brought moist air to the region—all of which contributed to the increases in precipitation.

On 28 January, the front associated with the severe snowstorm moved to southeastern China, as can be seen in Fig. 1h. With the adequate water supply associated with the front, increases in precipitation exceeding 1.5 mm were predicted over the Guizhou and Hunan provinces during 28 January, where BC deposition led to large changes in albedo.

Table 2 gives average changes in precipitation over Areas A, B, and C during 27–28 January. The 48-hour accumulated changes in precipitation were –0.050 mm, –0.062 mm, and –0.014 mm over Areas A, B, and C, respectively. The 48-hour accumulated changes in precipitation ranged from –2.91 to 3.10 mm over Areas A and B—the two areas with the largest deposition of BC.

4 Summary and discussions

Using the WRF-Chem model, we simulated the severe snowstorm that occurred in southern China during 0800 26 January to 0800 29 January, 2008. We focused on the impacts of BC-induced changes in snow/ice albedo on simulated temperature and precipitation. Model results show that surface-albedo averaged over 0000 27 January to 2400 28 January can be reduced by up to 10%. Predicted surface air temperatures during 27–28 January can be perturbed by –1.95 to 2.70 K, and predicted accumulated precipitation over the same 48-hour period can differ by –2.91 to +3.10 mm over Areas A and B, with large BC deposition.

Predicted BC-induced changes in temperature agree in magnitude with those in Qian et al. (2009). While surface air temperatures were predicted to always increase in Qian et al. (2009), based on the average of five-year climate integration during late winter to early spring, temperature changes shown in this work for weather prediction can be either positive or negative, depending on the feedbacks in clouds. In the absence of clouds, BC-induced reductions in snow albedo lead to positive feedbacks; reductions in albedo increase absorption of solar radiation at the surface, and the subsequent increases in surface temperature lead to the melting of snow, further reducing surface albedo. Considering the feedbacks of clouds, BC-induced increases in temperature lead to increases in evaporation and, hence, cloud cover. This can shield the incoming solar radiation, reduce surface temperatures, and eventually increase snow cover and surface albedo.

BC-induced changes in precipitation depend on the complex responses in clouds, as mentioned above, and the availability of water vapor. It was found that, with adequate water vapor supply, BC-induced increases in temperature can lead to increases in precipitation in areas that are far away from the front. If BC deposition overlaps with the front, the sign of BC-induced changes in precipitation can be either positive or negative because of the complex feedbacks. This will be further examined in our future studies on snowstorms.

It should be noted that BC aerosol in the atmosphere can have a large impact on weather prediction by its direct effect of absorbing and scattering solar radiation, as well as by its indirect radiative effect involving the formation of clouds. We isolated the role of BC deposition in weather prediction here; the overall effect of deposition, direct radiative effect, and the indirect effect of BC will be the subject of forthcoming work.

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