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Radiative effect of black carbon aerosol on a squall line case in North China

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ABSTRACT

The radiative effect of black carbon aerosol (BC) on a squall line case in north China is studied with the Weather Research and Forecasting model. Before the initiation of the squall line, the surface-emitted BC is mixed only in the boundary layer (BL). BC is then transported from the BL into the free troposphere by the updrafts in the squall line system. Once distributed in the atmosphere, BC absorbs solar radiation and heats the surrounding air. The maximum increase of temperature is 0.05 K for the moderately polluted case bc2 and 0.37 K for the heavily polluted case bc20. In case bc2, where the BC concentration is not very high, the solar flux reaching the surface, the sensible heat flux, and the latent heat flux are not significantly affected by BC. In case bc20, the solar flux reaching the surface, the sensible heat flux, and the latent heat flux are reduced by up to 80, 30, and 21 W m^{-2}, respectively. The reduced surface evaporation leads to a reduced vapor amount at the early stage. After some time, the heating effect causes a large-scale convergence and brings slightly more vapor into the domain. The effect of BC on the cold pool strength and low-level wind shear is small and hence does not significantly affect the triggering of new convections. In addition, our results show that the effect of BC is negligible on the strength and rain rate of the squall line case.

1. Introduction

Black carbon aerosol (BC) is one of the most important light-absorbing aerosols. It strongly absorbs solar radiation and hence has an important influence on the radiative balance of the earth system (e.g., Wang et al., 2011; Wang, 2013; Qian et al., 2015). Bond et al. (2013) estimated that the total radiative forcing of BC for the industrial-era (1750 to 2005) was +1.1 W m^{-2}, meaning that BC was the second strongest driver of global warming. However, the radiative forcing of BC is still associated with remarkable uncertainty (Koch and Genio, 2010). In particular, the interaction between BC and clouds is an important source of this uncertainty (IPCC, 2013).

Previous studies found that light-absorbing aerosols could suppress the development of clouds by stabilizing the atmosphere (Feingold et al., 2005; Vendrasco et al., 2009). When light-absorbing aerosols were located from 1 to 2.5 km, the heating effect increased the temperature of the aerosol-loading layer and hence increased the stability of the boundary layer (BL), leading to significantly-reduced liquid water path (LWP), cloud fraction and precipitation.

Light-absorbing aerosols could further stabilize the atmosphere by reducing the surface fluxes. Previous studies have found that most of the radiative heating at the surface was balanced by surface fluxes (Ramanathan et al., 2001; Ramanathan et al., 2005). Once the amount of solar flux reaching the surface was reduced by BC, the surface fluxes would also be reduced. This subsequently decreased the temperature near the surface and increased the stability of the atmosphere (Fan et al., 2008). As a result, both the LWP and the cloud fraction were significantly reduced (Koren et al., 2004; Feingold et al., 2005; Jiang and Feingold, 2006; Fan et al., 2008).

However, some study reported that light-absorbing aerosols could strengthen the development of clouds by destabilizing the atmosphere (Feingold et al., 2005). When light-absorbing aerosols were located below the cloud, and the reduction of surface fluxes (including sensible heat flux and latent heat flux) was not considered, the heating could destabilize the layer from 0 to 1.5 km. Therefore, the convection became stronger and the LWP became larger.

Other studies reported that light-absorbing aerosols could induce deep convective clouds by suppressing weak convective clouds. Wang et al. (2013) proposed that when the effect of BC warmed the upper BL and cooled the lower BL, the BL became more stable. This resulted in the suppression of the weak convections. This suppression could contribute to the accumulation of the convective available potential energy (CAPE) and resulted in larger CAPE in the later time. In this situation, if the lifting was strong enough, a much stronger convection could be initiated. This conceptual model was then supported by observational and modeling studies (Fan et al., 2015; Guo et al., 2016; Lee et al.,

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2016), where it is found that the presence of light-absorbing aerosols could suppress the precipitation before mid-afternoon and enhance the precipitation after the mid-afternoon.

Most previous studies used ideal simulations instead of real case simulations to investigate the radiative effect of light-absorbing aerosols on clouds (Feingold et al., 2005; Jiang and Feingold, 2006; Fan et al., 2008; Lee et al., 2016) and the simulated domains were usually small (< 120 km in any dimension). The radiative effect of light-absorbing aerosols on self-organized convective systems has not been well understood. In this study, we use Weather Research and Forecasting (WRF) model to simulate the radiative effect of light-absorbing aerosols on a case of self-organized convection, i.e., a squall line in north China. In this real case simulation, the domain covers an area of ~970 km × 780 km, which is much larger than the domain sizes in previous studies and can better resolve the meso-scale convective system.

Squall lines are self-organized, linear or quasi-linear severe convective systems consisting of multi convective cells. They occur both in the mid-latitude and in the tropics (e.g., Houze, 1989; Meng and Zhang, 2012; Meng et al., 2013). Squall lines are usually associated with strong winds and heavy precipitations, and can hence cause terrible disasters (e.g., Parker and Johnson, 2000). Several studies have focused on the microphysical effect of aerosols on squall lines (e.g., Li et al., 2009; Khain et al., 2005; Khain et al., 2009; Tao and Li, 2016), while less studies have focused on the radiative effect of light-absorbing aerosols on squall lines. In one of the few studies that considered the radiative effect of light-absorbing aerosols (Toll and Mannik, 2015), it is found that an extremely dense smoke could reduce the strength of the squall line case.

Squall lines occur with a high frequency in east and north China (Meng and Zhang, 2012; Meng et al., 2013). The BC concentration is also very high in this region (Fu et al., 2014; Feng et al., 2014; Wang et al., 2016; Cheng et al., 2016; Li et al., 2016; Zhang et al., 2016). In this study, we focus on the radiative effect of BC on the development of a squall line case in north China. In Section 2, we introduce the model, the squall line case, and the local balance theory that is invoked to determine whether the squall line can be maintained or not. Section 3 presents the results. Section 4 gives the discussion, and Section 5 summarizes this study.

2. Method

2.1. Model

WRF model (Skamarock et al., 2008) is used in this study to simulate the effect of BC on the squall line case. It is a non-hydrostatic, fully compressible 3-dimensional (3D) model, which uses the terrain-following pressure coordinate to solve the governing equations. WRF is capable of simulating processes spanning a wide spatiotemporal scale. Particularly, when WRF is running at a resolution of ~1 km, it is capable of resolving the convection-scale processes. In addition, WRF allows the flexibility of adding tracers into the model. In this study, a prognostic tracer is used to represent the movement of BC in the 3D flow.

The new Goddard shortwave scheme (Chou and Suarez, 1999) is used to calculate the shortwave radiative transfer. This scheme uses the Delta-Eddington approximation to calculate the radiative fluxes in 11 bands ranging from 0.175 to 10.0 μm, considering the absorption by water vapor, ozone, molecular oxygen, carbon dioxide, clouds, and aerosols, and the scattering by clouds, aerosols, and gases. The radiative properties of each type of particles are described with three parameters, namely, the single scattering albedo (SSA), the extinction coefficient, and the asymmetric factor, all of which are wavelength dependent.

In order to incorporate the radiative properties of BC into the radiative transfer scheme, the three parameters are first calculated using the Mie code (Bohren and Huffman, 1983), where BC is treated as monodisperse spheres with radii of 100 nm. The refractive index of BC is obtained from laboratory experiment, where the optical property of fresh BC is measured (Chang and Charalampopoulos, 1990). Fresh BC is usually not mixed with other substances, so that BC is considered to be externally mixed with other aerosols. The radiative properties are calculated at 2002 wavelengths, at which the solar irradiances are available (http://rredc.nrel.gov/solar/spectra/am1.5/astmg173/astmg173.html). Then the parameters for the 11 bands are obtained by the weighted averaging method, where the solar irradiances are used as weights (Chou and Suarez, 1999). In addition, in order to estimate the net energy gain of the atmosphere (see Section 3), the SSA for the whole solar spectrum is also calculated, which is 0.23 for the BC in this study. This value of SSA is consistent with the result of another laboratory experiment which directly measures the SSA of fresh BC (Singh et al., 2016). In order to calculate the optical depth of BC, the mass concentration of BC is converted to number concentration by assuming a density of 2000 kg m^{-3}.

The Noah land surface model (Ek et al., 2003) is used to simulate the surface processes. The surface temperature is calculated by solving the surface energy balance equation (Chen and Dudhia, 2001). The surface evaporation, which determines the latent heat flux into the atmosphere, is the combination of the direct evaporation from the bare soil, the evaporation of the precipitation intercepted by the canopy, and the transportation through the roots and the canopy (Chen et al., 1996). The sensible heat flux is iteratively calculated based on the similarity theory (Chen et al., 1997).

2.2. The squall line case and experimental setup

The squall line case occurred on August 9, 2014 over north China and caused heavy precipitation. It was triggered at about 13:00 (local time, the same hereinafter) in Inner Mongolia. Then it moved toward the southeast and dissipated at about 23:00 near Beijing. This was a typical well-organized convective system, with the stratiform cloud to the rear of the convection line. In addition, heavy pollution (aerosol optical depth > 0.7) was observed over the studied area on this day by the Moderate Resolution Imaging Spectroradiometer (MODIS).

WRF can run in multiple nested domains in two-way or one-way nesting mode. This study uses one-way nesting domains with horizontal resolutions of 9 km and 3 km, respectively. The outer domain covers 95.7–123.4E and 30.7–46.3 N. The inner domain covers 109.5–121.4E and 36.3–43.4 N. All the analyses shown here are based on the result in the inner domain. Because the regions with high BC emission rate are mainly in the inner domain, BC is emitted into the inner domain only, and the one-way nesting is used to facilitate this configuration. For simplicity, the emission rate is set to be a constant in the inner domain. The BC emission rate is calculated from an emission inventory developed by Wang et al. (2012), which gives the total BC emission in 2007 at a resolution of 0.1° × 0.1°. Based on the inventory, the mean emission rate in the inner domain is 2 mg m^{-2} day^{-2}. Wang et al. (2012) also found that the BC emission rate in China leveled off after 2000. This is consistent with another emission inventory (Evaluating the CLimate and Air Quality ImPacts of Short-livEd Pollutants; ECLIPSE), where the BC emission rate in the inner domain shows small change from 2000 to 2015. We therefore assume that the emission rate in the inner domain in 2014 is the same as that in 2007.

The emission inventory of BC is usually associated with remarkable uncertainty (Wang et al., 2012; Bond et al., 2013). As a result, the emission rate of 2 mg m^{-2} day^{-1} should only be used as a reference value instead of the true value. More importantly, the inventory gives only the yearly emission, which may be very different from the daily emission. With this in mind, we perform simulations with very different emission rates. Case bc0 is the clean case, where no BC is released. Case bc2 is the moderately polluted case, where the BC emission rate is 2 mg m^{-2} day^{-1}. Case bc20 is the heavily polluted case, where the BC emission rate is 20 mg m^{-2} day^{-1}. In the three cases, the simulated