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Modeling of black carbon in Asia using a global-to-regional seamless aerosol-transport model

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ABSTRACT

In Asia, the evaluation of black carbon (BC) using global aerosol-transport models has been incomplete due to a lack of available measurements. Recently, new measurements and datasets at various Asian sites have become available for use in model validation. In this study, we compared the BC mass concentrations obtained by an aerosol-coupled global nonhydrostatic model adopting a uniform-grid system with in-situ measurements and other models over Asia. The results revealed that our model, as well as other global models, was unable to reproduce the observed BC values at most sites in China and India, most likely due to strong local hotspots. To overcome the inconsistency between the models and measurements, we developed a new aerosol-transport model using a stretched-grid system for high-resolution simulations with up to approximately 10 km grids. Our model can be used as a global-to-regional seamless aerosol-transport model for low to high horizontal resolution simulations.

1. Introduction

Black carbon (BC), also known as elemental carbon (EC) or soot, strongly absorbs shortwave radiation and thus exerts a greater influence on climate than other aerosol components (Hansen et al., 1997; Jacobson, 2002; Forster et al., 2007). Estimates of the radiative impact of BC aerosols due to the direct aerosol effect caused by fossil fuel and biomass burning remain uncertain, with reported positive forcings of $+0.20 \pm 0.15$ and $+0.03 \pm 0.12$ W m^{-2}, respectively (Forster et al., 2007). BC can also affect air quality and human health (Janssen et al., 2012).

Globally, Asia emits the largest amount of BC from fossil fuel, biomass, and biofuel combustion (e.g., Lamarque et al., 2010). However, due to limited network BC measurements throughout the continent, the BC concentrations obtained from most global aerosol-transport models have not been fully evaluated (e.g., Koch et al., 2009). To validate these aerosol-transport models, including the Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS), a global aerosol transport model developed by Takemura et al. (2005), coupled with the Model for Interdisciplinary Research on Climate (MIROC), an atmospheric general circulation model developed by Watanabe et al. (2010), Goto et al. (2011b) collected the BC mass concentrations measured throughout India during the period 2000–2008. The authors suggested that over India the worldwide BC emission inventory by Diehl et al. (2012) was dramatically underestimated. Recently, Zhang et al. (2012) measured aerosol compounds, including BC, during the period 2006–2007 at more than 10 stations over China as part of the China Atmospheric Watch Network (CAWNET). As a result, it was possible to obtain global BC mass concentrations observed by various networks, including the United States (IMPROVE), Europe (EMEP), China (CAWNET), India (Goto et al., 2011b), and other areas, as shown in Fig. 1. Therefore, we evaluated the BC concentrations simulated by an aerosol-coupled global nonhydrostatic model developed by Suzuki et al. (2008) through implementing SPRINTARS into a global cloud-resolving Nonhydrostatic Icosahedral Atmospheric Model (NICAM) developed by Tomita and Satoh (2004) and Satoh et al. (2008).

NICAM was employed for the global simulation of atmospheric processes with a high-resolution grid spacing of 1–3.5 km by Miura et al. (2007) and Miyamoto et al. (2013) and used as a global tracer model of aerosols and gases with a low-resolution grid spacing of approximately 220 km by Niwa et al. (2011) and Dai et al. (2014). Niwa et al. (2011) reported that NICAM with low-resolution grid spacing was effective in simulating the transport patterns of CO_2 and long-lived gases. Dai et al. (2014) demonstrated that NICAM with low-resolution grid spacing can properly simulate aerosols through a comparison with retrieved aerosol optical properties (i.e., aerosol optical thickness and single scattering albedo) from remote ground sensing data on a global scale. However, NICAM-simulated aerosol chemical compositions have not yet been evaluated,

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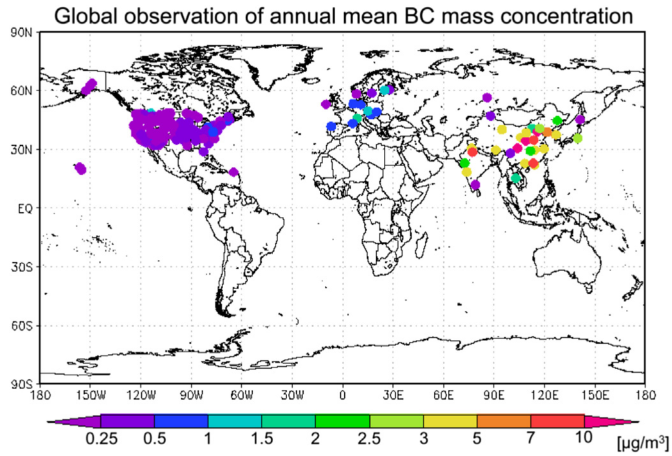

Fig. 1. Global BC mass concentrations at surfaces used in a previous study by Goto et al. (2012). The observations were collected in the United States in 2003 (IMPROVE), Europe in 2002–2003 (EMEP), China in 2006–2007 (Zhang et al., 2012), and at Indian and Pakistani sites (Goto et al., 2011b) as well as other Asian sites (Tokyo/Japan in 2003–2005 by Kondo et al., 2006; Minoura et al., 2006; Rishiri/Japan in 2001–2003 by Matsumoto et al., 2007; Incheon/Korea in 2004 by Kim et al., 2006; Seoul/Korea in 2003–2005 by Kim et al., 2007; Tomsk/Russia in 1997–2005 by Kozlov et al., 2008; Phimai/Thailand in 2007–2008 by H. Tsuruta, Personal communication). In the measurement, BC was obtained as an elemental carbon by analyzing measured quartz fiber filters, except for the sites at Delhi/India, Chandigarh/India, and Karachi/Pakistan, where BC was obtained with an Aethalometer.

whereas MIROC-simulated compositions have been shown to exhibit generally good agreement with measurements (Takemura et al., 2000; 2002; 2003; Goto et al., 2011a; 2011b; 2011c; 2012) and international model inter-comparisons, such as AeroCom (Kinne et al., 2006; Koch et al., 2009). Therefore, in this study we evaluated NICAM-simulated BC using both in-situ measurements and MIROC results.

2. Model description

2.1. Nonhydrostatic Icosahedral Atmospheric Model (NICAM)

NICAM, which employs an icosahedral grid-point method with a nonhydrostatic equation system (Tomita and Satoh, 2004; Satoh et al., 2008), is run with a maximum horizontal resolution of 0.87 km (Miyamoto et al., 2013) and can be applied to transport models of aerosols and gases as a conventional atmospheric general circulation model (Suzuki et al., 2008; Niwa et al., 2011; Dai et al., 2014). NICAM can also be employed for regional-scale simulations by adopting a stretched-grid system (Tomita, 2008a; Satoh et al., 2010; Goto et al., 2014). In the stretched-grid system, the grid interval on a sphere becomes finer as it approaches the center of the target region.

In the present study, we first executed NICAM using the global uniform-grid system. The horizontal and vertical resolutions were set to glevel-5 resolution, where "glevel" refers to the number of divisions of an icosahedron used to construct the horizontal grid and where a glevel of 5 comprises 220 km, and 40 layers including 10 layers with a height of approximately 2 km. NICAM implements comprehensive physical processes for aerosols, radiation, turbulence, and cloud dynamics. The aerosol model is known as SPRINTARS (Takemura et al., 2000, 2002, 2005), as described in detail in Section 2.2. The radiation transfer model is a two-stream k-distribution radiation scheme known as MSTRN, which considers the scattering, absorption, and emission of aerosols and cloud particles as well as the absorption by gaseous compounds (Sekiguchi and Nakajima, 2008). The vertical turbulent scheme comprises the level 2 turbulence closure scheme used by Mellor and Yamada (1974), Nakanishi and Niino (2004, 2009), and Noda et al. (2009). The cloud dynamics consider the Arakawa-Schubert-type cumulus convection scheme (Arakawa and Schubert, 1974) and the diagnostic variables of cloud water and cloud cover using the scheme of Le Treut and Li (1991). Meteorological fields (wind, water vapor, and temperature) were nudged from the NCEP-FNL data (http://rda.ucar.edu/datasets/ds083.2/) every 6 h. The monthly averaged sea surface temperature was also nudged using the NCEP-FNL data.

To resolve high-spatial grids, we also executed the stretched-grid system in Stretch-NICAM to focus on East Asia, especially Tokyo, Japan, as described in Goto et al. (2014). The horizontal resolution was set to glevel-6 and a stretching ratio of 100, which is the ratio of the largest horizontal grid spacing to the smallest horizontal grid spacing. As a result, the minimum horizontal resolution was 11 km in the stretching center around Tokyo. The majority of physical modules are identical to those used in the simulation using the uniform-grid system, except for cloud physics, which considers cloud microphysics of the six-class one-moment bulk scheme (water vapor, cloud water, rain, cloud ice, snowflakes, and graupel) (Tomita, 2008b) and does not include cumulus parameterization, in accordance with previous studies (e.g., Tomita et al., 2005; Sato et al., 2009).

2.2. Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS)

Based on the approach of Suzuki et al. (2008), the three-dimensional aerosol-transport model SPRINTARS (Takemura et al., 2000, 2002, 2005) was coupled to NICAM in this study. The SPRINTARS model calculates the mass mixing ratios of primary tropospheric aerosols, i.e., carbonaceous aerosols (BC and OC, organic carbon), sulfate, soil dust, sea salt, and the precursor gases of sulfate, namely, SO_2 and dimethylsulfide. The aerosol module considers various processes, such as emission, advection, diffusion, sulfur chemistry, wet deposition, and dry deposition, including gravitational settling. For carbonaceous aerosols, the 50% mass of BC from fossil fuel sources is composed of externally mixed particles, whereas other carbonaceous particles are emitted and treated as internal mixtures of BC and OC (BC-OC internal mixtures). The size distribution of these particles is assumed to follow a logarithmic normal distribution using a 1-modal approach with dry mode radii of 18 nm (pure BC) and 100 nm (BC-OC internal mixture) (Takemura et al., 2002). The pure BC is hydrophobic, whereas the BC-OC internal mixture is hydrophilic, with the same wet growth values used by Takemura et al. (2002). The atmospheric removal of aerosols in SPRINTARS includes wet (due to rainout and washout) and dry (due to turbulence and gravity) deposition processes.

For the low-resolution simulation using the uniform-grid system, we used the emission inventories of anthropogenic BC and SO_2 in Asia provided by Zhang et al. (2009) in Asia. For the other areas, sources, and chemical compounds, we used the same emission inventories as those described by Goto et al. (2011a). For the high-resolved simulation using the stretched-grid system, the emission inventories of anthropogenic BC in this experiment were based on EAGrid2000 with a horizontal resolution of 1 km over Japan (Kannari et al., 2007) and the IPCC inventory with a horizontal resolution of 0.5° over other areas of the world (Lamarque et al., 2010). To determine the sulfur chemistry in SPRINTARS, the monthly averaged oxidants (O_3, H_2O_2, and OH) distributions were derived from the global chemical transport model CHASER (Sudo et al., 2002).