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Modeling black carbon and its potential radiative effects over the Tibetan Plateau

JI Zhen-Ming

Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

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Abstract

A regional climate model (RegCM4.3.4) coupled with an aerosol−snow/ice feedback module was used to simulate the deposition of anthropogenic light-absorbing impurities in snow/ice and the potential radiative feedback of black carbon (BC) on temperature and snow cover over the Tibetan Plateau (TP) in 1990−2009. Two experiments driven by ERA-interim reanalysis were performed, i.e., with and without aerosol−snow/ice feedback. Results indicated that the total deposition BC and organic matter (OM) in snow/ice in the monsoon season (May−September) were much more than non-monsoon season (the remainder of the year). The great BC and OM deposition were simulated along the margin of the TP in the non-monsoon season, and the higher deposition values also occurred in the western TP than the other regions during the monsoon period. BC-in-snow/ice decreased surface albedo and caused positive surface radiative forcing (SRF) (3.0−4.5 W m^{-2}) over the western TP in the monsoon season. The maximum SRF (5−6 W m^{-2}) simulated in the Himalayas and southeastern TP in the non-monsoon season. The surface temperature increased by 0.1−1.5 °C and snow water equivalent decreased by 5−25 mm over the TP, which showed similar spatial distributions with the variations of SRF in each season. This study provided a useful tool to investigate the mechanisms involved in the effect of aerosols on climate change and the water cycle in the cryospheric environment of the TP.

Keywords: Black carbon; Tibetan Plateau; Aerosol−snow/ice radiative effects; Regional climate model

1. Introduction

Light-absorbing impurities in snow/ice are derived from the wet and dry deposition of light-absorbing particles in the atmosphere. A few light-absorbing impurities in snow/ice can reduce ground albedo and increase the absorption efficiency of solar radiation, resulting in the melting of snow/ice at the surface. The main components of light-absorbing impurities in snow/ice are mineral dusts, black carbon (BC), brown carbon, and organic matter (OM). Mineral dusts and BC have strong absorption in the visible band, whereas brown carbon and OM absorb in the ultraviolet band. In general, mineral dusts originate from natural sources, whereas BC and brown carbon are mainly emitted from the incomplete combustion of fossil fuels and biomass during anthropogenic activities.

The Tibetan Plateau (TP), which has an abundance of snow and ice cover, is referred to as the water tower of Asia. Melting snow/ice makes a large contribution to regional hydrological resources and has direct impacts on local society and economic development. Recent studies have found that light-absorbing impurities, which may accelerate snow/ice melting, are considered as a key factor in cryospheric changes (Flanner et al., 2009; Doherty et al., 2010; Xu et al., 2009; Wang et al., 2013; Dumont et al., 2014). However, there

E-mail address: jzm@itpcas.ac.cn.
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have been few assessments of the radiative effects of light-absorbing impurities on snow/ice cover over the TP (Ming et al., 2009a; Qu et al., 2014). Flanner et al. (2007) coupled a snow radiative model with a global climate model (GCM) and estimated the anthropogenic radiative forcing by the deposition of BC in snow averaged 1.5 W m^{-2} over the TP. Qian et al. (2011) also found the effects of BC and mineral dusts on changes in surface radiative forcing with the range of 5−25 W m^{-2} and increased the temperature by 1.0 °C on average and reduced the snowpack in spring over the TP through a GCM. However, the coarse resolution of GCMs cannot capture the spatial distribution of snow cover against observations. In this study, we used a regional climate model, which performed well in climatology over the TP (Ji and Kang, 2013), to simulate the concentrations and deposition of anthropogenic light-absorbing impurities (BC and OM) in snow/ice and to investigate the potential radiative effects of BC on snow/ice melting.

2. Model, data, and details of the experiments

The Regional Climate Model version 4.3.4 (RegCM4.3.4) updated from RegCM4 (Giorgi et al., 2012) was used in this study. RegCM series models follow a hydrostatic equilibrium transplanted from the dynamic core in mesoscale model MM5 (Grell et al., 1994). The radiative transfer module is taken from the U.S. National Center for Atmospheric Research (NCAR) Community Climate Model 3.0 (CCM3) (Kiehl, 1996). In this study, we used the Grell (1993) convective precipitation scheme due to its good performance over these regions (Ji et al., 2015). The land surface module was coupled with the Community Land Model version 4.5 (CLM4.5) (Oleson et al., 2010). The snow module in CLM4.5 was modified by coupling it with the Snow and Ice Aerosol Radiation package (SNICAR), which can reproduce the effect of light-absorbing impurities (e.g., BC and mineral dust) on snow albedo (Flanner et al., 2007). In this study, the top of snow layer with the maximum thickness of 0.02 m was applied.

The initial conditions and lateral boundary conditions (ICBC) were derived from European Centre for Medium-Range Weather Forecasts (ECMWF) re-analysis ERA-interim data at 1.5° × 1.5° horizontal resolution (Dee et al., 2011). Sea surface temperatures were obtained from the National Oceanic and Atmospheric Administration (NOAA; Reynolds et al., 2002). The land cover data were obtained from the moderate-resolution imaging spectroradiometer (MODIS) (Lawrence and Chase, 2007). A BC and organic carbon (OC) emissions inventory (Junker and Liousse, 2008; Liousse et al., 1996) was interpolated to the model grid via a bilinear method. Emissions of OC were multiplied by 1.4 to represent OM. This OM/OC ratio is appropriate for representing fossil fuel-derived OC emissions (Russell, 2003). The effect of OM on snow is not considered in the current model version; therefore, only the BC in snow was investigated in this study. The model resolution was 50 km, and the domain was centered at 27°N, 85°E, with 90 and 95 grids in the north−south and west−east directions, respectively. Two simulations were performed, one with and one without aerosol−snow radiative feedback, for the period of 1989−2009 (the first year was the model spin-up). According to Wu and Zhang (1998), we defined the monsoon season as May to September, and the non-monsoon season to be the remainder of the year.

3. Results

A previous study (Ji et al., 2015) validated RegCM4.3 performance and confirmed that the model could reproduce the spatial distributions of atmospheric circulation, temperature, and precipitation over the TP. The model also captured the aerosol concentration and optical depth well compared with observations. Therefore, we did not repeat the model evaluation of the climatology in this study.

Fig. 1 shows BC and OM deposition on top of the snow layer based on simulations of the monsoon and non-monsoon seasons. The deposition of OM was much greater than that of BC, consistent with the difference in their atmospheric concentrations. OC emissions were 2−3 times greater than BC emissions in Asia (Ohara et al., 2007; Ji et al., 2015). In the monsoon season, BC (Fig. 1a) and OM (Fig. 1c) depositions were in the range of 20−120 and 60−200 μg m^{-2}, respectively, over the western TP and Himalayas. Aerosol deposition was very low in the inland regions of the TP. In the non-monsoon season, there were high levels of BC deposition along the margin of the Third Pole, and low levels in the inland regions (Fig. 1b). These topographic patterns were probably associated with a terrain blocking effect on the particles in the atmosphere. In the Himalayas, Hindu-Kush, Tianshan, Kunlun, and Qilian Mountains, BC and OM depositions (Fig. 1d) were in the range of 40−70 and 120−200 μg m^{-2}, respectively. In terms of seasonal differences, both BC and OM depositions were greater during the monsoon season than the non-monsoon season over the western TP. However, in the Tianshan, Kunlun, Qilian, and Himalayas, the maximum values occurred in the non-monsoon season.

We summarized the mass concentrations of BC and OC in snow from 11 sites (Table 1) for comparison with model-simulated carbonaceous impurities on top of the snow layer. Muztagh Ata in the eastern Pamir Mountains experiences prevailing westerlies throughout the year. Meikuang Glacier is located in the eastern Kunlun Mountains, on the southern margin of the Qaidam Basin, Laohugou No. 12 Glacier, and Qiyi Glacier are located in the western Qilian Mountains, northeast of the TP. Dongkemadi Glacier is in the Tanggula Mountains in the central TP, and Lanong Glacier and Zhadang Glacier are situated in the eastern Nyainqentanglha Mountains. Qiangyong Glacier is located in the southern TP, Namunani Glacier is in the western Himalayas, and Kangwuer Glacier on Mount Shishapangma and East Rongbuker Glacier on Mount Qomolangma are located in the central Himalayas, where the monsoon climate dominates in summer. At Muztagh Ata, Qiyi, Qiangyong, Namunani, and Kangwure Glaciers, measured BC and OC concentrations were obtained from