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Investigation of mineral aerosols radiative effects over High Mountain Asia in 1990–2009 using a regional climate model

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A B S T R A C T

Mineral aerosols scatter and absorb incident solar radiation in the atmosphere, and play an important role in the regional climate of High Mountain Asia (the domain includes the Himalayas, Tibetan Plateau, Pamir, Hindu-kush, Karakorum and Tienshan Mountains). Dust deposition on snow/ice can also change the surface albedo, resulting in perturbations in the surface radiation balance. However, most studies that have made quantitative assessments of the climatic effect of mineral aerosols over the High Mountain Asia region did not consider the impact of dust on snow/ice at the surface. In this study, a regional climate model coupled with an aerosol–snow/ice feedback module was used to investigate the emission, distribution, and deposition of dust and the climatic effects of aerosols over High Mountain Asia. Two sets of simulations driven by a reanalysis boundary condition were performed, i.e., with and without dust–climate feedback. Results indicated that the model captured the spatial and temporal features of the climatology and aerosol optical depth (AOD). High dust emission fluxes were simulated in the interior of the Tibetan Plateau (TP) and the Yarlung Tsangpo Valley in March–April–May (MAM), with a decreasing trend during 1990–2009. Dry deposition was controlled by the topography, and its spatial and seasonal features agreed well with the dust emission fluxes. The maximum wet deposition occurred in the western (southern and central) TP in MAM (JJA). A positive surface radiative forcing was induced by dust, including aerosol–snow/ice feedback, resulting in 2-m temperature increases of 0.1–0.5 °C over the western TP and Kunlun Mountains in MAM. Mineral dust also caused a decrease of 5–25 mm in the snow water equivalent (SWE) over the western TP, Himalayas, and Pamir Mountains in DJF and MAM. The long-term regional mean radiative forcing via dust deposition on snow showed an rising trend during 1990–2009, which suggested the contribution of aerosols surface radiative effects induced by snow darkening was increased since 1990.

1. Introduction

The cryosphere has been in an accelerated transition over High Mountain Asia (refer to the domain including the Himalayas, Tibetan Plateau, Pamir, Hindu-kush, Karakorum and Tienshan Mountains) during the last few decades (Kang et al., 2010). Most of the glaciers located in the Tienshan (Sorg et al., 2012; Farinotti et al., 2015), Tibetan Plateau (TP) (Yao et al., 2012a), and Himalayas (Bolch et al., 2012) have been rapidly shrinking since the 1990s, although a few glaciers in the Karakorum and East Pamir Mountains have presented a positive mass balance since the beginning of the 21st century (Copland et al., 2011; Gardelle et al., 2012). Seasonal snow characteristics have experienced great interannual variability during the last 50 years over the TP. In general, snow cover duration (SCD: the total number of days with snow cover in an annual cycle) and snow water equivalent (SWE: the depth of water that theoretical result if the whole snow pack instantaneously melts) have increased over the period of 1960–1990 (Qin et al., 2006); however, there has been a decreasing trend in SWE since the 1990s (Ma and Qin, 2012) over the TP. The linear regression explaining the spatial variation in SCD has shown an increase over the Karakorum, Qilian, and Tanggula Mountains, but a decreasing trend has been observed in the central and eastern Himalayas (Tang et al., 2013). As the region is referred to as the "water tower of Asia," these changes in the cryosphere, including the variability of glaciers and seasonal snow over High Mountain Asia, could potentially have a large impact on regional water resources (Immerzeel et al., 2010) and natural hazards (Yao, 2010; Bolch et al., 2011).

Many previous studies have connected cryospheric changes with large-scale internal climate variability (Bednorz, 2004; Huss et al., 2010; Marzeion and Nesje, 2012; Birsan and Dumitrescu, 2014). Yao et al. (2012b) found that the shrinkage of glaciers could probably be attributed to decreased precipitation due to the weakening Indian

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monsoon in the Himalayas, whereas the positive mass balance in the eastern Pamir Mountains may be linked to increased precipitation induced by strengthened westerlies. Warming has also been determined to be a dominant factor, with air temperature anomalies over the Northern Hemisphere mid-latitude land areas explaining almost 50% of the observed variability in the extent of snow cover (Brown and Robinson, 2011). Small amounts of insoluble light absorbing particles (ILAP) deposited on snow and glaciers can significantly decrease the surface albedo and enhance solar radiation absorption at the surface (Warren and Wiscombe, 1980). Consequently, ILAP and the related snow/ice albedo feedback are also considered key factors in cryospheric changes. Recent studies have found that ILAP from anthropogenic (Wan et al., 2015) and natural sources deposited on the ground surface may accelerate the melting of snow and glaciers over High Mountain Asia (Flanner et al., 2009; Ming et al., 2009; Kaspari et al., 2011; Xu et al., 2012). Black carbon (BC) is a product of incomplete combustion during the burning of biomass and fossil fuels (Ramana et al., 2010). BC has strong absorption properties, and it is considered a main anthropogenic contribution to the levels of ILAP. Flanner et al. (2007) used a snow radiative model coupled to a global climate model and estimated that the greatest human-induced radiative forcing by the deposition of BC in snow averaged 1.5 Wm^{-2} over the TP. Ming et al. (2009) used the BC concentration obtained from an ice core to estimate radiative forcing due to the deposition of BC in a glacier over the Himalayas. Their study found a significant increase in radiative forcing since the 1990s, with a value greater than 4.5 Wm^{-2} in the summer of 2001. Xu et al. (2009) also found that the increased BC concentration was an important factor in the retreat of glaciers over the southwestern TP during the last 20 years. Mineral aerosols are also the main source of ILAP over High Mountain Asia, which is very close to great Asian dust source regions. Fujita (2007) indicated that the effect of dusts deposition on snow and glaciers should be considered when the surface albedo was less than 0.7. Some studies based on the field samples (Chen et al., 2013; Qu et al., 2014) also found the mineral dusts are the majority insoluble impurities than BC over the TP. The investigation of ILAP's effects on snow/ice was first conducted through a winter snowpack on the Nyainqentanglha located in the central TP (Ming et al., 2013). Their study suggested that the effects of mineral dusts on snow are greater than that of BC over the TP due to much larger concentrations of dust. Although there is no accurate estimate of the mineral aerosol fraction of ILAP over High Mountain Asia, its concentration and effects are likely to be considerable and require further investigation. However, most previous studies have reported similar implications for the effects of ILAP on glaciers and seasonal snow variation, quantitative investigations of the effects of ILAP on climate feedback are very limited. Qian et al. (2011) indicated that BC in snow increased the surface temperature by 1.0 °C on average and reduced the spring snowpack over the TP. However, the coarse resolution of global climate models (GCMs) cannot effectively capture the complex terrain that generates the observed spatial variability in fractional snow cover (Qian et al., 2011).

In this study, we used a high-resolution regional climate–dust model to simulate the emission, distribution, and deposition of mineral aerosols and investigate the climatic effects of mineral dust over High Mountain Asia. The paper is organized as follows. Section 2 describes the model, data, and experimental design. Section 3 is model evaluation. Section 4 is simulation of mineral dust emissions, loadings and depositions. Section 5 assesses the radiative effects focusing on the long-term trends and the seasonal differences. Section 6 summarizes and concludes the research.

2. Model, data, and experimental design

The Regional Climate Model version 4.3.4 (RegCM4.3.4) developed at the Abdus Salam International Center for Theoretical Physics (ICTP) was used in this study. RegCM4.3.4 is a new version of the model and is updated from RegCM4 (Giorgi et al., 2012). It is a hydrostatic equilibrium model with a dynamic core, based on the mesoscale model MM5 from National Center for Atmospheric Research / Pennsylvania State University (NCAR/PSU) (Grell et al., 1994). The radiative transfer package is taken from the NCAR Community Climate Model 3.0 (CCM3, Kiehl, 1996). There are several optional convection schemes included in RegCM4.3.4, but for our experiments, we used the Grell (1993) convective precipitation scheme with the Arakawa and Schubert closure assumption (Arakawa and Schubert, 1974) due to its good performance over this region (Ji et al., 2015c).

The Community Land Model version 4.5 (CLM4.5) (Oleson et al., 2010) is coupled in RegCM4.3.4 with some modifications (Wang et al., 2016). The snow model is significantly modified via the incorporation of the SNow and Ice Aerosol Radiation module (SNICAR), which represents the effect of aerosol deposition (e.g., black and organic carbon and mineral dust) on albedo, introduces a grain-size-dependent snow aging parameterization, and permits vertically resolved snowpack heating (Flanner and Zender, 2005, 2006; Flanner et al., 2007). The new snow model also includes a new density-dependent snow cover fraction parameterization (Niu and Yang, 2007), a revised snow burial fraction over short vegetation (Wang and Zeng, 2009), and corrections to snow compaction (Lawrence and Slater, 2010).

The dust module uses a dynamic emission scheme (Marticorena and Bergametti, 1995; Alfaro and Gomes, 2001) based on soil aggregate saltation and sand blast processes, which includes three steps (Zakey et al., 2006): 1) the specification of soil aggregate size distribution for each grid cell in the model; 2) the calculation of a threshold friction velocity which leads to erosion and saltation processes; 3) the calculation of the horizontal and vertical saltating soil aggregate mass flux. Transport processes are described by a tracer transport equation (Solmon et al., 2006; Zakey et al., 2006), which is calculated through advection, horizontal and vertical turbulent diffusion and deep convection. Wet deposition is treated following Giorgi (1989) for large-scale precipitation and Giorgi and Chameides (1986) for convective precipitation. The gravitational settling and dry deposition processes are described by Zakey et al. (2006). The gravitational settling term depends on the size of particles and a dry deposition scheme contains turbulent transfer processes at the surface layer. The dry deposition velocity is calculated as a function of particle size and density and involves the contributions of turbulent transfer, Brownian diffusion, impaction, interception, gravitational settling and particle rebound (Giorgi, 1986; Zhang et al., 2001). Four dust size bins are considered, including fine (effective diameter: 0.01–1.0 μm), accumulation (1.0–2.5 μm), coarse (2.5–5.0 μm), and giant-sized (5.0–20.0 μm) particles. Previous RegCM-dust models have been widely applied in investigations of climatic effects over different regions, including East Asia (Zhang et al., 2009), Southwest Asia (Marcella and Eltahir, 2010), South Asia (Das et al., 2013), and West Africa (Konare et al., 2008; Solmon et al., 2012; Ji et al., 2015a, 2015b).

The initial and lateral boundary conditions (ICBC) were obtained from ERA-Interim data at 1.5° × 1.5° resolution, which are produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al., 2011). Sea surface temperatures were obtained from the National Oceanic and Atmospheric Administration (NOAA; Reynolds et al., 2002). The land use data were taken from Lawrence and Chase (2007). The soil texture data were derived from the U.S. Department of Agriculture texture classification (USDA, 1999).

The model has a horizontal resolution of 30 km, and includes 18 vertical sigma levels, with the model top at 10 h Pa. The model center is fixed at 36°N, 74°E, with 192 and 120 grid cells in the west–east and north–south directions, respectively. Fig. 1 shows the model domain and mineral dust source regions (stippled areas). The annual mean SCD is greater than 150 days and SWE is in the range of 25–75 mm over the most regions of High Mountain Asia. In the Tienshan Mountains, Pamir and southeastern TP, the annual mean SCD and SWE are more than 200 days and 75 mm, respectively (Ji and Kang,