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Study of aerosol effect on accelerated snow melting over the Tibetan Plateau during boreal spring

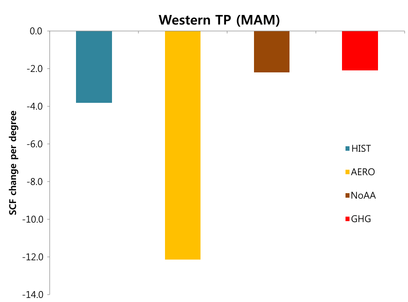
Woo-Seop Lee [a,*], Rohini L. Bhawar [a], Maeng-Ki Kim [b], Jeong Sang [b]

[a] *APEC Climate Center, Busan, Republic of Korea*
[b] *Department of Atmospheric Science, Kongju National University, Gongju, Republic of Korea*

HIGHLIGHTS

- A coupled atmosphere–ocean global climate model (CSIRO-Mk3.6) is used to investigate the role of aerosol forcing agents.
- Aerosol effect on snow melting is high, or comparable to the effect of GHG.
- The efficacy of snow melt induced by aerosol is about five to six times larger than the increase in CO_2

GRAPHICAL ABSTRACT



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ABSTRACT

In the present study, a coupled atmosphere–ocean global climate model (CSIRO-Mk3.6) is used to investigate the role of aerosol forcing agents as drivers of snow melting trends in the Tibetan Plateau (TP) region. Anthropogenic aerosol-induced snow cover changes in a warming climate are calculated from the difference between historical run (HIST) and all forcing except anthropogenic aerosol (NoAA). Absorbing aerosols can influence snow cover by warming the atmosphere, reducing snow reflectance after deposition. The warming the rate of snow melt, exposing darker surfaces below to short-wave radiation sooner, and allowing them to heat up even faster in the Himalayas and TP.

The results show a strong spring snow cover decrease over TP when absorbing anthropogenic aerosol forcing is considered, whereas snow cover fraction (SCF) trends in NoAA are weakly negative (but insignificant) during 1951–2005. The enhanced spring snow cover trends in HIST are due to overall effects of different forcing agents: When aerosol forcing (AERO) is considered, a significant reduction of SCF than average can be found over the western TP and Himalayas. The large decreasing trends in SCF over the TP, with the maximum reduction of SCF around 12–15% over the western TP and Himalayas slope. Also accelerated snow melting during spring is due to effects of aerosol on snow albedo, where aerosol deposition cause decreases snow albedo. However, the SCF change in the "NoAA" simulations was observed to be less.

1. Introduction

Atmospheric aerosols are of great importance to global climate because of their absorbing as well as scattering properties and in turn significantly influence the Earth's radiation budget (Ramanathan et al., 2001; Haywood and Boucher, 2000; Bellouin et al., 2005). In general, aerosols could offset the greenhouse

* Corresponding author. APEC Climate Center, 12 Centum 7-ro, Haeundae-gu, Busan 612-020, Republic of Korea.
E-mail address: wslee@apcc21.org (W.-S. Lee).

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warming by directly scattering the sunlight back to space and by indirectly enhancing cloud albedo, thereby cooling the climate. However, absorbing aerosols heat the atmosphere because of their absorption of solar radiation, which in turn raise the greenhouse warming (Jacobson, 2001; Lee et al., 2009; Kim et al., 2006). Therefore, absorbing aerosols such as black carbon (BC) and dust are thought to affect the hydrology and radiative forcing over Asia (Ramanathan and Carmichael, 2008; Menon et al., 2002; Lau and Kim, 2006; Lee and Kim, 2010) as well as increase snow melt in snow covered regions (Jacobson, 2005; Flanner et al., 2007; Koch et al., 2009; Lau et al., 2010; Lee and Kim, 2013).

The Tibetan Plateau (TP) is located close to regions in South and East Asia that have been and are predicted to continue to be the largest source of black soot in the world (Bond et al., 2007; Ohara et al., 2007). Li et al. (2005) and Filipiak et al. (2005) found the pollution (as indicated by CO, an index for absorbing aerosols) in South Asia region are trapped over the TP during the summer, which could have a strong regional impact; Park et al. (2007) and Jiang et al. (2007) further studied TP region pollution in term of dynamics, transport and the importance of their impact on climate and air quality; Jiang et al. (2011) also show aerosols in south Asia (include TP) could alter cloud properties in the region. The extensive black carbon and dust aerosols could be lofted to the high TP and are incorporated in snowflakes that when falling on the glaciers darken their surface, This has led to initial studies of the amount of BC in the snow and ice of Himalayan glaciers (Flanner et al., 2007). Etienne et al. (2007) showed that 915 km^2 of Himalayan glaciers have thinned by an annual average of 0.85 cm over a decade period between 1994 and 2004. The snow cover of the Tibetan Plateau and Himalayas is very important for the regional climatic change and hydrological cycle. In recent years, there have been growing evidences of increased warming, accompanied by early snow melt, and retreat of high mountain glacier in the Himalayas and the TP regions (IPCC, 2007; He et al., 2003; Jain, 2008; Ren et al., 2006; Kulkarni et al., 2007). Also recently, a model study by Lau et al. (2010) showed that the heating of the troposphere by elevated dust and black carbon aerosols in the boreal spring can lead to widespread enhanced warming of the land-atmosphere, and accelerated snow melt in the Himalayas and western TP region.

Up to now, most studies about snow melt in the Himalayas and TP are focused on greenhouse warming (Duan et al., 2006; Oerlemans, 2005; Jiawen et al., 2006). Yet, the greenhouse warming rate is of the order of 0.1–0.15 K/decade, while the warming of the TP has been estimated to be much faster, at 0.32 K/decade (Liu and Chen, 2000). Over Himalaya foothill regions and Middle Mountain regions in Nepal, the warming rate is even faster, estimated at 0.7–1.2 °C per decade since 1977–94 (Shrestha et al., 1999). Based on these differences in warming rates, it is not difficult to summarize that global warming is not the sole agent of change in these regions, and that local forcing and feedback processes are likely to play an important role in causing the faster warming rate, and accelerated retreat of the mountain glaciers.

Many factors besides greenhouse warming could have led to accelerated warming over the Himalayas and TP. These include increased land-use and land change, increased sunlight duration from reduction in cloudiness, increased water vapor feedback, and reduction of snow albedo by deposition of soot and dust on snow surface (Kang et al., 2000; Prasad and Singh, 2007; Flanner et al., 2007, 2009). Recently Ramanathan and Carmichael (2008) estimated that atmospheric heating by Asian Brown Clouds (ABC) doubles the greenhouse warming over South Asia, and may contribute substantially to the loss of glacier mass in the Himalayas. Also, absorbing aerosol induced reduction of snow cover/albedo and its contribution to snow/ice retreat have only begun to receive attention, hence, there is a need for more extensive coupled modeling data, such as CMIP5 simulations to understand this aspect.

In this article, we investigate the impact of atmospheric heating by aerosol in boreal spring in possibly leading to enhanced premonsoon surface warming and early snow melt in the Himalayas and TP region using CMIP5 model simulation. Our analysis focuses on the change of spring time snowpack over the TP and their subsequent impacts on surface radiative flux change.

2. Data and methodology

2.1. Observation data

For model evaluations, Moderate Resolution Imaging Spectroradiometer (MODIS) data, which is a 36-channel visible-to-thermal-infrared sensor that was launched as part of the EOS Aqua payload, is used. Various snow and ice products are produced with MODIS imagery and the data are available at a variety of spatial and temporal resolution (Hall et al., 2001). The quality of MODIS snow data has been evaluated (e.g., Pu et al., 2007) and results indicate that the overall accuracy is about 90% over the TP region. In this study, gridded global monthly snow cover product MYD10CM is used, at a 0.05° resolution covering from August 2002 to 2012. The most challenging task in the compiling of monthly files was the correct handling of missing values in the daily product, MYD10 Level 2 from which the monthly values are derived. The aerosol optical depth has been obtained using Level-3 MODIS gridded atmosphere monthly global product 'MYD08_M3' (ESDT Long Name: MODIS/Aqua Aerosol Cloud Water Vapor Ozone Monthly L3 Global 1Deg CMG). The monthly average MYD08_M3 product files are produced at a spatial resolution of 1° by 1° (L'Ecuyer and Jiang, 2010). The Atmospheric Infrared Sounder (AIRS) is on board NASA's Earth Observing System satellite Aqua (EOS-Aqua). The geophysical parameters have been averaged and binned into 1° × 1° grid cells, from −180.0° to +180.0° longitude and from −90.0° to +90.0° latitude. AIRS provides several atmospheric parameters, including vertical profiles of atmospheric temperature. The accuracy of temperature and water vapor profiles is expected to be 1 K for 1 km levels and 15% for 2 km layers in the troposphere, respectively (Tobin et al., 2006). In this study we use the AIRS Level 3 Monthly Gridded Retrieval Product.

For wind, we use the reanalysis data from Modern Era Retrospective-analysis for Research and Applications (MERRA) (Kim et al., 2006). This study uses a standard monthly mean output that is provided on 42 pressure levels at a horizontal resolution of 1.25° latitude × 1.25° longitude for the period 2000–2011.

2.2. Model description

The results of this paper are based on coupled atmosphere–ocean global climate model (CSIRO-Mk3.6) with dynamical sea ice and soil canopy scheme with prescribed vegetation properties (Gordon et al., 2002, 2010). The CSIRO-Mk3.6 has an approximately 1.875° × 1.875° horizontal resolution, 18 vertical levels, and is coupled on version 2.2 of the Modular Ocean Model (Gordon et al., 2010); which is one of the CMIP5 climate models and has been recently validated by Jiang et al. (2012) using multiple observations from NASA A-train satellite. Their results show good performance of CSIRO-Mk3.6 model in mid- and lower-troposphere.

This model is the inclusion of an interactive aerosol scheme, which takes into account sulfate, dust, carbonaceous, and sea salt aerosols. The radiation scheme treats the direct effects of all these aerosol species on short-wave radiation and the effects of dust on long-wave radiation. The indirect effects of sulfate, carbonaceous