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Impacts of meteorological parameters and emissions on decadal, interannual, and seasonal variations of atmospheric black carbon in the Tibetan Plateau

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Abstract

We quantified the impacts of variations in meteorological parameters and emissions on decadal, interannual, and seasonal variations of atmospheric black carbon (BC) in the Tibetan Plateau for 1980−2010 using a global 3-dimensional chemical transport model driven by the Modern Era Retrospective-analysis for Research and Applications (MERRA) meteorological fields. From 1980 to 2010, simulated surface BC concentrations and all-sky direct radiative forcing at the top of the atmosphere due to atmospheric BC increased by 0.15 μg m^{-3} (63%) and by 0.23 W m^{-2} (62%), respectively, averaged over the Tibetan Plateau (75−105°E, 25−40°N). Simulated annual mean surface BC concentrations were in the range of 0.24−0.40 μg m^{-3} averaged over the plateau for 1980−2010, with the decadal trends of 0.13 μg m^{-3} per decade in the 1980s and 0.08 in the 2000s. The interannual variations were −5.4% to 7.0% for deviation from the mean, 0.0062 μg m^{-3} for mean absolute deviation, and 2.5% for absolute percent departure from the mean. Model sensitivity simulations indicated that the decadal trends of surface BC concentrations were mainly driven by changes in emissions, while the interannual variations were dependent on variations of both meteorological parameters and emissions. Meteorological parameters played a crucial role in driving the interannual variations of BC especially in the monsoon season.

Keywords: Black carbon; Tibetan Plateau; Interannual variations; South Asian summer monsoon

1. Introduction

Black carbon (BC), formed from incomplete combustion (Bond et al., 2013; IPCC, 2013), has substantial impacts on climate because of its strong absorption of solar radiation (e.g., Horvath, 1993; Ramanathan and Carmichael, 2008). BC deposited on snow and ice can significantly decrease the surface albedo (Warren and Wiscombe, 1980; Flanner et al., 2007, 2009), enhance surface snowmelt (Zwally et al., 2002; Flanner et al., 2007), and potentially change the regional hydrological cycle over the plateaus and mountain ranges (e.g., Qian et al., 2009, 2011). Ample evidences have shown that BC aerosols deposited on the Tibetan glaciers are responsible for the observed rapid glacier retreat in the region (e.g., Xu et al., 2009). Model simulations have shown that the annual direct radiative forcing (DRF) due to the atmospheric BC are 0.58−1.46 W m^{-2} at the top of the atmosphere (TOA) averaged over China (Li et al., 2016). The regional warming

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effect of BC over snow-covered regions can be even stronger (Jacobson, 2004; Flanner et al., 2007, 2009).

The Tibetan Plateau is the world's highest plateau with the third largest snow and ice mass (Xu et al., 2009). The snowmelt from the Tibetan glaciers is the primary source of freshwater supply for hundreds of million people in Asia (Immerzeel et al., 2010). Recent studies have shown that a strong BC-induced regional warming over the plateau results in the reduction of snow/ice cover and snow albedo (Lau et al., 2010; Menon et al., 2010; Yasunari et al., 2010), and an increase of runoff in early spring (Qian et al., 2011). Moreover, changes of snow cover in the region would affect energy and hydrological cycle, and further disturb the formation of the Asian summer monsoon (Lau and Kim, 2006).

Observations have shown strong warming and accelerated glacier retreat in the Tibetan Plateau in the past decades (Qin et al., 2006; Prasad et al., 2009). The major contributions of BC to the Tibetan Plateau are the emissions from South Asia and East Asia (Kopacz et al., 2011; Lu et al., 2012; Wang et al., 2015), which are the world's two largest BC sources and are increasing in the past decades (Lu et al., 2011). Recent studies have shown that the increasing amount of BC transported to the Tibetan Plateau (Ming et al., 2008; Lu et al., 2012) accounts for half of the observed warming in the region (Ramanathan et al., 2005, 2007).

Better understanding the changes of BC in the Tibetan Plateau on a decadal time scale would provide useful information for guiding measures to reduce BC emissions and to mitigate near-term climate warming in the region. To our knowledge, few studies have systematically examined the decadal, interannual, and seasonal changes of BC and analyzed their driving factors, especially in the Tibetan Plateau, due to the lack of observations and the limitation of models. Here we present the decadal, interannual, and seasonal variations of BC in the Tibetan Plateau for a 31-year period (1980−2010) using a global 3-dimensional chemical transport model (GEOS-Chem) driven by the Modern Era Retrospective-analysis for Research and Applications (MERRA) meteorological fields. We aim to quantify the roles of variations in meteorological parameters and anthropogenic and biomass burning emissions in the changes of BC in the Tibetan Plateau between monsoon and nonmonsoon seasons. We describe the GEOS-Chem model and numerical simulations in Section 2. In Section 3, we quantify the impacts of variations in emissions and meteorological parameters on the changes of BC and present the changes in all-sky TOA DRF of atmospheric BC in the Tibetan Plateau. Finally, summary and conclusions are given in Section 4.

2. Methods

2.1. GEOS-Chem model

The GEOS-Chem model is driven by assimilated meteorology from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling and Assimilation Office (GMAO) (Bey et al., 2001). Here we use GEOS-Chem version 9-01-03 (available at http://geos-chem.org) driven by the MERRA meteorological fields (Rienecker et al., 2011), with 6-h temporal resolution (3-h for surface variables and mixing depths), 2° (latitude) × 2.5° (longitude) horizontal resolution, and 47 vertical layers from the surface to 0.01 hPa. The GEOS-Chem simulation of carbonaceous aerosols has been reported previously by Park et al. (2003). Eighty percent of BC emitted from primary sources is assumed to be hydrophobic, and hydrophobic aerosols become hydrophilic with an e-folding time of 1.2 d (Cooke et al., 1999; Chin et al., 2002; Park et al., 2003). BC in the model is assumed to be externally mixed with other aerosol species. The schemes of tracer advection, convection, and dry and wet depositions are discussed in details in the study by Mao et al. (2016).

The annual anthropogenic emissions of BC for 1980−2010 are from Bond et al. (2007) globally and updated in Asia (60°E−150°E, 10°S−55°N) with the Regional Emission inventory in Asia (REAS) (Ohara et al., 2007, available at http://www.jamstec.go.jp/frsgc/research/d4/emission.htm). Seasonal variations of anthropogenic emissions are considered in China and Indian using monthly scaling factors taken from Kurokawa et al. (2013). Global biomass burning emissions of BC are taken from the Global Fire Emissions Database version 3 (GFEDv3) (van der Werf et al., 2010) with a monthly temporal resolution. More details about the configurations of BC emissions are discussed by Mao et al. (2016).

2.2. Simulations

We conduct six simulations (Table 1) driven by MERRA for 1980−2010 to identify the relative roles of changes in meteorological parameters and emissions in the variations of BC in the Tibetan Plateau. All simulations are preceded by 1-year spin up. In the simulation VALL, meteorological parameters and anthropogenic and biomass burning emissions are allowed to vary year to year. In the simulation VMET (VEMIS), meteorological parameters (anthropogenic and biomass burning emissions) are allowed to vary over 1980−2010, but anthropogenic and biomass burning emissions (meteorological parameters) are fixed at year 2010 levels. To test the influence of emissions (meteorological fields) on decadal and interannual variations of BC in VMET (VEMIS), we conduct sensitivity simulations same as VMET (VEMIS) but with fixed anthropogenic and biomass burning

Table 1
GEOS-Chem simulations of BC.

Model experiments	Meteorological parameters	Emissions	
		Anthropogenic	Biomass burning
VALL	1980−2010	1980−2010	1980−2010
VMET	1980−2010	2010	2010
VEMIS	2010	1980−2010	1980−2010
VEMISAN	2010	1980−2010	Not included
VEMISBB	2010	Not included	1980−2010
VNOC[a]	1980−2010	1980−2010	1980−2010

[a] Anthropogenic and biomass burning emissions in China are set to zero in VNOC.