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Impacts of Himalayas on black carbon over the Tibetan Plateau during summer monsoon

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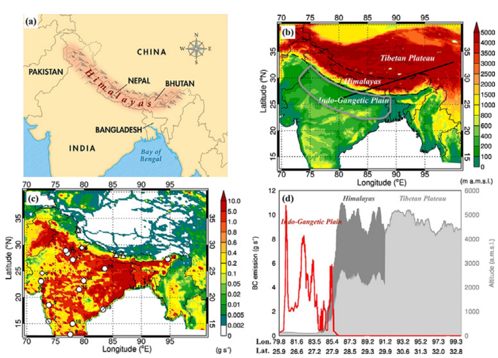
HIGHLIGHTS

- The trans-Himalayas transport of black carbon from South Asia to the Tibetan Plateau is investigated by the WRF-Chem model.
- The reduction of the Himalayas' altitude was in favor of more BC over the Himalayas, but not more BC in the TP.
- Effects of the Himalayas on BC transport were strongly dependent on the cyclonic activities in the IGP during summer monsoon
- In convergent airflows, BC concentrations significantly increased in the southeastern TP, and reached to 0.6-0.8 μg m^{-3}.
- A cyclone located in the eastern IGP, BC transport clearly weakened. While moving to the west, BC transport enhanced.

GRAPHICAL ABSTRACT



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ABSTRACT

The Tibetan Plateau (TP) plays important roles in global climate and environment. This study combines in-situ BC measurements in the Himalayas and the Indo-Gangetic Plain (IGP) with a regional dynamical and chemical model (WRF-Chem model) to investigate the effect of the trans-Himalayas on black carbon (BC) from the IGP to the TP during Indian summer monsoon. To determine topographic effects of the trans-Himalayas on BC concentrations over the TP, sensitive experiments were conducted by applying the WRF-Chem model. The results showed that the reduction of the altitude of the Himalayas had an important effect on the trans-Himalayas transport of BC. There was an obvious increase in BC concentration over the trans-Himalayas region, but no significant increase over the TP because the TP (a.m.s.l ~4 km) always acted as a wall to prevent BC transport from the IGP to the TP. The trans-Himalayas transport of BC was strongly dependent upon meteorological conditions over the IGP. During summer monsoon, there were three types of cyclones at different locations and one kind of convergent circulation in the IGP. Under the condition of convergent airflows, a strong northeastward wind produced the trans-Himalayas transport of BC. As a result, BC concentrations in the southeastern TP significantly increased to 0.6–0.8 μg m^{-3}. When the cyclone located in the eastern IGP, high BC concentrations over the IGP were

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transported along the foothill of the Himalayas, resulting in a significant reduction of the trans-Himalayas transport. When the cyclone moved to the west, the dynamical perturbations for the trans-Himalayas transport were weaker than the eastern cyclone, and the trans-Himalayas transport were enhanced in the middle and eastern Himalayas. This study will be helpful to assess the impacts of BC particles emitted from South Asia on regional climate change and ecological environment over the TP in the future.

1. Introduction

The Tibetan Plateau (TP) in the north of the Himalayas is away from the influence of the human beings due to an extremely high elevation and severe natural environment. On the contrary, the Indo-Gangetic Plain (IGP) with dense population and massive farming in the south of the Himalayas is increasingly emitting large amount of pollutants, especially black carbon (BC), a light-absorbing particle, into the atmosphere since 1990 (Ramanathan et al., 2005). In recent decades, a few in-situ measurements and pollution events validated BC emitted from South Asia have penetrated into the Himalayas and TP regions. Backward trajectories show that BC particles deposited in the Everest are mainly from South Asia (Ming et al., 2008). An ice core drilled by Xu et al. (2009) in the southeast TP records that BC particles from South Asia are transported into the TP by summer monsoon and the south branch of westerlies since 1990. Aerosol optical depth observations at Nam Co in the central TP record an intense pollution episode during springtime in 2009, and the characteristics of particle size and absorption are similar to the IGP and South Asia, indicating that pollutants come from the IGP (Xia et al., 2011). Therefore, the TP is experiencing a profound impact of BC particles from South Asia.

Ramanathan and Carmichael (2008) state that BC in the elevated Himalayas likely plays an important role as carbon dioxide in the melting of snowpacks and glaciers by increasing solar heating. The TP, called as "the third pole", is an extremely important region where numerous mountain glaciers develop (Menon et al., 2010). However, the region is also too vulnerable to BC particles because the particles decrease ice and snow albedo and increase melting and runoff (Yasunari et al., 2010). It is found that BC particles significantly reduce albedos of visible wavelengths, and 15 $\mu g\ kg^{-1}$ of BC in snow can decrease albedo by 1%–3% (Warren and Wiscombe, 1980; Light et al., 1998; Flanner et al., 2009). Consequently, increased surface-incident solar radiation induced by BC particles further enhances snow and ice melting, resting in the increase in glacial runoff (Ramanathan et al., 2005; Lau et al., 2010). For example, BC concentration of 26.0–68.2 $\mu g\ kg^{-1}$ in surface snow can increase 70–204 mm water of annual runoff, exerting a profound impact on regional water cycle (Yasunari et al., 2010). The results from numerical simulations show increasing BC emission in India during 2000–2010 contributes 36% to snow/ice decrease in the Himalayas (Menon et al., 2010). Base on the importance of BC impacts on the cryosphere and consequent climate change over the TP, it is a critical issue to determine how BC from the IGP are transported into the TP while the huge Himalayas mountains lie between them.

A previous study suggests that the Himalayas is like a natural barrier that limits exchanges of airflows between the TP and the IGP (Nieuwolt, 1977). Recent studies suggest that the southern slope of the Himalayas is directly exposure to atmospheric brown cloud and that pollutants in the IGP can be lifted to an upper height of 5000 m in the afternoon during pre-monsoon (Bonasoni et al., 2010). Lawrence and Lelieveld (2010) point out that pollutants in South Asia are lifted to mid- and upper troposphere by intense ascending airflows in deep convective clouds, and then transport a long distance in summer. A recent study investigates transport mechanisms of the pollution in such a complex topography of the Himalayas and the TP, founding that westerlies adjustment nearby the Himalayas and the TP interacts with local-scale weather conditions in the IGP, resting in the transport of pollutants from the IGP to the TP (Lüthi et al., 2015). Clearly, available studies mainly concentrated on how the pollutant from the IGP and South Asia transport over the Himalayas during the pollution episode, but the quantitative calculation by the application of numerical modeling were rare.

The present study will use WRF-Chem model to calculate the impacts of the Himalayas region on BC concentrations over the TP during Indian summer monsoon. This study expects to improve the understanding of the Himalayas' impacts on the transport pathways of regional pollution and provide a preliminary support for investigating the impacts of BC emitted from South Asia on the cryosphere in the TP.

2. Data and methods

2.1. WRF-Chem model description

Black carbon particles were simulated over South Asia using a state-of-the-art regional dynamical and chemical model (Weather Research and Forecasting Chemical model, WRF-Chem model). The spatial resolution was degraded to 9 × 9 km in the horizontal direction, with 600 grids in longitude and 400 grids in latitude. The domain was concentrated in the IGP and the Himalayas and TP regions, with the center location in the South Tibet (94.44°E, 29.46°N). There were 28 levels in the vertical direction from the surface to 50 hPa. The meteorological fields in WRF-Chem model were driven by NCEP 1° × 1° reanalysis data, with a temporal resolution of 6 h. The lateral BC tracer concentrations were provided by a global chemistry transport model - MOZART4 (Model for OZone And Related chemical Tracers, Version 4), with a 6-h output (Tie et al., 2005; Emmons et al., 2010). The WRF model included online calculation of dynamical inputs (winds, temperature, planetary boundary layer etc.), transport (advection, convection and diffusion), dry deposition (Wesely, 1989) and wet deposition. The physical scheme used Yonsei University (YSU) PBL scheme (Hong et al., 2006), the microphysics scheme (Hong and Lim, 2006), the Noah land-surface model (Chen and Dudhia, 2001), the long-wave radiation parameterization (Mlawer et al., 1997), and the shortwave radiation

Table 1
WRF-Chem model configurations.

Regions	South Asia and the TP
Simulation period	July 2012
Domain size	600 × 400
Domain center	94.4°E, 29.5°N
Horizontal resolution	9 km × 9 km
Vertical resolution	28 vertical levels from the surface to 50 hPa
Microphysics scheme	WSM 5-classes microphysics scheme (Hong and Lim, 2006)
Boundary layer scheme	YSU PBL scheme (Hong et al., 2006)
Surface layer scheme	MM5 similarity (Zhang and Anthes, 1982)
Land-surface scheme	Noah land-surface model (Chen and Dudhia, 2001)
Longwave radiation scheme	RRTM scheme (Mlawer et al., 1997)
Shortwave radiation scheme	MM5 shortwave scheme (Dudhia, 1989)
Meteorological boundary and initial conditions	NCEP 1° × 1° reanalysis data
Chemical boundary and initial conditions	MOZART 6-h output (Tie et al., 2005; Emmons et al., 2010)
Anthropogenic emission inventory	Non-residential sources (industry, power, transportation) and residential sources related to fossil fuel and bio-fuel combustions (Zhang et al., 2009; Li et al., 2017)