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Review

Brown carbon in the cryosphere: Current knowledge and perspective

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Abstract

Recently, the light-absorbing organic carbon, i.e., brown carbon (BrC), has received an increasing attention, because they could significantly absorb the solar radiation in the range of short wavelengths rather than the purely scattering effect. BrC is ubiquitous in the troposphere. It could undergo long range transport within the atmospheric circulation. After the deposition on the surface of snow or ice in the cryospheric region, as the major light absorbing impurities with black carbon and dust, BrC could reduce the snow albedo and accelerate the glacier melting. In this context, this paper summarized the current knowledge of BrC (in aerosols and snow) in the cryospheric regions including the Arctic, Antarctic, and Alpines. Although some works have been conducted in those region, the current dataset on the optical properties of BrC like Absorption Ångström Exponent (*AAE*) and Mass Absorption Efficiency (*MAE*) is still limited, which hampers stimulating an accurate evaluation of its climate effects. Especially in the Himalayas and Tibetan Plateau, where very limited information concerning BrC is available. Considering biomass burning as a dominant source of BrC, a large amount of emissions from biomass burning in South Asia could reach the Himalayas and Tibetan Plateau, where the climate effect of BrC merits more investigation in the future.

Keywords: Brown carbon; Black carbon; Atmospheric aerosol; Snow; Glacier

1. Introduction

Carbonaceous components in the atmospheric aerosols play an important role in the climate system, mainly due to their solar absorption and scattering properties (Seinfeld and Pandis, 2012). It is well established that black carbon (BC) could strongly absorb the solar radiation in visible bands (Ramanathan and Carmichael, 2008; Xu et al., 2009), resulting in a direct radiative forcing ranging from 0.17 to 1.48 W m^{-2} (Bond et al., 2013). In contrast to BC, organic carbon in the atmospheric aerosols is traditionally considered to be purely scattering by climate models. However, recent research

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demonstrated that substantial fraction of organic carbon in aerosols could absorb the light in the range of short wavelengths. Such kinds of organic substances with wavelength-dependent absorption are defined as brown carbon (BrC) (Andreae and Gelencser, 2006). BrC has multiple primary sources such as biomass burning (Saleh et al., 2014; Washenfelder et al., 2015), fossil fuel (e.g., coal) combustion (Bond, 2001; Yang et al., 2009), biogenic aerosols (e.g., plant debris and fungi) and soil humic matters. Meanwhile BrC could also be secondarily formed from anthropogenic or biogenic precursors (Lack et al., 2013; Zhang et al., 2011). Such precursors like isoprene (Limbeck et al., 2003) and, lignin pyrolysis products (Gelencser et al., 2003; Hoffer et al., 2004) could yield BrC through heterogeneous or multiphase reactions in the presence of sulfuric acid or hydroxyl radicals. Although the source of BrC may varied with different locations and environment (e.g., urban, rural, forest, ocean, mountain), globally, biomass burning was identified as the most important source of BrC (Chung et al., 2012; Lack et al., 2012; Laskin et al., 2015).

BC, BrC, and mineral dust are the dominant light-absorbing substances in atmospheric aerosols. After deposited on the surface of snow and glaciers through dry/wet deposition processes, those light-absorbing substances could efficiently reduce the snow albedo (surface darkening), decrease the upwelling radiation, thereby accelerating snow melting (Flanner et al., 2007; Kaspari et al., 2015; Yang et al., 2015). A brief illustration of the sources, transport and deposition of BrC, as well its effects on the climate system is presented in Fig. 1.

The cryosphere, comprising snow, river and lake ice, sea ice, glaciers, ice shelves and ice sheets, and frozen ground, is crucial in the Earth's climate system (IPCC, 2014). The cryosphere is very sensitive to climate changes and anthropogenic activities. Currently, most efforts dedicated to the light-absorbing substances were focused on BC and dust, which were well documented in recent review literatures (Bond et al., 2013; Gertler et al., 2016; Wang et al., 2014). However, in this review, the state of art on the BrC in the cryosphere will be specifically summarized. Section 2 introduces the basic optical parameters of BrC, as well the current dataset available for the occurrence of BrC in aerosol and snow in the Artic, Antarctic, and mountain glaciers. Section 3 presents the current knowledge about the chemical speciation of BrC. Section 4 describes the radiative forcing of BrC in the atmosphere and snow, i.e., its impact on the cryosphere. Finally, research perspectives for the future research are proposed in Section 5.

2. Optical properties of BrC

The basic theory used to describe light absorption properties of BrC is the well-known power-law relationship. It can be defined as the following equation:

$$Abs_{\lambda} = K * \lambda^{-AAE}, \quad (1)$$

where Abs_{λ} (unit: Mm^{-1} or M^{-1}) refers to the absorption coefficient of BrC at wavelength λ (unit: nm). K is a constant. *AAE* indicates the wavelength dependence of light absorption.

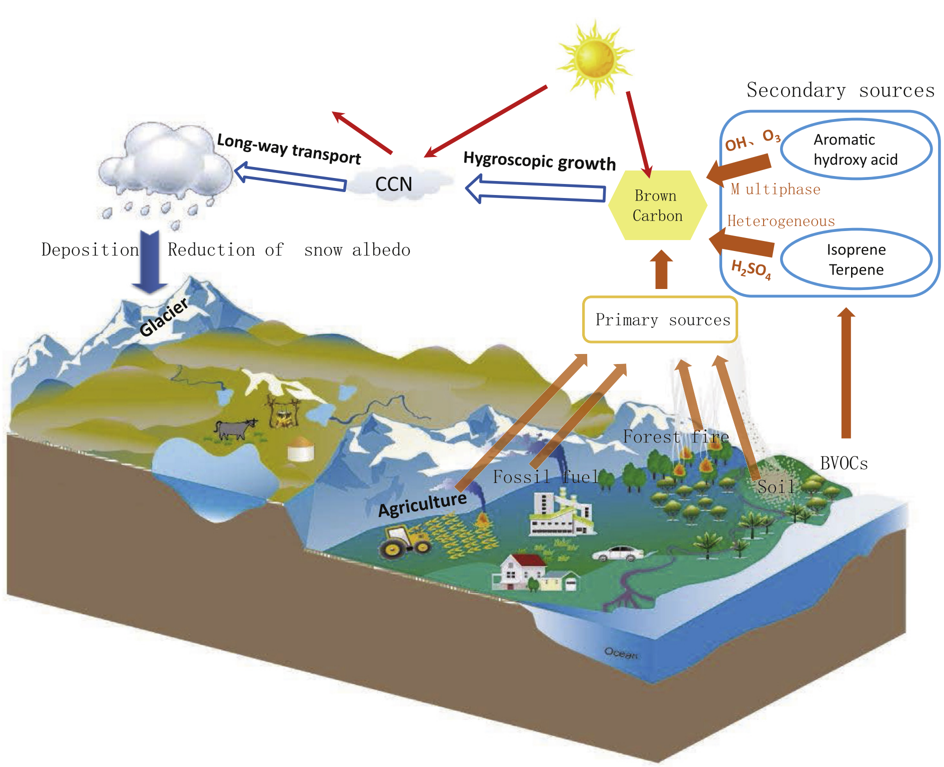

Fig. 1. Schematic overview on the sources, transport, and radiative forcing of BrC, as well as its impact on the snow and glaciers after deposition.