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Black carbon and the Himalayan cryosphere: A review

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HIGHLIGHTS

- Regional estimates of BC emissions in HKH differ greatly.
- Modeled concentrations of BC do not agree with observations.
- BC in HKH changes albedo (2–10%), surface forcing (0–28 W m^{-2}), and DRF (−2–7 W m^{-2}).
- We urge model verification, increased observation, and consistent measurement.

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ABSTRACT

The Himalayan cryosphere borders global hotspots for emissions of black carbon (BC), a carbonaceous aerosol with a short atmospheric lifespan and potentially significant impacts on glaciers and snow cover. BC in the atmosphere absorbs radiation efficiently, leading to localized positive climate forcing. BC may also be deposited onto snow and ice surfaces, thereby changing their albedo. This review presents up-to-date observational data of BC in the atmosphere and in snow and ice, as well as its effects on the cryosphere in the Hindu-Kush-Himalayan (HKH) region along the northern edge of South Asia. Significant spatial variation exists in the measured concentrations of BC in the atmosphere and cryosphere. A strong seasonal pattern exists, with highest concentrations in the pre-monsoon and lowest during the monsoon. Existing observations show bias towards certain areas, with a noticeable lack of measurements on the south side of the Himalaya. Significant uncertainty persists in the emissions estimates of BC in the HKH region, with a standard deviation of regional emissions from various emission inventories of 0.5150×10^{-9} kg m^{-2} s^{-1}, or 47.1% of the mean (1.0931×10^{-9} kg m^{-2} s^{-1}). This and other uncertainties, including poor model resolution, imprecision in deposition modeling, and incongruities among measurement types, propagate through simulations of BC concentration in atmosphere and cryosphere. Modeled atmospheric concentrations can differ from observations by as much as a factor of three with no systematic bias, and modeled concentrations in snow and ice can differ from observations by a factor of 60 in certain regions. In the Himalaya, estimates of albedo change due to BC range from about 2 to 10%, estimates of direct radiative forcing due to BC in the atmosphere from (−2)–7 W m^{-2}, and surface forcing estimates from 0 to 28 W m^{-2}, though every forcing estimate uses its own definition, with varying degrees of complexity and numbers of feedbacks. We find the most important course of further study to be model verification, enabled by increasing observational data and in this region and consistent measurement protocol.

1. Introduction

1.1. BC and the Himalayan cryosphere

The Himalaya, often referred to as the “water towers of Asia, are on the front lines of climate change. Global glacier loss since the early 1990s may be as much as 70% anthropogenic (Marzeion et al., 2014). While there are spatial variations, mass loss in the Hindu

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Kush-Himalaya (HKH) seems to be similar to or slightly less than other glacierized regions (Bolch et al., 2012). In general, the mass balance patterns are contrasted from the northwest to southeast portions of the HKH, due to prominent westerlies in the northwest and monsoon-driven climate in the southeast. However, the processes affecting Himalayan glaciers remain poorly understood (Bolch et al., 2012). The changes to snow and ice in the HKH region have implications that go deeper than climate: more than 1.3 billion people are supported by major rivers originating in the HKH region, and a large fraction of source water in areas can be attributed to snow and glacier melt water (Brown et al., 2014). Changes to the quantity and timing of seasonal melt has broad implications for the livelihood of a large portion of the Earth's population.

The HKH contains 52,000 glaciers, covering 60,000 km^2. Glaciers range in elevation from 2409 m a.s.l. (Indus basin) to 8806 m a.s.l. (Koshi basin) (ICIMOD, 2011). Maximum seasonal snow cover in the HKH region can exceed 1.79 million km^2, or 42.9% of the total land area (ICIMOD, 2011). This review focuses on the glacierized portion of this region, shown in Fig. 1.

Recently, the effects of black carbon (BC) on the cryosphere have attracted significant interest, as BC may be contributing to melt through various mechanisms, including atmospheric warming and albedo reduction from BC deposition on snow and ice surfaces (Ramanathan and Carmichael, 2008). The proximity of the HKH to some of the largest sources of BC and identified transport pathways (Bond et al., 2013) make this area particularly vulnerable. BC has been shown to be the second most climatically important pollutant behind only carbon dioxide, with total global emissions of 7500 Gg yr^{-1} (uncertainty range 2000–29000 Gg yr^{-1}) and an overall global climate forcing estimated to be 1.1 W m^{-2} with high uncertainty (0.17–2.1 W m^{-2}) (Bond et al., 2013). IPCC (2014) excludes cloud forcing, and estimates global forcing to be somewhat smaller, at 0.64 W m^{-2} (uncertainty 0.25–1.09 W m^{-2}). While the history of BC transport to the Himalaya has fluctuated over the last century, emissions and transport to the Himalaya are increasing in recent decades (Bond et al., 2013; Lu et al., 2012; Kaspari et al., 2011).

1.2. Study outlook

This review provides an update on current observational data of BC in the HKH and describes up-to-date mechanisms and modeling of the impact of BC on the Himalayan cryosphere. Various review papers have addressed BC in the cryosphere recently; Qian et al. (2015) admirably summarize observational techniques for BC in snow and ice and compile observations of BC in various areas (including the HKH). Bond et al. (2013) provide a comprehensive review of the global climate forcings due to BC. This review, however, will focus on BC in the HKH region specifically, and in some ways builds upon Bonasoni et al. (2012), which summarizes observations of BC in the HKH atmosphere and cryosphere but does not fully discuss transport, modeling, or effects on the cryosphere. Section 2 of this review defines BC and identifies the main mechanisms by which it may influence climate. Section 3 describes the regional and global emissions of BC, the major transportation pathways to the HKH, the current status of in situ observations in atmosphere and cryosphere, and the state of concentration modeling. Section 4 then discusses the current understanding concerning the effect of BC on the Himalayan cryosphere. In Section 5, we discuss knowledge gaps and recommendations for future research.

2. BC definitions and properties

Most broadly, "black carbon" (BC) is a qualitative description for particles that share certain properties relevant to atmosphere and climate. BC refers to carbonaceous aerosol formed during incomplete combustion, characterized by strong absorption of visible light and resistance to chemical transformation

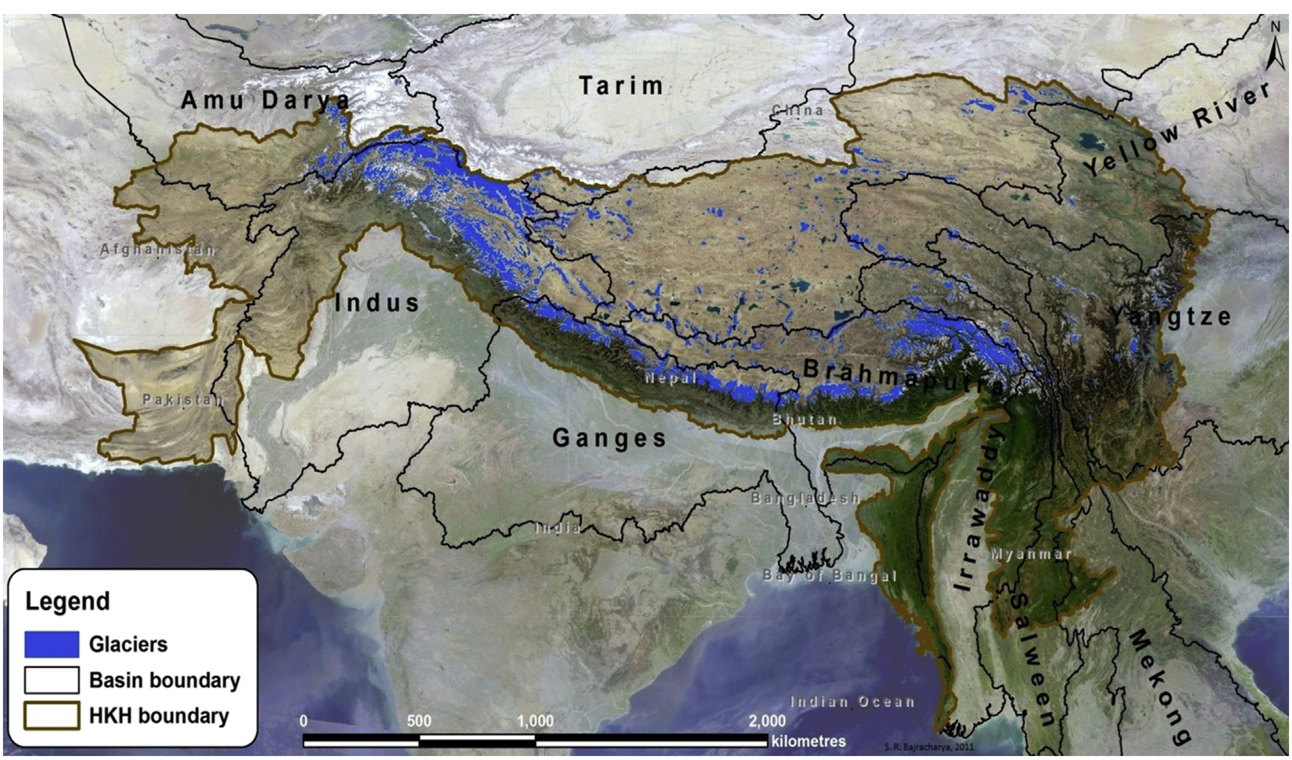

Fig. 1. Glaciers in the Hindu-Kush Himalayan (HKH) Region (ICIMOD, 2011).