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Research paper

The Himalayan cryosphere: A critical assessment and evaluation of glacial melt fraction in the Bhagirathi basin

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A B S T R A C T

The cryosphere constitutes an important subset of the hydrosphere. The Himalayan cryosphere is a significant contributor to the hydrological budget of a large river system such as the Ganges. Basic data on the cryosphere in the Himalaya is inadequate and also has large uncertainties. The data on glacial melt component in the Himalayan rivers of India also shows high variability. The Gangotri glacier which constitutes nearly a fifth of the glacierized area of the Bhagirathi basin represents one of the fastest receding, large valley glaciers in the region which has been surveyed and monitored for over sixty years. The availability of measurement over a long period and relatively small glacier-fed basin for the Bhagirathi river provides suitable constraints for the measurement of the glacial melt fraction in a Himalayan river. Pre- and post-monsoon samples reveal a decreasing trend of depletion of $\delta^{18}O$ in the river water from glacier snout (Gaumukh) to the confluence of the Bhagirathi river with the Alaknanda river near Devprayag. Calculations of existing glacial melt fraction (~30% at Rishikesh) are not consistent with the reported glacial thinning rates. It is contended that the choice of unsuitable end-members in the three component mixing model causes the overestimation of glacial melt component in the river discharge. Careful selection of end members provides results (~11% at Devprayag) that are consistent with the expected thinning rates.

1. Introduction

Frozen waters (snow and ice cover over land and sea, glaciers and ice caps, permafrost and seasonally frozen ground and solid water precipitation) are together termed as cryosphere (Dobrowolski, 1923). Two major facets of the cryosphere concern us. First, it is the storehouse of a major portion of the worlds freshwater in the form of frozen glaciers. Second, the cryosphere has a direct bearing on climate and its fluctuations through its influence on surface energy and moisture fluxes, clouds and precipitation, ocean and atmosphere circulations and hydrology. The two major domains where frozen freshwater is stored are the icecaps of Arctic and Antarctica. Outside these regimes, the Himalayan cryosphere spreads with in the geographic domain of India in an area of ~33,050 km^2 and provides ~8.6 × 10^6 m^3 of water annually (Dyurgerov and Meier, 1997).

In terms of the ice mass and its heat capacity, the cryosphere plays a significant role in the global climate system as it is the second largest storehouse of water after the ocean (Barry, 1987, 2002a). All parts of the cryosphere contribute to short-term climate changes, with permafrost, ice shelves and ice sheets also contributing to longer-term changes including the ice age cycles. Considering its implications on climate and sea level changes, the monitoring and evaluation of cryosphere regions and the climate change effects on the cryosphere are of crucial importance (IPCC, 2013). Such an impact study requires the availability of reliable basic data on cryosphere volumes and their seasonal variability. We critically assess the status of this information for the Himalaya and

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attempt to estimate a realistic glacial melt component in the discharge in the Bhagirathi basin.

2. The Himalayan cryosphere

Glaciers occupy about 10% of the Earth's land surface but hold roughly 77% of its fresh water. More than 96% of glacier ice lies in the Polar Region (Dyurgerov and Meier, 2005). The largest glacial cover outside the polar region ($\sim 116 \times 10^3$ km^2) is in the Indian Himalaya and the surrounding High Mountains of Asia (Dyurgerov, 2001), which together are termed as the 'third pole'.

There are 9575 glaciers spread across the Indian part of the Himalayas (Sangewar and Shukla, 2009), some of which form the perennial source of major rivers. Changes in glaciers are one of the clearest indicators of alterations in regional climate, since they are governed by changes in accumulation and ablation. The difference between accumulation and ablation or the mass balance is crucial to the health of a glacier. The Geological Survey of India has given details about Gangotri, Bandarpunch, Jaundar Bamak, Jhajju Bamak, Tilku, Chipa, Sara Umga Gangstang, Tingal Goh Panchi nala I, Dokriani, Chaurabari and other glaciers of Himalaya (Raina and Srivastava, 2008; Sangewar and Shukla, 2009) in the 'Glacial Atlas of India' besides documenting various aspects of the Himalayan glaciers covering their origin, classification, landforms, snow cover assessments and basin wise inventory.

Since glaciers are strongly controlled by precipitation and the Himalaya depict variability of climate (and weather) across its length, a west to east zonation can form a starting point of analyzing glacier behavior (Fig. 1). The western domain experiences strong winter precipitation (Karakoram and the western Himalayas) while summer monsoon precipitation is intense over central and eastern Himalaya (UNEP, 2012). The westernmost Zone 1 (mainly Afghanistan) has 'westerlies' dominated precipitation and the glaciers grow mainly by winter snow accumulation. In this zone the glacier disintegration is minimal and the retreat rates are slow to neutral. This grades into Zone 2 (Karakoram and western Himalayas) where there is spatial variability on account of merging influences of the summer monsoon and the westerlies, less intense melting and more intense sublimation, relatively less debris cover and high sensitivity to wind and precipitation on account of being in the marginal zone. The central Himalayas located in Zone 3 (India, SW Tibet, western Nepal) have increased and intense melting, higher debris cover, higher proportion of soot effect on ice surfaces and higher retreat rates of the glaciers (Bhambri and Bolch, 2009). The easternmost Zone 4 is dominated by the summer monsoon influence and the glacier growth is mainly by summer snow accumulation. The glacier disintegration and growth of glacial lakes are significantly higher in this zone. The summer monsoon causes an elevated heat pump effect and glaciers are most unstable in this zone. Complexity of the variability with an underlying geographic control has also been recognized elsewhere (Scherler et al., 2011).

2.1. Ice volume

Estimates of the ice volume in the Himalayan cryosphere vary considerably depending on the quality of remote sensed data and the model adopted. To illustrate considering slope dependent ice thickness the volume works out to $\sim$2300 km^3 while it varies between 3600–6500 km^3 considering volume area scaling (Bolch et al., 2012). Ice thickness is an important factor in this context which is mostly lacking for the glaciers in the Indian Himalayan region and only sparsely available for the Himalayan glaciers outside India's geographic boundaries. Gades et al. (2000) reported maximum ice thicknesses of 160 and 450 m for Lirung and Khumbu glaciers in Nepal (mean value $\sim$125 m) while lower 1/3rd of Zuoqiupu glacier in Tibet averages around 125 m (Aizen et al., 2002). In a temporal (2004–2007) IRS LISS III based study, the Indian Space Research Organization (ISRO) mapped a total of 16,049, 6237 and 10,106 glaciers in Indus, Ganges and Brahmaputra basins with the glaciated areas in these basins estimated as 32,246, 18,393 and 20,543 km^2 respectively. These estimates lead to total glaciated area in these three basins to be 71,182 km^2 for 32,392 glaciers (ISRO report, 2010). Earlier a total of 16,117 glaciers constituting a total of 32,182 km^2 area and 3421 km^3 ice volume were estimated for the Ganga, Brahmaputra and Indus basins (Qin, 1999). Considering an area of 40,800 km^2 (22,800 km^2 for the Himalayas and 18,000 km^2 for Karakoram, Bolch et al., 2012) and an average thickness of

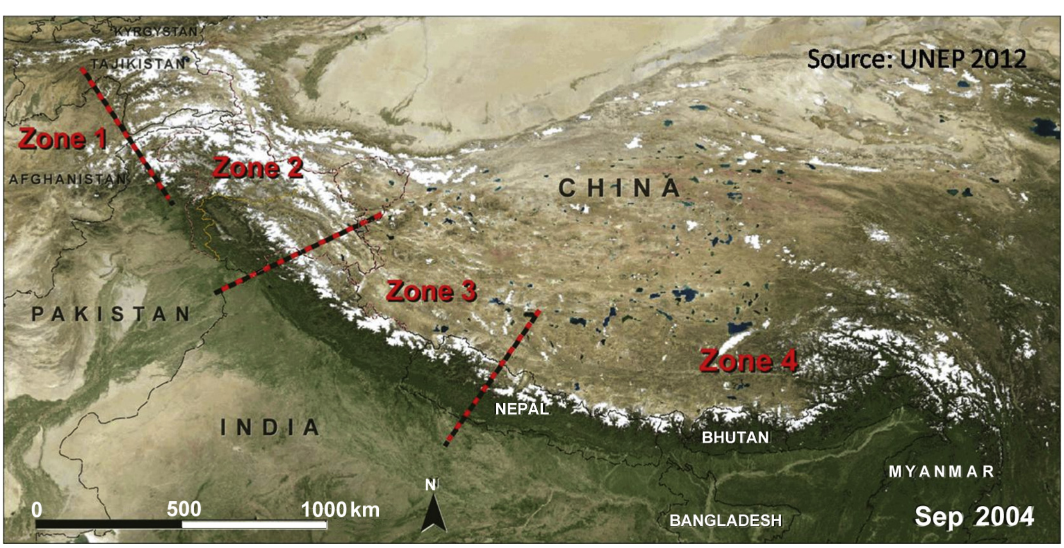

Figure 1. Map showing 4 major climatic zones in Himalayas and adjacent regions (UNEP, 2012). Zone 1—represents mainly Afghanistan, westerlies dominated, with in this zone glaciers grow mainly by winter snow accumulation. Zone 2—this zone includes Karakoram and western Himalaya, both westerlies and summer monsoon. Zone 3—Central Himalaya zone include parts of India, SW Tibet and western Nepal, with in this zone glaciers are highly debris covered and retreat rate is high. Zone 4—easternmost zone, summer monsoon is dominated with in this zone and glaciers are growing by summer snow accumulation and are most unstable.