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Cumulative and relative impact of aerosol species on snowmelt runoff from the Hindu Kush Himalayan glaciers

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Himalayan glaciers are a significant contributor to the global supply of snowmelt water and serve as the primary source for major rivers in South Asia. In this study, we have evaluated the effect of aerosol species on glaciers in the Hindu Kush Himalayan (HKH) region and identified the glaciers most affected, as well as the relative and cumulative impact of different aerosol species, including black carbon (BC). We estimate the surface concentration of organic carbon (OC), sulfate (Sul), and dust aerosols in the HKH region. We also measured the concentration of these aerosol species in the snow of nine glaciers and investigated their influence on annual glacier runoff. Furthermore, we identified the source regions and sectors that are responsible for aerosol loading in the region. In this study, we combined free-running ($freesimu$) and constrained ($constrsimu$) aerosol simulations with an atmospheric general circulation model, an aerosol-snow radiative interaction model, and a novel hypsometric glacier energy mass balance model. The $freesimu$ estimates of aerosol species concentrations were more accurate at high-altitude (HA) stations than at low-altitude (LA) stations. However, the $constrsimu$ estimates performed significantly better at LA stations. A hotspot location of high concentration of aerosol species was identified near Manora Peak, located almost at a central location in the HKH region. Although the concentration of other aerosol species was 2 to 5 times higher than BC (< 70 μg kg^{-1}), they caused significantly less reduction in snow albedo than BC over the HKH glaciers. The cumulative snow albedo reduction (SAR) due to all aerosol species, including BC, was estimated to be as much as 7 to 8% over the Gangotri and Chorabari glaciers, with Gangotri being one of the most important glaciers responsible for the formation of the Ganges River. The Pindari glacier was found to have the highest annual runoff increase (ARI) of all glaciers studied despite having a lower aerosol-induced SAR than the Gangotri and Chorabari glaciers. Five of the nine glaciers (Pindari, Sankalpa, Milam, Gangotri, and Chorabari) had ARI higher than 300 mm w.e. y^{-1} due to aerosol-induced SAR. Glaciers located in the HKH region were found to be two to three times more sensitive to SAR than cold Tibetan glaciers. This, combined with the recent increase in temperature due to global warming, paints a worrying picture for the future. Analysis of the fractional contribution of aerosol species revealed that BC aerosols, although having a less than 15% contribution to the total aerosol loading, contribute 55 to 70% of total aerosol-induced ARI, followed by dust (20 to 30\%), Sul and OC aerosols respectively. Analysis of region- and source-tagged simulation data revealed that the main sources of OC and Sul aerosols south of 30°N were biomass burning and open burning (for OC), and fossil fuel burning (for Sul) from the nearby Indo-Gangetic plain. For regions located north of 30°N and for dust aerosols, the main contributor was identified as long-range

intercontinental transport from far-off regions of Africa and West Asia.