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Simulations of black carbon (BC) aerosol impact over Hindu-Kush Himalayan sites: validation, sources, and implications on glacier runoff

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Absorbing aerosols such as black carbon (BC) affects the cryospheric equilibrium by altering the ablation rate of snow. The influence of the albedo change on the glacial mass balance due to excess and earlier snow melting, and thereby an earlier glacier runoff, is expected to impact the downstream hydrology. This impact is specifically of concern for the Hindu Kush Himalayan (HKH) region as the Himalayan glaciers are the source of major rivers in South Asia, namely Ganges, Indus, Yamuna, and the Brahmaputra. While the measured data may serve as location and time-specific information, the ability of coarse-gridded models to adequately simulate the snow depth and thereby the BC concentration in snow and atmospheric BC radiative forcing is limited. In order to spatially map the estimates of atmospheric BC concentration and BC concentration in snow as adequately as possible, including the corresponding snow albedo reduction (SAR) over the HKH region, an integrated approach merging the relevant information from observations with a relatively consistent atmospheric chemical transport model estimates is applied in the present study. These estimates were based on free-running aerosol simulations (*freesimu*) and constrained aerosol simulations (*constrsimu*) from an atmospheric general circulation model, combined with numerical simulations of glacial mass balance model. BC concentration estimated from freesimu performed better over higher altitude (HA) HKH stations than that over lower altitude (LA) stations. The estimates from constrsimu mirrored well the measurements when implemented for LA stations. Estimates of the spatial distribution of BC concentration in the snowpack (BC_C) over the HKH region led to identifying a hot-spot zone located around Manora peak. Among glaciers over this zone, BC_C (> 60 µg kg^{-1}) and BC-induced SAR (≈5%) were estimated explicitly being high during the pre-monsoon for Pindari, Poting, Chorabari, and Gangotri glaciers. The rate of increase of BC_C in recent years (1961-2010) was, however, estimated being the highest for the Zemmu glacier. Sensitivity analysis with glacial mass balance model indicated the increase in annual runoff (ARI) from debris-free glacier area due to BC-induced SAR corresponding to BCC estimated for the HKH glaciers was 4%-18%, with the highest being for the Milam and Pindari glaciers. The rate of increase in annual glacier runoff per unit BC-induced SAR was specifically high for Milam, Pindari, and Shunkalpa glacier. Further analysis is carried out for other significant aerosol species, both anthropogenic and natural by origin (e.g. Sulfate, Organic carbon (OC) and

Dust). Comparison of relative impact of aerosol constituents on the melting of snow from the glaciers, as well as the combined effects are estimated. The estimated ARI taking into account the effect of all the aerosols found to be significantly higher than in the case of only BC. The source-specific contribution to atmospheric BC aerosols by emission sources led to identifying the potential emission source being primarily from the biofuel combustion in the Indo-Gangetic plain south to 30° N, and open burning in a more remote region north to 30° N.