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Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate

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The Tibetan Plateau (TP) has long been identified to be critical in regulating the Asian monsoon climate and hydrological cycle. In this modeling study a series of numerical experiments with a global climate model are designed to simulate radiative effect of black carbon (BC) and dust in snow, and to assess the relative impacts of anthropogenic CO_2 and carbonaceous particles in the atmosphere and snow on the snowpack over the TP and subsequent impacts on the Asian monsoon climate and hydrological cycle. Simulations results show a large BC content in snow over the TP, especially the southern slope. Because of the high aerosol content in snow and large incident solar radiation in the low latitude and high elevation, the TP exhibits the largest surface radiative flux changes induced by aerosols (e.g. BC, Dust) in snow compared to any other snow-covered regions in the world.

Simulation results show that the aerosol-induced snow albedo perturbations generate surface radiative flux changes of 5-25 W m-2 during spring, with a maximum in April or May. BC-in-snow increases the surface air temperature by around 1.0oC averaged over the TP and reduces spring snowpack over the TP more than pre-industrial to present CO_2 increase and carbonaceous particles in the atmosphere. As a result, runoff increases during late winter and early spring but decreases during late spring and early summer (i.e. a trend toward earlier melt dates). The snowmelt efficacy, defined as the snowpack reduction per unit degree of warming induced by the forcing agent, is 1-4 times larger for BC-in-snow than CO_2 increase during April-July, indicating that BC-in-snow more efficiently accelerates snowmelt because the increased net solar radiation induced by reduced albedo melts the snow more efficiently than snow melt due to warming in the air.

The TP also influences the South (SAM) and East (EAM) Asian monsoon through its dynamical and thermal forcing. Simulation results show that during boreal spring aerosols are transported by southwesterly, causing some particles to reach higher altitude and deposit to the snowpack over the TP. While BC and Organic Matter (OM) in the atmosphere directly absorb sunlight and warm the air, the darkened snow surface polluted by BC absorbs more solar radiation and increases the skin temperature, which warms the air above through sensible heat flux. Both effects enhance the upward motion of air and spur deep convection along the TP during the pre-monsoon season, resulting in earlier onset of the SAM and increase of moisture, cloudiness and convective precipitation over northern India. BC-in-snow has a more significant impact on the EAM in July than CO_2 increase and carbonaceous particles in the atmosphere. Contributed by the significant increase of both sensible heat flux associated with the warm skin temperature and latent heat flux associated with increased soil moisture with long memory, the role of the TP as a heat pump is elevated from spring through summer as the land-sea thermal contrast increases to strengthen the EAM. As a result, both southern China and northern China become wetter, but central China (i.e. Yangtze River Basin) becomes drier - a near-zonal anomaly pattern that is consistent with the dominant mode of precipitation variability in East Asia.

The snow impurity effects reported in this study likely represent some upper limits as snowpack is remarkably overestimated over the TP due to excessive precipitation. Improving the simulation of precipitation and snowpack will be important for improved estimates of the effects of snowpack pollution in future work.