What do we know the snow darkening effect over Himalayan glaciers?

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Role of snow darkening effect on the Himalayan glaciers

The atmospheric absorbing aerosols such as dust, black carbon (BC), organic carbon (OC) are now well known warming factors in the atmosphere. However, when these aerosols deposit onto the snow surface, it causes darkening of snow and thereby absorbing more energy at the snow surface leading to the accelerated melting of snow. If this happens over Himalayan glacier surface, the glacier meltings are expected and may contribute the mass balance changes though the mass balance itself is more complicated issue. Glacier has mainly two parts: ablation and accumulation zones. Those are separated by the Equilibrium Line Altitude (ELA). Above and below ELA, snow accumulation and melting are dominant, respectively. The change of ELA will influence the glacier disappearance in future. In the Himalayan region, many glacier are debris-covered glacier at the terminus (i.e., in the ablation zone). Debris is pieces of rock from local land and the debris-covered parts are probably not affected by any deposition of the absorbing aerosols because the snow surface is already covered by debris (the debris-covered parts have different mechanism of melting). Hence, the contribution of the snow darkening effect is considered to be most important "over non-debris-covered part" of the Himalayan glacier (i.e., over the snow or ice surface area). To discuss the whole glacier retreat, mass balance of each glacier is most important including the discussion on glacier flow, vertical compaction of glacier, melting amount, etc. The contribution of the snow darkening is mostly associated with "the snow/ice surface melting". Note that the surface melting itself is not always directly related to glacier retreats because sometimes melt water refreezes inside of the glacier. We should discuss glacier retreats in terms of not only the snow darkening but also other contributions to the mass balance.

1. What are the historical trends in black carbon and dust deposition in the Himalayan region?

The historical trends of dust and BC deposition can be discussed only from ice cores which are obtained over the Himalayas. A limited number of ice cores have been drilled over the Himalayas and Tibetan Plateau thus far. Some results indicated the dust and BC increases recently but the magnitude of concentration varies at each location. BC concentrations from some ice cores were obtained from different analytical methods and direct comparisons among the ice cores still have some uncertainties. Some ice cores discussed the positive relationship between atmospheric warming and dustiness in this region. The recent increase of BC from an ice cores was discussed with the recent BC emission increase but not fully explained recent BC fluctuations.

2. What are the spatial and temporal distributions of black carbon and dust?

Spatial and temporal variation of BC and dust deposition is a very important factor in determining the extent and magnitude of snowmelt effects over the Himalayan region. The deposition of dust and BC on snow surface also depends on the sources of pollutants and regional transport pathways, and deposition conditions. For example, aerosol loading over the Indo-Gangetic Plains, which is one of the main sources of atmospheric pollution residing in the vicinity of the Himalayas, is quite variable in terms of BC and dust composition from west to east of its vast domain, south of the Himalayas. In terms of temporal distribution of dust and BC in snow mostly limited within some sporadic snow samplings over glacier including ice core, surface snow, and precipitated snow. The timing of snow sampling also affects the discussion on the concentration in snow. If we sampled from the dust layer mostly corresponding to spring season, dust and BC concentrations get higher but lower in non-dust layer samples. Hence, surface snow samples are not always representative at the location and we should take snow samples or ice core samples at least covering one year to discuss this point. The spatial information on dust and BC can only be obtained from satellite data or model simulations. But because of the complicated topography satellite data over the Himalayas is still difficult to quantitatively discuss and very limited available for its assessment. Hence, currently regional or global model simulation is only useful over the Himalayas. However, there are a few model can consider the snow darkening effect in their land surface models and also still less observations to validate the model results (i.e., model uncertainty is very large).

3. How much albedo reduction is due to black carbon and dust or regional variation?

Currently it is difficult to separate the dust and black carbon contributions on snow albedo reductions in terms of in situ observations except for model simulations. Moreover, the topography in the Himalayas is very complicated and many factors such as instrument error, shadow effect, slope inclination, snow grain size, solar radiation condition, etc. affect the snow albedo variations. It is very difficult to directly say that a few percent change of snow albedo regarding to the snow darkening effect or not even if some measurements are available. Even if we carry out in situ measurements on snow albedo, always sophisticated snow albedo models are necessary to discuss those absorbing aerosol contributions. Some limited estimates on the snow albedo reduction due to BC contamination suggested that up to 6% of snow albedo reductions are possible based on sporadic snow samples and the estimate from pre-monsoon BC deposition onto the snow surface. But the estimates still include much uncertainty because of their simple estimates. Detailed in situ snow albedo measurements with sophisticated snow albedo model simulations are necessary over the Himalayan glacier in future studies. From some results of spatial simulations from the National Center for Atmospheric Research (NCAR) Community Atmosphere Model, version 3 (CAM3) and the NASA Goddard Earth Observing System version 5 (GEOS-5) considering the snow darkening effect in their land surface model, the snow albedo reductions on the Himalayan snow of more than 3% in visible snow albedo is possible during pre-monsoon season. This result is consistent with the range from the simplified studies above. However, the NCAR CAM3 and the NASA GEOS-5 results are also still "not well validated" over the Himalayas and future observations are necessary to validate their results.

4. How much anomalous glacier melt or runoff could be caused by such an albedo reduction?

This question also can only be addressed by model simulations currently. In addition, most of the global and regional model only can discuss the seasonal snowpack changes over the glacier surface because of not considering glacier mass balance in each simulation grid point. Therefore, even if we can consider some snow melting due to the snow darkening effect, whole mass balance change for each Himalayan glacier due to the darkening effect is currently difficult to discuss from regional or climate models. Combining in situ observations, the simulations of glacier mass balance model for each glacier, satellite data analyses, regional or global model simulations is necessary to assess glacier melt or runoff from each Himalayan glacier in future studies.

5. What are the nature and extent of black carbon and dust contributions to regional climate change?

Most of those are expected due to the changes of heat balance in the atmosphere and the surface only discussed by model simulations. Heating the atmosphere at the foothills of the Himalayas in pre-monsoon period strengthen the vertical motion of the air changing the precipitation patterns in monsoon season. Note that this feedback has been only discussed from some limited number of climate model simulations. The feedback due to the heat balance change is still hard to validate from observations. Overall, climate modeling has demonstrated that absorbing aerosols over South Asia can potentially induce changes on seasonal as well inter-annual scales related to monsoon precipitation variations.