Mineral dust characterization over the Himalayan cryosphere using space-borne lidar depolarization observations

N. B. Lakshmi* [(1)], S. Suresh Babu [(1)], Vijayakumar S. Nair [(1)]

(1) Space Physics Laboratory, Vikram Sarabhai Space Centre, Indian Space Research Organization,
Thiruvananthapuram, Kerala, India

Abstract

Present study represents the first time quantitative characterization of mineral dust aerosols based on depolarization observations of the space-borne lidar CALIOP (Cloud Aerosol Lidar with Orthogonal polarization) over the Himalayas. Dust loading is dominant during pre-monsoon season and weak during winter/summer monsoon seasons. Average dust extinction coefficient over a period of 11 years (2006 - 2017) shows regionally and seasonally distinct characteristics over the Himalayas. Dust loading is observed highest over the Mid Himalayas. Over the mid-Himalayas almost 10 fold increase is observed from winter to pre-monsoon. Dust aerosols mostly occur in the form of polluted dust (dust mixed with anthropogenic aerosols) during pre-monsoon season. The contribution of polluted dust to the total aerosols over western, mid and eastern Himalayas are estimated to be 63%, 67% and 57% respectively. A significant amount of dust aerosols (12.5 mgm^{-2}day^{-1} over mid Himalayas) are deposited through dry deposition over the Himalayas which is capable of producing enhanced snow melting and reduction in snow cover over the Himalayan cryosphere.

1 Introduction

Aerosol characterization over Himalayas assumes importance mainly due to two processes, (1) Reduction in snow albedo (snow darkening) due to the deposition of insoluble light absorbing aerosols (such as black carbon or mineral dust) over the snow surface which accelerates snow melting [1] and (2) the enhanced radiative forcing of absorbing aerosols over highly reflective snow surface[2]. Radiative forcing due to absorbing aerosols critically depend on the underlying surface. High albedo of snow surface strengthens their radiative forcing efficiency in the atmosphere by reflecting more radiation thereby increasing the probability of interaction between aerosols and radiation which leads to enhanced absorption. Over the Himalayas, along with global warming, the enhanced surface warming is attributed to the aerosol induced heating of the atmosphere and reduction of snow albedo by the absorbing aerosols [2]. Thus it is important to have quantitative characterization of the altitude structure of aerosols over the Himalayas in order to address the role of elevated aerosols in enhanced radiative effects and snow melting process over the Himalayas.

Being an absorptive species, dust aerosols has enhanced radiative effects over the cryosphere and its deposition over the snow surface accelerates snow melting through snow albedo-feedback mechanism. Though the effects of mineral dust aerosols on the snow albedo and snow melting over the Himalayas have been investigated through modeling studies, detailed characterization based on observational datasets are limited over this region. Overall understanding on the radiative implications of mineral dust aerosols on the Himalayas is actually hindered by the lack of quantitative estimation of mineral dust using direct experimental observations. Present paper characterize mineral dust aerosols, it's spatial, vertical and columnar variations and mass flux of dust aerosols deposited over the region through dry deposition over the Himalayas using polarization resolved observations of Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) on board Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO).

2 Methodology and dataset

2.1 Study Region

The topography of the Himalayas is highly complex with high mountain ranges and valleys with drastically varying surface elevation. While western part of the Himalayas constitute high altitude mountains, mid/eastern Himalayas have lower surface elevations. Based on the topography and glacier area the entire Himalayas is divided into three sub-regions of major river basins (Indus, Ganges and Brahmaputra) for the regional characterization of aerosols (following [3]). They are (1) western Himalayas (including Karakoram), (2) mid-Himalayas, and (3) eastern Himalayas as shown in figure 1.

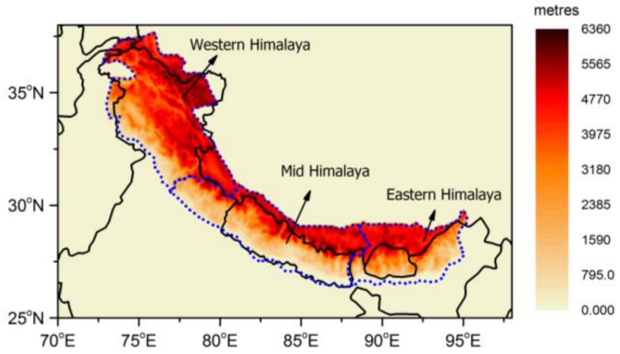

Figure 1 – Study regions are denoted with blue dotted contours and color variation indicates the surface elevation in metres.

The color variation represents the surface elevation above mean sea level (amsl) over the Himalayas. The study regions, western Himalayas (including Karakoram), mid-Himalayas and eastern Himalayas, are with a mean elevations of 3.7 km, 2.6 km and 2.8 km respectively and the magnitude of aerosol optical depth varies drastically with altitude. Northwesterly winds prevails over the Himalayan region throughout the year. 75% of the daily back-trajectories reaching Himalayas during a typical year are originated from the western land mass.

2.2 CALIOP

One of the major challenges in the retrieval of aerosols with passive remote sensing over the Himalayas is the highly varying enhanced surface contribution to the radiance received by the satellite from the highly reflecting snow surface. CALIOP overcome this difficulty through the active probing of the atmosphere and retrieves information from the altitude resolved back scattered signal of the atmosphere. In addition CALIOP measures polarization resolved back-scatter radiation at 532nm and provide vertical profiles of particulate depolarization Ratio (PDR) of the particles in the atmosphere. PDR indicates relative dominance of non-spherical particles in the aerosol system. Dust being highly non-spherical, has distinct depolarization ratio that enable to separate dust from a mixture of dust and nondust particles based on the assumption of a simple two-component (dust and non-dust particles) aerosol model. Following [4], simultaneous observations of vertically resolved depolarization ratio and aerosol back-scattering coefficient are used to estimate the dust back-scattering fraction (f_d) which is the ratio of dust backscatter coefficient (β_d) to the total back-scattering coefficient (β). f_d can be written as a function of measured depolarization ratio (δ), depolarization ratio of dust (δ_d=0.25) and that of nondust aerosols (δ_{nd}=0.045) as given in equation (1).

$$f_d = \frac{\beta_d}{\beta} = \frac{(\delta - \delta_{nd})(1+\delta_d)}{(1+\delta_d)(\delta_d - \delta_{nd})} \qquad (1)$$

The product of f_d and total back-scattering coefficient (β) gives the dust back-scattering coefficient (β_d) and the dust extinction coefficient (σ_d) is obtained as the product of β_d and dust lidar ratio (S_d=44sr), as given below

$$\sigma_d = S_d \times \beta_d \qquad (2)$$

Since dust extinction coefficient is retrieved from PDR measurements, total backscattering coefficient, and other a priori information like depolarization ratio of dust (δ_d), that of non-dust aerosols (δ_{nd}) and dust lidar ratio (S_d), uncertainty involved in the assumption of a single lidar ratio (as in CALIOP lidar ratio selection algorithm) for different mixtures of dust-nondust, is minimized.

3 Results and discussion

The monthly mean vertical profiles of aerosol back-scattering coefficient measured by CALIOP during 2006 to 2017 over the three different regions of the Himalayas are shown in figure 2.

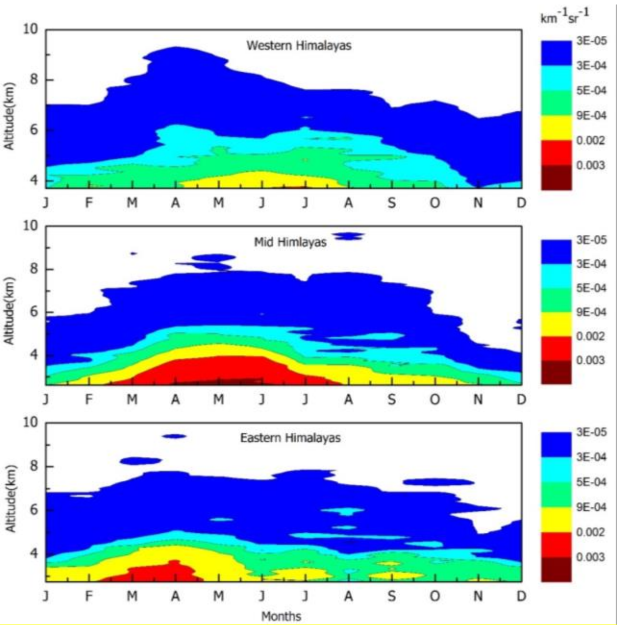

Figure 2 - Annual variation of vertically resolved aerosol back-scattering coefficient (CALIOP) over the western, mid and eastern Himalayas averaged for the period 2006–2017.

Aerosol vertical distribution shows distinct regional pattern over the Himalayas. Aerosol loading is lowest over the western Himalayas and highest over the Mid Himalayas. Prevailing westerly facilitate the transport of convectively lifted particles from the regions west of Himalayas during pre-monsoon season. Still aerosol loading is observed over the western Himalayas is low, which can be attributed to its high surface elevation, and enhanced precipitation rate during early pre-monsoon months. Over the Mid Himalayas, aerosol loading is found to be highest compared to the west and eastern Himalayas with mean back-scattering coefficient exceeding 0.003 km^{-1}sr^{-1} at ~ 3 km during April-June owing weak precipitation rates that makes aerosol wet scavenging less effective over this region.

Aerosols advected from the western arid regions can carry aerosols rich in mineral dust. The annual variation of the altitude distribution of dust extinction coefficient estimated using CALIOP depolarization observations during 2006 to 2017 over western, mid and eastern regions of the Himalayas is shown in figure 3. Dust activity starts at the month of February over the study regions. Seasonal variation in dust loading is similar to total aerosol loading over the Himalayas though effect of wet scavenging associated with the monsoon rainfall is predominantly shown by dust aerosols with a sudden drop in dust concentration during July. Effect of monsoon induced aerosol depletion starts during June over the eastern Himalayas and from July in the mid Himalayas. The dust extinction coefficient peaks during the month of May over western and mid Himalayan regions where the dust reaches as high as 6 km amsl during this period. Over eastern Himalayas, dust extinction coefficient peaks during the month of April where the dust influence is seen up to ~5 km amsl.

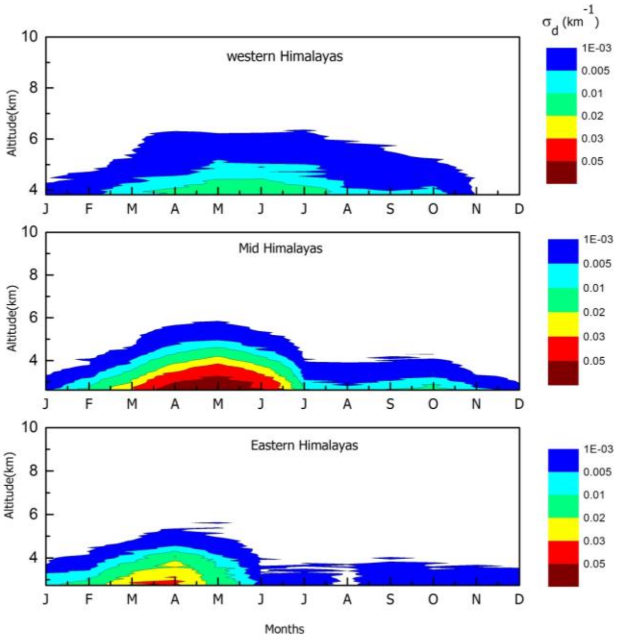

Figure 3 – Annual variation of the vertically resolved monthly mean dust extinction coefficient over the western, mid and eastern Himalayas above mean elevation averaged during the period 2006 – 2017.

Western Himalayas which are close to source regions in the west, shows comparatively less dust loading compared to mid/western Himalayas. Dust loading during winter is negligibly small. Mid-Himalayas shows the highest dust loading with almost 10 fold increase from winter to pre-monsoon season. Dust loading spreads up to 5 to 6 km over the Himalayas during pre-monsoon (σ_d >1Mm^{-1}). Though the magnitude of dust optical depth is smaller at this altitude range, given the high availability of radiation from the bright surface and lower number concentration due to pristine environment along with atmospheric thinning, can lead to higher heating rate at this altitude range.

Figure 4 shows the percentage occurrence of pure dust, polluted dust, and non-dust over the study regions. About 55% (east) to 65 % (mid) of the aerosols over Himalayas are characterized as polluted dust. In mixed state, absorption characteristics of dust aerosols can significantly increase. [5] studied dust absorption characteristics by estimating dust induced depression in terrestrial infrared radiation and showed that pure dust originated over desert regions is less absorbing than that transported to other locations having anthropogenic activities are significantly more absorbing than pure dust aerosols. Here polluted dust represents the case where the scattering volume with dust fraction varying from 1% to 99%. 25% to 35% of the aerosols are mixed aerosols with more than 50% of mineral dust as indicated by the grey bar (diagonal pattern).

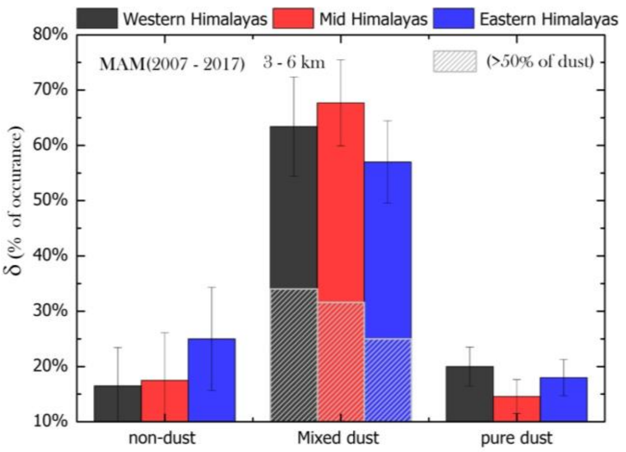

Figure 4 – Percentage occurrence of pure dust, polluted dust, and non-dust over the study regions as measured by CALIOP within 3 - 6 km amsl over the study regions during MAM of 2007 to 2017.

Snow darkening effect of mineral dust aerosols is still unexplored as quantitative estimate of mineral dust deposition on snow surface over the Himalayas is very limited. Near surface dust mass concentration (M_d) is estimated as the product of CALIOP derived dust extinction coefficient (σ_d) and dust mass extinction efficiency (σ*) for pre-monsoon season during which dust loading is observed to be the highest. Using mass absorption cross-section (σ*) value of 0.37 m^{2}gm^{-1}, dust mass concentration close to surface is estimated over the Himalayas. Deposited mass flux of dust through dry deposition is estimated as the product of dust mass concentration and deposition velocity of dust particles. Dry deposition flux is estimated for dust deposition velocity varies from ~ 0.08 cm/s to 0.2 cm/s and the average flux is represented in figure 5. Error bar represents the possible variability due to assumed deposition velocity.

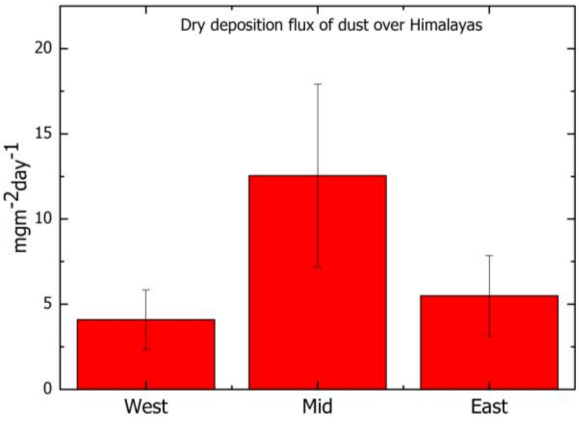

Figure 5. Dust mass flux on the surface due to dry deposition over the Himalayas. Error bar represent the variability in mass flux due to uncertainty in the assumed deposition velocity of dust aerosols.

4. Radiative Implications

Warming induced by the elevated aerosols can enhance to snow melting mechanism through different physical mechanisms. Firstly it can effectively transfer from the atmosphere to the surface as sensible heat flux and promote snow melting, and secondly it can affect conditions favouring snow formation and reduce rate of snowfall on the surface. [6] carried out aerosol profiling using micro-pulse lidar and estimated aerosol radiative forcing of 25 Wm^{-2} with a heating rate of about 1 $Kday^{-1}$ within 2 km from the surface. With numerical experiments, [2] associates accelerated snow melt with enhanced warming of the atmosphere over the Tibetan Plateau and Himalayas, induced by absorbing aerosols accumulated in the IGP and foothills of Himalayas during this season. The effective transfer of sensible heat flux from the atmosphere to the land set off the snow melting process which is accelerated by an evaporation–snow–land feedback associated with the increase in atmospheric moisture over the Tibetan Plateau induced by the EHP effect. The warmer atmosphere with more moisture reduces the effective transfer of sensible/latent heat fluxes from the surface to the atmosphere, instead contributes to snow melting which accelerates the process over the Tibetan Plateau and the Himalayas. Presence of light absorbing particles in the snow reduces snow albedo there by counteracts the dimming effect induced by aerosols. Model simulations shows that, snow-darkening effect due to mineral dust aerosols weakens the Indian monsoon rainfall while the direct radiative forcing strengthens it [7]. To have a more complete understanding on impact of aerosols on cryosphere, it is necessary to address the coupling of radiative balance of atmosphere and snow using radiative transfer computations and regional models which forms the future scope of this study.

4 Summary

Aerosol loading shows seasonally distinct regional pattern over the Himalayas. Overall understanding on the radiative implications of mineral dust aerosols on snow albedo and snow melting is actually hindered by the lack of quantitative estimation of mineral dust using direct experimental observations. Present chapter attempted to characterise mineral dust aerosols, it's spatial, vertical and columnar variations over the Himalayas and estimated the mass flux of dust aerosols deposited over the region through dry deposition. Dust aerosol loading shows regionally and seasonally distinct characteristics over the Himalayas with highest loading over the Mid Himalayas during pre-monsoon season. During this season, the entire Himalayas is significantly influenced by polluted dust where the contribution of polluted dust to the total aerosols over western, mid and eastern Himalayas are 63 %, 67 % and 57 % respectively. A significant amount of dust aerosols (12.5 $mgm^{-2}day^{-1}$ over mid Himalayas) are deposited through dry deposition over the Himalayas which is capable of producing enhanced snow melting and reduction in snow cover over the Himalayan cryosphere.

6 Acknowledgements

This study was carried out as part of Aerosol Radiative Forcing over India Project of ISRO GBP. S. S. Babu would like to thank the Department of Science Technology, Government of India, New Delhi, for Swarna Jayanti Fellowship. The CALIPSO data are obtained from the LARC Atmospheric Sciences Data Center through their website at http://eosweb.larc.nasa.gov/.

7 References

[1] M. G. Flanner et al., “Springtime warming and reduced snow cover from carbonaceous particles,” Atmos. Chem. Phys., vol. 9, no. 7, pp. 2481–2497, 2009.

[2] W. K. M. Lau, M. K. Kim, K. M. Kim, and W. S. Lee, “Enhanced surface warming and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols,” Environ. Res. Lett., vol. 5, no. 2, p. 025204, Apr. 2010.

[3] T. Bolch et al., “The State and Fate of Himalayan Glaciers,” Science, vol. 336, no. 6079, pp. 310–314, 2012.

[4] N. Sugimoto and C. H. Lee, “Characteristics of dust aerosols inferred from lidar depolarization measurements at two wavelengths,” Appl. Opt., vol. 45, no. 28, p. 7468, 2006.

[5] S. Deepshikha, S. K. Satheesh, and J. Srinivasan, “Regional distribution of absorbing efficiency of dust aerosols over India and adjacent continents inferred using satellite remote sensing,” Geophys. Res. Lett., vol. 32, no. 3, pp. 1–4, 2005.

[6] M. V. Ramana, V. Ramanathan, I. A. Podgorny, B. B. Pradhan, and B. Shrestha, “The direct observations of large aerosol radiative forcing in the Himalayan region,” Geophys. Res. Lett., vol. 31, no. 5, pp. 0–3, 2004.

[7] Z. Shi et al., “Snow-darkening versus direct radiative effects of mineral dust aerosol on the Indian summer monsoon onset: role of temperature change over dust sources,” Atmos. Chem. Phys., vol. 19, no. 3, pp. 1605–1622, 2019.