

Aerosol Optical Depth and Black Carbon Aerosol on the Foothills of Glaciers, Northwestern Himalaya, India

Kesar Chand*, Jagdish Chandra Kuniyal, Neetu Ram and Gulshan Sharma

G.B. Pant Institute of Himalayan Environment and Development, Himachal Unit
Mohal-Kullu, 175 126, India
✉ kesar82@yahoo.com

Received December 11, 2015; revised and accepted December 29, 2015

Abstract: Ground based measurement of aerosol optical depth (AOD) and black carbon (BC) aerosol were carried out on the foothills of the three important selected glaciers (i.e., Parbati, Hamta and Beas Kund) in winter season in the northwestern Indian Himalayan Region. The AOD values were found to be in the range of 0.05–0.19. The aerosol loading was observed relatively to be higher (0.15) on 10 November 2014. Besides the biomass burning and frequent incidents of forest fire at local levels, long-range transportation of aerosol particles by air mass from the desert region also contribute to aerosol loading at observing sites. The average value of BC concentration ranges from 283 to 2026 ng m⁻³. BC concentration increases more than three times during morning and evening compared to night hours, in addition to shallow boundary layer and a larger possibility of BC intrusion from it during morning and evening. Variations of BC shows high concentration during winter dry season associated with the air masses predominantly coming from Indian plain rich in carbonaceous aerosols. The BC concentration is found to have relationship with anthropogenic activities, fossil fuel burning and biomass burning which has been observed in past in this region.

Keywords: Aerosol optical depth; Black carbon; Air mass back trajectory; Northwestern Indian Himalaya.

Introduction

Aerosol is an important component of earth–atmosphere–ocean system. It affects climate through three primary mechanisms—direct radiative forcing (absorption and scattering of sun radiation), indirect radiative forcing (modifying the cloud properties; thereby affecting albedo of clouds) and have indirect effect in the atmospheric chemistry by modifying the concentration of climate-influencing constituents (Schwartz et al., 1995) (such as GHGs). Aerosol enhances the back scattering of solar radiation leading to negative radiative forcing while the absorbing black carbon (BC) aerosol leads to the positive effect. Black carbon aerosol, the optically absorbing part of the carbonaceous aerosols,

is the major anthropogenic component of atmospheric aerosol system. Black carbon is one of the important constituents of ambient particulate matter, which is emitted into the atmosphere as a by-product of combustion processes such as fossil fuel, vegetation burning, industrial effluents, motor vehicle and aircraft exhausts and are generally in the sub-micron region and considered as tracers of anthropogenic impact on environment.

The increase in anthropogenic emission would increase in aerosol loading, thereby reducing the incoming solar radiation reaching the ground surface. These effects influence regional aerosol radiative forcing (Haywood and Shine, 1997). It has been reported that one of the principal contributor in the atmospheric

*Corresponding Author

radiative forcing and climate change is black carbon (Chung et al., 2005; Jones et al., 2005). The role of BC and organic aerosols is getting increasingly recognized in the atmospheric chemistry and radiative forcing models (IPCC, 2007). It has been reported that the global mean clear sky radiative forcing at the top of the atmosphere due to BC ranges from 0.27 to +0.54 Wm⁻², (Jacobson, 2001). The measurement and understanding of altitudinal variation of BC is important in estimating the radiative and environmental impact in a particular ecosystem. The lifetime of BC is of few days to weeks depending on the meteorological conditions in an area. The average atmospheric residence time of BC is high during dry season compared to wet periods (Babu and Moorthy, 2001).

The sink for BC is through wet and dry deposition (not degraded in the atmosphere) (Orgen and Charlson, 1983). BC may have influence on the regional climate and on the regional hydrological cycle. Studies have shown there is heating of lower troposphere and cooling of surface due to BC aerosol. It absorbs and reflects incoming solar radiation. In that way it enhances the temperature gradient with stronger pre-monsoon rainfall and reducing monsoon rainfall over India (Chung et al., 2002; Lau and Kim., 2006; Menon et al., 2002; Ramanathan et al., 2005). There have been many studies over India showing the seasonal and diurnal variation of BC concentration at different types of environment (Babu et al., 2002; Latha and Badarinath, 2003; Badarinath et al., 2007; Tripathi et al., 2005; Safai et al., 2007). Here, in this present paper, AOD and BC concentrations in the foothills of glacier

environment are located on the slope of Kullu valley in the northwestern Himalaya. This paper investigates how AOD and BC behave in the foothill of glacier or valley type topography. Identification of possible sources of pollution with the help of different tools have been described.

Study Sites

Under the present context, the foothills of three important glaciers in terms of AOD and BC were studied. The aerial distances of the selected glaciers from their foothill observation sites were 24 km for the Parbati Glacier, 13 km for the Hamta Glacier and 6 km for the Beas Kund glacier. The Parbati Glacier is the first which is located between 31° 45' - 31° 49' N latitude and 77° 45' - 77° 51' E longitude in the Beas Valley and falls in the Lesser Himalayan sub-humid belt of the Western Himalaya. The Beas valley, where the present study sites belong, ranges from 1000 to 3978 m above mean sea level (amsl) and located at 31° 38' N latitude and 77° 60' E longitude. The Parbati Glacier is the source of the River Parbati along with two large hydro projects named Parbati-II (800 MW) and Parbati-III (550 MW). Second glacier studied here is Hamta Glacier which expanded into two districts of Himachal Pradesh. This glacier is located between 32° 17' N - 77° 16' E latitude in the upper Beas Valley. Allain Duhangan (192 MW) hydropower project is run by this glacier fed stream. The third glacier studied, is the Beas Kund Glacier (32° 36' N - 77° 08' E, 3610 m) which is one of the debris fall or rock covered glacier in the northwestern Himalaya (Figure 1).

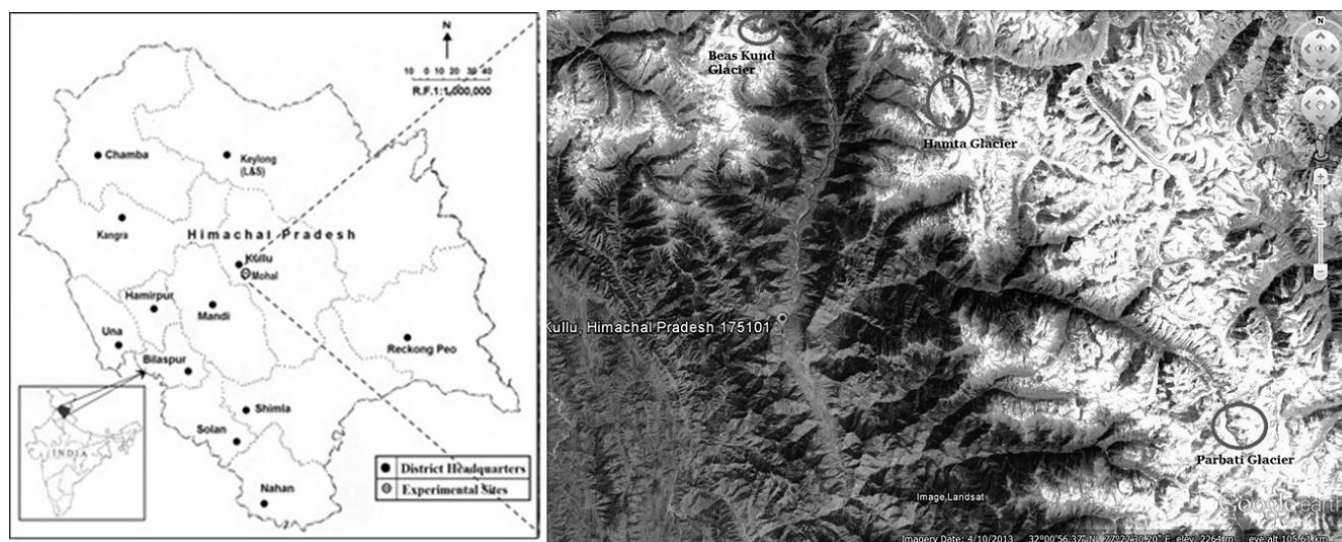


Figure 1: Study locations on the foothills of the glaciers.

Material and Method

Measurements of Aerosol Optical Depth (AOD)

Observation of columnar AOD was obtained by using Microtops-II Sunphotometer (Solar Light Co, USA). This equipment is a hand-held photometer that measures direct solar radiation. Sunphotometer is working on five wavelengths which are 380, 440, 500, 675 and 870 nm and having a bandwidth of 6 to 10 nm. Observations were taken approximately at an interval of fifteen minutes. The observations were made from sunrise to afternoon, whenever the sky was clear or partly clear and no visible clouds were present in the neighbourhood of the solar disc.

Measurements of Black Carbon (BC)

BC is measured continuously as 5-min average by quartz-fibre filter tape at seven-wavelengths (370, 470, 520, 590, 660, 880 and 950 nm) with an Aethalometer (Model AE-43 Magee Scientific Company, USA). BC is the sole absorbent of light at 880 nm; as a result this channel is used in this study.

Back-trajectories

To examine external sources that contribute to the existing columnar aerosol, 5-day backward trajectories using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model were plotted in terms of their transport (Draxler and Rolph, 2010). The trajectories were calculated for 0600 UTC at three arrival heights: 4000, 5500 and 8000 m above ground level. The lowest level was selected as 4000 m keeping in mind the local topography and mountain peaks surrounding the experimental site. Lower trajectories less than 4000 m, even if they are calculated properly, will be significantly influenced by the topography. The 4000 and 8000 m levels were selected with the criterion of being within the boundary layer and the free troposphere over Mohal, respectively.

CALIPSO

Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) is a part of the A-Train constellation of satellites and have been making global measurement of aerosols and clouds since 13 June 2006. The main objective of CALIPSO is to study the impact of clouds and aerosols on the Earth's radiation budget and climate. Unlike the space-based passive remote-sensing instruments, CALIPSO can observe aerosols over bright surfaces and beneath thin clouds, as well as with clear sky conditions (Huang et al.,

2008). Using depolarization techniques, CALIPSO can easily distinguish dust from other types of aerosols (Liu et al., 2008). The CALIPSO satellite comprises three instruments: the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP), the Imaging Infrared Radiometer (IIR) and the Wide Field Camera (WFC). CALIPSO Lidar is designed to acquire vertical profiles of elastic backscatter at two wavelengths (532 and 1064 nm) from a near-nadir viewing geometry during both day and night phases of the sun-synchronous orbit. CALIPSO has a 98° inclination orbit and flies at an altitude of 705 km, providing daily global maps of the vertical distribution of aerosols and clouds. The CALIPSO Lidar Level 1 (version 3.01) consisting of optical and physical properties of the detected aerosol layers is used in the present study. For more detail, see Powell et al. (2009).

Results and Discussion

Spectral Variation of AOD

Mean AOD_{500nm} variation during observational period of three glaciers named Parbati, Hamta and Beas Kund are shown in Figure 2. The spectral variation of AOD shows relatively strong wavelength dependence of optical depth at shorter wavelengths that gradually decreases toward longer wavelengths attributing to the dominance of accumulation mode of particles. A slight increase in AOD is observed at longer wavelengths suggesting presence of high concentration of coarse mode particles. The AOD value during winter period close to glaciers was found to be in the range of 0.05–0.19. The AOD range found at Parbati Glacier between 0.06 and 0.15, Hamta Glacier between 0.07 and 0.19 and Beas Kund Glacier between 0.07 and 0.19. The concentration of particles is due to the dust winds coming from the far off western direction of the Thar Desert region besides the biomass burning and frequent incidents of forest fire at foothills of the Himalaya (Sapna et al., 2009). Table 1 shows the AOD concentration at 500 nm in different sites of India.

Black Carbon

The daily diurnal variation of BC aerosols is shown in Figure 3 (a and b). The diurnal variation shows that the BC concentrations are observed to be low during the day time and night, while peak is observed during morning and evening hours. From the graph it is made clear that for all days, a sharp peak is observed during the morning (0600–0900 hrs IST) and evening hours (1600–2000 hrs IST) at Parbati and Hamta Glacier. But at the Beas

Kund Glacier sharp peak is observed during daytime (1100 -1300 hrs IST) due to fuel wood burning in late morning. The valley is a bowl shaped which during winter traps cold air produced by substantial nighttime cooling. The cold dense air settles to the valley floor and suppresses the vertical exchange of low level air. The suppression leads to a buildup of pollutants (Priyanka et al., 2013). There is increase in solar radiation in day time which results in an elevated boundary layer and also low traffic density thereby reducing the BC concentrations. The concentration decreases till 1700 hrs IST and then gradually increases due to increase in local anthropogenic activities and of the decrease in boundary layer and BC concentration peaks during 1900-2200 hrs during all the day.

There is a slight variation in peaks which corresponds to the local variation in boundary layer conditions and has been reported by Latha and Badarinath (2003), Tripathi et al. (2005) and Safai et al. (2007). The observation at Manora peak, Nainital (a station in the Central Himalayas at an altitude of 1958 m a.m.s.l) showed that mean BC concentration of $1.4 \pm 0.99 \mu\text{g m}^{-3}$ contributed to $\sim 5\%$ to the composite aerosols mass (Pant et al., 2006). These large BC concentrations are found to have relationship with the anthropogenic activities, biomass burning and to the boundary layer dynamics. Understanding diurnal variations in BC is very important to know the role of atmospheric processes and the effect of local human activities. The diurnal variation in the above boundary layer (ABL) height and its structure indicate to influence the surface BC concentrations (Moorthy et al., 2003; Nair et al., 2007). During observation period all the study sites show diurnal variation of BC with two peaks, during morning hours (06:00-09:00 hrs IST) and another during early evening hours (15:00-20:00 hrs IST). The primary peak is also known as fumigation peak in the morning, while secondary peak is less prominent during evening. The highest mean value of diurnal BC at Parbati and Hamta glaciers are 3901 ng m^{-3} and 1688 ng m^{-3} which were observed in winter season during evening hours

(Figure 3b). However, the morning peak was not as dominant as the evening peak.

Daytime highest concentration of BC (1054 ng m^{-3}) is observed at Beas Kund glacier. Minimum concentration of BC was noticed in daytime between 10:00-16:00 hrs IST. High values of BC concentration in the morning evidently could be interpreted as the effect of vertical mixing processes after break-up of the night time stable layer as well as because of increased anthropogenic activities such as biomass burning and vehicular emissions (Latha and Badarinath, 2005; Pathak et al., 2010). The gradual increase in BC in morning is due to the combined effects of fumigation (Stull, 1998; Fochesatto et al., 2001; Babu et al., 2002; Beegum et al., 2009) of the boundary layer as well as increase in anthropogenic activities (Safai et al., 2007; Kumar et al., 2012) in the glacier environment. The observation sites are surrounded by dense forest and biomass burning has been a common phenomena in the valley. It is noted that during daytime BC may not be lost from atmosphere, but only is redistributed over a large spatial extent by the boundary layer dynamics (Chen et al., 2001).

When BC gets transported to higher heights, their radiative forcing values increases compared to the values when they are near the surface (Hoywood and Shine, 1997). Diurnal variations in BC mainly occur because of differences in the extent of contraction and expansion of boundary layer as a result of differential solar heating of the Earth's surface as well as differences in emission sources (Kunhikrishnan et al., 1993). Gradual increase in BC in evening is due to increased production of BC aerosols and gradual formation of a surface-based inversion opposing vertical mixing in the atmosphere (Kunhikrishnan, et al., 1993; Stull, 1998). Anthropogenic activity increased in the valley due to the international week-long Dusshera festival as well as common forest fire incidents in the valley. The weakening of convection due to cloudy skies and mechanical turbulence due to wind shear, results in reduced concentrations in the residual layer (Babu et al., 2002).

Table 1: AOD concentration at different sites of India

<i>Study sites</i>	<i>Geographical location</i>	<i>AOD range</i>	<i>Reference</i>
Nainital	29° 22' N, 79° 27' E (~1950 m)	~0.16-0.45	Dumka et al., 2008
Mohal	39° 54' N, 77° 7' E (~1154 m)	~0.24-0.27	Kuniyal et al., 2009
Patiala	30° 21.5' N, 76° 27' E (~249 m)	~0.26-0.58	Singh et al., 2008
Dibrugarh	27° 18' N, 74° 30' E	~0.20-0.50	Bhuyan et al., 2005
Rajkot	22° 18' N, 70° 44' E (142 m)	~0.20-0.30	Ranjan et al., 2007
Anantapur	14° 37' N, 77° 39' E	~0.43-0.49	Raghavendra et al., 2009

During winter, the surface boundary layer is shallow resulting in trapping of pollutants in a lesser volume and concentration which leads to a higher BC concentrations (Ramachandran and Rajesh, 2007). The similar diurnal variations in BC mass concentration were also reported by researchers at other continental, coastal and urban sites such as Babu and Moorthy (2002), Beegum et al. (2009) and Kumar et al. (2012). An opposite diurnal pattern is observed with high value in the afternoon hours and low in the early morning hours over Nainital (29.4°N, 79.5°E, 1958 m asl), a high altitude remote location in the Central Himalaya (Dumka et al., 2010; Kumar et al., 2012), Sinhagad (18°21'N, 73°45'E, 1450 m asl), another high altitude station. It is mainly due to the hilly nature of the sampling site and the nearby populated valley; mountain/valley.

Investigation of Aerosol Transport

To investigate the influence of long-range transport from different sources of origin to study sites, besides local sources contributing to the existing columnar aerosols, external sources are also identified. The study of transported aerosol towards study sites are investigated with the help of back trajectory and CALIPSO. Kuniyal et al. (2009) also investigated the aerosol origin by taking into account back trajectories analysis. That study indicated that AOD was largely influenced due to the desert aerosols (Figure 4). These dust storms remain associated with the westerly flow and play a major role in building the aerosol layer, which is an effective dust source for the Indian sub-continent (Dey et al., 2004; Bollasina and Nigam, 2009). The depolarisation ratio is defined as the ratio of the perpendicular and the parallel components of the attenuated backscatter signal, and is a good proxy to distinguish different dust aerosols. Higher depolarisation suggests the presence of large concentrations of dust particles in the layer in cloud-free conditions (Gautam et al., 2009). The air parcels suggest the transport of dust aerosols towards study sites from a desert-prone region. The CALIPSO-derived image is used to identify the dust aerosols along the overpass of the trajectory. Typical examples of the highest value of AOD noticed over study sites during the dust storm period are taken under consideration.

Meteorological Parameter

Meteorological parameter was measured at Kothi (2475 m) during year of 2014. This site is situated near to

studied glaciers in Kullu valley. The maximum daily average temperature at Kothi was observed to be 20.8°C on May 1, 2014 which was followed by 20.6°C on June 5, 2014 during observation period and minimum was minus -0.6°C on January 30, 2015. The relative humidity was 92% on 12 December, 2014 followed by 90% on August 22, 2014. The lowest ever humidity was 10.6% at Kothi on December 28, 2014. Rainfall plays a major role in determining the humidity level in this region. The maximum wind speed was 11 m s⁻¹ on 23 May 2014 and minimum was 0.3 m s⁻¹ on 6 November 2014. As far as its direction at Kothi is concerned, the maximum winds blow here from north (22.5°) direction, whereas at Kothi it was noted from 00 or North. These meteorological conditions play their role dominantly in affecting the aerosols concentrations at experimental site of the Kullu valley (Kuniyal et al., 2009). Rainfall plays a major role in determining the humidity level in this region. The daily maximum total rainfall at Kothi was measured 90 mm on June 11, 2014. The monthly highest rainfall at Kothi was recorded 258 mm in June 2014. Snowfall in winter was recorded maximum with 106 inch in the month of February 2014. The monthly maximum rainfall recorded 718 mm in the month of July 2013 followed by 423.1 in August 2013. Minimum rainfall was recorded 20 mm in the month of October 2014. Minimum snowfall recorded 4 inch in April 2014.

Conclusions

Measurements of aerosol optical depth and black carbon aerosol have been carried out in the foothills of three important glaciers, i.e., Parbati, Hamta and Beas Kund. The AOD₅₀₀ varied between 0.05 and 0.19 at the foothills of the Parbati Glacier and Beas Kund Glacier respectively. Continuous measurements of aerosols and BC carried out at distinct geographical locations over the western trans-Himalayas (Hanle, Satopanth), central Himalayas and lower Himalayan regions (Dehradun, Kullu, Nainital) indicate significant BC concentration in the atmosphere during the pre-monsoon period and winter period. The results obtained in the present analysis of aerosol and BC concentration shows that the changes are largely influenced by anthropogenic aerosols at local level as well as long-range transported air mass from outside region. The concentration of aerosol loading is high due to the winds bringing air mass with significant loading originating far from the western direction. On average, BC concentration in the foothills of the Parbati, Hamta and Beas Kund glaciers stood to be 796 ng m⁻³, 416 ng m⁻³ and 432 ng

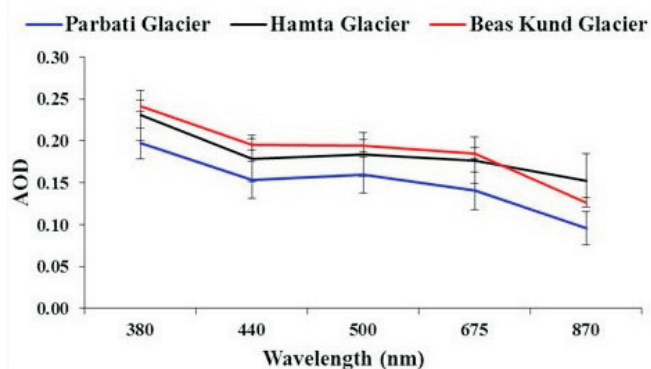


Figure 2: Aerosol on the foothill of the glaciers: (a) spectral variation in AOD, and (b) mean AOD at Parbati, Hamta and Beas Kund glaciers.

m^{-3} , respectively. BC concentration showed significant diurnal variations with low values during day and night time while peak is observed during morning and evening hours. There is a gradual built up of BC in the morning hours between 0600 and 0900 hrs IST and evening hours from 1900 to 2200 hrs IST. High BC concentration during the winter season over the area is attributed to the air masses predominantly coming from Arabian deserts rich in carbonaceous aerosols.

Acknowledgements

The authors are heartily thankful to the Director, G.B. Pant Institute of Himalayan Environment and Development, Kosi-Katarmal, Almora, Uttarakhand,

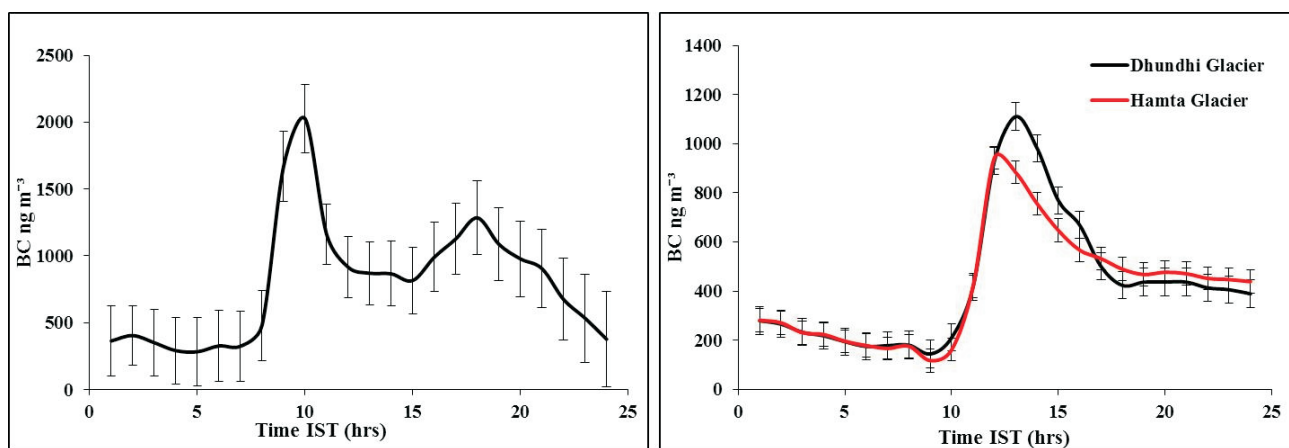


Figure 3: Diurnal mean black carbon concentration during 9-19, November 2014 on the foothill of the glaciers: (a) BC near the Parbati Glacier, and (b) BC near the Hamta and Beas Kund glaciers.

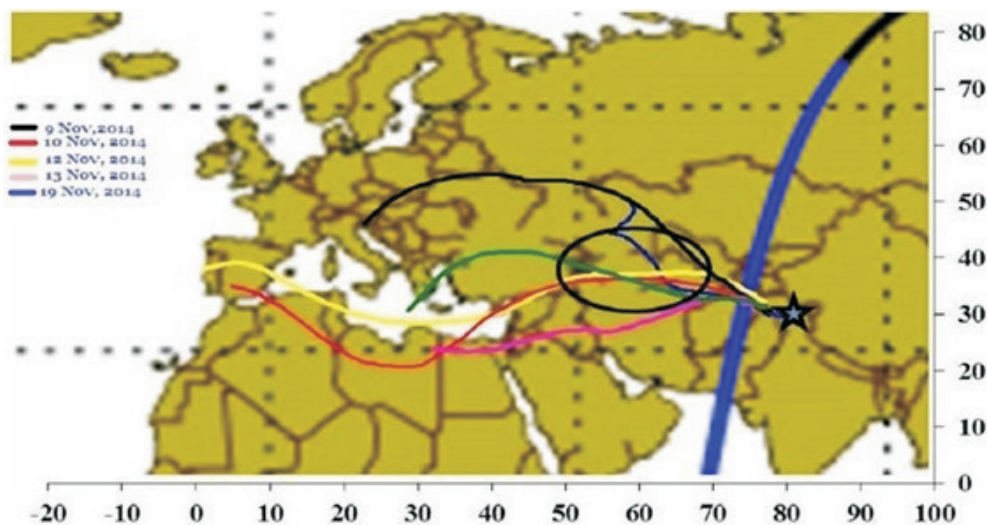


Figure 4: Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) – derived image Lidar Level 1 (version 3.01) showing the desert dust aerosol along the overpass trajectory.

India for providing the necessary facilities in Himachal Unit of the Institute which could make the present study possible. We highly acknowledge the Department of Science and Technology, New Delhi as well as ISRO, Bangalore through SPL, VSSC, Trivandrum under Aerosol Radiative Forcing over India (ARFI) for providing financial assistance. We also acknowledge the NOAA Air Resource Laboratory for the provision of the HYSPLIT model and other related data.

References

- Babu, S.S. and Moorthy, K.K., 2001. Anthropogenic impact on aerosol black carbon mass concentration at a tropical coastal station: A case study. *Current Science*, **81**: 1208-1214.
- Babu, S.S., Satheesh, S. K. and Moorthy, K.K., 2002. Aerosol radiative forcing due to enhanced black carbon at an urban site in India. *Journal of Geophysical Research*, **9**. doi: 10.1029/2002GL015826.
- Badarinath, K.V.S., Kharol, S.K., Chand, T.R.K., Parvathi, Y.G., Anasuya, T. and Jyothsna, N., 2007. Variations in black carbon aerosol, carbon monoxide and ozone over an urban area of Hyderabad, India during the forest fire season. *Atmospheric Research*, **85**: 18-26.
- Bhuyan, P.K., Gogoi, M.M. and Moorthy, K.K., 2005. Spectral and temporal characteristics of aerosol optical depth over a wet tropical location in North-East India. *Advance in Space Research*, **35**: 1423-1429.
- Chung, C., Ramanathan, E.V. and Kiehl, J.T., 2002. Effects of the South Asian absorbing haze on the northeast monsoon and surface-air heat exchange. *Journal of Climate*, 2462-2476.
- Chung, C., Ramanathan, E.V., Kim, D. and Podgorny, A., 2005. Global anthropogenic aerosol direct forcing derived from satellite and ground based observation. *Journal of Geophysical Research*, **110**: D24207, doi: 10.1029/2005JD006356.
- Draxler, R.R. and Rolph, G.D., 2010. Silver Spring, MD. HYbrid Single-Particle Lagrangian Integrated Trajectory Model Access via NOAA ARL READY Website NOAA Air Resources Laboratory, <http://ready.arl.noaa.gov/HYSPLIT.php>.
- Dumka, U.C., Moorthy, K.K., Satheesh, S.K., Sagar, R. and Pant, P., 2008. Short-Period Modulation in Aerosol Optical Depth over Central Himalayas: Role of Mesoscale Processes. *Journal of Applied Meteorological and Climate*, **47**: 1467-1475.
- Hoywood, J.M. and Shine, K.P., 1997. The effect of anthropogenic sulfate and soot on the clear sky planetary radiation budget. *Geophysical Research Letter*, **22**: 603-606.
- Huang, J., Minnis, P., Chen, B., Huang, Z., Liu, Z., Zhao, Q., Yi, Y. and Ayers, J., 2008. Long-range transport and vertical structure of Asian dust from CALIPSO and surface measurements during PACDEX. *Journal of Geophysical Research*, **113**: D23212. doi: 10.1029/2008JD010620.
- IPCC, Climate Change, 2007. Contribution of working Group I to the fourth assessment report of the inter-governmental panel on climate change. Cambridge Univ. Press, Cambridge, United Kingdom and New York.
- Jacobson, M.Z., 2001. Strong radiative heating due to mixing state of black carbon on atmospheric aerosols. *Nature*, **409**: 695-697.
- Jones, G.S., Jones, A., Roberts, D.L., Stott, P.A. and Williams, K.D., 2005. Sensitivity of global scale climate change attribution results to inclusion of fossil fuel black carbon aerosol. *Geophysical Research Letter*, **32**: L14701, doi: 10.1029/2005GL023370.
- Kuniyal, J.C., Thakur, A., Thakur, H.K., Sharma, S., Pant, P., Rawat, P.S. and Moorthy, K.K., 2009. Aerosol optical depths at Mohal-Kullu in the North-West Himalayan high altitude station during ICARB. *Journal of Earth System Science*, **118**: 41-48.
- Latha, M.K. and Badarinath, K.V.S., 2003. Black carbon aerosol over tropical urban environment: A case study. *Atmospheric Research*, **69**: 125-133.
- Latha, M.K. and Badarinath, K.V.S., 2005. Characterization of aerosols and its impacts over urban and rural environments: A case study from Hyderabad and Srisilam. *Environmental Pollution*, **132**: 463-468.
- Lau, K.M. and Kim, K.M., 2006. Asian summer monsoon anomalies induced by aerosol direct forcing: The role of the Tibetan Plateau. *Climate Dynamic*, **26**: 855-864.
- Liu, Z., Liu, D., Huang, J., Vaughan, M., Uno, I., Sugimoto, N., Kittaka, C., Trepte, C., Wang, Z., Hostetler, C. and Winker, D., 2008. Airborne dust distributions over the Tibetan Plateau and surrounding areas derived from the first year of CALIPSO lidar observations. *Atmospheric Chemistry and Physics*, **8**: 5045-5060.
- Meehl, G.A., Collins, W.D., Boville, B.A., Kiehl, J.T., Wigley, T.M.L. and Arblaster, J.M., 2000. Response of the NCAR Climate System Model to increased CO₂ and the role of physical processes. *Journal of Climate*, **13**: 1879-1898.
- Menon, S., Hansen, J., Nazarenko, L. and Luo, Y., 2002. Climate effects of black carbon aerosols in China and India. *Science*, **297**: 2250-2253.
- Orgen, J.A. and Charlson, R.J., 1983. Elemental carbon in the atmosphere: Cycle and lifetime. *Tellus*, **35**: 241-254.
- Pant, P., Hegde, P., Dumka, U.C., Sagar, R., Satheesh, S.K., Moorthy, K.K., Saha, A. and Srivastava, M.K., 2006. Aerosol characteristics at a high-altitude location in central Himalayas: Optical properties and radiative forcing. *Journal of Geophysical Research*, **111**: D17206, doi: 10.1029/2005JD006768.
- Powell, K.A., Hostetler, C.A., Vaughan, M.A., Kuehn, R.E., Hunt, W.H., Lee, K.P., Trepte, C.R., Rogers, R.R., Young,

- S.A. and Winker, D.M., 2009. CALIPSO Lidar calibration algorithms. Part I: nighttime 532-nm parallel channel and 532-nm perpendicular channel. *Journal of Atmospheric Oceanic Technology*, **26(10)**: 2015-2033.
- Raghavendra, K.K., Narasimhulu, K., Reddy, R.R., Gopal, R.K., Reddy, L.S.S., Balakrishnaiah, G., Moorthy, K.K. and Babu, S.S., 2009. Temporal and spectral characteristics of aerosol optical depths in a semi-arid region of southern India. *Science of Total Environment*, **407**: 2673-2688.
- Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J.T., Washington, W.M., Sikka, D.R., 2005. Wild, M. Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. *Proceeding of National Academy of Science*, **102**: 5326-5333.
- Ranjan, R.R., Joshi, H.P. and Iyer, K.N., 2007. Spectral variation of total column aerosol optical depth over Rajkot: A tropical semi-arid Indian station. *Aerosol Air Quality Research*, **7**: 33-45.
- Safai, P.D., Kewat, S., Praveen, P.S., Rao, P.S.P., Momin, G.A., Ali, A. and Devara, P.C.S., 2007. Seasonal variation of black carbon aerosols over a tropical urban city of Pune, India. *Atmospheric Environment*, **41**: 2699-2709.
- Sapna, R., Yogesh, K. and Dadhwal, V.K., 2009. Diurnal and seasonal variation of spectral properties of aerosols over Dehradun, India. *Aerosol Air Quality Research*, **9**: 32-49.
- Schwartz, S.E., Arnold, F., Blanchet, J.P., Durkeem, P.A., Hofmann, D.J., Hoppel, W.A., King, M.D., Lacis, A.A., Nakajima, T., Ogren, J.A. and Toon, O.B., 1995. Group Report: Connections between aerosol properties and forcing of climate. In: *Aerosol Forcing of Climate*. Charlson, R.J. and Heintzenberg J. (eds). John Wiley and Sons.
- Singh, M., Singh, D. and Pant, P., 2008. Aerosol characteristics at Patiala during ICARB – 2006. *Journal of Earth System Science*, **117**: 407-411.
- Tripathi, S.N., Day, S., Tare, V. and Satheesh, S.K., 2005. Aerosol black carbon radiative forcing at an industrial city in northern India. *Geophysical Research Letter*, **32**: doi: 10.1029/2005GLO22515.