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Journal of the Institute of Engineering, Vol. 8, No. 3, pp. 42–51

Fax: 977-1-5525830

Black Carbon Aerosol over a High Altitude (~ 4.52 km) Station in Western Indian Himalayas

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Abstract: Continuous measurements of mass concentration of Black Carbon (BC) aerosols, measured from a high altitude (~ 4.5 km above msl) location, Hanle (32.78°N, 78.95°E) in the western Himalayas, during August 2009 to July 2010 have been examined. The day-to-day variations in BC mass concentration (M_B) were rather subdued in winter months while quite conspicuous during the spring months. It showed a well defined annual cycle with a maximum (109 ± 78 ng m^{-3}) during spring and minimum during the winter (66 ± 62 ng m^{-3}) season with an annual average M_B of 78 ± 64 ng m^{-3}. Examining the frequency distribution, it was found that 64 % of the values were below annual mean M_B showing a rather pristine nature for this near free tropospheric region. Trajectory clustering and concentration weighted trajectory (CWT) analysis indicated that, most of the year, the site is influenced from the advection from west and south west Asian locations and only for a small period from the Indo-Gangetic Plains (IGP). The observations are compared with other high altitude measurements, over the globe in general and around the Himalayan region.

Introduction

In the recent years, black carbon [BC] aerosols has been receiving special attention primarily due to its property to absorb solar radiation in the atmosphere over a wide spectrum (*IPCC*, 2007; *Bond and Bergstrom*, 2006), thereby contribution towards global warming (*Ramanathan and Carmichael*, 2008) unlike the majority of the aerosol which reflect radiation (*Penner et al.*, 1998) and have a cooling affect in the atmosphere. Simulation studies have shown that the regional radiative forcing by aerosols containing significant amount of BC have strong impact on the hydrological cycle (*Ramanathan et al.*, 2001) and Indian Asian summer monsoon (*Lau et al.*, 2006). It has become evident from the several field experiments and ground based network studies conducted in the Asian region over the last decade that absorbing aerosols play a crucial role in impacting global and regional climate. BC aerosol, lofted above by strong convective motions over landmass can reach well above the atmospheric boundary layer and in the entrainment zone (*Babu et al.*, 2008) where the meso stable conditions are conducive for increased layer lifetime of this aerosols which results in elevated warming in the atmosphere (*Satheesh et al.*, 2008). As such information of BC aerosol characteristics in the free troposphere is very important in understanding the consequences of regional weather and climate implications. BC aerosols due to their relatively higher life time than other absorbing species (such as dust) enables their long range transport to the background and remote locations like Arctic (*Stohl et al.*, 2006) and Antarctica (*Tomasi et al.*, 2007, *Chaubey et al.*, 2010). Not only that, measurement of BC is also important in snow covered regions as deposition of BC over snow will modify the albedo of snow (*Warren and Wiscombe*, 1980; *Hansen and Nazarenko*, 2004; *Flanner et al.,* 2009). *Mikhailov et al.* (2006) reported that coatings of snow on BC particles can enhance their absorption of solar radiation by a factor of 2. All this above emphasizes the need for measurements of BC in the higher altitudes of the atmosphere and above snow covered regions.

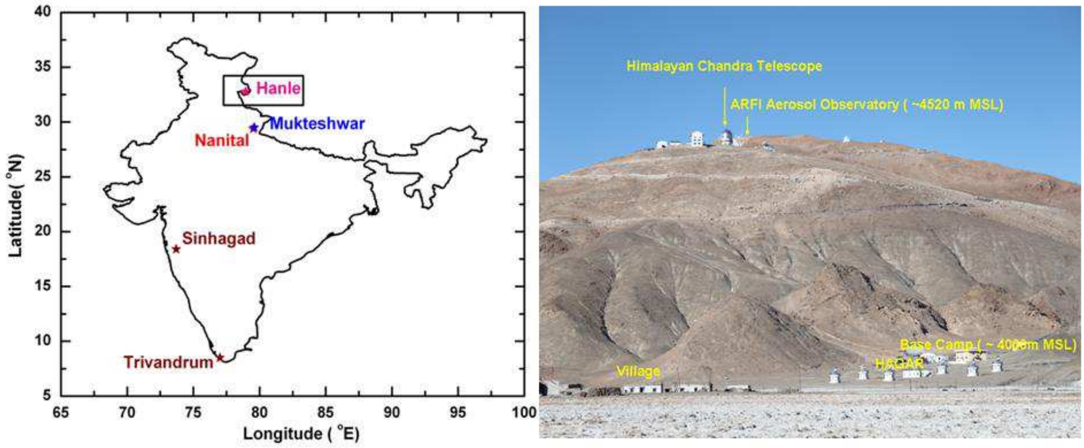

Figure 1: In the left: Location map showing the ARFINET station Hanle (in rectangle), other high altitude stations in India i. e. Nainital, Mukteshwar and Sinhagadh and Trivanrum; In the right: Mt Saraswati at Hanle and location of aerosol observatory, Himalayan Chandra Telescope, village, base camp and other facilities at Hanle

The Himalayan and Tibetan Plateau Glaciers, which are the largest glaciers outside of the Polar Regions, have shown signs of retreat (*Kulkarni et al.,* 2007). In the backdrop of this and the discussions that have forgone on the importance of BC aerosols in the atmosphere warming, it becomes imperative to investigate aerosol characteristics especially over the Himalayas. As the south Asian region is believed to be one of the hot spots of BC aerosols (*Lawrence et al.,* 2010) and the Himalayas form a natural orographic barrier for its northward dispersion, several field experiments have recently formed to measure BC in the Himalayan region (*Lau et al.,* 2006). In line with this and to explain climate implication due to elevated aerosols, a field experiment, Regional Aerosol Warming Experiment (RAWEX) was formulated under Indian Space Research Organization – Geosphere Biosphere Program. As a part of the program, a high altitude aerosol observatory was established in western Indian Himalayas, on Mt. Saraswati at Hanle (32.5°N, 78.5°E and 4520 m msl; Figure 1 left panel), where the Indian Institute of Astrophysics (IIA) is operating Himalayan Chandra Telescope. Continuous measurements of BC mass concentration were made from this station for a period of 1 year from August 2009 to July 2010. These data are examined and the results are presented in the paper.

Experimental site and Instrumentation

The experimental site is located at top of Mt. Saraswati in the Hanle valley of Leh-Ladakh region of India in western Indian Himalayas (as shown in Figure 1) which also falls in southern slope of Tibetan Plateau and represents a rather free tropospheric region far removed from any significant human activities. The area around the observatory is mostly rocky. There is very little vegetation (like shrubs) which disappears by the end of summer and re appears by next spring. Mt. Saraswati is surrounded immediately by valley, which are bounded by high mountain peaks which are higher in elevation than the observatory site itself. Mountains surrounding Mt Saraswati are subject to snow cover especially during winters and monsoon periods. This site is at an altitude of about 600 m above the base camp area located in a small village and other experimental facilities [like High Altitude GAama Ray Observatory (HAGAR) etc]. The nearest township, Leh (34.1°N, 77.58 °E, 3.52 km msl) has a population of merely 27,513 persons and located almost 270 km away from the base camp. The power required for the observatory and the base camp comes from the batteries charged by the solar energy in order to minimize the perturbations to the local environment and maintaining the clean air conditions.

A two channel (370 nm and 880 nm) rack mount aethalometer is used for measuring the BC mass concentration (M_B) at 880 nm from the observatory at Mt Sarswati. Aethalometer aspirates ambient dry air from 1m above the roof of measurement station building (~ 6m above the ground), through an inlet tube. The inlet pipe is first connected to heating inlet and then to an external pump (internal pump of the instrument was replaced with a more sophisticated and durable external pump). Aethalometer provided automatic and near real time mass concentration of BC. The particles impact on a quartz filter tape, the change in transmittance of which after each collection interval is calibrated in terms of the mass of BC. The instrument was operated at a mass flow rate of 6 lpm and at a time base of 5 min, so that BC estimates are available every 5 min, on all the days and round the clock for reducing the data gaps. Mass flow rate was 6 lpm [V] under standard temperature (T 293°K) and pressure (1013 hPa). However, as the ambient pressure at higher altitudes is lower, the pumping speed is increased to maintain the set mass flow rate, and hence more volume of air is aspirated. The data are corrected for pressure and then used for further analysis. Aethalometer is well established and widely used instrument for the BC measurement all around the world and more details are available in literature (*Moorthy et al.,* 2005; *Nair et al.,* 2007; *Moorthy et al,* 2009).

Synoptic and local meteorology

The daily meteorological conditions during the study period are inferred from the regular and high resolution measurements of the surface meteorological parameters [temperature (T, °C), pressure (P, mb), relative humidity (RH, %), wind speed (W_S, m s^{-1}) and wind direction (W_D, °)] measured using automatic weather station at a height of ~ 3 m above surface and very near to the measurement location. Ambient temperature showed diurnal variations with minimum during the early morning hours and maximum during the late afternoon hours. Maximum T measured during the study period was 23.1°C during August 2009 and minimum temperature measured was in January 2010 (-19.6°C). It showed the highest monthly mean value of 12.4 ± 4.6 °C occurred during August 2009 month while the minimum monthly mean value of -11.05 ± 3.48°C occurred during December 2009 month. The ambient pressure showed very little variation; being the highest in September with a value of 590.99 ± 2.52 mb and lowest in February (583.25 ± 3.571 mb). The Monthly mean RH showed a maximum (monthly mean of 40 ± 18 %) during July month and it showed lowest values of 24 ± 14 % during March. Nevertheless, maximum and minimum values of RH in all the season varied in same range (4 - 98 %) with most of the time values at the site were < 40% and showed an increase at the time of heavy clouds and precipitation (rain or snowfall) periods. On the contrary surface winds varied significantly during the study period. It showed the influence of mountain winds, with strong winds during the evening hours in comparison to the morning hours. The monthly mean wind speed was the highest during July (mean value of 6.15 ± 4.39 m s^{-1}) and lowest during the month of January (3.77 ± 3.72 m s^{-1}). Most of the time, the wind arrives from south and southwest direction. There were occasions when winds reached from west or east direction but these were very insignificant. We have classified the year into four seasons (based on the basis of temperature) defined as Summer (JJA), Autumn (SON), Winter (DJF) and Spring (MAM). Seasonally, summer corresponds to high mean T (10.29 ± 5.09 °C) and P (~ 589 ± 2 mb) while winter corresponds to lower mean T (-10.0 ± 4.01 °C) and P (585 ±3.17 mb).

Results and Discussions

Temporal variations of the daily mean yield BC mass concentrations (M_B), estimated from the 5 min measurements by the aethalometer, and are shown in the top panel of Figure 2, where the vertical lines through the symbols are the standard errors. In general, M_B remained below 400 ng m^{-3}. Daily average M_B showed random variations (within 40 - 150 ng m^{-3}) in August 2009 which subdued at the end of this month and start of September. These variations remained up to November and then started decreasing in early December. The day to day variations in December and January were comparatively lower as compared to other months. The increase in M_B was again measured at the end of February with more pronounced day to day variations. Except for the small dip in the M_B during the start of March, there was significant increase in the day to day variations during March April and May months. Not only the variations but the absolute magnitude of M_B was also higher in comparison to all the other months. The variation again subdued in the June and July months with decrease in the absolute magnitude of M_B values. It is important to note that, daily average M_B varied from a minimum of 6.7 ng m^{-3} to maximum value of 295.7 ng m^{-3} with an annual mean 77 ng m^{-3}, and low standard deviation of 64 ng m^{-3}. It is also important to note that except for the few days in a year (mainly in April and May month), most of the times in the year, daily average M_B remained < 250 ng m^{-3} at the station. The large increase in M_B seen at the location early in the spring season could be attributed to the increased vertical mixing into boundary layer due to increase in solar heating of the surface starting from spring. The extremely low temperatures and lower pressure keeps the local/ regional emissions (however small it might be) very close to surface. With the beginning of spring, the surface gets increasingly warmed by the solar heating and thermals develop, pushing up the species confined in the valley to higher altitudes to reach the peak from where they would be circulated by the local topographical winds. As Hanle is a part of very large mountain area of Himalayas this effect would be meso regional in nature than local. Besides, the densely populated and industrialized vast area of the Indo Gangetic Plane (IGP), lying to the south of western Indian Himalayas might also get transported to the higher altitudes with the prevailing winds and contribute to BC at Hanle. The low temperatures, low trade winds inversion, dry and calm ambient winds continued with the low level anticyclone that prevails over the entire Indian plains during winter inhibits the ventilation and dispersion of pollutants from the densely populated regions, resulting in a build up of BC in lower troposphere as has been reported by several investigators (for example; *Nair et al.*, 2007; *Ramanathan et al.*, 2007).

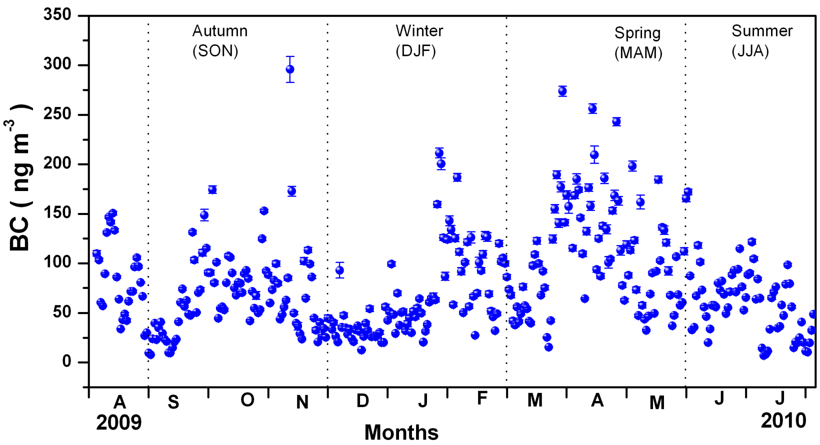

Figure 2: Temporal variation of daily average black carbon (BC) mass concentration for the period August 2009 to July 2010. The spheres present the mean value for the day and the vertical line passing through them are the standard error. Different season are separated by dotted line.

For each day of the full study period, 7-day HYSPLIT back trajectories (*http://www.arl.noaa.gov/ready.html)*, ending at 100 m above ground level, at 1130 hrs local time, have been computed to identify the air masses reaching Hanle to distinguish the potential sources contributing to aerosol burden over the sampling location. The ending height of 100 m was chosen due to the higher elevation and remote location where the surface layer is very close to the ground whereas time period of 7 days was chosen based on the higher life time of BC aerosol in free troposphere (*Ramanathan,* 2001; *Babu and Moorthy*, 2002). In Table 1, we list the originating location, number of trajectories and relative percentage of contribution from a particular direction. Our analysis showed that, although there are three major direction for the clusters but major contribution comes from the air mass arriving at Hanle from west and south west of Hanle i. e. west Asia, south west Asia and north African region. There are very fewer occasions, that too in summer (9%) and autumn (15%) when trajectories arrived from south east of location i.e. Indo Gangetic Plain (IGP). Even though the cluster analysis gives absolute quantitative differences between the different clusters in terms of aerosol parameters, it is not effective in better delineation of potential source regions. *Seibert et al.,* (1994) developed the concentration weighted trajectory (CWT) method, which assigns the concentration values at the receptor site to the respective backward trajectories. More details can be found in *Gogoi et al.,* (2011). The CWT concentration gradients shows that the most important potential source region during spring season (maximum BC mass concentration) is the west Asia, Saudi Arabian desert regions and north Africa regions while the location is getting least advection of aerosols from the IGP location in all the season represented by lower BC mass concentration values at the receptor site. A weak to moderate sources spreading occurs at the location during the spring season producing high values of BC mass concentration at the receptor site. Overall the receptor site is influenced by advection from west (as discussed above) but the amount of contribution varies from season to season.

Table 1: Cluster mean values of black carbon mass concentration (M_B, ng m^{-3}) for different seasons

Season	Cluster	Originating location	% of trajectories	Mean M_B (ng m^{-3})
Summer	**1**	SE	9	18.35 ± 14.86
	2	W	82	66.87 ± 32.12
	3	NE	9	88.80 ± 30.62
Autumn	**1**	NW	44	75.69 ± 49.33
	2	SE	15	31.68 ± 16.57
	3	W	41	74.26 ± 37.36
Winter	**1**	SW	28	84.72 ± 53.36
	2	W	63	63.46 ± 37.93
	3	W	9	33.66 ± 12.88
Spring	**1**	SW	33	124.96 ± 58.22
	2	W	17	73.42 ± 33.92
	3	W	49	110.11 ± 56.81

Comparison with other high altitude locations

It is expected to be a very low value at this elevation from any other region of the Indian subcontinent but the striking feature was that the reported values in this paper for, Hanle are the least among the measured values elsewhere in the Himalayas also referred as third pole of Earth. We examined the available seasonal mean values of M_B at aother high altitude location in Himalayas and elsewhere in world. Annual mean M_B at Hanle (77 ± 64 ng m^{-3}), is half of the 2 year averaged value (160.5 ± 296 ng m^{-3}) reported for NCOP- Nepal (*Marinoni et al.,* 2010), almost 1/10 times lower than the 1 year average (806 ± 590 ng m^{-3}) reported for Mukteshwar (*Hyvarinen et al.,* 2009) and Nanital (*Dumka et al.,* 2010). Not only that, M_B at Dibrugarh, which is a low altitude station but in northeastern Himalayan region of India, showed very high values compared to Hanle in all the seasons (*Pathak et al.,* 2010). This is indicative of the strong existing gradient in M_B, as we move northwest of Himalayan ridge and attitudinally higher in the free troposphere. Our measured M_B values were similar to the reported values at Nam Co station over Tibetan Plateau (*Ming et al.,* 2010), which is further east of Hanle but north to NCOP-Nepal. As the values reported in *Ming et al.,* (2010) were limited for few months; it does not give clear information about the seasonal characteristics of the region. Mukteshwar, Nainital in central

Himalayas and Dibrugarh in north eastern Himalayan region are comparatively at lower altitude than Hanle. As such, NCOP-Nepal provides us a best location for comparison due to its high altitude (~ 5079m above msl) similar to Hanle and availability of long term measurements of M_B. We found that, except during the summer season, M_B at Hanle was almost half of the M_B at NCOP-Nepal. Most importantly, M_B at both the location showed similar trends with high during the spring season and low during the summer season similar to those reported for Nainital and Mukteshwar in Indian Himalayas. M_B reported at Hanle (the third pole) is comparable to the measured BC at Indian station Maitri in Antarctica during the southern hemispheric summer (*Chaubey et al.*, 2010) but comparatively higher than the M_B reported for the Indian station in Antarctica at Larsemann hills (*Chaubey et al.*, 2010). On the other hand, M_B measured at South Pole (*Bodhaine et al.*, 1995) almost 15 years before were very lower than Hanle. It is also interesting to note that, M_B values for Hanle are comparable to the long term averaged M_B for winter season in Canadian Arctic region (Alert, *Sharma et al.*, 2004) and Norwegian Arctic region (Ny Alesund, *Elfethredias et al.*, 2009) but marginally higher for summer. In contrast to this, seasonal values of M_B, for Indian continental high altitude station Sinhagad, Pune (*Kewat et al.*, 2005) were higher in all season owing to its strong influence of the populated cities nearby the station location. For the M_B reported for Jungfraujoch (*Nyeki et al.*, 1998), La Reunion Island (*Bhugwant et al.*, 2001) and Mauna Loa (*Bodhaine et al.*, 1995), Hanle values are comparable to their values during summer and spring season, but order of magnitude higher in other season.

Summary / Conclusion

Our important findings from this particular study are:

- The annual mean M_B for the full year of study period is 77 ± 64 ng m^{-3}. This value is much lower than the long term reported values from the other high altitude station in Himalayas.
- M_B showed a seasonal variation with maximum M_B (108.9 ± 77.9 ng m^{-3}) during spring and minimum M_B (66.21 ± 41.88/ 66.17 ± 61.95 ng m^{3}) during summer/ winter season. Even though the absolute magnitude are lower than the other high altitude station in Himalayas but the trend in seasonality is similar.
- Trajectory clustering and CWT analysis indicate that the potential sources across the west Asia, south west Asia and North African regions which also contribute to the seasonal maximum during spring and minimum during summer/winter months. On the other hand, very low contribution comes from the IGP regions.

Acknowledgements

This study was carried out as a part of Aerosol Radiative Forcing over India (ARFI) project of ISRO-GBP project. We thank Director of Indian Institute of Astrophysics, Bangalore for rendering support for the observations. Thanks are also due to entire staff of Indian Astronomical Observatory, Hanle for invaluable help during installing instruments and during observations. The authors greatly acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or READY Web site [available online at *http://www.arl.noaa/gov/ready.htm*] used in this publication.

REFERENCES

[1] Babu S. S., Satheesh S. K., Moorthy K. K., Dutt C. B. S., Nair V. S., Alappattu D. P. and Kunhikrishnan P. K., Aircraft measurements of aerosol black carbon from a coastal location in the north-east part of peninsular India during ICARB, J. Earth Syst. Sci. **117**, S1, pp. 263–271, 2008.

[2] Babu S. S. and Moorthy K. K., Aerosol black carbon over tropical coastal station in India, Geophys. Res. Lett., **29**, doi: 10.1029/2002GL015662, 2002.

[3] Bhugwant C., Bessafi M., Riviere E. and Leveau J., Diurnal and Seasonal variation of carbonaceous aerosols at a remote MBL site of La Reunion island, Atmos. Res. **57**, 105–121, 2001.

[4] Bodhaine B. A., et al., Aerosol absorption measurements at Barrow, Mauna Loa and South Pole, J. Geophys. Res., **100**, 8967–8975, doi: 10.1029/95JD00513, 1995.

[5] Bonasoni P., et al., Atmospheric Brown Clouds in the Himalayas: first two years of continuous observations at the Nepal Climate Observatory-Pyramid (5079 m), Atmos. Chem. Phys., **10**, 7515–7531, doi:10.5194/acp-10-7515-2010, 2010.

[6] Bond T. C. and Bergstrom R. W., Light absorption by carbonaceous particles: An investigative review, Aerosol Sci. Technol., **40**, 1–41, 2006.

[7] Chaubey J. P., et al., Black Carbon aerosols over Coastal Antarctica and its scavenging by snow during the Southern Hemispheric Summer, J. Geophys. Res., **115**, D10210, doi:10.1029/2009JD013381, 2010.

[8] Dumka et al., Characteristics of aerosol black carbon mass concentration over a high altitude location in the Central Himalayas from multi-year measurements, Atmos. Res. **96** (2010), 510–521, 2010.

[9] Eleftheriadis K., Vratolis S. and Nyeki S., Aerosol black carbon in the European Arctic: Measurements at Zeppelin station, Ny-Alesund, Svalbard from 1998–2007, Geophys. Res. Lett., **36**, L02809, doi:10.1029/2008GL035741, 2009.

[10] Flanner M. G., et al., Springtime warming and reduced snow cover from carbonaceous particles, Atmos. Chem. Phys., **9**, 2481–2497, 2009.

[11] Ganguly D., and Jayaraman A., Physical and optical properties of aerosols over an urban location in western India: Implications for shortwave radiative forcing, J. Geophys. Res., **111**, D24207, doi:10.1029/2006JD007393, 2006.

[12] Gogoi M. M., et al., Multi-year investigations of near-surface and columnar aerosols over Dibrugarh, ortheastern location of India: Heterogeneity in source impacts doi: 10.1016/j.atmosenv.2010.12.056, Atmos. Environ., 2011.

[13] Hansen J., and Nazarenko L., Soot climate forcing via snow and ice albedos, Proc. Natl. Acad. Sci. U. S. A., **97**(101), 423–428, doi:10.1073/ pnas.2237157100, 2004.

[14] Hsu N. C., Herman J. R. and Tsay S. C., Radiative impacts from biomass burning in the presence of clouds during boreal spring in southeast Asia, Geophys. Res. Lett., **30**(5), 1224, doi:10.1029/2002GL016485, 2003.

[15] Hyvairinen A. P., et al., Continuous measurements of optical properties of atmospheric aerosols in Mukteshwar, northern India, J. Geophys. Res., **114**, D08207, doi:10.1029/2008JD011489, 2009.

[16] Kewat et al., Characteristics of carbonaceous pollutants at high altitude station Sinhagad in India, 2005.

[17] Koch D. and Hansen J., Distant origins of Arctic black carbon: A Goddard Institute for Space Studies ModelE experiment, J. Geophys. Res., **110**, D04204, doi:10.1029/2004JD005296, 2005.

[18] Kulkarni et al., Glacier retreat in Himalaya using Indian remote Sensing satellite data, Curr. Sci., Vol. **92**(1), 69-74, 2007.

[19] Latha M. and Badarinath K. V. S., Environmental pollution due to black carbon aerosols and its impacts in a tropical urban city, J. of Quant. Spectro. and Rad. Trans. **92**(3), 311–319, 2005.

[20] Lau K. M., et al., Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau, Clim. Dynam., **26**(7–8), 855–864, 2006.

[21] Lawrence M. G. and Lelieveld J., Atmospheric pollutant outflow from southern Asia: a review, Atmos. Chem. Phys., **10**, doi:10.5194/acp-10-11017-2010, 11017–11096, 2010.

[22] Marinoni A., et al., Aerosol mass and black carbon concentrations at NCO-P, Atmos. Chem. Phys., **10**, 8551–8562, doi:10.5194/acp-10-8551- 2010, 2010.

[23] Mikhailov E. F., et al., Optical properties of soot–water drop agglomerates: An experimental study, J. Geophys. Res., **111**, D07209, doi:10.1029/2005JD006389, 2006.

[24] Ming J. et al., Carbonaceous particles in the atmosphere and precipitation of the Nam Co region, central Tibet, J. of Environ. Sci., **22**(11) 1748–1756, 2010a.

[25] Moorthy K. K., et al., Spatial and vertical heterogeneities of aerosol radiative forcing over the oceanic regions surrounding the Indian peninsula: climate implications, Quart. J. Roy. Meteor. Soc., **135**: 2131–2145, 2009.

[26] Moorthy K. K., et al., Temporal heterogeneity in aerosol characteristics and the resulting radiative impact at a tropical coastal station – Part 1: Microphysical and optical properties, Ann. Geophys., **25**, 2293–2308, 2007.

[27] Moy L. A., Dickerson R. R. and Ryan W. F., Relationship between back trajectories and tropospheric trace gas concentrations in rural Virginia, Atmos. Environ. **28**, 2789-2800, 1994.

[28] Nair V. S., et al., Wintertime aerosol characteristics over the Indo-Gangetic Plain (IGP): Impacts of local boundary layer processes and long range transport, J. Geophys. Res., **112**, D13205, doi: 10.1029/2006JD008099, 2007.

[29] Nyeki S., et al., The Jungfraujoch high-alpine research station (3454 m) as a background clean continental site for the measurement of aerosol parameters, J. Geophys. Res., **103**(D6), 6097–6107, 1998.

[30] Pathak B. G., et al., Aerosol temporal characteristics and its impact on shortwave radiative forcing at a location in the northeast of India, J. Geophys. Res., **115**, D19204. doi:1029/2009JD013462, 2010.

[31] Penner J. E., et al., Climate forcing by carbonaceous and sulphate aerosols, Clim. Dyn., **14**, 839-851, 1998.

[32] Rai K., et al., Chemical characterization of aerosols at NPL, Delhi. In: Proceedings of Conference on Aerosol Remote Sensing in Global Change and Atmospheric Pollution, IASTA Bulletin Spl. Issue, **14**(1), 2002, pp. 155–158, 2002.

[33] Ramanathan V. and Carmichael G., Global and regional climate changes due to black carbon, Nature Geosci., 221–227, 2008.

[34] Ramanathan V., et al., Indian Ocean Experiment: An integrated analysis of the climate forcing and effects of the great Indo-Asian haze, J. Geophys. Res., **106**, 28371– 28398, 2001.

[35] Safai P. D., et al., Seasonal variation of black carbon aerosols over a tropical urban city of Pune, India, Atmos. Environ. doi:10.1016/j.atmosenv.2006.11.044, 2007.

[36] Satheesh S. K., et al., Climate implications of large warming by elevated aerosols over India, Geophys. Res. Lett., **33**, L20816, doi:10.1029/2008GL034944, 2008.

[37] Seibert P., et al., Trajectory analysis of aerosol measurements at high alpine sites, in Transport and Transformation of Pollutants in the Troposphere, Academic publishing, Den Haag, pp. 689 – 693, 1994.

[38] Seinfeld J., Black carbon and brown clouds, Nature Geosci. **1**, 15-16, 2008.

[39] Sharma S., et al., Long-term trends of the black carbon concentrations in the Canadian Arctic, J. Geophys. Res., **109**, D15203, doi: 10.1029/2003JD004331, 2004.

[40] Stohl A., et al., Pan-Arctic enhancements of light absorbing aerosol concentrations due to North American boreal forest fires during summer 2004, J. Geophys. Res., **111**, D22214, doi:10.1029/2006JD007216, 2006.

[41] Tomasi C., et al., Aerosols in polar regions: A historical overview based on optical depth and in situ observations, J. Geophys. Res., **112**, D16205, doi:10.1029/2007JD008432, 2007.

[42] Tripathi S. N., et al., Enhanced layer of black carbon in a north Indian industrial city, Geophys. Res. Lett., **32**, L12802, doi:10.1029/2005GL022564, 2005.

[43] Venzac H., et al., High Frequency New Particle Formation in the Himalayas, PNAS, **105**, 41, 15666–15671, 2008.

[44] Warren S. and Wiscombe W., A model for the spectral albedo of snow. II: Snow containing atmospheric aerosols, J. Atmos. Sci., **37**, 2734–2745, doi:10.1175/1520-0469(1980)037<2734:AMFTSA>2.0.CO;2, 1980.