Physical and optical characteristics of atmospheric aerosols during ICARB at Manora Peak, Nainital: A sparsely inhabited, high-altitude location in the Himalayas

U C Dumka[1,*], K Krishna Moorthy[2], P Pant[1], P Hegde[1], Ram Sagar[1] and K Pandey[3]

[1]*Aryabhatta Research Institute of Observational Sciences, Nainital, India.*
[2]*Space Physics Laboratory, Vikram Sarabhai Space Center, Thiruvananthapuram 695 002, India.*
[3]*Department of Physics, DSB College, Nainital, India.*
[*]*e-mail: dumka@aries.ernet.in*

Collocated measurements of the optical and physical properties of columnar and near-surface aerosols were carried out from Manora Peak, Nainital (a sparsely inhabited, high altitude location, $\sim$2 km above mean sea level, in the Himalayas), during the Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB) under the Geosphere Biosphere Programme of the Indian Space Research Organization (ISRO-GBP). Under this, observational data of spectral aerosol optical depths (AOD), mass concentration of aerosol black carbon (M_B), mass concentration (M_T) and number concentration (N_t) of composite (total) aerosols near the surface and meteorological parameters were collected during the period February 15 to April 30, 2006. Though very low (<0.1 at 500 nm) AODs were observed during clear days, as much as a four-fold increase was seen on hazy days. The Ångström exponent (α), deduced from the spectral AODs, revealed high values during clear days, while on hazy days α was low; with an overall mean value of 0.69 ± 0.06 for the campaign period. BC mass concentration varied between 0.36 and 2.87 μg m^{-3} and contributed in the range 0.7 to 1.8% to the total aerosol mass. Total aerosol number concentration and BC mass concentration showed diurnal variation with a midnight and early morning minimum and a late afternoon maximum; a pattern quite opposite to that seen in low altitude stations. These are attributed to the dynamics of the atmospheric boundary layer.

1. Introduction

An integrated campaign for aerosol, gases and radiation budget (ICARB) was conducted during the March–May period of 2006 as a part of the Indian Space Research Organization's Geosphere Biosphere Programme (ISRO-GBP). The ICARB was conceived as an integrated campaign (Moorthy *et al* 2006), comprising of three segments, namely, the land, ocean, and aircraft segments. In each one of these segments, collocated measurements of the optical, physical and chemical properties of atmospheric aerosols were carried out. The land segment comprised of a network of ground-based observatories, representing distinct geographical features of India, providing a time series observation during the period when spatially resolved measurements are made using the moving platforms in the other two segments. The Aryabhatta Research Institute of Observational Sciences (ARIES) participated in the land segment of the campaign, during the period February 15 to April 30, 2006 by making collocated measurements from the Manora Peak (29.4°N, 79.5°E, $\sim$1951 m AMSL), at Nainital, the results of which are presented in this paper.

Keywords. Atmospheric aerosols; Himalayan aerosols; size distribution; BC aerosols.

J. Earth Syst. Sci. **117**, S1, July 2008, pp. 399–405

Table 1. *List of instruments operated during ICARB, for aerosol parameters.*

Sl. no	Instrument and references	Parameter measured/ estimated and method	Conditions/remarks
1	10 channel multi-wavelength solar radiometer, MWR (Moorthy *et al* 1999; Sagar *et al* 2004)	Mean spectral AOD at 380, 440, 450, 500, 650, 750, 850, 935 and 1025 nm by Langley plot method	Clear, cloud free days or partly cloudy days when part of the sky within $\sim 10^{\circ}$ of the solar disc is cloud free
2	15 channel Optical Particle Counter (OPC, model 1.018 of Grimm Aerosol Technik www.grimm-aerosol.com) (Pant *et al* 2006)	Number concentration and number size distribution in 15 channels of composite aerosols, in the size range 0.3 to 20.0 μm	Automatic, portable, battery operated
3	Aethalometer (AE-42 of Magee Scientific, USA) (Babu *et al* 2004; Pant *et al* 2006) (http://www.mageesci.com/ Aethalometer_book_2009.pdf)	Continuous and near-real time estimates of mass concentration M_B of black carbon at every 5 min	Automatic, continuous, operational (only from March 2006)
4	High Volume Air Sampler (Envirotech Inc., model APM 430) (Pant *et al* 2006)	Total mass concentration of composite aerosols (TSP)	Automatic
5	Automatic Weather Station (Campbell Scientific, Inc.) (Pant *et al* 2006)	Relative humidity, temperature, wind speed, wind direction, etc.	Automatic

2. Experimental set-up and methodology

The experiments were conducted from Manora Peak – a remote, sparsely inhabited, hilly terrain in the Himalayas, ~ 3 km southwest of Nainital town (with a population of $\sim 100{,}000$). To the north and northeast are tall Himalayan ranges, with insignificant anthropogenic or industrial activities, while to the south and southwest are densely populated valleys and plains (with mean elevation of ~ 300 m), at an aerial distance of ~ 10 km. The information on the surface meteorological parameters such as wind speed (WS, m s^{-1}), direction (WD in $^{\circ}$), relative humidity (RH, %) and temperature (T, °C) on hourly basis and daily total rainfall (RF in cm) was recorded by using a set of meterological sensors mounted on a tower and located at the observing site. Aerosol parameters were measured using a number of instruments, which are listed in table 1, alongwith reference to their details, data deduction and parameter retrieval, and error budget.

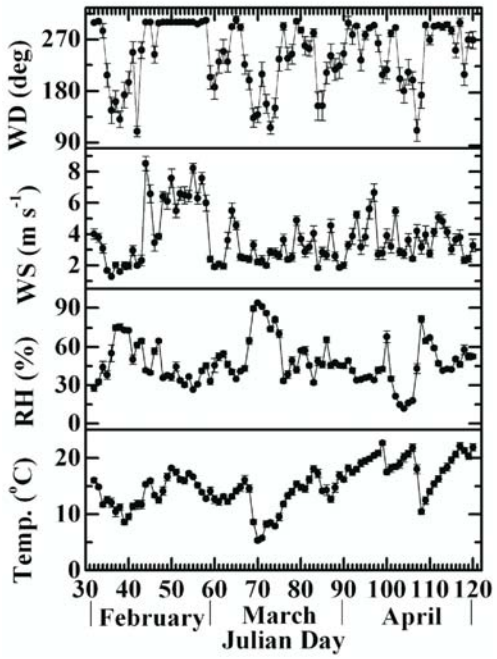

Figure 1. Temporal variations of daily mean meteorological parameters, in the panels bottom to top are temperature, relative humidity, wind speed and wind direction respectively. The bars through them are the standard errors.

3. Results and discussions

3.1 *General meteorology*

The prevailing meteorology at Manora Peak during the period of study comprised of a synoptic northwesterly circulation and a dry ambient with low relative humidity (RH $\sim 50\%$) for most of the days. Figure 1 shows the day-to-day variations of various meteorological parameters during the study period (February to April 2006). Generally, wind speed is higher (> 4 m s^{-1}) during February, gradually slanting through March to April (~ 3 m s^{-1}).

Table 2. *Summary of database during the campaign.*

Months	MWR* number of datasets	OPC number of days	Aethalometer number of days	HVS datasets
February	13	–	26	1
March	25	21	29	2
April	21	28	30	2

*On few days the Langley plots showed different slopes for the FN and AN parts of the same day and on such days each part of the day has been considered as an independent dataset.

The direction of arrival varied between northwest, southwest and southeast. Air temperature was low (between 5 and 18°C) during February and March and increased significantly by April to be in the range 15 to 23°C. The general pattern was in-line with the climatological pattern. The strong winds, coming from the surrounding dusty plains, facilitate transport of the dry airmass carrying the soil dusts into the measurement region. More details regarding the location and prevailing meteorology over the site are given elsewhere (Sagar *et al* 2004; Pant *et al* 2006).

3.2 *Spectral Aerosol Optical Depths (AODs)*

The MWR was operated regularly on all clear/partly-clear sky conditions. The raw data were analysed, following the conventional Langley plot technique (Shaw *et al* 1973), to estimate AODs ($\tau_{p\lambda}$) at ten wavelengths (centered at 380, 400, 450, 500, 600, 650, 750, 850, 935 and 1025 nm with a nominal bandwidth of 5 nm). Normally, the data collected on a day are considered as a single set and daily mean AODs are derived, unless the Langley plot revealed distinctly different slopes in the forenoon (FN) and afternoon (AN) part of the same day. On such days, the FN and AN parts of the data are considered as independent sets and mean AODs are estimated separately for each set. More details on the instrumentation, data analysis, and error budget are already published (Moorthy *et al* 1999; Sagar *et al* 2004). The typical uncertainty in the AOD measurements using MWR is ±0.02. A total of 59 datasets were obtained from the MWR measurements during the campaign period, the monthly distribution of datasets is given in table 2.

The temporal variations of AODs obtained during the campaign period are shown in figure 2, at four representative wavelengths 380, 500, 750 and 1025 nm in panels from bottom to top, respectively. Each point in the plot corresponds to the mean AOD value as discussed earlier, vertical bars through these points represent the standard deviations. The figure reveals two important points:

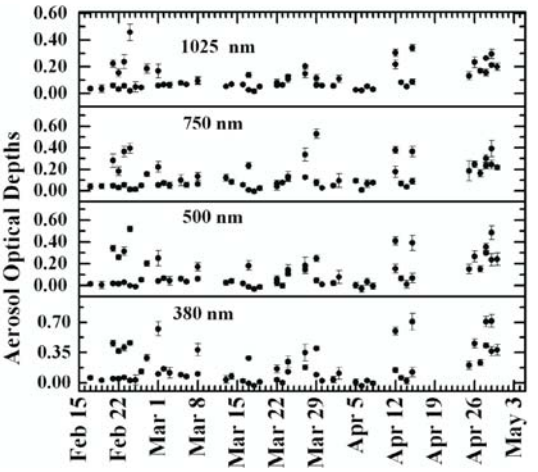

Figure 2. Temporal variations of AODs over Manora Peak, Nainital at four representative wavelengths 380, 500, 750 and 1025 nm are shown respectively from bottom to top panels.

- There is a large day-to-day variation, and
- notwithstanding the day-to-day variations, AOD in general remains very low (∼0.01 to 0.1) during February and March. After April 14, it starts increasing substantially. The increase is more conspicuous at the lower wavelengths and on the lowest AODs. The monthly mean values were 0.14 ± 0.05 for February, 0.09 ± 0.02 for March and 0.20 ± 0.04 for April, 2006.

3.3 *Ångström parameters*

The spectral AODs contain information on the columnar aerosol size distributions as the maximum contributions to AOD at a given wavelength come from the particles whose radii are comparable to that wavelength (McCartney 1976). The simplest way of examining this is to estimate the Ångström parameters α and β in the relation (Ångström 1961) $\tau_{p\lambda} = \beta\lambda^{-\alpha}$, where β is the Ångström turbidity coefficient, α is the wavelength exponent, and λ is the wavelength in μm. The Ångström exponent depends on the size distribution of aerosols and is a measure of the ratio of the concentration of coarse to accumulation mode aerosols, with higher values

representing increased abundance of accumulation mode aerosols, whereas β depends on the total aerosol loading in the atmosphere (Shaw *et al* 1973; Satheesh and Moorthy 1997). The values of α and β are estimated for each day by obtaining linear least square fit to the measured AOD spectra on a log-log scale. In general, the values of α were in the range 0.06 to 1.45 with a mean value of 0.69 ± 0.06 during the campaign period. Higher and positive values of α indicate dominance of fine/accumulation mode aerosols in the aerosol size spectrum, whereas lower and negative values of α indicate the dominance of coarse mode aerosol particles (Moorthy *et al* 2001; Singh *et al* 2005). The values of α at Manora Peak in the present study are comparable to those reported by Ramana *et al* (2004), for Kathmandu and Nagarkot, both being high altitude sites in Nepal, due southeast of Manora Peak, and also within the range of values observed in December 2004 (Pant *et al* 2006). Higher values of α (1.5 to 2.1) are reported by Singh and Singh (2004) for the two western Himalayan sites, having the elevations of $\sim$4.5 km and $\sim$3.4 km respectively. These high values of α result from the reduced concentration of coarse mode aerosols at these high altitude stations. However, when there is an increase in their concentration due to transport by wind etc., then the spectra tend to flatten and α decreases. Based on the measurements from Persian Gulf, Smirnov *et al* (2002) have reported a low value of α ($\sim$0.7) when dust aerosol dominated in the atmosphere as compared to the dust free conditions ($\alpha \sim 1.2$).

3.4 *Number concentration of composite aerosol*

The total number concentration (N_t) of composite aerosols near surface was obtained through the optical particle counter (OPC). The data, obtained at 5 min intervals, are averaged to get the daily mean and their temporal variations are shown in the bottom panel of figure 3. As the instrument was installed only in March, the figure shows the results only for March and April, 2006. There is a slight decrease in N_t towards the end of March followed by a gradual increasing trend in April, so that by the end of April, N_t is more than twice its value in mid-March. In the upper panels, we have shown the temporal variation of the concentrations of accumulation mode (N_a) and coarse mode (N_c) aerosols respectively, which are respectively the sum of the concentrations of channels 1 to 6 (radius $<1\,\mu$m) and 7 to 16 (radius $>1\,\mu$m) of the OPC. It shows a very close resemblance in the nature of variations of N_t and N_a, suggesting that the accumulation mode aerosols contribute to a great extent, to the total number concentration. The monthly mean diurnal variations of N_t, N_a and N_c are shown in figure 4. The points are the monthly means and the vertical bars through them, the standard errors. A well-defined diurnal variation is depicted in all the three panels (though less conspicuously for N_c), with relatively low values during midnight and early morning periods, followed by a gradual increase in the daytime and the diurnal peaks occurring in the afternoon about an hour or so before sunset. The diurnal variation is

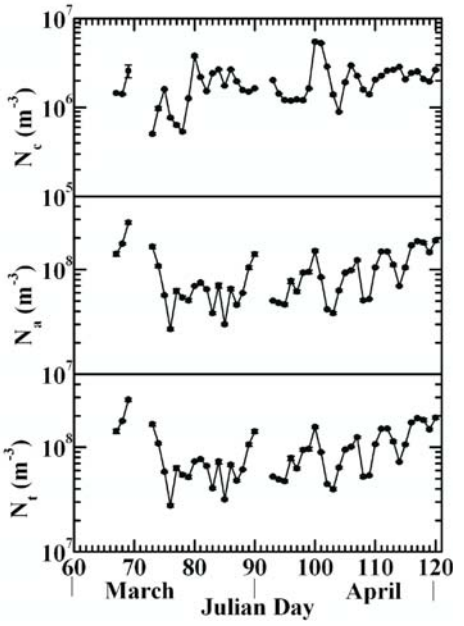

Figure 3. Day-to-day variations of number concentration of composite aerosols near the surface during March and April 2006. The vertical bars through the solid points are standard error.

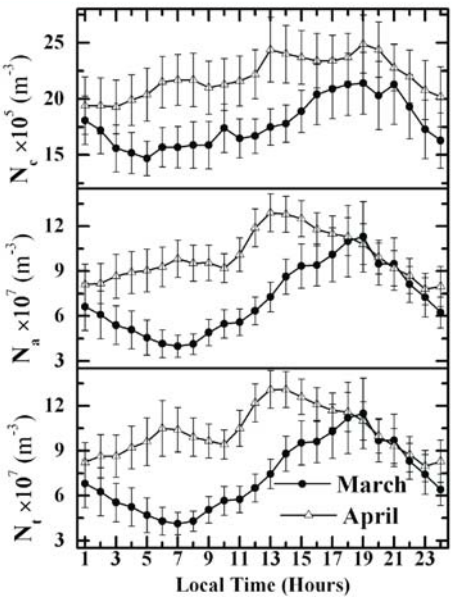

Figure 4. Diurnal variations of aerosol number concentration of composite aerosols near surface during the study period March and April 2006.

seen more prominently in the case of small particles (size $<1\,\mu$m), rather than in the large particles ($>1\,\mu$m) and for the month of March. In April, though the concentrations go up in all the three panels, the diurnal variation becomes less prominent and the afternoon peak occurs earlier. The nature of the diurnal variation over Manora Peak is distinctly different from that seen at other locations in the plains such as Trivandrum (Babu and Moorthy 2002) or Kanpur (Tripathi *et al* 2005), where the diurnal minimum occurs in the afternoon and evening period and the maximum during night and in the morning. This is attributed to the elevated nature of the site, due to which the station is normally above the nocturnal boundary layer. As the day progresses and the land gets heated, the boundary layer deepens and convective eddies start lifting the aerosols and pollutants from the valley below. As this process strengthens, these pollutants rise to the height of the station or the capping inversion breaks and a significant vertical transport occurs leading to an increase in the concentration of aerosols (Pant *et al* 2006). This also contributes partly to the increased aerosol concentration in April and the earlier occurrence of the afternoon peak (because the thermal convections are stronger in April than in March).

The sub-micron/accumulation mode aerosols that dominate the total aerosol number concentration are very important as they provide a large surface area for scattering and as such, the knowledge of the share of sub-micron aerosols to the total aerosol number concentration is very useful for assessing the radiative impacts. With this consideration, we have estimated the accumulation mode fraction (N_a/N_t) and coarse mode fraction (N_c/N_t). It was noticed that the accumulation mode aerosols account for more than 90% of the total aerosol number concentration during the ICARB period.

The number size distributions of near surface aerosols are constructed from the OPC data. The average number-size distributions for March and April 2006 are shown in figure 5. The distributions are quite similar for both the months and resemble a combination of an inverse power-law distribution (in the accumulation regime) and a unimodal log-normal distribution in the coarse regime, with a mode at $\sim 1\,\mu$m. The concentration at this secondary mode is about 1000 times lower than the concentration at the smallest size.

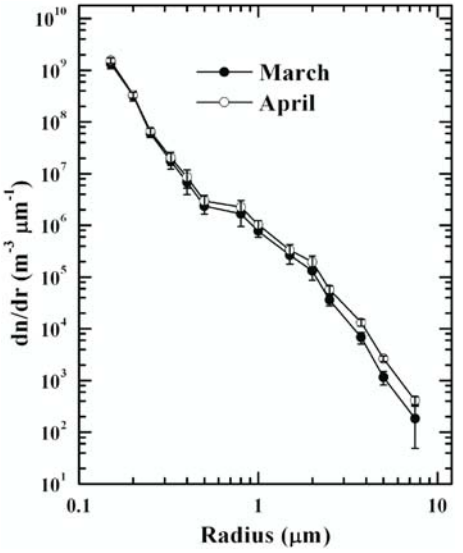

Figure 5. Typical features of monthly mean number size distributions of near surface aerosols during March and April 2006. The vertical bars through the solid points are standard errors.

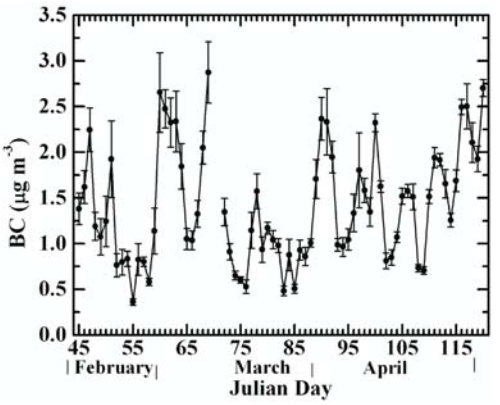

Figure 6. Day-to-day variations of aerosol black carbon mass concentration during February, March and April 2006.

3.5 *Aerosol black carbon (BC) mass concentration*

Aerosol black carbon is considered as a tracer of anthropogenic impacts at remote locations. Being strongly absorbing in the visible and infrared, BC plays a significant role on the regional as well as global radiation budget (Haywood and Shine 1995; Haywood and Ramaswamy 1998; Babu *et al* 2002, 2004). BC is chemically inert and has a long life-time of about 7 to 10 days (Reddy and Venkataraman 1999) in the lower atmosphere, particularly during dry/winter seasons. The individual measurements of BC mass concentration made using the Aethalometer are averaged over each day to get the daily mean values and its temporal variations are shown in figure 6. The figure shows considerable day-to-day variations ranging from 0.36 to 2.87 μg m^{-3}. Nevertheless, M_B values are generally low at Manora Peak in comparison to the other urban locations in India as reported by various investigators (Babu and Moorthy 2002; Babu *et al* 2002, 2004; Latha and Badarinath 2003; Tripathi *et al* 2005).

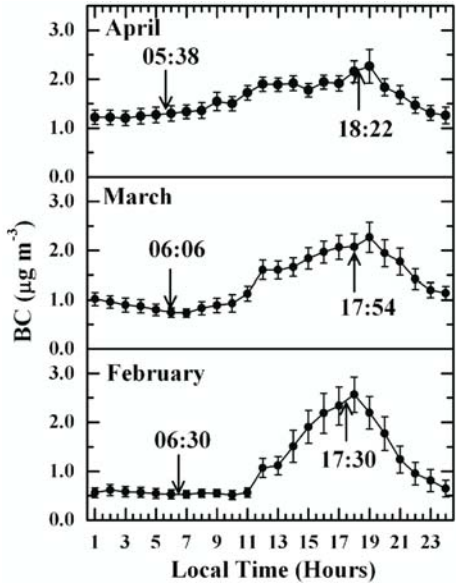

Figure 7. Monthly mean diurnal variation of BC mass concentration during the study period. The arrows represent the sunrise and sunset times for the 15th of respective months.

The monthly mean diurnal variations of M_B are shown in figure 7, which are quite similar to those seen in the aerosol number concentration (N_t), with low values during midnight, early morning hours (up to 11 am), followed by a gradual increase as the day advances to reach the peak late in the afternoon hours and then decrease rapidly after the sunset to reach the midnight low. The diurnal variation is attributed to the ABL dynamics discussed earlier. A similar diurnal variation for BC was also reported by Bhugwant *et al* (2001) from a high altitude station in La Reunion.

3.6 *Mass mixing ratio (F_{BC})*

BC mass fraction F_{BC} (which is the ratio; M_B/M_T) is an important parameter in estimating the aerosol radiative forcing (Babu *et al* 2004). From the simultaneous measurements of mass concentrations of composite aerosols (M_T) using the high volume sampler and M_B using the Aethalometer, F_{BC} was estimated. It varied between the highest value of 1.8% during 27–28 April 2006 and the lowest value of 0.7% during 12 to 13 April 2006. Even the highest value is considerably lower than that (6.5%) reported by Moorthy and Babu (2006) from an island location of Port Blair in the Bay of Bengal and comparable to the value seen over the Arabian Sea during June (Babu *et al* 2004). Based on cruise measurements over the Bay of Bengal, Sumanth *et al* (2004) have reported F_{BC} values of $2.9 \pm 1.1\%$ and $5.8 \pm 0.6\%$, during the post-monsoon and pre-monsoon seasons respectively, while over the Indo Gangetic Plains, Tripathi *et al* (2005) have reported F_{BC} to range between 7 and 15% at Kanpur. The very low values in our study signify the pristine nature of the site.

4. Conclusions

Measurements of spectral AODs, concentration and size distributions of near surface aerosols are carried out at a remote, high altitude station Manora Peak in the Himalayas during ICARB. The main results of our study are as follows:

- The AODs are significantly low (<0.1 at 500 nm) during clear day conditions and in the months of February and March. The average AOD increases by a factor of 2 in April.
- The AOD spectra are steeper with high (>1) values for the Ångström wavelength exponent α during clear days with low AOD. On hazy days, with high AOD, the spectrum flattens and α falls. The mean value of α during the campaign period was 0.69 ± 0.06.
- Mass concentration of BC and number concentration of composite aerosols showed significant diurnal variation with a late afternoon peak and early morning low. The diurnal variations are mainly attributed to the dynamics of atmospheric boundary layer, which lifts up aerosols from the polluted valley surface to the peak.
- The aerosol number size distributions showed bimodal characteristics, with a secondary mode occurring at $r \sim 1.0\,\mu$m, while the primary mode does not appear explicitly.
- The accumulation mode aerosol contributes as much as 90% to the total aerosol number concentration.
- The mass mixing ratio (F_{BC}) of BC with composite aerosols varies between 0.7% and 1.8% and is very low compared to the values reported for the plains.

Acknowledgement

This work was carried out as a part of ICARB campaign, under the ISRO-Geosphere Biosphere Program.

References

Ångström A 1961 Techniques of determining the turbidity of the atmosphere; *Tellus* **13** 214–223.

Babu S S and Moorthy K K 2002 Aerosol black carbon over a tropical coastal station in India; *Geophys. Res. Lett.* **29(23)** 2098, doi: 10.1029/2002GL015662.

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; *Geophys. Res. Lett.* **29(18)**: art. No. 1880.

Babu S S, Moorthy K K and Satheesh S K 2004 Aerosol Black Carbon over Arabian Sea during Inter Monsoon and Summer Monsoon Seasons; *Geophsys. Res. Lett.* **31** L06104, doi: 10.1029/2003GL018716.

Bhugwant C, Bessafi M, Riviere E and Leveau J 2001 Diurnal and seasonal variation of carbonaceous aerosols at a remote MBL site of La Reunion Island; *Atmos. Res.* **57** 105–121.

Haywood J M and Shine K P 1995 The effect of anthropogenic sulfate and soot aerosol on the clear sky planetary radiation budget; *J. Geophys. Res.* **22(5)** doi: 10.1029/95GL00075 603–606.

Haywood J M and Ramaswamy V 1998 Global sensitivity studies of the direct forcing due to anthropogenic sulphate and black carbon aerosols; *J. Geophys. Res.* **103** 6043–6058.

Latha K M and Badarinath K V S 2003 Black carbon aerosols over tropical urban environment – A case study; *Atmos. Res.* **69** 125–133.

McCartney E J 1976 Optics of the Atmosphere (New York: John Wiley & Sons) 135–136.

Moorthy K K, Niranjan K, Narasimhamurthy B, Agashe V V and Murthy B V K 1999 Aerosol Climatology over India, 1. ISRO GBP MWR network and database; *Scientific Report ISRO GBP SR 03* **99** Indian Space Research Organization, India.

Moorthy K K, Saha A, Prasad B S N, Niranjan K, Jhurry D and Pillai P S 2001 Aerosol optical over peninsular India and adjoining oceans during the INDOEX campaigns: Spatial, temporal and spectral characteristics; *J. Geophys. Res.* **106** 28,539–28,554.

Moorthy K K, Satheesh S K and Babu S S 2006a ICARB – An Integrated Campaign for Aerosols, gases and Radiation Budget over India; *Proc. SPIE* **6408** 64080P-1,7, 0277-786X/06/$15, doi: 10.1117/12.696110.

Moorthy K K and Babu S Suresh 2006b Aerosol black carbon over Bay of Bengal observed from an island location, Port Blair: Temporal features and long-range transport; *J. Geophys. Res.* **111** D17205 doi: 10.1029/2005JD006855.

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; *J. Geophys. Res.* **111** D17206 doi: 10.1029/2005JD006768.

Ramana M V, Ramanathan V and Podgorny I A 2004 The direct observations of large aerosol radiative forcing in the Himalayan region; *J. Geophys. Lett.* **31** L05111 doi: 10.1029/2003GL018824.

Reddy M S and Venkataraman C 1999 Direct radiative forcing from anthropogenic carbonaceous aerosols over India; *Curr. Sci.* **76** 1005–1011.

Sagar R, Kumar B, Dumka U C, Moorthy K K and Pant P 2004 Characteristics of aerosol spectral optical depths over Manora Peak: A high altitude station in the central Himalayas; *J. Geophys. Res.* **109** D06207 doi: 10.1029/2003JD003954.

Satheesh S K and Moorthy K K 1997 Aerosol characteristics over coastal regions of the Arabian Sea; *Tellus* **49B** 417–428.

Shaw G E, Regan J A and Herman B M 1973 Investigations of atmospheric extinctions using direct solar radiation measurements made with a multiple wavelength radiometer; *J. Appl. Meteor.* **12** 374–380.

Singh S and Singh R 2004 High-altitude clear-sky direct solar ultraviolet irradiance at Leh and Henle in the western Himalayas: Observations and model calculations; *J. Geophys. Res.* **109** D19201 doi: 10.1029/2004JD004854.

Singh S, Nath S, Kohli R and Singh R 2005 Aerosols over Delhi during pre-monsoon months: Characteristics and effects on surface radiation forcing; *Geophys. Res. Lett.* **32** L13808 doi:10.1029/2005GL023062.

Smirnov A, Holben B N, Dubovik O, O'Neill N T, Eck T F, Westphal D L, Goroch A K, Pietras C and Slutsker I 2002 Atmospheric Aerosol Optical Properties in the Persian Gulf Region; *J. Atmos. Sci.* **59** 620–634.

Sumanth E, Mallikarjuna K, Joshi Stephen, Moole Mahesh, Vinoj V, Satheesh S K and Moorthy K K 2004 Measurements of aerosol optical depths and black carbon over Bay of Bengal during post-monsoon season; *Geophys. Res. Lett.* **31** L16115, doi: 10.1029/2004GL020681.

Tripathi S N, Dey S, Tare V and Satheesh S K 2005 Aerosol black carbon radiative forcing at an industrial city in northern India; *Geophys. Res. Lett.* **32** L08802, doi: 10.1029/2005GL022515.

MS received 17 July 2007; revised 21 September 2007; accepted 29 October 2007