Aircraft measurements of aerosol black carbon from a coastal location in the north-east part of peninsular India during ICARB

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During the Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB) over India, high-resolution airborne measurements of the altitude profiles of the mass concentrations (M_B) of aerosol black carbon (BC) were made off Bhubaneswar (BBR, $85.82°E, 20.25°N$), over northwest Bay of Bengal, in the altitude region upto 3 km. Such high-resolution measurements of altitude profiles of aerosols are done for the first time over India. The profiles showed a near-steady vertical distribution of M_B modulated with two small peaks, one at 800 m and the other at ~ 2000 m. High resolution GPS (Global Positioning System) sonde (Vaisala) measurements around the same region onboard the research vessel *Sagar Kanya* (around the same time of the aircraft sortie) revealed two convectively well mixed layers, one from ground to ~ 700 m with an inversion at the top and the other extends from 1200 m to ~ 2000 m with a second inversion at ~ 2200 m and a convectively stable region in the altitude range 700–1200 m. The observed peaks in the M_B profile are found to be associated with these temperature inversions. In addition, long-range transport from the Indo-Gangetic Plain (IGP) and deserts lying further to the west also influence the vertical profile of BC. Latitudinal variation of M_B showed a remarkable land ocean contrast at the 500 m altitude (within the well mixed region) with remarkably lower values over oceans, suggesting the impact of strong sources over the mainland. However, above the ABL (at 1500 m), the latitudinal variations were quite weak, and this appears to be resulting from the impact of long-range transport. Comparison of the altitude profiles of M_B over BoB off BBR with those obtained during the earlier occasion over the inland stations of Hyderabad and Kanpur showed similarities above ~ 500 m, with M_B remaining around a steady value of $\sim 1\,\mu g\ m^{-3}$. However, large differences are seen within the ABL. Even though the observed M_B values are not unusually high, their near constancy in the vertical column will have important implications to radiative forcing.

1. Introduction

Aerosol black carbon (BC) or soot, the byproduct of all incomplete combustion processes, is believed to be mostly of anthropogenic origin and is generally in the fine, submicron size range. As such, it has a long atmospheric lifetime (e.g., Babu and Moorthy 2002) making them amenable for easy transport both horizontally, and vertically to higher regions of the atmosphere. In the nascent form, graphitic carbon is hydrophobic, but eventually becomes hydrophilic by oxidation or after coating by soluble aerosols such as sulfate and organics. Thus, a significant fraction of BC can

be in an internally mixed state in the atmosphere, which affects its nucleation and optical properties (Möhler *et al* 2005) and makes the quantification of its impact on climate difficult (Clarke *et al* 2004). Because of its strong absorption over a wide range of wavelengths, BC contributes significantly to atmospheric warming (Jacobson 2001) and its forcing potential strongly depends on the vertical profile (Haywood and Ramaswamy 1998; Satheesh 2002). It also contributes to indirect forcing of climate by acting as cloud condensation nuclei (Lohmann *et al* 2000). The presence of BC aerosols are identified and even quantified (even though in a limited way) in upper troposphere and lower stratosphere (Pueschel *et al* 1992; Blake and Kato 1995; Strawa *et al* 1999). Thus the study of vertical distribution of BC has immense relevance in aerosol characterization. Despite, available information is limited even globally and especially over India except for a few recent efforts (Moorthy *et al* 2004; Tripathi *et al* 2005).

During the Integrated Campaign for Aerosol gases Radiation Budget (ICARB, Moorthy *et al* 2006 and this issue) extensive observations on the altitude profiles of BC were made in the lower troposphere (upto 3 km from ground) onboard a propeller aircraft (beechcraft 20) of the National Remote Sensing Agency (NRSA). In all, 26 sorties were made from 5 bases during the campaign; two each along the east (Bhubaneswar and Chennai) and west coasts (Thiruvananthapuram and Goa) and one from the inland station Hyderabad. In this paper, we present the results obtained from the measurement of the altitude variation of BC off Bhubaneswar (BBR, 85.82°E, 20.25°N), over the Bay of Bengal (BoB) in the east coast of India.

2. Experimental setup

The black carbon mass concentration (M_B) measurements were made using a portable, single channel, aethalometer (model AE 42 of Magee Scientific, Hansen *et al* 1996). It is a simple, rugged instrument for field experiments of long duration and provided data almost without a break. The details of the sampling technique and configuring the aethalometer in an aircraft are available in Moorthy *et al* (2004) and Tripathi *et al* (2005). The instrument was mounted inside the cabin of the aircraft, which was kept unpressurised. The ambient air was aspirated through a stainless steel pipe, fitted to the body of the aircraft under its nose, such that the inlet opens into the incoming air as the aircraft flies. The instantaneous position of the aircraft at every second was recorded using a global positioning system (GPS). The flight tracks
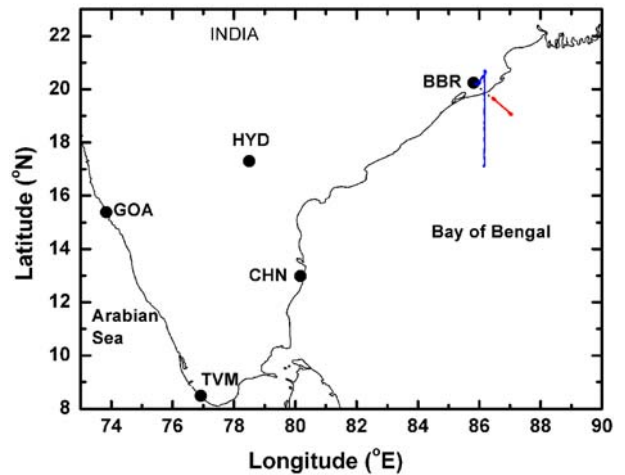

Figure 1. The flight paths of the aircraft from Bhubaneswar. The red line corresponds to the track in which the high resolution vertical profiling was done at 8 levels and the blue line corresponds to the sortie used for examining latitudinal gradient at two altitudes.

of the sorties performed from BBR are shown in figure 1. The inlets of the instrument was connected to the pipe using a Teflon tube, ∼1.5 m long. The aethalometer estimated M_B by measuring the change in the transmittance of its quartz filter tape on to which the particles impinge. The flow rate was determined by its internal pump operated under standard mass flow condition and the timebase is programmable. The measured concentrations were corrected for the change in pumping speed caused by change in the ambient pressure as the aircraft climbs to different height levels following the principle outlined in Moorthy *et al* (2004). Reports are available in the recent literature on uncertainties in the aethalometer estimated BC (for e.g., Weingartner *et al* 2003; Arnott *et al* 2005; Sheridan *et al* 2005 and Corrigan *et al* 2006) with several suggestions to account for it and these were followed in analyzing the data. In the present case we used an amplification factor of 1.9 and an 'R' factor (shadowing effect) of 0.88.

During the flight off BBR, the aethalometer was operated at a time base of 2 min and a flow rate of 6.5 standard litres per minute (under standard temperature (T_0, 293 K) and pressure (P_0, 1017 hPa)). However, because the ambient pressure decreases while the aircraft climbs higher, the pumping speed increases to maintain the set mass flow rate, and as such, more volume of air is aspirated. The actual volume V of air aspirated at an ambient pressure P and temperature T is thus

$$V = V_0 \cdot \frac{P_0}{P} \cdot \frac{T}{T_0}. \qquad (1)$$

Since the measured BC concentrations (M_B^*) are calculated based on standard flow rate V_0, the actual BC concentration M_B, after correcting for the change in flow rate, is:

$$M_B = M_B^* \left[\frac{P_0 T}{P T_0} \right]^{-1}. \qquad (2)$$

Following the above equation, each measurement of M_B^* was converted to the true BC concentration M_B.

The aircraft sorties were made from Bhubaneswar (BBR, 85.82°E, 20.25°N), an urban location located towards the east coast of India and very close to the eastern end of Indo-Gangetic Plain. The eastern part of Indo-Gangetic Plain is 'the coal belt' of India and has a cluster of coal-based thermal power plants, which are considered as significant emitters of BC aerosols in this region (Nair *et al* 2007). In addition, the vehicular emission as well as the domestic activities in and around the urban area of BBR also contribute to the BC concentration near the sampling site.

3. Results and discussion

3.1 *Altitude profile of M_B*

In general, all airborne measurements were carried out during the period 09:30 to 12:30 LT. This means that the observations commenced nearly four hours after the local sunrise ($\sim$05:30 LT). Thus the boundary layer has fully developed and strong convective motions have set in by the time profiling has started. The ambient temperatures were in the range 35 to 40°C at the BBR airport during this period, implying strong thermal convections. The altitude distribution of M_B (after the correction mentioned earlier) from the aircraft measurement made on 28 March 2006 is shown in figure 2. On this day, the flight took off at 09:26 LT and leveled at an altitude of 500 m, about 50 km off the coast. The profiling was done over the ocean (BoB) at eight different levels (namely 500 m, 800 m, 1100 m, 1400 m, 1700 m, 2000 m, 2500 m and 3000 m above AGL (average ground level)) to get a good height resolution (which was not available in earlier measurements, Moorthy *et al* 2004; Tripathi *et al* 2005). At each level, the aircraft flew steadily for about 12 min, and the data obtained during this period are corrected using equation (2) and averaged to obtain the mean value representing that altitude. This procedure was repeated at each altitude. The data obtained during the aircraft manoeuvers were rejected (Moorthy *et al*
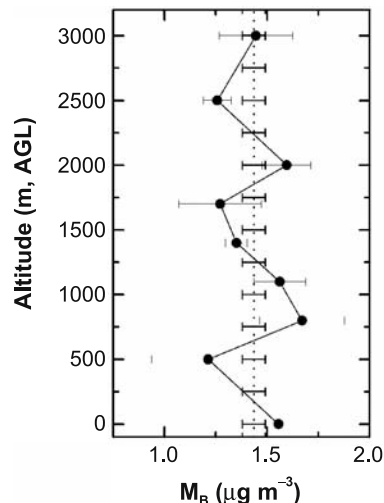

Figure 2. Altitude profile of M_B off BBR on 28 March 2006. The points are mean concentration at each level and the bars through them are the standard errors. The dotted vertical line with horizontal bar shows the column mean value of M_B with standard error.

2004). The solid circles in figure 2 represent this mean value at each altitude level, and the horizontal bars through the points represent the standard error of the mean, a statistical parameter signifying the uncertainty in M_B at the respective heights due to the natural atmospheric variabilities. These are much higher than the intrinsic errors in the instrument. During the same period, independent measurements of M_B were also being made onboard the ship *ORV Sagar Kanya*, along the coastal water off BBR as part of the ocean segment of ICARB (Moorthy *et al* this issue) using another aethalometer, which was intercompared with the one onboard the aircraft before the campaign under the same ambient conditions. The surface level value of M_B (for '0' altitude) is obtained as the average of the shipboard measurements conducted in the same region, on days closest to the sortie.

The altitude distribution of M_B in figure 2 shows a near steady vertical distribution with two small peaks at 800 m and 2000 m. The mean value of M_B (for the entire altitude range) was 1.43 ± 0.06 μg m^{-3} and this is shown by the vertical dotted line in figure 2 with the horizontal bars on it representing the standard deviation of the mean. The peaks and valleys in the profile, though not highly developed, are significant deviations from the mean. The figure reveals several interesting features.

- At the surface level (over the ocean) M_B is $\geq 1.5\,\mu$g m^{-3}. It initially decreased with height to reach 1.2 μg m^{-3} at 500 m and increased to attain a peak value of 1.7 μg m^{-3} at $\sim$800 m.
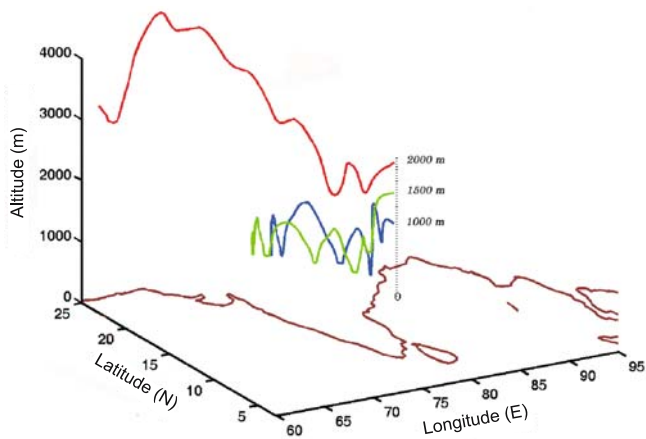
Figure 3. A 3D representation of the 5-day airmass back trajectories arriving at 1000 m, 1500 m and 2000 m over the region (86.7°E, 19.4°N) where vertical profiling was done. The study region is projected over to the ocean surface by the dotted line.

- Above 800 m, M_B decreased gradually to reach the lowest value of $\sim 1.27 \pm 0.2\,\mu g\,m^{-3}$ at 1700 m.
- Above 1700 m, M_B again increased and the second peak occurred at 2000 m above the surface where the value of M_B was $\sim 1.6\,\mu g\,m^{-3}$.

3.1.1 *Role of long-range transport*

Thus, significant amounts of BC concentrations are observed above 500 m. In order to examine the role of long range transport from potential source regions for the high BC concentrations above the atmospheric boundary layer (ABL) at these levels, 5-day back trajectories were computed using Hybrid Single Particle Legrangian Integrated Trajectory (HYSPLIT, http://www.arl.noaa.gov/ready/hysplit4.html) model of the National Oceanic and Atmospheric Administration (NOAA) at 1000 m, 1500 m and 2000 m above the study location and are shown in figure 3. It shows that the trajectories reaching at 1000 m and 1500 m above the surface are originating from the Indo-Gangetic Plains and are traveling mainly through the boundary layer before reaching the study location. In sharp contrast to this, the trajectory at 2000 m, originating from the west Asian region ($\sim 60°$E), clearly shows the existence of a pathway, which favours advection of aerosols from west Asia, along northwest and central India to the observing site. It is also important to note that the trajectory originated at 3 km over west Asia, traveled along the upper region (> 2 km) till it arrived at the measurement site. Thus, there is a significant contribution of (in the free troposphere) aerosols originating

at distant sources and subsequently transported horizontally by upper air motions. It is important to note at this juncture that increased advection from the west Asian region resulted in significant increase in AOD over Indo-Gangetic Plain during ICARB (Beegum *et al* this issue). It is also important to note that even though these M_B values are not abnormally high (compared to the surface values) the near-steady nature of the profile up to 3 km will have important implications to radiative forcing.

Several investigators have reported the existence of aerosol layers with enhanced concentration above the atmospheric boundary layer (ABL) over the Indian region. From the vertical profile of aerosol back scatter measured using micro pulse lidar (MPL) at Visakhapatnam (17.7°N, 83.3°E) located on the east coast of India (near to the present profiling region), Niranjan *et al* (2007) reported aerosol layers with increased extinction and having a few kilometer thickness in the height region between 1.6 and 5 km during the summer months (March–April) of 2005 and 2006. Based on back trajectory analysis, they inferred that these layers are caused by airmasses originated from Arabia during 60% of the cases, while in the rest of the cases they originated from the Indian subcontinent. Based on the MPL measurements from Bangalore, Satheesh*et al* (2006) also reported the existence of aerosol layers above the ABL (between 1.0 and 1.5 km).

3.1.2 *Role of the ABL*

In the ocean segment of ICARB, regular daily launches of high resolution GPS balloonsondes were made from *ORV Sagar Kanya*. These provided information on the thermodynamics of the atmosphere upto ~ 25 km. In figure 4, we have shown the vertical profiles (upto 3 km) of temperature (T), potential temperature (θ), wind speed (m s^{-1}) and wind direction (°, clockwise from north) obtained closest in space and time to the day of aircraft measurements.

The potential temperature 'θ' was calculated as

$$\theta = T \left(\frac{P_0}{P} \right)^{\kappa}, \qquad (3)$$

where $\kappa = R/c_p$; R is the specific gas constant for dry air and c_p is the specific heat capacity of dry air at constant pressure.

Figure 4 shows several structures in all these parameters. The most significant are the presence of two strong inversions in θ, one at ~ 700 m and the other at ~ 2200 m, and a less pronounced one at
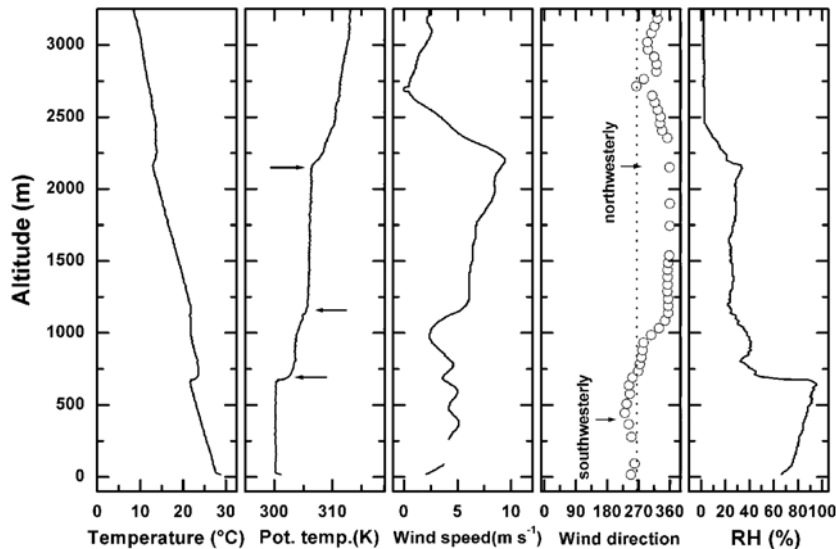
Figure 4. Vertical profile of meteorological parameters obtained from the GPS sonde (Vaisala) measurements off Bhubaneswar. The arrows in the potential temperature panel identify the increases discussed in the text.

1200 m (all being identified with arrow marks in the figure). From ground to 700 m (the region of first inversion in θ) the potential temperature remains constant (300 K) implying an adiabatic condition favouring the prevalence of a convectively well-mixed region, extending upto 700 m. The height of the mixed layer is the altitude of the base of the elevated inversion, which separates the mixed layer from the stable layer above and from the figure it is 700 m. In this region, weak ($\sim 4\,\mathrm{m\,s^{-1}}$) southwesterly winds are observed. Above that θ increases with altitude showing a sub-adiabatic lapse rate and a convectively stable atmospheric region upto 1200 m. Above 1200 m, the lapse rate again changes to adiabatic condition (θ is steady with altitude), which extends upto ~ 2100 m. In this region, the wind speeds are higher (up to $\sim 10\,\mathrm{ms^{-1}}$) (as compared to the weak southwesterly winds ($\sim 4\,\mathrm{ms^{-1}}$) in the mixed layer below), and are basically westerlies/northwesterlies implying strong advection from the dry landmass even beyond 3 km. The sharp decrease in relative humidity (RH) above 700 m, in figure 4, also corroborates advection of a dry airmass in this region. This, along with the back trajectory at 2000 m level in figure 3 leads strong support to the presence of a different airmass probably associated with long-range transport from the western dry-arid and semi-arid regions. The convective region below and the elevated inversion above (which act as a lid) significantly dampening vertical mixing of air and aerosols and favours transport to long distances. The presence of such long range transport has also been reported at Chennai, well down BBR in the east coast of India by Moorthy *et al*

(this issue) based on lidar and back trajectory analysis.

3.2 *Comparison of the profile off BBR with earlier measurements over inland stations*

A comparison of M_B profile obtained off BBR over the BoB with those obtained over Kanpur (Tripathi *et al* 2005) and Hyderabad (Moorthy *et al* 2004), in different years, but almost in the same seasons, during the forenoon hours is shown in figure 5. At Hyderabad, the ABL extends upto
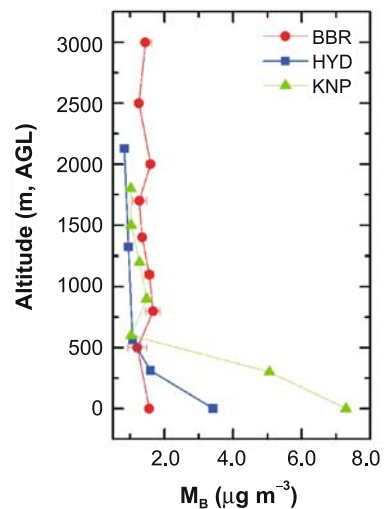

Figure 5. Comparison of the altitude profile of BC observed over BoB off BBR with those obtained over Hyderabad (blue line with square symbol) and Kanpur (green line with triangle) during earlier airborne measurements.

~800 m during the profiling; but there was no indication of long-range transport. At Kanpur, there was an elevated layer of enhanced BC at ~1 km, which was attributed to long-range transport (Tripathi *et al* 2005). However, while comparing these profiles over different regions, it is to be borne in mind that the atmospheric measurements are subject to inherent large, natural variabilities. In order to have a statistically significant data, which represents a particular region in a given season, an average of the large number of such measurements from the same region spanning the entire season is always better. Nevertheless, it is important to note the most striking difference of the profile off BBR as revealed by the limited observations, which are:

- Over Hyderabad and Kanpur, M_B showed a sharp decrease with height from the surface upto ~500 m. While at Hyderabad, the decrease in M_B was from ~3.5 μg m^{-3} at the surface to ~1 μg m^{-3} at 500 m, at KNP it was much more sharp, from 7 μg m^{-3} at surface to 1 μg m^{-3} at 500 m. These decreases are attributed mostly to the sharp decrease in the source strength. However, as there are no primary sources of BC over the ocean, this decrease is only marginal in the BoB profile.
- Above the convectively mixed region (~500 to 700 m), however, M_B remained at a nearly steady level with altitude, with the lowest value over Hyderabad and highest off BBR.
- While the Hyderabad profile did not show any structures in the profile, KNP and BBR profiles showed a peak (though weak) at ~800 m. The KNP profile extended only upto 1800 m. The profile off BBR shows the existence of small structures at even beyond 2 km AGL, which are mainly attributed to the thermodynamics of the atmosphere and long-range transport. As low-level clouds would be present at or even below 3 km, our observations mean that significant amounts of BC would be with in and above clouds. This enhances the radiative forcing of the atmosphere, than if the entire BC were confined only within the ABL (Haywood and Ramaswamy 1998; Satheesh 2002).

It is also interesting to compare the altitude distribution M_B with those reported from measurements made elsewhere by other investigators with special focus to the Asian region. Based on the C-130 aircraft experiments over Indian Ocean during INDOEX, Mayol Bracero *et al* (2002) indicated the presence of substantial amounts of BC, as high as ~6 μg m^{-3} at 2.9 km, above the marine atmospheric boundary layer. From aircraft measurements during TRACE A experiment over Brazilian forests, very high values of BC upto 12 μg m^{-3} were reported at altitudes 2.5 km (Pereira *et al* 1996). Aircraft measurements during ACE-Asia over Sea of Japan, East China Sea, and Philippine Sea, by Mader *et al* (2002) showed that M_B values below 3 km ranged from 0.20 to 1.8 μg m^{-3}. Based on the measurements of BC onboard aircraft as a part of the Arctic Gas and Aerosol Sampling Program (AGASP) over Barrow, Alaska, Hansen and Rosen (1984) reported substantial concentrations of BC at all altitudes in the Arctic troposphere. They reported a very pronounced layer below 1 km altitude (with a peak concentration of ~1.2 μg m^{-3} between 400 and 500 m altitude) and a substantial concentration of 0.1 μg m^{-3} upto 5 km during the flight conducted on 11 March 1983. During the flight conducted on 15 March 1983, even though the vertical distribution of BC was different, the total air column burden was similar to the former flight. During the AGASP-II conducted in April 1986, Hansen and Novakov (1989) observed BC values typically ranged from 0.3 to 0.5 μg m^{-3} at lower altitudes, decreasing gradually to 0.025 to 0.1 μg m^{-3} at 8 to 10 km. Based on the measurements made during April 1992, Hansen *et al* (1997) reported an increase in BC concentrations from 0.1 to 0.2 μg m^{-3} below, to 0.8 to 1.0 μg m^{-3} above 850 hpa over East Siberian Sea (~74°N, 152°E).

3.3 *Latitudinal variation in M_B: Land–ocean contrast*

With a view to examining the latitudinal variations of BC and its altitude structure, we conducted another sortie on March 27, 2006 (blue line in figure 1), during which the aircraft made a north-south sampling over the BoB, off BBR and M_B was estimated for two heights, 500 m (within the ABL) and 1500 m (above the ABL). During this, the aircraft covered a latitudinal span of ~3.6°, which was much higher than the spatial coverage in the earlier sorties at HYD and KNP. The limit of the latitudinal coverage was basically due to the endurance of the aircraft. The results are shown in figure 6. The flight originated from BBR (around 20.66°N) and went southward over the BoB (upto ~17.09°N) crossing the coastline in between. As the instrument was operated with a timebase of 1 min and the aircraft was moving at a speed of ~360 km per hour, measurements were available on an average at every 6 km along the track. At 500 m level, M_B showed high values with large fluctuations over land as well as coastal regions over ocean (upto 19.2°N) but very close to the mainland, about 50 km off the coastline (at ~19.7°N). In this region M_B values varied between 1.0 μg m^{-3} and 5 μg m^{-3} with a mean value of 3.0±0.3 μg m^{-3}.
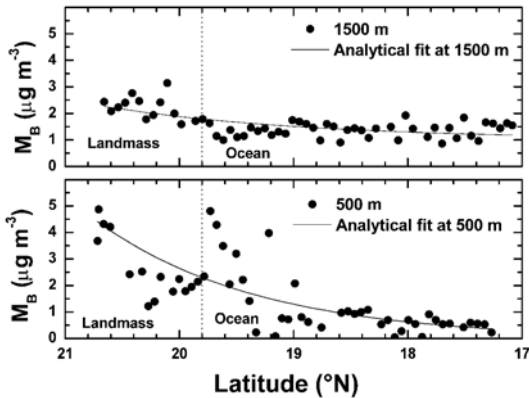
Figure 6. Latitudinal variation of BC mass concentration at 500 m level (bottom panel) and 1500 level (top panel) over BoB off BBR. The curves in each panel represent the best-fit exponential growth curves to the measurements. The dotted vertical line parallel to the Y-axis represents the coastline that separates the landmass from the ocean. The abscissa is shown with the starting point of the sortie as origin and latitude decreasing to the right.

Table 1. *Latitudinal gradient of M_B at 500 and 1500 m.*

Altitude	A	B	Λ_D (in km)	R^2
500	0	0.0016	140 ± 20.0	0.57
1500	1.03	0.0067	170 ± 100.5	0.44

The large fluctuations are attributed to the local emission, being mixed by the turbulent eddies arising from thermal convection. Further to the south, over the ocean, M_B values reduced significantly to below $1\,\mu$g m^{-3}, still showing minor variations (between $0.05\,\mu$g m^{-3} and $1\,\mu$g m^{-3} with a mean value of $0.9 \pm 0.14\,\mu$g m^{-3}). At 1500 m level, however the variations were considerably reduced because the impacts due to local sources and turbulent mixing are well shielded by the capping inversion at ~ 700 m and showed a mean value of $2.2 \pm 0.1\,\mu$g m^{-3} over land. Over the ocean the values were lower (between $1\,\mu$g m^{-3} and $2\,\mu$g m^{-3}) with a mean value of $1.35 \pm 0.04\,\mu$g m^{-3}. (The values given after the $\pm$ symbol for each mean value are the standard deviation of the mean). However, the land–ocean contrast in M_B is highly subdued at 1500 m compared to that at 500 m level.

The latitudinal variations in M_B at 500 m level and 1500 m level, shown in figure 6, have been parameterized using an exponential growth function of the form

$$M_B(\Lambda) = A + B \exp\left(\frac{\Lambda}{\Lambda_D}\right), \qquad (4)$$

where A is an offset (which might represent the non-local contribution to BC), $M_B(\Lambda)$ is the value of M_B at latitude $\Lambda°$, B is the amplitude and Λ_D is the scaling length for an e-fold growth. The solid line in figure 6 represents the fit to equation (4) through the measurement points. A good fit is apparent with moderate to high values of squared correlation coefficients (R^2), which are given in table 1, along with other parameters of equation (4).

The table shows that the variation at 500 m level has little offset, and the distribution is mostly attributed to local effects (like local sources and convective mixing). As such, it has a much shorter scaling length, implying steeper gradient, and has a higher correlation to the analytical function. Compared to this, at 1500 m, there is a significant non-local contribution of $\sim 1\,\mu$g m^{-3} of BC (which could be attributed to the long range transport and/or the background) over which there is a much slower spatial variation with a longer scale length of 170 km. This non-local contribution to aerosol loading at higher levels have been observed along the east coast of India and in the IGP in earlier studies also (Nair *et al* 2007; Niranjan *et al* 2007), who have attributed this to advection from the continental regions including west Asia and north west India. These non-local sources appear to play a major role in determining BC concentrations at higher altitudes.

Another interesting feature revealed in figure 6 is that while at 500 m level M_B over the land was always higher than $1\,\mu$g m^{-3} and over ocean it was always less than $1\,\mu$g m^{-3}; at the 1500 m (above the convective boundary layer) the scenario was different, with M_B values over the ocean being always higher than the corresponding value at 500 m (over the entire latitude region covered). In other words, over the ocean, M_B at 1500 m was higher than that at 500 m, again confirming non-local sources contributing to M_B in the free troposphere. In the latitudinal variation of BC reported by Moorthy *et al* (2004) and Tripathi *et al* (2005) over the inland stations (though in their studies the latitudinal coverages were much shorter and the measurements were confined only over the landmass) we note that, while over Hyderabad Moorthy *et al* (2004) reported a weak increasing trend within the ABL, as the aircraft moved out of the urban centre, they did not find any gradient at higher altitudes. Tripathi *et al* (2005), on the other hand, reported a weak decreasing trend with latitude, as the aircraft moved out of the industrial area towards the rural area, at 300 m and 600 m altitudes. However, at 900 m altitude, they reported a weak increasing trend similar to the pattern seen off BBR. It suggests the possibility of regional differences in the

latitudinal gradients, caused apparently by long-range transport.

3.4 *Implications*

As stated earlier, the altitude distribution of BC has important implications in aerosol radiative forcing and the influence of BC on cloud properties. Tripathi *et al* (2005) have reported that the difference in the short-wave, clear sky forcing between the steadily decreasing and increasing BC aloft is as much as a factor of 1.3. Lubin *et al* (2002) have shown that this difference can be as much as a factor of two in the case of long wave. Haywood and Ramaswamy (1998) have reported from GCM simulation that the direct radiative forcing of a BC aerosol layer increases approximately by a factor of 5, as the layer is moved between the surface and 20 km. Satheesh (2002) reported that the elevated BC layer over landmass with high reflectance or over scattering aerosol/cloud layer will enhance the atmospheric forcing and can even reverse the 'white house effect' of aerosols. Based on model simulation and observation during INDOEX, Ackerman *et al* (2000) reported that enhanced layer of BC aerosols reduce the cloud cover by BC induced atmospheric heating and hence offset the aerosol induced radiative cooling at the top of the atmosphere on a regional scale.

4. Conclusions

Altitude distribution of the mass concentrations of aerosol black carbon over the BoB off Bhubaneswar (BBR) was obtained at high spatial resolution. In addition, the latitudinal gradients in M_B at different altitude regions (within and above ABL) were examined. The investigation revealed:

- A nearly steady vertical distribution of M_B superposed with small fluctuations lead to two peaks (at 800 m and 2000 m) over the mean value of $1.43 \pm 0.06\,\mu\text{g m}^{-3}$.
- Examination of the vertical structure of the atmosphere using high resolution GPS sonde ascents over the same region show that these peaks were associated with the occurrence of temperature inversions; the lower one occurring around the region of the top of the convective marine atmospheric boundary layer while the peak at 2000 m was associated with the elevated inversion.
- Significant amount of BC is observed above the MABL, even beyond 2 km.
- A comparison of the profile obtained over BoB off BBR with those reported over the continental

locations (Hyderabad and Kanpur) in earlier investigations showed that while the profile over the inland locations showed sharp decrease in concentration with height within the ABL (upto $\sim 500\,\text{m}$) probably due to sharp decline in local surface impacts the decrease was much weaker over the BoB. Above the ABL, nearly the same value of $1\,\mu\text{g m}^{-3}$ were observed at all the locations suggesting significant quantities of elevated BC.

- Latitudinal distribution of M_B shows that at 500 m level, M_B over land is always higher than $1\,\mu\text{g m}^{-3}$ and over ocean it is always less than $1\,\mu\text{g m}^{-3}$; at 1500 m the scenario was different, with M_B values over ocean being always higher than the value at 500 m, over the latitude region covered. Parameterization of the latitudinal distribution in M_B using an exponential function gave a shorter scaling length with very little offset at 500 m showing the influence of local effects in the distribution of M_B. At 1500 m, the spatial variation is slower with longer scale length and significant offset showing a substantial amount of M_B of non-local origin, which confirms the role of long-range transport at higher altitude.
- Back trajectory analysis showed strong pathways favouring advection from western landmass to contribute significantly to the BC concentration above ABL. The ABL structure along with the latitude gradient and back trajectory analysis showed that, while local sources contribute significantly to M_B and its variations within the ABL (below 800 m), long-range transport and non-local sources attribute significantly to M_B at higher levels.

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