Latitudinal and longitudinal variation in aerosol characteristics from Sun photometer and MODIS over the Bay of Bengal and Arabian Sea during ICARB

Sumita Kedia* and S Ramachandran**

Space and Atmospheric Sciences Division, Physical Research Laboratory, Ahmedabad 380 009, India.
**e-mail: sumita@prl.res.in*
***e-mail: ram@prl.res.in*

Spatial variations in aerosol optical properties as function of latitude and longitude are analysed over the Bay of Bengal and Arabian Sea during ICARB cruise period of March–May 2006 from *in situ* sun photometer and MODIS (Terra, Aqua) satellite measurements. Monthly mean 550 nm aerosol optical depths (AODs) over the Bay of Bengal and Arabian Sea show an increase from March to May both in spatial extent and magnitude. AODs are found to increase with latitude from 4°N to 20°N over the Bay of Bengal while over Arabian Sea, variations are not significant. Sun photometer and MODIS AODs agree well within $\pm 1\sigma$ variation. Bay of Bengal AOD (0.28) is higher than the Arabian Sea (0.24) latitudinally. Aerosol fine mode fraction (FMF) is higher than 0.6 over Bay of Bengal, while FMF in the Arabian Sea is about 0.5. Bay of Bengal $\alpha(\sim 1)$ is higher than the Arabian Sea value of 0.7, suggesting the dominance of fine mode aerosols over Bay of Bengal which is corroborated by higher FMF values over Bay of Bengal. Air back trajectory analyses suggest that aerosols from different source regions contribute differently to the optical characteristics over the Bay of Bengal and Arabian Sea.

1. Introduction

Atmospheric aerosols influence the earth's climate in many characteristic ways. The direct and indirect aerosol radiative forcings remain a significant uncertainty for climate studies (IPCC 2007). The direct interaction of aerosols involves both scattering and absorption of radiation, and the relative importance of these processes depends on their chemical composition, refractive index and size distribution. The indirect effect of aerosols on climate occurs by modifying the optical properties and lifetimes of clouds. Thus the concentration, size and composition of aerosols that can act as cloud condensation nuclei determine the cloud properties, evolution and development of precipitation. The physical and chemical properties of aerosols are strong functions of their sources. The sources of aerosols are widely varied and differ on a regional basis leading to regional variations in the earth's radiative budget. The Indian subcontinent is densely populated and has industrialized areas on the east and western sides. The prevailing meteorological conditions during winter transport the pollutants mainly anthropogenic from these areas to the surrounding marine environments such as the Arabian Sea, Bay of Bengal and Indian Ocean; while during the southwest monsoon the winds are stronger, moist and are from the marine and western regions surrounding India.

The Indian subcontinent and the surrounding regions are rich sources for many kinds of aerosols of both natural and anthropogenic origin such as mineral dust, soot, nitrates, sulfate and organic aerosols. A number of observational campaigns have been conducted over the Indian

Keywords. Aerosol optical characteristics; latitudinal and longitudinal variations; Bay of Bengal; Arabian Sea; pre-monsoon season; *in situ* and satellite measurements; remote sensing.

J. Earth Syst. Sci. **117**, S1, July 2008, pp. 375–387

subcontinent and surrounding oceanic regions in recent times to investigate the role of aerosols in altering the atmospheric radiation budget and the cloud properties, Indian Ocean Experiment (INDOEX) (Ramanathan *et al* 2001), Land Campaigns (LC) LC-I (Moorthy *et al* 2005) and LC-II (Ramachandran *et al* 2006), to name a few. Land Campaign-I conducted in February 2004 was an intensive field campaign with an objective of generating a spatial composite of aerosol characteristics over peninsular India. LC-II was conducted over the Indo-Gangetic plain in northern India during December 2004 to study aerosols, trace gases and their variations during clear, hazy and foggy periods at eight fixed stations, namely, Delhi, Kanpur, Hisar, Nainital, Agra, Allahabad, Jaduguda and Kharagpur. The above observations over Indian mainland and the surrounding oceanic regions were conducted during the winter monsoon season when the winds are calm and from the northern hemisphere.

Recently, during the intermonsoon season of March–May 2006 an Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB) was conducted over the Indian subcontinent and adjoining oceanic regions (Moorthy 2006). The over-all objective of this multi-institutional and multi-platform observational campaign was to characterize the spatio-temporal distribution of aerosols, trace gases and radiative forcing over the study regions. In addition, the ICARB campaign objectives included delineating the natural and manmade aerosol hot spots, sinks and vertical distribution of aerosols and trace gases. Finally, from the results obtained during the ICARB campaign the aerosol impact on regional radiative forcing will be assessed. The March–May time frame was chosen as during this season the atmospheric lifetimes of aerosols are longer (Moorthy 2006). The ship tracks were designed to travel into the oncoming wind and away from it alternatively so that the issue of potential long range transport from different source regions can be examined over these oceanic regions (Moorthy 2006).

The ocean segment of ICARB comprised of a month-long cruise expedition each over the Bay of Bengal (18 March–12 April) and Arabian Sea (18 April–10 May) (Moorthy 2006). In its first leg the ship originated from Chennai (13.1°N, 80.2°E), a metro city on the eastern coast of India, and sailed towards north Bay of Bengal. The second phase of ICARB ocean segment began on 18 April when the ship left Kochi towards the Arabian Sea. The ship moved towards the west of Arabian Sea in the initial days following a near straight path and reached the interior oceanic region (Moorthy 2006). Over Bay of Bengal the surface level winds were calm and showed mixed origin; winds during the first phase arise mainly from Bay of Bengal with signatures of transport from continental India (figure 1a). The wind patterns were found to be more clear and stronger during the second phase over the Arabian Sea (figure 1b). In this study aerosol characteristics measured *in situ* using sun photometer (aerosol optical depths and Ångström wavelength exponents) and derived from MODIS Terra and Aqua (aerosol optical depths, fine mode fraction and Ångström wavelength exponents) as function of latitude and longitude across Bay of Bengal and the Arabian Sea are analysed.

2. Data analysis and methodology

A hand-held sun photometer was used to measure aerosol optical depths at five wavelength bands centered around 400, 500, 650, 750, and 875 nm each with a bandwidth of about 10 nm. The solar radiation intensities measured using the sun photometer are then analysed to determine aerosol optical depths using Beer-Lambert's law. The total field of view of the photometer is restricted to 8° using baffles in the front. The photometer mainly consists of an interference filter, photodiode and necessary electronics (Ramachandran 2004), and has been used in many studies including INDOEX (Ramanathan *et al* 2001; Ramachandran 2004). All the sun photometer measurements are taken under clear sky conditions. During the cruise of 55 days, 50 days were found to be clear for taking sun photometer observations. The sun photometer measurements were made each day at 15 minute intervals in all the wavelength bands from 0800 Local Standard Time (LST) to 1700 LST at different solar zenith angles.

The MODerate resolution Imaging Spectroradiometer (MODIS) is a remote sensor with two Earth Observing System (EOS) Terra and Aqua satellites which provide an opportunity to study aerosols from space with high accuracy and on a nearly global scale (Yu *et al* 2004; Remer *et al* 2005). In this work, Level 3 MODIS collection 5 atmosphere daily global products (aerosol optical depth, fine mode fraction and Ångström exponent α) at $1° \times 1°$ grid (Remer *et al* 2005) are utilised. The aerosol products derived daily from both Terra and Aqua satellites are obtained during the ship cruise period and analysed. During the cruise, for most of the days aerosol data were available from only one of the satellites; for 4 days no data were available from both the satellites. MODIS Terra and Aqua satellites operate at an altitude of 705 km with Terra spacecraft crossing the equator at about 10:30 LST (ascending northward) while Aqua spacecraft crosses the equator

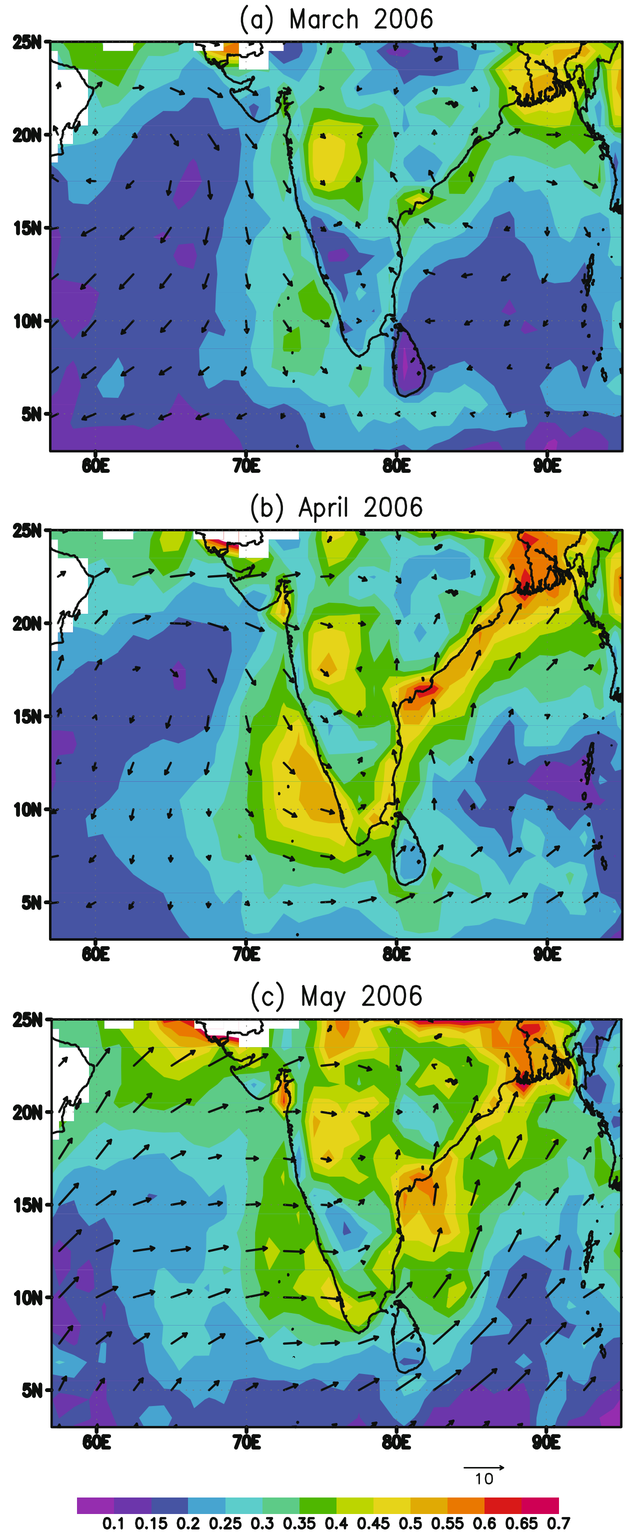

Figure 1. Monthly mean 550 nm aerosol optical depths over the Bay of Bengal and Arabian Sea for **(a)** March 2006, **(b)** April 2006 and **(c)** May 2006. The shaded contours correspond to aerosol optical depths on which, surface level winds represented by arrows are overlaid.

at around 13:30 LST (descending southward) (Yu *et al* 2004; Remer *et al* 2005). The oceanographic research vessel *Sagar Kanya* on which ICARB ocean segment was conducted sailed at a speed of about 20 km per hour during the day. This corresponds to a sailing of more than 400 km in a day. The aerosol products from MODIS Terra and Aqua are obtained for the mean latitude-longitude positions (Moorthy 2006) on each day (table 1).

Fine mode fraction (FMF) is defined as the ratio of the accumulation mode optical depth to the total optical depth at 550 nm (Remer *et al* 2005). The fine mode fraction value (ranges from 0 to 1) provides quantitative information on the nature of the size distribution of aerosol particles in the atmosphere. When FMF = 1, it represents pure accumulation mode particles (below 1 μm which are formed due to gas to particle conversion mainly from anthropogenic activities and produce sulfate, black carbon, organic carbon, nitrates, etc.); whereas FMF = 0 represents single coarse mode particles (originating from natural sources such as wind blown mineral dust and sea salt). Any intermediate FMF value represents a bimodal type particle distribution, where both accumulation and coarse modes can contribute to the total AOD in proportion (Gassó and O'Neil 2006; Remer *et al* 2005). It is clear that low FMF represents a higher concentration of coarse particles like sea salt, dust, etc. In addition, lower FMF values can also result because of hygroscopic growth of water soluble aerosols such as sulfate in the presence of high ambient relative humidity (Ramachandran 2007). It has been seen that MODIS slightly over-estimates fine mode fraction for dust-dominated aerosols and under-estimates in smoke- and pollution-dominated aerosol conditions on the order of about 0.1–0.2 (Anderson *et al* 2003, 2005; Kleidman *et al* 2005; Gassó and O'Neill 2006).

The spectral variation of aerosol optical depth can be represented by Ångström power law (Ångström 1961) $\tau = \beta\lambda^{-\alpha}$, where λ is the wavelength in μm, α and β are Ångström parameters; α (slope) is the wavelength exponent which depends on the size distribution of aerosols and β corresponds to AOD at 1 μm. α depends on the ratio of concentration of larger to smaller aerosols in the aerosol distribution and β depends on columnar aerosol loading in the atmosphere. α values are derived from sun photometer measured AODs in the 500 to 875 nm wavelength range. MODIS Terra and Aqua α values derived from 550 and 865 nm AODs are analysed. Differences, if any, in α values owing to the difference in wavelength ranges will not be significant and are not accounted for in the study. Higher α signifies an increase in the concentration of smaller size particles and a decrease in the concentration of larger particles whereas lower value of α indicates a larger abundance of super micron aerosols.

Table 1. *Daily mean positions of the ICARB cruise conducted over the Bay of Bengal and Arabian Sea during March–May 2006. Data measured in situ and derived from MODIS Terra and Aqua satellites are classified and analysed in different latitude and longitude bins over the Bay of Bengal and Arabian Sea as shown.*

Bay of Bengal				Arabian Sea			
Latitude bin (°N)	Date	Lat. (°N)	Long. (°E)	Latitude bin (°N)	Date	Lat. (°N)	Long. (°E)
4–8	8 April	6.34	90.24	8–12	19 April	8.99	71.21
	10 April	5.63	83.07		21 April	8.99	61.83
	11 April	5.96	79.47		22 April	9.60	58.02
					23 April	11.00	61.17
					24 April	11.00	65.91
					25 April	11.02	70.62
8–12	31 March	11.50	84.89	12–16	26 April	11.06	75.19
	3 April	9.97	81.94		30 April	14.83	68.00
	4 April	9.93	85.80		1 May	14.00	64.30
	5 April	10.41	89.40		2 May	14.03	59.43
	6 April	11.76	91.68		10 May	15.40	73.80
	7 April	8.20	91.84				
	12 April	8.25	76.99				
12–16	18 March	13.14	80.36	16–20	27 April	13.92	73.86
	26 March	14.82	92.64		28 April	16.11	71.49
	28 March	15.00	84.06		29 April	18.00	69.47
	29 March	13.00	83.82		3 May	16.81	59.03
	30 March	12.38	87.94		6 May	14.00	64.30
	1 April	12.57	80.85		7 May	17.07	61.96
	2 April	12.55	80.28				
16–20	19 March	16.14	82.16	20–24	4 May	21.16	60.69
	21 March	20.69	90.18		5 May	20.99	63.56
	23 March	18.93	87.37		9 May	21.37	69.51
	24 March	17.00	86.69				
	25 March	16.99	91.44				

Aerosol optical depths and aerosol mass concentrations are found to exhibit large spatial and temporal variations; for example, AODs and mass measured over coastal India, the Arabian Sea and the tropical Indian Ocean are found to show large spatial variations during the winter monsoon (Moorthy *et al* 2001; Ramanathan *et al* 2001; Ramachandran and Jayaraman 2002; Ramachandran 2004). The 5-year mean (1996–2000) mass variations show that the aerosol mass concentrations over coastal India in the coarse, accumulation and nucleation modes are higher than those measured over the Arabian Sea and the tropical Indian Ocean (Ramachandran and Jayaraman 2002). The coastal India aerosol optical depths are found to be higher by a factor of about 1.2 when compared to the Arabian Sea measurements and are about four times higher than those measured over the tropical Indian Ocean (Ramachandran 2004). Aerosol optical depth was found to decrease rapidly as the distance from the coast increased over the tropical Indian Ocean (Moorthy *et al* 1997; Ramachandran 2004). Because of the large spatial variations in aerosols, in this study, the aerosol characteristics are analysed as a function of latitude and longitude over the Bay of Bengal and Arabian Sea during March–May 2006.

3. Results and discussion

The monthly mean 550 nm AODs from Terra and Aqua satellites for March, April and May 2006 over the study area are plotted in figure 1. The monthly mean surface level winds are overlaid on the mean AODs. At the outset, a gradual increase in AODs over both oceanic regions (Bay of Bengal and Arabian Sea) and on the Indian mainland from March to May is seen. The magnitude of AOD values and the spatial extent of higher AODs increase

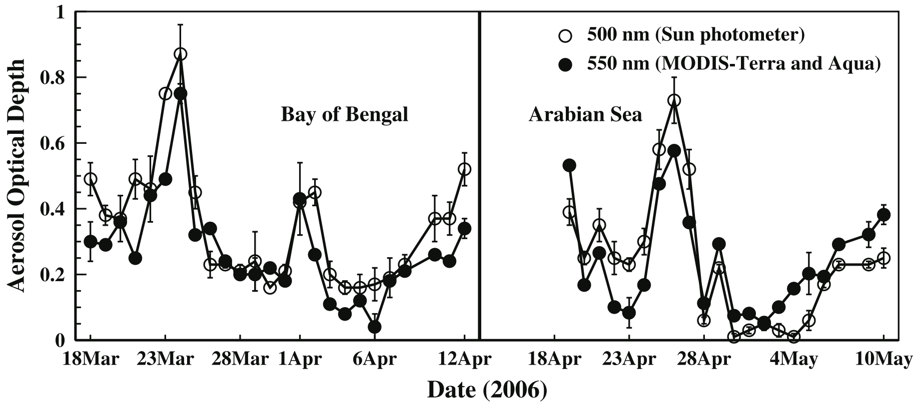

Figure 2. Day-to-day comparison of *in situ* sun photometer measured average aerosol optical depths at 500 nm and MODIS (Terra and Aqua average) aerosol optical depths at 550 nm during ICARB over Bay of Bengal and the Arabian Sea. Vertical bars indicate $\pm 1\sigma$ variation from the mean. See text for more details.

as the month progresses from March to May (figure 1). Over the Bay of Bengal during March, AODs are in the range of 0.15 to 0.45; over the Arabian Sea, the AODs are low and are in the range of 0.15–0.3. During April, AODs are found to be higher than 0.4 along the east coast of India from Kanyakumari to Kolkata. AODs higher than 0.6 are found around Visakhapatnam and Kolkata which are urban centres.

Visakhapatnam is a tropical, coastal station and has industrialized urban influence. Kolkata is a densely populated location in east India and has several automobile, textile, paper, engineering industries apart from jute manufacturing and tobacco processing units. The oceanic regime adjoining the east coast also shows higher AODs throughout the latitude band of 8–25°N. In May the AODs are higher over peninsular India than April and the regional high in AODs is clearly seen around Visakhapatnam and Kolkata. Over the Arabian Sea the winds are stronger during March (figure 1) than over Bay of Bengal. It should be noted that over the Indian subcontinent the dust activity is found to peak in the spring (March–May) which decreases in summer with the onset of southwest monsoon (Prospero *et al* 2002). Over the Arabian Sea during April–May, the surface level winds are stronger and come from the nearby arid and semi-arid regions of Africa and Arabia (figure 1). Over Bay of Bengal the winds are stronger during May and are found to have both marine and continental influence. Ship-borne *in situ* measurements during ICARB were made over Bay of Bengal during 18 March–12 April while over the Arabian Sea the measurements were made from 18 April to 10 May.

The LST 10:30 and 13:30 h of Terra and Aqua are the local times at the equatorial crossing point of the sub-satellite track. The local time at any other observation location can differ by as much as about ±42 min depending on the longitudinal distance from the sub-satellite track. An additional correction which arises due to the latitude of the observation point, is small in case of MODIS, as its orbit is nearly polar (Yu *et al* 2004). For the day-to-day intercomparison of MODIS and sun photometer AODs, in this study, the sun photometer measured AODs between 09:45 and 11:15 LST (corresponding to Terra), and 12:45 and 14:15 LST (corresponding to Aqua) taking into account the longitudinal dependence, are averaged and plotted in figure 2. The sun photometer measured AODs averaged in such a manner are compared with each $1^\circ \times 1^\circ$ latitude–longitude grid MODIS (Terra and Aqua) level 3 data and are plotted in figure 2. A comparison of this sort resulted in inclusion of all the ship-borne measurements and as a consequence the number of data points increased ($n = 46$) thereby improving the statistics.

In figure 2, the day-to-day variation in aerosol optical depths measured *in situ* using sun photometer and averaged as explained above are compared with MODIS (Terra and Aqua) derived AODs. Note that sun photometer AODs are at 500 nm while MODIS AODs are at 550 nm. AODs are about 0.4 in the initial phase of the cruise which increase to ≥ 0.8 during 23–24 March. AODs decrease to reach values of 0.2 during 25–30 March after which the AODs increase over Bay of Bengal. AODs are found to increase from 4 April to 13 April when the ship reached Kochi. Over the Arabian Sea, the AODs are found to be lower than those obtained over Bay of Bengal. AODs over the Arabian Sea are higher than 0.5 during 25–27 April. AODs are found to be around 0.1 from 30 April to 5 May 2006. AODs are found to increase thereafter reaching values of about 0.2 in case of sun photometer; MODIS AODs tend to be slightly higher during this period. MODIS (Terra and Aqua average) AODs are found to track well the *in situ* sun photometer measured AODs during the cruise period. A scatter plot between *in situ* sun photometer and MODIS derived AODs gave rise to a high correlation coefficient of 0.84 ($n = 46$). The differences between the *in situ* and MODIS derived AODs could arise due to **(a)** the difference in wavelengths (500 nm in case of sun photometer while the wavelength is 550 nm for MODIS) and **(b)** the uncertainties associated in deriving AODs from both *in situ* and satellite retrieval algorithms.

The uncertainty in the *in situ* AODs arises due to errors in the measurement (because of the contribution of forward scattered radiation while measuring direct irradiance) and assuming the contribution of Rayleigh scattering (for air molecules), absorption due to ozone, NO_2 (less than 0.5% in this wavelength regime and hence neglected here) and water vapour in the tropical atmosphere which is subtracted from the total optical depth value while deriving aerosol optical depths. These two sources of uncertainty can cumulatively contribute about 15% uncertainty in the derived aerosol optical depths (Ramachandran 2004). The error in MODIS (Terra and Aqua) derived AODs over the oceans is $\Delta\text{AOD} = \pm 0.03 \pm 0.05\,\text{AOD}$ (Remer *et al* 2005). It has been noted that, in general, MODIS retrievals meet expected accuracy, but in some conditions they do not. For example, it has been pointed out that non-spherical dust particles over the ocean can lead to errors in AOD retrievals (Remer *et al* 2005). It has been found that assuming constant surface reflectance conditions can lead to over-estimation of AOD in clean conditions along the east coast of U.S and errors in other regions (Remer *et al* 2005). In addition to the above differences, while calculating the daily mean AOD and α values the following factors could contribute to the variations between *in situ* and satellite derived values:

- temporal difference between the two systems (sun photometer AODs are average of few hours of data measured between 08:00 LST and 17:00 LST during a day while MODIS AOD is the mean of 10:30 and 13:30 LST AODs), and
- spatial difference (sampling error associated with the satellite AOD values, because while obtaining the satellite derived values, the mean latitude and longitude are only taken).

AODs measured *in situ* and derived from Terra and Aqua satellites have been grouped into latitude (table 1) and longitude bins during the cruise period and are analysed. Mean AODs from sun photometer and MODIS binned in 4° latitude and 5° longitude bins are plotted in figure 3. From the mean AODs in that particular bin (table 1) the latitudinal and the longitudinal means are calculated and plotted. Vertical bars indicate $\pm 1\sigma$ variation from the mean AODs in each latitude and longitude band. At the outset, the measured and MODIS AODs agree quite well within the $\pm 1\sigma$ variation. Over Bay of Bengal an increase in AODs as the latitude increases is seen. 16–20°N high in AOD is expected as the ship cruised very near to the densely populated Indo-Gangetic Plain and Kolkata.

Aerosols in the nucleation size range, undergo condensational growth or coagulate to form bigger particles and contribute to accumulation mode. The precursors for the formation of particles in the nucleation mode come mostly from the continents, such as sulfur dioxide, which through oxidation and condensation get transformed into sulfate aerosol and transported over long distances in the marine atmosphere. Such fine mode particles will be found in abundance near the coastal regions. The accumulation mode particles which are formed due to gas to particle conversion can get transported across the oceanic regions during favourable wind conditions (Ramachandran and Jayaraman 2002). The cruise track was designed in such a way that the aerosol variations both towards and away from the source regions could be captured and analysed. The AODs are about a factor of 2 higher in the 16–20°N latitude band when compared to 4–8°N. In the 4–8°N latitude band the cruise was located far away from the aerosol source regions, thus resulting in lower AODs.

Arabian Sea AODs show markedly different features than the Bay of Bengal AODs. No significant variability in AODs over the Arabian Sea is evident in different latitude bins. MODIS AODs are more or less similar in all the 4 latitude bins, while sun photometer AODs are found to decrease slightly from 8–12°N to 12–16°N. AODs are similar in the 16–20°N and 20–24°N latitude bands. Note that no measurements were made over the Arabian Sea in the 4–8°N latitude band. These latitudinal variations in AODs over the Arabian Sea occur despite the fact that the surface winds over the marine boundary layer were strong and clear (figure 1). The AODs are found to exhibit a larger deviation from the mean indicating not only a large temporal (day to day) but spatial variability in different latitude bins (figure 3a), as opposed to a significant increase in AODs with latitude over Bay of Bengal.

The scenario is different when the AODs are grouped as function of longitude (figure 3b). Over Bay of Bengal longitudes AODs are found to decrease from 76–81°E to 81–86°E whereafter the AODs increase in the 86–91°E band; AODs decrease slightly in the 91–96°E longitudinal band over Bay of Bengal. AODs in the 76–81°E and

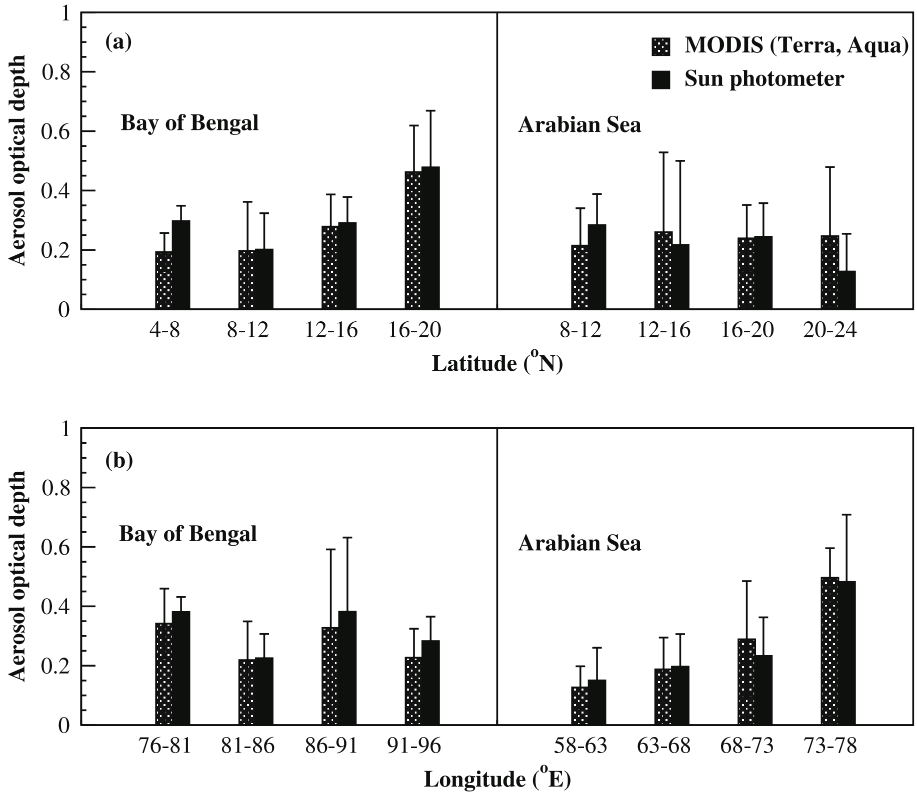

Figure 3. **(a)** Latitudinal and **(b)** longitudinal variations in aerosol optical depths measured *in situ* and MODIS (Terra and Aqua) satellites over the Bay of Bengal and Arabian Sea during ICARB. Refer text for details.

81–86°E longitudinal bands were measured when the cruise was close to the eastern coast along Chennai–Kolkata and near Kolkata resulting in higher values; 91–96°E longitudinal band AODs are obtained when the cruise was far away from the Indian coast, which resulted in lower AODs. Over the Arabian Sea, the AODs are found to increase as a function of longitude when the longitude changes from 58°E to 78°E. 58–63°E longitude band is quite far away from the coastline of India while the 73–78°E is very close to the western coast; urban centers such as Kochi, Goa and Mumbai are situated along the western coast and are manmade aerosol source regions. Note that *in situ* measured and MODIS AODs exhibit a good correlation over Bay of Bengal and the Arabian Sea. The variations in AODs over different latitude and longitude bins could be due to the differences in the anthropogenic environs, changes in the meteorological conditions, wind patterns, production and subsequently the transport of aerosols, and the various source regions from where the aerosols originated, in addition, to the local production of sea salt aerosols.

Air back trajectories are important to identify the source regions from where the pollutants originated and subsequently got transported to the measurement locations. As the typical residence time of different types of aerosols is about a week in the lower atmosphere, 7 days back trajectory analyses are performed. It is also important to know the heights from where aerosols descended while analysing the surface as well as columnar measurements. The back trajectories describe back in time the origin of air parcels and the paths they traveled at different heights before reaching the measurement location. All the back trajectories are calculated at 12:00 h Indian Standard Time (+05:30 h GMT). Air back trajectory calculated at 500 m heights are plotted in figure 4 as a function of latitude bins over the Bay of Bengal and Arabian Sea. Air back trajetories at 10 and 100 m obtained (not shown) for each day are more or less similar to the ones shown corresponding to 500 m.

Over Bay of Bengal in the 4–8°N and 8–12°N latitudinal bins air back trajectories are found to originate from the marine regions before reaching the observation point (figure 4a, b). While in the 12–16°N latitudinal bin airmasses are found to originate from the arid/semi-arid regions of Iran, Saudi Arabia, come through Pakistan, west, central and eastern India before reaching the measurement location. In the 16–20°N latitudinal band 500 m airmasses are found to originate from west, north and eastern India and reach the measurement locations over Bay of Bengal. The airmasses

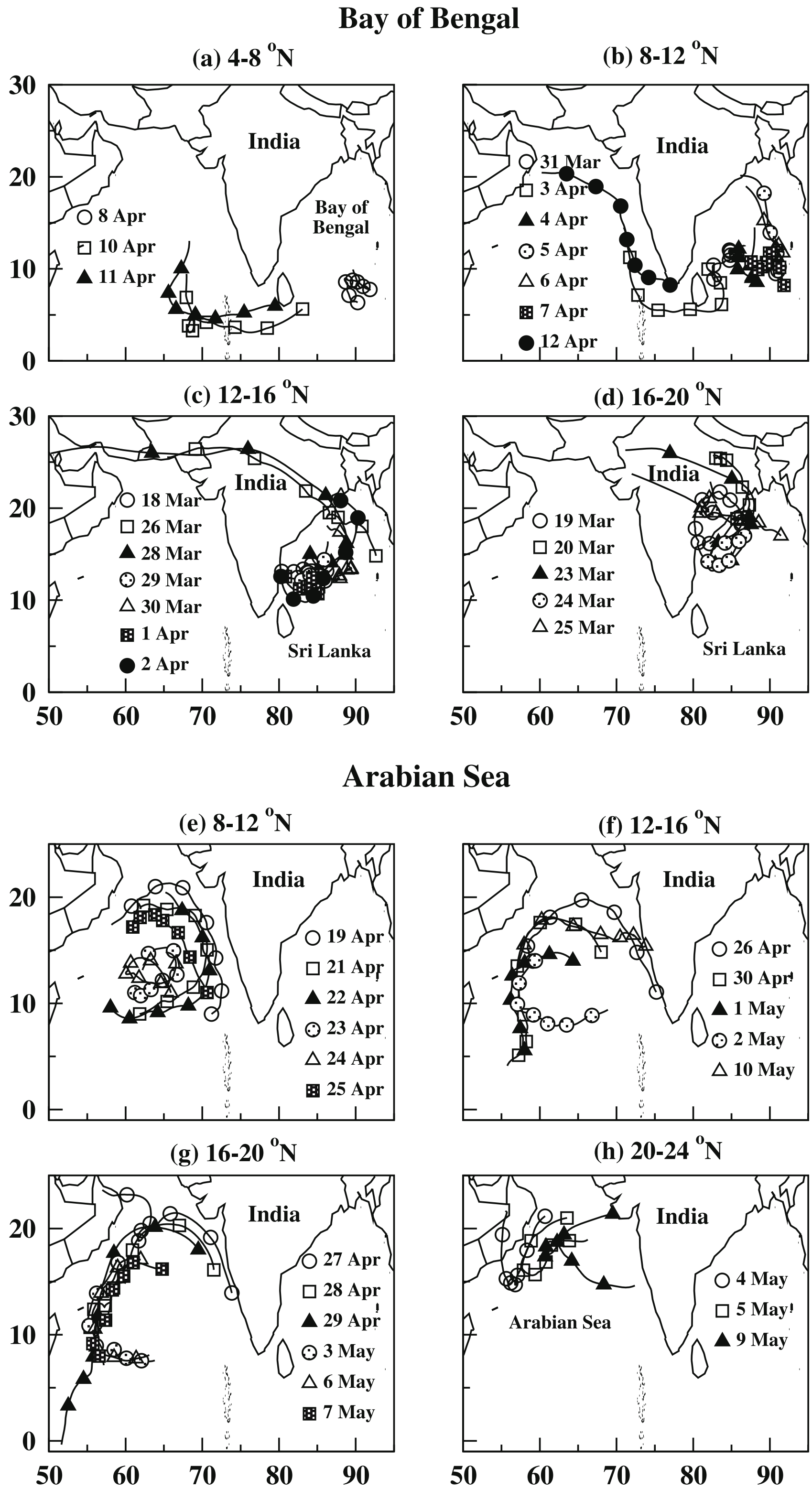

Figure 4. Seven days air back trajectories for different days in each latitude band over the Bay of Bengal and Arabian Sea. The back trajectories are plotted at an hourly interval. The symbols are shown at 24-h intervals and represent a day.

which originated from arid and urban regions could have resulted in higher AODs seen in the 16–20°N latitude band over Bay of Bengal (figure 3a). The 7 days air back trajectories over the Arabian Sea where the AODs did not exhibit significant variability as a function of latitude are found to mostly originate from the Arabian Sea and spend the entire duration of the 7 days over

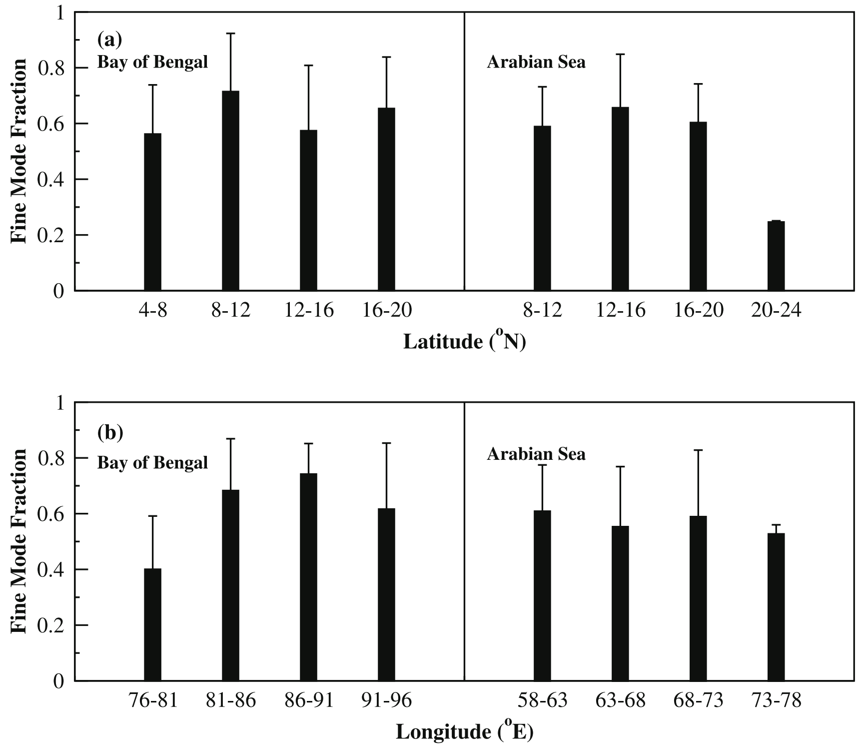

Figure 5. Variation in aerosol fine mode fraction as a function of **(a)** latitude and **(b)** longitude bands during ICARB over the Bay of Bengal and Arabian Sea.

the Arabian Sea before reaching the measurement site. It has been seen that when the airmasses originate and spend the entire duration over the marine regions before reaching the measurement location will result in lower AODs, while airmasses which either originate and/or travel through arid and densely populated locations will produce higher AODs (Ramachandran and Jayaraman 2003). The increase and decrease of AODs in the latitudinal and longitudinal bands over the Bay of Bengal and Arabian Sea are quite consistent with the back trajectory results.

FMF derived from MODIS can be used as a surrogate for separating anthropogenic from natural sources thereby increasing the accuracy of estimating the manmade impact on aerosol forcing (Kaufman *et al* 2002; Remer *et al* 2005). It was seen that aerosol from natural sources (sea salt and desert dust) comprise larger particles than those emitted by manmade combustion sources such as agriculture and deforestation burning, or urban/industrial pollution (Remer *et al* 2005). Anthropogenic aerosols downwind from vegetation fires and industrial pollution were found to have high concentration of fine particles (Kaufman *et al* 2002). It is expected that AODs dominated by pollution will result in a high FMF and AOD while natural aerosols (biogenic) can produce a high FMF and a range of AODs, and if the aerosols are mechanically generated (e.g., sea salt and desert dust) then that can result in a low FMF and a range of AODs (Kaufman *et al* 2002; Remer *et al* 2005).

FMF variations as a function of latitude and longitude over Bay of Bengal and the Arabian Sea are shown in figure 5. FMF is found to be about 0.6 or higher over Bay of Bengal, while over the Arabian Sea FMF is about 0.6 or higher in the 8°N to 20°N bands. FMF is about 0.3 over the Arabian Sea in the 20–24°N latitude region. A higher FMF value indicates the dominance of fine mode particles which were produced mainly due to manmade sources in the surrounding regions and got transported across the oceanic regions. The average FMF over Bay of Bengal is higher at 0.63 when compared to 0.52 over the Arabian Sea, though the variations are large over the Arabian Sea. A higher FMF over Bay of Bengal indicates a relatively higher fine mode contribution to the AOD than over the Arabian Sea. It is worth mentioning that the decrease in FMF over the Arabian Sea in the 20–24°N latitude could be due to higher wind speeds that can produce larger amount of sea salt aerosols and/or due to the transport of larger size mineral dust particles from the nearby desert regions (figure 4h). Dominance of larger size aerosols in the aerosol distribution would result in lower FMFs.

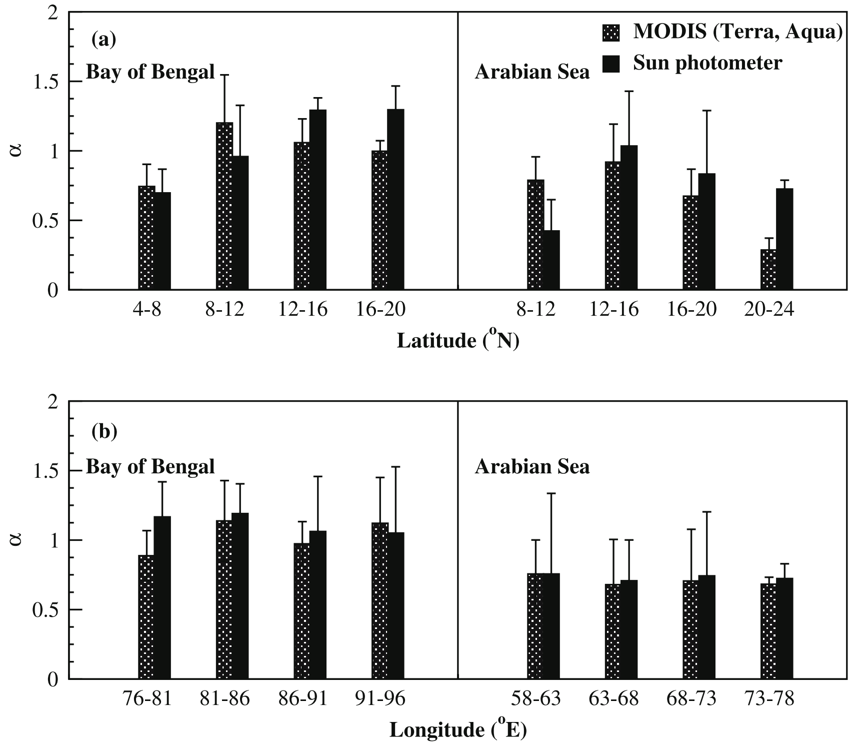

Figure 6. Ångström exponent α derived from *in situ* sun photometer measured spectral aerosol optical depths and MODIS (Terra and Aqua) satellite derived aerosol optical depths over the Bay of Bengal and Arabian Sea during ICARB as a function of **(a)** latitudinal and **(b)** longitudinal bins.

On the longitudinal scale FMF over the Bay of Bengal and Arabian Sea are more or less similar (figure 5b). Over Bay of Bengal FMF is found to be about 0.4 in the 76–81°E band, while in the 81–86°E and 86–91°E bands FMF is $\geq$0.7. In the 91–96°E band FMF is about 0.6. No significant longitudinal variation in FMF is seen over the Arabian Sea in the 58–78°E region. FMF is in the 0.53–0.61 range in the entire longitudinal sector over the Arabian Sea. Mean FMF values in the longitudinal belts over the Bay of Bengal and Arabian Sea are found to be 0.61 and 0.57 respectively.

Latitudinal and longitudinal variations in Ångström exponent α derived from sun photometer AODs and MODIS (Terra, Aqua) AODs over the Bay of Bengal and Arabian Sea are plotted in figure 6. α values derived from *in situ* measurements and satellite agree very well within $\pm 1\sigma$ variation over the Bay of Bengal and Arabian Sea both as a function of latitude and longitude. Only in the 20–24°N latitudinal band over the Arabian Sea sun photometer α is higher than the mean MODIS α. It should be noted that in the same latitude band MODIS derived AOD was higher than the sun photometer derived AOD (figure 3a), but both the values agreed within $\pm 1\sigma$. Difference in α values in the same latitude band indicates that though the AODs in the mid visible wavelengths are more or less the same, AODs in the higher wavelength region (850 nm) are probably different and gave rise to different mean α values. Higher 550 nm AODs and lower α from MODIS suggest that in this latitude band MODIS derived 865 nm AODs are higher than the *in situ* measured AODs; this indicates a dominance of coarse mode particles over this latitude band as derived by MODIS, which is corroborated by the lower FMF value of about 0.3.

In addition to the differences in the AOD retrievals between *in situ* and satellite measurements, discrepancy in α values obtained from *in situ* and satellite could arise due to the sampling and spatial and differences as discussed earlier. The average MODIS and sun photometer derived α over Bay of Bengal is 1.00 while over the Arabian Sea α is lower at 0.70. A higher α indicates the dominance of smaller size aerosols when compared to the coarse mode aerosols in the size distribution. The variations in MODIS derived α exhibit close correspondence with FMF variations. α is found be about 0.75 in the 4–8°N latitudinal band over Bay of Bengal, while α is close to 1 in the other latitudinal bins. Over the Arabian Sea only in the 12–16°N α is just about 1, while the other latitudinal bands α is lower than 1. In the 20–24°N latitudinal band, α is the lowest with a value close to 0.3 indicating the dominance of super micron aerosols in the distribution contributing to the AOD spectra, thus resulting in lower FMFs (figure 5a).

In contrast, as a function of longitude α values from MODIS and sun photometer exhibit much less variability over the Bay of Bengal and Arabian Sea (figure 6b). α values are more or less the same and vary from 0.9 to 1.1 over Bay of Bengal while α over the Arabian Sea varies from 0.7 to 0.76. Mean α values over the Bay of Bengal and Arabian Sea are 1.0 and 0.71 respectively; while sun photometer derived mean α values as a function of longitude are very close and are 1.1 and 0.73 respectively. Both as function of latitude and longitude FMF values are higher over Bay of Bengal when compared to those derived over the Arabian Sea which indicates a relatively larger number of smaller particles over Bay of Bengal. The features in α corroborate the higher FMF values obtained over the Bay of Bengal than those obtained over the Arabian Sea, thus suggesting the dominance of smaller fine mode aerosols over Bay of Bengal.

4. Conclusions

A cruise expedition was conducted as part of ICARB (Integrated Campaign for Aerosols, gases and Radiation Budget) during 2006 over the Bay of Bengal and Arabian Sea to map the aerosol and trace gases environment in the pre-monsoon season of March–May. The cruise covered extensively for about a month each oceanic region of the Bay of Bengal and Arabian Sea. In the first phase (Bay of Bengal) the ship left Chennai on the eastern coastline of India on 18 March and after cruising for about a month reached Kochi on the west. The second leg of the cruise was conducted over the Arabian Sea from 18 April to 10 May. The cruise tracks over both the oceanic regions were designed such that the measurements onboard the ship can explore the long range transport effects from the nearby Indian coast and far away source regions on aerosol and pollutant characteristics.

Aerosol optical properties measured *in situ* and derived from MODIS (Terra, Aqua) satellites over the Bay of Bengal and Arabian Sea are analysed. *In situ* spectral aerosol optical depths were measured using a sun photometer in the wavelength region of 400 to 875 nm. MODIS Terra and Aqua aerosol optical properties corresponding to the mean latitude–longitude position of the cruise on a daily basis are analysed over the Bay of Bengal and Arabian Sea, and compared and contrasted with the *in situ* measured aerosol optical properties. The surface level and the columnar aerosol properties over these oceanic regions were found to exhibit large spatial variations. In the present study, the spatial variability in aerosol characteristics is examined during the pre-monsoon season by classifying and analysing the aerosol characteristics in different latitudinal and longitudinal bins covering 4–20°N, 76–96°E over Bay of Bengal and 8–24°N, 58–78°E over the Arabian Sea. Variations in aerosol optical depths (AODs), fine mode fraction (FMF) and Ångström exponent α are analysed and discussed.

Monthly mean 550 nm AODs over both the oceanic regions (Bay of Bengal and Arabian Sea) show an increase from March to May both in the spatial extent and the magnitude. In April 2006, AODs are higher along the east coast of India and the adjoining Bay of Bengal starting from the south to the east. In addition, a high in AODs is seen around urban and industrialised locations of Visakhapatnam and Kolkata. Surface level winds are found to be stronger over the Arabian Sea during April and May and are seen to come from Africa and Arabia.

Day to day variations of sun photometer AODs and MODIS (Terra and Aqua) AODs are found to compare well during the campaign over the Bay of Bengal and Arabian Sea. MODIS AODs track well the *in situ* sun photometer AODs during the cruise period. Differences between the sun photometer and MODIS derived AODs could arise due to differences in wavelength (500 nm for sun photometer, 550 nm in case of MODIS (Terra and Aqua)), sampling errors and uncertainties associated while retrieving AODs from both the techniques. AODs are found to be high during 23–24 March when the values are ≥ 0.8; AODs decrease to about 0.2 end of March over Bay of Bengal. AODs tend to increase during the rest of the cruise over Bay of Bengal when the ship was moving closer to the coast and near populated urban locations. AODs are lower over the Arabian Sea during the cruise period when compared to Bay of Bengal.

Aerosol optical properties measured *in situ* and derived from MODIS (Terra, Aqua) are grouped into 4° latitude and 5° longitude bins to examine their spatial variations over the Bay of Bengal and Arabian Sea. Sun photometer and MODIS AODs are found to agree well within $\pm 1\sigma$ variation over the Bay of Bengal and Arabian Sea both as a function of latitude and longitude. AODs are found to increase as a function of latitude over Bay of Bengal when latitude increases from 4–8°N to 16–20°N. AOD is found to be the highest (0.5) in the 16–20°N latitude band which could have resulted due to the fact that the ship was cruising closely near the densely populated Indo-Gangetic Plain and Kolkata. The precursors for aerosols in the nucleation size regime which then condense and coagulate to form accumulation mode particles are found in abundance near the coastal regions;

these accumulation mode particles get transported across the adjacent oceanic regions in favourable wind conditions. The cruise track of ICARB campaign was designed exclusively to capture the variations in aerosol characteristics as the ship moved towards and away from the aerosol source regions. Over Bay of Bengal the AODs in the 4–8°N were low, as in this latitude band the cruise was sampling aerosols far away from the source regions.

In contrast to Bay of Bengal, AODs over the Arabian Sea are found to show little latitudinal variability; the mean AODs were low and were about 0.25. On a longitudinal basis over Bay of Bengal AODs are lower in 81–86°E and 91–96°E bands when compared to 76–81°E and 86–91°E bands. The high and low AODs in different longitudinal bins are attributed to the variations in the cruise track; the highs were obtained when the ship was close to the eastern coast along the Chennai–Kolkata sector and near Kolkata, while the lower AODs resulted when the cruise was quite far away from the coastline of India. AODs are found to increase as a function of longitude over the Arabian Sea. AODs are found to increase gradually from < 0.2 in 58–63°E band to about 0.3 in 68–73°E band with the value of AOD in the 63–68°E longitude region lying in between.

AOD was maximum in the 73–78°E longitude region over the Arabian Sea with a value of about 0.5, which could be due to the proximity of the cruise to the nearby urban centres of Kochi, Goa and Mumbai and subsequent transport of urban fine mode aerosols resulting in higher AODs. Analysis of the aerosol optical properties by classifying them in different latitude and longitude bins have revealed several interesting features over the Bay of Bengal and Arabian Sea. The variations in AODs can be attributed to the differences in the surrounding urban regions, changes in the meteorological conditions, wind patterns, production and subsequently the transport of aerosols, and the various source regions from where the aerosols originated, in addition, to the local production of sea salt aerosols. An analysis of 7 days air back trajectory over the Bay of Bengal and Arabian Sea revealed that over Bay of Bengal the airmasses originated and/or passed through arid, densely populated regions before reaching the measurement location; while the airmasses over the Arabian Sea are found to mostly originate from the Arabian Sea and spend the entire duration over the oceanic regions before reaching the observational site, thus, supporting the finding that aerosols from different source regions contributed differently to the optical properties over the Bay of Bengal and Arabian Sea.

The aerosol fine mode fraction (FMF) which can be utilised as a proxy to separate the urban and natural aerosol sources is found to be higher than 0.6 over Bay of Bengal; mean FMF in the Arabian Sea is about 0.5. FMF over Bay of Bengal in the 4–8°N, 8–12°N, 12–16°N and 16–20°N latitudinal bins are found to be close to 0.6 or higher. Over the Arabian Sea FMF is about 0.6 in the 8–20°N latitude band. However, FMF in the 20–24°N latitude band is about 0.3 indicative of the dominance of coarse mode aerosols in the size distribution. The wind speeds are higher in this latitude band over the Arabian Sea and are found to come from the west. This suggests the possibility of higher wind speeds producing more sea salt particles and/or transport of mineral dust particles contributing to the lower FMF value in this latitude band. Fine mode fraction was found to be more or less similar over the Bay of Bengal and Arabian Sea on longitudinal scales. Mean fine mode fraction over the Bay of Bengal and Arabian Sea as a function of longitude was found to be about 0.6.

Ångström wavelength exponent α obtained from sun photometer and MODIS is found to agree well within $\pm 1\sigma$ over the Bay of Bengal and Arabian Sea both in latitude and longitude bins. α was about 1.0 over Bay of Bengal while Arabian Sea α was 0.7. A higher α over Bay of Bengal suggests a dominance of smaller size aerosols when compared to the Arabian Sea. The variations in α are in good agreement with the FMF variations over the Bay of Bengal and Arabian Sea. In the 20–24°N latitude band over the Arabian Sea α is about 0.3 indicating the dominance of coarse mode aerosols which would result in lower FMF. Both as a function of latitude and longitude FMF values are higher over the Bay of Bengal when compared to those derived over the Arabian Sea suggesting a relatively larger number of smaller particles over Bay of Bengal. This study and the analysis documenting the spatial variation in aerosol properties over the Bay of Bengal and Arabian Sea during pre-monsoon will be important in the assessment of aerosol radiative forcing and its spatial variability.

Acknowledgements

We thank the ISRO-GBP program office, ISRO HQs, Bangalore for the funds and the Department of Ocean Development for giving us the opportunity to conduct aerosol measurements on board *Sagar Kanya*. MODIS aerosol optical properties used in this study are downloaded from the GES-DISC, NASA. Winds are obtained from NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.cdc.noaa.gov/. The HYSPLIT (version 4) model is obtained from http://www.arl.noaa.gov/ready/hysplit4.html.

We thank the reviewers for their constructive suggestions.

References

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

Anderson T L, Wu Y, Chu D A, Schmid B, Redemann J and Dubovik O 2005 Testing the MODIS satellite retrieval of aerosol fine-mode fraction; *J. Geophys. Res.* **110** D18204, doi:10.1029/2005JD005978.

Anderson T L, Charlson R J, Winker D M, Ogren J A and Holmén K 2003 Mesoscale variation of tropospheric aerosols; *J. Atmos. Sci.* **60** 119–136.

Gasso S and O'Neil N T 2006 Comparisons of remote sensing retrievals and in situ aerosol fine mode fraction during ACE-Asia; *Geophys. Res. Lett.* **33** doi:10.1029/2005GL024926.

IPCC 2007 Summary for Policymakers; In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (eds) Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K B, Tignor M and Miller H L (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press).

Kaufman Y J, Tanré D and Boucher O 2002 A satellite view of aerosols in the climate system; *Nature* **419** 215–223.

Kleidman R G, O'Neill N T, Remer L A, Kaufman Y J, Eck T F, Tanre D, Dubovik O and Holben B N 2005 Comparison of moderate resolution Imaging Spectroradiometer (MODIS) and Aerosol Robotic Network (AERONET) remote-sensing retrievals of aerosol fine mode fraction over ocean; *J. Geophys. Res.* **110** doi:10.1029/2005JD005760.

Moorthy K K, Satheesh S K and Krishna Murthy B V 1997 Investigations of marine aerosols over the tropical Indian Ocean; *J. Geophys. Res.* **102** 18,827–18,842.

Moorthy K K, Saha A, Prasad B S N, Niranjan K, Jhurry D and Pillai P S 2001 Aerosol optical depths 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 *et al* 2005 Wintertime spatial characteristics of boundary layer aerosols over peninsular India; *J. Geophys. Res.* **110** D08207, doi:10.1029/2004JD005520.

Moorthy K K 2006 Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB), A multi-instrumented, multi-institutional, multi-platform field campaign of ISRO-GBP: An overview; In: *First post-campaign meeting of ICARB*, 1–13.

Prospero J M, Ginoux P, Torres O, Nicholson S E and Gill T E 2002 Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol index; *Rev. Geophys.* **40** 1002, doi:10.1029/2000RG000095.

Ramachandran S and Jayaraman A 2002 Pre-monsoon aerosol mass loadings and size distributions over the Arabian Sea and the tropical Indian Ocean; *J. Geophys. Res.* **4738** doi:10.1029/2002JD002386.

Ramachandran S and Jayaraman A 2003 Spectral aerosol optical depths over Bay of Bengal and Chennai: II – Sources, anthropogenic influence and model estimates; *Atmos. Env.* **37** 1951–1962.

Ramachandran S 2004 Spectral aerosol optical characteristics during the northeast monsoon over the Arabian Sea and the tropical Indian Ocean: 2. Ångström parameters and anthropogenic influence; *J. Geophys. Res.* **109** D19208, doi:10.1029/2003JD004483.

Ramachandran S, Rengarajan R, Jayaraman A, Sarin M M, Das S K 2006 Aerosol radiative forcing during clear, hazy, and foggy conditions over a continental polluted location in north India; *J. Geophys. Res.* **111** D20214, doi:10.1029/2006JD007142.

Ramachandran S 2007 Aerosol optical depth and fine mode fraction variations deduced from Moderate Resolution Imaging Spectroradiometer (MODIS) over four urban areas in India; *J. Geophys. Res.* **112** D16207, doi:10.1029/2007JD008500.

Ramanathan V *et al* 2001 Indian Ocean Experiment: An Integrated analysis of the climate forcing and effects of the great Indo-Asian haze; *J. Geophys. Res.* **106** 28,371–28,398.

Remer L A *et al* 2005 The MODIS Aerosol Algorithm, Products and Validation; *J. Atmos. Sci.* **62** 947–973.

Yu H, Dickinson R E, Chin M, Kaufman Y J, Zhou M, Zhou L, Tian Y, Dubovik O and Holben B N 2004 Direct radiative effect of aerosols as determined from a combination of MODIS retrievals and GOCART simulations; *J. Geophys. Res.* **109** D03206, doi:10.1029/2003JD003914.

MS received 27 July 2007; revised 2 December 2007; accepted 13 December 2007