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Ship-Borne Measurements of Columnar and Surface Aerosol Loading over the Bay of Bengal during W-ICARB Campaign: Role of Airmass Transport, Latitudinal and Longitudinal Gradients

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ABSTRACT

The present study analyzes simultaneous and collocated measurements of spectral columnar aerosol optical depth (AOD) and the variations in total mass concentration of near surface aerosols in the marine atmosphere over the Bay of Bengal (BoB) during the winter phase of the Integrated Campaign for Aerosols, gases and Radiation Budget (W-ICARB) expedition of December and January 2008/2009 on board the Oceanographic Research Vessel (ORV) of Sagar Kanya. High AOD_{500} values (> 0.8) are found close to coastal regions in the western and northern BoB due to outflow of aerosols and pollutants from the densely populated Indo-Gangetic Plain (IGP). In these regions, the Ångström exponent $\alpha_{380-1020}$ values are also found to be high (~1.2–1.3), indicating relative abundance of accumulation-mode continental aerosols. Low AOD_{500} (0.1–0.2) values are observed in central and southern BoB, far away from the mainland. The AOD_{500} and total aerosol mass loading increased along with the latitude. The total mass concentration is found to vary between 15 $\mu g/m^3$ and 45 $\mu g/m^3$, with higher loadings near the east coast and northern parts of the BoB. NCEP reanalysis of the data with winds at 925 hPa, along with airmass trajectories calculated using the HYSPLIT model, suggest transport of continental aerosols from central and northern India over the BoB at lower heights, and mineral dust aerosol transport from arid regions in the west of India at higher altitudes; while the increase in aerosol loading over eastern BoB was strongly affected by airmasses originating from Southeast Asia. The spatial correlation map between the MODIS and MISR AOD data is analyzed, revealing a strong correlation between the two datasets. The influence of wind speed and continental airmass on AOD is also examined, which provides information on the effects of the adjoining landmass on the marine aerosol field.

Keywords: W-ICARB; Bay of Bengal; AOD; Curvature; Mass concentration; HYSPLIT.

INTRODUCTION

The role of tropospheric aerosols in the radiation budget of the atmosphere is one of the least understood but crucial aspects of the global climate system (Haywood and Boucher, 2000). Tropospheric aerosols affect the radiation budget by scattering and absorbing the incoming solar radiation (direct effect) and by modifying the cloud albedo and droplet size distribution, thereby changing the radiative properties and lifetime of clouds (indirect effect) and suppressing precipitation (IPCC, 2007). The influence of aerosols on climate is much more complex than those of greenhouse gases because of different sources and production mechanisms and short atmospheric residence times, from less than a day to more than a week. Thus, the radiative forcing and the resulting climate impact due to atmospheric aerosols still remain largely uncertain (Satheesh *et al.*, 2006), primarily due to inadequate data representing the spatio-temporal heterogeneity of the aerosol properties and to the poor understanding of the aerosol-cloud interactions (Patadia *et al.*, 2008). More systematic measurements of atmospheric aerosol properties, either through long-term global observation networks over land (e.g., AERONET), intensive field campaigns or from satellite monitoring (Kaskaoutis *et al.*, 2011) together with numerical modeling and data assimilation are needed to reduce the uncertainties (Yu *et al.*, 2006; Chin *et al.*, 2009).

The study of atmospheric aerosols over the Oceans is of paramount importance as the oceans cover most of the Earth's surface and act as major contributor of natural aerosols. The important sources contributing to the aerosol

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loading over the oceans is the mechanism of bubble bursting at the surface of the ocean and marine biogenic activity through oxidation of dimethyl-sulphide (DMS) emitted by marine phytoplankton (Moorthy *et al.*, 2005a; George and Nair, 2008). Even though the oceanic environment are less heterogeneous compared to land due to less diverse sources, several studies reveal that the aerosol properties over the oceanic regions show significant variations associated with the transport of anthropogenic aerosols from the mainland and adjoining continents (Moorthy *et al.*, 2010; Kharol *et al.*, 2011; Kumar *et al.*, 2011; Spandana *et al.*, 2012). In situ measurements of aerosols over the oceans are carried out mainly by campaign mode (ship-based) observations and/or from island stations. Bay of Bengal (BoB) occupies a special importance because of its proximity to the surrounding landmasses on its north, east and west which are densely populated and industrialized areas and therefore is a congenial platform for investigation of natural marine aerosols as well as their interaction with continental pollution.

In view of the importance of the study over BoB and other oceans surrounding Indian sub-continent, Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB) was conducted during the premonsoon (summer) season of March–May 2006 with an aim to identify the major sources of aerosols (natural and anthropogenic) and to characterize their role on regional climate over the Indian sub-continent and adjoining oceanic regions, e.g., Bay of Bengal (BoB) and Arabian Sea (AS). The main results of this campaign have been highlighted in numerous studies included in the special issue of Journal of Earth System Science (Volume 117, S1, July 2008). A follow-up campaign, W-ICARB (W stands for Winter), was carried out in the winter season, when the northern landmass experiences strong winter conditions, during the period December 2008–January 2009, following the same multiplatform integrated concept of ICARB 2006 (Moorthy *et al.*, 2010). The cruise covering a major portion of the BoB examining the aerosol properties over far eastern and southeastern BoB, which could not be covered in ICARB 2006, especially in view of the observed advection of anthropogenic aerosols from these regions to BoB (Moorthy and Babu, 2006).

The present study focused on the variations in marine aerosols over latitudinal and longitudinal sectors by characterizing their optical and physical properties measured onboard the oceanographic research vessel (ORV) Sagar Kanya (SK) on its cruise SK 254 over the BoB, to examine the influence of continental fluxes and sea-surface wind to the aerosol load and effect of wind speed and continental airmass to aerosol loading over the oceanic area were presented here. The present paper is structured as follows: information about the cruise track followed along which the experiments are conducted; instrument details with its limitations of use and a brief discussion about data analysis are given in section 2. Section 3 provides the meteorological conditions observed during the cruise campaign, while section 4 presents the signatures of advection of continental airmass transport that affect the BoB region. Finally, the results are discussed in section 5, while section 6 summarizes the main conclusions.

DETAILS OF CRUISE TRACK AND EXPERIMENTS

Study Region

W-ICARB was conducted from 27 December 2008 to 30 January 2009 over entire BoB focusing on the physical and optical properties of atmospheric aerosols and trace gases over the region. The ship originated from Chennai seaport (13.1°N, 80.2°E) on 27 December 2008 and sailed through the path shown in Fig. 1. During its return journey, it passed Sri Lanka on 28 January 2009 and returned back to Kochi port (9.6°N, 76.1°E) at Arabian Sea (AS) on 30 January 2009. The particular configuration of the cruise track (Fig. 1) enabled measurements on the coastal water adjoining the anthropogenically-dominated mainland and far off oceanic regions in rapid succession (Moorthy *et al.*, 2010). This provided a nearly homogenous spatially gridded aerosol database within a time span of about a month, during which the aerosol characteristics are considered to be statistically invariant (Moorthy *et al.*, 2008). This was also corroborated by the prevailing meteorology, which was devoid of any major synoptic weather systems, such as cyclone, depressions, or extensive cloud cover during the measuring period.

Ship-Borne Aerosol Measurements

Surface level and columnar integrated observations are helpful in gaining information on aerosols at higher altitudes especially, to explore the possibility of higher level transport. The onboard aerosol measurements were performed from a specially designed laboratory on the top deck of the ORV (~10 m above mean sea level, amsl). Continuous measurements of instantaneous size-segregated mass concentration of composite (total) aerosols were made using a 10-stage Quartz Crystal Microbalance (QCM) cascade impactor (model PC-2 California instruments, USA) having 50% lower size cut-off at each of its 10 size bins at > 25 µm, 12.5, 6.4, 3.2, 1.6, 0.8, 0.4, 0.2, 0.1, and 0.05 µm for size bins from 1 to 10; the sum of the individual-bin mass concentrations yielding the total mass concentration, M_T, of ambient aerosols. The QCM sampled the ambient air through an iso-kinetic community air inlet pipe fixed to the port side of the ship at a constant flow rate of 0.24 L/min with a sampling time of 300 s. Measurements were repeated at regular intervals of 30 min, round the clock. Measurements were restricted to the periods of RH (relative humidity) < 78% at the deck level, in view of the affinity of the quartz crystal to changes in RH for higher RH (Pillai and Moorthy, 2001; Nair *et al.*, 2008; Kumar *et al.*, 2009). But there were no data loss on application of this restriction, as there were only one or two points in the hourly data and in the present study we have taken the daily averages, omitting those values. In general, the uncertainties in the measured M_T values were in the range of 10–20% at very low mass concentration. (≤ 10 $\mu g/m^3$) and the error reduces to < 10% for the high mass concentrations (> 30 $\mu g/m^3$). An extreme care has been taken to avoid any contamination of the chimney smoke plume located the instrument in the upwind direction of the chimney plume. For this reason, the daily averages of the aerosol mass concentrations were used in the present work.

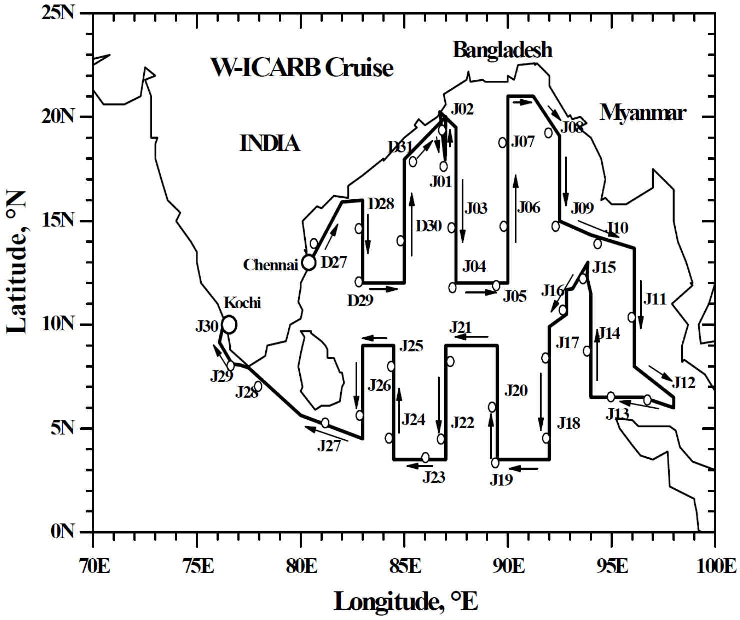

Fig. 1. The cruise legs (solid lines) of the Sagar Kanya (SK 254) in the Bay of Bengal during the period 27 December 2008–30 January 2009 with indications of the daily position of the ship at 05:30 UTC denoted with hollow circles.

More details of the instrumentation, analysis and error budget are given elsewhere (Pillai and Moorthy, 2001).

In addition to the above near-surface level aerosol characteristics, column spectral aerosol optical depths (AOD, $\tau_{p\lambda}$) were estimated using a MICROTOPS II Sun Photometer (Solar Light Co, USA) at 5 wavelengths centered about 380, 500, 870, 936 and 1020 nm, attached with a GPS (Global Positioning System) receiver to provide information on the geographical coordinates and times of the observations (Morys *et al.*, 2001; Ichoku *et al.*, 2002). Being a hand held instrument, consistency in accurate focusing to Sun cannot always be achieved, especially on moving platform such as ship. For this reason, it is always advisable to take many measurements in a quick succession so as to retain only those that correspond to the smallest AOD values, as they would represent measurements from most accurate Sunphotometry. Hence data was taken in 10 min interval, 3–4 scans in each observation and best of the values was used for the analysis. Typical combined error in AOD measurement using the Sun Photometer as described by Porter *et al.* (2001) and Ichoku *et al.* (2002) is in the range 0.009–0.119 (around 1%) at different wavelengths. Other measurement protocols (e.g., Morys *et al.*, 2001; Ichoku *et al.*, 2002) were strictly adhered during data collection.

The Ångström formula (Angstrom, 1964) has been fitted in spectral AODs in order to obtain the wavelength exponent (α) and the turbidity coefficient (β) using the least-squares method in the lnAOD vs. lnλ plot in the spectral band 380–1020 nm. The curvature of the lnAOD vs. lnλ was also used to have some insight on the aerosol distribution and fine-to-coarse mode dominance (Eck *et al.*, 1999; Schuster *et al.*, 2006; Kaskaoutis *et al.*, 2007). The curvature is characterized by the coefficient α_2 (Eq. (1)), which can be utilized in conjunction with AOD and α for the discrimination of different aerosol types (Eck *et al.*, 1999):

$$\ln\tau_{p\lambda} = \alpha_0 + \alpha_1 \ln\lambda + \alpha_2 (\ln\lambda)^2 \quad (1)$$

Along with aerosol measurements, concurrent surface layer meteorological observations were carried out using an Automatic Weather Station (AWS) fitted with several meteorological sensors on a 7 m long retractable boom fixed to the bow of the ship. Data from these sensors were recorded every 10 min. Beside these, hand-held meteorological instruments were also used to measure atmospheric pressure (P), air temperature (Temp), relative humidty (RH), wind speed (WS) and wind direction (WD) have been carried out on an hourly basis. In addition, manual sea surface temperature (SST) measurements were made at hourly intervals using the bucket thermometer from a few centimeters below the sea surface. The measured WS was corrected for the velocity of the ship using the method proposed by Smith *et al.* (1999). The navigation parameters of the ship such as its velocity, header angle from true North and exact geographical location in the terms of latitude and longitude were continuously recorded at every second using a GPS provided onboard the ship. More details of the sensors instrumentation and measurement techniques are given elsewhere (Subrahamanyam *et al.*, 2011).

In the time evolution of aerosol distribution, the wind field variables are computed from the daily National Centre for Environmental Prediction (NCEP) reanalysis at standard pressure levels. As the typical life time of aerosols is 7 days, HYSPLIT (HYbrid Single Particle Lagrangian Integrated Trajectory) Model (Draxler and Rolph, 2003) back trajectories were used, to identify the source regions as well as the transport pathways of the air parcels arriving over BoB during the cruise campaign.

Effect of Wind Speed on AOD

The dependence of aerosol optical depth on wind speed

(Kedia and Ramachandran, 2008a) is expressed as

$$\tau = \tau_o \exp(bU) \quad (2)$$

where τ is the AOD at wind speed U (m/s), b is the wind index (s/m) and τ_o is the background AOD when the wind speed reaches zero. Daily mean AODs and wind speeds are used to determine the influence of wind speeds on AODs over the Bay of Bengal.

Influence of Continental Airmass on AODs

For deriving the continental influence on the aerosol optical depth, the scaling distance is calculated upto which the continental effects are felt significantly. To determine the scaling distance mean, AOD for each day is plotted against the distance from the coast for the Bay of Bengal. The scaling distances for the oceanic region are estimated from an exponential fit which is of the form (Moorthy *et al.*, 2001; Ramachandran, 2004),

$$\tau = \tau_c \exp(-D/D_o) \quad (3)$$

where D is the normal distance from the observation point to the coast (Chennai for the Bay of Bengal), D_o is the scaling distance at which AOD decreases to 1/e of its value and τ_c is the AOD measured at the coast. The scaling distances are estimated over the BoB for the daily mean AODs measured during the cruise period.

SYNOPTIC WIND PATTERNS AND METEOROLOGICAL CONDITIONS

The distinct changes in the prevailing synoptic meteorology over South Asia including the BoB associated with Asian monsoon circulation system are well documented (Asnani, 1993). The NCEP/NCAR reanalysis (http://www.cdc.noaa.gov) meridional and zonal wind fields at the pressure 925 mb have been used to ascertain the synoptic meteorological conditions during the study period. The daily mean composite vector wind at 925 mb level over the Indian region is shown in Fig. 2 for the months December 2008 (Fig. 2(a)) and January 2009 (Fig. 2(b)) depict contrasting air masses from distinct geographical regions. The shaded contours correspond to the magnitude of wind speed with levels represented on color scale on which, surface level wind vectors represented by arrows are overlaid. The arrow heads show the wind direction and the length of the arrow represents the mean wind speed. Over the BoB the winds are calm and show mixed origins and arise mainly from the BoB with signatures of transport from continental India (Moorthy *et al.*, 2010; Kumar *et al.*, 2011). The low level anticyclone prevailed over the Indian mainland led to a continental outflow from Indo Gangetic Plain (IGP) over the northwestern BoB. The winds were below ~4 m/s over continental India, having larger intensities over BoB, mainly over its southern parts. The southern and southeastern BoB were influenced mainly be easterly airmass from the East and Southeast Asian region, with the wind speeds increasing toward the east. The stronger winds over southern BoB may be responsible for the production of coarse sea-salt aerosols (Kaskaoutis *et al.*, 2011; Sinha *et al.*, 2011a). Sky was clear during most days of the cruise barring a few days, while the ship was closer to the Andaman and Nicobar Islands, where the sky was cloudy for most of the time. While the ship was surveying in the southern BoB region, the weather was disturbed with moderate to heavy rain. Recently, similar synoptic wind pattern prevailed at 850 and 700 mb was reported by Kharol *et al.* (2011) over the entire BoB during the campaign period. It may be noted that these figures provide only the synoptic conditions that prevailed during the campaign period.

The daily mean calculated from the hourly data in Pressure, SST, RH, Temp, WD and WS over the BoB during W-ICARB are plotted in Fig. 3(a)–3(f) from top to bottom

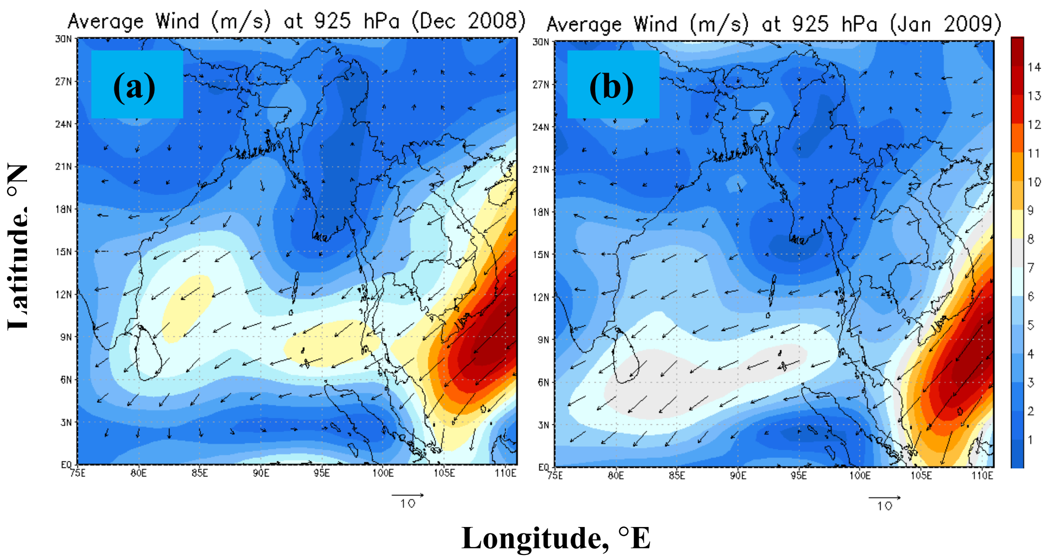

Fig. 2. Synoptic wind vectors at 925 hPa level for (a) December 2008 and (b) January 2009 during W-ICARB field experiment over the Indian subcontinent.

panels, respectively. On most of the days, it is found that SST is greater than air temperature varying between 24°C and 28.3°C with the lowest (highest) SST values were observed in the northern BoB (southern BoB) creating a pronounced latitudinal gradient. On 31 December (D) 2008, a dip is observed in SST at 25.6°C. Another decrease to 24.8°C is observed on 7 January (J) 2009. Afterwards, SST remained nearly constant around 27°C till 17J, and on the next day SST again increased to 28°C. An intense increase to 28.3°C was observed on 19 J. But after 20J, we can see that, the variation in SST was between 27°C and 28°C till the end of the cruise. Relative humidity (RH) showed considerable fluctuations during the W-ICARB campaign over the BoB. It increased up to 80% on 18J and recorded a minimum of 49% on 29D. But on most of the days, it is observed that RH was varying between 56% and 67%.

The maximum and minimum temperatures recorded during the cruise are 29.3°C and 24.5°C on 29J and 8J, respectively. From Fig. 3(d) during the cruise period, air temperature (Temp) remained between 25°C and 27°C during most of the days, with their little diurnal variation till 19J. Temperatures were greater than 27.6°C on 30D, 14J and after 31D and 8J, the temperature values again dropped to 25°C. While in southern BoB, the air temperature remained constant of 29°C till the end of the cruise from 18J to 29J. Wind speed (WS) show considerable fluctuations from the beginning of the cruise (Fig. 3(f)). On 14J, WS went up to 10 m/s. Another increase in wind speed can be observed on 20J recording a maximum of 12.2 m/s. After a spell of low winds (during which wind speed was as low as 5 m/s) an increase of 10 m/s was recorded on 24J. While the ship was sailing along the coast line and mid BoB, WS showed variation between 6.4 m/s and 8.5 m/s. Toward the end of the cruise, wind speed showed a marginal decrease on 25J onwards from 9 m/s to 3 m/s.

TRAJECTORY ANALYSIS: ROLE OF AIRMASS TRANSPORT

The aerosol load and type at any location are generally influenced by the background atmospheric conditions such as wind and convection, and hence affect the airmass transport

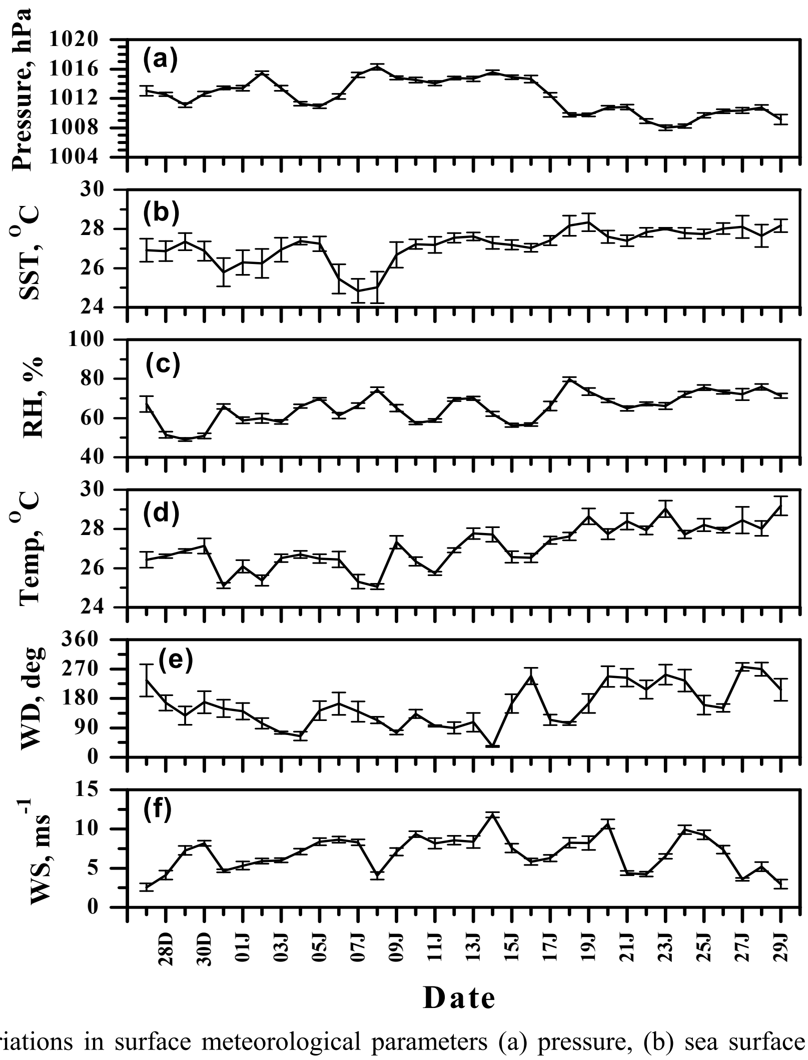

Fig. 3. Daily mean variations in surface meteorological parameters (a) pressure, (b) sea surface temperature (SST), (c) relative humidity, (d) air temperature, (e) wind direction and (f) wind speed (from top to bottom panels) recorded along the cruise track during W-ICARB experiment over the BoB region.

over the region. The role of background seasonal wind, and hence that of the airmass transport in aerosol loading over oceans adjoining Indian coast has been reported elsewhere (e.g., Li and Ramanathan, 2002; Satheesh *et al.*, 2006; Moorthy *et al.*, 2010). All these studies revealed the influence of the aerosol transport from the Indian subcontinent, Southeast Asia and Africa/Arabia on the oceanic areas around the Indian subcontinent during the Asian dry seasons (pre-monsoon and winter) through the lower tropospheric northerly (northeasterly or northwesterly) winds. Further, aerosol concentration over the BoB is due to airmass from Southeast Asia and northeasterly winds from the Indian subcontinent and also the African/Arabian desert dust by means of northwesterly winds. The present study also witnessed the similar wind features over the oceanic regions around India. Fig. 4 shows 168-hr (seven day) isentropic airmass back trajectories (at three heights) for the entire cruise period over BoB obtained from HYSPLIT version 4 (Draxler and Rolph, 2003) model, where different types of airmasses that influence the aerosol loading over BoB. This analysis further showed that the African and Arabian airmasses are also playing a significant role, besides Indian airmass, over the BoB especially over northern BoB region. The day-to-day back trajectory analysis revealed that the eastern BoB affected by east Asian airmass, western BoB affected by airmass pathways from the Indian region, while the northern and southern BoB is more influenced by the aerosol transport from Arabian/African desert dust and eastern countries, respectively. The eastern BoB is however, relatively less influenced from the airmass of Indian origin.

RESULTS AND DISCUSSION

Temporal Variations of Aerosol Optical Depth

Aerosol optical depths (AODs) were derived using a hand-held Microtops II Sun photometer for five wavelengths and their daily mean values are obtained. The variations in daily AOD observed large fluctuations at shorter wavelengths (~3 times higher than those measured at the longer ones) for all the days of the W-ICARB campaign in the BoB region which is shown in Fig. 5 indicating the dominance of smaller size aerosols. The mean AOD_{500} during W-ICARB was found to be 0.35 ± 0.07 which is comparable in magnitude with the (0.36 ± 0.12) found over BoB during ICARB 2006 (Kalapureddy and Devara, 2008). The high AOD_{500} (0.5 to > 0.8) was noticed for the days 30D–31D, 6J–7J and 14J–17J occurs when the ship was sailing close to densely populated, urbanized and industrialized eastern/northeastern Indian coast due to direct influence of the coastal urban centers and the long-range transport of continental aerosols (Kharol *et al.*, 2011; Kumar *et al.*, 2011). The anthropogenic emissions from the coastal regions of India can contribute to fine and accumulation mode aerosols through secondary production mechanisms (condensation, coagulation, and gas-to-particle conversion) in the warm and humid tropical environment (Babu *et al.*, 2009; Moorthy *et al.*, 2010). For the following days 3J–5J, 8J–10J and 26J–27J, lower AOD_{500} was noticed where the ship was cruising in the central BoB, far away from the coasts, and in a small area in the northeastern part of BoB close to Myanmar coast.

The very high value of AOD_{500} recorded on 2 January 2009 (not shown in Fig. 5) measured over northwest BoB is mainly attributed to some extreme hazy weather conditions in the morning. On that day, the observations performed with the Sun photometer were limited to a few scans in the morning only till ~11:30 LT and not favorable to do measurements in the noon due to formation of thick hazy layer and intense cloud coverage over this region of BoB. After adopting the criteria applied in Kaskaoutis *et al.* (2011) to avoid the cloud contamination in the Sun photometric measurements recorded in the morning hours of 2 January, only few data points were left that are not used in the present study are considered as high turbid. Kharol *et al.* (2011) reported the presence of intense hazy aerosol layer over Indo-Gangetic Plain (IGP) and Bangladesh which is clearly shown by Terra/Aqua MODIS true color images on 7 January 2009 traps the aerosols and pollutants near the ground, indicating a strong continental outflow towards the marine environment, results in dramatic increase in aerosol loading and limitation of visibility. The large amount of water-soluble aerosols over IGP provides the necessary condensation nuclei for the formation of fog near the ground, especially when the RH is high (Badarinath *et al.*, 2007a; Das *et al.*, 2008). Even the lidar systems on board satellites such as CALIPSO detected the presence of thick aerosol layer, extending from surface up to ~3 km altitude covering IGP and northwestern part of BoB (for more details see Fig. 7 of Kharol *et al.* (2011)). These elevated aerosol layers observed in variable intensity between 0.5 and 2.0 km over the whole BoB contribute to the vertical heterogeneity in aerosol load and characteristics over the region (Sinha *et al.*, 2011a).

Day-to-Day Variations in AOD, α, Curvature and Water Vapor

Time series of the daily mean values of columnar aerosol parameters (AOD_{500}, $\alpha_{380–1020}$ and curvature α_2) obtained from Sun photometer are presented in Fig. 6. An attempt has been made to compare the daily average of Sun photometer AOD_{500} measured with each 1° × 1° latitude-longitude grid MODIS (Terra and Aqua) Level 3 data and are plotted in Fig. 6(a). For this AOD comparison, high resolution Sun photometer observations are averaged for the entire scans in a day in order to match with daily MODIS observations. The daily AOD_{550} observed by Aqua and Terra has been collected for corresponding geographical position of the present ship based on daily mean Sun photometer observations of AOD_{500}. A comparison of this sort resulted in inclusion of all the ship-borne measurements and as a consequence the number of data points increased, thereby improving the statistics. Gaps in the observation of Sun photometer are due to unfavorable sky conditions. 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. The MISR AODs are not used for the trend analysis due to insufficient data points.

The mean value of MODIS AODs at 550 nm and Sun photometer obtained AODs at 500 nm over entire BoB during the entire cruise period are 0.32 ± 0.03 and 0.35 ± 0.07, respectively. Except on 31 December (near Visakhapatnam coast) and 7 January (near Bangladesh and Burma coast) the AOD_{500} values over BoB are low, varying in between 0.2–0.5. Higher AOD_{500} values (~0.7) over Visakhapatnam coast seem to be a regular feature, over this region, from

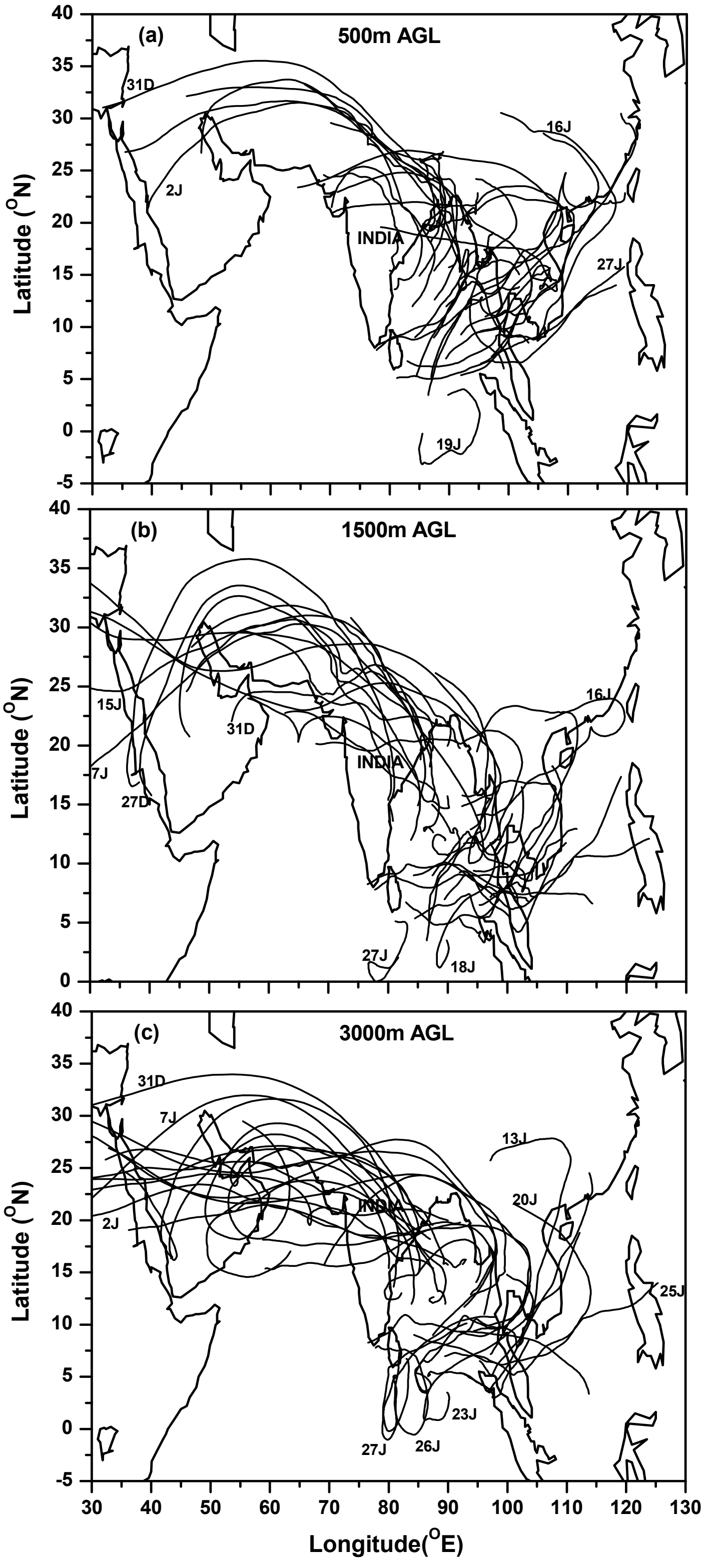

Fig. 4. 7-day HYSPLIT back trajectories over the BoB at (a) 500m (b) 1500m (c) 3000m during 27 December 2008–30 January 2009.

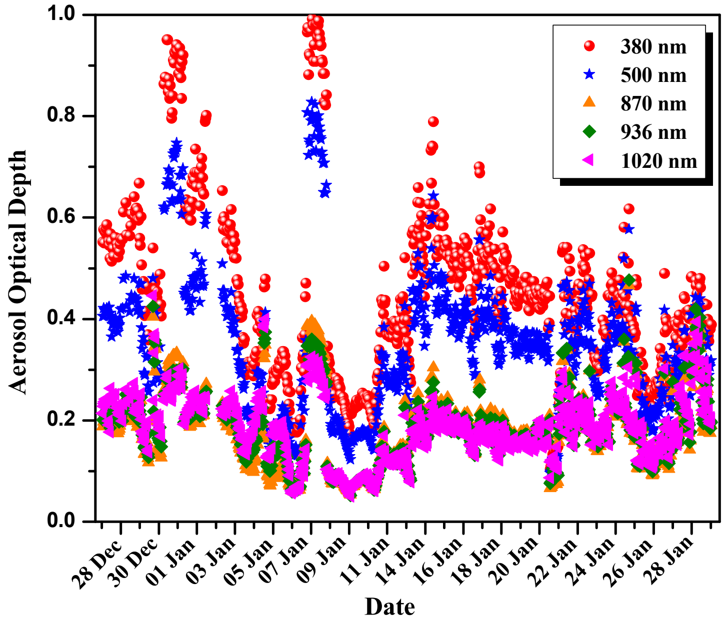

Fig. 5. Temporal variation of the AOD observed at all the wavelengths in the BoB during the W-ICARB campaign.

the knowledge of present and earlier cruises reports (e.g., Kalapureddy and Devara, 2008; Kedia and Ramachandran, 2008b; Moorthy *et al.*, 2010; Kaskaoutis *et al.*, 2011; Kumar *et al.*, 2011; Sinha *et al.*, 2011). It is found that variations in AOD derived using MODIS (Terra and Aqua) data track well the variation in AODs derived using Sun photometer. The increasing and decreasing trends are similar for ground based and satellite derived AODs. The slight underestimation of MODIS derived AOD_{550} was found during the study period (winter) relative to AOD_{500} with Sun photometer, which is comparable with the results reported by More *et al.* (2013) during winter over Pune. The inconsistency between aerosol microphysical and optical properties and surface reflectance used in the MODIS are possible reasons for these differences during winter. Otherwise, the comparison is found to be reasonably good with a correlation coefficient of above 80%. It has been pointed out that generally MODIS overestimates AOD for low aerosol loading and underestimates for high loadings (Remer *et al.*, 2005).

Mean daily values of Ångström exponent, $\alpha_{380\text{–}1020}$ shows higher values in the beginning and lower at the ending of the cruise with a sharp fall in α values during 17–19 and 26–28 January (Fig. 6(b)), which was found to be associated with airmass trajectories originating from southern BoB (see Fig. 4). The average value of α over the Bay of Bengal region is 1.03 ± 0.06 which is lower than the value 1.12 ± 0.09 measured earlier during ICARB 2006 in pre-monsoon season (March–April) (Kedia and Ramachandran, 2008a) and 1.80 ± 0.12 measured in February 2001 (Ramachandran and Jayaraman, 2003a). Lower value of 1.03 indicates a relatively larger concentration of bigger size particles over the BoB during December–January when compared to February 2001. A low α indicates low concentration of accumulation mode particle (mainly from anthropogenic activities and transported to these oceanic regions), while an increase in the larger size (sea salt, dust) particles. Therefore, α increases, when the ship traveled towards the coast. Similar observations have been noticed by Kedia and Ramachandran (2008a) and Kalapureddy and Devara (2008) over the BoB during ICARB 2006 in pre-monsoon season. From low α values and airmass trajectories at higher altitude (3000 m), it can be understood that there was a rather significant desert dust aerosol contribution during 26–28 January originating from long distant semi-arid regions (Arabian Peninsula) besides the locally generated coarse-mode (shorter life) sea salt aerosols (see Fig. 4). Nevertheless, the absence of low α values during the campaign differentiates BoB from other oceanic regions. It is rather strange to observe such high α values over an oceanic environment, but it was found that on those days airmasses came from continental India and the winds were rather low (see Fig. 2) not favoring the production of marine aerosols. Therefore, with the absence of intense sea-surface winds and the absence of airmasses originating from the nearby landscapes surrounding BoB from north and east, the aerosol loading over the area is mainly dominated by small anthropogenic components, thus explaining the relative high α values.

The curvature, α_2, shows mostly negative values indicating the significant contribution of fine-mode aerosols in the aerosol size spectrum. It can be noted that α_2 and, as a consequence, α' values show relatively higher standard deviation when the AOD_{500} values are critically below 0.2. The fine mode (negative curvature) aerosols are mainly depicted in the coastal, northern and far BoB regions associated with the nearby arid areas while coarse mode (positive curvature) aerosols are mainly observed over the southern BoB region (Fig. 6(c)). It may be noted here that under such low turbid conditions, the uncertainty associated with the computed α_2 and α' through the polynomial fit (Eqs. (2) and (3)) will be more and hence their physical significance, during such conditions, can be less reliable. This was also apparent in numerous studies since the above

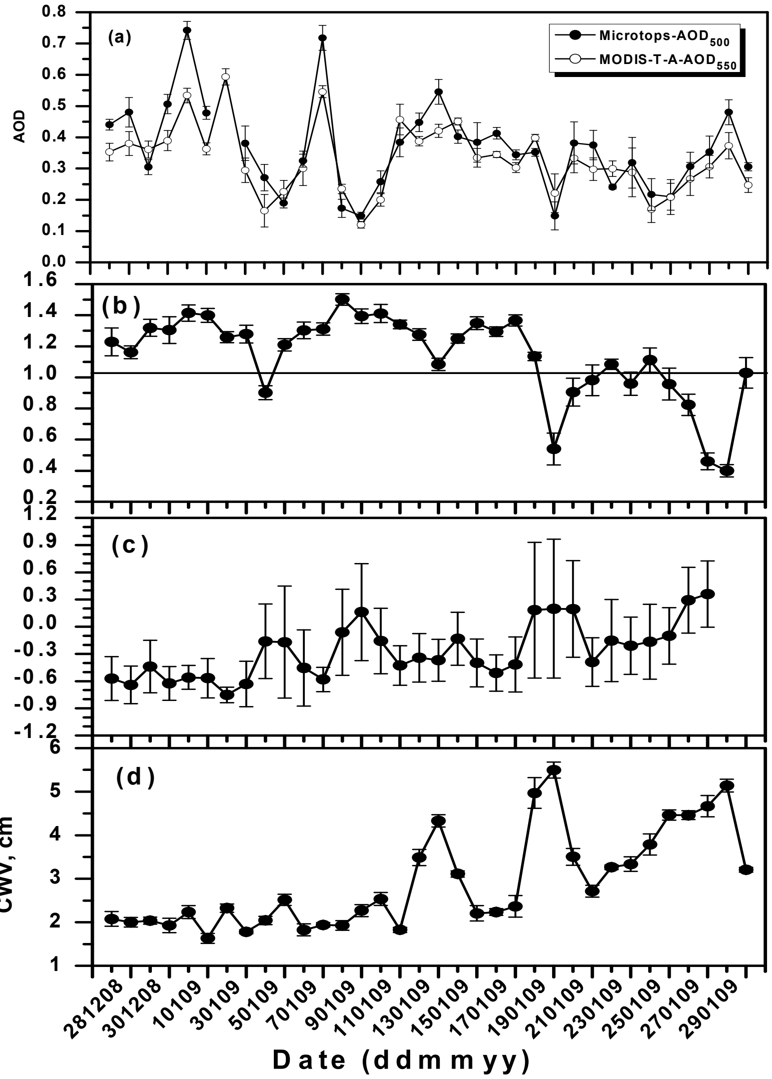

Fig. 6. Time series of the daily average values of (a) Microtops observed AOD_{500} compared with MODIS (Terra and Aqua) daily mean AOD_{550} (b) Ångström exponent, $\alpha_{380-1020}$ (c) Curvature, α_2 and (d) Columnar water vapor, CWV measured during W-ICARB. The solid line in (b) represents the mean value of α for the entire study period.

retrievals deal with greater uncertainties under low turbid conditions. However, in general, they provide reliable information about the type of aerosols to the aerosol size distribution under sufficiently high aerosol loading environments (Kalapureddy and Devara, 2010). The columnar water vapor (CWV) content is high with a value of ~5 cm when the ship is sailing away from the coast and in the pure oceanic environment (southern BoB) whereas it is found to decrease in the magnitude of CWV near the coastal regions.

Spectral AOD Variations

All the data collected during the cruise are grouped according to the regions i.e., BoB and NIO (North Indian Ocean extending from 3°N to 6°N in the present study). The mean spectral distribution of AOD with its respective standard deviation (vertical bars) observed over the two regions is shown in Fig. 7. Out of 35 days of the cruise, only observations taken on 32 days including 15 clear sky days and 17 days haze with patches of clouds. During the measurement period, the sky was clear at the most part of the day, especially in the morning hours where the majority of the measurements (~60%) obtained. In some days on midday and afternoon formation of cirrus clouds was observed obscuring the spectral measurements. It was found that the AODs continuously decrease as wavelength increases. This decrease, expressed by the Ångström exponent α, depends on the aerosol optical properties (single scattering albedo, asymmetry factor, particle size distribution) and has been investigated by Reid *et al.* (1999). At 0.38 µm, a mean AOD value of 0.49 ± 0.07 (0.37 ± 0.08) was derived over the BoB (NIO) during the whole experimental period. At 0.5 µm the mean AOD value is 0.42 ± 0.05 (0.30 ± 0.05) over the BoB (NIO), which further drops to 0.20 ± 0.03 at 0.87 and 1.02 µm. Fine mode aerosol particles cause larger variations in the AODs at shorter wavelengths than those caused by coarse mode particles, thus increasing the slope of the AOD versus wavelength, which expressed by the Ångström exponent, α.

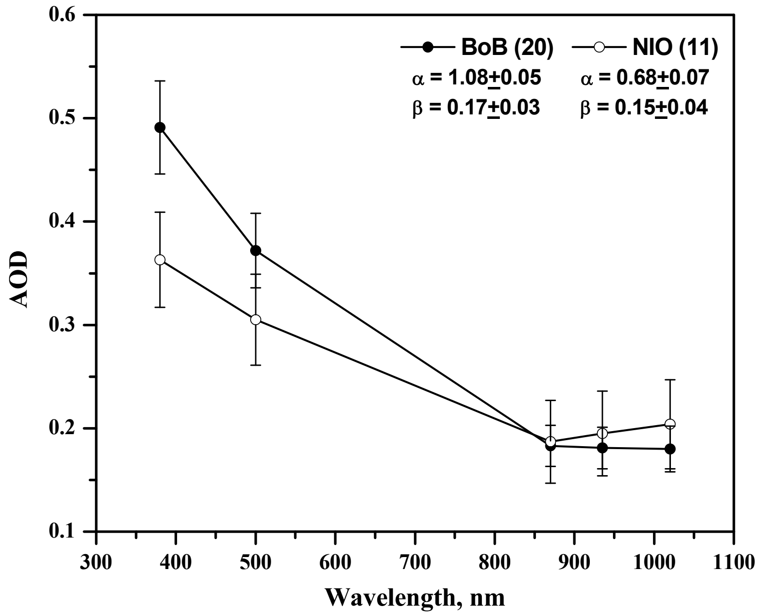

Fig. 7. Spectral characteristics of AOD over the BoB and NIO regions. Values in bracket stand for number of observational days. The mean values of α and β are also given for each region.

The reason for the observed difference in AOD among the two regions could be due to the variation of the concentration of the aerosols content transported wind speed and wind direction. The variability is also associated with the airmass and also partly due to non-availability of adequate water vapor in the atmosphere (Kalapureddy and Devara, 2008). The overall aerosol loading is relatively more over the BoB and less over the NIO region. Apart from the expected wavelength dependence of AOD according to the Mie theory, the results reveal greater α values indicating dominance of smaller size (fine) aerosol particles over the BoB than over NIO region. The high aerosol loading with predominant fine mode aerosols (large α) suggests that BoB is more polluted with anthropogenic sources. It is also revealed from the Fig. 7 that, AOD is higher at longer wavelengths over NIO region indicating dominance of coarse mode aerosols (small α) compared to BoB, which is typical of the pristine ocean environment. The observed regional AOD spread is significantly influenced by the airmass over the BoB coming mainly from Indian subcontinent and Southeast Asia during the winter (Satheesh *et al.*, 2006; Kalapureddy and Devara, 2008; Moorthy *et al.*, 2010; Spandana *et al.*, 2012).

To gain a better understanding of the aerosol characteristics over these oceanic regions, spectral aerosol optical depths in the wavelength range of 0.38–1.02 µm for two selected days over the BoB is shown in Fig. 8. These days are chosen as Ångström parameters are different. Over the BoB, on 7 January Ångström parameters α and β are 1.24 and 0.26 respectively, while α and β values on 8 January are 1.25 and 0.07. α value is lower on 7 January as compared to that on 8 January while β is high. On 7 January, a higher β represents an increase in the total columnar aerosol concentration and therefore a higher AOD. Though α on 7 and 8 January do not show significant difference, β on 7 January is 4 times higher than that of 8 January indicating a large increase in the columnar aerosol loading. On 8 January a higher α indicates an increase in the smaller size particles but owing to lower β, AODs are found to be lower. A noticeable decrease in spectral AODs is seen on 8 January as compared to 7 January.

Intercomparison of MODIS and MISR Derived AODs

An intercomparison of AOD values from different satellite sensors is necessary for climatological studies, and also to improve the accuracy and the coverage achievable with a single sensor (Prasad and Singh, 2007). Xiao *et al.* (2009) recently examined MODIS and MISR AOD retrievals for Southeast Asia from a spatial perspective and found good correlation between the retrievals from each of these sensors. Figs. 9(a) and 9(b) shows the daily mean spatial variation of AOD derived from MODIS (at 550 nm) and MISR (at 555 nm) data products for the study period. It may be observed that the mean spatial distribution of MODIS and MISR AODs and the spatio-temporal variation from ship borne measurements during the measurement period were comparable. Kumar *et al.* (2011) and Spandana *et al.* (2012) reported that the scatter plot of AOD measured on board ship at 500 nm and the MODIS AOD at the cruise point for that day at 550 nm shows an excellent correlation (with a correlation coefficient R = 0.92) indicating the qualitative agreement between these two measurements.

The spatial correlation for MODIS-MISR AODs has been analyzed using daily average Level 3 MODIS (MOD08_ D3.005) and MISR (MIL3DAE004) data for the period 27 December 2008–30 January 2009 which is shown in Fig. 9(c). MISR products are available with a spatial resolution of 0.5° by 0.5°, whereas MODIS products are only available at a spatial resolution of 1° by 1°. MISR data were converted to the same spatial resolution as MODIS data on the basis of the Giovanni re-gridding algorithm, using the box averaging

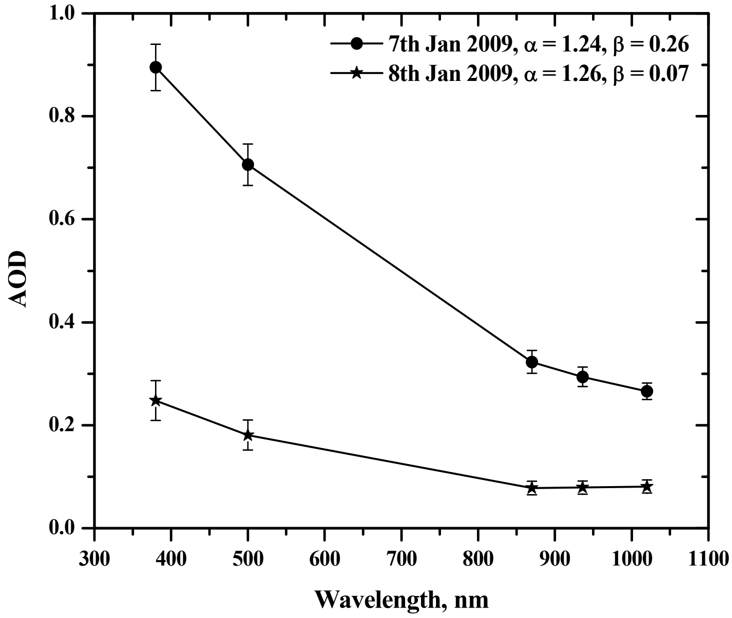

Fig. 8. AOD variations in the wavelength range of 380 to 1020 nm for two selected days over the Bay of Bengal which showed different values of Angstrom parameters.

method. The correlation coefficient between MODIS and MISR AODs was found to be high (> 0.92) for most of the regions under investigation. In addition, the spatial correlation between MODIS and MISR AODs was analyzed separately for the entire months of December 2008 and January 2009, and the correlation coefficient found to be higher in January than in December (figure not shown). The correlation was high (0.9–1.0) for the regions of northern BoB, along east coast of India and far East BoB due to sufficient number of data points retrieved by both the sensors and with a moderate correlation (between 0.6 and 0.8) in the central BoB which is sufficient to produce reliable results. The negative correlation between MODIS and MISR could be seen in the southern BoB. Cloud cover and frequent rains in this region leads to insufficient MODIS and MISR data points in the area, consequently weaker data analysis.

Latitudinal Analysis of Optical Properties

In Fig. 10(a) we showed the latitudinal variation (4–21°N) of AOD at 500 nm, averaged over the longitudes from 77°E to 98°E (so as to eliminate the values that are too close to the coast). The latitudinal step is defined to 1 degree, while the vertical bars indicate ± 1σ variation from the mean AODs due to longitudinal variation of each parameter. At the outset, it is seen over the Bay of Bengal the AOD_{500} increases steadily with latitude which can fitted by an exponential growth function. It shows a gradual build-up from the lowest values (~0.2) at 5°N to reach the peak at 20°N and then a weak decrease. 18–20°N latitudes presents high in AOD are expected as the ship cruised very near to the densely populated IGP and Kolkata coast, which includes cement factories, coal based thermal power plants, steel plants, etc. Fine mode particles transported over long distances from the continents will be found in abundance near the coastal regions. The AODs are about a factor of 2 higher in the 18–20°N latitudes when compared to 4–6°N. In the 4–6°N latitude the ship was located far away from the aerosol source regions, thus resulting in lower AODs. No significant variability in AODs over the BoB is evident in different latitudes. AODs are more or less similar in all the latitudes from 4°N to 14°N. These latitudinal variations in AODs over the BoB occur despite the fact that the surface winds over the MABL are strong and clear. The AODs are found to exhibit a larger temporal (day to day) but spatial variability in different latitudes, as opposed to a significant increase in AODs with latitude over the Bay of Bengal.

The latitudinal variation in Ångström exponent, $\alpha_{380-1020}$ during the study period over the BoB is shown in Fig. 10(b) and vertical bars represents deviation of the mean. $\alpha_{380-1020}$ shows a gradual build-up from the lowest (0.8) values at smaller latitudes (4–6°N) to reach a peak value of 1.4 at 18°N and thereafter it remains almost steady at higher latitudes (18–21°N). This clearly shows that $\alpha_{380-1020}$ is low at 4–6°N latitude which indicates dominance of coarse particles as the aerosol source regions are away from the measurement position and the ship is sailing in the southern BoB region where sea salt (natural) contribution is more compared to the anthropogenic sources. When the ship is crossing very near to coastal regions at higher latitudes (> 14°N), $\alpha_{380-1020}$ values observed to be high (1.4) represents the abundance of fine particles which are mainly from anthropogenic sources that are transported from central Indian peninsula and IGP. The similar spatial features for AOD_{500} and $\alpha_{380-1020}$ are reported by several authors over the BoB for the W-ICARB cruise campaign (Moorthy *et al.*, 2010; Kaskaoutis *et al.*, 2011; Kharol *et al.*, 2011; Kumar *et al.*, 2011; Sinha *et al.*, 2011a). In Fig. 10(c), CWV variation is shown as a function of latitude observed over BoB. It was found that water vapor is high (> 4 cm) at lower latitudes (< 7°N) and decreases gradually as the latitude increases attains a low value of 1.5

cm at higher latitudes (> 12°N). Latitudinal gradients in AOD and water vapor indicated higher aerosol loading with

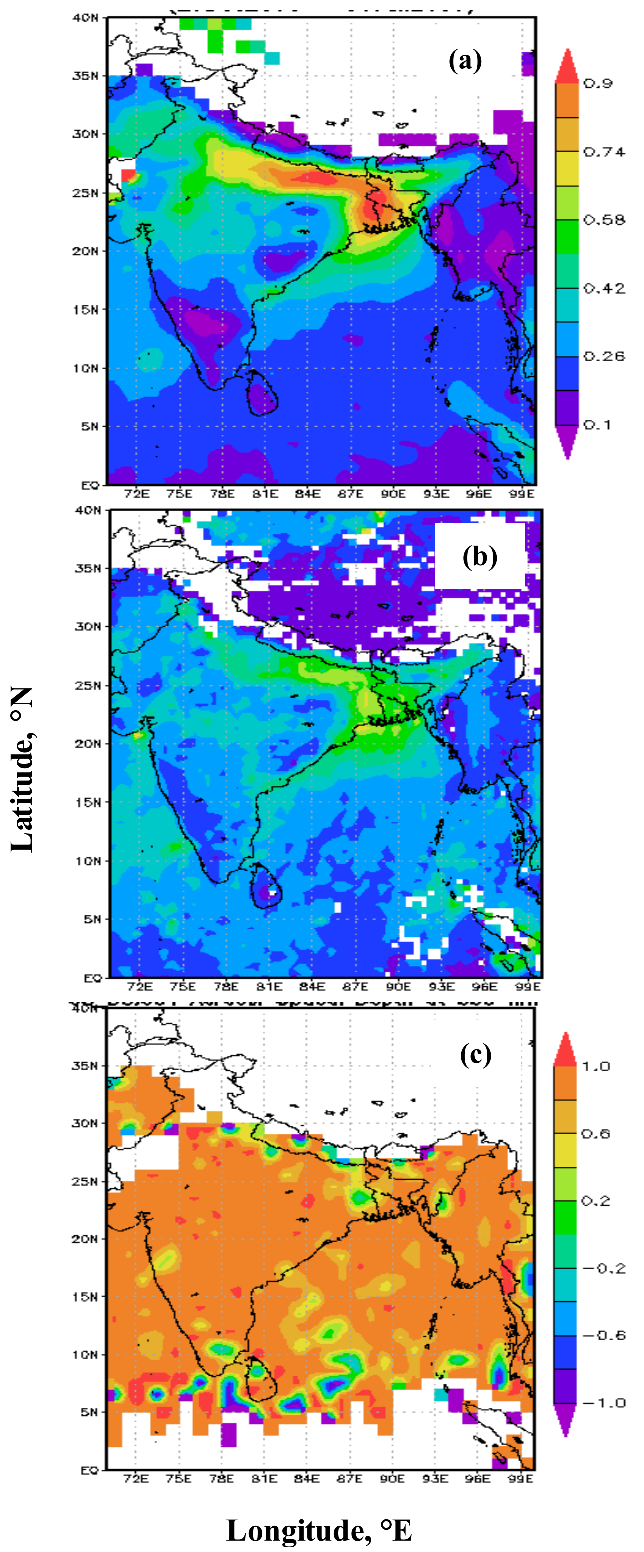

Fig. 9. Monthly mean spatial distribution of AOD over BoB retrieved from (a) MODIS (b) MISR and (c) spatial correlation between MODIS and MISR derived AOD for the study period. The colored scale is common for both AODs retrieved from MODIS and MISR.

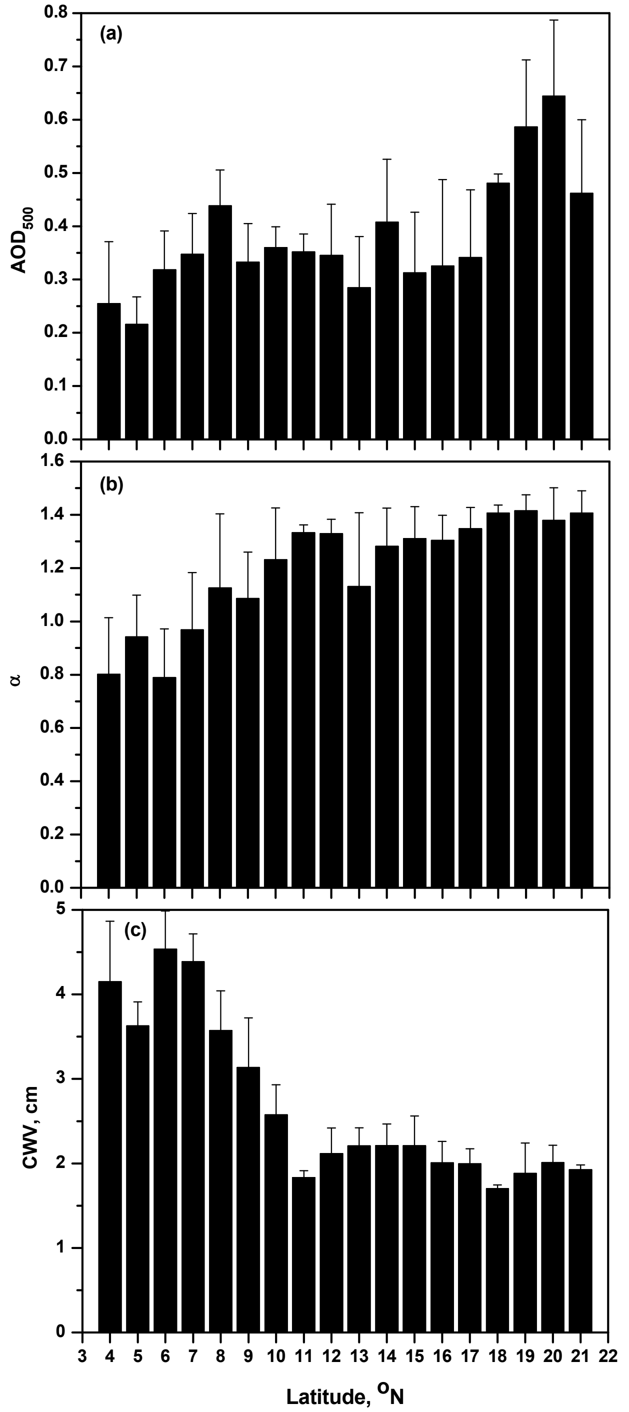

Fig. 10. Latitudinal variations in (a) AOD at 500 nm (b) Ångström exponent, α and (c) Columnar water vapor, CWV over the Bay of Bengal during W-ICARB.

low water vapor situations over North BoB region suggesting predominance of coarse mode aerosols. This is mainly due to the long range transport of adjoining arid airmass by the northwesterly wind during the study period.

Longitudinal Analysis in Aerosol Optical Properties

The scenario is different when the AODs are grouped as a function of longitude. Over the Bay of Bengal, longitudinal variations in AODs which is shown in Fig. 11(a) are found to increase from 77°E to 90°E thereafter, the AODs decrease between 91–96°E with a slightly increase in the 97–98°E longitude. Moderate AODs are observed in the 77–81°E longitude as measured when the ship is moving close to the west coast (Trivandrum and Kochi). From 80°E to 90°E longitude, higher AODs are expected as the ship cruised is along the east coast and near to the urban and densely populated IGP and Kolkata. Lower AODs are obtained in the 91–96°E longitude as the ship is cruising far away from the Indian coast. The longitudes 96–98°E shows again unexpected high AODs during which the cruise was in the far BoB and near to Myanmar coast. The variations in AODs over different latitudes and longitudes could be due to the differences in the anthropogenic environments, 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.

The longitudinal variation in $\alpha_{380-1020}$ observed over the BoB during W-ICARB is shown in Fig. 11(b) with vertical bars representing deviation of the mean. It reveals that $\alpha_{380-1020}$ shows high values (> 1) at lower longitudes when the ship is sailing along the west coastal regions and sudden dip at 78°E longitude and thereafter gradually increases from 79°E to 90°E longitudes and attains a peak value of 1.4 at 91°E. α is more or less similar in all the latitude from 91°E to 98°E. It is found that $\alpha_{380-1020}$ exhibits the highest values near Bangladesh and Myanmar coast during the cruise period. Similarly, variations in CWV as a function of longitude is shown in Fig. 11(c) which clearly depicts higher values in NIO and lower values near coastal regions.

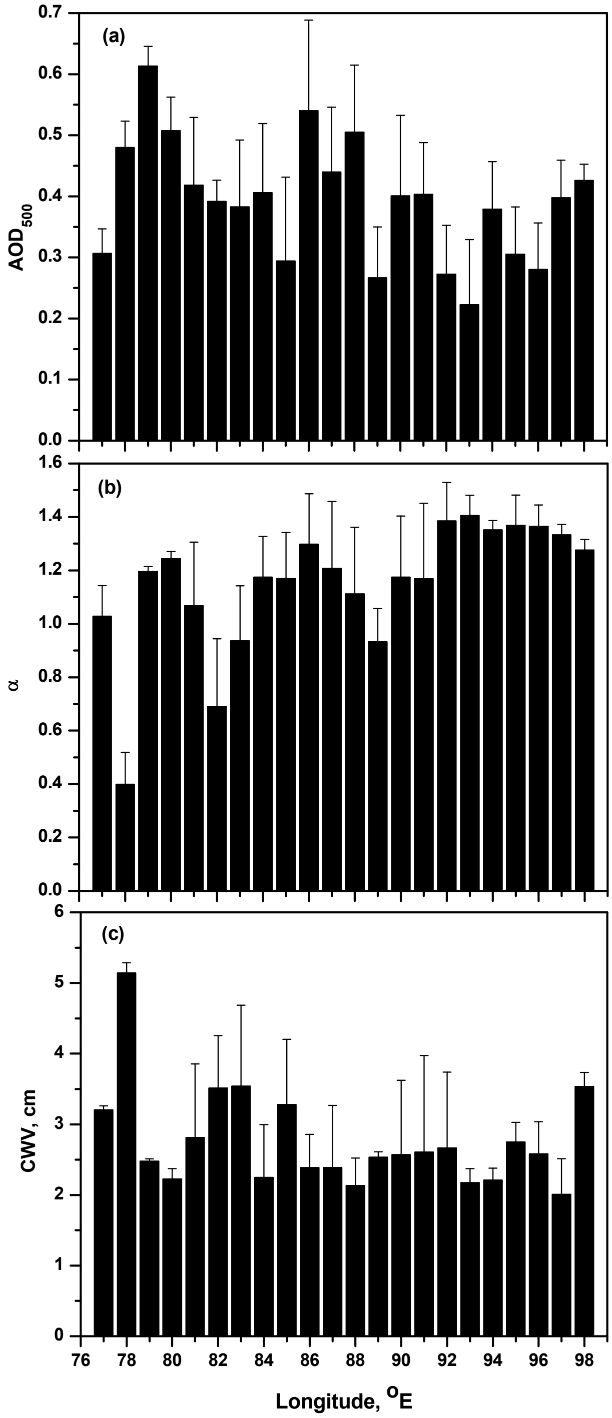

Fig. 11. Same as Fig. 10 but as a function of longitude.

Latitudinal and Longitudinal Variations in Total Aerosol Mass Loading

Fig. 12(a) shows variations in total mass concentration of surface aerosols over the MABL of BoB as a function of latitude with vertical bars representing deviations of the mean. It is observed that the aerosol mass loading increases with increase in latitude. At lower latitudes from 4°N to 6°N, M_T is low of 15 μg/m^3 and thereafter it gradually increases with a high value of ~50 μg/m^3 at 21°N. High values of mass concentration are noticed along the east coast regions of BoB due to the presence of two major ports Chennai and Vishakhapatnam and over northern BoB as such this region is covered with highly urbanized and densely populated IGP and Kolkata. Similar variations have been observed over the BoB in M_T as a function of longitude. M_t showed the lowest value of ~15 μg/m^3 at 80°E and the highest mass concentration of ~40 μg/m^3 at 92°E longitude (Fig. 12(b))

Relationship between Columnar and Surface Level Aerosol Characteristics

In order to investigate the correlation between columnar and surface level aerosol characteristics, a linear regression relation between the values of aerosol optical depth and mass concentration of surface aerosols is attempted. Such relation is useful as they can be used for the estimation of optical depth within a given accuracy, when only mass concentration measurements are available and vice-versa. Fig. 13(a)–13(d) shows the scatter diagram between AOD values at two different wavelengths (380 and 870 nm) and the PM_{10} (aerosols of size less than 10 μm) and $PM_{2.5}$ (aerosols of size less than 2.5 μm) mass concentrations measured simultaneously during the cruise period. In this correlation study only those datasets have been considered for which both observations are averaged for the whole day. The observed scatter in all these plots is due to the fact that while the

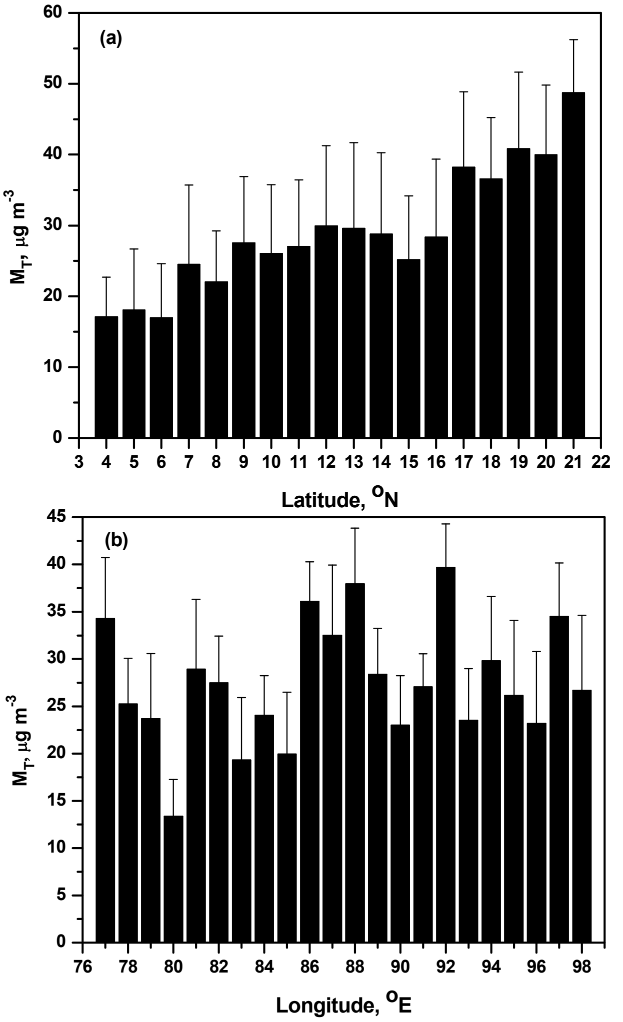

Fig. 12. Variations in total aerosol mass concentration, M_T over BoB during W-ICARB as a function of (a) latitude and (b) longitude. Vertical bars represent ± 1σ variation from the mean.

mass concentration values are for the aerosols present within the relatively well mixed marine atmospheric boundary layer (MABL), whereas AOD observations include the contribution from aerosols present not only within MABL, but also from those lying in the free troposphere, immediately above it (Alapattu *et al.*, 2008). Relative contribution from these two layers is dependent on the extent of vertical mixing between them, which in turn depends on other meteorological conditions. We also noticed that the correlation coefficients are good in case of scatter plots involving smaller aerosols and shorter wavelengths. Most interesting observation to be noted in these scatter plots is that all the regression lines yield a positive non-zero intercept on the AOD axis. This comes from the contribution of background aerosols in the free troposphere towards the total columnar AOD value which is higher in the case of observations at smaller wavelengths. Smirnov *et al.* (2002b) obtained a value of 0.04 as the intercept of the regression line for a similar scatter between AOD at 870 nm and dust aerosol concentration (correlation coefficient of 0.93) measured over Barbados.

A scatter plot of daily mean values of AOD at 500 nm with simultaneous daily mean values of total aerosol mass concentration (M_T) at the near surface level obtained from the QCM is shown in Fig. 14, which contains 34 simultaneous observation pairs. Notwithstanding the fair amount of scatter, AOD is found to increase with M_T. A linear regression analysis yields

$$AOD_{500} = 0.01M_T + 0.14 \quad (4)$$

with a correlation coefficient of 0.61, which is quite significant. The intercept (0.14) which gives AOD for M_T = 0, might be corresponding to the contribution from the aerosols present above the MABL. Based on Indian Ocean Experiment (INDOEX) observation, Parameswaran *et al.* (1999) reported a similar relationship between the AOD at 500 nm and near surface total aerosol mass concentration with a correlation coefficient of ~0.74 over the Arabian Sea (AS) and NIO during continental airmass period (January to March). Recently, Babu *et al.* (2009) noticed a correlation coefficient of 0.79 with 38 data simultaneous data pairs of surface aerosol mass concentration carried out with QCM and AOD at 500 nm obtained from Sun photometer over the eastern AS during the inter monsoon and summer monsoon seasons of 2003 as a part of the Arabian Sea Monsoon Experiment (ARMEX). The strong correlation between the surface and columnar aerosol properties shows that the variations in the surface can be taken as a representative of the variations in the column.

Wind Speed Influence on AOD

Many researchers have done extensive investigations on connecting wind speeds and the aerosol mass and number concentrations, optical depths, scattering coefficients at different marine locations (Lovett, 1978; Exton *et al.*, 1985; Hoppel *et al.*, 1990). These studies correlated the aerosol mass concentrations with the wind speeds measured over the Pacific, Atlantic and Indian oceans. Gong *et al.* (1997) from model simulations found that the wind index and the background sea salt aerosol mass concentrations varied with location. All the above measurements and the model simulations correlated the surface level aerosol mass concentrations or the scattering coefficients with the surface level wind speeds which indicated that as the wind speed increases the abundance of aerosols increases. The columnar optical depth is dependent on both the aerosol size distributions as well as the abundance of aerosol particles and so it is appropriate to expect that the AOD would exhibit an association with the wind speeds.

To examine the relation between the wind speed and AOD in the present case, the daily mean 500 nm AODs and wind speeds over the BoB during the observations period are correlated and shown in Fig. 15. The wind index by correlating the AOD and the wind speed measured onboard SK during W-ICARB cruise is found to be 0.01 over the BoB. The wind index is found to be smaller over the BoB when compared to the values 0.05 and 0.03 over the AS obtained during 1996–2000 (Ramachandran, 2004) and ICARB 2006 (Kedia and Ramachandran, 2008a), respectively. The smaller

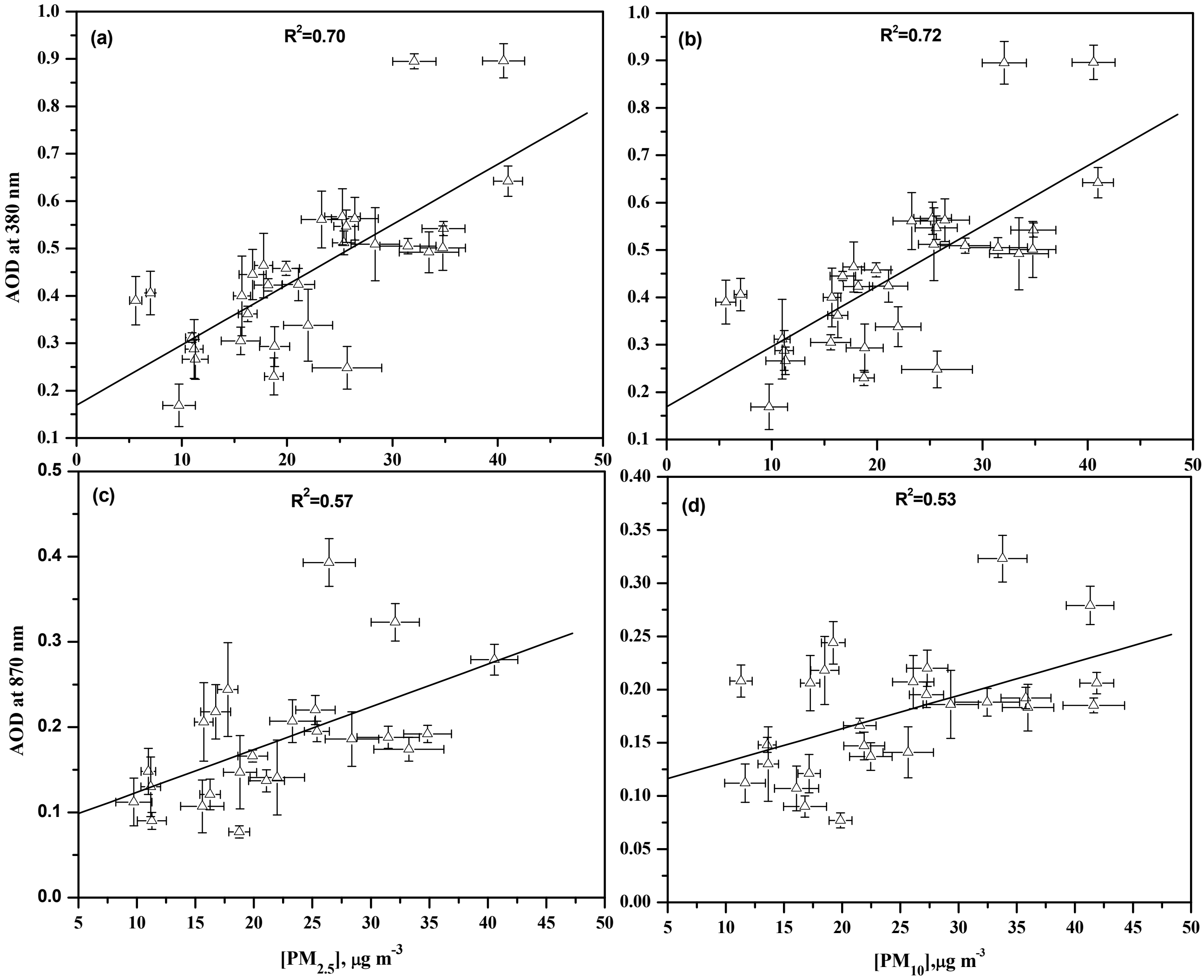

Fig. 13. Scatter diagrams between daily average values of columnar AOD for two selected wavelengths of 380 and 870 nm and surface level aerosol mass concentration for $PM_{2.5}$ and PM_{10} particles. The horizontal and vertical bars shows ± 1σ variation in the daily average mass concentration and AOD values, respectively and R^2 represents the correlation coefficient. The solid line represents the linear least square fit.

value of wind index over the BoB could be due to the fact that, unlike the other oceanic regions where sea salt contributes the most to aerosol concentration, the anthropogenic contribution is high. The background AODτ_o (which is the aerosol optical depth at 0 m/s wind speed) is found to be 0.37 over the BoB, which is higher than 0.30 and 0.25 over BoB and AS during ICARB 2006 as reported by Kedia and Ramachandran (2008a). Higher value of background AOD indicates a strong influence of non sea salt particles from the continent. It should be noted that an increase in the wind speed in the ocean causes an increase in the sea salt aerosol concentration alone, while the concentrations of other species will remain the same. Because of the enhancement of sea salt aerosols, the percentage contribution of sea salt in the composite aerosol optical depth will increase (Blanchard and Woodcock, 1980).

A weak correlation (correlation coefficient of 0.14) is observed between the wind speed and the AOD at 500 nm over the BoB (Fig. 15). This indicates that variation of wind speed is not able to explain the variance of AOD significantly over during the observation period. This could be due to the lower contribution by sea salt to the AOD. As sea salt is not contributing higher proportion (Rajeev and Ramanathan, 2001), an increase in the sea salt concentration will not increase the composite optical depth by the same amount (Ramachandran, 2004).

Effect of Continental Sources on AOD

The influence of continental sources over different oceanic regions provides information on the spatial distribution of aerosol by prevailing winds. In this estimate the variation of AODs is investigated as a function of distance from the India coast to various locations over the Bay of Bengal. This calculation is made assuming a straight line path along the mean downwind direction. This assumption in the strict sense may not hold good for oceanic aerosols which get transported across the oceanic regions from the nearby continents (Anderson *et al.*, 2003). So the present calculation

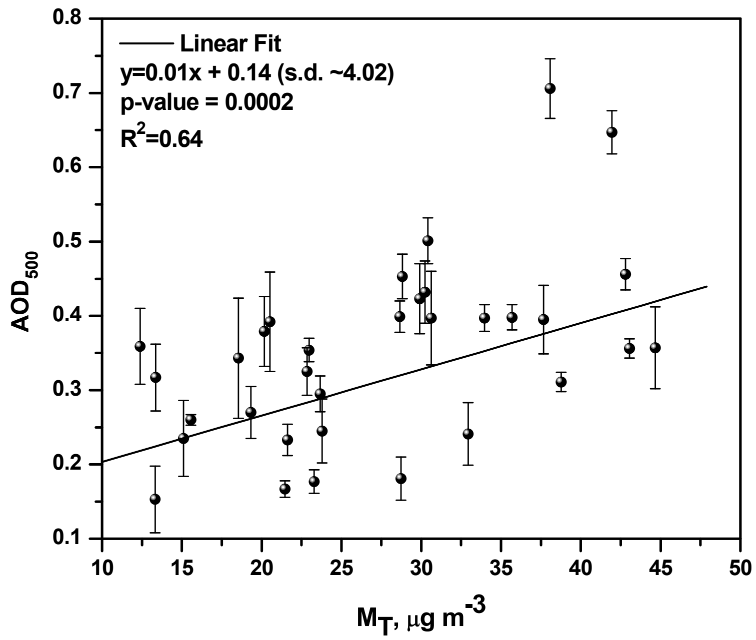

Fig. 14. Same as Fig. 13 but for AOD at 500 nm and total surface aerosol mass concentration, M_T observed during cruise experiment.

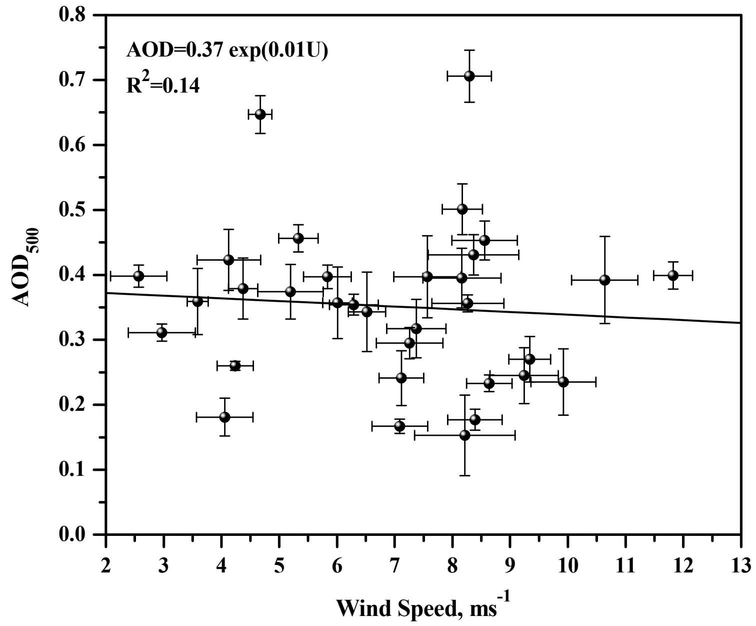

Fig. 15. Dependence of AOD at 500 nm on prevailing wind speed for the Bay of Bengal. Points represent the daily mean data collected during W-ICARB. Least square fit following Eq. (6) is drawn as solid line.

will provide a rough estimate on the gradient if the aerosols are transported from the nearby continents by the mean prevailing winds. Such estimates have been made earlier using the above described methodology for the AODs measured during INDOEX (Moorthy *et al.*, 2001; Ramachandran, 2004). The scaling distance calculations are made for the measurements made during a particular cruise instead of using the climatological data as the winds and transport patterns can show inter annual variability and hence can affect the scaling distance estimates.

Fig. 16 shows the variation of AOD at 500 nm with distance from the coast over the Bay of Bengal during the period of cruise experiment. The scaling distance (distance from the coast at which the AOD becomes 1/e of its value) is calculated over the BoB and it is found that D_o is only about 100 km with a low correlation of 0.01 for the BoB when compared to the AS (0.76) during ICARB 2006 as reported by Kedia and Ramachandran (2008a). The difference is mainly attributed to the use of high AOD values depicted over northern latitudes and moreover, the cruise covered

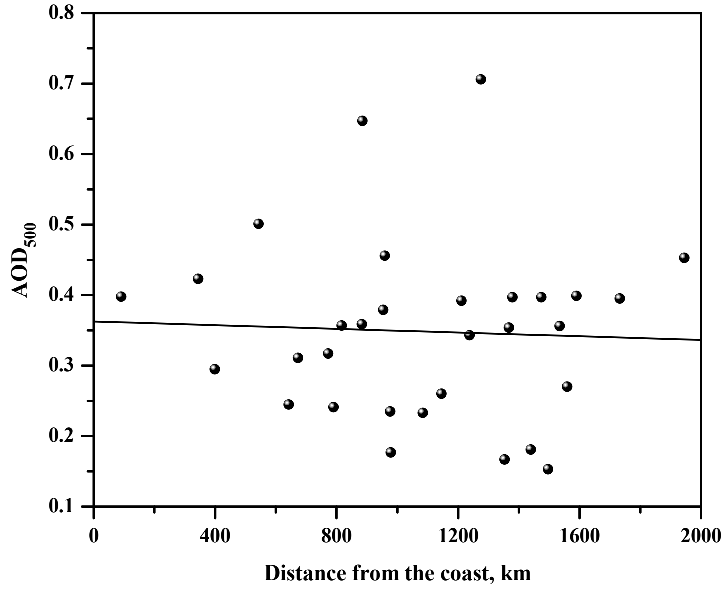

Fig. 16. Variation of AOD at 500 nm as a function of distance from the coast over the BoB considering, Chennai (13.1°N, 80.2°E) as the coast. The straight lines represent the least squares fit following Eq. (7).

large coastal distances which are near urban areas in the BoB. The high values of AOD at 500 nm over north BoB and close to the coast arise mainly from the anthropogenic activities. As the anthropogenic aerosols are generally in the sub micron size and hence have longer residence times, they get transported to greater distances over the ocean. Such instances of transport of aerosols and pollutants not only from India but also mineral dust from the arid regions of western India and Arabia have been reported from the airmass back trajectory analysis (see Fig. 4). As the distance increases from the coast these aerosols undergo changes in size due to coagulation, condensation and cloud cycling processes and are lost due to sedimentation and precipitation over ocean areas. These processes lead to a decrease in the aerosol concentration and hence the AOD decreases, as seen over the far BoB (refer Moorthy *et al.*, 2010; Kumar *et al.*, 2011).

Another reason for the lower scaling distance over the BoB arises due to the fact that the AODs are almost similar from near the coast to about 2000 km away. The constant AODs till about 2000 km from the coast could be either due to a higher in situ sea salt production or a nearly constant replenishment of continental aerosols over the BoB. Taking the mean wind speeds over the BoB (6.3 m/s) and the scaling distance, aerosols would take less than half a day to travel the distance 100 km over the BoB. As the scaling distance is lower over the BoB, the travel time for aerosols is much less.

SUMMARY AND CONCLUSIONS

The W-ICARB cruise expedition was conducted as part of ICARB project of Indian Space Research Organization (ISRO), Bangalore during 2008/2009 over the Bay of Bengal (BoB) to map aerosol and trace gases environment in the winter season of December and January. The main conclusions drawn from the present study are as follows:

Day to day variations of Sun photometer AOD_{500} and MODIS (Terra, Aqua) AOD_{550} are found to track well and are good agreement with each other during the campaign. The mean value of MODIS AODs at 500 nm and Sun photometer obtained AODs at 0.5 µm over entire BoB during the entire cruise period are 0.32 ± 0.03 and 0.35 ± 0.07, respectively. AODs are found to be high during 31 December and 7 January (> 0.8) and decreases to about 0.2 by the end of the cruise over the BoB during the study period. The average value of α over the Bay of Bengal region is 1.03 ± 0.06 which is lower than the value 1.12 ± 0.09 measured earlier during ICARB 2006 in pre-monsoon season. Lower value of α indicates a relatively larger concentration of bigger size particles over the BoB during December–January originated mainly from sea salt and long range transport of mineral dust particles. The curvature, α_2, shows mostly negative values indicating the significant contribution of fine-mode aerosols in the aerosol size spectrum.

Spectral mean AOD_{500} over the study region shows continuous decrease as wavelength increases. The mean AOD value noticed at 0.5 µm is 0.42 ± 0.05 (0.30 ± 0.05) over the BoB (NIO), which further drops to 0.20 ± 0.03 at 0.87 and 1.02 µm represents the overall aerosol loading is relatively more over the BoB. The high aerosol loading with predominant fine mode aerosols (large α) suggests that BoB is more polluted with anthropogenic sources. It is also revealed that, AOD is higher at longer wavelengths in NIO indicating dominance of coarse mode aerosols (small α) compared to BoB, which is typical of the pristine ocean environment.

AODs are found to increase as a function of latitude over the BoB when latitude increases from 4°N to 8°N and 18–20°N. A higher $\alpha_{380-1020}$ value (1.4) from 18–21°N latitude over BOB suggests a dominance of smaller size aerosols which are mainly from anthropogenic sources and $\alpha_{380-1020}$

is low (< 1) at 4–6°N latitude which indicates dominance of coarse particles. On a longitudinal basis over the BoB, AODs are lower in 81–86°E and 91–96°E when compared to 77–81°E and 86–91°E. At lower latitudes from 4°N to 6°N, M_T is low ~15 μg/m^3 and thereafter, it gradually increases with a high value of ~50 μg/m^3 at 21°N. M_T showed the lowest value of ~15 μg/m^3 at 80°E and the highest mass concentration of ~40 μg/m^3 at 92°E longitude.

The relation between the wind speed and AOD_{500} is investigated over the BoB with a weak correlation (0.14) indicates the variation of wind speed is not able to explain the variance of AOD significantly over BoB during the observation period. The scaling distance is calculated to be 100 km with nearly similar AODs over the BoB till 2000 km away from Chennai coast gives rise to a lower scaling distance. It is estimated that aerosols would take less than half a day to travel the 100 km distance over the BoB.

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