Temporal characteristics of aerosol physical properties at Visakhapatnam on the east coast of India during ICARB – Signatures of transport onto Bay of Bengal

K Niranjan*, V Sreekanth, B L Madhavan, T Anjana Devi and B Spandana

Department of Physics, Andhra University, Visakhapatnam 530 003, India.
e-mail: niranjankandula@hotmail.com

Realizing the importance of aerosol physical properties at the adjoining continental and coastal locations in the airmass pathways onto the oceanic region, extensive measurements of aerosol physical properties were made at Visakhapatnam (17.7°N, 83.3°E), an eastern coastal location in peninsular India during the ICARB period. The temporal variations of aerosol optical depth, near surface aerosol mass size distributions and BC mass concentrations show significantly higher aerosol optical depth and near surface mass concentrations during the first and last weeks of April 2007. The mean BC mass fraction in the fine mode aerosol was around 11%. The aerosol back scatter profiles derived from Micro Pulse Lidar indicate a clear airmass subsidence on the days with higher aerosol optical depths and near surface mass fraction. A comparison of the temporal variation of the aerosol properties at Visakhapatnam with the MODIS derived aerosol optical depth along the cruise locations indicates a resemblance in the temporal variation suggesting that the aerosol transport from the eastern coastal regions of peninsular India could significantly affect the aerosol optical properties at the near coastal oceanic regions and that the affect significantly reduced at the farther regions.

1. Introduction

In the recent past, several aerosol field campaigns have been carried out to evaluate the spatio temporal heterogeneity of aerosol distribution. However, aerosol measurements over the oceanic regions adjoining the Indian subcontinent are quite few, despite the fact that this region makes a potential impact on the Indian weather and monsoon (Satheesh *et al* 2006). During November to May, the mean wind flow favours the transport of aerosol from central and eastern India which can influence the radiation budget over northern Bay of Bengal. Aerosol Black Carbon (the absorbing aerosol) is an important constituent that needs to be characterized in evaluating the net aerosol radiative forcing. BC has a relatively longer residence time and hence can get transported downwind over long distances, even to the remote oceanic regions. Moorthy and Babu (2006) reported that when the airmass trajectories arrive at Port Blair (an island location of India in BoB) either from India or east Asia, the BC concentrations are high and are insensitive to the region from where they are arriving, indicating the importance of long range BC transport with potential impact over the oceanic regions in their transit. Such transport of aerosols from the source regions on the continent to remote oceans could play a significant role in global radiative forcing. The primary objectives of field campaigns over the oceanic regions could be to understand the extent to which continental aerosols, both natural and anthropogenic can be transported over the clean oceanic regions and to characterize the meteorological processes that are responsible for such transport, since neither the quantities of emissions

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nor the global distribution of aerosols, particularly in the tropics and sub-tropics, are even approximately known until recently. To address certain problems associated with changes in spectral transparency of the oceanic atmosphere, radiation and climatology, it is necessary to estimate the real variability of aerosol optical depth over different areas and relate their variability to the prevailing physical and geographic conditions (Volgin *et al* 1988 and Yershov *et al* 1990). When viewed from the aforesaid science background, the ICARB is an important field campaign undertaken by the ISRO-GBP with the prime objective of characterizing the aerosol characteristics over the oceanic regions surrounding the Indian subcontinent.

Field campaigns either over oceanic regions or over the land generally suffer from the deficiency of nonavailability of data along the airmass pathways that influence the point observations. From this point of view, the ISRO-GBP Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB) is unique as it was planned in such a way that the measurements over the oceanic regions are complemented with extensive measurements at closely spaced land locations in India, which are probable source regions in the airmass trajectories that bring the anthropogenic components onto the oceanic regions. Aircraft measurements around the point observations had the added advantage of providing vertical structures over select locations depending on the logistic infrastructure. The aim and objectives of the campaign are well defined in the concept paper of this special issue. During the first phase of the oceanic segment, the vessel was cruising in the Bay of Bengal and the mean wind direction was favourable for aerosol transport from peninsular India into Bay of Bengal. In this article we present the temporal characteristics of aerosol physical properties over Visakhapatnam, a station on the east coast of India located in the airmass pathways onto northern Bay of Bengal.

2. Data and methodology

Visakhapatnam (17.7°N, 83.3°E) is a coastal industrial location on the east coast of India. During the ICARB period, the Aerosol spectral Optical Depths (AOD) were measured using a Microtops II sun photometer operating at 380, 440, 500, 675 and 870 nm. Size segregated, near surface aerosol mass concentrations were measured using a Quartz Crystal Microbalance (California Measurements Inc., USA) in 10 size channels with 50% aerodynamic cut-off diameters at 25, 12.5, 6.4, 3.2, 1.6, 0.8, 0.4, 0.2, 0.1 and 0.05 μm respectively with an air inlet at a flow rate of 0.24 liters per minute and sampled for a duration of 300 seconds for each measurement. A seven-channel Magee Scientific Aethalometer was used to measure the near surface BC mass concentration. A SESI Micro Pulse lidar system was operated every evening from 18:00 to 20:00 h through out the period of ICARB campaign to evaluate the aerosol back scatter intensity profiles. The details of the experimental systems and the analysis methodology are available in Niranjan *et al* (2006, 2007) and Sreekanth *et al* (2007).

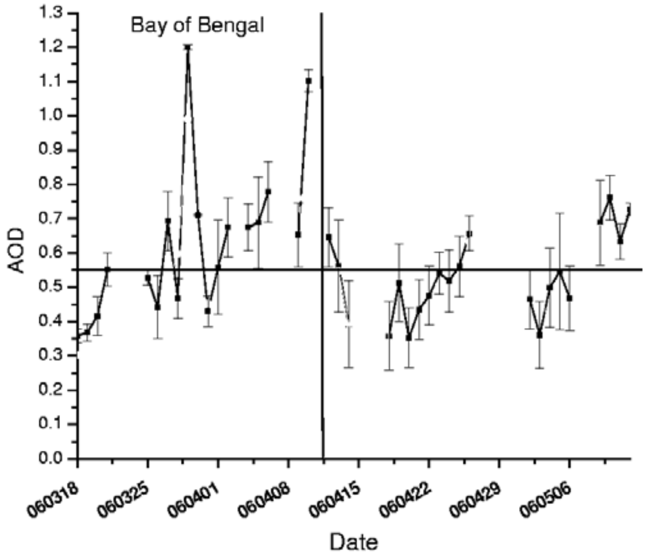

Figure 1. Temporal variation of Microtops AOD (0.5 μm). Horizontal line indicates mean values. The vertical line indicates the BoB leg.

3. Results and discussion

3.1 *Aerosol optical depth*

Aerosol optical depth is one single parameter that can characterize the atmospheric transparency. In figure 1 are shown the temporal variation of the aerosol optical depth at 500 nm measured using a Microtops II sun photometer at Visakhapatnam. The vertical line indicates the period when the ship was sailing in the Bay of Bengal. The AOD shows a distinct day-to-day variability during the campaign period at Visakhapatnam. Significantly large optical depths above the mean values (black line shown at 0.55 AOD) were observed during the first and last weeks of April 2006 with AOD at 500 nm crossing 0.7. An examination of the MODIS data for this station for the said period indicates a one-to-one correspondence between the ground-based measurements (Microtops).

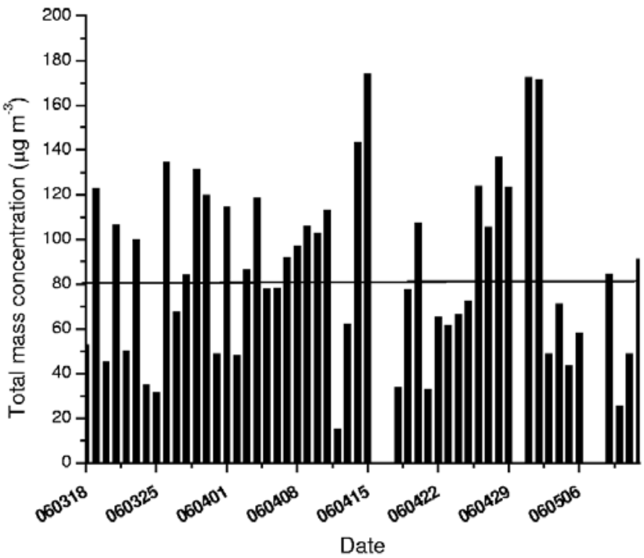

Figure 2. Temporal variation of near surface total mass concentration.

3.2 *Near surface aerosol mass concentration and BC mass concentrations*

In figure 2, are shown the near surface aerosol total mass concentrations measured by the QCM system. It may be seen that the near surface mass concentration also shows large day-to-day variability with relatively high values during the first half of April 2006. There was a slight increasing tendency during the last week of April. To see the relative change in the aerosol mass size distribution, we have sorted the size segregated data into nucleation (aerodynamic mean radius $< 0.1\,\mu$m), accumulation (aerodynamic mean radius between $0.1\,\mu$m and $1.0\,\mu$m) and coarse modes (aerodynamic mean radius $> 1.0\,\mu$m) and their day-to-day variability is shown in figure 3. The accumulation mode aerosol shows higher mass concentration and comparable day-to-day variability similar to total mass concentration during the first week of April 2006 while during the last week of April no significant increase in the surface accumulation mode mass is observed. On the contrary, the nucleation mode aerosol shows some increase in the last week of April 2006. This indicates decoupling of column integrated features as seen in AOD from the near surface features as seen from the QCM mass distributions.

To bring out the decoupling features more clearly, we have plotted the variation of the Ångström aerosol size index alpha as a function of surface nucleation and accumulation mode aerosol mass concentration measured by QCM in figures 4(a) and 4(b) respectively. Assuming that the aerosol size distribution is uniform in the column integrated properties, an increase in alpha should be associated with a proportionate increase in the surface fine mode mass. The solid line in both the plots indicates the regression line which supports this assumption. But in some cases shown as solid dots in these figures, an increase in alpha is not associated with a proportionate increase in surface fine mode aerosol mass (either in the nucleation or accumulation mode) indicating that the surface aerosol features differ from the column integrated aerosol physical properties. This indicates the need for vertical profiling of aerosol mass concentration as the difference observed in the near surface and column integrated feature could be due to the changes in the aerosol physical properties at altitudes above the mixing region. We present some typical Lidar derived aerosol back scatter intensity profiles in the next section, which show features of long range transport above the boundary layer over Visakhapatnam.

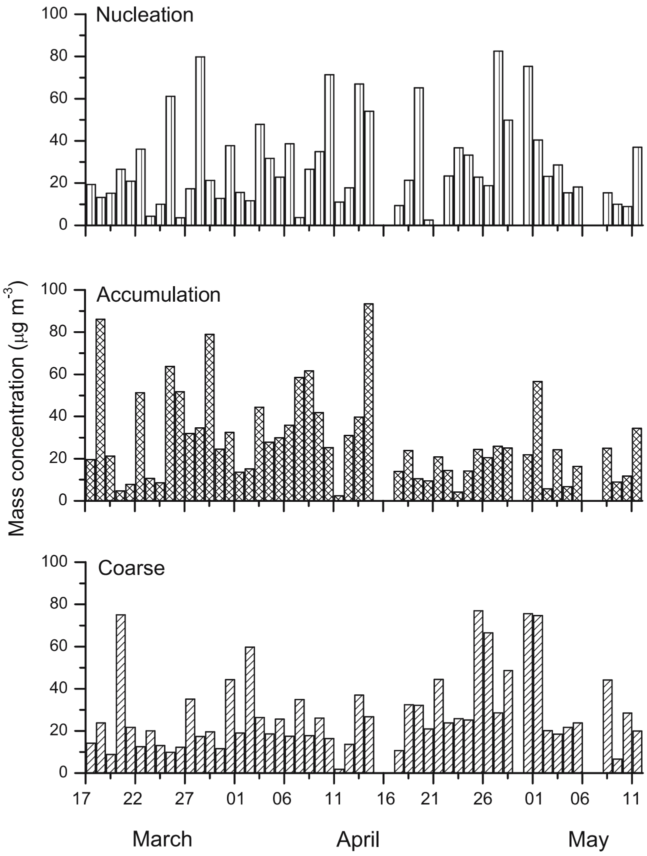

Figure 3. Temporal variation of size segregated mass concentration in the nucleation, accumulation and coarse mode.

In figure 5 are shown the surface BC mass concentrations at 10:00 h and 15:00 h IST for all the days of observations during the campaign period. It may be seen that the surface BC mass concentrations were higher during the first and last weeks of April 2006 as seen in the surface aerosol mass concentrations and the aerosol optical depths.

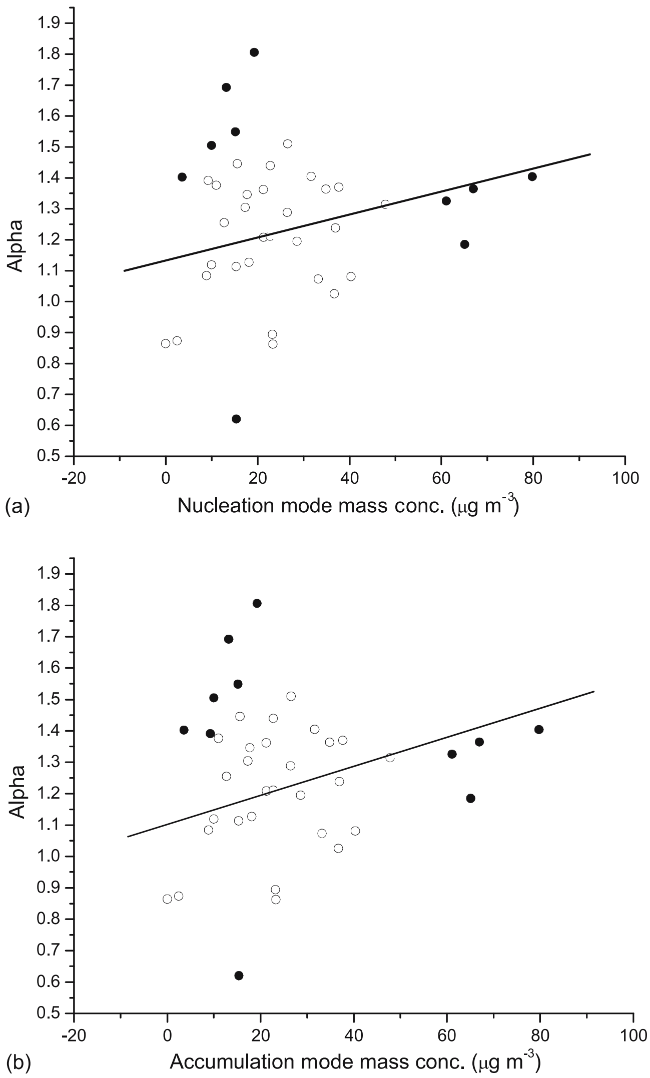

Figure 4. **(a)** Plot showing the variation of aerosol size index as a function of near surface nucleation mode aerosol mass concentration. **(b)** Plot showing the variation of aerosol size index as a function of near surface accumulation mode aerosol mass concentration.

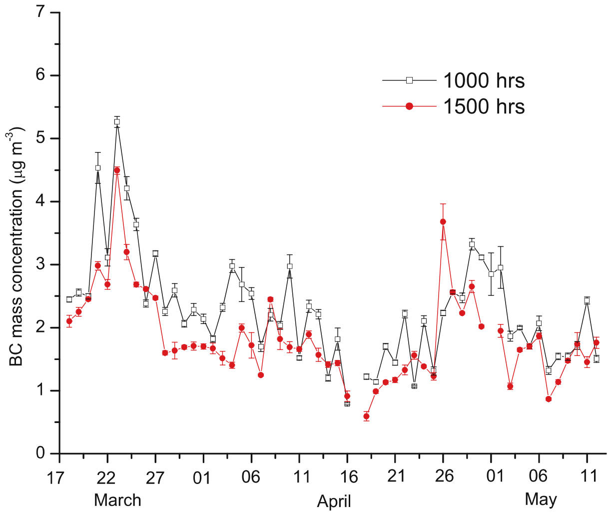

Figure 5. Temporal variation of near surface BC mass concentration at 10:00 and 15:00 h IST.

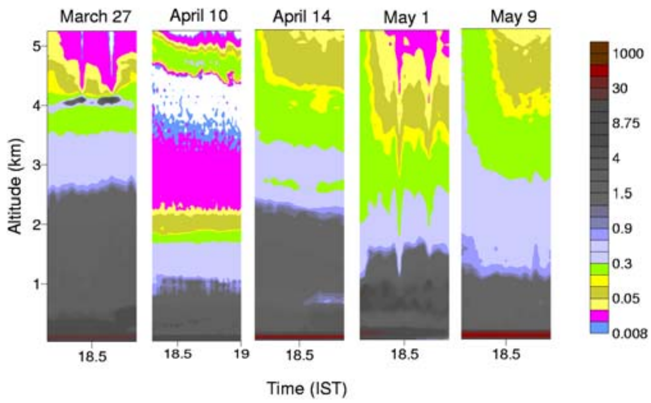

Figure 6. Colour map of aerosol backscatter intensity between 18:00 and 19:00 h IST on typical days during ICARB.

However, very large values of BC mass concentration were recorded during 19–24 March 2006. The percent BC mass fraction in the fine mode aerosol was 11 though on some days it fluctuated significantly from this mean value. A more detailed discussion on the BC mass fraction to the composite aerosol at Visakhapatnam, its relation to column AODs and the implications on BC radiative forcing are available in Sreekanth *et al* (2007).

3.3 *Lidar measured aerosol vertical back scatter profiles*

Micro Pulse LIDAR was operated on all days of the campaign period between 18:00 and 20:00 h IST. In figure 6 are shown the aerosol colour maps of aerosol back scatter intensity derived from Micro Pulse LIDAR at Visakhapatnam for five select days during the ICARB campaign for the time period 18:00 to 19:00 h IST. The profiles shown are corrected for range, overlap and for Rayleigh scattering. The details of the analysis are available in Niranjan *et al* (2006). Each vertical band shown in figure 6 represents one day (shown at the top of the band) for the altitude range 0–5 km for the period between 18:00 h IST and 19:00 h IST. On March 27, the aerosol backscatter intensity was significant upto an altitude of about 4 km. On this day a small layer like structure was seen around 4 km altitude. The colour map of 10 April 2006 shows an elevated aerosol layer between 4 and 5 km altitudes which is attributed to long range aerosol transport from the Arabian region (Niranjan *et al* 2007). On 1 and 9 May 2006, the colour map indicates a clear subsidence and strong aerosol back scatter was restricted to lower altitudes only.

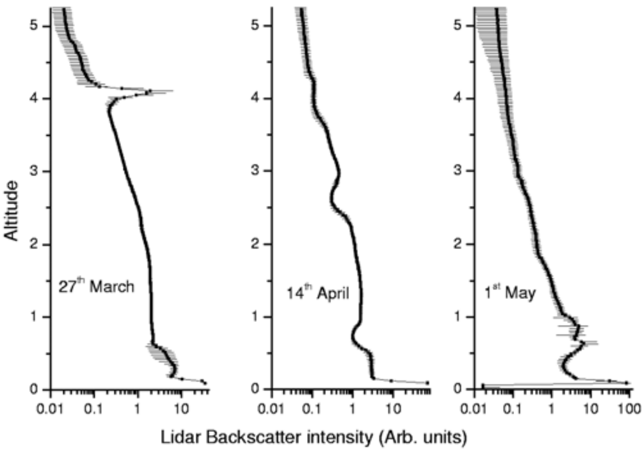

Figure 7. Vertical profiles of Lidar backscatter intensity on typical days during ICARB.

In figure 7 are shown the profiles of aerosol back scatter intensity for a day with layer and extended aerosol distribution upto 4 km (27 March 2006), a day with aerosol entrainment, probably due to changes in boundary layer altitude and a day with clear subsidence reflecting strong aerosol back scatter restricted to lower altitudes of upto 1–1.5 km. From Micro Pulse Lidar observations at Visakhapatnam, Niranjan *et al* (2007) reported the appearance of elevated aerosol layers reflecting the long range aerosol transport with sources located in the Arabian region in 60% of the cases, and from peninsular India in the rest of the cases reported. When the airmass transport is from the Arabian regions, Ångström size index which is a measure of the aerosol size distribution was low indicating that the elevated layers of Arabian origin could contain a significant fraction of dust aerosol.

It is also possible that accretion of aerosol occurs in a stable atmosphere sandwiched between two turbulent regions which are normally observed within the boundary layer. Stratified turbulence in a stable atmosphere tends to smooth out concentration gradients, causing formation of aerosol depleted regions which are ultimately observed as aerosol layers within the nocturnal boundary layer (Parameswaran *et al* 1997) which could possibly be the reason for the layer like structures on 1 May 2006. During daytime the surface gets heated due to clear sky conditions and in the evening the sudden cooling of the earth's surface after sunset leads to the formation of a stable layer close to the surface and elevated residual layer of enhanced aerosol concentrations. The enhanced concentrations between 1 and 2 km altitudes on the 14 April could possibly be due to entrainment of aerosol above the boundary layer. However, one important observation is that in 70% of the cases when high column AODs were observed over Visakhapatnam, the high surface mass and BC mass concentrations as measured by the QCM system and the Aethalometer respectively were associated with either aerosol subsidence restricting the aerosol ventilation and thereby increasing the near surface mass concentration or a strong back scatter in the form of an elevated layer. Extended aerosol back scatter upto higher altitudes in the MPL data indicates good aerosol ventilation and associated reduction in the surface mass concentrations.

3.4 *Discussion*

Systematic characterization of aerosols over the oceans is needed to understand the aerosol effect on climate and on transport of pollutants between continents (Smirnov *et al* 2002). Villevalde *et al* (1994) reported that the optical properties of maritime aerosols influencing the Pacific Ocean measurements are substantially different from those of the north Atlantic data indicating the regional differences in the aerosol properties of oceanic regions. It was reported that in coastal areas and inland seas the values of AOD are higher largely depending on the continental sources. In this context, the measurements at adjoining coastal locations like Visakhapatnam during ICARB assume importance, particularly with reference to the cruise observations in the Bay of Bengal region. Meteorological studies show that the high aerosol concentrations over the Arabian Sea and tropical Indian Ocean could be linked to transport from Indian subcontinent and also from sources in the middle east and north Africa (Krishnamurti *et al* 1998). In order to see if the observed temporal variation in the aerosol physical properties are in anyway affecting the spatio-temporal variations in the aerosol optical depth along the cruise track, we have compared the MODIS aerosol optical depth at 550 nm along the cruise track in the Bay of Bengal region with the temporal variation in the aerosol optical depth at Visakhapatnam and are shown in figure 8. The aerosol optical depths along the cruise track were in general low compared to the AODs observed at Visakhapatnam. But it is interesting to see that the temporal variation at Visakhapatnam is reflected as a spatial variability with a good resemblance. Satheesh and Moorthy (1997) reported significant enhancement in AOD at shorter wavelengths in the near coastal regions compared to far coastal regions and that the Ångström exponent 'α' doubles in the near coastal regions compared to far coastal regions. Airmasses that come from different source regions into the Bay of Bengal region carrying aerosols of different species are responsible for the spatial and temporal variations in the observed AOD spectra (Ramachandran and Jayaraman 2003).

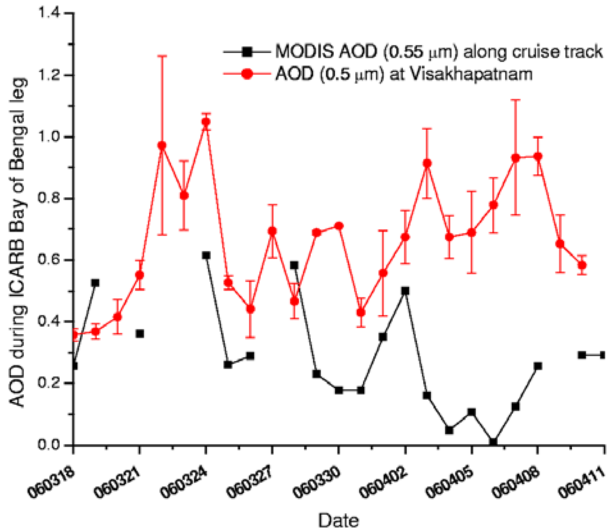

Figure 8. Temporal variation of MODIS AOD (0.55 μm) along the ICARB Bay of Bengal cruise track and Microtops AOD (0.5 μm) at Visakhapatnam.

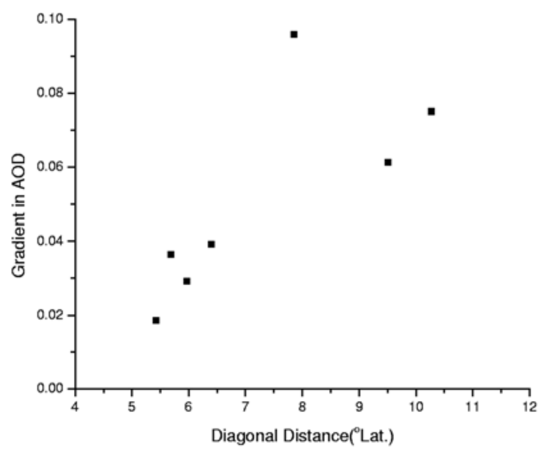

Figure 9. Gradients in aerosol optical depth (per degree latitude diagonal distance from Visakhapatnam to the different cruise locations.

Major sources of aerosols over the northern Bay of Bengal are the eastern coast of India (Ganguly *et al* 2005 and Satheesh *et al* 2006). Vinoj *et al* (2004) also reported that aerosol optical depths over BoB were high with α approximately equal to 1.1 indicating the presence of significant amount of sub-micron aerosol. It is known from the general wind pattern that the airmass pathways are from peninsular India on to the northern BoB and it is quite possible that the mean wind flow from the peninsular India via the eastern coastal regions could significantly contribute to the aerosol loading over the regions covered by the ICARB track. The observed results from the eastern coastal region of Visakhapatnam in conjunction with the MODIS derived AODs over the cruise track are in conformity with this proposition. To get an idea on the scaling distance of continental influence on the aerosol properties over the oceanic regions, we have evaluated the gradient in AOD (along the diagonal path) at various cruise locations, assuming Visakhapatnam as the source point for the outflow from the continental region and the results are presented in figure 9. It may be seen that in the near coastal locations, the AOD gradient is low (approximately 0.03 per degree latitude), while in the farther coastal regions the gradient is high. This indicates that the near coastal regions are significantly affected by the aerosol sources from the nearby continental locations while the influence falls off rapidly as the distance from the coast increases.

Acknowledgements

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