Influence of circulation parameters on the AOD variations over the Bay of Bengal during ICARB

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MODIS (Moderate Resolution Imaging Spectroradiometer) level-3 aerosol data, NCEP (National Centers for Environmental Prediction) reanalysis winds and QuikSCAT ocean surface winds were made use of to examine the role of atmospheric circulation in governing aerosol variations over the Bay of Bengal (BoB) during the first phase of the ICARB (Integrated Campaign for Aerosols, gases and Radiation Budget) campaign (March 18–April 12, 2006). An inter-comparison between MODIS level-3 aerosol optical depth (AOD) data and ship-borne MICROTOPS measurements showed good agreement with correlation 0.92 ($p < 0.0001$) and a mean MODIS underestimation by 0.01. During the study period, the AOD over BoB showed high values in the northern/north western regions, which reduced towards the central and southern BoB. The wind patterns in lower atmospheric layers (> 850 hPa) indicated that direct transport of aerosols from central India was inhibited by the presence of a high pressure and a divergence over BoB in the lower altitudes. On the other hand, in the upper atmospheric levels, winds from central and northern India stretched south eastwards and converged over BoB with a negative vorticity indicative of a downdraft. These wind patterns pointed to the possibility of aerosol transport from central India to BoB by upper level winds. This mechanism was further confirmed by the significant correlations that AOD variations over BoB showed with aerosol flux convergence and flux vorticity at upper atmospheric levels (600–500 hPa). AOD in central and southern BoB away from continental influences displayed an exponential dependence on the QuikSCAT measured ocean surface wind speed. This study shows that particles transported from central and northern India by upper atmospheric circulations as well as the marine aerosols generated by ocean surface winds contributed to the AOD over the BoB during the first phase of ICARB.

1. Introduction

Atmospheric aerosols are one of the important geophysical components, whose potential to cause long-term changes in the earth's climate is now widely accepted (Coakley and Cess 1985; Haywood *et al* 1999; IPCC 2001). Aerosols affect the energetics and the hydrological cycle of the atmosphere through their direct and indirect radiative effects (Twomey 1974; Charlson *et al* 1992). However, since aerosols are highly inhomogeneous spatially as well as temporally, attempts towards a quantitative assessment of aerosol impact on climate change has not been very successful so far. An essential requirement for such studies is the incorporation of global information on the continuously changing distribution of aerosols and their properties into standard climate prediction models (Haywood and Boucher 2000). Among various observation techniques, satellite-borne remote sensing is the best means to achieve regular monitoring of global distribution of aerosols in short time intervals. In recent times, operational satellites are providing regional as well as global

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measurements on a number of aerosol parameters with a typical temporal resolution of 1–7 days (Husar *et al* 1997; Kaufman *et al* 2002; Ichoku *et al* 2003). The MODIS (Moderate Resolution Imaging Spectroradiometer) sensor onboard NASA's polar sun-synchronous twin satellites *Terra* and *Aqua* performs daily global observations on atmospheric aerosols in seven channels in the range 470 nm to 2100 nm (Kaufman *et al* 1997; Tanre *et al* 1997; Remer *et al* 2005).

Being a tropical region with distinct seasonal patterns in the climate, aerosols over the Bay of Bengal (BoB) undergo characteristic variations in their properties governed by the changing meteorological conditions. The BoB is a small oceanic region surrounded by landmass on three sides having diverse natural and anthropogenic activities. Recent observations revealed that aerosols over BoB consist mostly of particles of anthropogenic origin (Satheesh 2001; Moorthy *et al* 2003; Ramachandran and Jayaraman 2003; Dey *et al* 2004). Besides contribution from regional transport, natural sea-salt aerosol production through wind-generated wave breaking is a very efficient mechanism for aerosol production over the oceans (Blanchard 1963; Blanchard and Woodcock 1980; Fitzgerald 1991; O'Dowd and Smith 1993).

The ICARB (Integrated Campaign for Aerosols, gases and Radiation Budget) field campaign organized under ISRO-GBP (Indian Space Research Organisation – Geosphere Biosphere Programme) during March 18 to May 12, 2006 carried out simultaneous observations over the Indian landmass and surrounding oceans using a network of ground stations, moving ships and aircrafts. The cruise measurements made onboard Oceanographic Research Vessel (ORV) *Sagar Kanya*, were in two phases; the first phase was over BoB, during March 18 to April 12 and the second was over the Arabian Sea during April 18 to May 12. In this work, we investigate the aerosol behaviour during the first phase of the cruise over the BoB (study domain: 10°–22.5°N, 80°–95°E) in response to the atmospheric circulation features. The first part of the exercise was an inter-comparison carried out between MODIS level-3 aerosol optical depth (AOD) data (at the wavelength 550 nm) and ship-borne MICROTOPS measurements conducted during the study period. Then the AOD from MODIS and reanalysis winds from NCEP (National Centres for Environmental Prediction) were utilized to investigate the role of atmospheric circulation variables like aerosol flux convergence and flux vorticity at different atmospheric altitudes on the day-to-day modulations of AOD over BoB (study domain: 10°–22.5°N, 80°–95°E). The association between AOD and ocean surface winds in the central BoB away from continental influences was also examined using QuikSCAT ocean surface winds.

2. Data

Ship-borne spectral AOD measurements were carried out with a MICROTOPS sun photometer (Solar Light Co.) at the wavelengths 340, 440, 500, 675 and 870 nm every day from ∼07:00 to 17:00 h local time at ∼20 minutes interval avoiding cases of obstruction of the sun by clouds. This instrument computes AOD from the detected direct solar irradiance using its internal calibration and the coordinates of the observation point provided by a GPS (Global Position System) attached to it (Morys *et al* 2001). The AOD measurements over the portions of cruise track lying in 1° × 1° latitude–longitude boxes were then averaged to generate 1° × 1° ship-borne AOD values.

MODIS level-3 daily AOD data at the wavelengths 470, 550, 660, 870, 1200, 1600, and 2100 nm from *Terra* and *Aqua* satellites were used for this study. The 1° × 1° pixel-wise data from the two satellites were averaged to obtain the daily mean values. For the pixels in which data were available from only one satellite, those values were retained as the daily mean. The NCEP reanalysis meridional and zonal wind fields at eight pressure levels from 1000 to 300 hPa were made use of for examining the aerosol transport and computation of atmospheric circulation variables.

Investigations on the relationship between spectral AOD and ocean surface winds over the BoB were carried out using surface winds at 10 m height acquired by the scatterometer onboard QuikSCAT satellite. Daily mean winds were computed by averaging the 0.25° × 0.25° data of the QuikSCAT for its ascending and descending passes and by degrading to 1° × 1° resolution.

3. Inter-comparison between AODs from MODIS and ship-borne measurements

Extensive validation experiments performed with ground measurements have shown uncertainties in AOD retrieval by MODIS to be within $\pm 0.05\tau \pm 0.03$ over the ocean and $\pm 0.15\tau \pm 0.05$ over the land (Remer *et al* 2005). The first time comparison of MODIS derived AOD over the oceanic regions surrounding India by Vinoj *et al* (2004) showed good agreement with ground measurements with a standard deviation 0.03 and a mean difference 0.01.

In this study also, before looking into the transport features of aerosols, an inter-comparison was

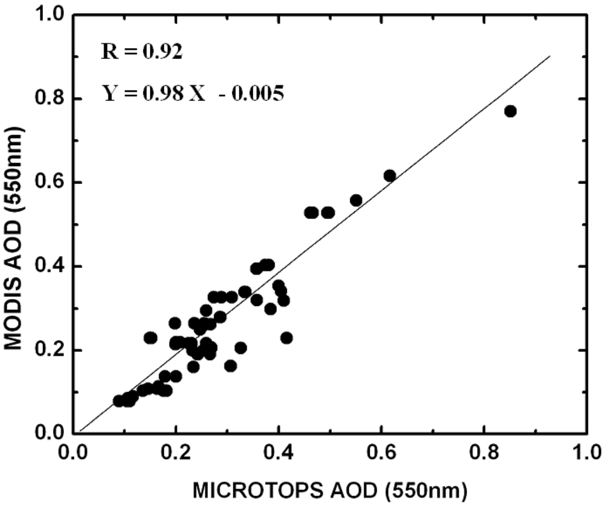

Figure 1. Scatter plot between MODIS derived AOD (550 nm) and MICROTOPS measured AOD (550 nm) along the cruise track over Bay of Bengal during the first phase of ICARB.

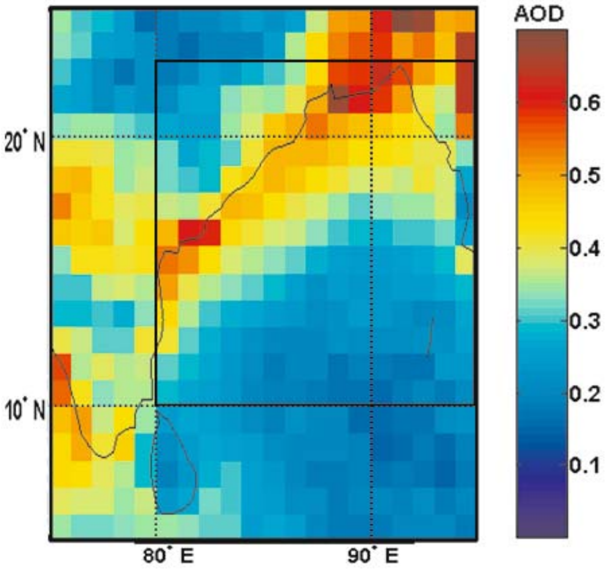

Figure 2. Spatial distribution of MODIS-AOD (550 nm) over the Bay of Bengal during the first phase of ICARB. The box indicates the extent of the study domain.

conducted between MODIS level-3 daily AOD (at 550 nm) and the 1° × 1° ship-borne MICROTOPS measurements over BoB. As the 550 nm channel was not available in MICROTOPS, AOD for this wavelength was estimated based on the Ångström exponent derived from the MICROTOPS spectral measurements. Figure 1 shows a scatter plot between AODs from MODIS and the corresponding values from ship measurements which displays a good agreement between the two with a correlation coefficient 0.92 ($p < 0.0001$). The standard deviation between the two measurements was 0.06 with a mean MODIS underestimation by 0.01. A least squares fit between the two AODs showed a linear regression in the form

$$\tau_{\mathrm{MODIS}} = \tau_{\mathrm{MICROTOPS}} \times 0.98 - 0.005 \qquad (1)$$

where τ_{MODIS} and $\tau_{\mathrm{MICROTOPS}}$ are the AODs from MODIS and MICROTOPS respectively.

4. AOD modulation by atmospheric convergence and vorticity

Figure 2 shows the mean AOD distribution over BoB generated by averaging MODIS data during the first phase of ICARB (March 18–April 12, 2006) for each pixel excluding the data blanks. During this period, data were available for 20–25 days for most of this region except for the south eastern corner (~5°–12°N, 88°–95°E) where the availability was for 10 to 20 days. The standard deviation of AOD over the area shown in this figure is ~10%. It can be seen in this figure that aerosols were mainly concentrated in the northern BoB and along the eastern coast of India.

An inspection of NCEP reanalysis wind fields showed the presence of a strong high pressure (indicated by anticyclonic or negative vorticity) and a divergence at lower atmospheric levels (>850 hPa) over the BoB (figure 3a and figure 3b) which prevented the direct transport of aerosols to BoB from the central and northern India by the westerly/north westerly winds (~3 m/s). But at higher levels (<850 hPa) this high pressure had weakened (figure 4a) and a strong anticyclone had developed over central India with stronger winds (>7 m/s) stretching over to BoB that could allow transport of aerosols from central and northern India towards BoB. Further, the low level divergence had transformed into a convergence in the higher altitudes (figure 4b). While convergence accumulates aerosols at a location, negative vorticity indicates downward transport of aerosols through the associated downdraft. After seeing this as a possible mechanism for the transport of aerosols from central India and concentrating them over BoB by higher level winds, we proceeded to confirm it by correlating day-to-day changes of AOD over BoB (averaged over the oceanic portion of the study domain) with convergence and vorticity at different altitudes.

With the above in view, the influence of circulation features at different atmospheric levels on the variations in AOD over the study domain was examined in detail. Since the change in aerosol amount by convergence is also proportional to ambient aerosol concentration, for this exercise we considered aerosol flux convergence (C) and aerosol

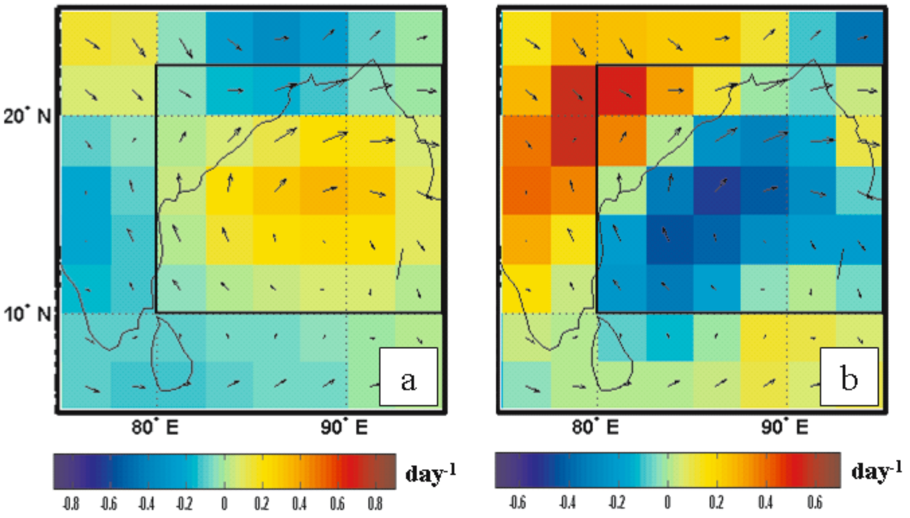

Figure 3. Spatial distribution of negative wind vorticity **(a)** and wind convergence **(b)** at 925 hPa level over the Bay of Bengal during the first phase of ICARB.

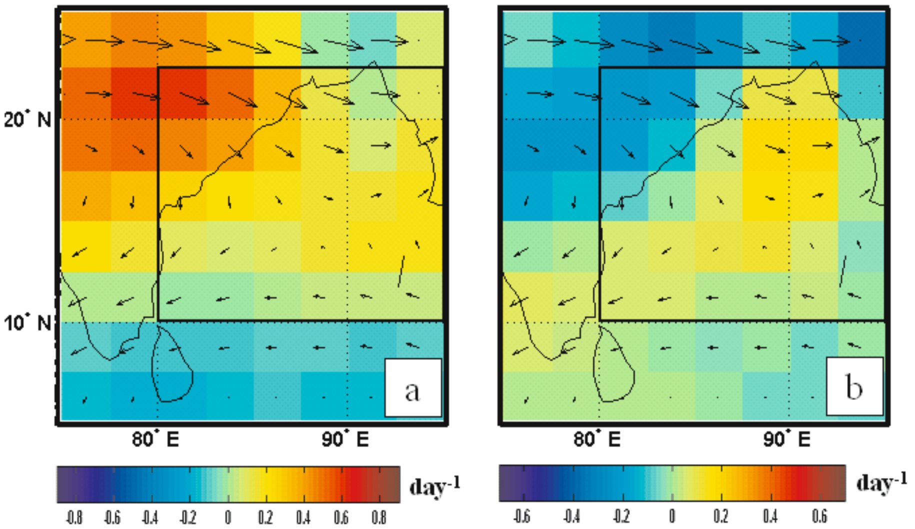

Figure 4. Spatial distribution of negative wind vorticity **(a)** and wind convergence **(b)** at 600 hPa level over the Bay of Bengal during the first phase of ICARB.

flux vorticity (V) as the appropriate circulation variables defined respectively as,

$$C = -\nabla \cdot (\rho \mathbf{v}) \tag{2}$$

and

$$V = -\mathbf{k} \cdot \nabla \times (\rho \mathbf{v}), \tag{3}$$

where $\mathbf{v}$ is the NCEP reanalysis vector wind at a given atmospheric level, $\mathbf{k}$ is the unit vector in the vertical direction and ρ is the aerosol extinction coefficient (a measure of aerosol concentration) which is related to AOD (τ) as,

$$\tau(x, y) = \int_0^\infty \rho(x, y, z)\, dz. \tag{4}$$

In the absence of aerosol sources/sinks, the change in aerosol concentration per day at every point in the atmosphere has to be completely accounted for by aerosol flux convergence over one day and the correlation between these two quantities is expected to be close to unity. On the other hand, if there are sources/sinks, depending on their strength, this correlation will reduce. Ideally, in order to study aerosol transport, one must have information on the vertical profile of aerosols at every point over the study area. But the aerosol

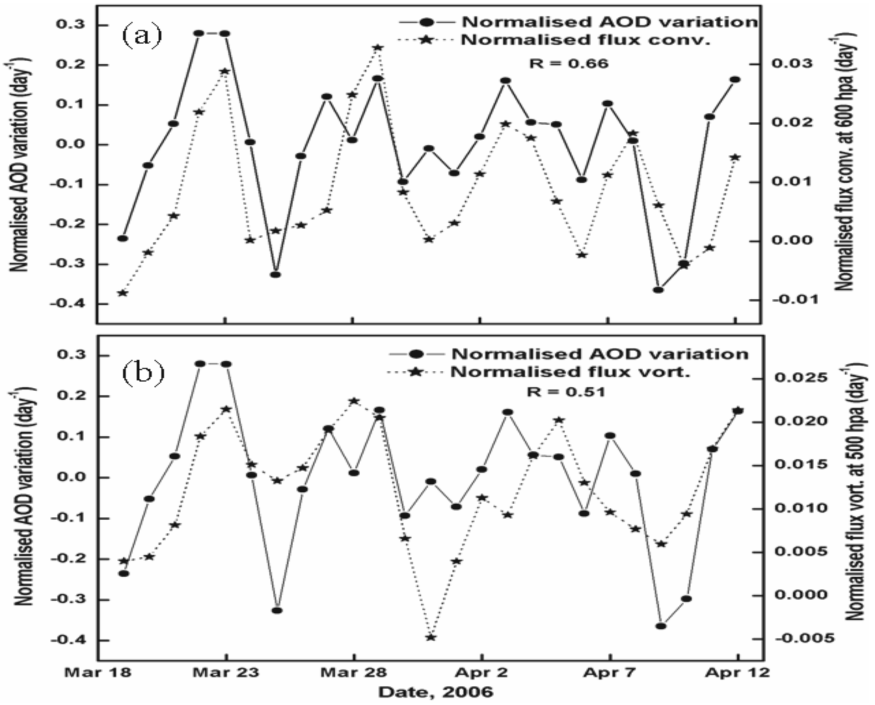

Figure 5. Time series of daily normalised change in AOD (550 nm) and normalised aerosol flux convergence at 600 hPa level **(a)** and daily normalised change in AOD (550 nm) and normalised negative aerosol flux vorticity at 500 hPa level **(b)** over the study domain during the first phase of ICARB.

information provided by MODIS is in terms of AOD which is column integrated aerosol extinction. During the first phase of ICARB, there were aerosol profile measurements made with airborne lidars over BoB off Bhubhaneswar (on March 28) and off Chennai (on April 5). However, these observations were isolated and mainly concentrated in the coastal regions and the profiles were not found to be the same. Therefore, in the absence of any knowledge on the actual profiles over the study domain, we assumed a typical form for aerosol extinction as

$$\rho(x, y, z) = \rho_0(x, y) \exp\left(-\frac{z}{L}\right), \qquad (5)$$

where $\rho_0(x, y)[= \tau(x, y)/L]$ is the extinction coefficient at the surface and L is the aerosol scale height parameter with a chosen value of 2 km.

The average AOD (at 550 nm) changes on each day and the amount of fluxes C and V over the study domain at different altitudes were estimated over the oceanic portion of the domain and these quantities were further normalised by dividing with the mean daily AOD. The standard deviation of daily AOD over the domain was ∼6%. The normalization was done in order to eliminate any influences that may arise from the absolute values of AOD in the correlations (between daily AOD changes and the flux variables) since the variables themselves are proportional to AOD.

The correlation between normalised AOD change and the normalised flux convergence showed an increase with altitude reaching its peak value 0.66 ($p < 0.0003$) at 600 hPa and decreasing thereafter. Similarly, the correlation between normalised AOD change and normalised flux vorticity was also found to increase with altitude to reach a peak value 0.51 ($p < 0.009$) at 500 hPa level. Figure 5(a and b) shows the time series plots of the day-to-day variation of AOD and the two circulation variables (all normalised) at the respective altitudes where the correlations were the highest. It can be seen that most of the variations in flux convergence and flux vorticity are reflected in AOD changes.

The reasons for the correlations not being very high are the possible presence of sources/sinks (e.g., aerosol generation by ocean surface winds, aerosol loss by gravitational settling, changes in AOD due to coagulation processes, etc. all of which are difficult to quantify on a day-to-day basis) and the fact that the correlations were done using fluxes at different layers computed with an assumed uniform aerosol profile. But still, it can be noticed that the values of correlations are significant (i.e., > 0.5) which means that transport of aerosols from central India to BoB by upper level winds supported by a convergence and vorticity was an important mechanism during the first phase of ICARB.

5. AOD and ocean surface winds

Marine aerosol generation by ocean surface winds has been explored in detail by a number of investigators (Blanchard 1963; Blanchard and Woodcock 1980; Fitzgerald 1991; Moorthy *et al* 1997; Moorthy and Satheesh 2000; Smirnov *et al* 2003; Satheesh *et al* 2006) over different oceanic regions in different seasons. The aerosol and wind data used in these studies came from a wide variety of sources, that is, AOD data in some investigations were ground-based sun photometer measurements while in some other cases, satellite derived. Likewise, the wind data was either ground-based (in the cases of measurements conducted over island stations) or ship-borne or NCEP reanalysis at different atmospheric heights. In spite of such differences in the nature of data, all these studies have indicated an increase in aerosol loading with increase in wind speed and various forms of empirical relationships have been suggested between the two. While some have reported linear relationships (Fitzgerald 1991; Smirnov *et al* 2003) some have reported nonlinear relations like polynomial (Shinozuka *et al* 2004) and exponential functions (Moorthy *et al* 1997; Moorthy and Satheesh 2000; Satheesh *et al* 2006).

In this work, we have used MODIS level-3 AOD data (at the wavelengths 470, 550, 660, 870, 1200, 1600, and 2100 nm) and the wind speed provided by QuikSCAT at 10 m level from ocean surface, both averaged over 1° × 1° pixels. At 1° × 1°, the QuikSCAT wind speed uncertainty is ∼1 m/s. Only those oceanic regions that are beyond ∼300 km from the coast (7°–14°N, 85°–95°E) were selected for this purpose to avoid continental influences.

In order to reduce the influence of uncertainties in wind and AOD data (arising from measurement errors, the spatial and temporal non-synchronicity in the MODIS and QuikSCAT measurements, etc.) we grouped the AODs into bins of wind speed of size 0.5 m/s (Moorthy and Satheesh 2000) for different wavelengths. Figure 6 shows the plot of mean AOD (at 550 nm) in each bin along with the standard deviation for different wind speeds.

We found that the best description for the AOD-wind speed relationship was provided by an exponential function as suggested in the earlier studies (Moorthy *et al* 1997; Moorthy and Satheesh 2000; Vinoj and Satheesh 2003) given by

$$\tau_\lambda = \tau_{\lambda 0} \exp(b_\lambda U), \tag{6}$$

where τ_λ is AOD at wavelength λ, U is wind speed, $\tau_{\lambda 0}$ is the AOD at zero wind speed (indicating the background AOD) and b_λ is the ‘wind index’.

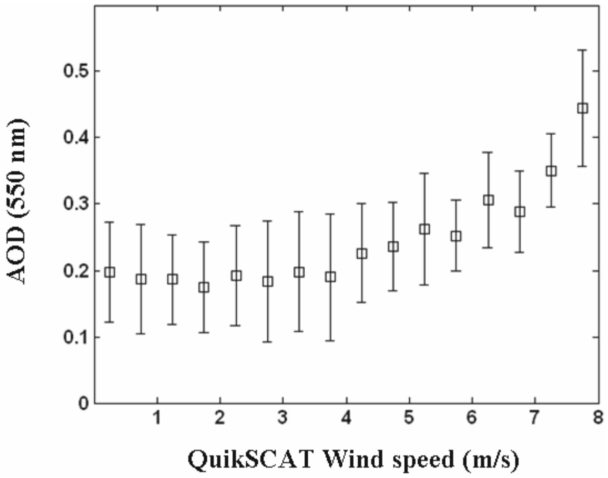

Figure 6. Scatter plot between AOD (550 nm) and QuikSCAT derived ocean surface wind speed in the far oceanic regions of Bay of Bengal during the first phase of ICARB.

Table 1. *Constants of AOD–wind relationship and correlation coefficients for different wavelengths.*

Wavelength (nm)	b_λ	$\tau_{\lambda 0}$	R
470	0.07	0.19	0.86
550	0.08	0.16	0.86
660	0.08	0.14	0.86
870	0.10	0.10	0.90
1200	0.12	0.07	0.92
1600	0.14	0.06	0.93
2100	0.16	0.04	0.93

The values of b_λ, $\tau_{\lambda 0}$ and the correlation coefficient (R) between AOD and wind speed for different wavelengths are given in table 1. It can be seen that the values of b_λ, are comparable to those reported earlier (Moorthy *et al* 1997; Moorthy and Satheesh 2000; Vinoj and Satheesh 2003). Increase in the values of wind index and the correlation coefficient towards longer wavelengths indicates the greater generation of large sized marine particles by ocean surface winds whose effect would be felt more in the longer wavelengths.

6. Conclusions

The influence of atmospheric circulation variables on day-to-day variations in AOD during the first phase of ICARB over BoB was investigated using

MODIS level 3 data of AOD and NCEP reanalysis wind fields. A comparison of MODIS level-3 aerosol optical depth (AOD) data (at 550 nm) with ship-borne MICROTOPS measurements displayed good agreement with a correlation 0.92 ($p < 0.0001$). It was seen that the day-to-day variations in AOD were modulated by aerosol flux convergence and flux vorticity at higher altitudes (∼500–600 hPa levels). Spectral AOD from MODIS over the far oceanic region of BoB showed a non-linear dependence on QuikSCAT ocean surface wind, which could be best expressed as an exponentially increasing function of wind speed with an increase in the value of wind index towards longer wavelength.

This study indicates that the aerosols over BoB during the first phase of ICARB were contributed by two physical processes. One is the advection from central and northern India through upper level winds followed by subsequent convergence and subsidence (associated with vorticity). The other is the *in situ* generation of marine aerosols by surface winds.

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