

## Measurements of aerosol optical depths and black carbon over Bay of Bengal during post-monsoon season

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[1] Extensive and collocated measurements of aerosol optical depths (AODs), mass concentration of composite aerosols and aerosol black carbon (BC) were made over the Bay of Bengal (onboard *R/V Sagar Kanya* during its cruise #197) region during post-Indian summer monsoon period. These data along with MODIS (onboard TERRA satellite) data shows that aerosol visible AODs were in the range of 0.2 to 0.7 (with mean value of  $0.43 \pm 0.12$ ) and Angstrom wavelength exponent of  $\sim 0.93 \pm 0.21$  which in conjunction with a single scattering albedo ( $\omega$ ) of  $\sim 0.94$  indicates the presence of weakly absorbing aerosols. The BC mass fraction was  $\sim 2.9 \pm 1.1\%$  during post-monsoon season compared to  $5.8 \pm 0.6\%$  (with  $\omega$  of  $\sim 0.88$ ) during pre-monsoon season. The presence of aerosols over Bay of Bengal during post-monsoon season decreases the short wave radiation reaching the surface by as much as  $25 \text{ W m}^{-2}$  and increases top of the atmosphere reflected radiation by  $14 \text{ W m}^{-2}$ . **INDEX TERMS:** 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 1610 Global Change: Atmosphere (0315, 0325); 1704 History of Geophysics: Atmospheric sciences; 1803 Hydrology: Anthropogenic effects. **Citation:** Sumanth, E., K. Mallikarjuna, J. Stephen, M. Moole, V. Vinoj, S. K. Satheesh, and K. K. Moorthy (2004), Measurements of aerosol optical depths and black carbon over Bay of Bengal during post-monsoon season, *Geophys. Res. Lett.*, 31, L16115, doi:10.1029/2004GL020681.

### 1. Introduction

[2] Aerosols influence climate directly by scattering and absorbing solar radiation [Charlson *et al.*, 1992; Hansen *et al.*, 1998; Kaufman *et al.*, 1998, 2003], indirectly by acting as cloud condensation nuclei; there by affecting the droplet concentration, optical properties, precipitation rate, and lifetime of clouds [Jones and Slingo, 1996]. Aerosol back-scatter of solar radiation enhances the planetary albedo, leading to a negative surface forcing (cooling). But the presence of absorbing aerosols such as black carbon (BC) can change the sign of forcing from negative to positive (heating) [Haywood and Shine, 1995; Heintzenberg *et al.*, 1997]. Observational studies have reported the significance of absorbing aerosols over rather remote oceanic regions [Satheesh and Ramanathan, 2000]. The impact of black carbon (BC) on radiation and hence on climate, though well

recognized, is still having large uncertainties due to the lack of comprehensive database [Intergovernmental Panel on Climate Change, 2001]. The Indian Space Research Organisation (ISRO) under its Geosphere Biosphere Program (GBP) has undertaken a major initiative since last two decades to characterize aerosols over Indian region (both over land and ocean). In addition, during Indian Ocean Experiment (INDOEX), extensive measurements of aerosol BC were carried out over Indian Ocean [Ramanathan *et al.*, 2001]. The results obtained from the above experiments clearly demonstrated the importance of absorbing aerosols over Indian region on the radiation budget and hence regional climate. Although there have been several studies carried out over Arabian Sea and Indian Ocean, prior to 2001, aerosol observations over Bay of Bengal (BoB) were non-existent. Thereafter, a few studies were conducted over BoB region, all of them, however, focussed to pre-monsoon season [Satheesh, 2002; Moorthy *et al.*, 2003; Vinoj *et al.*, 2004].

[3] In this paper, we report results of collocated measurements of aerosol optical depths (AODs), mass concentration of composite aerosols and aerosol black carbon (BC) over the Bay of Bengal (onboard *R/V Sagar Kanya* during its cruise #197) region (made for the first time) during post-Indian summer monsoon period (October 2003) and assess its regional impact on radiation balance.

### 2. Experiment, Data and Synoptic Meteorology

[4] The cruise (#197) started from Chennai (13.1°N, 80.2°E) (see also cruise track in Figure 1) on 3rd October and returned on 23rd October 2003. The numbers written in cruise track represent dates in October 2003. Surface meteorological parameters such as temperature, pressure, humidity, wind speed, and wind direction were measured using automatic weather station installed on the ship. Wind speed and direction were corrected for ship's motion. A Microtops sun-photometer was used to make aerosol optical depth (AOD) observations at five different wavelengths centered at 340, 380, 500, 675 and 870 nm with a full width half maximum bandwidth of 2 to 10 nm at different wavelengths (for details, see Ichoku *et al.* [2002]). The onboard measurements were carried out following all the precautions [Ichoku *et al.*, 2002; Babu *et al.*, 2004; Vinoj *et al.*, 2004]. Out of 20 days of the cruise, clear sky observations were possible only during 7 days (total of 174 sets of spectral AODs). Since cruise locations do not represent entire Bay of Bengal, we have used MODIS (onboard TERRA satellite; level 3) data product as well in this study.

[5] Near real time measurements of BC were made at  $\sim 10$  meter above sea level using an Aethalometer (model

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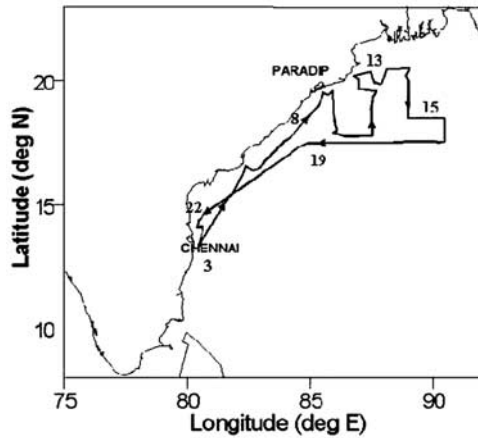


Figure 1. Cruise track of Sagar Kanya cruise #197.

AE-20, Magee Scientific, USA) (for details, see Babu *et al.* [2004]). The instrument was operated at a flow rate of 3 liters per minute; and at a time base of 5 minutes, so that BC estimates were available every 5 minutes and round the clock. The inlet for BC sampling was fixed near front bow of ship and were sampled only when ship was in motion. Composite aerosol mass was measured using a high volume aerosol sampler (Tisch Inc., Canada).

[6] Back trajectory analyses (using HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT4) Model, 1997; Web address: <http://www.arl.noaa.gov/ready/hysplit4.html>, NOAA Air Resources Laboratory, Silver Spring, MD) show (Figure 2a) that during the cruise period, the Bay of Bengal region covered by the cruise was mostly influenced by advection of aerosols from east coast of India and the northeastern regions (such as south China and Vietnam). The observed speed and direction of wind (at 1 minute interval) encountered at the ship's location is shown in Figure 2b as a polar diagram. This along with inference from National Center for Environmental Prediction (NCEP) data on wind shows that approximately 67% of the time air masses encountered by ship were from regions northeast of Bay of Bengal (mostly Chinese regions).

### 3. Results and Discussions

#### 3.1. Aerosol Optical Depth Spectra and BC

[7] The daily average aerosol optical depth (AOD) values at 500 nm for the seven (clear sky) days of observations were mostly in the range 0.2 to 0.7 with a mean value of  $0.43 \pm 0.12$ . A comparison of the daily mean sun photometer derived AOD (at 500 nm) with the corresponding values (at 550 nm) from MODIS data showed very good agreement with a mean difference of  $\sim 0.02$  and rms difference of  $\sim 0.08$  during October period. It may be noted that the cruise based AODs (500 nm) and MODIS (550 nm) derived AODs were at two slightly different wavelengths.

Table 1. Mean Aerosol Optical Depth and Angstrom Exponent

$\lambda$ , $\mu\text{m}$	380 nm	500 nm	675 nm	870 nm	$\alpha$
$\tau$	0.509	0.425	0.276	0.249	0.93
$\sigma$	0.168	0.123	0.095	0.082	0.21

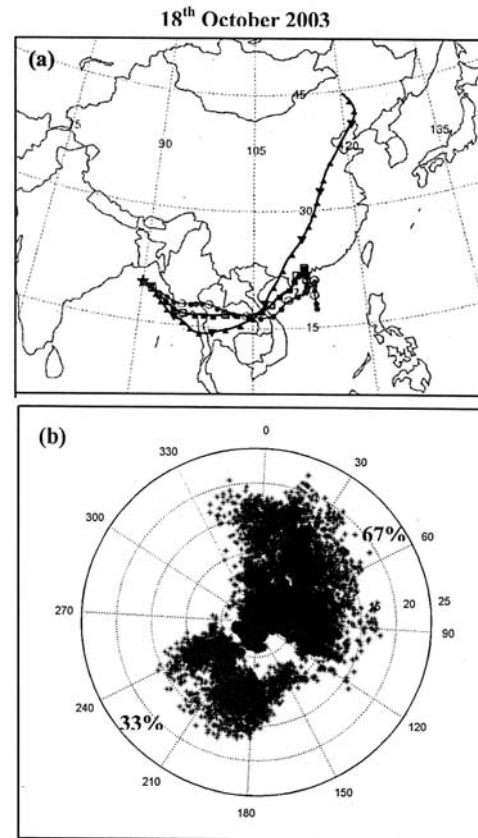


Figure 2. (a) Typical air mass trajectories encountered during the cruise period (b) Percent of occurrence of winds from Indian continent and east Asian regions encountered at the ship's location. See color version of this figure in the HTML.

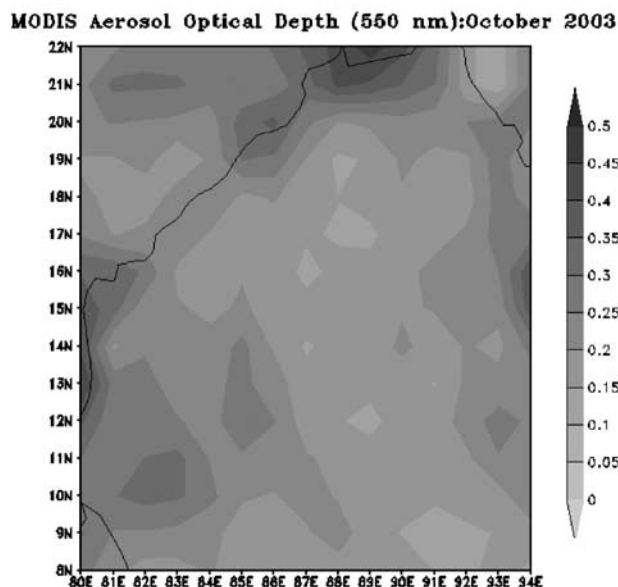
The average AODs (and standard deviations,  $\sigma$ ) at other wavelengths (over cruise region) are given in Table 1. It may be noted that the average AOD for October 2003 over entire BoB as inferred from MODIS data is  $\sim 0.24 \pm 0.08$  at 550 nm, which is significantly lower than the mean value of  $0.43 \pm 0.12$  seen at the cruise locations; thereby implying a spatial heterogeneity over the BoB. The distribution of aerosol optical depth (550 nm) during October 2003 is shown in Figure 3. By evolving an empirical fit of the cruise measured AOD spectra ( $\tau_{p\lambda}$ ) to the Angstrom power law,

$$\tau_{p\lambda} = \beta\lambda^{-\alpha} \quad (1)$$

the Angstrom wavelength exponent ( $\alpha$ ) was estimated. The  $\beta$  is the turbidity parameter indicating the aerosol loading and  $\lambda$  is the wavelength in  $\mu\text{m}$  [Angstrom, 1964; Shaw *et al.*, 1973]. Lower values of  $\alpha$  indicate larger abundance of super micron aerosols [Satheesh and Moorthy, 1997]. The value of  $\alpha$  showed variations over the cruise locations and yield an average value of  $0.93 \pm 0.21$ . This value is lower than those reported earlier ( $1.1 \pm 0.1$ ) over BoB for pre-monsoon season [Vinoj *et al.*, 2004].

[8] A scatter diagram of simultaneous estimates of  $\tau_p$  at 500 nm and surface BC mass concentration ( $M_b$ ) is shown in Figure 4. A linear regression analysis yields

$$\tau_p = \tau_{p0} + 0.36 M_b \quad (2)$$

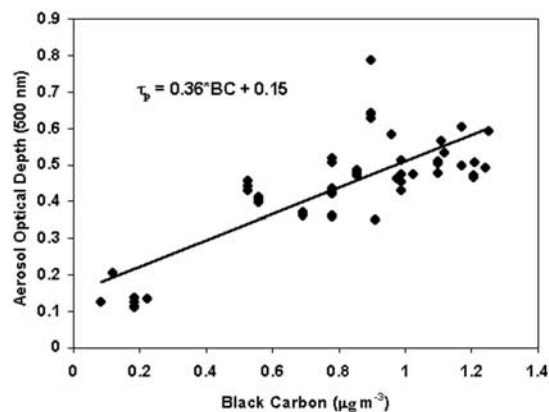


**Figure 3.** Distribution of aerosol optical depth (550 nm) during October 2003. See color version of this figure in the HTML.

with a correlation coefficient of 0.79, which is quite significant, and  $\tau_{p0} = 0.15$ . It may be noted that BC measurements were available for almost all days whereas AOD measurements were limited due to cloudy sky conditions. The  $\tau_{p0}$  is the optical depth due to all other (non-BC) constituents and the upper troposphere aerosol contribution. This result has important implications when we examine the aerosol radiative forcing and hence we have estimated the BC mass fraction to composite aerosol mass. Considering the entire data, the mean value of  $M_b$  was  $\sim 1.8 \pm 1.6 \mu\text{g m}^{-3}$ . The mass fraction of BC to total aerosol mass is obtained for each simultaneous measurements of BC mass and composite aerosol mass and the average value was computed as  $2.9 \pm 1.1\%$ . The BC mass fraction was more or less constant during all days irrespective of large variations in AODs. This value is significantly lower than those observed during INDOEX where BC accounted for 6% of the total aerosol mass and 11% of the composite visible AOD [Satheesh *et al.*, 1999]. Based on observations at an urban continental location (Bangalore), in India, Babu *et al.* [2002] reported a BC mass fraction of  $\sim 11\%$ . The slope of the AOD-BC plot (at Bangalore) was 0.024 [Babu *et al.*, 2002] compared to 0.36 in the present study over Bay of Bengal. It may be noted that over Bangalore large amount of BC was observed (as high as  $\sim 12 \mu\text{g m}^{-3}$ ) compared to  $\sim 1.8 \mu\text{g m}^{-3}$  over Bay of Bengal for similar values of AODs. This means that at Bangalore BC contributed significantly to AOD while at cruise locations aerosol species other than BC contributed a major fraction of AOD.

### 3.2. Implications to Radiative Forcing

[9] As measurements of aerosol chemical composition were not available, we have used a hybrid approach to estimate the aerosol radiative forcing. We have used the measured BC concentration and aerosol spectral optical depths as input to Optical Properties of Aerosols and Clouds

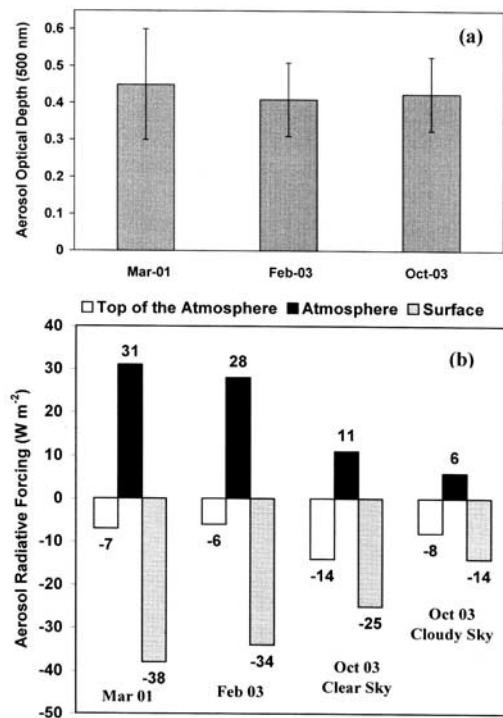


**Figure 4.** Scatter plot of column aerosol optical depth versus black carbon mass at the surface.

(OPAC) model of Hess *et al.* [1998] by adopting marine polluted aerosol model. The major components of this model are sulphate, nitrate, soot (BC), sea-salt and mineral dust. The optical properties of mineral dust were obtained from Kaufman *et al.* [2001] while those of other species were obtained from Hess *et al.* [1998]. We have introduced observed values of BC and total aerosol mass in OPAC model and the concentrations of other components are adjusted (constrained by observed BC mass fraction). This iterative procedure was continued such that estimated spectral optical depths and Angstrom wavelength exponent are consistent with the observations. This procedure is described in earlier papers [Satheesh, 2002; Babu *et al.*, 2002; Vinoj and Satheesh, 2003; Vinoj *et al.*, 2004]. The percentage contribution of the individual aerosol components to composite aerosol optical depth is given in Table 2 along with the physical (mode radii, standard deviation, and density) and optical properties (single scattering albedo). It may be noted from Table 2 that sub micron aerosols contribute a major fraction of the AOD. This is consistent with MODIS derived aerosol fine mode fraction of  $\sim 0.78 \pm 0.12$  during October 2003. The single scattering albedo of the composite aerosol is obtained as the average of individual species values weighted by the corresponding extinction coefficients and thus estimated single scattering albedo ( $\omega$ , at 500 nm) worked out to be  $\sim 0.94$ . Based on observations during pre-monsoon season over Bay of Bengal, Vinoj *et al.* [2004] have reported a single scattering albedo of  $\sim 0.88$  indicating a larger aerosol absorption during pre-monsoon period.

**Table 2.** Composition of Bay of Bengal Aerosols During October 2003

Aerosol Component	$\rho$ ( $\text{g cm}^{-3}$ )	Percentage Contribution to AOD (500 nm)	$r_m$ , $\mu\text{m}$	$\omega$ (500 nm)
Water soluble (sulphate, nitrate)	1.27	65%	0.029	0.99
Soot	1.00	7%	0.018	0.23
Sea-salt (accumulation mode)	1.15	17%	0.378	1.0
Sea-salt (coarse mode)	1.15		3.17	1.0
Mineral dust	2.60	11%	0.39	0.92



**Figure 5.** (a) Comparison of aerosol forcing during March 2001, February 2003 and October 2003 (b) Comparison of aerosol optical depth during March 2001, February 2003 and October 2003. Also shown is the aerosol forcing (October 2003) in the presence of clouds.

[10] The above value of  $\omega$  along with aerosol spectral optical depth and Angstrom wavelength exponent is incorporated in a Discrete Ordinate Radiative Transfer model [Santa Barbara DISORT Aerosol Radiative Transfer (SBDART) model] to estimate the short-wave clear sky aerosol radiative forcing at the surface and top of the atmosphere (TOA). This model is designed and developed by University of California, Santa Barbara [Ricchiuzzi *et al.*, 1998], which is based on a collection of well-tested and reliable physical models, which were developed by the atmospheric science community over the past few decades. We used eight streams in the radiative transfer calculation and computations were made for solar zenith angles at every  $5^\circ$ . The resulting diurnally averaged aerosol forcing at the surface was  $-25 W m^{-2}$  and at the TOA was  $-14 W m^{-2}$ .

[11] The forcing values reported above are estimated under clear sky conditions. It was observed from MODIS data that average cloud cover over northern BoB was  $\sim 0.68$  during October 2003. The cloud properties (inferred from MODIS) are incorporated into radiative transfer model and resulting diurnally averaged aerosol forcing (under cloudy skies) at the surface was  $-14 W m^{-2}$  and at the TOA was  $-8 W m^{-2}$ . It may be noted that there are subjective decisions (such as cloud base height) involved in estimations of aerosol radiative forcing under cloudy skies.

[12] A comparison of aerosol optical depth presented here with those observed over the same location during other seasons is given in Figure 5a and comparison of radiative forcing in Figure 5b. Even though the decrease in AOD from winter to post-monsoon is not very large, there is a very large reduction in the atmospheric forcing due to the

large decrease in the BC mass fraction. The Bay of Bengal region has an important role in Indian monsoon system (as a good part of the rainfall associated with Indian monsoon is generated by the westward moving depressions or low pressure systems in the Bay of Bengal. The large seasonal changes in aerosol radiative forcing may have impacts on regional climate.

### 3.3. Conclusions

[13] 1. Extensive aerosol measurements over the Bay of Bengal along with MODIS data shows that aerosol visible AODs were in the range of 0.2 to 0.7 (with mean value of  $0.43 \pm 0.12$ ), which in conjunction an Angstrom wavelength exponent of  $\sim 0.93 \pm 0.21$  and single scattering albedo ( $\omega$ ) of  $\sim 0.94$  indicates the presence of weakly absorbing aerosols.

[14] 2. The BC mass fraction was  $\sim 2.9 \pm 1.1\%$  (with  $\omega$  of  $\sim 0.94$ ) during post-monsoon season compared to  $5.8 \pm 0.6\%$  (with  $\omega$  of  $\sim 0.88$ ) during pre-monsoon season.

[15] 3. The presence of aerosols over Bay of Bengal during post-monsoon season decreases the short wave radiation arriving at the surface by as much as  $25 W m^{-2}$  and increases top of the atmosphere reflected radiation by  $14 W m^{-2}$ .

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