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Spatial heterogeneity in spectral variability of aerosol optical depth and its implications to aerosol radiative forcing in the Tropical Indian Ocean and in the Indian Ocean Sector of Southern Ocean

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ABSTRACT

The aerosol optical depths (AODs) in the wavelength range 380–875 nm and black carbon (BC) mass concentrations were estimated over the tropical Indian Ocean and in the Indian Ocean sector of Southern Ocean, between 14°N and 53°S, during December 2011–February 2012, onboard the Ocean Research Vessel (ORV) Sagar Nidhi. The data were analysed to understand the spectral variability, micro-physical characteristics of aerosols and the associated radiative forcing. Concurrent MODIS-derived chlorophyll a (Chl-*a*) and sea-surface temperature (SST) provided ancillary data used to understand the variability of biomass in association with fronts and the possible role of phytoplankton as a source of aerosols. AODs and their spectral dependencies were distinctly different north and south of the Inter-Tropical Convergence Zone (ITCZ). North of 11°S (the northern limit of ITCZ), the spectral distribution of AOD followed Ängstrom turbidity formule (Junge power law function), while it deviated from such a distribution south of 16°S (southern boundary of ITCZ). At the southern limit of the ITCZ and beyond, the spectral variation of AOD showed a peak around 440 nm, the amplitude of which was highest at ~43°S, the axis of the subtropical front (STF) with the highest Chl-*a* concentration (0.35 μg l^{-1}) in the region. To understand the role of Chl-a in increasing AOD at 440 nm, AOD at this wavelength was estimated using Optical properties of Aerosols and Clouds (OPAC) model. The anomalies between the measured and model-estimated (difference between the measured and estimated AOD values at 440 nm) AOD_{440} were correlated with Chl-*a* concentrations. A very high and significant association with coefficient of determination (R^2=0.80) indicates the contribution of Chl-*a* as a source of aerosols in this part of the ocean. On the basis of the measured aerosol properties, the study area was divided into three zones; Zone 1 comprising of the area between 10°N and 11°S; Zone 2 from 16°S to 53°S; and Zone 3 from 52°S to 24°S during the return leg. BC mass concentration was in the range 520 ng m^{-3} to 2535 ng m^{-3} in Zone 1, while it was extremely low in the other zones (ranging from 49.3 to 264.4 ng m^{-3} in Zone 2 and from 61.6 ng m^{-3} to 303.3 ng m^{-3} in Zone 3). The atmospheric direct-short wave radiative forcing (DRSF), estimated using a radiative transfer model (Santa Barbara DISORT Atmospheric Radiative Transfer – SBDART), was in the range 4.72–27.62 wm^{-2} north of 16°S, and 4.80–6.25 wm^{-2} south of 16°S.

1. Introduction

The longevity of aerosols in the troposphere is a topic of research ever since their significant role in moulding the climate have been realised (Kaufman and Holben, 1996). The heterogeneity of the aerosols concentration in the spatial domain and their strong correlation with activities such as biomass burning, combustion of fossil fuel, sea salt spray and dust from the deserts clearly underline the need for a proper and systematic analysis of their interaction with incoming solar radiation for climate related studies (IPCC, 2013). In this regards many region-specific experiments pertaining to columnar aerosols have been performed. Some examples are the Aerosol Characterisation Experiment (ACE I and II), the Smoke, Clouds, Aerosols, Radiation-Brazil (SCAR-B) (Kaufman and Holben, 1996), the Tropospheric Aerosol

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Radiative Forcing Observational Experiment (TARFOX) (Russell et al., 1999), the Indian Ocean experiment (INDOEX) (Ramanathan et al., 2001) and the Integrated Campaign for Aerosols, Gases and Radiation Budget (ICARB) (Krishnamoorthy et al., 2008). The possibility of anthropogenically-derived continental aerosols getting advected to neighbouring ocean basins due to seasonally-reversing winds cannot be ruled out. This was the objective while carrying out a coordinated campaign for concurrent observations of aerosols over land and ocean (ICARB, March–May 2006). The results of the study gave insight into the spatial and temporal variability of composite aerosols over the Indian subcontinent and the adjoining Arabian Sea and the Bay of Bengal (Kalapureddy et al., 2009; Kaskaoutis et al., 2009; Badarinath et al., 2010; Kaskaoutis et al., 2010, 2011). For the first time, the study revealed high BC mass concentration in the middle troposphere (Krishnamoorthy et al., 2008). This led to the installation of multi-wavelength radiometers for measurements of the aerosol optical depth (AOD), at carefully chosen locations across India under the aegis of the Aerosol Radiative Forcing over India (ARFI), project funded by the Geosphere Biosphere Programme of the Indian Space Research Organisation (ISRO). Many documents have already been published, highlighting the results of ARFI initiatives (Menon et al., 2011; Moorthy et al., 2013a,2013b; Narasimhan and Satheesh, 2013; Gogoi et al., 2014; Menon et al., 2014). While ICARB and ARFI acted as stimulus for aerosol studies, the knowledge on the spatial variation of aerosol properties from north to south is more important and has been less attempted, especially over the Indian Ocean sector of the Southern Ocean. Some of the limited studies carried out in this area (Babu et al., 2010; Chaubey et al., 2013) mainly focussed on the continental impact and sea spray aerosols on climate. However, the role of marine phytoplankton has virtually been unexplored in any of these studies. This encouraged researchers to extend the observations to different sectors of the Indian Ocean. One such study has been carried out between 14°N and 53°S from December 2011 to February 2012 as part of the Southern Ocean Expedition (SOE) program, organised by the National Centre for Antarctic and Ocean Research (NCAOR), Ministry of Earth Sciences (MOEs) of the Government of India. The results of the study are presented and discussed here. The study was carried out with the following objectives.

1. To understand the spatial heterogeneity of spectral characteristics of aerosols between 14°N and 53°S, area covering the southern Arabian Sea and the Indian Ocean sector of the Southern Ocean.
2. To generate a spectrally resolved Angstrom wavelength exponent (α) to delineate the source of aerosols in the area of study.
3. To examine the role of phytoplankton in modifying the aerosol properties in the area of study.
4. To quantify the spatial gradients of AOD/BC mass concentration and the north-south distinctiveness in aerosol types of the study area.
5. To examine the spatial variability of short wave direct aerosol radiative forcing (SDRF) in the study area.

2. Material and methods

The measurements have been carried out in a campaign mode, during the period 26 December 2011 to 4 February 2012, aboard the ORV Sagar Nidhi (Fig. 1). The measurements started from Goa, progressed along the track (Fig. 1) and culminated at Mauritius on February 4. During the campaign period, the ITCZ was located between 11°S and 16°S, and as such, the cruise provided an opportunity to examine the outflow of aerosols from Asian continent in association with the north-east monsoon winds beyond its northern limit, in contrast with the more pristine Southern Ocean.

A Microtops II Sunphotometer (Solar light Co) and an Aethalometer (Magee Scientific, AE 42) were used to estimate columnar spectral AOD and near-surface BC mass concentration on board ORV Sagar Nidhi during its cruise. A hand-held automatic weather station (AWS-Nielsen Kellerman) was used to derive wind parameters. The onward leg of the cruise terminated at 53°S on 23 January 2012, while the return leg ended at 24°S near Mauritius. Since the aerosol characteristics are known to be distinct on either side of the ITCZ (for example Moorthy et al., 1999), the first leg between 14°N and 53°S has been divided into two zones, namely; Zone 1 comprising of the area between 10°N and 11°S and Zone 2 from 16°S to 53°S. The return leg has been considered as separate zone (Zone 3) as it has more continental proximity than Zone 2. The numbers shown in Fig. 1 are AODs at 500 nm (AOD_{500}) corresponding to the locations of measurements. Since measurements were taken on clear sky conditions (only in the absence of visible clouds) while the ship was sailing, the AODs corresponding to those locations are shown in the figure. Moreover, long range transport of aerosols to the study area computed by the Hybrid Single Particle Lagrangian Interpolated Trajectory (HYSPLIT) model (http://ready.arl.noaa.gov/) (Draxler and Hess, 1998) for each measurement location, and arrival altitudes of 0.5 km, 1 km and 1.5 km above mean sea level are shown by plotting the back trajectory to various points on the track. Prior to the cruise, all the instruments were calibrated by the manufacturers. Details of estimation of AOD and BC are given below.

2.1. Aerosol optical depth (AOD)

AODs were estimated from the multichannel Microtops II sunphotometer measurements at five bands centered at 380, 440, 500, 675 and 870 nm, following a standard protocols (Frouin et al., 2003). A Sunphotometer works on the principle of the Beer-Lambert law. The field of view of the Microtops II is 2.5° at full-width half maximum. From the spectral measurements of direct solar flux, the instrument computes AOD using internal calibration coefficients (which represent the corresponding top of the atmosphere fluxes) and the coordinates of the observation points provided by a Global Position System attached to it. All the observations were made from 0900 h to 1730 h during clear-sky periods at an interval of 30 min. Typical accuracies in the estimated AOD over maritime environment using Microtops II instrument are $\sim \pm 0.015$ (Knobelspiesse et al., 2004).

2.2. Black carbon (BC)

A seven-band Aethalometer (model AE-42) operating at 370, 470, 520, 590, 660, 880 and 950 nm was used to estimate BC mass concentration. Filtration and optical transmission techniques were used to estimate BC mass concentration from the absorbance at 880 nm (Hansen et al., 1984). The instrument aspirated ambient air through a size-segregating inlet that pre-segregates all the particles larger than 1 μm. The instrument was operated at a rate of 3 l/minute (LPM) every 2 min till 11°S and at a rate of 5 LPM during the surveys south of 16°S (in view of the reduced BC concentrations in these regions). The particles in the airflow get deposited on the quartz fibre filter tape of the Aethalometer. The difference between the sample spot (deposit of particles on the quartz fibre filter tape of the Aethalmeter) and reference spot (particle free) gives the attenuation. Using the factory-set wavelength dependent calibration factors, the equivalent BC mass was computed. During the field measurement, the Aethalometer was placed in the ship's cabin and the inlet pipe was placed at a height of about 12 m at the bow of the ship (sampling into the wind) to avoid any contamination due to ship fumes. To protect the instrument from varying humidity, a heated sample line was