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Spatial heterogeneities in aerosol size distribution over Bay of Bengal during Winter-ICARB Experiment

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ABSTRACT

This work examines the aerosol physical properties and size distribution measured in the Marine Atmospheric Boundary Layer (MABL) over entire Bay of Bengal (BoB) and Northern Indian Ocean (NIO) during the Winter Integrated Campaign on Aerosols, Gases and Radiation Budget (W-ICARB). The measurements were taken using the GRIMM optical particle counter from 27th December 2008 to 30th January 2009. The results show large spatial heterogeneities regarding both the total aerosol number concentrations (N_T) and the size distributions over BoB, which in turn indicates the variations in the source strength or advection from different regions. The aerosol number size distribution seems to be bi-modal in the 72% of the cases and can also be parameterized by uni-modal or by a combination of power-law and uni-modal distributions for the rest of the cases. The mode radius for accumulation and coarse-mode particles ranges from ~0.1–0.2 μm and ~0.6–0.8 μm, respectively. In the northern BoB and along the Indian coast, the aerosols are mainly of sub-micron size with effective radius (R_{eff}) ranging between 0.25 and 0.3 μm highlighting the strong anthropogenic influence, while in the open oceanic areas they are much higher (0.4–0.6 μm). It was also found that the sea-surface wind plays a considerable role in the super-micron number concentration, R_{eff} and mode radius for coarse-mode aerosols. Using the relation between N_T and columnar AOD from Terra and Aqua-MODIS we found that the majority of the aerosols are within the lower MABL, while in some areas vertical heterogeneities also exist.

1. Introduction

Substantial amount of aerosols produced from both anthropogenic and natural sources in the rapidly developing south Asian region is loading over the Bay of Bengal (BoB) (e.g. Ramachandran, 2004; Moorthy et al., 2008; Nair et al., 2009) and, despite their radiative forcing effects (e.g. Ganguly and Jayaraman, 2006; Moorthy et al., 2009), they also suppress precipitation and affect the hydrological cycle (e.g. Gautam et al., 2009). The direct and indirect aerosol effects on global and regional climate are highly variable with space and time due to the aerosol short residence time, different types and characteristics and mixing processes causing large uncertainty in the assessment of aerosol radiative forcing (IPCC, 2007). Multiple platform measurements, such as ground-based networks, ships, aircrafts, balloons and satellites, as well as numerical modeling, are required to reduce these uncertainties (e.g. Kaufman et al., 2002; Hatzianastassiou et al., 2004; Yu et al., 2006). This is particularly needed for the south Asian region, with all its natural diversities, high population density, diverse living habits, and the growing industrialization and urbanization (Moorthy et al., 2008).

To address this serious issue in a comprehensive way over oceanic regions adjacent to the Indian sub-continent, various field campaigns have been conducted over the area, i.e., Indian Ocean Experiment (INDOEX) (Ramanathan et al., 2001), Arabian Sea Measurement experiment (ARMEX) (Moorthy et al., 2005), Integrated Campaign on Aerosols, gases and Radiation Budget (ICARB) (Moorthy et al., 2008). Other few field experiments conducted in recent years were limited to cruises along the Indian coasts and coastal northern BoB (e.g. Satheesh, 2002; Quinn et al., 2002; Sumanth et al., 2004; Vinoj et al., 2004) and focused mainly on columnar aerosol optical depth (AOD), aerosol size distribution and ambient total mass concentration measurements.

BoB, being surrounded by the rapidly developing southeast Asian regions, provides an excellent laboratory for monitoring the continental fluxes and has vital impacts in Indian monsoon circulation.

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Emphasizing the importance of these, Indian Space Research Organization under Geosphere Biosphere Program (ISRO-GBP) conducted the ship cruise campaign named Winter Integrated Campaign on Aerosols, Gases and Radiation Budget (W-ICARB) during 27th December 2008 to 30th January 2009. The main objective of the present work is to analyze the spatial distribution of the aerosol physical and optical properties in the marine atmospheric boundary layer (MABL) over BoB and to examine the influence of continental fluxes and sea-surface wind to the aerosol load and particle size over the oceanic area. Furthermore, the correlation between MABL and columnar aerosol characteristics may reveal the degree of the vertical heterogeneity over the entire BoB.

2. Experimental details and database

The cruise track during the W-ICARB campaign is shown in Fig. 1. The ship started from Chennai port (13.06° N, 80.18° E) on 27 December 2008 and during its return journey passed Sri Lanka on 28 January 2009 and returned back to Kochi (9.58° N, 76.14° E) at Arabian Sea (AS) on 30 January 2009 spanning 35 days.

The onboard aerosol measurements were performed from a specially designed laboratory on the top deck of the oceanic research vessel (ORV) (~10 m above mean sea level, amsl). The sampling instrument aspirated the ambient air through an isokinetic community air inlet pipe fixed to the port side of the ship. Size-segregated aerosol number concentrations were measured for all the 35 days of the cruise in 15 size bins in the diameter range 0.3–20 μm using optical particle counter (Portable aerosol spectrometer, GRIMM 1.108, Grimm Aerosol Technik GmbH & Co., Ainıng, Germany) at 5 min sampling time interval. The main drawback of this instrument is that the measurements are limited in the size range 0.3–20 μm and, therefore, all analyses are truncated in this range missing out particles below 0.3 μm. This fact affects the measured aerosol number size distribution and the simulated distributions in the fine and nucleation modes.

The ambient air is aspirated into the unit via an internal volume-controlled pump at a rate of 1.2 LPM. Optical particle counters (OPC) can provide rapid real time monitoring of the particle number concentration by optical sizing the particle in a volume-controlled

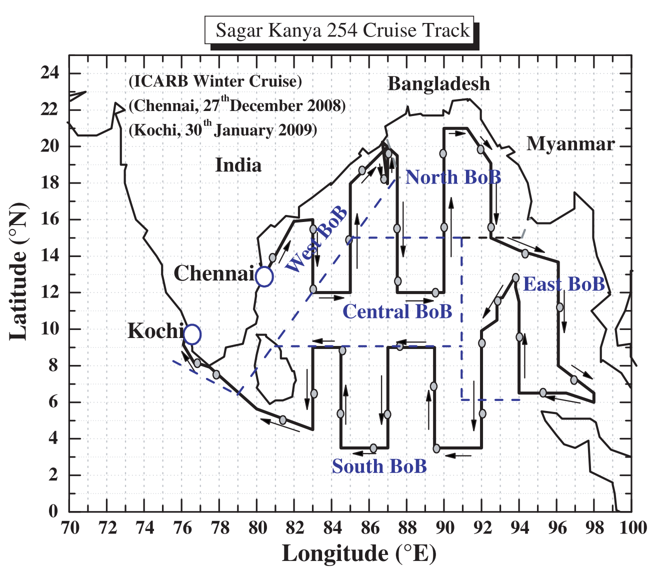

Fig. 1. The cruise track of Sagar Kanya-254 in the Bay of Bengal during the W-ICARB cruise experiment (27 Dec 2008–30 Jan 2009). The arrow shows the track of the ship while the circles show the position of the ship at 05:30 UTC (12:00 LST) for each day. The entire BoB is divided in 5 sub-regions, namely west, north, east, central and south.

flow. The instrument uses a light-scattering technique for single-particle counts, whereby a semiconductor laser serves as the light source, while is capable of counting from 1 particle L^{-1} to 2 million particles L^{-1}. The uncertainties in the aerosol number concentrations are in the range of 10%–20% at very low mass concentrations ($\sim$10 μg m^{-3}) and the error reduces to <10% for high mass concentrations (>30 μg m^{-3}) (Nair et al., 2009).

The accurate measurement and control monitoring of aerosol using OPC depends on the ambient temperature, relative humidity (RH) and pump flow rate, which is accomplished by in-built Grimm housing. The temperature and RH range for the smooth operation of the instrument is 0–40 °C and <95%, respectively and the instrument was out of order whenever RH exceeded the measurement limit. A major task that must be taken into account in aerosol measurements over marine environments is the hygroscopic growth of the particles. Rissler et al. (2006) have investigated the hygroscopic growth of aerosols in the Amazon and found no step-like deliquescent behavior of the aerosol in the dry and wet period. The particle growth factor (g_f) can be described as:

$$g_f = \left[1 + p\left(\frac{RH}{100}\right) \Big/ 1 - \left(\frac{RH}{100}\right)\right]^{\frac{1}{3}} \qquad (1)$$

Where p takes a value of ~0.1 for the most hygroscopic particles. It was reported that the hygroscopic growth of the most water-soluble particles is 1–2% for the RH range of 70–80%, while the error in aerosol number concentration measurements will be <10% due to hygroscopic growth (Fairall, 1984; Kowalski, 2001; Vong et al., 2004). 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 and ~50 m away; the instrument was switched off in cases that such criterion was not followed. However, we cannot ignore the fact that the ORV may be in the downstream trail of a large ship. For this reason, the daily averages of the aerosol particle concentrations are used in the present work.

Along with aerosol measurements, meteorological parameters, such as air temperature, sea-surface temperature, atmospheric pressure, RH, wind speed (WS) and wind direction (WD) have been carried out on hourly basis. The measured WS and WD were corrected for the velocity of the ship using the method proposed by Smith et al. (1999). A global positioning system (GPS) onboard provided continuous information of the spatial coordinates of the ship. The MODIS AOD_{550} was also used to analyze the columnar aerosol properties corresponding to collection (C005) level 2 and 3 from both Terra and Aqua satellites (Levy et al., 2007).

3. Prevailing meteorology

Measurements of several meteorological parameters controlling the air–sea interaction during the cruise campaign were taken using multiple sensors, which were kept at ~10 m amsl onboard the ship. The most of the days were cloudless or partly cloudy as observed by crew's own eyes during the measurements. The average convective mixed layer height ranged from ~100 m to ~1.7 km with a mean of ~710 m. During the beginning of the cruise (27 Dec–16 Jan), significant variability of the mixed layer height was observed, while in the second half (16 Jan–27 Jan) it remained nearly steady at ~650 m. This can be attributed to humid and cloudy conditions in this period, when the thermal convection was minimal and the wind shear controlled the turbulent mixing within MABL (Subrahamanyam et al., 2010). The spatial distribution of air temperature, atmospheric pressure, RH, WS, and WD are shown in Fig. 2(a–d). During the cruise campaign the air temperature varied from 24.5 °C (8 Jan) to 29.3 °C (27 Jan) presenting a remarkable