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Temporal variation of aerosol optical depth and associated shortwave radiative forcing over a coastal site along the west coast of India

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HIGHLIGHTS

- Temporal variation of AOD during the year 2008 exhibits a bimodal distribution.
- SSA in the atmosphere is regulated by BC, which results in a positive forcing.
- The surface forcing is governed by scattering aerosol leading to a negative forcing.
- These two neutralize and the resultant TOA negative forcing is constant annually.

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ABSTRACT

Optical characterization of aerosol was performed by assessing the columnar aerosol optical depth (AOD) and angstrom wavelength exponent (α) using data from the Microtops II Sunphotometer. The data were collected on cloud free days over Goa, a coastal site along the west coast of India, from January to December 2008. Along with the composite aerosol, the black carbon (BC) mass concentration from the Aethalometer was also analyzed. The $AOD_{0.500\ \mu m}$ and angstrom wavelength exponent (α) were in the range of 0.26 to 0.7 and 0.52 to 1.33, respectively, indicative of a significant seasonal shift in aerosol characteristics during the study period. The monthly mean $AOD_{0.500\ \mu m}$ exhibited a bi-modal distribution, with a primary peak in April (0.7) and a secondary peak in October (0.54), whereas the minimum of 0.26 was observed in May. The monthly mean BC mass concentration varied between 0.31 $\mu g/m^3$ and 4.5 $\mu g/m^3$, and the single scattering albedo (SSA), estimated using the OPAC model, ranged from 0.87 to 0.97. Modeled aerosol optical properties were used to estimate the direct aerosol shortwave radiative forcing (DASRF) in the wavelength range 0.25 μm4.0 μm. The monthly mean forcing at the surface, at the top of the atmosphere (TOA) and in the atmosphere varied between −14.1 W m^{-2} and −35.6 W m^{-2}, −6.7 W m^{-2} and −13.4 W m^{-2} and 5.5 W m^{-2} to 22.5 W m^{-2}, respectively. These results indicate that the annual SSA cycle in the atmosphere is regulated by BC (absorbing aerosol), resulting in a positive forcing; however, the surface forcing was governed by the natural aerosol scattering, which yielded a negative forcing. These two conditions neutralized, resulting in a negative forcing at the TOA that remains nearly constant throughout the year.

1. Introduction

One of the uncertainties in global climate studies is the inadequate incorporation of spatial heterogeneity of aerosol in climate models (Charlson et al., 1992; Schwartz et al., 1995; Inter Governmental Panel on Climate Change (IPCC), 2001; Solomon et al., 2006). To attain this requirement, numerous studies performing physical and chemical aerosol characterizations have been published in the last decade (Schwartz and Andreae, 1996; Kaufman et al., 2002; Penner et al., 2002; Takemura et al., 2002; Solomon et al., 2006). The co-existence of both scattering and absorbing aerosols complicates the atmospheric radiative forcing. The former leads to cooling (negative forcing), whereas the latter results in warming (positive forcing) (Charlson et al., 1992; Schwartz et al., 1995). In addition to the direct effect of aerosols on the climate, aerosols exhibit indirect effects via changing the residence time and radiative properties of clouds (Twomey, 1977). The presence of absorbing aerosol, BC, promotes large spatial variability in the atmospheric single scattering albedo (SSA). This concern prompted an analysis of the aerosol optical depth (AOD) variation from the winter to the summer monsoon over the tropical Indian Ocean using Advanced Very High Resolution Radiometer (AVHRR) data (Li and Ramanathan, 2001). Several attempts to retrieve and analyze AOD synoptically from the Ocean Colour Monitor (OCM) onboard the Indian Remote Sensing Satellite – IRS – P4 have

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been successful (Dey and Singh, 2002; Mishra et al., 2008; Menon et al., 2011).

To incorporate the chemical and physical aerosol characteristics with the climate models, various campaigns were organized, including the Indian Ocean Experiment (INDOEX) (Ramanathan et al., 2001), Arabian Sea Monsoon Experiment (ARMEX) (Moorthy et al., 2004; Babu et al., 2004), Aerosol Characterization Experiment (ACE 1&2) (Bates et al., 1998; Raes et al., 2000), Smoke, Clouds, Aerosols, Radiation-Brazil (SCAR-B) (Kaufman et al., 1998) and the Troposphere Aerosol Radiative Forcing Observational Experiment (TARFOX) (Russell et al., 1999). The Integrated Campaign on Aerosols, Gas and Radiation Budget (ICARB) and winter ICARB (WICARB), staffed by Indian atmospheric researchers, specifically surveyed the Indian subcontinent and adjoining Arabian Sea and Bay of Bengal. The literature documenting these data explains the physical and optical properties of the aerosol coupled with radiative forcing either over the ocean or over specific cities in the Indian subcontinent during the pre-monsoon season (Moorthy et al., 2008, 2010; Nair et al., 2008; Kedia and Ramachandran, 2008; Kedia et al., 2010; Kumar et al., 2010; Kharol et al., 2011). In continuation of these efforts, the Indian Space Research Organization (ISRO) initiated the Aerosol Radiative Forcing in India (ARFI) program, which involves uninterrupted aerosol measurements from 34 specific regions within the country. Under the aegis of the ARFI, continuous aerosol measurements in Goa began in 2008 (Fig. 1a). In this context, one of the pioneering studies performed by Suresh and Desa (2005) explained the optical properties of aerosol to develop a regional atmospheric correction algorithm for the ocean color satellite sensors. This publication further discussed the annual variability of AOD over the region. Additionally, there have been no studies that analyzed the spectral characteristics and radiative forcing of aerosol over Goa.

The Indian summer monsoon of 2008 was so irregular that the northern part of the sub-continent experienced heavy monsoon showers while the southern part underwent drought (Rao et al., 2010). This motivated the authors to analyze the aerosol optical properties from 2008, with the following objectives:

(1) Analyze the monthly mean variability of aerosol optical depth (AOD), angstrom wavelength exponent (α) and black carbon (BC) mass concentration.
(2) Estimate the single scattering albedo (SSA) and study the variability of the monthly SSA mean using the Optical Properties of Aerosol and Clouds (OPAC) model.
(3) Analyze the aerosol effects on incoming solar radiation by estimating the direct aerosol shortwave radiative forcing (DASRF).

2. Data and methods

2.1. Study site and general meteorology

The study site is located at 15.46°N and 73.83°E on a plateau ~50 m above the mean sea level and is surrounded by the Arabian Sea to the west and the Western Ghats to the east. The site is ≈700 m east of the Arabian Sea and 5 km away from Panjim, the thickly populated capital city of Goa. The seasonal rainfall associated with the reversing wind from the Southwest monsoon (June, July, August and September) to Northeast monsoon (December, January, February and March) is one of the most significant synoptic atmospheric processes that affect the site (Asnani, 1993). This process is changing because of the land and sea breeze, a mesoscale meteorological process confined within the atmospheric boundary layer, due to the proximity of the site to the coastline. The Northeast monsoon carries dry continental air-mass that may possess an anthropogenic component. Conversely, moisture-laden wind of the Southwest monsoon removes aerosol due to precipitation. Hence, the area experiences four distinct seasons, the winter monsoon (December, January, February and March, WMS), the spring inter-monsoon (April and May, SIMS), the summer monsoon (June, July, August and September; SMS) and the fall inter-monsoon (October and November; FIMS). Approximately nine industrial areas reside in the proximity of the study site (Fig. 1b). The Murmugao port, indicated as point 7 in Fig. 1b, is the closest. Mining is a prominent industry in Goa, and the transportation of ore from the mining site to Murmagao port relies primarily on two estuaries, Mandovi and Zuari.

2.2. In-situ measurements

2.2.1. Meteorological parameters

The relative humidity, rainfall, wind speed and direction, measured from an automatic weather station (AWS), are presented in Table 1.

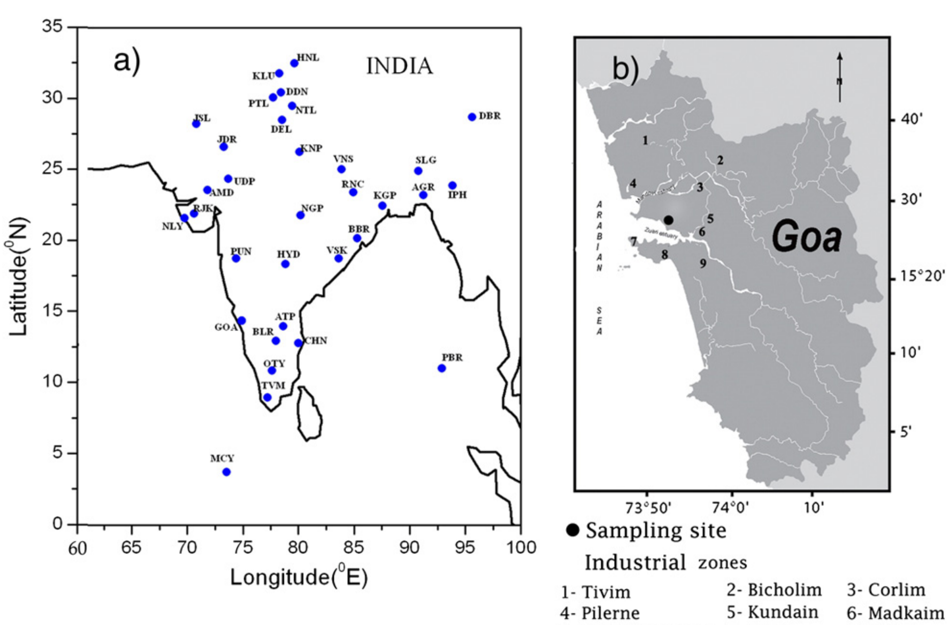

Fig. 1. (a) The network of ARFI stations across India. (b) Station at Goa under ARFI network, surrounded by different Industrial zones.