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Seasonal variation of vertical distribution of aerosol single scattering albedo over Indian sub-continent: RAWEX aircraft observations

S. Suresh Babu[a,*], Vijayakumar S. Nair[a], Mukunda M. Gogoi[a], K. Krishna Moorthy[b]

[a] Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram, India
[b] Indian Space Research Organization Head Quarters, Bangalore, India

HIGHLIGHTS

- Altitude profiles of aerosol SSA and its seasonality over Indian landmass.
- Enhancement in free tropospheric aerosol absorption in spring.
- Near-surface loading peaks during winter and decreases in spring.
- Pre-monsoon aerosols are more absorptive than winter.

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ABSTRACT

To characterize the vertical distribution of aerosols and its seasonality (especially the single scattering albedo, SSA) extensive profiling of aerosol scattering and absorption coefficients have been carried out using an instrumented aircraft from seven base stations spread across the Indian mainland during winter 2012 and spring/pre-monsoon 2013 under the Regional Aerosol Warming Experiment (RAWEX). Spatial variation of the vertical profiles of the asymmetry parameter, the wavelength exponent of the absorption coefficient and the single scattering albedo, derived from the measurements, are used to infer the source characteristics of winter and pre-monsoon aerosols as well as the seasonality of free tropospheric aerosols. The relatively high value of the wavelength exponent of absorption coefficient over most of the regions indicates the contribution from biomass burning and dust aerosols up to lower free tropospheric altitudes. A clear enhancement in aerosol loading and its absorbing nature is seen at lower free troposphere levels (above the planetary boundary layer) over the entire mainland during spring/pre-monsoon season compared to winter, whereas concentration of aerosols within the boundary layer showed a decrease from winter to spring. This could have significant implications on the aerosol heating structure over the Indian region and hence the regional climate.

1. Introduction

The atmospheric aerosols over the south and southeast Asia has been the topic scientific interest because of projected regional climate impacts as well as the implications of these fine particles on the hydrological cycle, air quality and health of the millions of people living in this region (Lau et al., 2008; Lawrence and Lelieveld, 2010). The regional radiative forcing due to aerosol-radiation and aerosol-cloud interactions are assessed (through observations and modelling) to be significantly higher than that of the other climate forcing agents (for eg: greenhouse gases) over this region (Ramanathan, 2003). The sustained efforts since the first regional compilation by Mani et al. (1969) and the subsequent systematic measurements made from a network of multi-instrumented observatories under the Aerosol Radiative Forcing over India (ARFI) project, and the extensive field campaigns from INDOEX (Indian Ocean Experiment) (Ramanathan et al., 2001) to ICARB (Integrated Campaign for Aerosols, gases and Radiation Budget) (Moorthy et al., 2009) have revealed significant amount of aerosol loading over the Indian sub-continent and surrounding oceans (Lawrence and Lelieveld, 2010), which has been depicting a steady increasing trend (Babu et al., 2013). South Asian aerosols show significant seasonality in association with the monsoon circulation; anthropogenic aerosols dominate during winter and natural aerosols dominate during summer seasons (Ramanathan et al., 2001; Moorthy et al., 2007a; Vinoj et al., 2014). Several studies

* Corresponding author.
E-mail address: s_sureshbabu@vssc.gov.in (S. Suresh Babu).

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have addressed the implications of these aerosols on summer monsoon (Ramanathan et al., 2005; Lau et al., 2006; Vinoj et al., 2014). However, heterogeneous processes associated with aerosol–climate interactions are still uncertain over this region.

During the last two decades, there have been numerous field campaigns, laboratory experiments and continuous observations from ground based and space borne instruments to characterize the extensive and intensive aerosol properties for the accurate estimation of aerosol radiative forcings (Ramanathan et al., 2001; Moorthy et al., 2009; Lawrence and Lelieveld, 2010). In general, aerosol optical depth, single scattering albedo and aerosol phase function are the most important aerosol parameters essential for understanding the aerosol-radiation interactions (Direct effect). Even though the accuracy of the estimation of aerosol optical depth has significantly improved in the past decade due to the expansion of network observatories and improvements in the satellite based observation techniques, the uncertainties in the estimation of single scattering albedo, which decides the sign of the aerosol direct radiative forcing, remain unaddressed for a quite long time (Heintzenberg et al., 1997). This arises mainly from the technical challenges in measuring the aerosol absorption continuously from the surface or space. The quantification of aerosol absorption is essential not only for the assessment of direct radiative forcing, but also for the aerosol-cloud (semi-direct effect) and aerosol-cryosphere (snow albedo reduction due to black carbon deposition) interactions (Nair et al., 2013a,b). Even though there exist continuous measurements of columnar aerosol properties and surface level aerosol parameters from ARFI network, the lack information on the vertical distribution of aerosols, especially aerosol absorption, have hindered providing observational evidence to various hypotheses put forward by numerical modelling (Lau et al., 2006). However, this is very important because the effects of a given aerosol layer strongly depends on its altitude in the atmosphere and position with respect to clouds. For example a given layer of absorbing aerosols can produce higher warming, if it is located higher in the atmosphere due to the exponentially decreasing air density with altitude.

Recognizing the importance of three dimensional information of aerosol properties and realizing the scarcity of such measurements over South Asia and especially over Indian mainland, Regional Aerosol Warming Experiment (RAWEX) has been conceived with its main objectives including (i) establish high altitude aerosol observatories for the continuous measurements of free tropospheric aerosols (Babu et al., 2011a) (ii) high altitude balloon experiments for vertical profiles of black carbon mass measurements (Babu et al., 2011b), and (iii) effect of black carbon deposition in snow albedo over Himalayas (Nair et al., 2013a). In the backdrop of the outcomes from these experiments, and to further investigate the vertical distribution of aerosol properties as well as the seasonality in their spatial variations, extensive campaign-mode measurements were carried out over the Indian mainland using an instrumented aircraft during the winter of 2012 and spring/pre-monsoon season of 2013. This paper presents the details of this campaign and the results of the characteristics of SSA derived from these measurements, perhaps providing this information for the first time over the entire mainland.

2. Instrumentation and campaign details

Exhaustive measurements of aerosol properties (concentration, size distribution, and coefficients of scattering and absorption) were carried out during the RAWEX campaign using an instrumented aircraft (Beechcraft, B200) of National Remote Sensing Centre (NRSC), Hyderabad during November–December, 2012 (winter phase) and May, 2013 (spring/pre-monsoon phase). Measurements were made from 7 base stations (Hyderabad, Nagpur, Lucknow, Patna/Ranchi, Jaipur, Jodhpur and Dehradun) as shown in Fig. 1. Due to foggy and low visibility conditions during the winter phase, measurements at Patna were called off at the last moment and the aircraft moved to the nearby airport, Ranchi for measurements. Table 1 shows the details of location, time period and instruments operated during the campaign. Over the mainland, Hyderabad and Nagpur are representatives of central India (CI), which are urban locations with relatively arid climate; Lucknow and Patna/Ranchi represent the Indo Gangetic Plain (IGP), the most populated and industrialized region of India; Jaipur and Jodhpur represent the west India (WI), which are close to Thar desert and exhibit mostly dry climate; and Dehradun representing the Himalayan foothills (HF).

In the present study we have used a shrouded solid diffuser inlet (University of Hawaii) to sample the ambient air at near-isokinetic conditions for all the instruments aboard the aircraft. The inlet is fitted under the fuselage of the aircraft opening into the flow as the aircraft flies. Based on laboratory calculations, a volumetric flow rate of 70 LPM (litres per minute) has been used and the aircraft flight speed was maintained around 300 km h^{-1} during sampling. The aerosol sampling onboard aircraft has inherent uncertainties associated with the sampling efficiency especially for particles above 1 μm. McNaughton et al. (2007), have reported (during DC-8 Inlet characterization Experiment (DICE)) that the 'University of Hawaii (UH) inlet (used in the present study)' can be used very effectively for sampling particles below 4 μm and they have reported very good association between the scattering coefficient measured using the UH inlet system and reference measurements. Based on inlet characterization experiments, McNaughton et al. (2007) and Huebert et al. (2004) have shown that solid diffuser inlet can be used for aerosol sampling in the sub-micron size range (50% passing efficiency aerodynamic diameters is 5 μm) efficiently.

The profiling at each station, consisted of three vertical sorties, made during consecutive days following a staircase pattern as shown in Fig. 2. All the sorties were made around noon time, so that the aerosols are well-mixed within the atmospheric boundary layer by thermal convections which of course is stronger

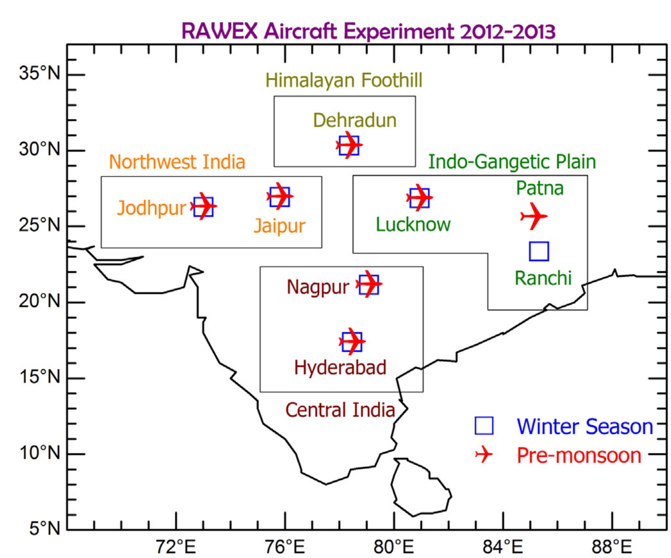

Fig. 1. Base stations from which aircraft sorties were carried out during winter (2012) and spring (2013) seasons. Hyderabad and Nagpur are representatives of central India, Jodhpur and Jaipur represent West India, Lucknow and Patna/Ranchi represent Indo Gangetic Plain and Dehradun represent Himalayan foothills.