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# Short wave Aerosol Radiative Forcing estimates over a semi urban coastal environment in south-east India and validation with surface flux measurements

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## HIGHLIGHTS

- Maximum ARF at Surface in South West monsoon and Winter.
- Increased atmospheric absorption in Pre monsoon and Winter.
- Increase of ARF with Relative Humidity (RH).
- Effect of RH on ARF studied for the first time.
- Net surface short wave flux values from model and measurement match well.

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## ABSTRACT

The short wave direct Aerosol Radiative Forcing (ARF) at a semi urban coastal location near Chennai (12.81 °N, 80.03 °E, ~45 m amsl), a mega city on the east coast of India has been estimated for all the four seasons in the year 2013 using the SBDART (Santa Barbara Discrete ordinate Atmospheric Radiative Transfer) model. As inputs to this model, measured aerosol parameters together with modeled aerosol and atmospheric parameters are used. The ARF in the atmosphere is found to be higher in the pre-monsoon and winter seasons compared to the other seasons whereas at the surface, it is found to be higher in the south-west (SW) monsoon and winter seasons. The estimated ARF values are compared with those reported over other locations in India. The effect of Relative Humidity on ARF has been investigated for the first time in the present study. It is found that the ARF increases with increasing RH in the SW monsoon and winter seasons. An unique feature of the present study is the comparison of the net surface short wave fluxes estimated from the model (SBDART) and measured fluxes using CNR 4 net radiometer. This comparison between the estimated and measured fluxes showed good agreement, providing a 'closure' for the estimates.



## 1. Introduction

Aerosols affect the Earth's radiation budget directly by scattering and absorption and indirectly by modifying the cloud properties like albedo and life time (e.g., Charlson et al., 1992; Twomey et al., 1984; Moorthy et al., 2007), contributing to significant heating in the troposphere (Babu et al., 2011). Also, aerosols can influence the general circulation patterns (Lau et al., 2006), biochemical cycling (Xin et al., 2005) and hydrological cycle (Ramanathan et al., 2001(a)) and play a crucial role in climate change predictions (Solomon et al., 2007).

A very useful and commonly adopted parameter for assessing the aerosol radiative effects is the Aerosol Radiative Forcing. The Aerosol Radiative Forcing is the change in the net (downward minus upward) radiative flux either at the surface or top of the

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atmosphere or at any level in the atmosphere with and without aerosols in the atmosphere (Russell et al., 1999; Sathessh et al., 2010) and is generally classified as direct (forcing due to scattering and absorption by aerosols in cloud-free atmosphere) and indirect (owing to influences of aerosols on albedo and life time of clouds). In the present study, we deal only with the short wave direct Aerosol Radiative Forcing (ARF). Aerosols by way of scattering and absorption of solar radiation reduce the surface reaching solar radiation flux. Black Carbon (BC) aerosols and some of the mineral dust aerosols which are mainly absorbing type could alter the vertical structure of the temperature of the atmosphere leading to cloud burning (Ackerman et al., 2000; Satheesh et al., 2010) and hence affecting the atmospheric stability (Moorthy et al., 2009; Gautam et al., 2009; Singh et al., 2010). Aerosols exhibit spatial and temporal heterogeneity unlike the greenhouse gases which are well mixed in the atmosphere with no significant regional variations. This is mainly due to the wide variety of aerosol sources, both natural and anthropogenic. According to IPCC (2013), aerosols contribute a major uncertainty to the total radiative forcing estimates globally. The ever increasing anthropogenic activities make it imperative to make a realistic assessment of the radiative forcing of aerosols for a reliable appraisal of their climatic impact. This can be achieved through extensive measurements in different environments in different regions to provide inputs to the radiative forcing estimates and validating the estimates with flux measurements.

Regular coordinated aerosol measurements are being carried out at a number of locations under the programmes of AErosol RObotic Network (AERONET; e.g., Holben et al., 1998; Smirnov et al., 2009) and Aerosol Radiative Forcing over India (ARFI; e.g., Moorthy et al., 1989). Several field campaigns under different programmes such as Indian Ocean Experiment (INDOEX; e.g., Ramanathan et al., 2001b), Arabian Sea Monsoon Experiment (ARMEX; e.g., Moorthy et al., 2005a; Babu et al., 2004), Troposphere-Aerosol Radiative Forcing Observational Experiment (TARFOX; e.g., P.B. Russell et al., 1999); ISRO-GBP Land campaigns (e.g. Babu et al., 2002; Moorthy et al., 2005(b); Niranjan et al., 2006; Ramachandran et al., 2006; Tripathi et al., 2006; Nair et al., 2007) and Integrated Campaign on Aerosols, Gas and Radiation Budget (ICARB and WICARB; e.g., Moorthy et al., 2008) have been carried out to study the aerosol characteristics and their impact on radiative forcing. These programmes provided a wealth of information on aerosols. Under Geosphere – Biosphere Programme, Indian Space Research Organization (ISRO) initiated Aerosol Radiative Forcing over India (ARFI) network which involves continuous aerosol measurements at various locations (42 stations) in India to assess radiative forcing (Moorthy et al., 1989). The main objective of this programme is to provide a comprehensive scenario of aerosol characteristics with a wide geographical coverage over India. As part of this programme, aerosol measurements are being carried out at a semi-urban coastal location, SRM University (12.81 °N, 80.03 °E, ~45 m amsl) located in the outskirts of Chennai, a mega city in India on the east coast. The authors have already reported the characteristics of BC aerosols and the effect of boundary layer dynamics on BC (Aruna et al., 2013) as well as the scattering and absorbing aerosol characteristics (Aruna et al., 2014) from measurements of BC aerosol concentration, Aerosol Optical Depth (AOD) and Total Particulate matter with size $<10\ \mu m$ (PM10). In the present study, using the measured aerosol parameters in the year 2013, the short wave radiative forcing of aerosols (ARF) has been estimated adapting a Radiative Transfer model (SBDART) on seasonal average basis. The effect of Relative Humidity (RH) on the ARF is delineated for the first time. A unique feature of the present study is comparison of the estimated values of net surface short wave solar flux with the measured values providing a 'closure' of the model estimates.

## 2. Methodology

### 2.1. Site details and meteorological parameters

The study location, SRM University Campus (12.81N, 80.03E, ~45 m amsl) is in a suburban region, in the outskirts of Chennai city. It is abutted by populated towns towards west, north-east and densely industrialized towns towards north and is situated ~45 m off the National Highway and 23 km from the coast of Bay of Bengal. More details about the study location are available in Aruna et al. (2013; 2014). In general, Chennai experiences both south-west (SW; summer) and north-east (NE; winter) monsoon rainfall. During the year 2013, NE monsoon contributed 40.8% of the total annual rainfall where as SW monsoon contributed 51.9% over Chennai. The RH was >70% throughout the year (2013) and was a maximum in the NE monsoon (76%). The temperature (in 2013) was maximum in the pre-monsoon (30.9 °C) season, followed by 30.4 °C, 27.2 °C and 26.7 °C during SW monsoon, NE monsoon and winter seasons, respectively. It may be noted that the accuracies of surface measurements of RH and Temperature as given by India Meteorological Department (IMD) are 2% and 0.1 K respectively.

### 2.2. SBDART model

SBDART (Santa Barbara Discrete ordinate Atmospheric Radiative Transfer; Ricchiazzi et al., 1998) model has been used to estimate the short wave direct Aerosol Radiative Forcing (ARF) at the Top of the Atmosphere, Surface and Atmosphere. The SBDART model, developed by University of California, is a Radiative Transfer code based on Discrete Ordinate method for a plane parallel and vertically inhomogeneous atmosphere for addressing a wide range of radiative transfer problems in remote sensing and atmospheric energy budget studies. For estimating the ARF, we used the wavelength range 0.25 μm–4 μm (in 38 bands). The SBDART includes molecular absorption due to $CO_2$, $O_2$, water vapor and $O_3$. The model requires various aerosol parameters such as AOD, Single Scattering Albedo (SSA), Asymmetry parameter (g) and atmospheric profiles (pressure, temperature, water vapor and ozone) as inputs. Some of the required aerosol parameters are being measured at the present study location and the other required aerosol parameters are obtained from available models.

### 2.3. Measured aerosol parameters

Measurements of Aerosol Optical Depth (AOD), BC concentration and Total Particulate Matter with sizes <10 μm (PM10) are being carried out at the study location. The AOD is being measured using a Sunphotometer (Microtops II, Solar Light Company, USA) since March, 2011. The Sunphotometer (e.g. Metwally and Alfaro, 2013) measures the intensity of direct solar irradiance at five narrow band spectral channels centered at 0.38 μm, 0.44 μm, 0.50 μm, 0.675 μm and 0.87 μm with a full width half – maximum bandwidth of about 2.0 ± 0.04 to 10 ± 1.5 nm and a field view of ~2.5°. A Global Positioning System (GPS) attached to the Sunphotometer provides the location coordinates, time, height and pressure. After aligning the instrument with the sun, five observations were recorded for a duration of ~10 s centered at each half an hour from 0900 to 1600 h IST (IST = UT + 0530 h) on clear sky days and the minimum of these was taken for obtaining the AOD. The overall error in AOD measurement from the Sunphotometer is reported as ±0.03 (Shaw, 1976; Box and Deepak, 1979; Russell et al., 1993; Morys et al., 2001; Ichoku et al., 2002 and Aruna et al., 2014).

The BC concentration (surface) measurements are being carried out since March 2011 using Aethalometer (AE-31). In the Aethalometer, ambient air is aspirated at a standard mass flow rate