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Aerosol characteristics in north-east India using ARFINET spectral optical depth measurements

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HIGHLIGHTS

- Aerosol characteristics in the North-East India exhibits a west to east gradient.
- Aerosol loading in the North-East India ranks second highest in Asia next to IGP.
- Surface forcing and consequent atmospheric heating exceeds many locations of India.
- Elevated aerosol layers are caused by upper air transportation.

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ABSTRACT

Four years (2010–2014) of spectral aerosol optical depth (AOD) data from 4 Indian Space Research Organisation's ARFINET (Aerosol Radiative Forcing over India) stations (Shillong, Agartala, Imphal and Dibrugarh) in the North-Eastern Region (NER) of India (lying between 22–30°N and 89–98°E) are synthesized to evolve a regional aerosol representation, for the first time. Results show that the columnar AOD (an indicator of the column abundance of aerosols) is highest at Agartala (0.80 ± 0.24) in the west and lowest at Imphal (0.59 ± 0.23) in the east in the pre-monsoon season due to intense anthropogenic biomass burning in this region aided by long-range transport from the high aerosol laden regions of the Indo-Gangetic Plains (IGP), polluted Bangladesh and Bay of Bengal. In addition to local biogenic aerosols and pollutants emitted from brick kilns, oil/gas fields, household bio-fuel/fossil-fuel, vehicles, industries. Aerosol distribution and climatic impacts show a west to east gradient within the NER. For example, the climatological mean AODs are 0.67 ± 0.26, 0.52 ± 0.14, 0.40 ± 0.17 and 0.41 ± 0.23 respectively in Agartala, Shillong, Imphal and Dibrugarh which are geographically located from west to east within the NER. The average aerosol burden in NER ranks second highest with climatological mean AOD 0.49 ± 0.2 next to the Indo-Gangetic Plains where the climatological mean AOD is 0.64 ± 0.2 followed by the South and South-East Asia region. Elevated aerosol layers are observed over the eastern most stations Dibrugarh and Imphal, while at the western stations the concentrations are high near the surface. The climate implications of aerosols are evaluated in terms of aerosol radiative forcing (ARF) and consequent heating of the atmosphere in the region which follows AOD and exhibit high values in pre-monsoon season at all the locations except in Agartala. The highest ARF in the atmosphere occurs in the pre-monsoon season ranging from 48.6 Wm^{-2} in Agartala to 25.1 Wm^{-2} in Imphal. Winter radiative forcing follows that in pre-monsoon season at these locations. The heating rate is high at 1.2 K day^{-1} and 1.0 K day^{-1} over Shillong and Dibrugarh respectively in this season. However, Agartala experiences higher surface forcing (−56.5 Wm^{-2}) and consequent larger heating of the atmosphere of 1.6 K day^{-1} in winter.
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1. Introduction

The rapid socio-economic development in the recent past has increased the anthropogenic emissions in the South Asian region along with several other parts of the world. The South Asian and East Asian regions, comprising of the Indian mainland, Bangladesh, Myanmar and the vast Chinese mainland are among the potential sources of a variety of aerosol species; both natural and anthropogenic, and extensive investigations are being made in the past years (e.g., Chin et al., 2000; Girolamo et al., 2004; Moorthy et al., 2013). These densely populated regions are also vulnerable to the impacts of atmospheric aerosols and traces gases, through climate change, regional air quality degradation and human health (e.g., Liu et al., 2009). To better understand and investigate atmospheric aerosols and their impact on climate in this region apart from ground based networks such as Aerosol Robotic Network (AERONET) (Holben et al., 1998), Sky Radiometer (SKYNET) (Nakajima et al., 2003), Aerosols Radiative Forcing over India NETwork (ARFINET) (Moorthy et al., 2013; Babu et al., 2013) etc., several research campaigns like the Indian Ocean Experiment (INDOEX), Aerosol Characterization Experiment-Asia (ACE-Asia), Pacific Exploratory Mission (PEM) A (1991) and B (1994), Transport and Chemical Evolution over the Pacific (TRACE-P), Atmospheric Particulate Environment Change Studies (APEX) and Atmospheric Environmental Impacts of Aerosols in East Asia (AIE), Pacific Exploration of Asian Continental Emission (PEACE), East Asian Regional Experiment (EAREX) 2005, ABC Maldives Monsoon Experiment (APMEX), Integrated Campaign for Aerosols, gases and Radiation Budget in Pre-monsoon (ICARB) and Winter seasons (W_ICARB), Regional Aerosol Warming Experiment (RAWEX) etc. have been conducted particularly in the Indo-Asia-Pacific region (Nakajima et al., 2007 and references therein; Takami et al., 2007 and references therein; Moorthy et al., 2008, 2010; Babu et al., 2011). Few major findings of these studies are: Asia with AOD ~0.36 is ranking second highest in aerosol burden in the world next to Africa as revealed by AERONET measurements (Li et al., 2007 and references therein), statistically significant increasing trend of aerosol optical depth in Indian subcontinent (~2.3% yr^{-1}) with considerable contribution from anthropogenic fraction and increasing atmospheric warming by aerosol absorption in the elevated aerosol layers over the Indian landmass as revealed by ARFINET measurements, contribution of anthropogenic aerosols on surface diming and atmospheric heating as well as on cloud formation as revealed by INDOEX. Moreover, the optical properties of Asian mineral dust-enriched aerosols look much different from that of other arid regions such as that of Saharan dust plumes, Asian aerosols are mixture of anthropogenic air pollutants and mineral dust in the spring season, contribution of aerosols to the suppression of precipitation and the slowdown of hydrological cycles by dust storms, to air pollution and to fire smoke plumes, larger reduction of the solar radiation budget at the surface than at the top of the atmosphere due to absorbing aerosols and strong radiative heating in the atmosphere due to the mixing state of black carbon etc are some other findings (Li et al., 2004 and references therein).

The Himalayan foothill regions have a special importance in this context. In the regional characterization of aerosols over south Asia, a study from the eastern Himalayan foothill region covering the North-Eastern part of India (NER) assumes significance owing to differences in aerosol sources, varying from the background continental aerosols to secondary biogenic aerosols emitted by the huge forest cover (66%) to anthropogenic biomass burning, industrial (oil wells, gas fields, coal mines, brick klins etc.) and vehicular emissions. In addition to its geographical position, being surrounded by East Asia, South-East Asia, China and the mainland of India, the characteristic dense vegetation, vast water bodies, heavy rainfall pattern and the unique topography and exposure to densely populated Indo-Gangetic plains towards the west (which makes the region prone to heavy external influence) results in a complex aerosol environment in NER. The blocking by mountains all around and convergence effects over the foothills of the Himalayas over NER produces favourable conditions for the accumulation of both remote and local aerosols establishing a sharp regional gradient. This region is conducive for troposphere–stratosphere exchange of atmospheric constituents including aerosols and gases. Li et al. (2005) from chemical transport model analysis have demonstrated how the boundary layer pollutants from NER and South-West China could be transported and orographically lifted to the upper troposphere over South Asia and are trapped by the Tibetan Plateau anticyclone. According to Bonasoni et al. (2010) the southern side of the high Himalayan valleys represent a “direct channel” able to transport pollutants up to 5 km above sea-level, where the pristine atmospheric composition can be strongly influenced, especially during the pre-monsoon season. This is consistent with the observation of enhanced aerosol optical depth (AOD) and black carbon concentration in pre-monsoon season over the pristine elevated Himalayan regions (Babu et al., 2011; Dumka et al., 2011; Gogoi et al., 2014). The enhanced deposition of absorbing aerosols over the snow and glaciers result in regional radiative forcing through direct and snow albedo forcing over the Himalayan regions (e.g., Krinner et al., 2006) adding to the vulnerability. This region is also found to support new particle formation from pre-cursors (Moorthy et al., 2011; Kompalli et al., 2014).

Several studies, based on long term database as well as campaigns, have been performed over western part of Himalayan foothills including the IGP in the recent years; however, extensive studies on aerosols in the eastern part of IGP and the eastern Himalayan foothills (i.e., NER) are virtually non-existent, except few isolated works form Dibrugarh and Darjeeling (Pathak et al., 2010, 2012; Adak et al., 2014) and short campaigns (Pathak et al., 2014; Rahul et al., 2014). These studies have recognized the pre-monsoon (March–May), as the season heavily loaded by column aerosols in Dibrugarh which results in the highest seasonal aerosol radiative forcing and consequent heating of the atmosphere. On the other hand, aerosol loading within the atmospheric boundary layer maximizes in winter, indicating heterogeneity between surface and column aerosol loading over the location and thereby demonstrating the existence of elevated aerosol layer. These studies have also established the influence of transported aerosols originating from different regions of India and west Asia and traversing Indo Gangetic Plains (IGP) and finding the way through the western corridor towards the Brahmaputra valley. Babu et al. (2013) has accounted a strong increasing trend of aerosols over Dibrugarh during last decade. The land campaigns revealed the spatial heterogeneity of particulate matter and Black Carbon (BC) aerosols across the Brahmaputra Valley of North-East India (Pathak et al., 2014) and also the presence of elevated BC layer in monsoon season (Rahul et al., 2014). As per few observations (e.g., Cao et al., 2010) Tibetan plateau and south China are affected by pollutants transported from the NER. However, systematic reports on extensive investigation on aerosol abundance and characteristics are still absent from locations other than Dibrugarh (Pathak et al., 2014 and references therein) and from Agartala (Guha et al., 2015).

In this paper we present the spatial and temporal distinction of optical and physical parameters (AOD, extinction coefficient, Ångström Exponent or size distribution) during 2010–September 2014 for the four ARFINET stations in NER: Dibrugarh (DBR), Imphal (IPH), Shillong (SHN), and Agartala (AGA) (Fig. 1). This is expected to derive a regional picture of aerosols and their impact on climate and environment in the NER for the first time in Asian aerosol domain. As such, the regional features are compared with those reported from other locations/regions in South, South-East

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