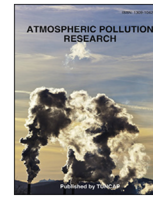
Atmospheric Pollution Research 7 (2016) 521–532

HOSTED BY ELSEVIER

Contents lists available at ScienceDirect

Atmospheric Pollution Research

journal homepage: http://www.journals.elsevier.com/locate/apr



Original article

Spatial variability in ambient atmospheric fine and coarse mode aerosols over Indo-Gangetic plains, India and adjoining oceans during the onset of summer monsoons, 2014

Avirup Sen [a], Yadiki Nazeer Ahammed [b], Tirthankar Banerjee [c], Abhijit Chatterjee [d], Anil Kumar Choudhuri [e], Trupti Das [f], Narayan Chandara Deb [g], Amit Dhir [h], Sangita Goel [i], Altaf Hussain Khan [j], Tuhin Kumar Mandal [a, *], Vishnu Murari [c], Shrimanta Pal [g], Padma Shrinivas Rao [i], Mohit Saxena [a], Sudhir Kumar Sharma [a], Ashima Sharma [a], Chaturvedula Viswanatha Vachaspati [b]

[a] *CSIR–National Physical Laboratory, Dr. K.S. Krishnan Road, New Delhi 110012, India*
[b] *Department of Physics, Yogi Vemana University, Kadapa 516216, Andhra Pradesh, India*
[c] *Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi 221005, Uttar Pradesh, India*
[d] *Centre for Astroparticle Physics and Space Science, Bose Institute, Kolkata 700091, West Bengal, India*
[e] *Indian Statistical Institute, Giridih 815301, Jharkhand, India*
[f] *CSIR–Institute of Minerals and Materials Technology, Bhubaneswar 751013, Odisha, India*
[g] *Indian Statistical Institute, B.T. Road, Kolkata 700108, West Bengal, India*
[h] *School of Energy and Environment, Thapar University, Patiala 147004, Punjab, India*
[i] *CSIR–National Environmental Engineering Research Institute, Nehru Marg, Nagpur 440020, India*
[j] *CSIR–Indian Institute of Toxicology Research, Lucknow 226001, Uttar Pradesh, India*

A R T I C L E I N F O

Article history:
Received 12 August 2015
Accepted 3 January 2016
Available online 27 January 2016

Keywords:
$PM_{2.5}$
PM_{10}
Cluster analysis
PSCF
CWT

A B S T R A C T

Enhanced transport of dust with the prevailing mid to upper tropospheric westerly winds from arid regions in South-west Asia and North-west India into the Indo-Gangetic Plain (IGP) and the influx of marine aerosol from the Arabian Sea (AS), Tropical Indian Ocean (TIO) and Southern Bay of Bengal (SBoB) into India along with the low level south-west wind flow during the onset of the South-west (SW) monsoon, 2014 was observed in campaign mode. Ambient airborne particulates ($PM_{2.5}$ and PM_{10}) were collected at 9 sites in and around IGP, India, viz. Patiala, Delhi, Lucknow, Varanasi, Giridih, Kolkata, Darjeeling, Bhubaneswar and Nagpur; over AS, TIO and SBoB providing a glimpse into the aerosol loading and its transport mechanisms. The highest average $PM_{2.5}$ (61.8 ± 18.6 μg m^{-3}) and PM_{10} (182.2 ± 58.0 μg m^{-3}) mass concentrations were recorded at Delhi (upper IGP) and Lucknow (middle IGP) respectively. Average $PM_{2.5}$ (18.1 ± 10.1 μg m^{-3}) and PM_{10} (39.6 ± 15.8 μg m^{-3}) levels recorded over the open oceanic regions in AS, TIO and SBoB were much lower than those observed over the land stations and the average $PM_{2.5}$ recorded over coastal AS and SBoB (49.1 ± 28.7 μg m^{-3}).

Cluster analysis, Potential Source Contribution Function (PSCF) and Concentration Weighted Trajectory (CWT) analysis portray that $PM_{2.5}$ and PM_{10} levels at the land stations were influenced by weak to moderate contributions from AS, BoB, the arid South-west Asia and North-west India, peninsular India and from the polluted IGP region.

1. Introduction

India along with its adjoining oceans, i.e. Bay of Bengal (BoB), Arabian Sea (AS) and tropical Indian Ocean (TIO), have a unique weather pattern, wherein they are subjected to the seasonal reversal of winds associated with the Indian monsoon system and their accompanying distinct air

* Corresponding author. Radio and Atmospheric Sciences Division, CSIR–National Physical Laboratory, Dr. K S Krishnan Road, New Delhi 110012, India.
E-mail address: tuhin@nplindia.org (T.K. Mandal).

Peer review under responsibility of Turkish National Committee for Air Pollution Research and Control.

http://dx.doi.org/10.1016/j.apr.2016.01.001

masses (continental and marine). The North-east or winter monsoon occurs during the boreal winter and is associated with weak low level north-easterly winds blowing from the Asian land mass towards BoB and Northern Indian Ocean (NIO), leading to the long range outflow of continental pollutants onto both coastal and open oceanic marine regions (Nair et al., 2007; Li and Ramanathan, 2002; Ramanathan et al., 2001a). The South-west or summer monsoon occurs during the boreal summer months and is associated with the advection of strong moisture laden marine air masses from the southern hemisphere, crossing the equator and blowing from a south-westerly direction towards the subcontinent. The summer monsoon provides maximum rainfall over the Indian mainland, accounting for up to 80% of the annual mean precipitation over most regions of India, making it the most important source of water for drinking, irrigation and power generation purposes (Bollasina et al., 2011).

There have been numerous observational campaigns conducted over various locations in India and adjoining oceans, either during the winter monsoon or during pre-monsoon seasons in the last two decades, focusing on the sources, transport pathways and physico-chemical, and optical properties of atmospheric particulates. A few notable examples are: INDOEX (Ramanathan et al., 2001a); Land Campaign-I over peninsular India in February, 2004 (LC-I: Moorthy et al., 2005), Land Campaign-II over IGP in December, 2004 (LC-II: Ramachandran et al., 2006; Tare et al., 2006; Nair et al., 2007), Integrated Campaign of Atmospheric Aerosols, gases, and Radiation Budget during March–May, 2006 (ICARB: Nair et al., 2008; Babu et al., 2008; Reddy et al., 2008; Moorthy et al., 2008), Winter ICARB during December, 2008–January, 2009 (W_ICARB: Moorthy et al., 2010; Kharol et al., 2011; Sharma et al., 2012a,b; Saxena et al., 2014a,b). However, with the exception of the Arabian Sea Monsoon Experiment (ARMEX: Vinoj and Satheesh, 2003) and some others, e.g. Madhavan et al. (2008); there is a noted scarcity of studies focusing on the aerosol properties over India and adjoining oceans during the summer monsoon, due to the unfavorable overcast sky conditions as well as the difficulty in conducting oceanic observations due to rough, choppy seas during that season. Recently, a field campaign was conducted during the 2013–14 winter monsoon by our group; involving the simultaneous collection of ambient aerosols ($PM_{2.5}$ and PM_{10}) from multiple locations across India and the BoB, with the objective of investigating the sources leading to the outflow of continental aerosols into the BoB (Sen et al., 2014). Several model studies have shown that dust transport from Sahara desert as well as Thar desert can alter distribution of particulate matter over Indo Gangetic Plain (IGP). Study of chemical characteristics of particulate matter could give an idea how transported particulate matter recombines with anthropogenic sources of IGP.

This current study involves sampling of ambient $PM_{2.5}$ and PM_{10} aerosols across multiple locations in India, the BoB, AS and TIO; carried out with the objective of picturing the transport of mineral dust with the westerly flow from the arid South-west Asian region into the IGP and the influx of marine aerosols from the AS and TIO into India along with the low level south-westerly wind flow prior to and during the onset of the summer monsoon as well as studying their interaction with the prevalent background continental aerosols over the land stations.

2. Data and methodology

2.1. Sampling locations

2.1.1. Land sites

The IGP is a vast expanse of fertile plain encompassing most of northern and eastern India, bound by the Himalayas to the north, Vidhyan Satpura ranges as well as the Chota Nagpur Plateau to the south, BoB to the east and the AS and Thar Desert to the west. It supports about ~40% of the Indian population (Nair et al., 2007), making it one of the most densely populated and heavily polluted regions in the world (Dey and Di Girolamo, 2010; Srivastava et al., 2011), subject to rapid industrialization, urbanization and a rampant increase in vehicular traffic and biomass burning to meet the needs of the growing population and resulting in a massive anthropogenic aerosol loading over it (Ram and Sarin, 2010; Rengarajan et al., 2007; Sharma et al., 2015a). The sampling sites situated in the IGP, viz. Patiala (30°21′ N, 76°22′ E), Delhi (28°38′ N, 77°10′ E), Lucknow (26°52′ N, 80°56′ E), Varanasi (25°15′ N, 82°59′ E) and Kolkata (22°34′ N, 88°21′E) are ideal for analyzing the alteration in the ambient aerosol composition due to indiscriminate biomass and fossil fuel combustion (Sharma et al., 2015a). These are located in the hearts of megacities having a high population density and are subjected to pollution from heavy roadside traffic as well as many small to large scale industries surrounding them. Bhubaneswar (20°17′ N, 85°49′ E) and Kolkata are coastal stations bordering the BoB, along the east coast of India. Giridih (24°10′ N, 86°17′ E) is located on the Chota Nagpur plateau and coal mining is one of its major industries. Nagpur (21°08′N, 79°05′E) is located in the Deccan plateau and serves as a representative station for central India. Ambient atmospheric conditions at these locations are also observed to vary greatly; from semi polluted Himalayan air at Darjeeling (27°01′ N, 88°15′ E), to highly polluted conditions prevailing in large metropolitan cities like Kolkata, Delhi, Varanasi and Lucknow. The co-ordinates of the sampling sites and duration of sampling carried out at each of the sites are summarized in Table 1.

2.1.2. Cruise details

Two scientific cruises were conducted during campaign, with the objective of covering both remote and coastal marine regions. ORV Sagar Kanya (SK-313) set sail from Mormugao Port, Goa on 3rd June, 2014; proceeded in coastal waters close to the west coast of India, sailed around Sri Lanka and carried out a few transects in Southern BoB (SBOB) near the Indian coastline, before finally arriving at Chennai Port, Chennai on 21st June 2014. ORV Sagar Nidhi (SN-85) set sail from Mormugao Port, Goa (15°24′ N, 73°48′ E) on 30th May, 2014 and proceeded to South West Tropical Indian Ocean (SWTIO) covering mostly remote marine regions in AS and SWTIO, the southernmost extent of the track being 8° S, 69° E (SWTIOTS), where the ship remained stationary for 10 days to facilitate time series observations, following which it proceeded to sail around Sri Lanka, cover a small extent of SBOB and finally call at Chennai Port, Chennai (13°4′ N, 80°17′ E) on 27th June, 2014.

Locations of the sampling sites along with the cruise tracks of SK-313 and SN-85, shown as solid lines over oceanic regions, have been plotted in Fig. 1.

2.2. Sample collection

Ambient particulates with aerodynamic diameters ≤2.5 μm ($PM_{2.5}$) and ≤10 μm (PM_{10}) respectively were collected simultaneously on pre-combusted and pre-weighed QM-A quartz fiber filters (Whatman, UK) using mass-flow controlled High Volume Samplers (HVS) installed on elevated surfaces free from obstacles. The QM-A filters used in the study were pre-combusted in a muffle furnace for 6 h at 550 °C and desiccated for a period of 48 h prior to sample collection to eradicate all traces of impurities and moisture. Simultaneously, $PM_{2.5}$ samples were collected from the marine atmospheric boundary layer (MABL) of coastal AS and SBoB utilizing a HVS installed onboard ORV Sagar Kanya (SK-313), while $PM_{2.5}$ and PM_{10} samples were collected from the MABL of AS, SWTIO and SBOB via two HVS installed onboard ORV Sagar Nidhi (SN-85). The samplers utilized onboard both vessels were installed on the upper