

# Atmospheric Fine and Coarse Mode Aerosols at Different Environments of India and the Bay of Bengal During Winter-2014: Implications of a Coordinated Campaign

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**Abstract:** In this paper, we present mass concentrations of particulate matter [PM<sub>2.5</sub>, PM<sub>10</sub> size fractions and total suspended particulates (TSP)] measured simultaneously over land stations (Kullu, Patiala, Delhi, Ajmer, Agra, Lucknow, Varanasi, Giridih, Kolkata, Darjeeling, Jorhat, Itanagar, Imphal, Bhubaneswar, and Kadapa), mostly distributed across the

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Indo-Gangetic plain (IGP) of India as well as in the marine atmosphere over Bay of Bengal (BoB) in the period from 20 January to 3 February, 2014. The main objective of this study was to quantify the continental outflow of particulates ( $PM_{2.5}$ ,  $PM_{10}$  and TSP) from IGP and associated regions into the BoB along with low level north-east wind flow during winter monsoon period. The present study provides a glimpse of the aerosol loading over the IGP region. During this campaign, the highest average  $PM_{2.5}$  ( $187.8 \pm 36.5 \mu\text{g m}^{-3}$ , range 125.6–256.2  $\mu\text{g m}^{-3}$ ),  $PM_{10}$  ( $272.6 \pm 102.9 \mu\text{g m}^{-3}$ , range 147.6–520.1  $\mu\text{g m}^{-3}$ ) and TSP ( $325.0 \pm 71.5 \mu\text{g m}^{-3}$ , range 220.4–536.6  $\mu\text{g m}^{-3}$ ) mass concentrations were recorded at Varanasi, Kolkata and Lucknow over middle and lower IGP regions. The  $PM_{2.5}$  (average  $41.3 \pm 11.9 \mu\text{g m}^{-3}$ ; range 15.0–54.4  $\mu\text{g m}^{-3}$ ),  $PM_{10}$  (average  $53.9 \pm 18.9 \mu\text{g m}^{-3}$ ; range 30.1–82.1  $\mu\text{g m}^{-3}$ ) and TSP (average  $78.8 \pm 29.7 \mu\text{g m}^{-3}$ ; range 49.1–184.5  $\mu\text{g m}^{-3}$ ) loading over BoB were found to be comparable to land stations and suggests possible continental outflow. Over the continental region, the highest  $PM_{2.5}/PM_{10}$  ratio was recorded at Delhi (0.87). The  $PM_{2.5}/PM_{10}$  ratio over BoB (0.77) was found to be quite high and comparable to Varanasi (0.80) and Agra (0.79).

**Keywords:**  $PM_{2.5}$ ;  $PM_{10}$ ; TSP and Bay of Bengal

## 1. Introduction

Atmospheric aerosols comprise only a minuscule fraction of the Earth's atmosphere and have short atmospheric residence times; however they are a highly important constituent, being capable of significantly altering the radiation budget of the atmosphere regionally, either directly by scattering or absorbing the incoming solar radiation or indirectly by cloud formation [1, 2]. Long term exposure to fine particulates could lead to acute health effects owing to the fact that they are able to penetrate into the lungs and are more likely to increase chances of cardiopulmonary and carcinogenic diseases [3]. Varotsos [4] carried out airborne measurements of the vertical distribution of aerosol number density and aerosol size (aerosol mean diameter), erythral ultraviolet irradiance (EUVI), ozone mixing ratio, relative humidity (RH) and temperature using research aircrafts and weather balloons, reporting aerosol mean diameter and ozone mixing ratio decrease with altitude thereby influencing a general increase in EUVI with altitude. Moreover, studies conducted in Greece have successfully documented the corrosive and soiling effects of aerosols on materials [5, 6].

Polluted air masses originating from the heavily populated south-Asian region could travel long distances maintaining their identity whilst being transported by the winds [7]. These air masses contain large concentrations of carbonaceous aerosols, emitted from bio-fuel and fossil fuel combustion [8]. Rapid urbanization, industrialization and a rampant increase in vehicular traffic across the megacities of India, particularly over the IGP region also contribute heavily to the ever increasing load of atmospheric particulates [9–12]. Pollutants from the IGP (being a source region) not only affect the local air quality but also undergo long range transport due to the high convective activity prevalent in the tropics [13]. The Bay of Bengal is landlocked from three sides and bordered by densely populated areas. It is considered to be one of the most suitable locations to study the influx of continental aerosols into the marine atmosphere

and their interaction with natural marine aerosols, due to their long range transport during winter on account of the near surface flow being primarily north easterly [14].

Numerous studies have been conducted in the Indian region as well as the BoB over the course of the last few years, with several authors reporting the chemical composition of the ambient  $PM_{2.5}$  and  $PM_{10}$  [15–22] and documenting the transport of natural (mineral dust) as well as anthropogenic aerosols from Indian subcontinent and south-Asian region [14, 21, 23–26]. However, these studies have been of an intermittent nature. This is probably the first time that ambient aerosols have been collected simultaneously at multiple locations across the Indian subcontinent and the BoB with the objective of examining the sources leading to the outflow of continental aerosols over the BoB during the winter monsoon period.

## 2. Experimental

### 2.1. Site Description

Sampling of ambient particulates falling in the  $PM_{2.5}$  and  $PM_{10}$  size fractions as well as TSP was carried out simultaneously at 15 locations across India. A majority of these stations are spread across the IGP-India. Three of the sampling sites, viz. Jorhat, Imphal and Itanagar are in North-East India. Kullu, Ajmer and Kadapa serve as representative stations for North, North-West and South India respectively. Ajmer is a semi-arid site which is cut off from the Thar Desert since it is surrounded by the Aravalli Mountains. Kadapa is located in the rain shadow region and is a tropical semi-arid continental site in Andhra Pradesh. Bhubaneswar and Kolkata were chosen with the objective of serving as coastal stations bordering the BoB. Giridih is positioned on a plateau slightly to the south of the IGP and coal mining is a major industrial activity there. The atmospheric conditions at these sites also vary greatly;

**Table 1** Description of sampling locations, period and instruments operated

| Sites   | Location      | State             | Coordinates  |               | Instruments operated |                      |                | Sampling Duration     |
|---------|---------------|-------------------|--------------|---------------|----------------------|----------------------|----------------|-----------------------|
|         |               |                   | Latitude (N) | Longitude (E) | PM <sub>2.5</sub>    | PM <sub>10</sub>     | TSP            |                       |
| Site 1  | Kullu         | Himachal Pradesh  | 31°37'       | 77°20'        | APM 550              | APM 460 NL           |                | 20 January–5 February |
| Site 2  | Patiala       | Punjab            | 30°21'       | 76°22'        | IPM-FDS-2.5 µm/10 µm |                      | IPM-115-BL-NL  | 20 January–5 February |
| Site 3  | New Delhi     | Delhi             | 28°38'       | 77°10'        | APM 550              | APM 460 NL           |                | 20 January–6 February |
| Site 4  | Ajmer         | Rajasthan         | 26°34'       | 74°51'        |                      | APM 460 NL           |                | 20 January–5 February |
| Site 5  | Agra          | Uttar Pradesh     | 27°13'       | 78°00'        | APM 550              | APM 460 NL           | APM 430        | 20 January–5 February |
| Site 6  | Lucknow       | Uttar Pradesh     | 26°52'       | 80°56'        | APM 550              | APM 460 NL           | APM 430        | 20 January–8 February |
| Site 7  | Varanasi      | Uttar Pradesh     | 25°15'       | 82°59'        | IPM-FDS-2.5 µm/10 µm | IPM-FDS-2.5 µm/10 µm |                | 20 January–5 February |
| Site 8  | Giridih       | Jharkhand         | 24°10'       | 86°17'        |                      | PEM-HVS-8NL          |                | 20 January–5 February |
| Site 9  | Kolkata       | West Bengal       | 22°34'       | 88°21'        | APM 550              | APM 460 NL           |                | 20 January–5 February |
| Site 10 | Darjeeling    | West Bengal       | 27°01'       | 88°15'        | APM 550              | APM 460 NL           |                | 20 January–4 February |
| Site 11 | Jorhat        | Assam             | 26°44'       | 94°09'        | APM 550              | APM 460 NL           | APM 430        | 20 January–4 February |
| Site 12 | Itanagar      | Arunachal Pradesh | 27°07'       | 93°44'        | APM 550              | APM 460 NL           | APM 430        | 20 January–4 February |
| Site 13 | Imphal        | Manipur           | 24°49'       | 93°55'        | APM 550              | APM 460 NL           | APM 430        | 20 January–4 February |
| Site 14 | Bhubaneswar   | Odisha            | 20°17'       | 85°49'        | PES-LFAS-10          | APM 460 NL           |                | 20 January–6 February |
| Site 15 | Kadapa,       | Andhra Pradesh    | 14°28'       | 78°55'        | Anderson Sampler     | Anderson Sampler     | F&J HV 1E      | 20 January–4 February |
| Site 16 | Bay of Bengal |                   |              |               | APM 550              | APM 550              | Tisch TE-2000P | 23 January–3 February |

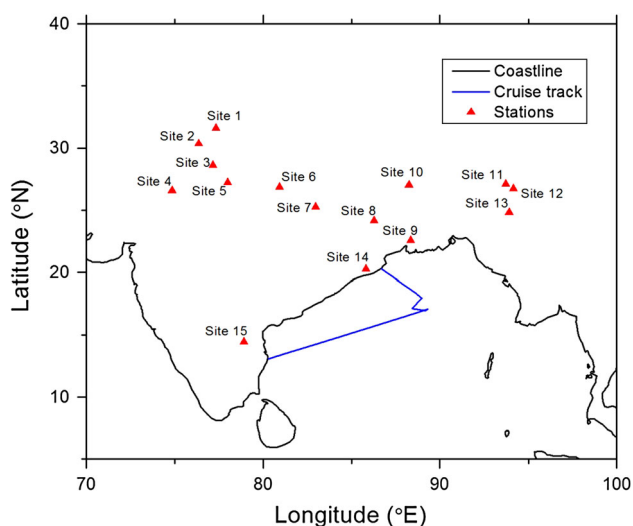
from pristine Himalayan air at Kullu and Darjeeling to highly polluted conditions prevailing in metropolitan cities like Kolkata and Delhi. The co-ordinates of the sampling sites are available in Table 1.

Ambient aerosol samples (PM<sub>2.5</sub>, PM<sub>10</sub> and TSP) were collected from the marine atmospheric boundary layer (MABL) of BoB during the cruise onboard ocean research vessel Sagar Kanya (SK-308). The cruise set sail from Paradip, Odisha (20.26°N, 86.67°E) on 23rd January (DOY-023), 2014 and culminated at Chennai (13.08°N, 80.29°E) on 3rd February, 2014 (DOY: 034) with the track (Fig. 1) covering 13–20°N latitudes and 83–89°E longitudes.

## 2.2. Sample Collection and Analysis

The APM 550, APM 460 NL and APM 430 samplers used during the campaign are manufactured by M/s. Envirotech

Instruments Pvt. Ltd., New Delhi. The APM 550 is utilized for sampling aerosols falling in the PM<sub>2.5</sub> and PM<sub>10</sub> size fractions (<http://www.envirotechindia.com>). The impactors are designed as per United States Environmental Protection Agency (USEPA) standards. Ambient air enters the sampler through an omni-directional air inlet. PM<sub>10</sub> aerosols in the air stream are separated by an impactor following which the PM<sub>2.5</sub> aerosols can be separated if a WINS impactor is used. Finally, the particulate fraction remaining in the air stream is deposited on to a 47 mm QM-A quartz micro fibre filter. A constant flow rate of 1 m<sup>3</sup> h<sup>-1</sup> (accuracy ±2 % of F.S) is maintained irrespective of voltage fluctuations. The APM 460 NL sampler uses a blower with an inbuilt thermal cut-off eliminating the requirement of a voltage stabilizer (<http://www.envirotechindia.com>). PM<sub>10</sub> aerosols are deposited onto 20 × 25 cm<sup>2</sup> QM-A filters. It has a flow rate ranging from 0.9 to 1.4 m<sup>3</sup> h<sup>-1</sup> (accuracy ±2 % of F.S). The



**Fig. 1** Site-map and cruise track

APM 430 is a High Volume Sampler (HVS) utilized for collecting the TSP in the ambient air. The IPM-FDS-2.5  $\mu\text{m}/10 \mu\text{m}$  and IPM-115-BL-NL samplers are produced by Instrumex (<http://www.instrumex.net>) and designed as per USEPA guidelines. IPM-FDS-2.5  $\mu\text{m}/10 \mu\text{m}$  is an ambient fine dust sampler whose mode of operation is similar to that of the APM 550 utilizing the same mechanisms for  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  aerosol separation. The flow rate meter has a resolution of 0.01 LPM under actual operating conditions and the flow control maintains a flow of  $1 \text{ m}^3 \text{ h}^{-1}$ . The IPM-115-BL-NL is a Respirable Dust Sampler and used for the measurement of TSP in the ambient atmosphere. Particles with aerodynamic diameter below 10 microns ( $D_p < 10 \mu\text{m}$ ) are collected onto the filter paper whereas the larger particles with  $10 \mu\text{m} < D_p < 100 \mu\text{m}$  are separated by a cyclone separator and collected in a separate bottle. It is a HVS, drawing in air at a flow rate of  $\sim 1.4 \text{ m}^3 \text{ h}^{-1}$ . PEM-HVS-8NL is a HVS manufactured by M/s. Polltech Instruments Pvt. Ltd. (<http://polltechinstruments.tradeindia.com>), drawing in ambient air at a constant sampling rate of  $1.13 \text{ m}^3 \text{ h}^{-1}$  (flow range:  $0.6\text{--}1.8 \text{ m}^3 \text{ h}^{-1}$ ). The particulates in the air stream are accelerated through numerous circular impactor nozzles and those with  $D_p > 10 \mu\text{m}$  impact on a greased collection plate while the aerosols with  $D_p < 10 \mu\text{m}$  are deposited onto  $20 \times 24 \text{ cm}^2$  QMA filter. The TE 2000P is a HVS manufactured by Tisch Environmental, Inc. used for estimating the TSP concentration in the ambient air (<http://tisch-env.com>). The airborne TSP is trapped onto a 110 mm diameter QM-A filter paper. The HV 1E is a HVS manufactured by F&J Specialty Products, Inc. featuring a single rotameter (<http://www.fjspecialty.com>) and working similar to the TE 2000P. The Andersen sampler has nine aluminum stages ( $D_p < 0.43 \mu\text{m}$ ,  $0.43 \mu\text{m} < D_p < 0.65 \mu\text{m}$ ,  $0.65 \mu\text{m} < D_p < 1.1 \mu\text{m}$ ,  $1.1 \mu\text{m} < D_p < 2.1 \mu\text{m}$ ,  $2.1 \mu\text{m} < D_p < 3.3 \mu\text{m}$ ,  $3.3 \mu\text{m} < D_p < 4.7 \mu\text{m}$ ,  $4.7 \mu\text{m} < D_p < 5.8 \mu\text{m}$ ,

$5.8 \mu\text{m} < D_p < 9 \mu\text{m}$ ,  $9 \mu\text{m} < D_p < 10 \mu\text{m}$ ) to measure the size distribution and concentration of aerosols in ambient air (<http://www.newstareenvironmental.com>). It is operated at a flow rate of 28 LPM.

$\text{PM}_{2.5}$  and  $\text{PM}_{10}$  Low Volume Samplers (LVS) were operated for a period of 24 h each along with a High Volume Sampler (HVS) having a run time of 24 h to collect the ambient particulate matter at the respective sampling sites. Samples were collected on prebaked Pallflex QM-A micro fibre filters. The QM-A filters were prebaked in a muffle furnace for 6 h at  $550 \text{ }^\circ\text{C}$  to remove any traces of impurities and were desiccated for a period of 48 h prior to sample collection. The instruments onboard oceanic research vessel (ORV) Sagar Kanya was installed on the upper deck at a height of 15 m from sea surface. While sampling, care was taken to avoid any contamination from the ship's exhaust. To understand and remove the contamination of the chimney, free-fall particulates were simultaneously collected on a separate filter paper along with the present observations. Description of sampling locations, period of sampling and details of the make and model of the instruments operated at each of the sites are available in Table 1.

The QMA filters were also desiccated for a period of 48 h prior to measurement of their final weights. PM mass was calculated by gravimetric analysis based on the difference between the final and initial weights of the QM-A filters measured using a microbalance (Make: M/s Sartorius, resolution  $\pm 1 \mu\text{g}$ ) and its concentration was determined by dividing it by the volume of air sampled for the duration of the experiment.

### 2.3. Meteorological Conditions

The meteorological conditions existing at each of the stations during the period of sampling has been depicted in Table 2. The data has been assimilated from the automatic weather stations (AWS) operating at the sampling sites and has been supplemented by data acquired from India Meteorological Department. Kadapa recorded the highest average ambient temperature ( $23.1 \pm 2.4 \text{ }^\circ\text{C}$ ) among the land stations while Delhi had the highest RH ( $82.2 \pm 9.5 \%$ ). Sporadic rainfall was received at Patiala, Delhi, Ajmer and Lucknow while the other stations didn't receive any. The highest average wind speed was recorded at Lucknow ( $7.4 \pm 1.9 \text{ km h}^{-1}$ ). Winds speeds encountered in the BoB were ranging between 0.6 and  $21.0 \text{ km h}^{-1}$  (mean  $10.0 \pm 5.0 \text{ km h}^{-1}$ ) and the average wind direction was  $76.0 \pm 83.8^\circ$ . True wind is defined as a vector wind with a speed referenced to the fixed earth and a direction referenced to the true north. The corrected true wind speeds and directions have been computed taking into account the ship speed and direction according to the

approach described in detail by Smith et al. [27]. A typical root mean square (RMS) error for a wind speed observation is averaging around  $2.5 \text{ m s}^{-1}$  ( $9 \text{ km h}^{-1}$ ) if the anemometer observation is not corrected for the height of the instrument above the sea surface, with the RMS wind speed errors smaller than average in the tropics [28]. A major cause of the error lies in the calculation of true wind speed and direction, with only 50 % of the reported wind speeds lying within  $1 \text{ m s}^{-1}$  ( $3.6 \text{ km h}^{-1}$ ) of the correct value and about 30 % of them being more than  $2.5 \text{ m s}^{-1}$  ( $9 \text{ km h}^{-1}$ ) inaccurate, while about 70 % of the winds were reported to blow within  $\pm 10^\circ$  of the correct direction and 13 % of them blowing from outside  $\pm 50^\circ$  [28]. The average temperature, pressure and RH were recorded as  $24.4 \pm 2.0 \text{ }^\circ\text{C}$ ,  $1,013.4 \pm 1.7 \text{ mb}$  and  $69.5 \pm 8.4 \%$  respectively over BoB. Clear sky conditions prevailed and there was absence of any rainfall during the duration of this cruise.

#### 2.4. Air Mass Back-Trajectory Analysis

Five day air mass back trajectories were computed using the NOAA (National Oceanic and Atmospheric Administration) Air Resource Laboratory (ARL) Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPPLIT) model with the Global Data Assimilation System data (<http://www.arl.noaa.gov>) as an input. The 5 day back trajectories are calculated every day at 12:30 h (IST) at 500 m above the ground level (AGL) for the sampling duration and have been represented in Fig. 2. They have been plotted in order to picture the origin of the air masses and their transport pathways to the sampling sites. All the air mass trajectories for the sites located within the IGP are seen to originate as well as undergo transportation within the IGP, thereby signifying the dominance of anthropogenic emission transport to the sampling sites. Lucknow is noted to have just one trajectory during the entire study period originating in the Arabian Peninsula and traversing Northern Arabian Sea, while Darjeeling is seen to receive air masses originating over a large area with three of the trajectories crossing the Arabian Sea. Kadapa is a noted exception among the land stations since all the air masses received by the site had to traverse across northern BoB. In fact, nearly all the air masses reaching at most of the land stations excluding Kadapa and Darjeeling, were seen to originate and traverse across continental land masses. Though Kolkata is a coastal station bordering the BoB, all the air mass trajectories culminating at the two sites originated and underwent transport across the IGP. Air masses originating in North-East India itself were seen to be transported to Jorhat and Itanagar. However Imphal is noted to receive a couple of trajectories depicting long range transport from the western coast of India. Most of the air masses sampled along the cruise had originated in the

IGP and could thus lead to the influx of continental aerosols into the marine atmosphere.

### 3. Results and Discussion

The mean and ranges of mass concentrations of ambient  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$  and TSP observed at the sampling stations and in BoB for the duration of the study period as well as the  $\text{PM}_{2.5}/\text{PM}_{10}$  and  $\text{PM}_{2.5}/\text{TSP}$  ratios were computed to determine the sites where the fine particulate loading in the ambient atmosphere overwhelms the coarser fractions and is outlined in Table 3.

In the present study, Varanasi ( $187.8 \pm 36.5 \mu\text{g m}^{-3}$ ) was observed to have the highest concentration of fine mode  $\text{PM}_{2.5}$  aerosols followed by two other major metropolitan cities, New Delhi ( $178.2 \pm 56.5 \mu\text{g m}^{-3}$ ) and Kolkata ( $168.7 \pm 77.9 \mu\text{g m}^{-3}$ ). Patiala averaged a slightly lower  $\text{PM}_{2.5}$  concentration ( $138.7 \pm 27.0 \mu\text{g m}^{-3}$ ) while Agra and Lucknow had almost similar concentrations of  $120.6 \pm 36.2 \mu\text{g m}^{-3}$  and  $120.4 \pm 47.8 \mu\text{g m}^{-3}$  respectively. Kullu ( $20.4 \pm 3.1 \mu\text{g m}^{-3}$ ), Kadapa ( $\text{PM}_{2.1} = 34.1 \pm 4.6 \mu\text{g m}^{-3}$ ), Darjeeling ( $43.3 \pm 19.7 \mu\text{g m}^{-3}$ ), Bhubaneswar ( $65.2 \pm 11.8 \mu\text{g m}^{-3}$ ) as well as all the sampling locations in North-East India, viz. Jorhat ( $43.6 \pm 12.3 \mu\text{g m}^{-3}$ ), Itanagar ( $77.4 \pm 27.1 \mu\text{g m}^{-3}$ ) and Imphal ( $87.4 \pm 31.9 \mu\text{g m}^{-3}$ ) had fine particulate mass concentrations lower than  $100 \mu\text{g m}^{-3}$ . The daily average  $\text{PM}_{2.5}$  at all the stations, except Kullu, Darjeeling, Jorhat and Kadapa, exceed the value set by the National Ambient Air Quality Annual Standard of India ( $40 \mu\text{g m}^{-3}$ ). The  $\text{PM}_{2.5}$  mass concentration observed in the BoB was ranging from  $15.0$  to  $54.4 \mu\text{g m}^{-3}$  with a mean concentration of  $41.3 \pm 11.9 \mu\text{g m}^{-3}$ .

If we compare our observation with sporadically measurement over different sites, one could find that the average  $\text{PM}_{2.5}$  mass concentration prevailing over Himachal Pradesh was observed to be  $41.78 \pm 7.92 \mu\text{g m}^{-3}$  while that over Kullu was estimated to be  $34.32 \pm 1.32 \mu\text{g m}^{-3}$  by Sharma et al. [12] during a campaign conducted in the period from 12 to 22 March, 2013. Delhi was reported to have an annual mean  $\text{PM}_{2.5}$  concentration of  $97 \pm 56 \mu\text{g m}^{-3}$  in 2007 [16]. In another study,  $\text{PM}_{2.5}$  mass concentration during winter over Delhi was observed to be  $151.2 \pm 26.1 \mu\text{g m}^{-3}$  [29]. Barman et al. [30] carried out a study to discern the mass concentrations of fine particulates in two residential areas of Lucknow in November, 2008 and reported the 24 h average  $\text{PM}_{2.5}$  to be  $131.74 \mu\text{g m}^{-3}$  and  $115.83 \mu\text{g m}^{-3}$  respectively. The fine particulate concentration in Lucknow was estimated to be  $101.05 \pm 22.55 \mu\text{g m}^{-3}$  (range  $75.87$ – $129.85 \mu\text{g m}^{-3}$ ) while the winter season average was  $212.35 \pm 55.0 \mu\text{g m}^{-3}$  ( $99.3$ – $299.3 \mu\text{g m}^{-3}$ ) [17]. In

**Table 2** Meteorological conditions at the sampling sites during the period of study

| Sites   | Temperature (°C) |            | Pressure (mb)   |                | RH (%)     |             | Rainfall (mm) |             | Wind Speed (km h <sup>-1</sup> ) |             | Wind Direction (°N) |              |
|---------|------------------|------------|-----------------|----------------|------------|-------------|---------------|-------------|----------------------------------|-------------|---------------------|--------------|
|         | Range            | Mean ± SD  | Range           | Mean ± SD      | Range      | Mean ± SD   | Range         | Mean ± SD   | Range                            | Mean ± SD   | Range               | Mean ± SD    |
| Site 2  | 12.7–21.3        | 16.9 ± 2.7 | 978.7–988.8     | 985.4 ± 3.4    | 40.4–89.0  | 62.2 ± 14.2 | 0.0–0.4       | 0.0 ± 0.1   | 0.0–8.0                          | 2.6 ± 2.7   | 0.0–360.0           | 229.7 ± 96.4 |
| Site 3  | 11.3–18.3        | 14.5 ± 1.8 | na              | na             | 67.5–97.0  | 82.2 ± 9.5  | 0.0–10.0      | 0.7 ± 2.4   | 2.0–7.0                          | 4.0 ± 1.6   | na                  | na           |
| Site 4  | 12.0–21.0        | 16.5 ± 2.3 | 955.3–967.5     | 962.6 ± 2.5    | 50.0–99.0  | 72.4 ± 15.4 | 0.0–7.0       | 0.6 ± 1.8   | 2.0–13.0                         | 5.3 ± 2.9   | 105–281             | 177.8 ± 43.1 |
| Site 5  | 12.0–25.0        | 18.0 ± 3.9 | 988.3–998.2     | 994.7 ± 3.1    | 47.2–94.5  | 78.7 ± 16.7 | 0.0–0.0       | 0.0 ± 0.0   | 0.5–5.0                          | 2.2 ± 1.5   | 0.0–360.0           | 231.7 ± 80.0 |
| Site 6  | 12.0–21.0        | 15.2 ± 3.0 | 1,010.0–1,012.0 | 1,016.6 ± 4.2  | 55.0–93.0  | 77.8 ± 11.2 | 0.0–2.0       | 0.1 ± 0.5   | 5.0–11.0                         | 7.4 ± 1.9   | 0.0–350.0           | 246.5 ± 84.8 |
| Site 7  | 11.6–19.2        | 14.8 ± 2.0 | 998.8–1,010.7   | 1,005.8 ± 3.1  | 75.4–99.3  | 93.9 ± 6.4  | 0.0–0.0       | 0.0 ± 0.0   | 2.6–12.0                         | 5.4 ± 2.3   | 106.8–290.9         | 220.2 ± 61.8 |
| Site 8  | 6.2–28.0         | 17.3 ± 1.2 | na              | na             | 49.0–100.0 | 85.4 ± 7.6  | 0.0–0.0       | 0.0 ± 0.0   | 5.6–42.2                         | 21.7 ± 9.3  | 135–315             | 272 ± 21.7   |
| Site 9  | 14.6–20.2        | 16.8 ± 2.1 | 1,006.7–1,017.4 | 1,012.6 ± 3.7  | 68.2–86.7  | 75.6 ± 5.1  | 0.0–0.0       | 0.0 ± 0.0   | 0.0–9.0                          | 2.4 ± 1.9   | 0.0–360.0           | 282.7 ± 77.7 |
| Site 10 | 9.7–20.0         | 13.9 ± 2.6 | 889.2–897.5     | 894.2 ± 2.3    | 53.4–83.4  | 68.1 ± 9.3  | 0.0–0.0       | 0.0 ± 0.0   | 0.0–6.0                          | 2.4 ± 1.4   | 0.0–350.0           | 232.8 ± 94.2 |
| Site 11 | 4.3–29.5         | 14.7 ± 3.6 | 991.4–1,012.6   | 1,004.2 ± 3.1  | 45.6–99.2  | 77.8 ± 12.6 | 0.0–1.1       | 0.4 ± 0.62  | 0.0–4.1                          | 0.69 ± 1.26 | na                  | na           |
| Site 12 | 6.8–27.6         | 11.0 ± 2.6 | 1,002.6–1,010.6 | 1,006.3 ± 2.42 | 38.0–99.0  | 87.6 ± 14.3 | 0.0–0.8       | 0.02 ± 0.14 | 0.0–1.4                          | 0.36 ± 0.54 | na                  | na           |
| Site 13 | 5.6–30.5         | 10.4 ± 5.5 | 913.5–1,004.8   | 998.7 ± 6.4    | 40.2–98.5  | 67.8 ± 10.2 | 0.0–0.0       | 0.0 ± 0.0   | 0.0–3.7                          | 0.41 ± 1.3  | na                  | na           |
| Site 14 | 20.7–24.8        | 22.0 ± 1.1 | 997.1–1,006.5   | 1,002.7 ± 2.8  | 59.2–86.8  | 73.3 ± 6.0  | 0.0–0.0       | 0.0 ± 0.0   | 2.1–3.7                          | 2.8 ± 0.4   | 162.7–254.3         | 200.3 ± 33.2 |
| Site 15 | 18.6–28.1        | 23.1 ± 2.4 | 989.5–997.5     | 993.8 ± 1.5    | 47.0–90.5  | 68.6 ± 11.9 | 0.0–0.0       | 0.0 ± 0.0   | 0.0–9.8                          | 3.1 ± 1.6   | 0.0–360.0           | 92.6 ± 80.2  |
| Site 16 | 15.7–28.7        | 24.4 ± 2.0 | 1,010.1–1,018.9 | 1,013.4 ± 1.7  | 42.6–94.3  | 69.5 ± 8.4  | 0.0–0.0       | 0.0 ± 0.0   | 0.7–21.0                         | 10.0 ± 5.0  | 5.0–359.0           | 76.0 ± 83.8  |

na not available



**Table 3** Average and range of mass concentrations of PM<sub>2.5</sub>, PM<sub>10</sub> and TSP at the sampling sites

| Sites   | Location      | PM <sub>2.5</sub> (µg m <sup>-3</sup> ) |              | PM <sub>10</sub> (µg m <sup>-3</sup> ) |               | TSP (µg m <sup>-3</sup> ) |              | PM <sub>2.5</sub> /<br>PM <sub>10</sub> | PM <sub>2.5</sub> /<br>TSP |
|---------|---------------|---|--------------|--|---------------|---------------------------|--------------|---|----------------------------|
|         |               | Range                                   | Mean ± SD    | Range                                  | Mean ± SD     | Range                     | Mean ± SD    |   |                            |
| Site 1  | Kullu         | 9.0–22.0                                | 20.4 ± 3.1   | 16.5–96.5                              | 46.9 ± 19.1   | 29.7–112.5                | 66.2 ± 27.7  | 0.44                                    | 0.31                       |
| Site 2  | Patiala       | 93.4–201.9                              | 138.7 ± 27.0 | na                                     | na            | 68.6–348.7                | 250.6 ± 68.2 |   | 0.55                       |
| Site 3  | Delhi         | 114.6–253.9                             | 178.2 ± 56.5 | 89.7–358.2                             | 205.7 ± 71.3  | 99.2–451.3                | 259.0 ± 92.9 | 0.87                                    | 0.69                       |
| Site 4  | Ajmer         | na                                      | na           | 28.8–89.9                              | 57.6 ± 18.7   | na                        | na           |   |                            |
| Site 5  | Agra          | 35.5–180.6                              | 120.6 ± 36.2 | 43.6–201.1                             | 152.7 ± 43.7  | 50.1–251.4                | 174.2 ± 49.6 | 0.79                                    | 0.69                       |
| Site 6  | Lucknow       | 51.8–233.9                              | 120.4 ± 47.8 | 101.1–348.8                            | 186.9 ± 67.3  | 220.4–536.6               | 325.0 ± 71.5 | 0.64                                    | 0.37                       |
| Site 7  | Varanasi      | 125.6–256.2                             | 187.8 ± 36.5 | 131.8–335.3                            | 235.1 ± 57.6  | na                        | na           | 0.80                                    |                            |
| Site 8  | Giridih       | na                                      | na           | 126.3–328.3                            | 223.9 ± 53.5  | na                        | na           |   |                            |
| Site 9  | Kolkata       | 71.7–396.4                              | 168.7 ± 77.9 | 147.6–520.1                            | 272.6 ± 102.9 | na                        | na           | 0.62                                    |                            |
| Site 10 | Darjeeling    | 16.8–92.2                               | 43.3 ± 19.7  | 59.8–78.9                              | 67.4 ± 5.8    | na                        | na           | 0.64                                    |                            |
| Site 11 | Itanagar      | 37.3–86.9                               | 77.4 ± 27.1  | 156.6–306.7                            | 267.8 ± 56.7  | 108.3–521.1               | 294.6 ± 78.5 | 0.29                                    | 0.26                       |
| Site 12 | Jorhat        | 16.8–51.6                               | 43.6 ± 12.3  | 76.0–237.5                             | 193.5 ± 46.1  | 75.4–572.0                | 287.9 ± 92.3 | 0.23                                    | 0.15                       |
| Site 13 | Imphal        | 41.5–116.7                              | 87.4 ± 31.9  | 124.6–326.3                            | 277.6 ± 61.2  | 121.9–567.4               | 306.4 ± 86.4 | 0.32                                    | 0.29                       |
| Site 14 | Bhubaneswar   | 49.6–87.7                               | 65.2 ± 11.8  | 92.0–191.7                             | 133.9 ± 30.6  | na                        | na           | 0.49                                    |                            |
| Site 15 | Kadapa        | 30.4–39.8*                              | 34.1 ± 4.6*  | 48.5–70.7                              | 60.1 ± 8.2    | 30.2–101.2                | 62.9 ± 17.0  | 0.57 <sup>#</sup>                       | 0.54 <sup>§</sup>          |
| Site 16 | Bay of Bengal | 15.0–54.4                               | 41.3 ± 11.9  | 30.1–82.1                              | 53.9 ± 18.9   | 49.1–184.5                | 78.8 ± 29.7  | 0.77                                    | 0.52                       |

na not available

\* PM<sub>2.1</sub>

# PM<sub>2.1</sub>/PM<sub>10</sub>

§ PM<sub>2.1</sub>/TSP

another study, the average mass concentration of PM<sub>2.5</sub> over Lucknow in the period from 2007 to 2009 was quantified to be  $87.3 \pm 64.2 \mu\text{g m}^{-3}$  (range  $28.0\text{--}196.9 \mu\text{g m}^{-3}$ ) by Pandey et al. [31]. Annual average PM<sub>2.5</sub> mass concentrations for Agra was estimated to be  $104.9 \pm 47.1 \mu\text{g m}^{-3}$  and  $91.1 \pm 50.3 \mu\text{g m}^{-3}$  at urban and rural sites respectively [18]. Pachauri et al. [15] also carried out sampling for ambient particulates across different sites in Agra and reported average mass concentrations of  $308.3 \pm 51.8 \mu\text{g/m}^3$  (high traffic area),  $140.8 \pm 22.3 \mu\text{g m}^{-3}$  (campus area) and  $91.2 \pm 17.3 \mu\text{g m}^{-3}$  (rural area). Das et al. [32] reported 24 h average PM<sub>2.5</sub> mass concentration of  $178.57 \pm 31.53 \mu\text{g m}^{-3}$  (range  $112.42\text{--}201.96 \mu\text{g m}^{-3}$ ) in Kolkata while Gupta et al. [33] reported the same to be  $181.19 \pm 90.86 \mu\text{g m}^{-3}$  (range  $49.47\text{--}537.77 \mu\text{g m}^{-3}$ ). The PM<sub>2.5</sub> concentration during winter in Jorhat was reported to be  $143.5 \pm 23 \mu\text{g m}^3$  [34]. PM<sub>2.5</sub> mass concentrations over the BoB were found to range from 2.0 to  $76.7 \mu\text{g m}^{-3}$  during 27 December, 2008 to 28 January, 2009 in the study conducted by Kumar et al. [25].

In this present study the sites in the upper and middle IGP region (Patiala, New Delhi, Agra, Lucknow and Varanasi) recorded elevated concentrations of fine particulates as expected and could be attributed to the fact that the winter in these regions are characterized by low and stable planetary boundary layer and relatively low wind

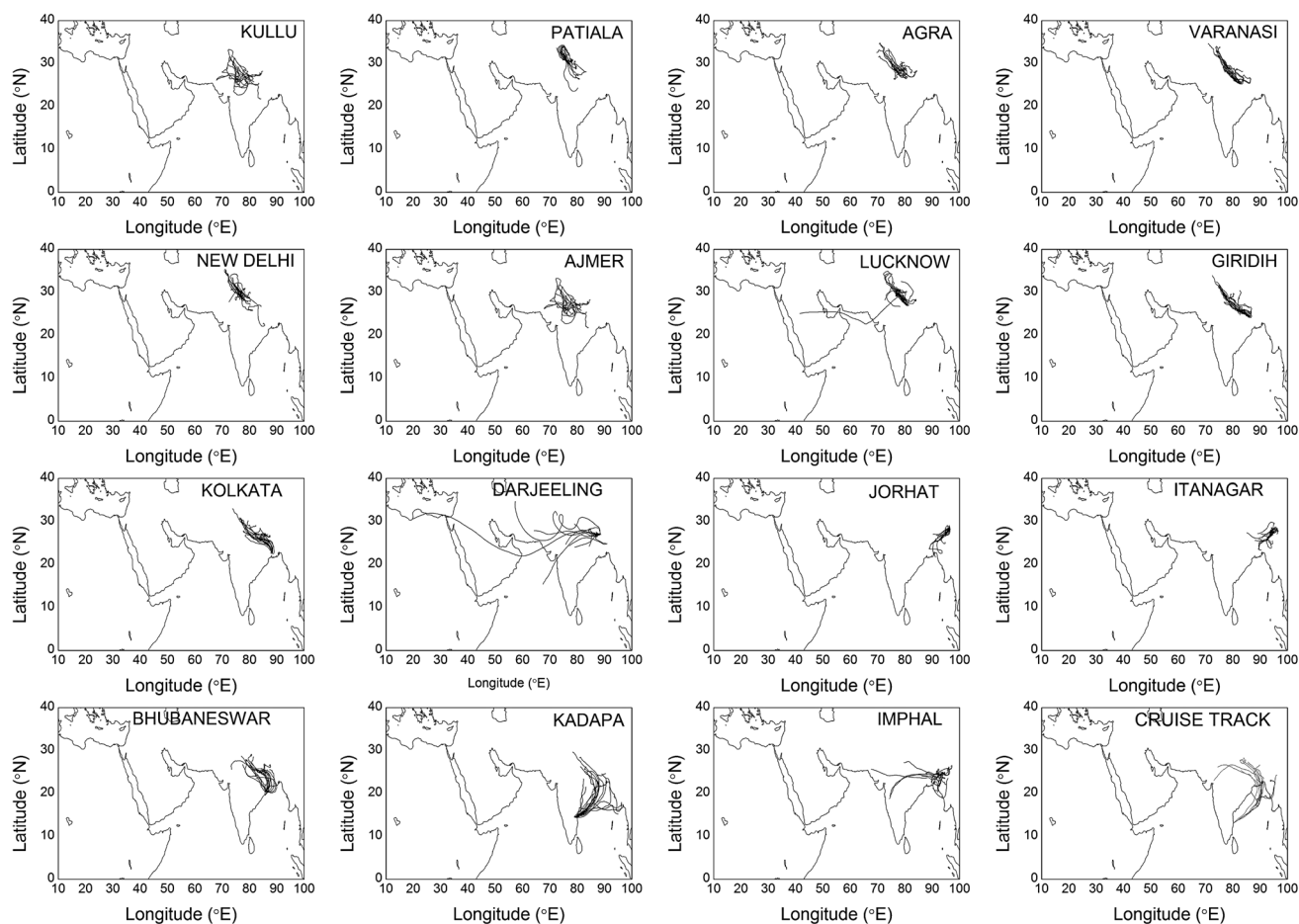
speeds leading to stagnation of pollutants due to little dispersion in the lower atmosphere [35]. In addition, during winter the increase in the usage of biomass for heating purposes might have caused an increase in fine particle loading into the atmosphere [15, 16]. Kolkata, being located in the lower IGP recorded very high PM<sub>2.5</sub> mass concentrations. The high concentrations of fine particulates at all of these sites can be attributed to the fact that these cities are highly populated metropolitan cities with a very high associated fine mode aerosol contribution from fossil fuel burning including vehicular exhaust. The average PM<sub>2.5</sub> mass concentration over Kolkata was found to be similar to that reported by Das et al. [32] ( $179 \mu\text{g m}^{-3}$ ) for the winter season. Moreover, elevated PM<sub>2.5</sub> concentrations at these sites could be attributed to the fact that the air masses received at these sites were observed to originate and undergo transport in the IGP itself and could thus be carrying fine mode continental pollutants to these sites. The gradient between the continental and marine (BoB) PM<sub>2.5</sub> concentrations suggest the possibility of continental outflow of pollutants to the clean pristine marine environment. All the sites located outside the IGP and thereby outside the fringes of the north-easterly flow had relatively lower PM<sub>2.5</sub> concentrations than the sites in the IGP. Low fine particulate mass concentrations observed at Kullu and Darjeeling could be because they are located in the Himalayas and have pristine Himalayan air. In Fig. 2, all

the air mass trajectories received at Kadapa during the period of this study had to traverse long distances across the BoB and this could possibly have led to the dilution of fine particulate concentrations at the site. Balakrishnaiah et al. [36] reported the similar order of concentration of fine particulate over Anantapur ( $21.29 \pm 2.31 \mu\text{g m}^{-3}$ ), a tropical semi-arid site located nearby, during the winter season. Though the air masses received at Bhubaneswar, a coastal station, originated from IGP, traversed a short distance across northern BoB encountering marine environment, this could be the prime cause for the relatively low  $\text{PM}_{2.5}$ . North-East India has dense forest cover and lower anthropogenic pollutant emissions compared to the sites in the IGP, as was observed in the low  $\text{PM}_{2.5}$  mass concentrations of Jorhat, Itanagar and Imphal. Imphal was seen to receive a few air masses which had to traverse across India picking up continental pollutants along the way, thereby resulting in it having the highest  $\text{PM}_{2.5}$  concentrations among the three stations.

The highest  $\text{PM}_{10}$  mass concentrations recorded over Kolkata ( $272.6 \pm 102.9 \mu\text{g m}^{-3}$ ), Varanasi ( $235.1 \pm 57.6 \mu\text{g m}^{-3}$ ), Giridih ( $223.9 \pm 53.5 \mu\text{g m}^{-3}$ ), Delhi

( $205.7 \pm 71.3 \mu\text{g m}^{-3}$ ) and all the sampling locations in North-East India, viz. Jorhat ( $193.5 \pm 46.1 \mu\text{g m}^{-3}$ ), Itanagar ( $267.8 \pm 56.7 \mu\text{g m}^{-3}$ ) and Imphal ( $277.6 \pm 61.2 \mu\text{g m}^{-3}$ ). The sampling sites which are located outside the IGP such as Kullu ( $46.9 \pm 19.1 \mu\text{g m}^{-3}$ ), Darjeeling ( $67.4 \pm 5.8 \mu\text{g m}^{-3}$ ), Kadapa ( $60.1 \pm 8.2 \mu\text{g m}^{-3}$ ) and Ajmer ( $57.6 \pm 18.7 \mu\text{g m}^{-3}$ ) were mostly observed to have the lowest  $\text{PM}_{10}$  concentration during campaign period within the National Ambient Air Quality Annual Standard ( $60 \mu\text{g m}^{-3}$ ). These values were comparable to that of BoB ( $53.9 \pm 18.9 \mu\text{g m}^{-3}$ , range 30.1 to  $82.1 \mu\text{g m}^{-3}$ ). Delhi (0.87) exhibited the highest ratio of  $\text{PM}_{2.5}/\text{PM}_{10}$ , followed by Varanasi (0.80) and Agra (0.79) while Jorhat (0.23), Itanagar (0.29) and Imphal (0.32) have the lowest  $\text{PM}_{2.5}/\text{PM}_{10}$  ratio. The two coastal stations, i.e. Kolkata (0.62) and Bhubaneswar (0.49) were noted to have intermediate  $\text{PM}_{2.5}/\text{PM}_{10}$  ratios.

The present observation of  $\text{PM}_{10}$  concentration over Delhi is very much similar to earlier observations (Tiwari et al. [16]:  $219 \pm 84 \mu\text{g m}^{-3}$  in 2007; Sharma et al. [22]:  $213.1 \pm 15.0 \mu\text{g m}^{-3}$ ; Sharma et al. [37]:  $191.4 \pm 45.5 \mu\text{g m}^{-3}$  in 2010–2011). Sharma et al. [37] reported higher concentration of  $\text{PM}_{10}$  ( $241.4 \pm 50.5 \mu\text{g m}^{-3}$ ) during the winter



**Fig. 2** Air mass HYSPLIT back trajectories plotted for the land stations and along the cruise track for the duration of the sampling period



season of 2010–2011. Over Lucknow, the  $PM_{10}$  mass concentration was quantified to be  $204.07 \pm 26.75 \mu\text{g m}^{-3}$  (range  $163.96\text{--}218.43 \mu\text{g m}^{-3}$ ) with the winter season average of the order of  $269.32 \pm 42.9 \mu\text{g m}^{-3}$  ( $99.3\text{--}299.3 \mu\text{g m}^{-3}$ ) and the annual  $PM_{2.5}/PM_{10}$  mass fraction ratio being  $0.42 \pm 0.26$  [17]. In another study, Pandey et al. [31] reported the  $PM_{10}$  mass concentrations over Lucknow during 2007 to 2009 as  $168.1 \pm 29.1 \mu\text{g m}^{-3}$  (range  $102.3\text{--}240.5 \mu\text{g m}^{-3}$ ). Sharma et al. [38] reported  $PM_{10}$  mass concentrations in residential, commercial and industrial sectors of Lucknow to be 146.9, 178.4 and  $107.6 \mu\text{g m}^{-3}$  respectively. Annual average  $PM_{10}$  mass concentrations at urban and rural sites in Agra was reported to be  $154.2 \pm 68.0$  and  $148.4 \pm 64.4 \mu\text{g m}^{-3}$  respectively [18]. The computed 24 h average  $PM_{10}$  mass concentration in Kolkata was quantified to be  $303.85 \pm 49.48 \mu\text{g m}^{-3}$  (range  $201.33\text{--}347.18 \mu\text{g m}^{-3}$ ) [32] while the  $PM_{2.5}/PM_{10}$  ratio was  $0.59 \pm 0.032$ . Meanwhile in a similar study conducted by Gupta et al. [33] in Kolkata the  $PM_{10}$  mass concentration was  $288.93 \pm 123.52 \mu\text{g m}^{-3}$  (range  $66.66\text{--}637.70 \mu\text{g m}^{-3}$ ). The  $PM_{10}$  concentration during winter in Jorhat was measured to be  $222.9 \pm 47 \mu\text{g m}^{-3}$  [34].  $PM_{10}$  mass concentrations over the BoB were found to range from 6.5 to  $108 \mu\text{g m}^{-3}$  in the study conducted by Kumar et al. [25]. In another study conducted in BoB during the same study period average  $PM_{10}$  mass concentrations of  $55.9 \pm 26.3 \mu\text{g m}^{-3}$  (range  $22.5\text{--}107.2 \mu\text{g m}^{-3}$ ) was reported [21].

Kolkata recorded the highest  $PM_{10}$  mass concentrations ( $272.6 \pm 102.9 \mu\text{g m}^{-3}$ ) during the study period; but the  $PM_{2.5}/PM_{10}$  ratio (0.64) in Kolkata was much lower than most other sites in the IGP. This could be due to the fact that it is a coastal station leading to the loading of coarse mode marine aerosols in addition to the influx of finer continental particulates from the IGP and the local pollutant emissions. The other coastal station, viz. Bhubaneswar was noted to have quite a low  $PM_{2.5}/PM_{10}$  ratio (0.49), representing almost equal loading of fine and coarse mode particulates. Both Varanasi and Delhi were observed to have high  $PM_{10}$  concentrations ( $>205 \mu\text{g m}^{-3}$ ). They also have the highest  $PM_{2.5}/PM_{10}$  ratios (Delhi: 0.87, Varanasi: 0.80), signifying that almost all of the  $PM_{10}$  mass at these sites is made up of fine mode particulates. Both these sites are located in the IGP and have very high fine particulate emissions locally as well as input from the surrounding IGP region, as suggested by trajectory analysis. Giridih is another site with a relatively high  $PM_{10}$  mass concentration which could be due to coal mining and associated activities near the site. Moreover all the air masses received by Giridih were seen to originate and traverse across the IGP, thereby leading to an influx of continental pollutants from the IGP into that region. It is observed among the stations in the IGP that the  $PM_{10}$  mass concentrations are the highest in the lower IGP region compared to the middle and upper IGP regions, suggesting

the possibility of outflow to the clean marine region. Low particulate concentrations at Kullu and Darjeeling could be attributed to the fact that these stations are located at elevated altitudes and have pristine Himalayan air with little local generation of aerosols. Ajmer was noted to have a low  $PM_{10}$  concentration which can be accounted for by the fact that air mass sampling was carried out in a university campus (Central University of Rajasthan) with few local sources of aerosols. Moreover, Ajmer is surrounded by the Aravalli Range, which could result in lower windblown dust from the adjoining Thar Desert. Kadapa was observed to have a  $PM_{2.5}/PM_{10}$  ratio of 0.57 with fine particulates accounting for a little more than half of the  $PM_{10}$  mass. Absence of rainfall, low RH and cloud free skies prevailing at the site during the sampling period were conducive to the enhanced loading of fine continental aerosols. Trajectory analysis suggests that the influx of marine coarse mode aerosols from the BoB to Kadapa could be adding to the relatively low local input of coarse particulates into the atmosphere, resulting in an intermediate  $PM_{2.5}/PM_{10}$  ratio.  $PM_{10}$  concentrations observed for the North-Eastern sites broadly concur ( $\pm 50 \mu\text{g m}^{-3}$ ) with the concentration reported for Jorhat during winter by Khare et al. [34]. The  $PM_{2.5}/PM_{10}$  (0.77) ratio for BoB was observed to be quite high compared to a majority of the land stations. This could be due to the fact that the proximity of the cruise track to India allowed sampling of continental pollutants which had undergone long range transport and outflowed into the BoB during the sampling period due to favorable wind patterns. The trajectory analysis performed along the cruise track also suggests that the air masses encountered in the BoB were originating in and travelling across the IGP, and could thus be capable of picking up fine mode pollutants along its path from those regions.

Among the few selected sites where TSP could be monitored, Lucknow ( $325.0 \pm 71.5 \mu\text{g m}^{-3}$ ) had the highest, while Kadapa ( $62.9 \pm 17.0 \mu\text{g m}^{-3}$ ) and Kullu ( $66.2 \pm 27.7 \mu\text{g m}^{-3}$ ) had the lowest TSP mass concentrations in India. TSP mass concentration was found to average  $78.8 \pm 29.7 \mu\text{g m}^{-3}$  (range  $49.1\text{--}184.5 \mu\text{g m}^{-3}$ ) over the BoB. In an earlier study, TSP mass concentrations in BoB was found to average  $22 \mu\text{g m}^{-3}$  (range  $5\text{--}47 \mu\text{g m}^{-3}$ ) with the mean TSP concentration in northern BoB being  $41 \mu\text{g m}^{-3}$  and the average concentration for the rest of BoB being only  $16 \mu\text{g m}^{-3}$  [39]. It is also interesting to note that the  $PM_{2.5}/TSP$  ratio in Lucknow was only 0.37 was much lower than Delhi (0.69) and Agra (0.69) which had the highest contribution of fine particulates to the total TSP loading. The  $PM_{2.5}/TSP$  (0.52) ratio was observed to be quite high for BoB, indicating that more than half of the total suspended particulates in the bay during the study period were made up of fine particulates and providing further evidence of the influx of continental particulates into BoB.

#### 4. Conclusions

This study was aimed at estimating the mass concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> size fractions as well as TSP in the ambient atmosphere at different sites across India as well as the BoB. The salient features of this study are as follows:

- The IGP region (Patiala, Varanasi, Lucknow, Kolkata etc.) had the highest concentration of PM<sub>2.5</sub> suggesting that anthropogenic activity e.g., biomass burning occurring there could outflow to the clean marine region over Bay of Bengal. However two sites (Darjeeling and Kadapa) which are outside the fringes of the north-east flow reported low PM<sub>2.5</sub> ( $43.3 \pm 19.7 \mu\text{g m}^{-3}$ ) and PM<sub>2.1</sub> ( $34.1 \pm 4.6 \mu\text{g m}^{-3}$ ) concentrations.
- As expected, the lower IGP region was observed to have the highest PM<sub>10</sub> concentration compared to the upper and middle IGP region. Kolkata recorded the highest average PM<sub>10</sub> ( $272.6 \pm 102.9 \mu\text{g m}^{-3}$ ) concentration across India while Kullu ( $46.9 \pm 19.1 \mu\text{g m}^{-3}$ ) had the lowest mass concentration. Darjeeling ( $67.4 \pm 5.8 \mu\text{g m}^{-3}$ ), Ajmer ( $57.6 \pm 18.7 \mu\text{g m}^{-3}$ ) and Kadapa ( $60.1 \pm 8.2 \mu\text{g m}^{-3}$ ) had very low PM<sub>10</sub> concentrations and were found to be comparable to Bay of Bengal ( $53.9 \pm 18.9 \mu\text{g m}^{-3}$ )
- In the north eastern region of India, highest concentration for PM<sub>2.5</sub>, PM<sub>10</sub> and TSP was observed at Imphal ( $87.4 \pm 31.9$ ,  $277.6 \pm 61$  and  $306.4 \pm 86.4 \mu\text{g m}^{-3}$  respectively) while the lowest concentration of the same were noted at Jorhat ( $43.6 \pm 12.3$ ,  $193.5 \pm 46.1$  and  $287.9 \pm 92.3 \mu\text{g m}^{-3}$  respectively).
- Lucknow recorded the highest average TSP ( $325.0 \pm 71.5 \mu\text{g m}^{-3}$ ) concentration across India while Kadapa had the lowest ( $62.9 \pm 17.0 \mu\text{g m}^{-3}$ ). TSP mass concentration in BoB was ( $78.8 \pm 29.7 \mu\text{g m}^{-3}$ ).
- Delhi and Agra recorded very high PM<sub>2.5</sub>/PM<sub>10</sub> and PM<sub>2.5</sub>/TSP ratios while Varanasi displayed a high PM<sub>2.5</sub>/PM<sub>10</sub> ratio. This is indicative of a higher loading of fine ambient pollutant particulates compared to the natural coarser aerosols.
- Similarly both the PM<sub>2.5</sub>/PM<sub>10</sub> (0.77) and PM<sub>2.5</sub>/TSP (0.52) ratios in the BoB were observed to be on the higher side signifying outflow of fine pollutants from the landmasses.

Chemical properties (inorganic ionic composition, carbonaceous fraction and metal fraction of PM<sub>2.5</sub>, PM<sub>10</sub> and TSP) may lead to more evidence of the outflow of continental pollutants to the clean marine region. This will be reported in future.

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