Hindawi Publishing Corporation
Advances in Meteorology
Volume 2016, Article ID 8318453, 11 pages
http://dx.doi.org/10.1155/2016/8318453

Research Article

Investigating Incursion of Transboundary Pollution into the Atmosphere of Dhaka, Bangladesh

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Received 15 March 2016; Revised 8 June 2016; Accepted 26 June 2016

Academic Editor: Antonio Donateo

Concentrations of particulate matter (PM) in Dhaka, Bangladesh, during November 2013 to April 2014 were found 7-8 times higher than the World Health Organization (WHO) guideline value. Probability of contribution of transboundary sources to this PM pollution was investigated through different approaches. Ninety-six-hour backward trajectories with every 3-hour interval were computed and clustered into 06 groups based on angle distance matrix. Probabilities of individual cluster to be associated with different ranges of coarse and fine particles were studied. Gazipur station near Dhaka city was found to have 68% probability of receiving PM_{10} concentration higher than 150 $\mu g/m^3$ when air masses followed the route of Middle East through the Himalayan valley to the station. This channel was identified as the main route of PM transport to Bangladesh during dry season. Transboundary source-regions were spotted by concentration weighted trajectory (CWT) method and also by the monthly average aerosol optical depths (AOD) over South Asia. North-western Indian regions, Nepal and its neighboring areas, and Indian state of West Bengal were identified as the most probable zones that might have contributed to PM pollution in Gazipur, Dhaka. November to January was the high time the station had experienced fine particles from those transboundary regions.

1. Introduction

The city of Dhaka, Bangladesh, and its vicinity severely suffer from high level of particulate matter (PM) concentrations in the atmosphere, especially during dry season (November–April) [1–3]. The region experiences several air pollution episodes in winter (November–January) when the atmosphere gets polluted with $PM_{2.5}$ concentrations 10–14 times greater than the World Health Organization guideline value [4]. Most of this pollution originates from the local sources like brick manufacturing kilns, vehicles, and resuspended dusts [5, 6]. According to an estimation made through receptor modeling approach [5], an average contribution of 22% and 36% of fine particles in Dhaka during the year of 2007 to 2009 originated from brick kilns and motor vehicles, respectively. Not only do the Gangetic Delta regions suffer from this severe pollution, but many other countries in Asia including India, Pakistan, Nepal, and China also report heavy pollution scenarios in this season [7–9]. Transboundary transport of PM is crucial in such a continental pollution scenario as fine particles ($PM_{2.5}$: particulate matters with aerodynamic diameter less than 2.5 micrometers) having days to weeks of lifetime in the atmosphere can travel hundreds or thousands of kilometers [10] and can pollute transboundary regions. PM outflow from the South Asian countries studied by [11] revealed that the pollution from this region in winter season transports towards the north-eastern direction (to which Bangladesh is located). Biofuel and biomass burning in this region is the major source of carbonaceous aerosols that form a thick haze layer in the lower troposphere spreading out over millions of square kilometer [11]. PM inflow into the Indo-Gangetic Plain from the western regions like Arabia, Thar Desert, and Afghanistan in dry season was studied by [12].

This study identified hotspots of PM pollution in South Asia throughout the dry season and investigated probabilities of transboundary PM transport towards Dhaka city through different routes. For this purpose, 96-hour backward trajectories equated on Gazipur, Dhaka, throughout the dry season (November 2013 to April 2014) and their associations with respective hourly PM_{10} concentrations and $PM_{2.5}$ to PM_{10} ratio were exhaustively examined. Such long term associations and their analyses against local source profiles are important to understand the features of transboundary pollution into a region. When many back trajectories (over several months) are analyzed in specific ways, they begin to show the geographic origin most associated with elevated concentrations at the station. Concentration weighted trajectory (CWT) method applied in this study can identify transboundary regions of different source strengths and can distinguish moderate source-regions from strong ones in the same plot. CWT method equates concentration in each grid cell of a trajectory domain based on concentrations at the receptor and the residence time of the associated trajectories in that grid cell [13]. Thus, the method can sometimes misread a transboundary source-region due to the local source interference from a particular direction. In this study, source-regions identified by the CWT method have been verified by the monthly aerosol optical depth over South Asia measured by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's satellite Terra and also by the local source profile around the air monitoring station in Gazipur, Dhaka.

2. Materials and Methods

2.1. Observation Site and Data Collection. Air monitoring station (Figure 1) located in latitude 23.99N and longitude 90.42E in a suburban area of Gazipur was selected for this study. Overall area has very flat topography with height above the sea level of about 12.0 m. Sampling probe at the station is set at about 7.0 m above the ground. Vehicles, brick kilns, and road dusts are the major local sources of PM in the area. This study was confined to dry season (November to April) when this region severely suffers from high level of PM concentrations in the atmosphere [3, 4].

Hourly PM_{10} and $PM_{2.5}$ concentration data captured at Gazipur station were collected from the Clean Air and Sustainable Environment (CASE) Project of the Department of Environment (DoE), Dhaka. DoE applied Beta-Gauge monitors (Model BAM-1020, Met One Instrument Inc., USA) to continuously monitor atmospheric PM concentrations. The concentration data were carefully scrutinized; uneven and irrational data were expelled out from the data series before they were associated with air trajectories and analyzed further. Valid data capture of PM_{10} and $PM_{2.5}$ concentrations in Gazipur during the study period was 94% and 93%, respectively.

2.2. Local Meteorology. According to [4], the meteorology of Dhaka and its vicinity is divided mainly into two groups: (1) dry season (November to April) and (2) wet season (May to October). For air quality study, dry season is further divided into two classes: (a) winter (November to January) and (b) summer (February to April). Winter is characterized with low temperature, high relative humidity (RH), weak sun, and rare precipitation, whereas summertime experiences higher solar radiation and temperature, and lower RH. Cloud coverage and rainfall in April are remarkably greater than those in other months in dry season. Gazipur receives mainly westerly, north-westerly, and northerly wind during November to March and southerly wind in April. Rainy season starts from May [4]. Wind patterns in association with PM pollution in winter and summer seasons are shown in Figure 8.

2.3. Trajectory Calculation and Clustering. Ninety-six-hour backward trajectories centered on Gazipur station with every 3-hour interval for the duration of November 2013 to April 2014 were calculated using Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT-4) model [14] on the platform of the analytical software "R" [13, 15] which was used to analyze the trajectories and concentration data. Global Reanalysis Meteorology Data downloaded from the archive of National Oceanic and Atmospheric Administration (NOAA) was used as input to the model. As those trajectories were associated with station concentration data, starting point of the trajectories was kept at 10.0 m above the ground. Trajectories equated for the whole dry season were grouped into 06 clusters according to their "angle distance matrix" which is a measure of how similar two back trajectory points are in terms of their angle from the origin, that is, the starting location of the back trajectories. The angle-based distance measure ($d_{1,2}$) is defined by (1) [13] as follows:

$$d_{1,2} = \frac{1}{n}\sum_{1}^{n}\cos^{-1}\left(0.5\frac{A_i + B_i + C_i}{\sqrt{A_i B_i}}\right), \quad (1)$$

where $A_i = (X_1(i) - X_0)^2 + (Y_1(i) - Y_0)^2$; $B_i = (X_2(i) - X_0)^2 + (Y_2(i) - Y_0)^2$; $C_i = (X_2(i) - X_1(i))^2 + (Y_2(i) - Y_1(i))^2$.

X_0 and Y_0 are the coordinates of the Gazipur station, that is, the starting location of the trajectories, and X_1, Y_1, X_2, Y_2 are the latitude and longitude coordinates of the trajectories 1 and 2.

2.4. Probability of PM Association of Trajectories. Local source profile in a region and the dominating particle-size in the trends in PM_{10} concentrations may provide initial important information about the sources. The prime local sources of PM pollution in Gazipur are vehicles, brick kilns, and fugitive dusts [5, 16]. $PM_{2.5}$ fractions in PM_{10} concentration emitted from brick kilns and fugitive dusts are not so remarkable, 0.33 [17] and 0.15 [18, 19], respectively. Vehicles around Gazipur station are also not so crowded like Dhaka where vehicle emission accounts for about 36% of PM pollution [5]. $PM_{2.5}$ to PM_{10} ratio in such an environment may be an important indicator of long range pollution. We calculated the probability of each trajectory cluster to associate with different ranges of PM_{10} concentrations and $PM_{2.5}$ to PM_{10} at the station. We

Figure 1: Location around the study area (Gazipur, Bangladesh).

assessed the correlation between trajectories and long range PM pollution at the station following several conditions: (a) degree of PM_{10} concentrations associated with each cluster's trajectories, (b) degree of $PM_{2.5}$ fraction associated with each cluster's trajectories, and (c) type of local sources on the paths of the trajectories. High PM_{10} concentrations with higher $PM_{2.5}$ fraction from the directions with weak local source profile should indicate high probability of carrying pollution from distant sources. We later distinguished the months being dominated with those responsible trajectories using "timeprop" plot (Figure 6). Assessment on the long range pollution resulting from this trajectory-concentration association was matched and judged with transboundary source-regions identification by CWT method (Figure 7), with the pollution roses at the station (Figure 8), and also with the monthly AOD over South Asia (Figure 10).

Hourly concentrations of PM_{10} and $PM_{2.5}$ to PM_{10} ratio were associated with trajectories arrived at the respective hours at the station. Probabilities of each trajectory cluster to carry different range of PM_{10} concentration and of $PM_{2.5}$ to PM_{10} ratio at the station were then calculated according to the following:

$$P(cx) = \frac{N(cx)}{N(c)} \times 100, \quad (2)$$

where $P(cx)$ is the probability (in percent) of trajectories under cluster c to be associated with PM_{10} concentration (or $PM_{2.5}$ to PM_{10} ratio) > x; $N(cx)$ is the number of trajectories under cluster c associated with PM_{10} concentration (or $PM_{2.5}$ to PM_{10} ratio) > x; $N(c)$ is the total number of trajectories under cluster c. Thus, C1 trajectories had 81% probability of associating with PM_{10} concentrations greater than 150 $\mu g\, m^{-3}$—meaning that whenever air blew along the route of C1 trajectories, PM_{10} concentrations at the station were, in 81% of the time, greater than 150 $\mu g\, m^{-3}$.

2.5. Spotting Long Range Source-Region. Long range source-regions and their strengths within the 96-hour trajectory domain were plotted using concentration weighted trajectory (CWT) method [20, 21] (Figure 7). In this method, for each grid cell of a domain, mean CWT or logarithmic mean concentration of a pollutant species was calculated according to the following:

$$\ln\left(\overline{C}_{ij}\right) = \frac{1}{\sum_{k=1}^{n} \tau_{ijk}} \sum_{k=1}^{n} \ln\left(C_k\right) \tau_{ijk}, \quad (3)$$

where i and j are the indices of grid, k is the index of trajectory, N is the total number of trajectories used in analysis, C_k is the pollutant concentration ($PM_{2.5}$ conc. in our case) measured upon arrival of trajectory k, and τ_{ijk} is the residence time of trajectory k in grid cell (i, j). A high value of $\overline{C}_{ij}$ means that air parcels passing over cell (i, j) would, on average, cause high concentrations at the receptor site.

3. Results and Discussions

3.1. Trends in PM Concentration. Trends in PM concentrations during November 2013 to October 2014 in Gazipur

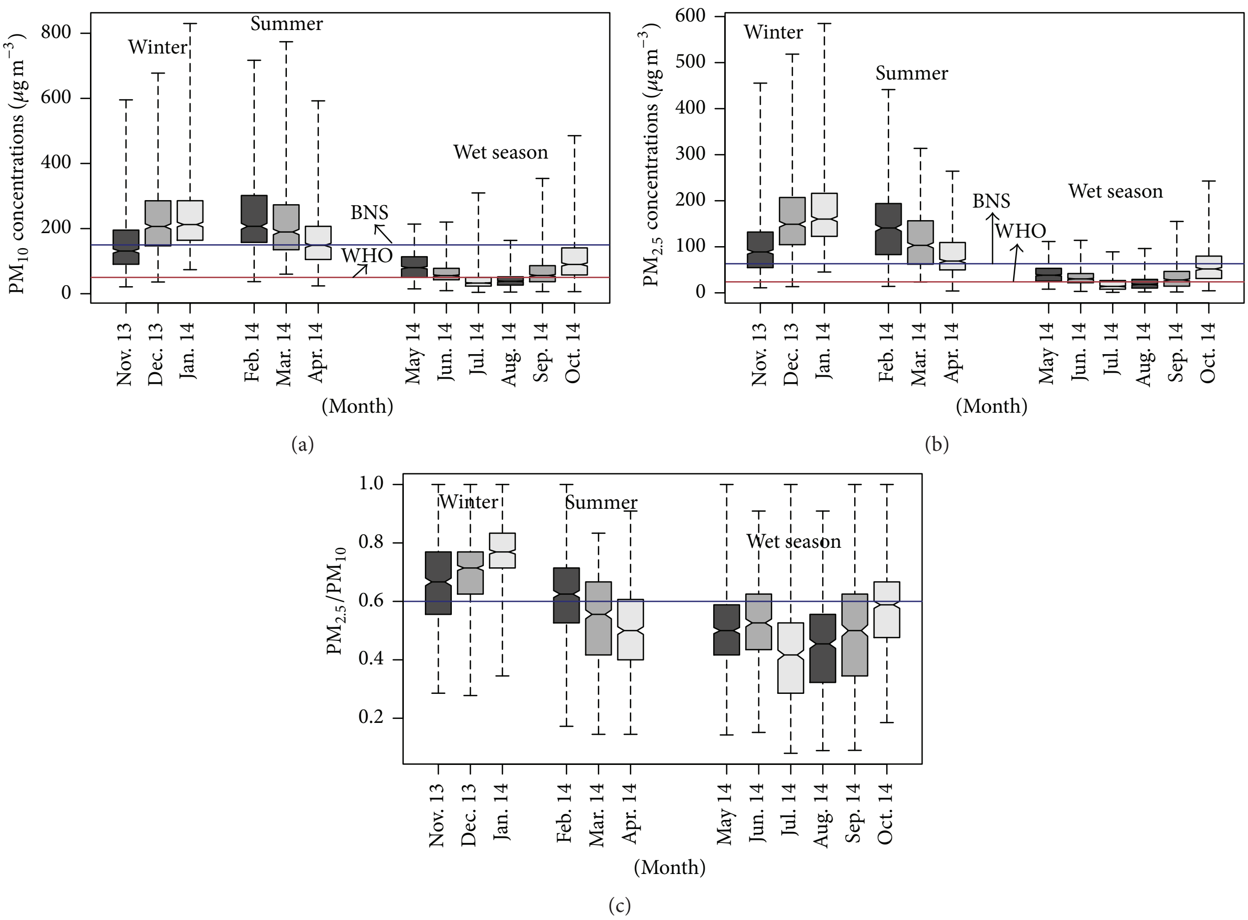

Figure 2: Box-Whisker plots of (a) PM_{10} concentrations, (b) $PM_{2.5}$ concentrations, and (c) $PM_{2.5}$ to PM_{10} ratio plotted using hourly concentration data and shown for different months from November 2013 to October 2014 in Gazipur; BNS: Bangladesh National Standard and WHO: World Health Organization guideline value for 24-hour average concentration.

(Figure 2) reveal that the town suffered from high degree of PM concentrations in atmosphere during dry season (winter and summer), whereas in wet season the concentrations were generally compliant. December to March was the most polluted time in terms of the overall PM_{10} concentration. However, the higher contribution of fine particles to PM_{10} concentration was found in December and January. Being the transition period between winter and summer, February was characterized by both high and moderate $PM_{2.5}$ to PM_{10} ratio (Figure 2(c)). Massive dusts from roads, bare lands, and construction works get into the atmosphere during summertime and help balance the ratio of fine and coarse particles in the atmosphere. PM pollution in November was not so high compared to those in December to March; but $PM_{2.5}$ contribution to PM_{10} concentration in this month was considerably greater. Seasonal local sources like brick kilns, open burning for heating, and so forth in and around Gazipur area start functioning from December. $PM_{2.5}$ contribution to PM_{10} concentration during wet season was not remarkable (Figure 2(c)). Based on the domination of fine particles in PM_{10} concentration (Figure 2), it can be primarily assumed that long range pollution in the Gazipur area might be a fact in the months of November to mid-March.

3.2. Trajectory Clustering and Analysis. Ninety-six-hour backward trajectories with every 3-hour interval equated using the HYSPLIT-4 model for the whole dry season were grouped into 6 clusters according to their "angle distance matrix." Figures 3 and 4 present, respectively, the mean directions of the clusters and the paths of individual trajectories under each cluster. Characteristics of trajectories in each cluster and their probabilities of being associated with different ranges of PM_{10} concentration and of $PM_{2.5}$ to PM_{10} ratio at the receptor are given in Tables 1 and 2.

Trajectories under C1 cluster (Figures 3 and 4) had traveled comparatively shorter distance within the time of trajectory calculation (96-hour), came mostly from the west and south-west, and had greater probability of associating very high PM_{10} concentration at the station (Table 1), whereas the trajectories under C2 cluster had traveled a long distance and were associated with high proportion of fine particles.

Table 1 shows that Gazipur station had 68% probability of receiving PM_{10} concentration higher than 150 $\mu g/m^3$ when air masses traveled along the C2 trajectories and there was 61.1% probability that the fine particle contribution to those PM was more than 70% by mass. Ranks of the clusters in

Table 1: Probability of cluster trajectories to be associated with different ranges of PM_{10} concentration and of $PM_{2.5}$ to PM_{10} ratio at Gazipur station.

Cluster	Trajectory number	Probability (%) of getting PM_{10} concentrations ($\mu g/m^3$)					Trajectory number	Probability (%) of getting $PM_{2.5}/PM_{10}$				
		>50	>100	>150	>250	>350		>0.4	>0.5	>0.6	>0.7	>0.8
C1	143	100	95	81	46	23	137	84.7	73.0	48.9	28.5	8.8
C2	214	100	90	68	29	13	211	98.6	94.8	82.9	61.1	21.3
C3	416	100	91	73	30	11	407	89.2	77.9	61.4	34.9	7.9
C4	192	95	73	52	22	8	192	90.6	82.8	67.2	42.7	15.1
C5	92	99	76	52	21	9	90	97.8	91.1	78.9	56.7	27.8
C6	299	97	83	56	21	9	247	80.2	61.9	40.9	19	4.5

Table 2: Trajectory paths and ranks in their association with high pollution at Gazipur station.

Cluster	96-hour trajectory path and direction of entering the station	Pollution association (rank)		Contribution from long range sources
		PM_{10} conc.	$PM_{2.5}$ fraction	
C1	Most of them started from the middle of India and entered the station from the west.	Very high (1)	Moderate (5)	Low
C2	Most of them started from Iran and the Middle East, several from north-Europe, travelled with good height, over Nepal, and entered the station from the north.	Moderate (3)	Very high (1)	High
C3	Started from several directions; some from the Middle East, some from India; some had long flight; some had shorter paths and entered the station from the north-west.	High (2)	Moderate (4)	Moderate
C4	Starting point somewhere in Afghanistan or Tajikistan; took a zigzag and entered the station from the north.	Low* (6)	Moderate (3)	Moderate
C5	Started from the east and entered the station from the east. Shorter length.	Low* (5)	High (2)	Moderate
C6	Marine air; started from the south and entered the station from the south.	Low* (4)	Low (6)	Low

*Compared to C1, C2, and C3, but the pollution level is still very high.

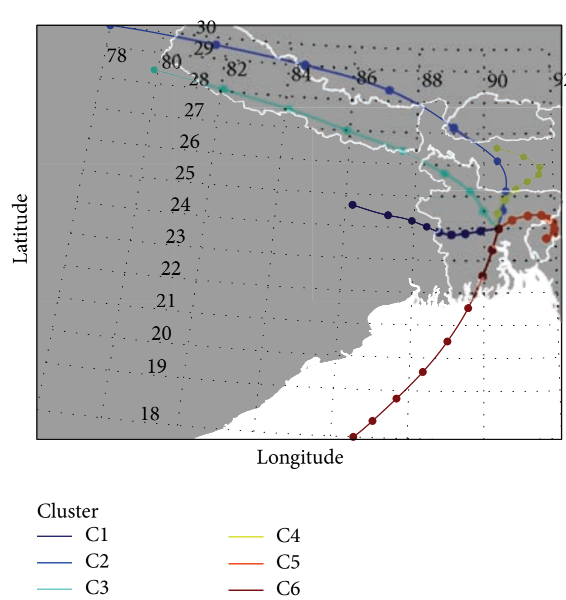

Figure 3: 6-cluster solution to back trajectories calculated for Gazipur site during dry season of 2014, showing the mean trajectory for each cluster.

terms of their association with PM_{10} concentration and with fine particle fractions are given in parentheses in Table 2.

Gazipur station may be polluted with windborne dust which is a common problem in dry season in this region. A small bus terminal is located about 400 meters away to the west direction. Brick kiln clusters are located nearly 8 km to the west, 13 km to the north-west, and 20 km to the north-east directions (Figure 1). Coal fired brick kilns are one of the prime sources of PM in dry season as studied by [5, 16]. However, fine particles constitute only one-third of PM_{10} emissions from coal fired brick kilns [17]. Thus, the high pollution with the C1 trajectories was simply the combined effect of pollution from the bus terminal (emission and resuspended road dust) and brick kilns. In contrast, high proportion of fine particles in PM with the C2 trajectories strongly suggests that the station was receiving fine particles originated from long range sources as powerful local sources of fine particles to that direction (entrance of C2 trajectories) were not recorded. C2 and C3 trajectories followed nearly the same flight (Figures 4 and 5); however, their characteristics of associating particle concentrations at the station greatly differed.

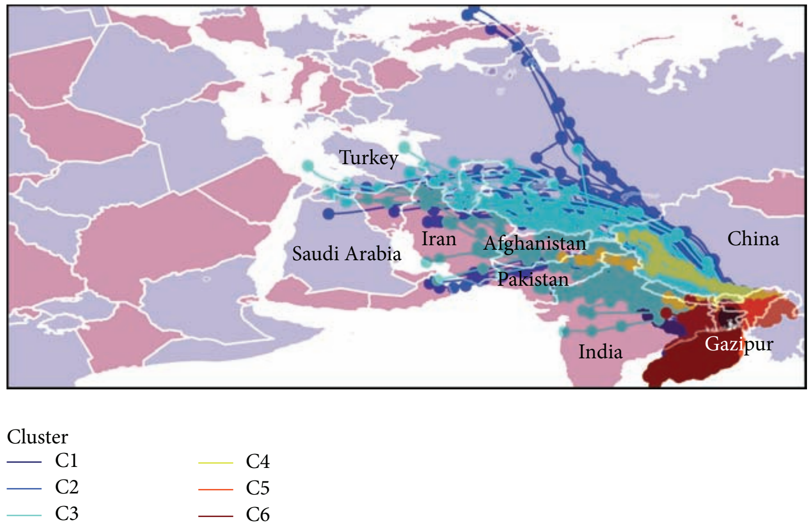

Figure 4: 96-hour HYSPLIT back trajectories centered on Gazipur station during dry season grouped as cluster and colored accordingly.

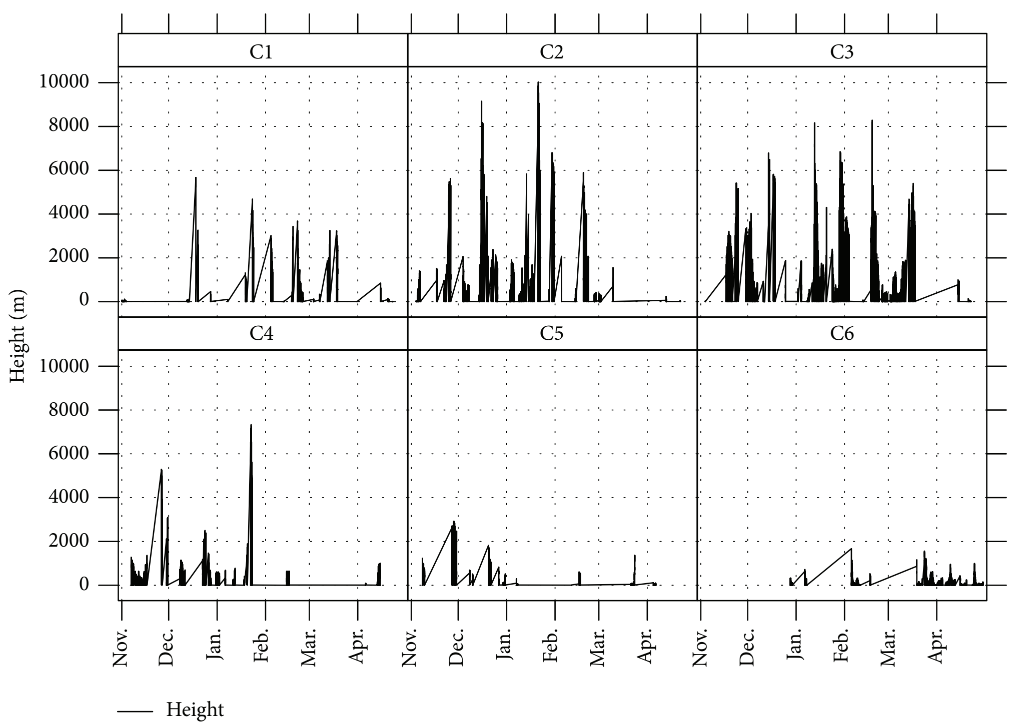

Figure 5: Time-plots of heights of the trajectories shown for each cluster.

Such differences perhaps lied in their grouping patterns and entering directions. Most of the C2 trajectories had flown as a group over the Middle East and Himalayan valley and gained about the same pollution before entering the station (Figure 4). In contrast, C3 trajectories originated from various regions; some were long and some were short (Figure 4). Moreover, C3 trajectories encountered brick kilns on their way (Figure 1) and gained coarse particles as was the case for C1 trajectories. Overall, trajectory count under C5 cluster was very low but its association with higher $PM_{2.5}$ to PM_{10} ratio indicates long range PM or local sources from the eastern side. Long range pollution from the south is denied as fine fraction of particle associated with C6 trajectories coming from that direction was really poor (Tables 1 and 2 and Figures 2 and 3).

December and January were the months when C2 trajectories dominated in contributing to $PM_{2.5}$ concentrations at the station. On the other hand, C3 trajectories dominated in January and March (Figure 6). Domination of other trajectory clusters in injecting $PM_{2.5}$ concentrations in the Gazipur area is provided in Figure 6. Combined with Figure 4, Figure 6 can express the wind patterns and the

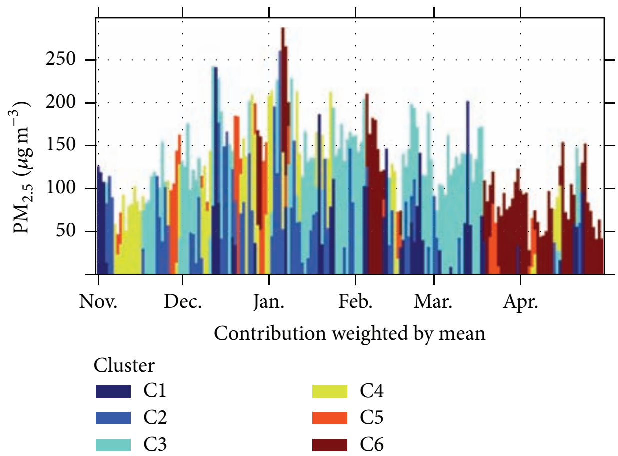

FIGURE 6: Temporal variation in daily $PM_{2.5}$ concentrations at the Gazipur station shown by contribution of each cluster.

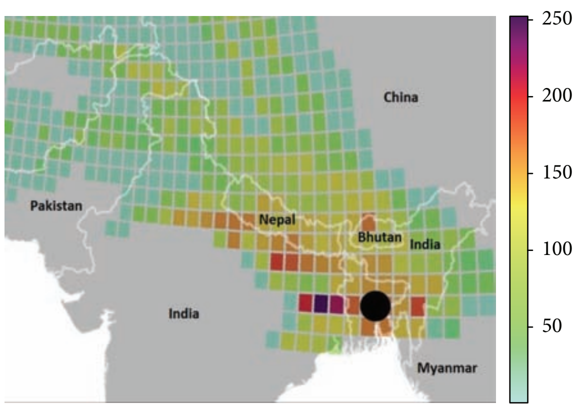

FIGURE 7: Gridded back trajectory concentrations showing mean $PM_{2.5}$ concentrations ($\mu g\,m^{-3}$), using CWT approach.

contribution of each wind sector to $PM_{2.5}$ concentrations at the station in different months of dry season. It is obvious from Figure 6 that the station started getting southerly wind (i.e., air trajectories under C6 cluster) dominantly from the last week of March. Before that, the wind was mainly northerly, westerly, and north-westerly. C5 trajectories which came mostly from the east did not have any specific time zone in Figure 6. C1, C2, C3, and C4 trajectories were the prime air masses responsible for higher concentrations at the station during November to March (Tables 1 and 2 and Figure 6). As found in Table 1, C2, C3, and C4 trajectories were associated with comparatively higher $PM_{2.5}$ to PM_{10} ratio at the station.

Figure 7 shows gridded back trajectory concentrations of $PM_{2.5}$ calculated using CWT method (3). The figure shows the geographic areas most strongly associated with high $PM_{2.5}$ concentrations at the station [13]. Such concentrations were calculated by recording the associated $PM_{2.5}$ concentrations for each point on the back trajectory based on the arrival time concentrations (3). Figure 7 suggests that the sources in the eastern Indian regions bordering Bangladesh, in the northern and north-eastern Indian regions bordering Nepal, and in Nepal and its neighboring areas had high probability of contributing to the $PM_{2.5}$ concentrations at Gazipur station. Spotted regions are along the paths of C1, C2, C3, and C4 trajectories. C5 trajectories were responsible for carrying pollution from the east. As discussed earlier, number of C5 trajectories was very low and they did not have domination in any specific time period (Figure 6). Transboundary PM from the eastern direction might not be important as high mountains are in between; this issue will be verified further by the satellite images (Figure 10).

Pollution roses and bivariate polar plots (Figure 8) express similar findings as were found from the analyses of trajectory-concentration association on the advent of pollution at the station. The directions of entrance of trajectories and the wind directions at the station should be the same. North-westerly winds dominated in contributing to the PM pollution during winter (November–January), whereas mixed wind directions were observed in summer (February–April). Depending on the frequency of wind direction in dry season, the station was experiencing higher pollution from all the directions (Figures 8(a), 8(b), 8(c), and 8(d)); however, higher contributions of fine particles were observed from the north-west, north, and the north-east directions (Figures 8(e) and 8(f)). It is also remarkable that the 50th percentile of $PM_{2.5}$ to PM_{10} ratio in winter (0.71) equals the 90th percentile of that in summer (Figures 8(e) and 8(f))—meaning that PM pollution in winter was characterized by fine particles whereas that in summer was characterized by coarse particles. Thus, it may be assumed that long range fine particulate matters from the directions of north and north-west might have joined with those from local sources during winter season.

3.3. Satellite Image Analysis. It is hard to trace transboundary pollution in a region where local pollution is strong, and both of them seem to come from the same directions (Figures 7 and 8). Images produced by the satellites in the space may add valuable information on this regard. Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra satellite records the frequency and distribution of cloud cover and measures the properties of clouds such as the distribution and size of cloud droplets in both liquid water and ice clouds. MODIS also measures the properties of aerosols—tiny liquid or solid particles in the atmosphere. With its sweeping 2,330 km wide viewing swath, MODIS sees every point on this world every 1-2 days in 36 discrete spectral bands [22].

The image on the South Asian countries (Figure 9) captured by MODIS on 12 December 2013 shows that a white fume/cloud type something was spreading from the north-west India to Bangladesh along the valley of the Himalaya. Closer view (Figure 9(b)) and the local experience confirm this cloud type material in Figure 9 as fog, which is seen to be extremely thick over Bangladesh, Indian state of Assam, and the parts of West Bengal bordering Bangladesh (Figure 9(a)).

Fogs can be viewed as clouds that are in contact with earth surface. Typical fog liquid water contents vary from 0.02 to 0.5 $g\,m^{-3}$ and fog droplets have sizes from a few micrometers to 40 micrometers [10]. Fog can be formed in heavily polluted regions; it scavenges acidic particles and gases. Although

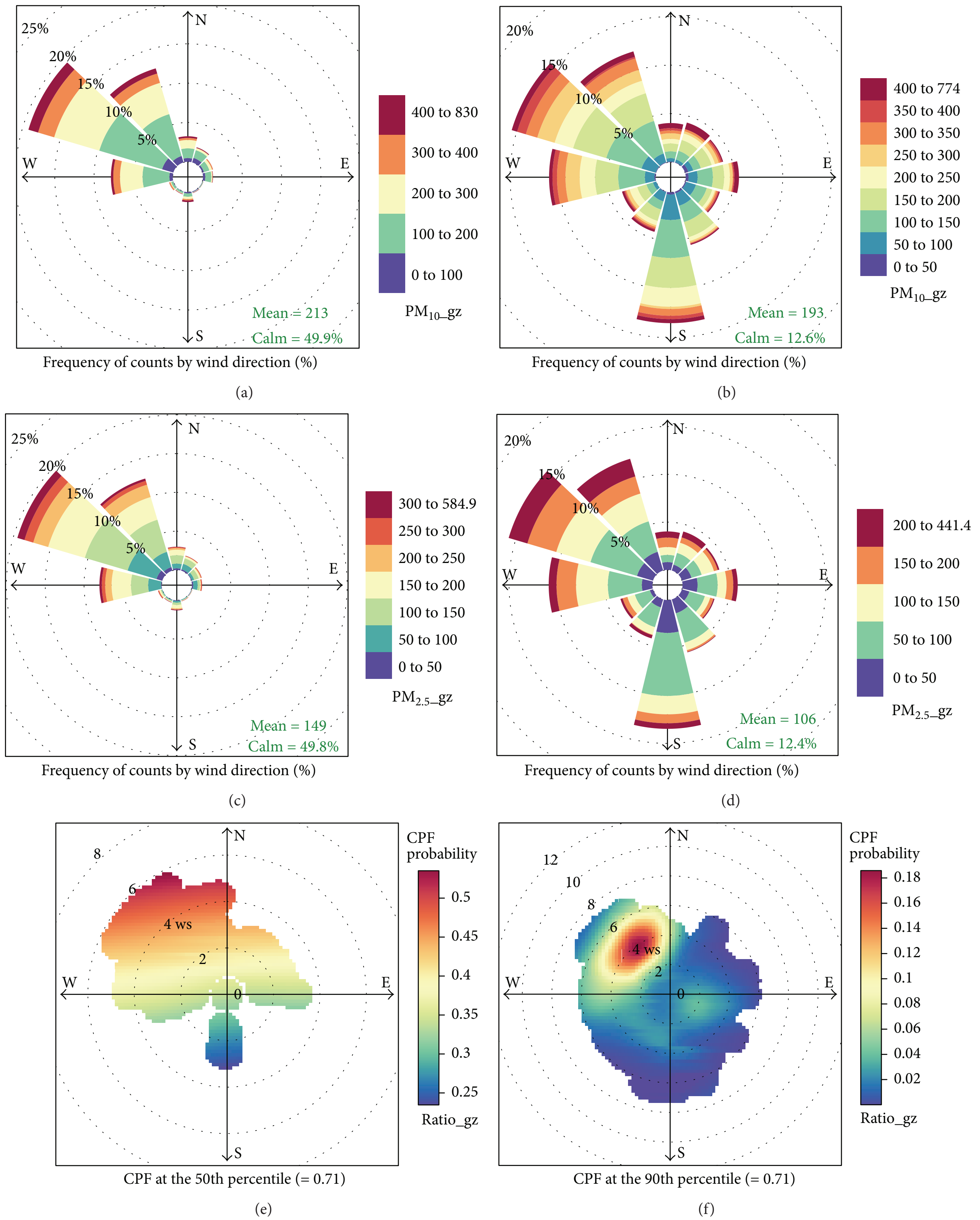

FIGURE 8: (a) PM_{10} pollution rose in winter, (b) PM_{10} pollution rose in summer, (c) $PM_{2.5}$ pollution rose in winter, (d) $PM_{2.5}$ pollution rose in summer, (e) polar plot of $PM_{2.5}/PM_{10}$ ratio in winter, and (f) polar plot of $PM_{2.5}/PM_{10}$ ratio in summer at Gazipur station.

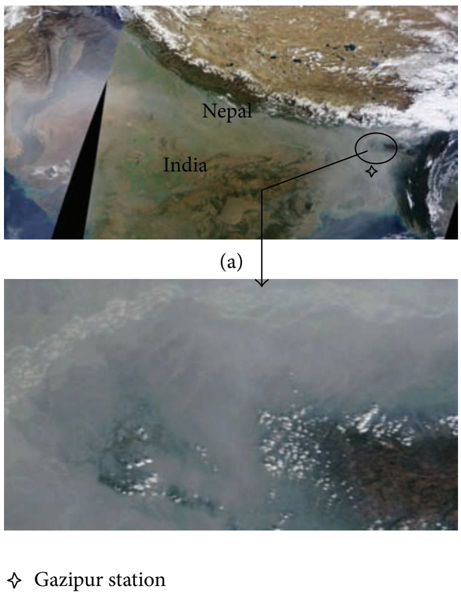

Figure 9: (a) Satellite image captured on 12 December 2013 by MODIS aboard Terra on South Asia and (b) zoomed-in version of the circled area in the figure (a).

fogs seem to rally towards Bangladesh in Figure 9, for their weight and closeness to ground, it is unlikely that these fogs scavenged with pollutants can travel 100s of km from transboundary regions and pollute the regions around Dhaka city. These foggy days are, in fact, the worst case scenario of air pollution in Bangladesh and the surroundings. However, particles already suspended into the atmosphere before fogs started to form may rise up and travel towards downwind direction.

Figure 10 shows monthly average aerosol amounts over South Asia in the form of aerosol optical depth (AOD) measured by MODIS aboard Terra. Images in Figure 10 have been downloaded from (http://neo.sci.gsfc.nasa.gov/view.php?datasetId=MYDAL2_M_AER_OD&year=2014). AOD is defined as the integrated extinction coefficient over a vertical column of unit cross section. Extinction coefficient is the fractional depletion of radiance per unit path length. In fact, AOD is a measure of the extinction of the solar beam by dust and haze. Particles in the atmosphere (dust, smoke, or pollution) can block sunlight by absorbing or by scattering light. AOD tells how much direct sunlight is prevented from reaching the ground by these aerosol particles. It is a dimensionless number that is related to the amount of aerosol in the vertical column of atmosphere over the observation location. An optical depth of less than 0.1 (palest yellow) indicates a crystal clear sky with maximum visibility, whereas a value of 1 (reddish brown) indicates very hazy conditions.

Figure 10 includes images of monthly AOD over South Asia in different months of dry season and the months immediately before and after the dry season (October and May). The high-polluted zones are seen spreading from the north-west India to Bangladesh along the Himalayan valley, which is the path of air trajectories under C2 and C3 clusters (Figures 3 and 4). According to the wind pattern in Dhaka (Figures 4, 6, and 8), air blew dominantly from the north and north-west directions from November to mid-March. PM from high-polluted north-west Indian regions, Nepal and its neighboring Indian regions, may travel along the Himalayan valley and enter the territory of Bangladesh through the northern and north-western borders according to the routes of C2 and C3 trajectories. This statement is also supported by the study on concentration-trajectory association (Tables 1 and 2) and Figure 7. PM from the West Bengal region of India bordering Bangladesh may enter through the western border of Bangladesh, as per the path of C1 trajectories. High AOD along the line of the Brahmaputra River to the north-east direction of Bangladesh is probably due to the dense fog formed over the river-way. According to Figure 10, PM from the Indian state of Mizoram located to the east of Bangladesh is not expected to have contributed to PM pollution around Dhaka city. Thus, we should not expect transboundary PM from the east and north-east directions. High AOD over Bangladesh in April and May is due to the dust (course) particles emitted from the local sources like resuspended dusts, constructions, and so forth. Forest fires in Myanmar during March and April may not affect the regions around Dhaka city because of unfavorable wind direction and also because of high mountains in between.

4. Conclusion

Air pollution during dry season (November–April) in Dhaka and its neighboring areas is found to be extremely unhealthy due to the high concentration of particulate matter (PM) in atmosphere. We investigated through different approaches the contributions of transboundary sources to this pollution in Dhaka. Our works and outcomes were as follows:

(a) Trends in PM concentrations at the station during dry season (November 2013 to April 2014) were much higher than the national standards of Bangladesh (150 $\mu g\, m^{-3}$ for PM_{10} concentration and 65 $\mu g\, m^{-3}$ for $PM_{2.5}$ concentration on 24 hours average); however, from May 2014 to October 2014 the concentrations were mostly compliant, even with the World Health Organization guideline value. High contribution of $PM_{2.5}$ to PM_{10} concentration was found during November to February.

(b) Pollution roses on Gazipur station showed that high PM concentrations during dry season were received from all the directions depending on the wind direction frequency. However, north-western wind particularly was always associated with higher contributions of fine particles.

(c) Ninety-six-hour backward trajectories during the whole dry season period were computed on Gazipur air monitoring station near Dhaka and were associated with respective hourly PM_{10} concentrations and $PM_{2.5}$ to PM_{10} ratio at the station. This association showed that higher $PM_{2.5}$ contribution to PM_{10} concentration was observed at the station whenever

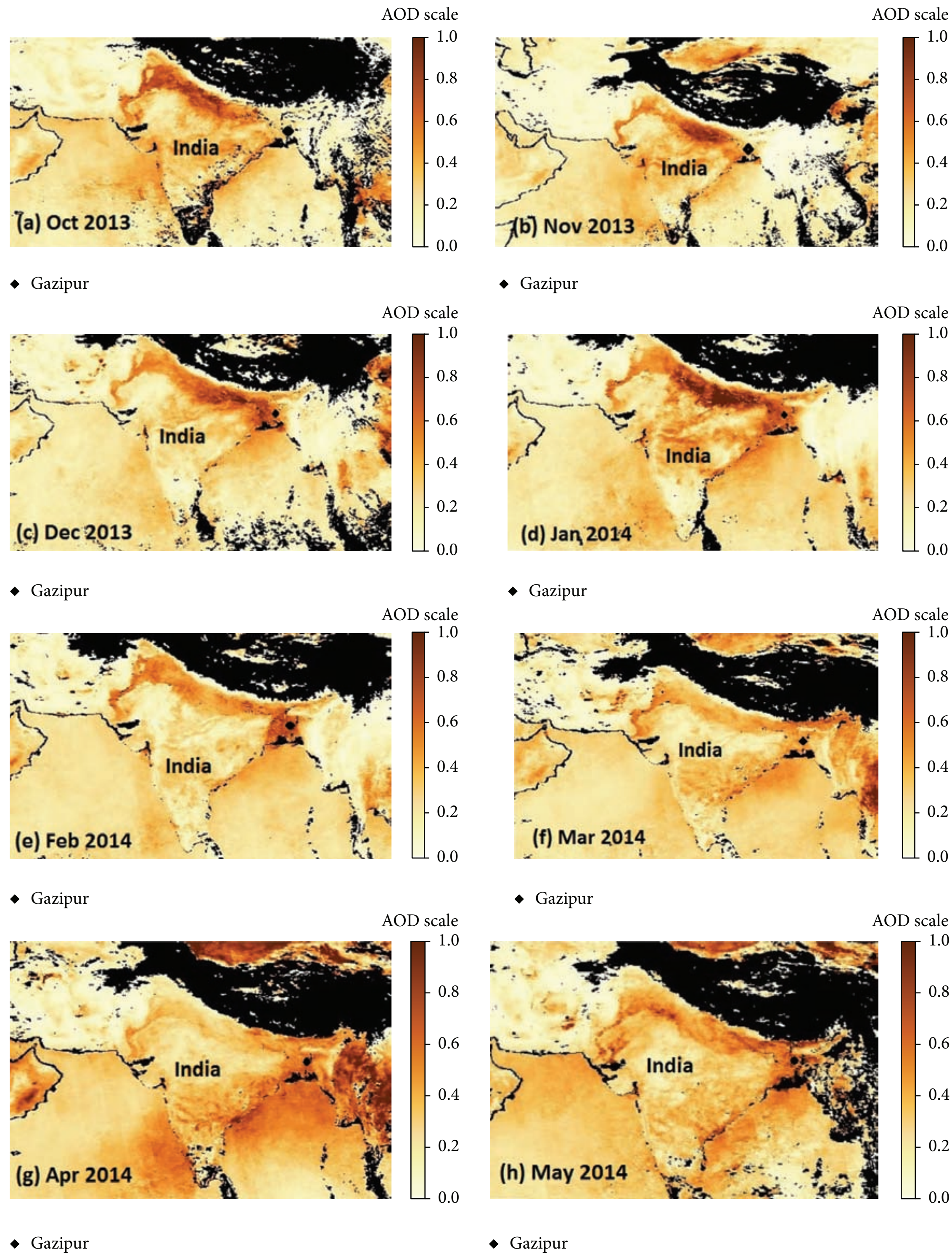

Figure 10: Monthly average AOD on South Asia captured by MODIS aboard Terra of NASA.

air masses traveled over northern India through Himalayan valley to the station.

(d) Northern Indian regions, Nepal and its neighboring Indian regions, and the areas of the Indian state of West Bengal adjacent to the western border of Bangladesh were identified by concentration weighted trajectory (CWT) method as responsible for contributing to PM pollution in Gazipur, Dhaka. Higher aerosol optical depth (AOD) was also recorded over those areas. November to February was found as the high time when Dhaka and its neighboring areas received PM emitted from those transboundary sources.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

The authors acknowledge research grant (Code: DIP-2014-017) of the Universiti Kebangsaan Malaysia for financial support to Md. Masud Rana. The authors are grateful to Ms. Shahanaj Rahman, Assistant Director, DoE, Dhaka, for her support with information.

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