Trajectory-Based Models and Remote Sensing for Biomass Burning Assessment in Bangladesh

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ABSTRACT

Biomass burning is a major global source of fine primary carbonaceous particles including strongly light absorbing compounds and marker compounds. In a prior study, particulate matter (PM) sampling was conducted during 2010–2012 period at sites in Rajshahi, Dhaka, Khulna, and Chittagong. PM samples were collected using dichotomous samplers in the PM2.5 and PM2.5–10 size fractions. The samples were analyzed for mass, black carbon at 370 nm (UVBC) and 880 nm (BC), Delta-C (UVBC-BC), and elemental compositions with X-ray fluorescence. Source apportionment using PMF was performed to identify and quantify the PM sources. Results showed that biomass burning contributions during winters in Rajshahi were substantially higher than in Dhaka, Khulna, or Chittagong. Agricultural burning areas of the Indo-Gangetic Plain were highlighted as the primary source region. The present study explores the relationships between the source regions using trajectory ensemble models and determines if transported biomass PM has disproportionately affected air quality in Rajshahi. The probable source locations that were identified included Pakistan, northern India, Nepal, Bangladesh, Northeastern India, and Myanmar. To assess the model results, satellite measurements of fire radiative power (FRP) were calculated based on fire data acquired by the MODerate-resolution Imaging Spectroradiometer (MODIS) sensor in six defined areas. High fire occurrences from MODIS coincident with the source regions identified in Nepal, Northeastern India and Myanmar in winter. The instantaneous FRP values ranged between 4.4 MW and 2449 MW. The mean winter FRP values for Nepal and Northeastern India were higher than for the other regions with Nepal having the overall highest value. Fire locations with their mean power, NASA Satellite pictures and particles speed along trajectories have been analyzed. In summary, the integrated outcome of the different techniques has identified Northern India and Nepal as the main source area responsible for the increased biomass burning concentration difference at Rajshahi.

Keywords: Biomass burning; PM2.5; Trajectory ensemble models; Fire radiative power (FRP); MODIS.

INTRODUCTION

High particulate matter (PM) concentrations in Asia have been recognized as a substantial challenge. Cohen et al. (2005) estimated that 2/3 of the global air pollution burden originates in Asia. Particularly in South Asia, the atmospheric brown cloud has been observed across the region (Ramanathan et al., 2001; 2007). The haze consists of layers of mineral dust and of light absorbing particles of anthropogenic origin (Ramanathan and Ramana, 2005). It occurs every year between November and April, and covers most of Bay of Bengal region (Begum et al., 2011a). During haze periods, PM concentrations are substantially increased and thus, the Bangladesh National Ambient Air Quality Standards (BNAAQS) are often exceeded in the region. The winter concentrations are sufficiently high that they also result in exceeding annual average AAQS even with PM concentration decreases of factors of 5 to 7 during the monsoon season (Begum et al., 2010).

To address the high PM concentrations in Bangladesh, particularly PM2.5 (PM smaller than 2.5 µm in diameter) connected to mortality from cardiopulmonary diseases and lung cancer previously reported in Asia (Zhang et al., 2014), and inform governmental actions for the PM reduction, several chemical composition studies have been performed (Azad and Kitada, 1998; Salam et al., 2003; Begum et al., 2004, 2005, 2006). Multiple source apportionment studies using positive matrix factorization (PMF) have also been conducted (e.g., Begum et al., 2004, 2005, 2009, 2010). These results suggested that the typical haze aerosol comes from domestic wood, dung and bagasse burning, forest fires, and combustion connected to agriculture activities and brick kiln making, i.e., biomass burning in general, but also from traffic, power plants, industry emissions, soil and

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road dust, and also sea salt (Begum et al., 2014). Ramanathan and Carmichael (2008) report that biomass burning is the major source of black carbon and particulate matter across southern and southeastern Asia.

Originally, monitoring efforts focused on Bangladesh’s capital, Dhaka (Begum et al., 2005, 2006, 2011a), resulting in regulations such as the ban on two-stroke engines three-wheel taxis, support of CNG vehicles, etc. (Begum et al., 2006). Improvements in air quality have been reported although PM concentrations continued to exceed the AAQS. However, an early study in Rajshahi in the western part of Bangladesh (Begum et al., 2004) found that the PM$_{2.5}$ concentrations were comparable to Dhaka. All of the prior work has suggested the necessity to address not only local sources, but regional sources as well (Begum et al., 2011b).

Recently, source apportionments were performed for four cities in Bangladesh: Dhaka, Rajshahi, Khulna, and Chittagong (Begum et al., 2014) to determine changes in the PM sources resulting from governmental interventions and compare source strengths across the country. The results showed that the AAQS was not attained in any of the cities and thus, further regulation would be necessary. They observed that the mean PM$_{2.5}$ concentration in Rajshahi on the Bangladesh-India border was more than twice as high as in any other city. The main difference was in the impacts of wood burning and brick kiln factors, both connected to biomass burning. That study concluded that long-range transport of biomass burning aerosol from northern India was the possible explanation for the higher values and suggested that a "further study of the role of this transported aerosol will be needed to assess the source locations and contributions in more detail" (Begum et al., 2014).

Thus, this study has used several trajectory ensemble models combined with MODIS (Moderate Resolution Imaging Spectroradiometer) fire data to explore the sources of the high PM$_{2.5}$ concentrations measured in Rajshahi relative to the other 3 cities.

**METHODS**

The sample collection, filter analyses, and source apportionments were described in detail by Begum et al. (2014), and only a short summary is presented here.

**Sampling**

PM$_{2.5}$ sampling was conducted in four major cities in Bangladesh: Dhaka, Chittagong, Khulna and Rajshahi (Fig. 1). Dhaka (23 42'N, 90 22'E, 4 m asl) is the capital city and one of the fastest growing megacities in the world. The second largest city is Chittagong (22 22'N, 91 48'E, 0 m asl), and a major coastal seaport. Khulna (24 49'N, 89 33'E, 9 m asl) is the third largest city in Bangladesh, and also an industrial port with both light and heavy industries. Rajshahi (24 22'N, 88 36'E, 18 m asl) is the industrial center of North Bengal, and lies close to the Indian border. Sampling was conducted every third day between September 2010 and July 2012 from 10 AM to 10 AM. The samples were collected on 37 mm Teflon filters using Thermo Andersen dichotomous samplers, and later analyzed for PM$_{2.5}$ mass by gravimetric analysis, black carbon at 880 nm (BC$_{880}$ nm), UV black carbon at 370 nm (BC$_{370}$ nm) and Delta-C (BC$_{370}$ nm - BC$_{880}$ nm) (Wang et al., 2011; Laskin et al., 2015; Lin et al., 2016) concentration using a two-wavelength transmissometer (OT-21, Magee Scientific, Berkeley, CA), and elemental composition using X-ray fluorescence technique (X-LAB2000, Spectro, Germany).

The meteorological conditions in all cities are driven mainly by monsoons, dividing the year into four seasons - pre-monsoon, monsoon, post-monsoon, and winter (Salam et al., 2003). During the pre-monsoon season (March–May) there is high RH, high temperatures, moderate rainfall, and prevailing SW winds; the monsoon (June–September) brings high rainfall with high speed SW winds; the post-monsoon season (October–November) typically has low rainfall, RH, and NE winds, and in winter (December–February), the

![Fig. 1. Location of sampling sites, background map taken from https://www.google.com/maps.](image-url)
conditions are very dry with low NW winds (Begum et al., 2013).

**Positive Matrix Factorization**

Begum et al. (2014) used positive matrix factorization (PMF) to analyze the PM$_{2.5}$ compositional data from Rajshahi, Dhaka, Khulna and Chittagong. Concentrations of Na, Mg, Al, Si, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Br, Pb, BC and Delta-C were used. Data matrices of 22 columns (elements/species) and 206, 175, 136, and 114 rows (samples) for Rajshahi, Dhaka, Khulna and Chittagong, respectively, were analyzed. The PMF results reported six common factors in all four cities: Fugitive Pb, Biomass burning, Motor vehicles, Brick kilns, Soil dust, and Road dust. In all cities except Rajshahi, a sea salt/Zn factor was also resolved (Begum et al., 2014).

**Trajectory Ensemble Methods**

To identify the source locations of transported PM, trajectory ensemble methods are used to combine the data from multiple sampling days to provide estimates of the probabilities of upwind areas being the locations of the observed pollutant emissions. These methods include Potential Source Contribution Function (PSCF) (Ashbaugh et al., 1985; Zeng and Hopke, 1989), Residence Time Weighted Concentration (RTWC) (Stohl, 1996; Zhou et al., 2004), and Simplified Quantitative Trajectory Bias Analysis (SQTBA) (Zhou et al., 2004; Brook et al., 2004). These methods have been described in detail by Hopke (2016). The trajectories were computed using HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model (Stein et al., 2015), based on the NOAA-NCEP/NCAR Global Reanalysis data with 2.5° × 2.5° horizontal resolution and 17 pressure levels (Kalnay et al., 1996). Five-day backward air parcel trajectories were calculated at a starting height of 500 m AGL from each station four-times a day (00, 06, 12, and 18 local times) for each of the four stations. This starting height was selected based on the results of Cheng et al. (1993) who showed that higher altitude starting points resulted in unrealistically long transport of PM and Bisht et al. (2016) who found that nighttime mixing heights in Delhi were of the order of 200 to 300 m. The daily contribution of each source was assigned to the 4 trajectories belonging to that particular day.

**MODIS Active Fire Products**

Satellite information is used in this study to determine the fire locations within the identified probable biomass burning source regions identified by the trajectory ensemble methods. Based on the detection of the thermal radiation emitted by a fire, monthly global 1 × 1 km gridded active fire products produced from Terra and Aqua MODIS (Giglio, 2010) spanning 2010–2012 were used. The MODIS sensor aboard the NASA Terra and Aqua satellites detects fire pixels and estimates fire radiative power (FRP), the rate of fire energy released per unit time, globally on a daily basis. It is a multi-spectral sensor with 36 spectral bands from 0.4 to 14.2 μm. To calculate FRP as the relationship between the brightness temperature of fire and background pixels, only the 4-μm channel measurements are used (Kaufman et al., 1998). These measurements usually relate to the amount of biomass burnt (Wooster, 2003), the strength of fires (Mottram et al., 2005; Ichoku et al., 2008) and aerosol emissions (Pereira et al., 2009). Considering the potential of FRP, we used this product to compare the power of each source location in order to identify the reason of Rajshahi concentration difference with the other sites.

The UTC dates of MODIS data were first converted to Bangladesh local time, and the fire pixels with below 30% confidence value were neglected in the calculations. Six sectors were used to define the probable source locations based on the trajectory ensemble results. The 6 ‘fire regions’ are listed in Table 1 with their corresponding box numbers, bounding box-corner coordinates, and the total area enclosed by each box. To simplify the comparative analyses, all FRP data from two winters of 2010–2012 were aggregated. Total FRP and number of fire pixel (NFP) values along with the mean FRP were calculated on a daily basis for each region. To make NFP comparable between sectors, they are here divided by their respective regional areas (in 10$^4$ km$^2$) as listed in Table 1.

**RESULTS AND DISCUSSION**

**Source Apportionment and Trajectory Ensemble Results for Biomass Burning**

Begum et al. (2014) determined the PM sources using PMF for Rajshahi, Dhaka, Khulna and Chittagong sites in the winters of 2010 to 2012. These results found much larger biomass burning contributions in Rajshahi relative to these contributions than in the other three cities (Fig. 2). In order to infer locations and the spatial distribution of the biomass burning sources, three back trajectory ensemble analyses were applied to the PMF results.

As shown in Fig. 3(A), the PSCF analyses of the biomass factor suggested that East Pakistan, NW India, and Nepal along with local Bangladeshi sources were major regions influencing Rajshahi. For Dhaka, the Ganges Valley (India), Bangladesh, and NW India are potential source areas (Fig. 3(B)). For Chittagong (Fig. 3(C)), the contributions of biomass burning from west Myanmar and NE India are visible in the PSCF plot. Medium and high potential grid cells for Khulna are located in the Ganges Valley and in western Bangladesh (Fig. 3(D)). Since the PSCF results suggest that Chittagong is affected more by Myanmar in sharp contrast with the other sites, this site has been neglected in the other analyses. RTWC and SQTBA are multiple site methods (Hopke, 2016) and including a site with such a different transport pattern would skew the results.

Fig. 4(A) shows the RTWC results for the three sites. It indicates eastern Pakistan, northern and northwestern India, western Nepal, and western Bangladesh are the potential source areas. Trajectory length can affect the possible source locations identified by SQTBA. In this case, one-day back trajectories were employed. Initial studies with longer trajectories moved the location of the source region further upwind into areas that were not logical source areas. The SQTBA shows locations in northern India and western
Table 1. Fire regions selected for this study, as delineated by the boxes in Fig. 6.

<table>
<thead>
<tr>
<th>Map box number</th>
<th>Map box name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Total boxed area (10^5 km^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Rajshahi)a</td>
<td>Pakistan</td>
<td>34.88</td>
<td>71.37</td>
<td>24.91</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30.07</td>
<td>66.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>29.99</td>
<td>73.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>32.32</td>
<td>75.15</td>
<td></td>
</tr>
<tr>
<td>2 (all sites)</td>
<td>North India</td>
<td>31.28</td>
<td>74.36</td>
<td>66.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28.30</td>
<td>72.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.47</td>
<td>88.51</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>24.85</td>
<td>87.97</td>
<td></td>
</tr>
<tr>
<td>3 (Rajshahi)</td>
<td>Nepal</td>
<td>30.90</td>
<td>80.95</td>
<td>22.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28.92</td>
<td>79.45</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.40</td>
<td>88.07</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>27.99</td>
<td>88.24</td>
<td></td>
</tr>
<tr>
<td>4 (Rajshahi, Chittagong)</td>
<td>Bangladesh</td>
<td>26.43</td>
<td>89.21</td>
<td>15.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23.56</td>
<td>88.33</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>21.12</td>
<td>90.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.37</td>
<td>93.25</td>
<td></td>
</tr>
<tr>
<td>5 (Rajshahi, Dhaka, Chittagong)</td>
<td>Northeastern India</td>
<td>27.84</td>
<td>92.19</td>
<td>16.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26.43</td>
<td>89.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.05</td>
<td>94.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>27.99</td>
<td>96.15</td>
<td></td>
</tr>
<tr>
<td>6 (Chittagong)</td>
<td>Myanmar</td>
<td>25.72</td>
<td>95.27</td>
<td>36.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.96</td>
<td>92.29</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>17.98</td>
<td>96.59</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>21.94</td>
<td>100.28</td>
<td></td>
</tr>
</tbody>
</table>

a Observed biomass source locations for the site.

Fig. 2. Biomass burning concentrations during 2010–2012 winters for Rajshahi, Dhaka, Chittagong and Khulna sites estimated by Begum et al. (2014).

Nepal as biomass burning sources (Fig. 5(A)). The common regions between the SQTBA and RTWC results are western Nepal and part of northern India. There is substantial agricultural burning as well as biomass burning for space heating and cooking across the Indo-Gangetic Plain resulting in substantial PM concentrations in this area (Tiwari et al., 2009, 2013, 2015a, b). In rural areas, bio-fuels such as wood, dung cake, bagasse, and other crop wastes are commonly used fuels (Habib et al., 2006). In urban areas, low grade coal is commonly used for brick manufacture and is an important source particularly during the winter (Begum et al., 2004; 2005; Ram and Sarin, 2010; Tiwari et al., 2010; Begum et al., 2011a, 2014).

Rajshahi having the highest biomass burning concentrations was expected to have the largest influence on the RTWC and SQTBA results. Hence, second analyses
were made for Dhaka and Khulna with Rajshahi omitted. Northern and northwester India remained as main source areas in RTWC results (Fig. 4(B)). Fig. 5(B) shows that the probable source locations moved southward from the India-Nepal border in the SQTBA plot. These outcomes suggest Ganges Valley and parts of northwestern India...
were potential source regions for all three sites and west Nepal along with Himalaya range in India had an additional influence for Rajshahi.

Quantification of Potential Sources: Satellite Observations

High concentrations of light absorbing aerosol emissions including black carbon and inorganic oxidized matter, which is mostly particles from open burning of crop waste/forest-fires were reported over Indo-Gangetic Plain (Habib et al., 2006). The time series of normalized NFP and average of FRPs in the six identified source regions (Fig. 6) are presented in Fig. 7. Assuming similar combustion characteristics in each fire region, differences in mean FRP suggest differences in actual fire sizes within the region suggesting a strong covariance between FRP and fire size (Ichoku et al., 2008). Although NE India and Myanmar have the highest normalized NFPs, Nepal and northeastern India have the highest mean subpixel fire intensities (FRP) compared to other investigated locations (Fig. 7).

Further, for each fire region considered in this study, winter MODIS data were binned at 0 to < 100 MW (category 1), 100 to < 500 MW (category 2, warm fire), 500 to < 1000 MW (category 3, Peppin fire), 1000 to < 1500 MW (category 4, geysers) and ≥ 1500 MW (category 5, crown fire) (Ichoku et al., 2008) and used to generate frequencies normalized by the total NFP for each region and expressed as percentages for comparison (Table 2). All of the regions appear to have their highest frequency in the lowest category (0 to < 100 MW) and decreasing frequency with increasing FRP. Four of the regions did not have any category 4 and 5 FRP values. Nepal, northeastern India, and Myanmar had a reasonable fraction of fires in category 3. The total NFPs of the winter period corresponding to the sectors are also listed in Table 2.

Examination of the FRP data for the different regions shows that category 1 fires make up over 90% of fire pixels observed in most regions, with northeastern India and Nepal with between 80% and 90%, respectively. The proportion of Category 2 fires is between 0.8% and 14%, category 3 between 0% and 2%, while categories 4 to 5 each constitutes less than 0.5% of all fires detected in the regions. Pakistan, northern India, and Bangladesh showed no fires above category 2. These differences in fire strengths could lead to different biomass burning emissions.

To further refine the analysis, fire categories 4 and 5 were merged. The total fire numbers (during winters 2010–2012) for each cell is presented along their mean FRPs in Fig. 8. Sector one shows a distribution of fires in category 1 with low FRP. It also has some warm fires (Table 2). However, Fig. 8 shows that they are not located along trajectories leading to Rajshahi. Category 1 fires for sector two have a uniform spread with low FRP. This sector had a few fires (15) in category 2 in locations around the Ganges Valley. Northern India had fewer higher power fires, but sources like agricultural burning would generally be low power with high PM emission strengths. Northwestern parts of sector three (the high mountain region of Nepal) have the highest FRP in category 1 (57 NFPs above 70 MW).

These fires could affect the pollution in this area. Warm fires cover most of Nepal including Terai-Bhabar (southernmost physiographic region of Nepal), Siwaliks or inner Terai (next northerly physiographic region), the Middle Mountains (from 1000 m along the southern foothills of the Mahabharat Range to the hills of Nepal to an altitude of 2500 m), the High Mountains and High Himal Region (north) regions. It continues to the Himalaya range to western Nepal to parts of northwestern India. Nepal's capital domain (Kathmandu) had 3 NFPs with radiative power over 800 MW. Twelve percent of Rajshahi’s trajectories pass within 30 km of this city. NE India was the only sector that experienced all 5 fire categories. There was no observable transport from this sector to Khulna during this period based on the air mass trajectories.

The RTWC results suggested contributions from the southern part of this section as a probable source for the three other sites. The presence of the Garo-Khasi and Purvanchal mountains range in the path may reduce the pollution arrived to the sites in Bangladesh. Thus, this sector could not be as effective a source region as sector 3 because the mountains would block the transport of the PM.

Fig. 6. The map of investigated area; Numbered red boxes delineate different regions identified for independent and comparative MODIS fire analysis.
Table 2. Regional relative frequency distributions of categorized NFPs.

<table>
<thead>
<tr>
<th>Map box name</th>
<th>Fire category 1</th>
<th>Fire category 2</th>
<th>Fire category 3</th>
<th>Fire category 4</th>
<th>Fire category 5</th>
<th>Total NFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pakistan</td>
<td>97.88 (1153)</td>
<td>2.12 (25)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1178</td>
</tr>
<tr>
<td>Northern India</td>
<td>99.17 (1794)</td>
<td>0.83 (15)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1809</td>
</tr>
<tr>
<td>Nepal</td>
<td>88.72 (527)</td>
<td>10.77 (64)</td>
<td>0.51 (3)</td>
<td>0.00</td>
<td>0.00</td>
<td>594</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>98.10 (411)</td>
<td>1.90 (8)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>419</td>
</tr>
<tr>
<td>Northeastern India</td>
<td>84.55 (3552)</td>
<td>13.50 (567)</td>
<td>1.50 (63)</td>
<td>0.28 (12)</td>
<td>0.17 (7)</td>
<td>4201</td>
</tr>
<tr>
<td>Myanmar</td>
<td>96.73 (7006)</td>
<td>3.23 (234)</td>
<td>0.02 (2)</td>
<td>0.01 (1)</td>
<td>0</td>
<td>7243</td>
</tr>
</tbody>
</table>

*The values in parenthesis show the NFP for each fire category.

The last sector, Myanmar, only affects Chittagong as a likely source region. It has the highest NFPs with low mean FRPs within the first category, i.e., the fires that cover the smallest areas or are burning with low power (Wooster et al., 2012). Based on Fig. 8, most fires in Myanmar were behind the Arakan Mountains (with the highest elevation 3000 m) relative to Bangladesh. These mountains could potentially block the transport pathway and reduce the amount of PM arriving at Chittagong.

Forest fires occur annually in all the major physiographic/ climatic regions of Nepal, including north and south. Forest fires occur during the dry season (winter and spring) and the nature (surface fire, crown fire, etc.) as well as the severity varies greatly depending upon weather, fuel conditions, and physiography. Once the monsoon is established, usually by the middle of June, the fire prevalence disappears. Forest fires destroy timber and non-timber forest products and make the entire countryside...
hazy during the dry season (Fire | DPNET-Nepal, 2012). The high mercury concentration in areas near the mines could lead to other devastating effects (AsiaNews.it, 2012; BBC, 2012).

In Fig. 9, haze built up around the southern edge of the Himalayan Mountains in the winters of 2010–2012 (Nepal Images, 2016). Dull gray haze can be seen over Nepal, northern India and Pakistan, and parts of Bangladesh. Radiational inversions trap pollutants along with warm air at the surface, contributing to the buildup of haze.

The trajectory ensemble results show that the Indo-Gangetic Plain and southern Nepal have high probabilities of being source areas contributing to Rajshahi, Dhaka and Khulna. Fig. 10 shows the wind speed during the hours prior

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Fig. 8. (A) FRPs range 0 to < 100 MW (fire category 1) (B) FRPs range 100 to < 500 MW (fire category 2) (C) FRPs range 500 to < 1000 MW (fire category 3) (D) FRPs range ≥ 1000 MW (fire categories 4 and 5) (I) Number of fire pixels and (II) average FRP gradient for 2010–2012 winter seasons in each 0.74° × 1° cell
Fig. 9. Pollution and fog mixed at the base of the Himalayas in Nepal in (A) 8 February 2010 (B) 20 January 2011 (C) 5 December 2011 (D) 11 December 2011 (Nepal Images, 2016).

Fig. 10. Mean wind speed along sites’ trajectories due to the endpoint locations for Rajshahi, Dhaka, Chittagong and Khulna.

to arrival at Chittagong, Dhaka, and Khulna are significantly lower compared to Rajshahi. Thus, part of the higher concentrations observed at Rajshahi may be the result of more effective advection from the source areas by the higher wind speeds and channeling along the southern border of the Himalayan Mountains.

SUMMARY
This study has assessed the possible sources of the major difference between Rajshahi site biomass burning concentrations with 3 other sites in Bangladesh during the winters of 2010 to 2012. PSCF, RTWC, and SQTBA analyses suggested some differences in source locations for Rajshahi, Dhaka, Chittagong, and Khulna with areas of Myanmar have been investigated and quantified. Western Nepal, and the Himalaya Mountain areas in India, NE India and Myanmar were distinguished as the most likely source locations. Considering prevailing wind directions, western Nepal and the Himalayan Mountain area of India
have a greater impact on Rajshahi potential because of higher wind speeds advecting the biomass burning particles more effectively to Rajshahi. Some trajectories ending at Dhaka, Chittagong, and Khulna do pass through this same region, but most of those trajectories have lower mean wind speed. The Garo-Khasi and Purvanchal Mountains may also serve as a barrier from these areas.

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