AMBIENT AIR QUALITY IN BANGLADESH

CLEAN AIR AND SUSTAINABLE ENVIRONMENT PROJECT

Department of Environment
Ministry of Environment, Forest and Climate Change
Government of the People's Republic of Bangladesh

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Minister

Ministry of Environment, Forest and Climate Change
Government of the People's Republic of Bangladesh

FOREWORD

The Ministry of Environment, Forest and Climate Change has given utmost attention to address environmental pollution in the country.

Air pollution is one of the major environmental threats Bangladesh is experiencing in recent years. Although the air pollution is a phenomenon of only four months of the dry season, we have given special attention to control the air quality throughout the country. The Ministry of Environment, Forest and Climate Change has undertook Clean Air and Sustainable Environment (CASE) Project with a view to identify the gross air polluting sectors, to design and demonstrate cleaner technologies in brick manufacturing sectors, and to study the emissions from other major sources like vehicles, industries, etc., and the means to curb the emissions. However, the air quality monitoring is the foremost task which reveals the extent and type of the problem, and the possible cost effective measures to be exerted for the remedy.

It is a matter of great happiness that the CASE project has prepared this report with the massive air quality database produced in 08 cities from 2012 to 2018. This report will certainly express many critical information on the nature and characteristics of air quality in the urban areas of Bangladesh, which may be helpful for formulating air quality management program for the cities to curb air pollution in the country.

I thank to the team involved in preparing this report, and hope utmost utilization of this report.

13.09.18

Anisul Islam Mahmud, M.P

Deputy Minister
Ministry of Environment, Forest and Climate Change
Government of the People's Republic of Bangladesh

FOREWORD

The report "Ambient Air Quality in Bangladesh" prepared by the Clean Air and Sustainable Environment (CASE) Project of the Department of Environment bears high importance in the sector of air quality of Bangladesh. The report is the outcome of the continuous monitoring of air quality performed in eight cities for six years period. Such an immense work on air quality sector had not been taken place before in the country, and so it is believed that the results and recommendations brought out from the analyses in this report would serve as a realistic ground for air quality management in the country.

I expect the monitoring work will continue with expanded monitoring coverage in the country, and such report be produced time to time. This is how we may assess the effect of any policy interventions made by the government to reduce environmental pollution including air. I truly appreciate the work and thank to the team behind this.

Abdullah Al Islam Jakob, M.P

Secretary
Ministry of Environment, Forest and Climate Change
Government of the People's Republic of Bangladesh

FOREWORD

The Ministry of the Environment, Forest and Climate Change has been implementing the Clean Air and Sustainable Environment (CASE) Project in Bangladesh with the financial assistance from the World Bank. The project has been performing excellently in monitoring the air quality in the urban areas of the country. All parts of the country are now under the monitoring network which provides real-time information on the characteristics of air quality in the country. This is an immense task which is expected to provide adequate baseline information to fight the air pollution problem of the country.

The CASE project has prepared this report on the basis of six years (2012-2018) trends of air quality in the urban areas of Bangladesh. This sort of great work is not found to happen before in the country. The report has excellently analyzed from many views the long term data accrued from the stations, and unfurls many characteristics of air quality of the cities. The results and recommendations from the report will help undertake decisions to control air quality in the country.

I appreciate this worthy work done by the CASE project and expect continuation of the work.

Abdullah Al Mohsin Chowdhury

Additional Secretary
Ministry of Environment, Forest and Climate Change
Government of the People's Republic of Bangladesh
And
Project Director
Clean Air and Sustainable Environment Project
Department of Environment

FOREWORD

The Ministry of Environment, Forest and Climate Change is responsible for sustainable environmental management of Bangladesh. The ministry has taken many initiatives towards environmental issues including environmental pollution control.

Air is an important component of the environment. It is so essential that the human being cannot survive more than a minute without it. Alarmingly, this crucial component of the environment is getting severely polluted by some anthropogenic activities, which wreaks great damage to the human health, nature and the properties. The medical science has found air pollution closely related with many fatal and harmful diseases in human body. The World Health Organization (WHO) reveals about 7.0 million people die worldwide due to the inhalation of polluted air. It is thus an imperative task to continuously monitor air quality status in the country and to take useful measures to control its quality.

The Clean Air and Sustainable Environment (CASE) Project of the Department of Environment (DoE) with the financial assistance from the World Bank has been implementing numbers of activities for the air quality management in Bangladesh. In addition to the continuous air quality monitoring in major cities, the project performs several studies on source apportionment, emission inventory, and dispersion modeling. Conversions of high polluting Fixed Chimney Kilns to improved Zigzag kilns have been done with demonstrations in 08 cities. More than 50% emission reductions are achieved at the converted improved zigzag kilns for brick manufacturing. To lessen emissions from this sector, the project helps the DoE formulate brick burning rules under the brick burning and control act- 2013, and also conducts studies on manufacturing alternative building materials. Besides the brick sector, the project conducts regular emission testing on the on-road vehicles and assists in revising the vehicle emission standards in Bangladesh.

This report analyzes and illustrates various characteristics of air quality measured under this project in Dhaka, Chittagong, Gazipur, Narayanganj, Khulna, Rajshahi, Sylhet, and Barisal cities from 2012 to 2018. This work is first of its kind in the country and is expected to be utilized in making policy decisions to control air quality in Bangladesh.

I would like to thank to the team members of the CASE Project involved in air quality data generation, processing, interpretation, and preparation of this comprehensive report.

Dr. S.M. Munjurul Hannan Khan

PREFACE

This report "Ambient Air Quality in Bangladesh" illustrates, interprets and discusses the trend characteristics of air quality in 8 cities of Bangladesh. At present, Eleven (11) continuous air and meteorology monitoring stations have been continuously recording the concentrations of the criteria air pollutants and meteorology parameters in 8 cities from 2013; the cities are Dhaka, Chittagong, Narayanganj, Gazipur, Khulna, Rajshahi, Barisal and Sylhet. In this report, short and long term trends of air quality in the cities are studied and demonstrated, and compared with the standards set by the Government of Bangladesh. In addition to the seasonal and diurnal trends of the components, directional influences and statistical parameters (mean and percentile values) of especially PM concentrations in each city are calculated and demonstrated. Calculation of Air Quality Index (AQI) and its publication for the public awareness are also shown; records of AQI from 2014 to 2017 are provided in the appendix to the report for realizing the number of days in a year with good, bad and worse air quality in the cities. Principles of measuring the components, quality control, and data management and analysis techniques are also provided in details. Additionally, Brief discussions on the socio-economic and source characteristics, topographical features, and meteorological trends of the cities are provided in the report.

CONTENTS

ABBREVIATIONS

AQI	Air Quality Index
AQM	Air Quality Monitoring
BARC	Bangladesh Agricultural Research Corporation
BARI	Bangladesh Agricultural Research Institute
BNAAQS	Bangladesh National Ambient Air Quality Standard
BRRI	Bangladesh Rice Research Institute
BS	Bangladesh Standard
BSMRAU	Bangabandhu Sheikh Mujibur Rahman Agricultural University
CAMS	Continuous Air Monitoring Station
CAP	Criteria Air Pollutants
CASE	Clean Air and Sustainable Environment Project
CDS	Central Data Station
CNG	Compressed Natural Gas
COPD	Chronic Obstructive Pulmonary Disease
DCC	Dhaka City Corporation
DoE	Department of Environment
DTCA	Dhaka Transport Coordination Authority
FCK	Fixed Chimney Kiln
GDB	Global Burden of Disease
GDP	Gross Domestic Product
GoB	Government of Bangladesh
GPRS	General Packet Radio Service
IR	Infrared
NCDC	National Climatic Data Centre
NOAA	National Oceanic and Atmospheric Administration of the United States of America
NDIR	Non Dispersive Infrared

NSTI	National Institute of Standards and Technology
PAN	Peroxyacetyl Nitrate
PM	Particulate Matter
PMT	Photo Multiplier Tube
QA/QC	Quality Control/Quality Assurance
SQL	Structured Query Language
SRO	Statutory Regulatory Order
USEPA	United States Environment Protection Agency
UV	Ultra Violet
WB	World Bank
WHO	World Health Organization

SYMBOLS

CO	Carbon Monoxide
CO_2	Carbon Dioxide
HNO_3	Nitric Acid
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
O_3	Ozone
OH	Hydroxyl Radical
Pb	Lead
PM	Particulate Matters
PM_{10}	Particulate Matter with Aerodynamic Diameter less than 10 Micrometer
$PM_{2.5}$	Particulate Matter with Aerodynamic Diameter less than 2.5 Micrometer
SO_2	Sulfur Dioxide
SO_3	Sulfur Trioxide
SO_x	Oxides of Sulfur

UNITS

ppb	parts per billion
ppm	parts per million
$\mu g/m^3$ or $\mu g\ m^{-3}$	microgram per cubic meter
^oC	Degree Centigrade
%	Percent

ACKNOWLEDGEMENT

The CASE project, DoE component would like to offer special thanks to the Ministry of Environment, Forest and Climate Change of the Government of Bangladesh for its continued support, encouragement and guidance. The Department of Environment (DoE) also contributes greatly to the activities of the project; the cooperation of the DoE in the administrative works, and in establishing and managing the air monitoring stations are remembered with great sense. The project would like to acknowledge the efforts and contributions of the officials of the DoE and CASE project to the operations and maintenance of the air monitoring stations. Finally, the project deeply acknowledges the financial assistances from the World Bank vide its credit facility (id # 4581 BD and 5924 BD). The encouragement, assistances and guidance of the team members of the CASE project of the World Bank office helped manage the tasks of the project in time.

1 EXECUTIVE SUMMARY

The urban areas of Bangladesh has been suffering from heightened level of particulate matter in air, especially in dry season (November – April) when this region experiences scarce rainfall, northwesterly wind and low relative humidity. The Government of Bangladesh has issued in 2005 a set of limit values for the criteria air pollutants (PM, Pb, SO_2, CO, NO_x and O_3). Several measures were taken at different times to improve the air quality in urban areas of the country, major of which were, (a) removal of lead from the gasoline in 1999, (b) phase-out of 2-stroke 3-wheeled baby taxis from Dhaka in early 20's, (c) introduction of cleaner fuel CNG to transport sector in early 90's, (d) enlargement of the chimney height of the fixed chimney kiln (FCK) for brick production, and recently (e) adoption of new brick burning and control law – 2013 (revised) which prohibits energy-extensive FCKs in brick manufacturing sector. These interventions instantly improved the air quality during the time of implementation; however, the massive influx of populations in urban centers in the following years, and consequently the requirement and use of excessive fuel canceled out the benefits gained from those interferences.

The Ministry of Environment, Forest and Climate Change of the Government of Bangladesh has been implementing Clean Air and Sustainable Environment (CASE) project with the financial assistance from the World Bank. Started in 2010, the project is set to end in June 2019. Three agencies, Department of Environment (DoE), Dhaka City Corporation (DCC) and Dhaka Transport Coordination Authority (DTCA) are executing their respective part of the project; while the DoE component is building up the infrastructures for continuously monitoring the air quality, tracking sources and finding ways of reducing industrial emissions, the DCC and DTCA components are finding solutions to lessen the vehicular emissions by modernizing traffic systems, building up facilities for pedestrians' movement, and by facilitating smooth traffic flow and mass transit.

The DoE component of the CASE project (from now, only CASE Project) has so far established 11 continuous air monitoring stations (CAMS) in 8 major cities; 05 more

CAMS and 15 compact monitoring systems will be installed in different locations in short time. The monitoring network encompasses all the regions of the country - Dhaka, Narayanganj, Gazipur in the center, Chittagong in the south-east, Khulna and Barisal in the south, Rajshai in the west, and Sylhet in the north-east regions of the country. Five (05) criteria air pollutants (PM, SO_2, NO_x, O_3, and CO) and meteorology parameters are being monitored every minute in the CAMS. All of the stations are connected via GPRS with a central server system at Dhaka office where the historical data at 15 minutes average are stored and analyzed.

In this report, the results of the analyses of air quality and meteorological data produced at the stations from 2013 to 2018 are illustrated and described. Rigorous statistical analyses have been performed to understand the seasonal, diurnal and directional trends of the components in the cities. Statistical parameters (mean, percentiles, etc.) of especially particulate matter (PM) concentrations are calculated for every year to observe the year-wise and city-wise stances of air quality in the country. The outcome of the analyses are summarized as follows,

1. The trends and characteristics of air quality in all the regions of the country are highly affected by the meteorological changes in different seasons. Dry seasonal (November – April) PM pollution all over the country is found the main concern.
2. The gaseous pollutants (i.e. SO_2, CO, NO_x, and O_3) in air of the cities, irrespective of the seasons, satisfy well the respective standards set by the government. Only in several cases, NO_2 and O_3 concentrations at Chittagong station are found very close to the limit values.
3. The analyses reveal Narayanganj as the most polluted city in Bangladesh. PM concentrations in dry season in Dhaka and Gazipur are found mostly similar although Dhaka site is urban, congested and the Gazipur site is urban background. Compared to Dhaka station, Chittagong, Sylhet and Barisal stations experience about 25, 30 and 25 % lower annual PM_{10} concentrations, and 13, 30 and 10 % lower annual $PM_{2.5}$ concentrations. Thus, Sylhet is found the least polluted city among the cities being monitored, and Chittagong and Barisal stations experience relatively higher $PM_{2.5}$ mass contribution to PM_{10} concentration.
4. A declining trend in annual PM_{10} and $PM_{2.5}$ concentrations in Dhaka is observed. Compared to 2013-14, the Dhaka station experiences about 12 and 14 % lower PM_{10} and $PM_{2.5}$ concentrations (annual) respectively in 2017. This reduction in yearly PM concentrations in air may be attributed to the ongoing reforms in the brick kiln sector.
5. Wind patterns in dry and wet season in Bangladesh are opposite. Most of the regions of the country in dry season experience wind from the west, north and northwest directions; only the northeast region (Sylhet) of the country acquires wind from the northeast and southwest directions in dry season. The wet seasonal wind comes mostly from the south and southeast directions.
6. Fine particles ($PM_{2.5}$) in dry season usually dominate in the contributions to PM concentrations all the time of the day except in the evening when the coarse particles (PM_{10} – $PM_{2.5}$) are found equal to or sometimes greater than the fine particles. However, in Chittagong and Sylhet coarse fractions of PM get equal to or sometimes greater than the fine particles from noon to 9:00 pm.

2 INTRODUCTION

Air pollution in recent time has become a grave concern all over the world especially for its association with multidirectional adverse effect on health, climate, ecosystem, culture and customs, etc. The medical science has been discovering every-time newly the affiliation of air pollution with many of the serious health burdens like, (a) the WHO recently affirms the organic particles carcinogenic, (b) a European research has found exposure to air pollution during pregnancy may alter the structure of the infant-brain, (c) the Chinese University of Hong Kong observes exposure to fine particle increases the risk of reduced lung function and could result in the development of chronic obstructive pulmonary disease (COPD). The mortality count calculated in recent studies due to the air pollution is also alarming – about 7.0 million premature deaths globally relate to air pollution, according to the WHO. A report on global burden of disease (GDB) by the US-based Health Effect Institute has ranked air pollution as one of the top ten killers in the world, and sixth most dangerous killer in South Asia.

With the rapid growth in urbanization and industrialization, the air pollution situation is getting aggravated around the urban centers worldwide. Bangladesh is not exceptional - the urban population has been growing quite rapidly in the country. The average decadal urban population growth is 2.92%; while for Dhaka it is around 5%. More than one-third of Bangladesh's population is already urban and this share is expected to grow substantially should the growth rate persist. Bangladesh GDP is estimated at $216 billion in 2016 with a share of industry at 17.3% ($37 billion). Such an influx in urban habitats, motor vehicles and industries, and the primitive practices in biomass burning worsen the urban air quality in the country. Source apportionment of air pollution in the major urban centers (i.e. Dhaka, Chittagong) has been changing from the last two/three decades for the major switch in fuel-use in vehicle sector, government policies, and upsurge in other sources like brick kilns, steel mills, etc. Latest source apportionment study attributes about 58% of the fine particle concentration in Dhaka to the brick kiln industry, 10.4% to vehicles and 15.3% to dusts (CASE project, 2014[1]), whereas in the previous apportionment result the contributions from these prime sources were 22.0, 36.0 and 24.5 % respectively (Begum et al. 2013[2]). The implementation of any policy, reforms in source sectors, or major switch in fuel-use or technology should be reflected in the results of air quality monitoring, which is so an important primary tool of air quality management in a region/country.

The Clean Air and Sustainable Environment (CASE) Project of the Department of Environment (DoE) has been establishing a countrywide air quality monitoring (AQM) network. Eleven (11) continuous air monitoring stations (CAMS) have so far been established in 8 major cities; 05 more CAMS and 15 compact monitoring systems will be installed in different locations of the country in short time. The network encompasses all the regions of the country - Dhaka, Narayanganj, Gazipur in the center, Chittagong in the south-east, Khulna and Barisal in the south, Rajshai in the west, and Sylhet in the north-east region of the country. Five (05) criteria air pollutants (PM, SO_2, NO_x, O_3, and CO) and useful meteorology parameters are being monitored every minute in the CAMS; the data are transferred to the central server system at Dhaka office where the historical data at 15 minutes average are stored and analyzed. Air Quality Index (AQI) for each city is calculated and published online daily for notifying the public about the status of air quality in their respective city.

In this report, air quality trends in the cities from 2013 to April 2018 have been illustrated. Seasonal, diurnal and directional variations of hourly concentrations of the pollutants are demonstrated and analyzed. Within this time period, a major intervention on the brick kiln sector has been done – the government has adopted a new brick burning and control law- 2013, for which energy-extensive Fixed Chimney Kilns are getting converted, slowly though, to relatively environment-friendly zigzag kilns in the country.

2.1 Criteria Air pollutants

Six pollutants (i.e. particulate matter, sulfur dioxide, nitrogen oxides, ozone, carbon monoxide and lead) are termed as the criteria air pollutants (CAP) for their abundances as pollutants in the atmosphere and ability to harm human health, plants, and properties. The Government of Bangladesh (GoB) has set standards for each of the CAP for controlling their presence in air. The CASE project under the DoE monitors all of the CAPs, except lead, in air of the major cities of the country. Lead concentrations in ambient air are significantly reduced after the phase-out of lead additives in gasoline in mid 1999 (Begum and Biswas 2008[3]). An introductory notes on the characteristics, sources and health impact potential of each of the CAP is given below,

2.1.1 Sulfur Dioxide (SO_2)

Sulfur dioxide is a colorless gas with characteristics of pungent odor, more soluble in cold than in hot water. The largest sources of SO_2 emissions are fossil fuel combustion at power plants and other industrial facilities like brick kilns. Emissions that lead to high concentrations of SO_2 generally also lead to the formation of other sulfur oxides, of which SO_3 is important. Other gaseous SO_x (such as SO_3) are found in the atmosphere at concentrations much lower than SO_2.

Sulfur dioxide gas is corrosive and severe irritant. Some individuals especially children, the elderly, and those who suffer from asthma are extremely sensitive to the effects of sulfur dioxide. Exposure to high concentrations of SO_2 for several minutes produces respiratory paralysis and pulmonary edema with a risk of death. At high concentrations, gaseous SO_x can harm trees and plants by damaging foliage and decreasing growth. SO_2 is also responsible for acid rain

1 Identification and apportionment of sources from air particulate matters at urban environments in Bangladesh http://case.doe.gov.bd/

2 "Air pollution by fine particulate matter in Bangladesh" Atmospheric Pollution Research, 2013

3 "Trends in particulate matter and lead pollution in ambient air of Dhaka city in Bangladesh" Journal of Bangladesh Academy of Sciences, 32(2)

which affects the ecosystem and damage building and historical monuments. SO_2 oxidized by OH^- in the atmosphere reacts with oxygen and water to form sulfuric acids which then mix with water and other materials before falling to the ground. Winds can blow SO_2 over long distances and across borders making acid rain a problem for everyone and not just those who live close to these sources.

2.1.2 Nitrogen Oxides (NO_x)

Nitrogen oxides (NO_x) in the ambient air consist primarily of nitric oxide (NO) and nitrogen dioxide (NO_2). These two forms of gaseous nitrogen oxides are significant pollutants of the atmosphere. Another form, nitrous oxide (N_2O), is a greenhouse gas. At the point of discharge from anthropogenic sources, more than 90% of NO_x is released as NO, a colorless and tasteless gas; the rest is mainly NO_2. NO is readily converted to the much more harmful NO_2 by chemical reaction with ozone present in the atmosphere. NO_2 is a yellowish-orange to reddish-brown gas with a pungent, irritating odor, and is a strong oxidant.

Nitrogen oxides are released into the air from motor vehicle exhaust or the burning of coal, oil, diesel fuel, and natural gas, especially in electric power plants. They are also released during industrial processes such as welding, electroplating, etc. Exposure to high levels of nitric oxide and nitrogen dioxide can cause collapse, rapid burning and swelling of tissues in the throat and upper respiratory tract, difficult breathing, throat spasms, and fluid build-up in the lungs. It can interfere with the blood's ability to carry oxygen through the body, causing headache, fatigue, dizziness, and a blue color to the skin and lips.

Nitrogen oxides are precursors to ozone which itself is an air pollutant and a short lived climate pollutant. Both the NO_x and O_3 are dominant components of photochemical smog long-term exposure to which can trigger serious respiratory problems, including damage to lung tissue and reduction in lung function. Peroxyacetyl Nitrate (PAN) produced in the troposphere by photochemical oxidation of carbonyl compounds in the presence of NO_x is another damaging by-product of the smog. A portion of nitrogen dioxide in the atmosphere is converted to nitric acid (HNO_3) and ammonium salts.

2.1.3 Ozone (O_3)

Ozone molecules in the stratosphere while are benign for the living species on earth, its presence in the troposphere is malignant. In the troposphere, ground-level ozone molecules are both air pollutants and greenhouse gases. Unlike most other air pollutants, ozone is not directly emitted into the air; it is formed by the interaction of sunlight, particularly ultraviolet light, with hydrocarbons and nitrogen oxides, which are emitted by automobile tailpipes and smokestacks.

When inhaled, ozone can damage lung tissues. Ozone is harmful to all types of cells. It may create more frequent attacks on individuals with asthma, cause eye irritation, chest pain, coughing, nausea, headaches and chest congestion. It can worsen heart disease, bronchitis, and emphysema. Tropospheric ozone is a major component of photochemical smog. Children, older adults and people with lung or cardiovascular diseases are particularly at risk of adverse health effects. Ozone has detrimental impacts on trees and plants too; it is responsible for important reductions in crop yields. O_3 reduces the ability of plants to absorb CO_2, altering their growth and variety. It damages ecosystem structures and functions, as well as the health and productivity of crops, thus threatening food security.

2.1.4 Carbon Monoxide (CO)

Carbon monoxide is a colorless, odorless, tasteless gas. It is also flammable and is quite toxic to humans and other oxygen-breathing organisms. Hemoglobin, the protein in blood that carries oxygen from the lungs to cells throughout the body, is more than 200 times more prone to bind with carbon monoxide than it is with oxygen. This means that someone who breathes too much CO can have their hemoglobin become saturated with it, making it impossible for the blood to deliver oxygen to their cells. Carbon monoxide (CO) is present in the troposphere as a product of fossil fuel combustion, biomass burning and the oxidation of volatile hydrocarbons. CO is often a product of incomplete combustion – if there is too little oxygen, or too much carbon, present when something burns, the burning produces carbon monoxide (CO) instead of (or as well as) carbon dioxide (CO_2).

Atmospheric carbon monoxide levels in typical urban areas are around 10 ppm (parts per million), about 100 times higher than in Earth's atmosphere overall. In areas with heavy traffic, CO levels can rise to as high as 50 ppm. Carbon monoxide indirectly contributes to the buildup of some greenhouse gases in the troposphere. It reacts with certain chemicals that would otherwise destroy methane and ozone, thus helping to elevate the concentrations of methane and ozone in the atmosphere.

2.1.5 Particulate Matters

Particulate Matters (PM) are the mixture of solid particles or liquid droplets suspended in air. This complex mixture includes both organic and inorganic particles, such as dust, pollen, soot, smoke, and liquid droplets. Particles in air vary greatly in size, composition, and origin, and are divided into two categories depending on the size of the particles (aerodynamic diameter). Coarse particles are relatively large airborne particles mainly produced by mechanical processes. Coarse particles include dust, pollen, spores, fly ash, and plant and insect parts. Coarse particles have an aerodynamic diameter ranging from 2.5 to 10μm ($PM_{10-2.5}$). Fine particles are airborne particles which are smaller than coarse particles. They have an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$). The fine particles which are smaller than 0.1 μm are referred to as the ultrafine particles ($PM_{0.1}$) which is actually a part of fine particles. Fine particles are largely formed from gases through the chemical processes in the atmosphere.

The fine fraction of particles is the most noxious components in air for impacting human health. The fine fraction contains most of the acidity (hydrogen ion) and mutagenic activity of particulate matter. Chemically enriched fine particles can penetrate deep into the respiratory system and inflict a great damage to the system. Recent studies reveal relations of fine/ultrafine particles with fatal diseases like cancers, diabetes, heart attack, etc.

2.2 Objective of the Report

Air quality monitoring serves as the baseline of any air quality management program for a city/region. The CASE project has been entrusted with a pivotal role of generating and supplying regular air quality data to the policy makers, stakeholders and the public. The outcome of the air quality monitoring primarily indicates necessity and extent of controlling emission from the sources. Many times, the presence and nature (point, area/volume etc.) of sources responsible for air pollution at a site may be inferred from monitoring data analyses (both chemical and statistical). Air quality monitoring results also reflect the effect of pollution abatement measures taken by the authority in a city or a country. For example, the air monitoring results certified the improvement of the air quality in Dhaka city by about 40% after phasing out of two stroke three wheel baby taxis in 2001 (Begum et al. 2006[4]).

The main purpose of this report is to present, analyze and make available the air quality data generated at 8 major cities of Bangladesh to the public, stakeholders, researchers and policy makers.

4 "Impact of Banning of Two-Stroke Engines on Airborne Particulate Matter Concentrations in Dhaka, Bangladesh", Journal of the Air & Waste Management Association, 56, 85-89

Specific Objectives of this report are:

- To analyze the concentration data of SO_2, NO_x, CO, O_3, PM_{10} and $PM_{2.5}$ in ambient air of the cities;
- To evaluate ambient air quality compliance of the cities with respect to BNAAQS;
- To evaluate short and long term trends in the concentrations of the CAPs;
- To squeeze out the characteristics of air quality in the cities;

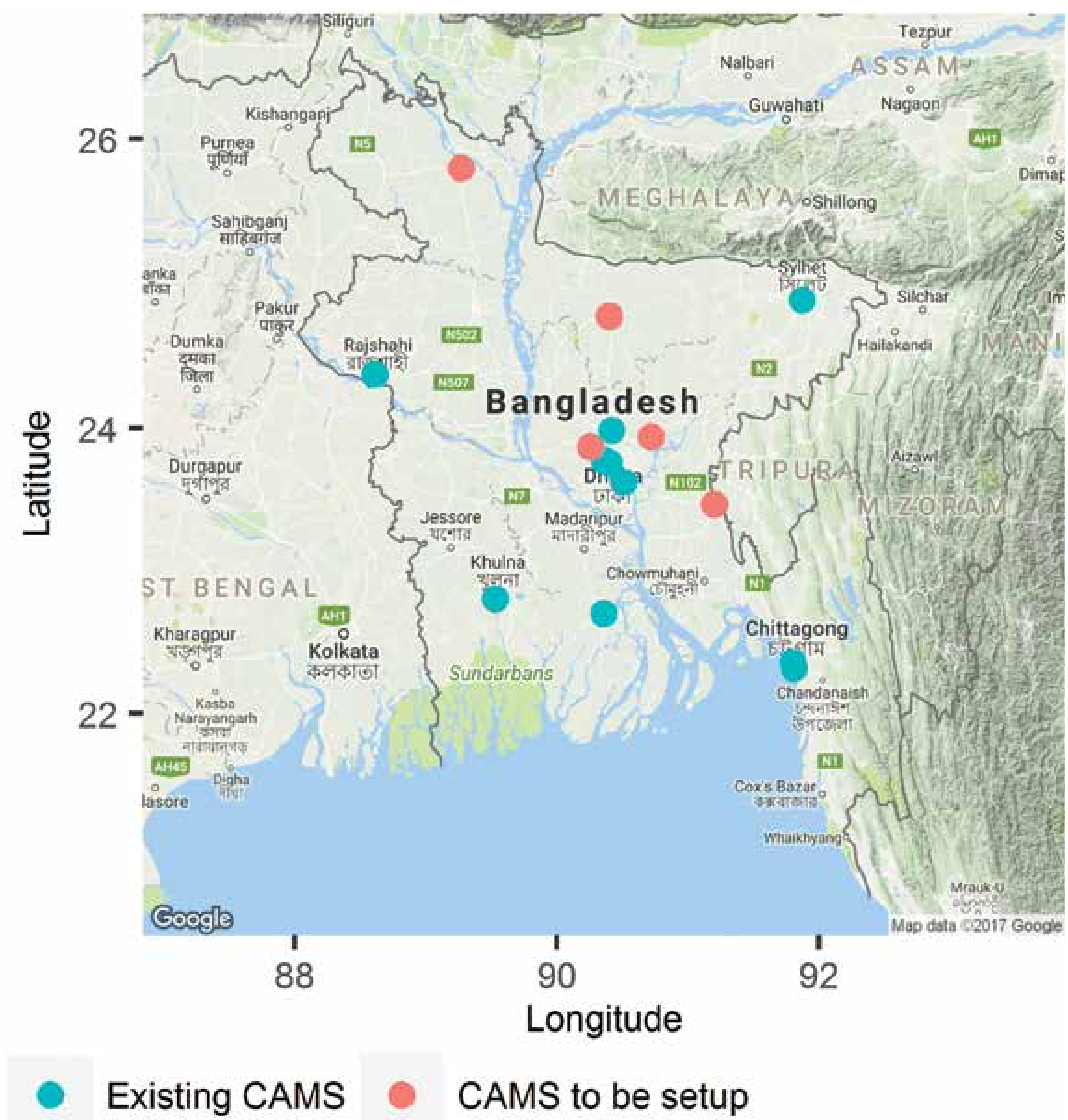
In addition, this report may also serve

- To validate air quality assessment measured by other means like models;
- To assess the impacts of changes in source characteristics in the cities;

2.3 Air Monitoring Network

General guidance suggests regular air quality monitoring in cities with populations exceeding 500,000. The populations of the divisional cities and

Figure 1 Locations of existing and future establishment of Continuous Air Monitoring Stations (CAMS) under CASE Project in Bangladesh



some district cities of Bangladesh surpass this number and need regular monitoring of air quality. Several cities like Dhaka, Chittagong, etc. have much greater population and require air monitoring at multiple sites. Under the CASE project of the Department of Environment, three CAMS are operating in Dhaka city, two in Chittagong, and one each in Khulna, Rajshahi, Sylhet, Barisal, Gazipur and Narayanganj cities. Expansion of the network is under process; five CAMS will be established, each in Savar, Narsindhi, Comilla, Mymensingh, and Rangpur very soon. Fifteen (15) compact air monitoring systems will also be joined with the network in short time. The monitoring network is designed based on the requirement of the cities, wind direction profiles and critically importance of the sites. Figure 1 shows the air monitoring network being established under the CASE project of the DoE and table 1 provides information on the CAMS.

Table 1 Overview of the locations and capacity of the CAMS

City	CAMS ID	Location	Lat/Lon	Monitoring capacity
Dhaka	CAMS-01	Parliament building area, Sher-e-Bangla Nagar	23.76N 90.39E	PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X, O_3, with meteorological parameters.
	CAMS-02	BARC, Farmgate	23.76N 90.39E	PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X, O_3, with meteorological parameters.
	CAMS-03	Darus-Salam	23.78N 90.36E	PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X and O_3 with meteorological parameters.
Gazipur	CAMS-04	Gazipur	23.99N 90.42E	PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X and O_3 with meteorological parameters.
Narayangonj	CAMS-05	Narayangonj	23.63N 90.51E	PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X and O_3 with meteorological parameters.
Chittagong	CAMS-06	TV station, Khulshi	22.36N 91.80E	PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X and O_3 with meteorological parameters.
	CAMS-07	Agrabad	22.32N 91.81E	PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X and O_3 with meteorological parameters.
Khulna	CAMS-08	Baira	22.48N 89.53E	PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X and O_3 with meteorological parameters.
Rajshahi	CAMS-09	Sopura	24.38N 88.61E	PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X and O_3 with meteorological parameters.
Sylhet	CAMS-10	Red Crecent Campus	24.89N 91.87E	PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X and O_3 with meteorological parameters.
Barisal	CAMS-11	DFO office campus	22.71N 90.36E	PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X and O_3 with meteorological parameters.

2.3.1 Dhaka

Dhaka (latitude 23.42N, longitude 90.22E) is the capital of Bangladesh. It is the home of about 12 million people, living in an area of about 360 km^2. Dhaka is one of the most densely populated cities in the world and facing a high level of air pollution (Rana et al. 2016[5]). The city is congested with high emitting vehicle fleet; lots of small-scale factories are also operating in the city. Construction of roads, buildings, etc. is a good source of air pollution. High influx of people from rural areas, emissions from various kinds of badly maintained motor vehicles and biomass/coal burning for cooking and brick manufacturing, huge number of construction works, re-suspended road dust etc. contribute to bad air quality in the city.

5 "Trends in atmospheric particulate matter in Dhaka and the vicinity" Environmental Science and Pollution Research, (2016) 23:17393–17403

Figure 2 Location of the CAMS-01 at Parliament Building Area in Dhaka

Three Continuous Air Monitoring Stations (CAMS) are operating in Dhaka city under DoE's monitoring network; brief descriptions on these sites are given below:

2.3.1.1 CAMS-01(Parliament Building Area, Dhaka)

The CAMS is operating at the National Assembly premises at Manik Mia Avenue. Established in 2002, this is the first continuous monitoring station in the country. No local source very close to the station is present; however, major city roads with moderate traffic density cross the area with a distance of 500 m. The sampling inlets are located on the flat roof of the CAMS shelter about 3 m above the ground and the intake nozzle is located 1.8 m above the roof with good natural ventilation. Figure 2 shows the location of the CAMS.

2.3.1.2 CAMS-02 (BARC, Farmgate, Dhaka)

The second CAMS in Dhaka is located at the first floor of the guardhouse of Bangladesh Agricultural Research Council (BARC) at Farmgate. The location is characterized with high traffic area with an intersection of several main roads with heavy traffic (Figure 3). The sampling inlets are placed on the flat roof of the CAMS shelter. The roof height is about 7 m above the ground and the intake nozzle of the sampler is located 1.8 m above the roof. The site is about 5 meter away from the major traffic artery with good natural ventilation.

2.3.1.3 CAMS-03 (Darus Salam, Mirpur, Dhaka)

The third CAMS is situated at the Mass Communication Institute at Darus Salam area. This location is also characterized with heavy traffic; a large number of vehicles from the northern part of the country enter the city through this way. Major brick kiln clusters are also near the site. The CAMS site is situated about 100 meter away from the main road. The roof height is about 7 m above the ground and the intake nozzle of the sampler is located 1.8 m above the roof.

Figure 3 Location of the CAMS-02 at Farmgate area in Dhaka

2.3.2 CAMS-04 (Gazipur)

Gazipur (latitude 24.00 N, longitude 90.43 E) is a district town of Dhaka Division. The City Corporation area covers about 329 square kilometer with a population of about 2.5 million. Various establishments such as Islamic University of Technology, Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Bangladesh Rice Research Institute (BRRI), Bangladesh Agricultural Research Institute (BARI), Dhaka University of Engineering and Technology are situated in this district.

Figure 4 Location of the CAMS-03 at Darus-Salam area in Dhaka

The Gazipur CAMS is located in the City Corporation graveyard premises at East Chandana, which is 0.5 km southeast of the City Corporation office. It is about 15 meter away from a local road carrying low traffic and 0.5 Km away from the national rail tract. The location is relatively unaffected by nearby air pollution sources except some construction activities around. This site can be used as the background station and the data collected from the CAMS can be used as the base information for further air pollution studies of the area.

The sampling inlets are placed on the flat roof of the CAMS shelter. The roof height is 7 m above the ground and the intake nozzle of the sampler is located 1.8 m above the roof.

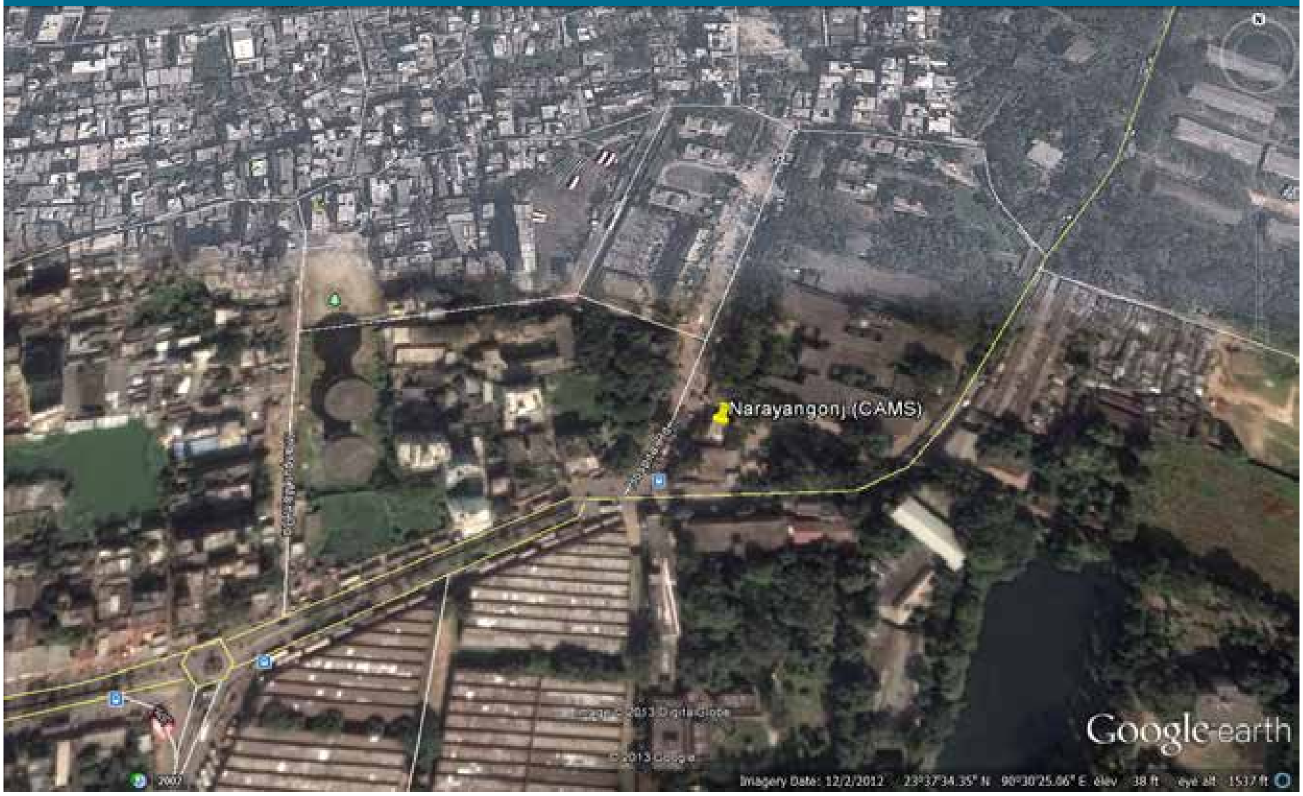
2.3.3 CAMS-05 (Narayangonj)

Narayanganj (latitude 23.60 N, longitude 90.50 E) is a district town, about 30 km southeast from the capital city of Dhaka. The river port of Narayanganj is one of the oldest in Bangladesh. It is also a hub of business and industry, especially the jute trade and processing plants, and the textile sector of the country. Small and medium industries of cotton are increasing day by day. Due to the establishment of various industries and traffic movement, air pollution of the city has been increasing and posing threat to the city dwellers.

A CAMS is monitoring criteria air pollutants at the first floor of the guardhouse of 200 Bed Government Hospital in Khanpur, Narayanganj. Different emission sources are located around the CAMS site, i.e. Diesel run water vessels run just about 200m south from the site, Chasara intersection is located at 1.0km west from the site and some industries are located just 0.5km north from the CAMS. This site is characterized by different emission sources. The sampling inlets for gaseous and particulate matter are placed on the flat roof of two storied building of the CAMS shelter. The roof height is 7 m above the ground and the intake nozzle of the sampler is located 1.8 m above the roof. The site is about 5.0 meter away from the traffic artery with good natural ventilation.

Figure 5 Location of the CAMS-04 in Gazipur

Figure 6 Location of the CAMS-05 in Narayanganj

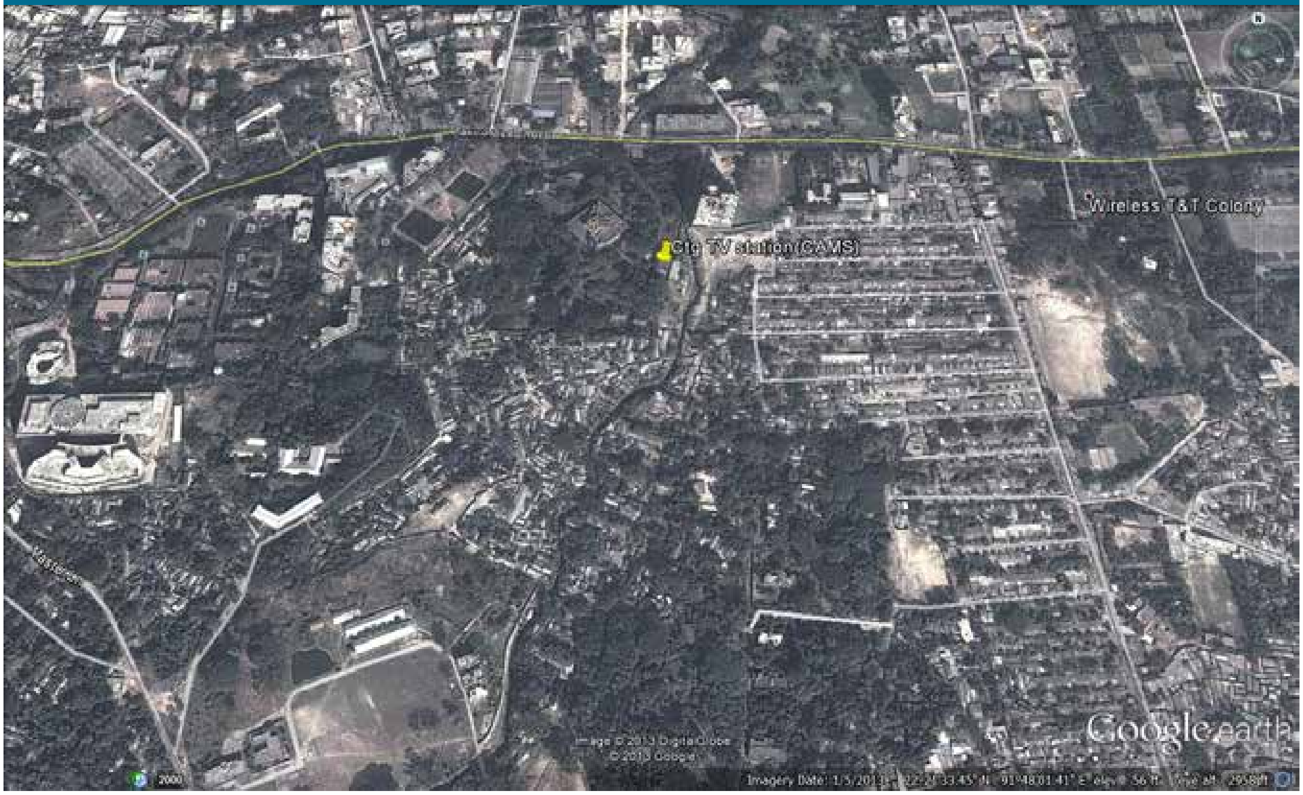


2.3.4 Chittagong

Chittagong (latitude 22.22N, longitude 91.47E) is the main seaport and second largest city of Bangladesh. The city is located in the southeastern part of Bangladesh, straddles the hilly terrain at the mouth of the Karnaphuli River, and is bounded by the Bay of Bengal to the west. Chittagong is heavily trafficked; especially the central city area covering about 10 km^2. The city has an estimated population of over 4.0 million living in an area of about 158 km^2. The main road network in the city goes towards the port area and northward towards the industrial areas. These roads are also heavily trafficked, with persistent traffic jams most of the day. Trucks transporting goods between the port and the industrial areas constitute a significant part of the traffic, and the combination of the hilly nature of the area, the stop and start mode of the congested traffic and the age and heavy loading of most of the trucks cause large emissions of black diesel smoke. Brick kilns are an important source of building materials and pollution. There are several industrial zones in and around the city; heavy industries operate in those industries.

The geographical layout of the city, with dispersed industrial areas mostly at significant distances from the port area, results in a high number of road kilometers with high diesel traffic and their emissions. The large number of auto-rickshaws (three-wheel, two stroke engine taxis) represents another significant air pollution source in the city. Steel re-rolling mills and brick kilns have substantial emissions that affect their immediate surroundings as well as the overall air quality of Chittagong. The largely uncontrolled steel mills are located within commercial and residential areas. The cement factories in Chittagong that only perform cement mixing operations, may also affect their neighborhoods to some extent. Brick kilns are large emitters, especially since there are so many of them, about 200, located in two clusters on the northern side of the city. There are two Continuous Air Monitoring Stations (CAMS) operating in Chittagong,

Figure 7 Location of the CAMS-06 in Khulshi, Chittagong



2.3.4.1 CAMS-06 (TV Station, Khulshi, Chittagong)

The CAMS is located at the Chittagong Television Station Campus at Khulshi, which is on a hilltop, about 2.5 km northwest of the downtown and about 100 meters above the surrounding area. Because of the topography of the city (hilly) and no significant source of air pollution close to the site, this location is relatively unaffected by nearby sources. As

Figure 8 Location of the CAMS-07 in Agrabad, Chittagong

the site is within the boundary layer (500 meter height), it is representative of the air pollution concentrations levels of the city. The sampling inlets are placed on the flat roof of the CAMS shelter about 3 m above the ground and the intake nozzle of the sampler is located 1.8 m above the roof with good natural ventilation.

2.3.4.2 CAMS-07 (Agrabad R/A, Chittagong)

The CAMS is located at the CDA residential area near the "Hatekhary" School. The site is residential and hence not much influenced by local sources. The sampling inlets are placed on the flat roof of the CAMS shelter, about 7 m above the ground and the intake nozzle of the sampler is located 1.8 m above the roof with good natural ventilation.

2.3.5 CAMS-08 (Sylhet)

Sylhet is a hub of tea industry and also a center of the Bangladeshi oil and gas sector, with the country's largest natural gas reservoir located in Sylhet Division. The Sylhet metropolitan area (latitude 24.54 N, longitude 91.52 E), situated in the north-eastern region of the country, has a population of 0.5 million with an area of 26.50 km^2. Topography of the city is characterized with hills and basins located on the banks of the Surma River in the Surma Valley.

The CAMS is located just beside the Surma River at the roof top of the district Red-Cross office building. The Divisional office of the Forest Department is situated just beside the CAMS, and the historical and famous Kin Bridge is about 20 meters far from the site. The location is characterized with moderate traffic.

The sampling inlets are placed on the flat roof of the CAMS housing constructed over the district Red-Cross building. The roof height is about 12 m above the ground and the intake nozzle of the sampler is located 1.8 m above the flat roof.

Figure 9 Location of the CAMS-08 in Sylhet

2.3.6 CAMS-09 (Khulna)

Khulna (latitude 23.42N, longitude 90.22E) is the third largest city of Bangladesh, located in south-western part of the country and on the banks of the river Rupsha and Bhairab. It is part of the largest delta in the world. The population of the city, under the jurisdiction of the Metropolitan Area is 1,435,422, living in an area of about 59.6 km^2. Khulna is one of the important industrial and commercial areas of the country; the second seaport of Bangladesh "Mongla" is situated about 40 km south from the Khulna City.

Like other big cities of Bangladesh Khulna is also undergoing a major transformation due to increasing population and steady economic growth. The growing demand of transportation results in a high number of road kilometers with high diesel traffic and their emissions. Significant numbers of brick kilns are also operational to meet the ever increasing construction demand. Khulna is known as the city of shrimp, because 75% of shrimp exported from Bangladesh are cultivated in the Khulna zone. Khulna has some heavy and medium industries like hardboard mills, jute mills, match factory, ship yard etc.

A CAMS operates in Khulna to measure the criteria air pollutants. The CAMS is located in the Department of Social Forestry Office Campus at Baira, which is about 4 km northwest of the downtown and is about 10 meter away from a local road carrying moderate traffic. Because of the topography of the city (flat) and good natural ventilation of the CAMS site representative air pollution levels of the city would be measured at this site. The location is relatively unaffected by nearby air pollution sources.

The sampler is placed on the flat roof of the CAMS shelter. The roof height is 5.0 m above the ground and the intake nozzle of the sampler is located 1.8 m above the roof.

2.3.7 CAMS-10 (Rajshahi)

Rajshahi, a metropolitan city, is situated in the northwestern region of Bangladesh (latitude 24.37N, longitude 88.70 E) and near the border with India. The metropolitan area has a population of 0.76 million with an area of 97 km^2. Rajshahi is home to many educational institutions, and is often referred to as an Education City. It is famous for its silk and its fruits, especially mangoes and litchis. There are also number of ancient mosques, shrines and temples in and around the city. Apart from the usual agricultural products such as rice, wheat, potatoes and lentils, Rajshahi and its neighboring regions are specially suited for various crops such as Watermelons, Sugarcanes, Mangoes and Litchis. In spite of being an important city and located on a riverbank, industrial development in Rajshahi isn't fast; an Industry Park was established in 90's, now mainly home to industries producing products of the famous Rajshahi silk. Rajshahi is also home to a jute mill, a sugar mill and mango based industries.

A Continuous Air Monitoring Station (CAMS) is operating in Rajshahi to measure criteria air pollutants. The location of the CAMS is in the Department of Social Forestry Office Campus at Sopura, which is about 3 km north from the downtown and is about 10 meter away from the moderate local traffic artery with good natural ventilation.

The sampler inlet is placed on the flat roof of the CAMS housing. The roof height is 5.0 m above the ground and the intake nozzle of the sampler is located 1.8 m above the roof.

2.3.8 CAMS-11 (Barisal)

Barisal, a metropolitan city, is situated in the southern region of Bangladesh (latitude 22.48 N, longitude 90.30 E). Barisal metropolitan area has a population of about 0.38 million with an area of 20 km^2 with density of population 10,524/km^2. Barisal has a tropical monsoon-type climate, with a hot and rainy summer and a dry winter. Barisal is one of the biggest river ports in Bangladesh and large numbers of diesel powered water transports operate from this port. Barisal is fast growing city, stands on the Kirtankhola River. The economy of Barisal is mainly agriculture based and there are no significant industries around the city.

The CAMS has been established in the Campus of Forest Department Office at Uttar Bagura Road near Natun Bazar. The sampler inlet is placed on the flat roof of the two storied CAMS shelter. The roof height is 5.0 m above the ground and the intake nozzle of the sampler is located 1.8 m above the roof.

2.4 Quality Assurance/Quality Control

Quality assurance and Quality control (QA/QC) is an essential part of any monitoring system, as well as data processing and analyses. Practices of proper QA/QC in all steps of data generation, management, and storage can ensure build up a database with high validity and acceptability. Valid air quality data is a good primary tool that upon analyses expresses the necessity and aspect of possible air quality management in a city. Analyses of a series of valid air quality and meteorology data may even hint at the presence of possible sources of air pollution around a site. Invalid data production may be a curse for it may lead to take wrong decisions by the government on managing the air quality.

QA/QC is a program of activities which upon implementation ensures that overall measurements meet pre-defined standards of quality, with a stated level of confidence. In order to ensure production of quality data, the CASE/DoE carries out following exercises:

2.4.1 Training to the staffs

The CASE project conducts training programs regularly for the staffs affiliated with the CAMS operation. The technicians from the project and the DoE have been developed with both theoretical and

Figure 10 Location of the CAMS-11 in Barisal

Figure 11 Theoretical and practical training on the operation and maintenance of CAMS

practical knowledge on the instrument operation and maintenance. Sometimes, the technicians are sent abroad to the instrument manufacturing centers and are trained up on the instrument diagnoses, spare changes, calibration processes and troubleshooting. Tens of such training activities have so far been accomplished under the project, which has successfully developed more than 100 technicians from the DoE and the project.

In addition to the training on the instrument operation and maintenance, training on the fundamental concept of air quality, chemical and physical characteristics of criteria pollutants, air quality index (AQI), atmospheric dispersion principles, etc. were also arranged for the officials of the DoE and the project.

2.4.2 Calibration, Servicing and Repair of Instruments

CASE/DoE has developed QA/QC protocols which include documentation for quality assurance and quality control that is followed in all monitoring stations to obtain harmonized reliable air quality data. This covers calibration, servicing and repair of instruments/equipments, and evaluation of status of ambient air quality monitoring stations under the network. Weekly inspection checklist describing overall status of the CAMS and ZERO/SPAN checks which ensures the validity of the calibration of each of the analyzers is properly documented and implemented. Calibrations of the analyzers are performed using NIST traceable calibration gases usually quarterly and after repair. Particulate monitors based on beta gauge attenuation are calibrated using standard foils of known areal mass density. Servicing including preventive maintenance and repair of the analyzers are performed by trained service engineers under maintenance contract with the local representative of the instrument manufacturers. The overall servicing and repair are centrally coordinated to ensure quality.

2.4.3 Data flow, management, and analyses

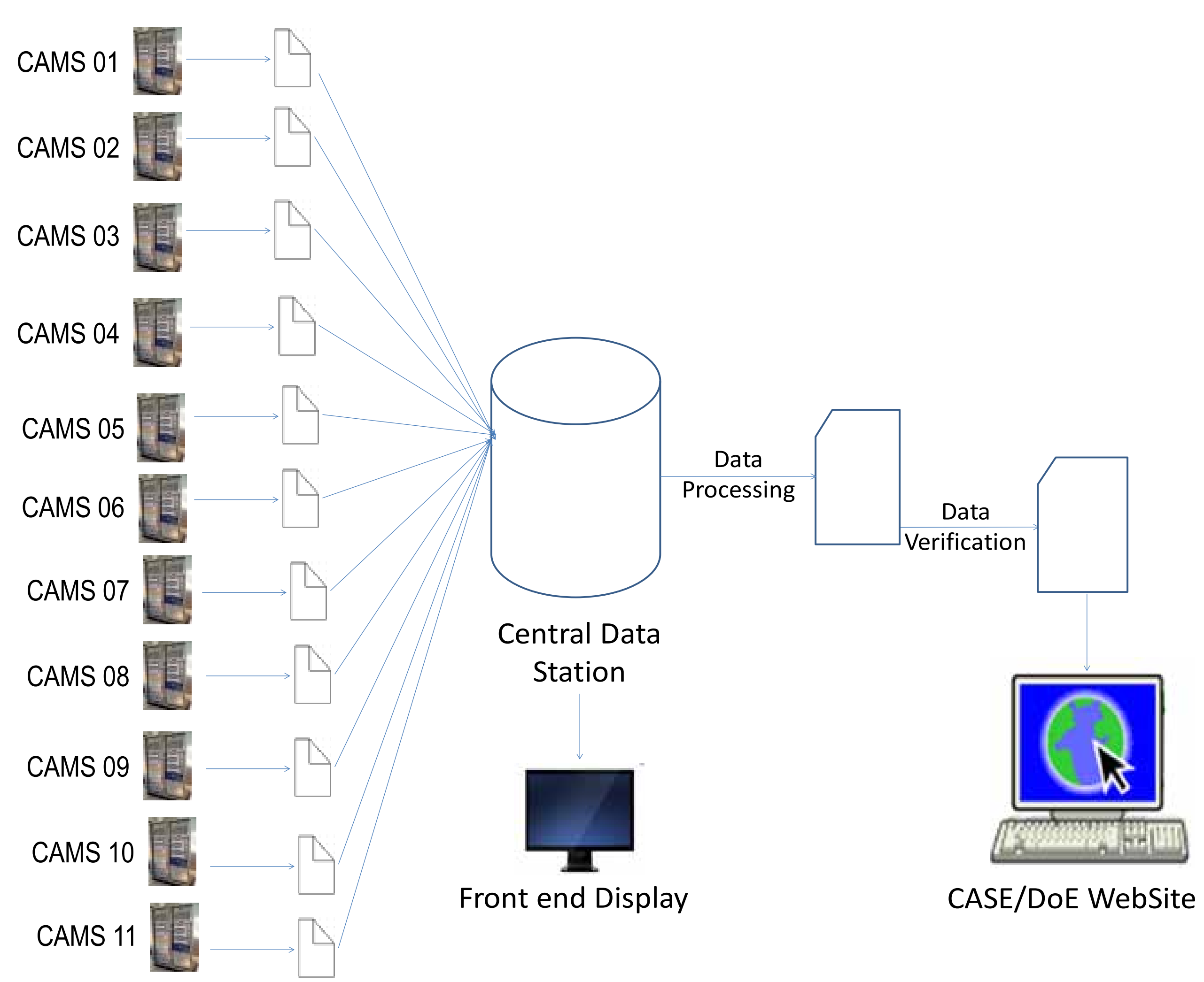
All of the CAMS are connected using GPRS system with a Central Data Station (CDS) at the head office of DoE in

Agargaon, Dhaka. The air quality and meteorology data generated every minute at the monitoring stations are retrieved as SQL database at the CDS using EnVIEW 2000 software. The structure of air quality data flow under CASE, DoE is shown in Figure 12. The data is scrutinized for outliers and invalid ones; later it is checked, compiled, processed and analyzed statistically.

Data generation from 11 stations is continuous and enormous. Managing large database is challenging; special cautions are taken to ensure quality during data handling, management and storage. The EnVIEW software at the CDS stores the data primarily at 15-minute average; however, the software has options of calculating and aggregating data in other averaging period like 1-hour, 8-hour, etc. Regular scrutiny on the concentration data is performed to check outliers/invalid ones which are sometimes accrued from the malfunctioning of the instrument due to power disruptions.

For the preparation of this report, valid hourly concentration data got from the CDS is imported to the analytical software "R" and analyzed further to observe statistical characteristics, and temporal and directional variations of the pollutants in each station. Concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_x, CO and O_3 from November 2012- April 2018 are analyzed and illustrated.

Figure 12 Air Quality Monitoring Network under CASE, DoE



2.5 National Ambient Air Quality Standards

The GoB revised the Environment Conservation Rules–1997 in 2005 vide a statutory regulatory order (SRO no. 220) and set with further clarity the National Ambient Air Quality Standard (NAAQS) (Table 2).

Table 2 National Ambient Air Quality Standards (NAAQS) for Bangladesh

Pollutant	Limit Value	Averaging time
CO	10 mg/m^3 (9 ppm)	8 hours[a]
	40 mg/m^3 (35 ppm)	1 hour[a]
Pb	0.5 $\mu g/m^3$	Annual
NO_x	100 $\mu g/m^3$ (0.053 ppm)	Annual
PM_{10}	50 $\mu g/m^3$	Annual[b]
	150 $\mu g/m^3$	24 hours[c]
$PM_{2.5}$	15 $\mu g/m^3$	Annual
	65 $\mu g/m^3$	24 hours
O_3	235 $\mu g/m^3$ (0.12 ppm)	1 hour[d]
	157 $\mu g/m^3$ (0.08 ppm)	8 hours
SO_2	80 $\mu g/m^3$ (0.03 ppm)	Annual
	365 $\mu g/m^3$ (0.14 ppm)	24 hours[a]

Notes:

[a]Not to be exceeded more than once per year

[b]The objective is attained when the annual arithmetic mean is less than or equal to 50 $\mu g/m^3$

[c]The objective is attained when the expected number of days per calendar year with a 24- hour average of 150 $\mu g/m^3$ is equal to or less than 1

[d]The objective is attained when the expected number of days per calendar year with the maximum hourly average of 0.12 ppm is equal to or less than 1 (Source: DOE).

2.6 Air Quality Index (AQI)

The air quality index (AQI) is a value representing the status of air quality in an area. In Bangladesh the AQI is calculated based on the prevailing concentrations of 5 criteria pollutants, PM (PM_{10} and $PM_{2.5}$), NO_2, CO, SO_2 and O_3. AQI value tells how much clean or polluted the air is, and what the associated health impacts might be on the public. The AQI focuses on health effects that one might experience within a few hours or days after breathing polluted air. The AQI is a single number from 0 to 500 calculated on the basis of pollutant concentrations measured in an area. The higher the AQI, the greater is the air pollution level and thus indicates greater public health concern.

AQI is calculated based on five major pollutants:

1. Ozone (O_3)
   i) 1–hour average
   ii) 8–hour average
2. Carbon monoxide (8–hour average)
3. Sulfur dioxide (24–hour average)
4. Nitrogen dioxide (24–hour average)
5. Particulate Matter
   i) $PM_{2.5}$ (24–hour average)
   ii) PM_{10} (24–hour average)

AQI for a particular pollutant I_p is

calculated using the following equation developed by the USEPA[6].

$$I_p = I_{Lo} + (C_p - BP_{Lo}) * (I_{Hi} - I_{Lo}) / (BP_{Hi} - BP_{Lo}) \qquad (1)$$

Where,

I_p = The Air Quality Index Value for Pollutant P

C_p = Concentration of Pollutant P

BP_{Hi} = The Break Point that is greater than or equal to C_p

BP_{Lo} = The Break Point that is less than or equal to C_p

I_{Hi} = The AQI value that is corresponding to BP_{Hi}

I_{Lo} = The AQI value that is corresponding to BP_{Lo}

An AQI value of 100 generally corresponds to the national air quality standard for the pollutant, which is the level set by the mandated Environment Protection Agency (e.g., the Department of Environment in Bangladesh) to protect environmental threat. AQI values below 100 are generally thought of as satisfactory. When AQI values are above 100, air quality is considered to be unhealthy-at first for certain sensitive groups of people, then for everyone as AQI values get higher. The AQI standard for Bangladesh is given in Table 3.

Table 3 Air Quality Index (AQI) for Bangladesh

Air quality index (AQI)	Category		Colour
	In English	*In Bangla*	
0-50	Good	ভালো	Green
51-100	Moderate	মোটামুটি	Yellow Green
101-150	Caution	সতর্কতামূলক	Yellow
151-200	Unhealthy	অস্বাস্থ্যকর	Orange
201-300	Very Unhealthy	খুব অস্বাস্থ্যকর	Red
301-500	Extremely Unhealthy	অত্যন্ত অস্বাস্থ্যকর	Purple

6 USEPA, *Air Quality Index Reporting; Final Rule, USEPA 40 CFR Part 58, Federal Register, Vol. 64, No. 149*, 1999.

3 PRINCIPLES OF MONITORING EQUIPMENT

All of the eleven CAMS under the DoE measure the criteria air pollutants using the principle of multiple on-line gas sensors for CO, SO_2, NO_x and O_3 and PM (both $PM_{2.5}$ and PM_{10}) using beta-gauge monitors. The working principles of these analyzers and PM samplers are described in the following sections. All the monitoring devices are Federal Reference Method Samplers to ensure the data quality.

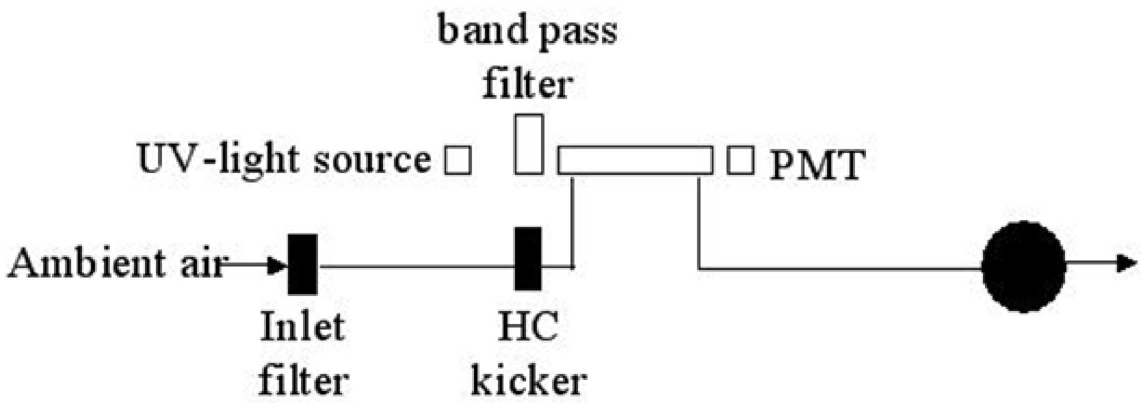
3.1 Sulfur Dioxide Analyzer

The sulfur dioxide analyzer measures the concentration of sulfur dioxide present in the ambient air by **Ultraviolet Fluorescence** method**.** The analyzer works as follows:

1. Sample air passes through a particulate filter. This particulate filter removes particulates and other contaminants from the sample air.
2. Then the sample air goes through the hydrocarbon kicker, which removes hydrocarbon from the sample.
3. After that, the sample enters into the fluorescence cell.
4. A zinc lamp is used as a UV source. This UV lamp supplies UV light of 214 nm wavelength which passes through an optical filter and enter in to the fluorescence cell.
5. In the fluorescence cell, SO_2 molecules absorb the UV light and become excited.
6. When the excited SO_2 molecule returns to the ground state, it emits radiation. This radiation produces small electric current which is detected by a Photo Multiplier Tube [PMT]. The intensity of this current is directly proportional to the concentration of SO_2.

$$SO_2 + UV \longrightarrow SO_2^* \longrightarrow SO_2 + \text{Photon}$$

Figure 13 Simple flow diagram of SO_2 analyzer

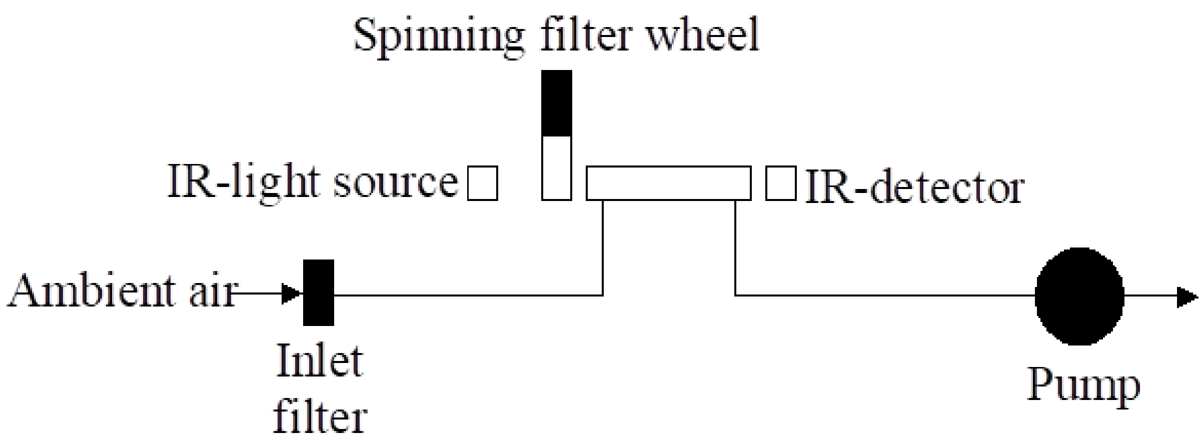


3.2 Carbon monoxide Analyzer

The carbon monoxide analyzer measures the concentration of carbon monoxide present in the ambient air by **Non-Dispersive Infrared Radiation [NDIR]** method**.** It is also called Gas Filter Wheel Correlation method. The analyzer works as follows:

1. Sample air passes through a particulate filter. This particulate filter removes particulates and other contaminants from the sample air.
2. Then the sample air goes to the measurement cell through a pre-heater which warms the air.
3. On the other hand there is an Infrared source that generates infrared radiation.
4. After the IR source, a gas filter correlation wheel is present which is rotated by a motor. This gas filter correlation wheel includes two gas filled chambers: A. A reference chamber which is filled with CO [500,000 ppm]. B. A measure chamber which is filled with nitrogen.
5. When IR radiation pass through the reference chamber it removes all of the CO sensitive wavelengths which are centered at 4.7 microns and the reference chamber allow the CO insensitive wavelengths.
6. Then the IR enters into the measurement cell and absorbed by sample air. Finally it reaches the IR detector and the detector measure the amount of absorption as voltage signal.
7. Again the IR radiation passes through the measure chamber which is filled with nitrogen and passes the CO sensitive wavelengths.
8. Then this IR enter into the measurement cell and absorbed by sample air i.e., CO. Finally it reaches the IR detector and the detector measure the amount of absorption as voltage signal.
9. The difference between these two signals is used to compute the concentration of CO.

Figure 14 Simple flow diagram of CO analyzer



3.3 Nitrogen Oxides Analyzer

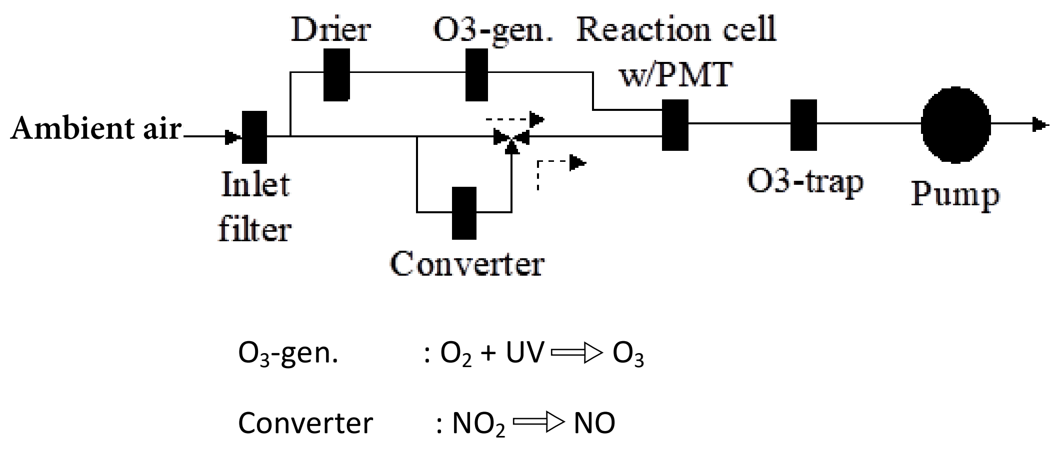
The NO_x analyzer measures the concentration of oxides of nitrogen present in the ambient air by **Chemiluminescence** method**.** The analyzer works as follows:

1. The sample air pass through a micron filter which removes the unwanted particulates from the sample air.
2. Then the sample goes to the chemiluminescence reaction cell through one way. In the cell, NO molecules present in the sample react with ozone to form excited NO_2*.

   $NO + O_3 \longrightarrow NO_2^* + O_2$
   [Chemiluminescence Reaction]
   The ozone comes to the cell from ozone generator which produces10,000 ppm ozone.
3. This excited NO_2* molecule returns to the ground state and emits radiation. This radiation is detected by Photo Multiplier Tube [PMT] that produces a small electric current. This current is directly proportional to the concentration of NO.
4. On the other way sample air goes to the molycone converter which converts NO_2 to NO.
5. Then this sample air which contains NO and NO_2 [as converted NO] goes to the measurement cell. Again react with ozone and create a chemiluminescence reaction, produce radiation and current. The intensity of current is directly proportional to the total concentration of nitrogen oxides i.e., NO_x
6. NO_2 concentration is measured by the subtraction of NO concentration from NO_x concentration.

   $NO_2 = NO_x - NO$

Figure 15 Simple flow diagram of NO_x analyzer

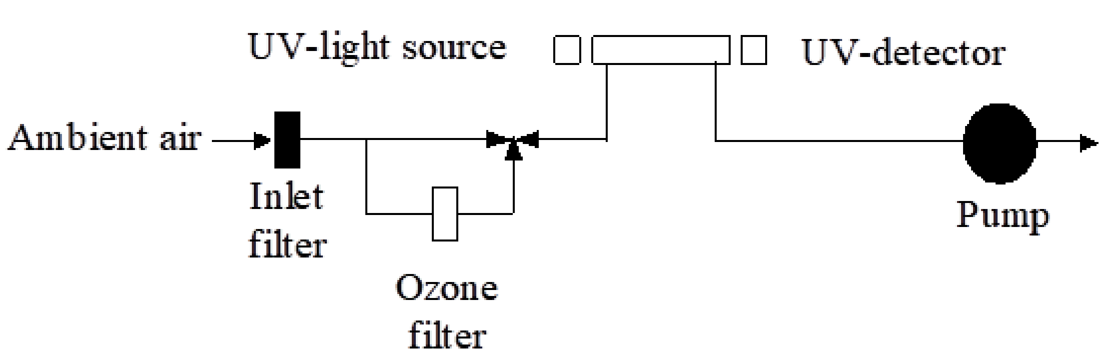


3.4 Ozone Analyzer

The O_3 analyzer measures the concentration of ozone present in the ambient air by **Ultra Violet Absorption** method**.** It is also called **UV Photometry**. The analyzer works as follows:

1. The sample air goes through the particulate filter to remove particulates and other contaminants from the sample air.
2. Then the sample enters into the measurement cell.
3. A mercury vapor lamp is used to emit UV light at 254 nm wave length. In the measurement cell this UV light is absorbed by the sample.
4. After absorption, the intensity of UV light is measured.
5. Again the sample enters into the measurement cell through an ozone scrubber. The ozone scrubber contains manganese dioxide which removes only ozone from the sample air. This scrubbed sample absorbs UV light in the measurement cell and intensity of UV light is measured again.
6. Finally, the difference between the two intensity of UV light (absorption by non-scrubbed sample and absorption by scrubbed sample) is used to determine the ozone concentration.

Figure 16 Simple flow diagram of O_3 analyzer



3.5 PM_{10} and $PM_{2.5}$ Analyzer

When beta rays pass through a material, they can be absorbed, reflected or pass directly through. The attenuation of intensity in beta rays is proportional to the amount of material present. The attenuation through most materials is relatively consistent and is based on the electron density of the material.

The attenuation for most materials is about 0.5, except for hydrogen and heavy metals. Beta attenuation has been used in production lines as a quality control check of product thickness for more than 40 years. For example, in the production of cellophane plastic wrap, a beta gauge is used to ensure that the thickness of the cellophane remains within specification.

The principle behind beta attenuation particulate sampling instruments (beta gauge) is that energy is absorbed from beta particles as they pass through PM collected on a filter media. Beta gauge instruments have been designed to take advantage of this scientific principle to monitor/measure PM concentrations. The attenuation due to only the PM is measurable if a baseline beta count through just the filter can be established prior to sampling. The difference between the baseline beta count and the beta count after sampling is directly proportional to the mass of PM in the sample.

The two main components of a beta attenuation measuring system are the beta source and the detector. The beta source must be selected so that: it has an energy level high enough for the beta particles to pass through the collection media (i.e., the filter tape) and the particulate, it has enough source material so that a high count rate is present, it is stable over long periods of time, and it does not present a danger to the health of personnel that come into contact with the instrument. The source of choice has been Carbon-14 because: it has a safe yet high enough energy level, it has a half-life of 5,568 years, and it is relatively abundant. Many different types of detectors can quantify beta particle counts, but the ones most widely used are the Geiger Mueller counter or a photodiode detector.

The beta gauge works by measuring beta counts before and after collecting PM on a filter media. The instrument will measure a clean area of the filter media for a fixed period to determine the baseline (e.g., 2 minutes), then it will advance that area of the filter to a sampling apparatus for another set period of time (e.g., 50 minutes), and finally return that area of the filter to the detector for the same period used to establish the baseline reading. The difference in the beta count can be directly correlated to particulate mass through calibration of the instrument using a filter media containing a known mass of a particulate-like material.

The beta gauge instrument is designed to provide a mass concentration. The instrument measures the volume of gas extracted through the stack/duct for each sample interval and calculates mass concentration in the specified units (e.g., $\mu g/m^3$)

4 AIR MONITORING RESULTS

4.1 Dhaka

There are three stations operating in Dhaka; however, the results shown in this report are representing the data produced from the CAMS 03 at Darus Salam, Mirpur area. Data from the other two stations (CAMS 01 & 02) in Dhaka are not analyzed because of the low data capture rates.

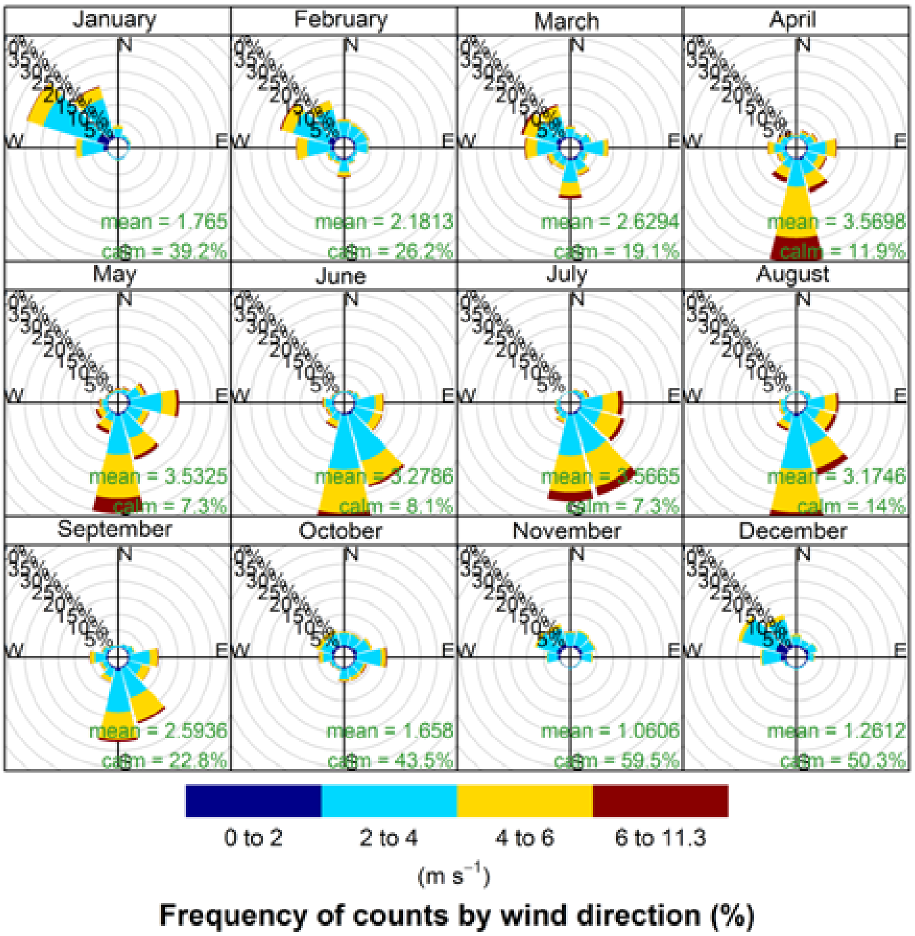
4.1.1 Meteorology

The wind data from 2013 to 2018 at the Hazrat Shahjalal International Airport of Dhaka (23.843N, 090.398E) is retrieved from the ftp sites of the National Climatic Data Centre (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) of the USA ftp://ftp.ncdc.noaa.gov/pub/data/. Temperature and relative humidity data are captured at the CAMS, Gazipur and are considered typical for this region (Dhaka, Narayanganj, Gazipur) of Bangladesh. In addition, typical monthly cloud coverage, monthly precipitation and monthly solar radiation are plotted with the data from the Department of Meteorology, Dhaka.

4.1.1.1 Wind Roses

The monthly wind roses for Dhaka city (Figure 17) demonstrate opposite characteristics in wind pattern between wet (May – October) and dry (November – March) seasons. While the wind during the wet season blows mainly from the south and southeast directions, that in the dry season dominantly blows from the northwest direction. Directional dominance of airflow is not so strong in the month of October and November. Wet seasonal wind is also found relatively stronger than the dry seasonal wind.

Figure 17 Monthly Wind Roses for Dhaka city



4.1.1.2 Temperature, Relative Humidity, Rainfall, Solar Radiation

All of these meteorological parameters have profound relation with the air quality in a region. High temperature with sunny environment facilitates ozone production, and high relative humidity assists some salts in the atmosphere to absorb water and to transform to liquid form. Solar radiation and cloud cover influence atmospheric dispersion of pollutants, and precipitation helps downwash of pollutants from the atmosphere.

Trends in temperature and relative humidity in Dhaka (Figure 18) show that temperature remains at the lowest range in the month of January, starts to rise from February and climbs at the peak in April when ~38^{o}C temperature is experienced in some days. March to April is characterized with low cloud cover, high solar radiation, high temperature and low relative humidity. Rainy season in Bangladesh (May – October) is characterized with high temperature, high relative humidity, heavy rainfall and high cloud cover; excess downpour during this time helps wash out the pollutants from the atmosphere. Calm weather, low solar radiation and rare rainfall are characteristic meteorology of winter season (December – January); lower mixing height and strong temperature inversion at night in the winter season aid in increasing pollution level drastically.

Figure 18 Trends in weekly temperature (ºC) and relative humidity (%) at Gazipur station from 2013 to 2017, considered typical for this region

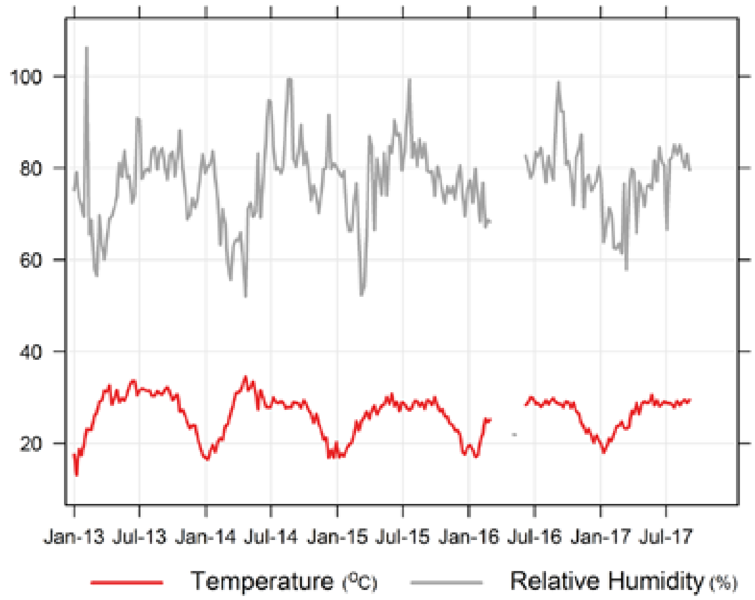
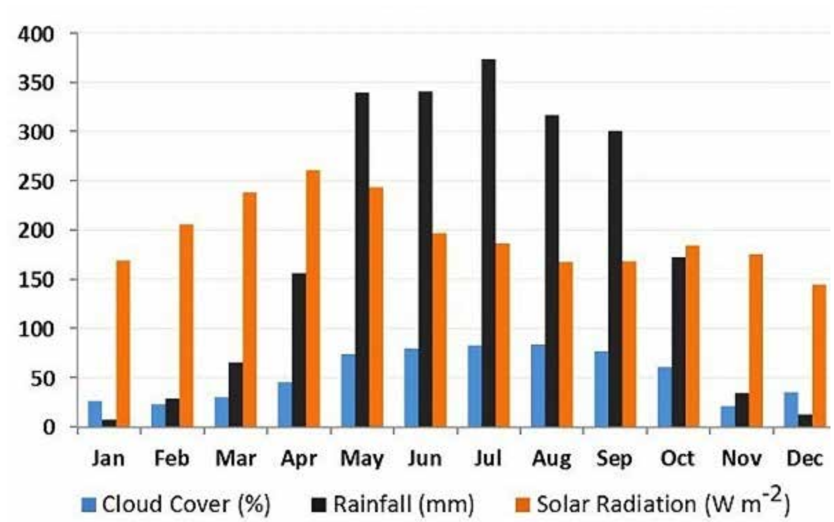


Figure 19 Typical monthly Cloud Cover, Rainfall and Solar Radiation in Dhaka



4.1.2 Criteria Air Pollutants

4.1.2.1 Particulate Matters (PM_{10} & $PM_{2.5}$)

PM is the main responsible pollutant for bad air quality in dry season in Dhaka. Table 4 shows an overview of the PM concentrations in different years in Dhaka city. The concentrations are daily averaged, calculated when minimum 80% hourly concentration data is present in a day. Thus, the rate of valid daily-averaged data for PM_{10} concentrations in 2013 is 90.6% (Table 4) means that 330 days of the year 2013 have PM_{10} concentration data for at least 19 hours; the rest 35 days of 2013 are excluded from the analyses for not having PM data at minimum 19 hours. Poor data capture rates are found for both the PM_{10} and $PM_{2.5}$ in 2016; the rate of PM_{10} in 2015 is poor but fortunately that of $PM_{2.5}$ is good. Data capture rate is important for the comparison of air quality in different years because of the strong seasonal and diurnal variations of air quality in Bangladesh.

Table 4 primarily reveals a declining trend in yearly PM concentrations in Dhaka; both the PM_{10} and $PM_{2.5}$ concentrations have declined from 2016. Compared to 2013-14, Dhaka experiences about 12% lower PM concentration (annual) in 2017. This reduction in yearly PM concentrations in air may be attributed to the ongoing reforms in the brick kiln sector. According to a government directive, all of the high emitting Fixed Chimney Kilns (FCK) will have to be converted to low emitting technologies for brick production. A good portion of the FCKs are already converted to zigzag technologies. However, the PM trends in Dhaka need to be monitored in the following years to find a conclusion on whether the pollution level is actually declining, and to realize the possible causes for this.

Table 4 Overview of daily PM concentrations in Dhaka in recent years; daily concentrations are determined when minimum 80% valid hourly data is available in a day

Year	PM_{10} Conc. (μg m^{-3})						$PM_{2.5}$ Conc. (μg m^{-3})					
	Data capture rate %	percentile				mean	Data capture rate %	percentile				mean
		25	50	75	95			25	50	75	95	
2013	90.7	66	122	221	394	161.4	87.6	32	57	127	259	92.0
2014	82.2	66	120	237	393	159.4	86.5	34	70	145	236	95.0
2015	62.7	80	160	254	349	172.8	90.0	35	62	143	222	90.0
2016	69.3	58	98	214	395	145.1	64.0	28	44	92	211	68.0
2017	85.7	65	103	207	362	142.6	85.5	34	53	118	200	80.5

As dry season is the main concern for harsh air pollution, it is important to observe the trends in PM concentrations especially in dry season (November to April). Figure 22 ratifies the reduction of PM concentrations in dry season of 2016 – 2017 compared to that of 2013 – 2014. For example, the 25 percentiles of $PM_{2.5}$ concentrations in dry season of 2013, 2014 and 2015 were 78.7, 92.2 and 92.0 μg m^{-3}, whereas those in 2016, 2017, and 2018 are 69.0, 74.0, and 80 μg m^{-3} respectively. Number of high concentration values has also decreased in dry seasons in recent years. For example, the 75 percentiles of $PM_{2.5}$ concentrations in the dry seasons of 2013, 2014 and 2015 were 218.3, 180.5 and 200.5 μg m^{-3}, whereas those in 2016, 2017, and 2018 are 174.2, 177.0, and 175.0 μg m^{-3} respectively. The average $PM_{2.5}$ concentration in dry seasons of 2013 to 2015 was 146.5 μg m^{-3}, whereas that in dry seasons of 2016 to 2018 is 133.0 μg m^{-3}. Although the data proves some reduction in PM concentrations in recent years, it is worrying to find little high PM concentrations in dry season of 2018 compared to its previous two years (Figure 22).

Temporal trends (Figure 20 & Figure 21) in PM concentrations demonstrate seasonal variations sharply; PM_{10} and $PM_{2.5}$ concentrations in air remain higher than the standards of Bangladesh during November to April, and during the time from May to October the PM levels satisfy the limit values. The month of January is found to be the most polluted month, followed by December and February. Winter season (December – January) is also characterized with higher fraction of fine particles to PM_{10} mass concentrations and the summer time (February – April) is typified with coarse particles in air.

Figure 20 Trends in daily PM concentration (data threshold 80%) in Dhaka from 2013 to 2018. The red and grey horizontal lines are standards for PM_{10} and $PM_{2.5}$ respectively

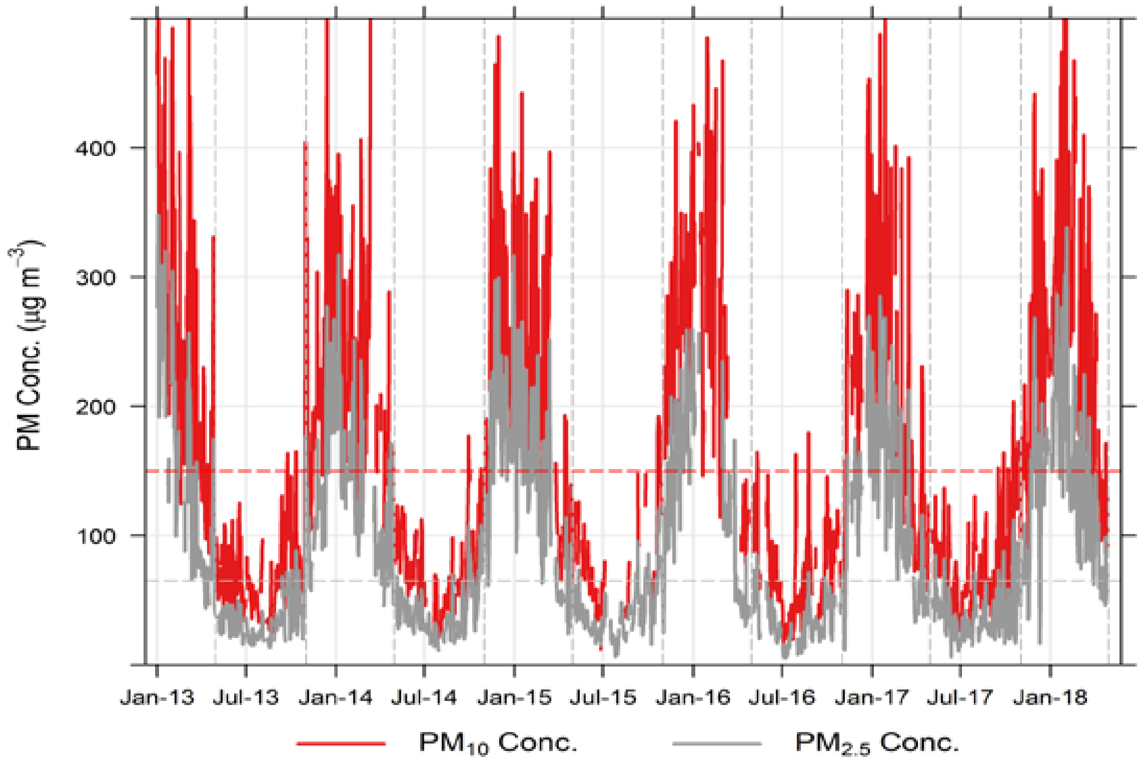


Figure 21 Box-whisker plots of PM concentration in different months in Dhaka

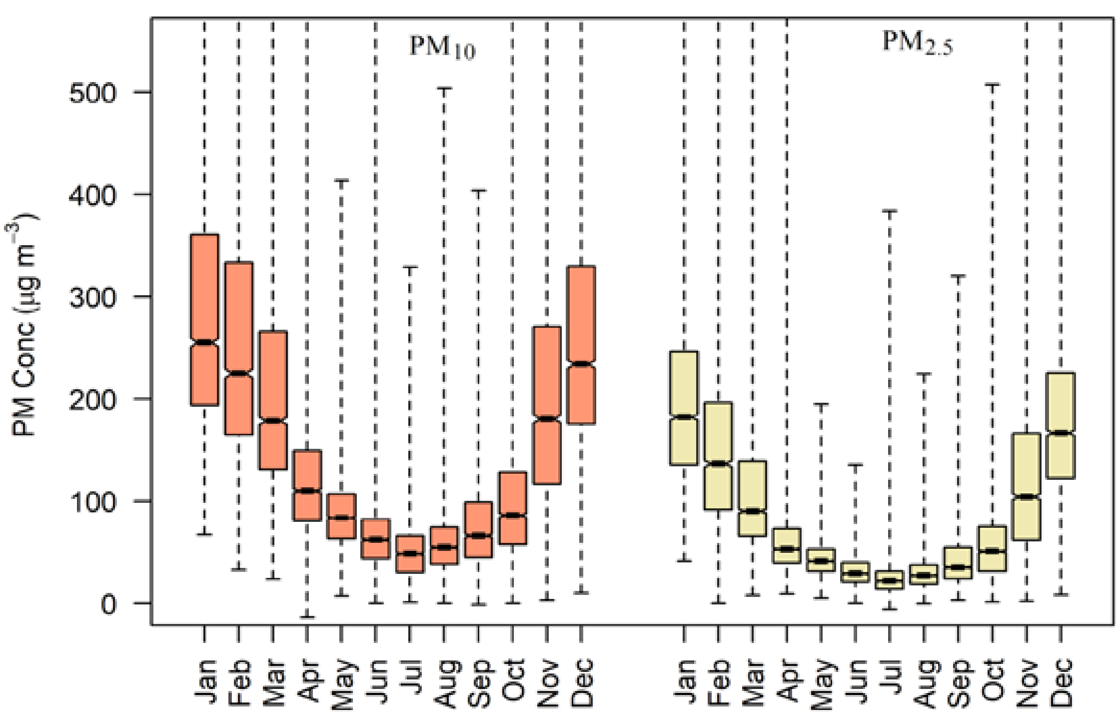
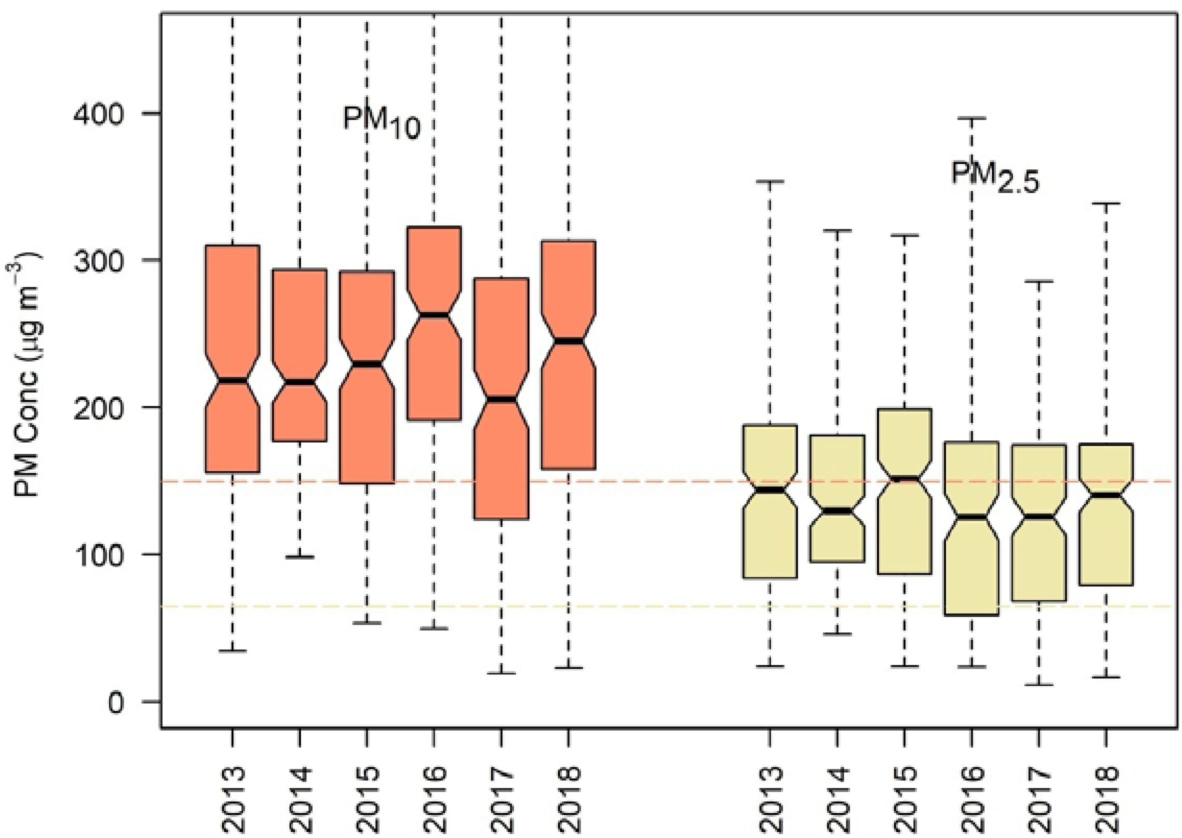


Figure 22 Box-whisker plots of daily PM concentration in dry season in Dhaka shown for different years; horizontal lines are standards for daily PM_{10} (maroon) and $PM_{2.5}$ (lemon) Conc. Dry season is measured from November (previous year) to April (current year)



Diurnal variations of PM concentration in dry season is very steep (Figure 23), gets upward from 7:00 am to 9:00 am especially for the fumigation effect and office bound traffic, since then the concentration goes sheer downward up to 5:00 pm. PM concentration in dry season gets at the peak at 8:00 pm to 9:00 pm, since then it continues diving up to the morning next day (Figure 23).

Unlike dry season, daytime PM concentrations during wet season do not steeply fall down; rather, it follows a wave pattern with little lateral deviations from 9:00 am to 5:00 pm. PM variations in weekdays show the concentration levels do not change much in weekdays in dry season, although it gets down to some extent in Saturday to Monday. PM concentrations during dry season do not decrease in Friday, the first weekly holiday although in wet season the concentration wanes in Friday (Figure 23).

Northwestern winds carry most of the PM to the city of Dhaka (Figure 24), especially during dry season when a large number of brick kilns operate to that direction. Dry season in Bangladesh is characterized with huge dusts in air, come from bare lands, road dusts, pedestrians, constructions and agricultural activities. Continuous influx of dusts into the air and the increase in residence time of the tiny particles in air maintain high PM concentrations during dry season. Furthermore, as the air flows from the north and northwest directions during dry season, all of the sources of PM, especially the clusters of brick kilns located to those directions pour excessive PM into the atmosphere of the city.

Figure 23 Variations of PM concentration in different time of day and in different day of week in both dry and wet season in Dhaka

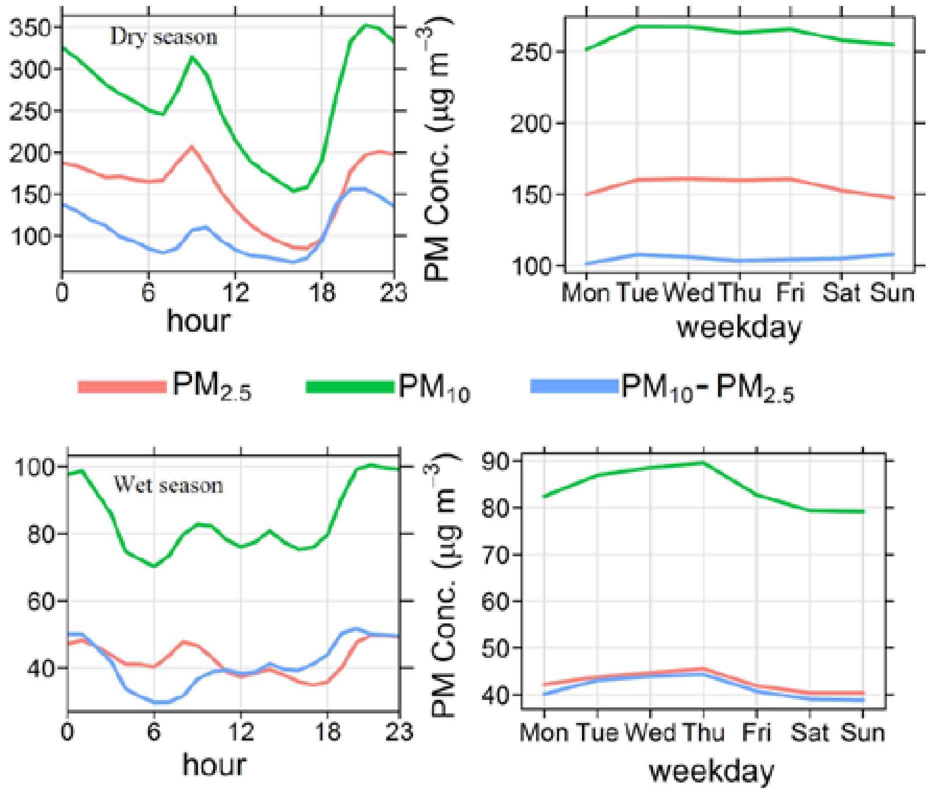
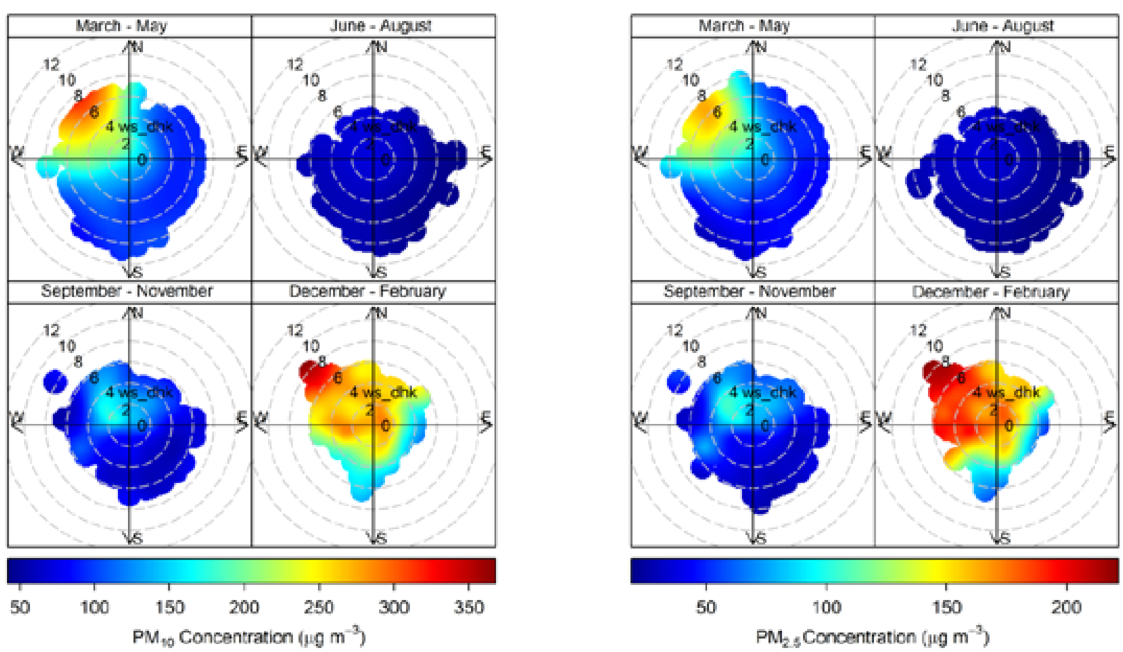


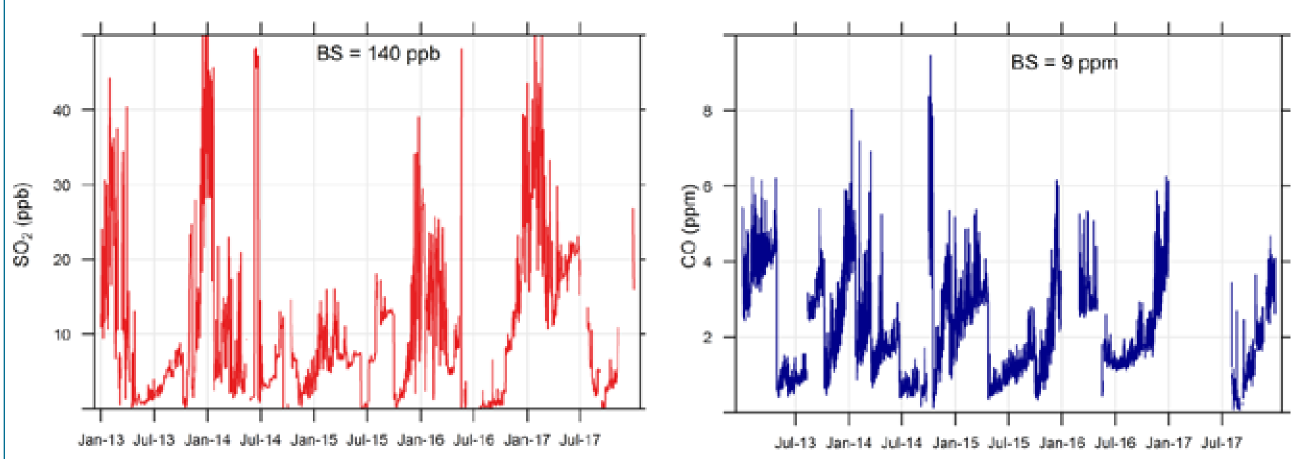
Figure 24 Directional influences on the PM concentrations in different seasons in Dhaka



4.1.2.2 Gaseous pollutants

SO_2 and CO concentrations show similar trend characteristics throughout the year, with heightened level in dry season (Nov – April), although not threatening at all compared to the standard value, and low level in wet season. The main sources of SO_2 in air during dry season could be the burning of coal (1.5 – 4.0 % sulfur content) in brick kilns and the burning of sulfur rich octane and diesel in vehicles. CO concentrations all the time of a year remain much below the permissible limit (Figure 25). Vehicles are the prime sources of CO in an urban area, and thanks to the decision of introduction of cleaner fuel compressed natural gas (CNG) to the vehicle sector, which helps reduce total emissions from this sector.

Figure 25 Trends in daily average SO_2 Conc. (left) and 8-h average CO Conc. (right) in Dhaka

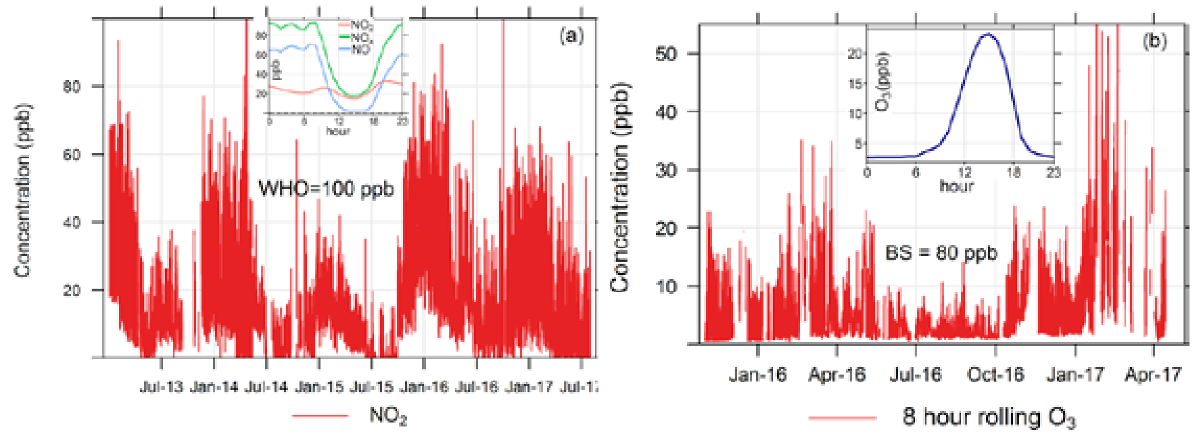


For air quality study, NO_2 is the vital component of NO_x group. Under sunlight NO_2 dissociates and releases atomic oxygen that finally produces O_3 upon reaction with oxygen molecule in air. NO_2 is also responsible for acid rain. Thus, the monitoring of NO_2 concentration against a standard in a region is pivotal. WHO and USEPA have set 100 ppb as limit value for NO_2 concentration over a one hour time period. Bangladesh does not have standard for NO_2 concentration, it has set standard for NO_x (NO + NO_2) concentration of 53 ppb over an annual time period.

Figure 26a shows that the NO_2 concentrations do not violate the WHO guideline value even a day from 2013 to 2017 time period in Dhaka. In winter, the concentrations sometimes rise up to 80 ppb, very close to the WHO guideline value. Seasonal meteorology influences greatly on the NO_2 and O_3 concentrations in Dhaka; the concentrations are high during dry season and low in wet season (Figure 26 a&b).

Diurnal variations of NO, NO_2 (Figure 26a inset) and O_3 (Figure 26b inset) concentrations are related to each other. NO concentrations remain higher than NO_2 concentration at nighttime when O_3 concentrations are at the minimum. But at daytime, with higher O_3 concentrations NO_2 concentrations dominate over NO concentrations. O_3 reacts with NO to produce NO_2. Thus, the rate of NO_2 production expedites when O_3 concentration is high. However, as NO is the prime component (>90%) of NO_x emitting from a source, NO concentration usually remains higher than NO_2 concentration when O_3 concentration is low. The trend in 8-hour rolling average O_3 concentrations in Dhaka (Figure 26b) certifies the levels remain within the limit value set by Bangladesh. Not only the NO_x hydrocarbons (HC) are also good precursors to O_3 productions at daytime, and vehicles are good source of HC emission in urban environment.

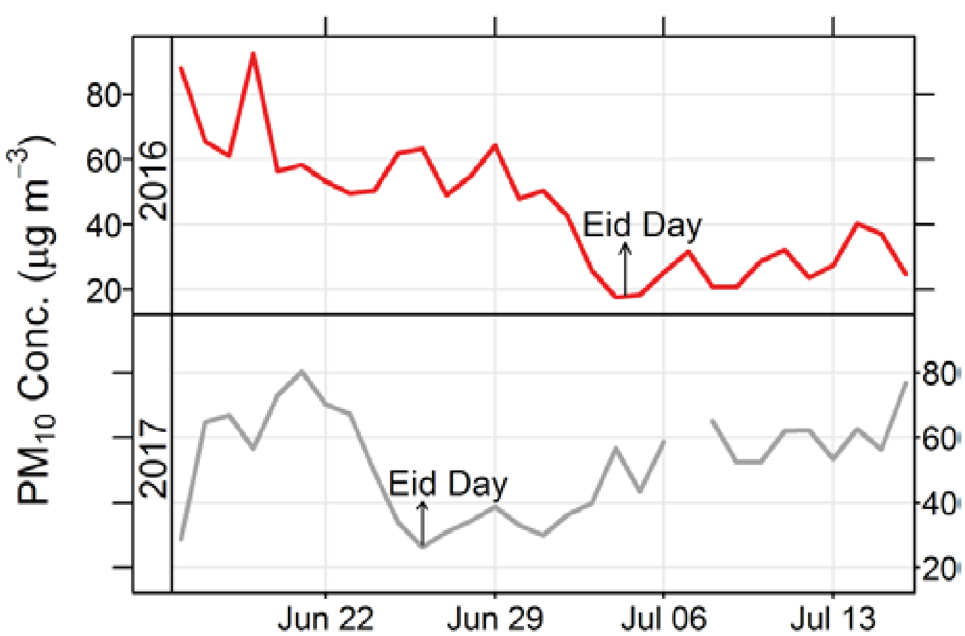
Figure 26 (a) Trends in hourly NO_2 Conc. in Dhaka with the diurnal variations of NO_2, NO_x and NO Conc. in dry season shown in inset. (b) Trends in 8-hour rolling average O_3 Concentration in Dhaka with the diurnal variations of O_3 concentrations in dry season shown in inset. BS=Bangladesh Standard, WHO=WHO guideline value.



4.1.3 Effect of Mass evacuation on PM Concentration

The city of Dhaka experiences huge exodus (~50-60 %) of people during two large events for Muslims – Eid ul Fitre, and Eid ul Adha. The inhabitants leave the city for their home districts to celebrate the events with their relatives. Most of the industries shut off and number of vehicles in roads drops proportionately. Although the Eid vacations in recent years happen in wet season when the pollution level is already low for frequent wet depositions of the pollutants, more than 50% reduction in PM concentration is observed in Eid days compared to the regular adjacent days (Figure 27).

Figure 27 Reduction of PM_{10} Conc. in Dhaka due to mass evacuation of people from the city during holidays on Eid al Fitre in 2016 and 2017



4.2 Gazipur

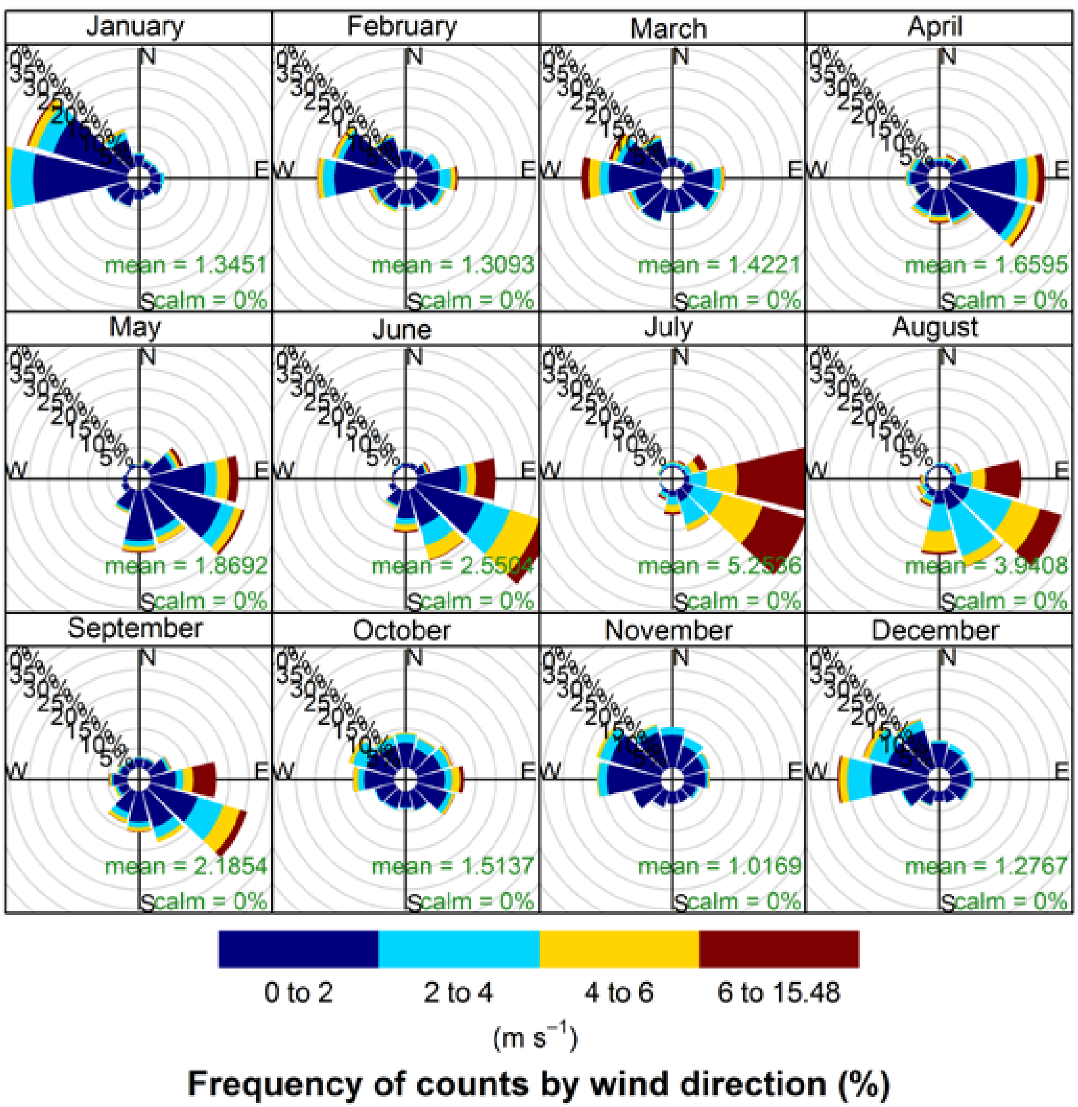
4.2.1 Meteorology

The site of the station is about 30 km to the north from the Dhaka station, and the meteorology is very similar to that of Dhaka. The topography of this region is very flat. The wind data from 2013 to 2018 are captured at the station. Temperature and relative humidity data produced at the Gazipur station are shown in Figure 18, and the nature and effect of meteorology on air pollution in this regions is described in sections 4.1.1.1 and 4.1.1.2.

4.2.1.1 Wind Roses

The wind pattern is very similar to that of Dhaka; westerly and northwesterly winds dominate during November to March, and easterly and southeasterly winds during April to September (Figure 28). However, in October, air flows from all the directions without any domination from any side. The wet seasonal (May – October) wind is comparatively stronger and brings enough moisture from the Bay of Bengal.

Figure 28 Monthly wind roses generated from wind data from 2013 to 2017 at Gazipur station



4.2.2 Criteria Air Pollutants

4.2.2.1 Particulate Matters

Air quality of Gazipur is nearly similar to that of the Dhaka city although the Gazipur station is located far from the direct urban activities and is considered as urban background station. Annual daily average PM_{10} and $PM_{2.5}$ concentrations at Gazipur station are found approximately at 160 μg/m³ and 100 μg/m³ respectively. Air quality of Gazipur depends greatly on seasonal conditions – while the wet seasonal air is very pleasant to breathe, the dry seasonal air filled with high amount of PM causes health hazards. December to February is the most polluted time in Gazipur when PM_{10} concentrations remain two/three times higher than the country standard, and the contributions of fine particles ($PM_{2.5}$) to the PM_{10} concentrations during this period remain high.

Table 5 Overview of daily PM concentrations in Gazipur in recent years; daily concentrations are determined when minimum 80% valid hourly data available in that day

Year	PM_{10} Conc. (μg m^{-3})					$PM_{2.5}$ Conc. (μg m^{-3})				
	percentile				mean	percentile				mean
	25	50	75	95		25	50	75	95	
2013	47	144	232	349	153	31	83	146	231	96.2
2014	60	135	238	341	158	38	96	156	218	104
2015	67	150	249	347	166	nc	nc	nc	nc	nc
2016	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
2017	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

nc = not calculated for inadequate data capture

Figure 29 Trends in daily PM concentration (valid data threshold 80%) in Gazipur from 2013 to 2018. The red and grey horizontal lines are standards for PM_{10} and $PM_{2.5}$ concentrations respectively in Bangladesh

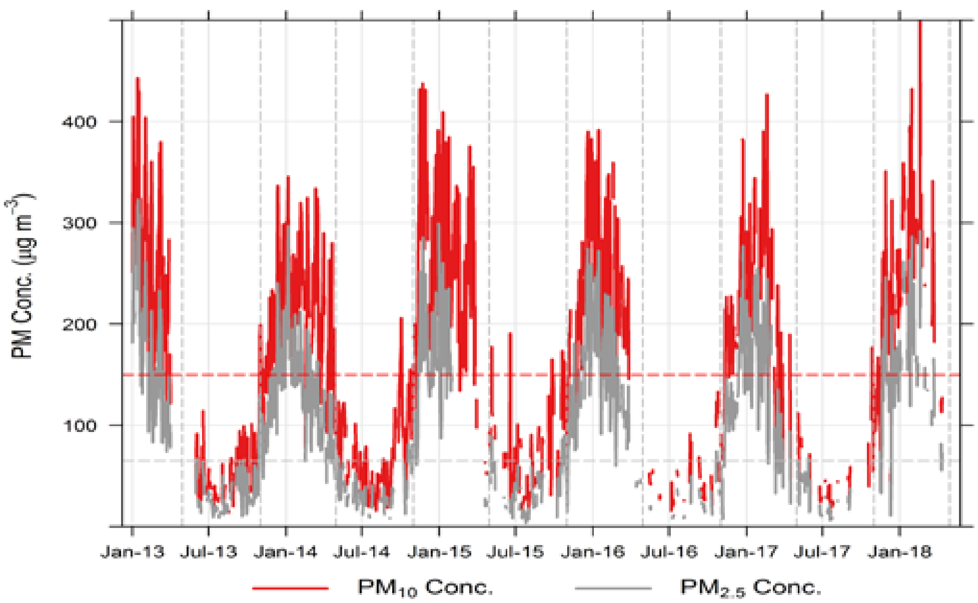
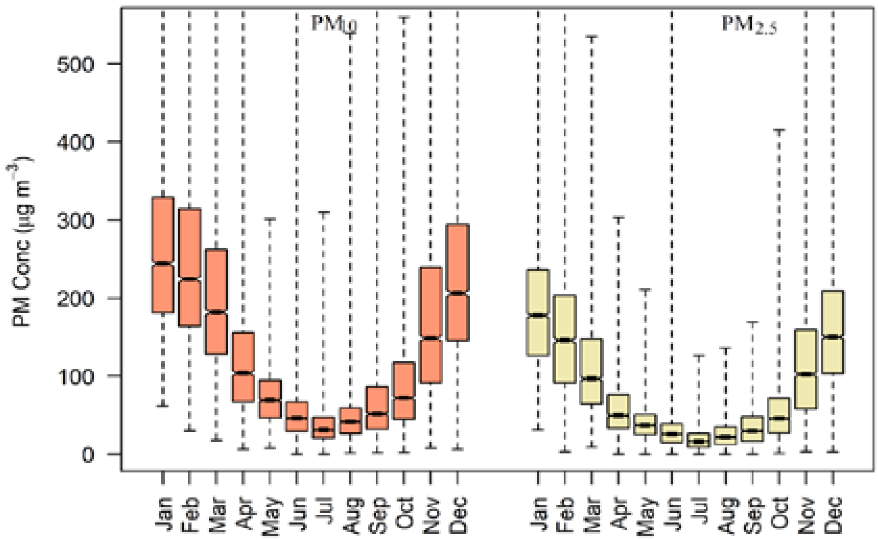


Figure 30 Box-whisker plots of PM concentration in different months in Gazipur from 2013 to 2018



Diurnal variations of PM concentrations in Gazipur are mostly similar to that in Dhaka city. Daytime PM concentrations in dry season in Gazipur wane continuously till the evening since when it starts to rise and reaches to the peak at 8:00 pm to 9:00 pm (Figure 31). Concentration level decreases throughout the night and gets amassing in the atmosphere again in the morning.

During winter, high level of PM concentrations at the Gazipur station are achieved from the west and the northwest directions; the station also experiences moderate level of PM concentrations from the east (Figure 32).

Figure 31 Variations of PM concentration in different time of day and in different day of week in both dry and wet season in Gazipur

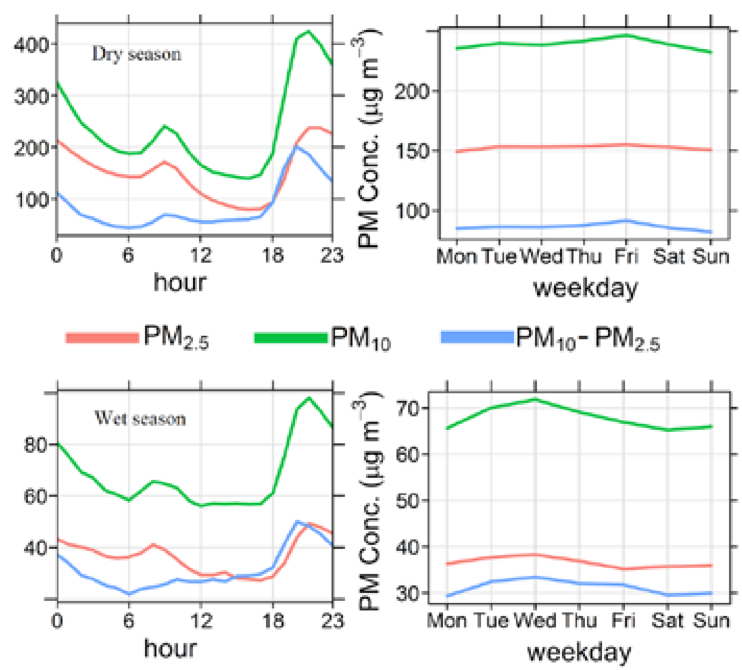
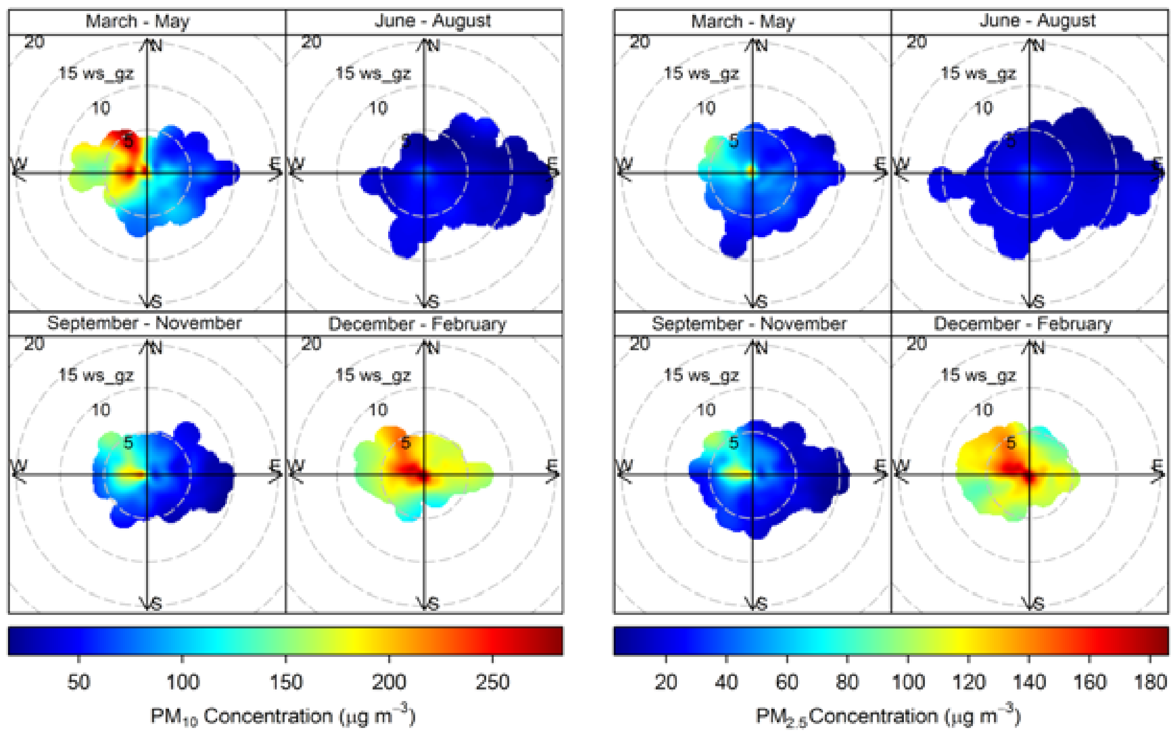


Figure 32 Directional influences on the PM concentrations in different seasons in Gazipur



4.2.2.2 Gaseous pollutants

The levels of gaseous pollutants in air of Gazipur (Figure 33 & 34) are not so worrying. The low concentration values of CO and NO_2 notify weak vehicular emissions around the station. So, the high PM concentrations are expected to be produced from the sources other than vehicles. Brick kilns, industries, local dusts, long range pollutions, etc. could be the sources for higher PM concentrations at the station.

Figure 33 Trends in daily average SO_2 Conc. (left) and 8-h average CO Conc. (right) in Gazipur; BS = Bangladesh Standard

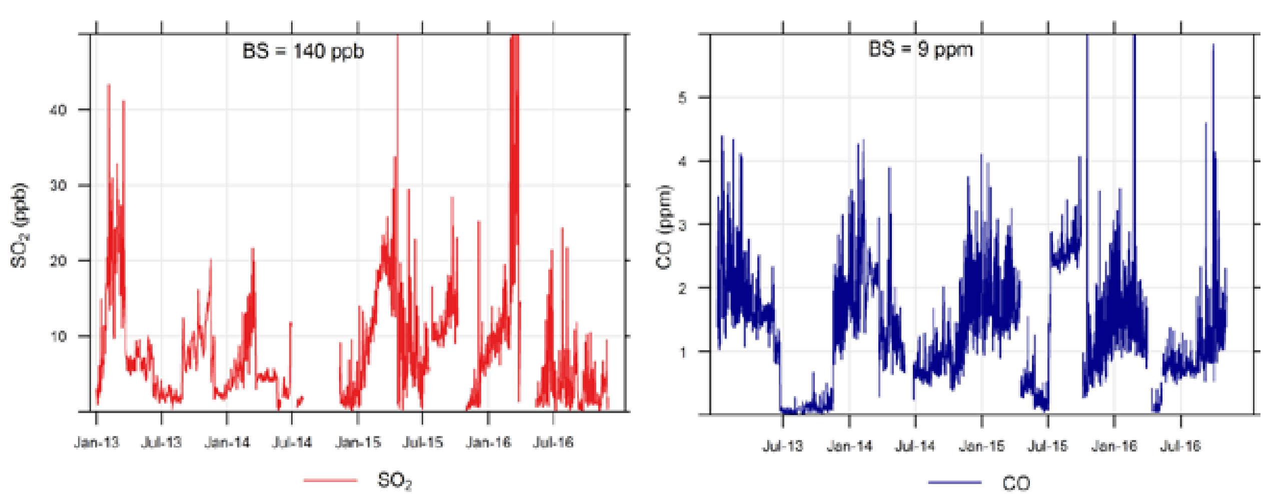
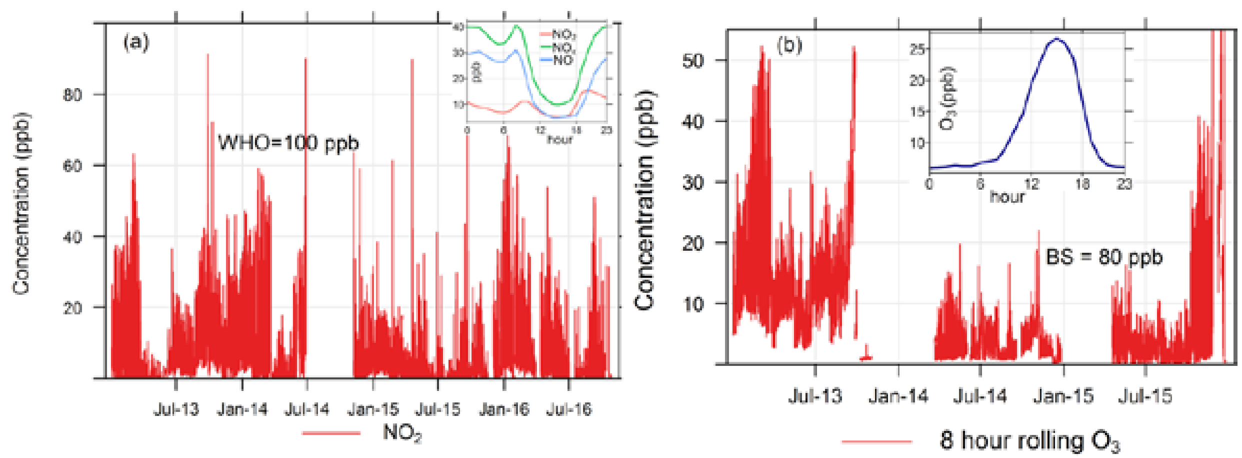


Figure 34 (a) Trends in hourly NO_2 Conc. in Gazipur with the diurnal variations of NO_2, NO_x and NO Conc. in dry season shown in inset. (b) Trends in 8-hour rolling average O_3 Conc. in Gazipur with the diurnal variations of O_3 conc. in dry season shown in inset. BS=Bangladesh Standard, WHO=World Health Organization guideline value.



4.3 Narayanganj

4.3.1 Meteorology

The site is about 25 km to the southeast direction from the Dhaka station. The meteorology is very similar to that of Dhaka; the wind roses and trends in other meteorology parameters are shown in Figure 17 to Figure 19.

4.3.2 Criteria Air Pollutants

4.3.2.1 Particulate Matters

Narayanganj station is found as the most polluted site being monitored under the CASE project. Annual daily PM_{10} concentration in Narayanganj is observed at about 210 µg m^{-3} (Table 6) which is about 30% greater than that of Dhaka (Table 4). However, the annual daily concentrations of $PM_{2.5}$ in Narayanganj is very similar to that in Dhaka, which indicate presence of robust sources of coarse particles (PM_{10} – $PM_{2.5}$) around the station. High PM concentrations in Narayanganj are experienced during the month of December and January when fine particles share the most of the PM_{10} concentrations (Figure 36). Diurnal variations of PM_{10} and $PM_{2.5}$ concentration in both dry and wet seasons in Narayanganj are very similar to those in Dhaka although some dissimilarities in the contributions of coarse and fine particles to the PM concentrations are observed. In all of the cases during dry season, fine particles contribute greatly at night; coarse particles' contributions start to increase from the afternoon and in the evening it surpasses the fine particles' contribution to the PM_{10} concentrations (Figure 37, dry season). Contrasted to the dry seasonal diurnal variations of PM concentrations, wet seasonal variations at daytime do not steeply fall down, and the coarse fractions of PM (PM_{10} – $PM_{2.5}$) dominate over the fine fractions all over the day (Figure 37, wet season). The station experiences most of the PM in dry season from the northwest directions, high PM concentrations are also found from the northeast direction (Figure 38). As wind flows from the north and west directions during dry season, all the local and remote sources located to those directions contribute greatly to the high PM concentrations in that season, which is reflected in the Figure 38. The city of Dhaka lies upwind of Narayanganj and the massive emissions from the megacity of Dhaka may also contribute highly to the PM pollutions in Narayanganj during dry season.

Table 6 Overview of daily PM concentrations in Narayanganj in recent years; daily concentrations are determined when minimum 80% valid hourly data available in that day

Year	PM_{10} Conc. (µg m^{-3})					$PM_{2.5}$ Conc. (µg m^{-3})				
	percentile				mean	percentile				mean
	25	50	75	95		25	50	75	95	
2013	67	115	268	414	172	17	33	115	280	79
2014	80	156	325	447	205	33	71	187	290	110
2015	104	199	325	440	218	nc	nc	nc	nc	nc
2016	88	153	303	475	201	22	54	167	266	96
2017	112	188	324	446	221	nc	nc	nc	nc	nc

nc= not calculated for inadequate data capture

Figure 35 Trends in daily PM concentration (valid data threshold 80%) in Narayanganj from 2013 to 2018. The red and grey horizontal lines are standards for PM_{10} and $PM_{2.5}$ respectively in Bangladesh

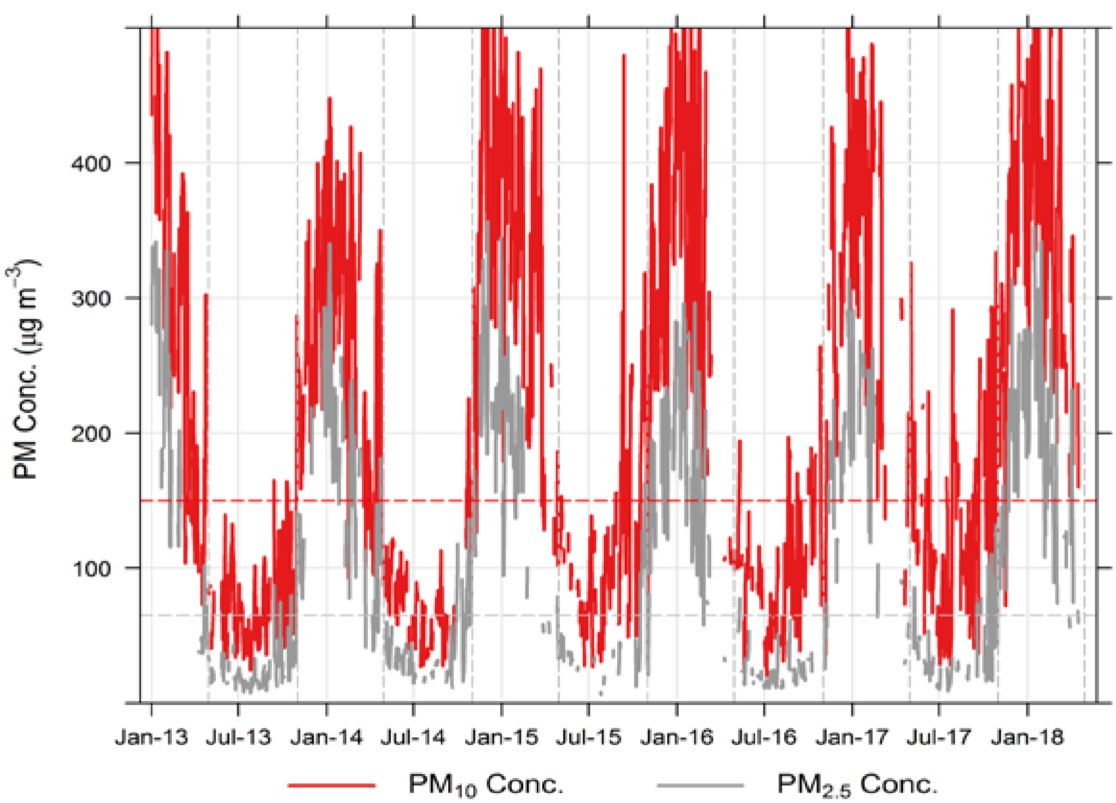


Figure 36 Box-whisker plots of PM concentrations in different months in Narayanganj

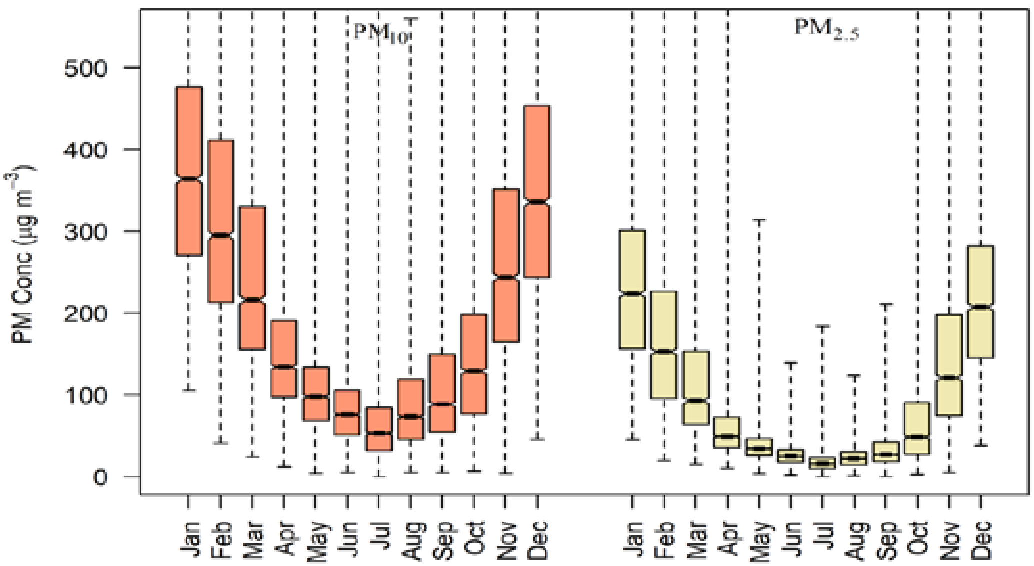


Figure 37 Variations of PM concentration in different time of day and in different day of week in both dry and wet season in Narayanganj

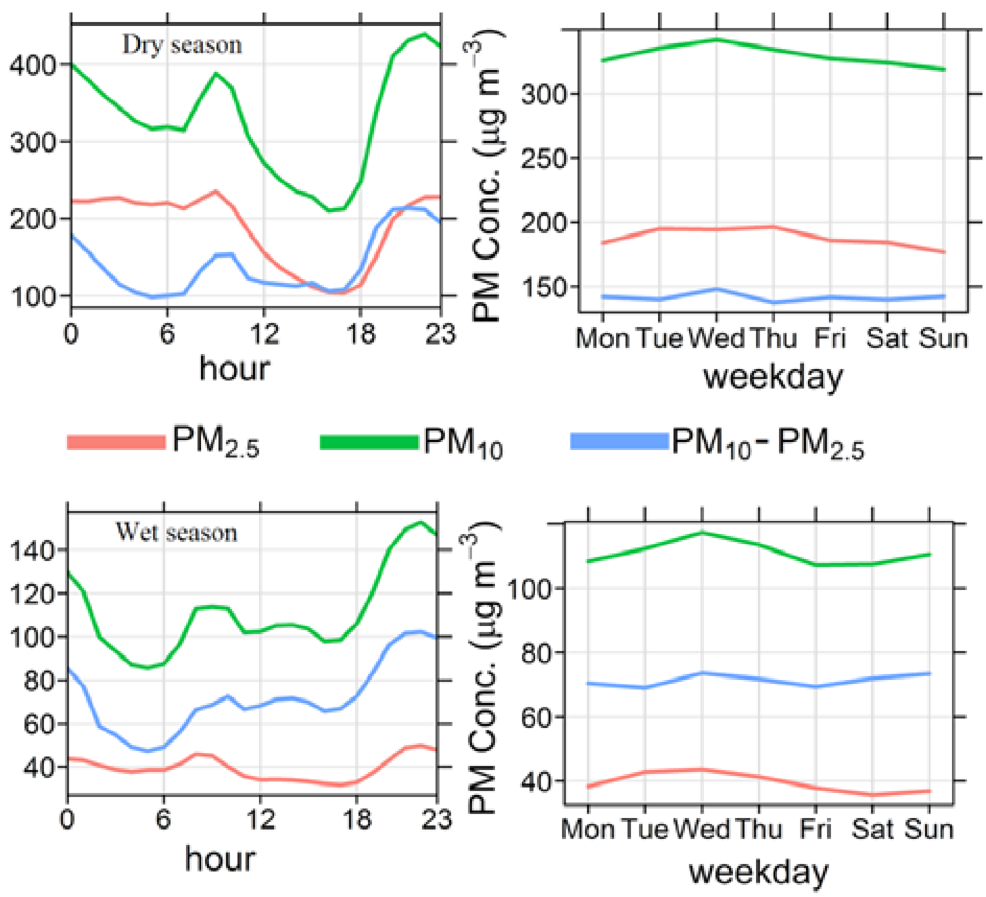
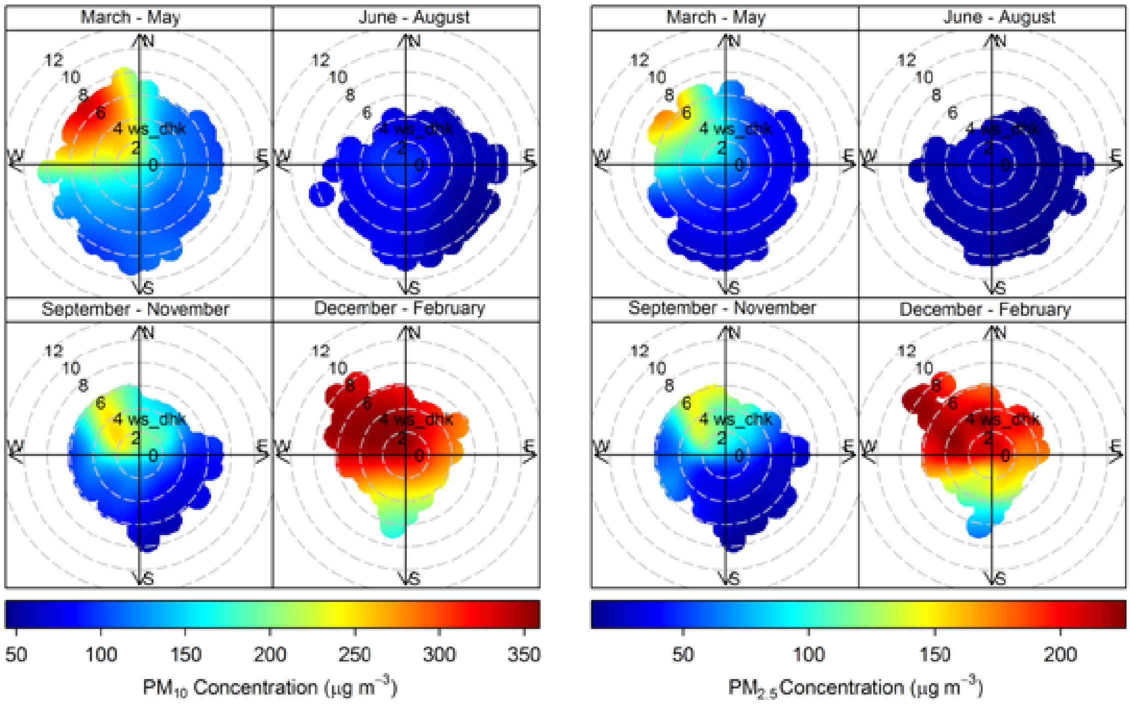


Figure 38 Directional influences on the PM concentrations in different seasons in Narayanganj



4.3.2.2 Gaseous pollutants

Although Narayanganj is highly polluted with PM, the presence of gaseous pollutants is not found worrisome. The trends in SO_2 and CO concentrations in Narayanganj (Figure 39) are found within the acceptable level throughout the year; the concentrations tend to increase in dry season though. The NO_2 and O_3 concentrations are also compatible throughout the year (Figure 40) except some days in May to June, 2017 when the NO_2 concentrations, for some unknown reasons, are found very close to the WHO guideline value of 100 ppb on hourly average. The diurnal variations of NO_2 and O_3 concentrations are very typical for urban sites, as is found for Dhaka and Gazipur stations also.

Figure 39 Trends in daily average SO_2 Conc. (left) and 8-h average CO Conc. (right) in Narayanganj; BS = Bangladesh Standard

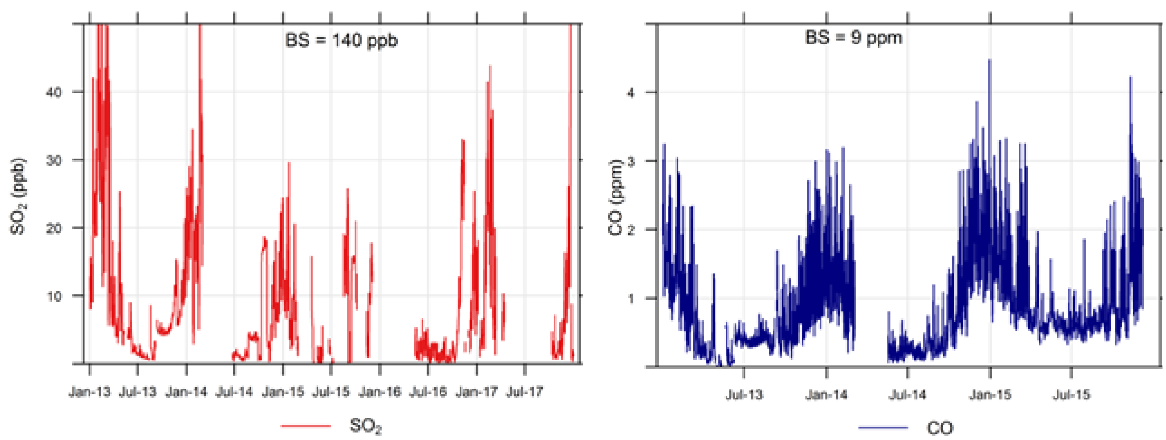
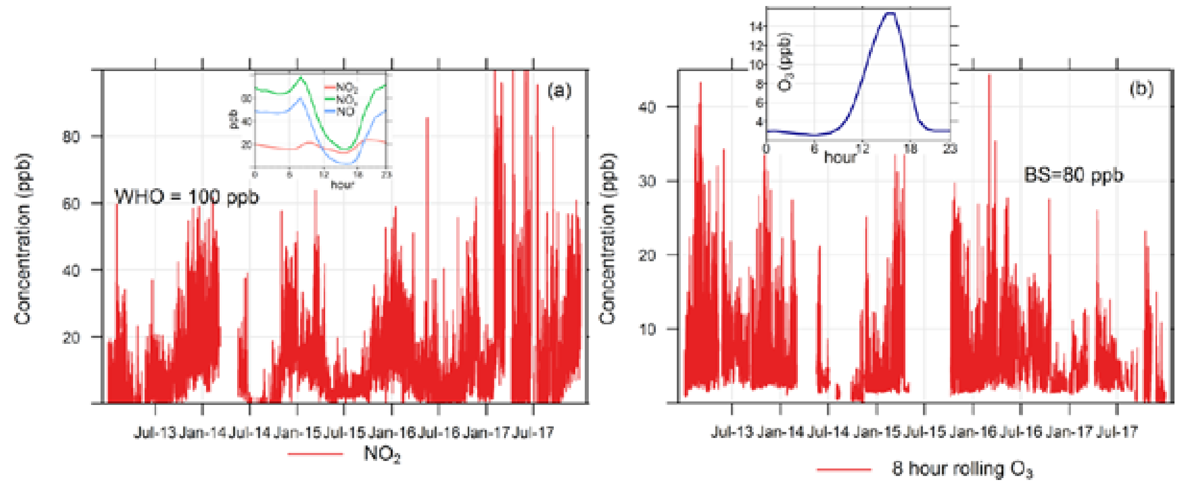


Figure 40 (a) Trends in hourly NO_2 Conc. in Narayanganj with the diurnal variations of NO_2, NO_x and NO Conc. in dry season shown in inset. (b) Trends in 8-hour rolling average O_3 Conc. in Narayanganj with the diurnal variations of O_3 conc. in dry season shown in inset. BS=Bangladesh Standard, WHO=World Health Organization guideline value.



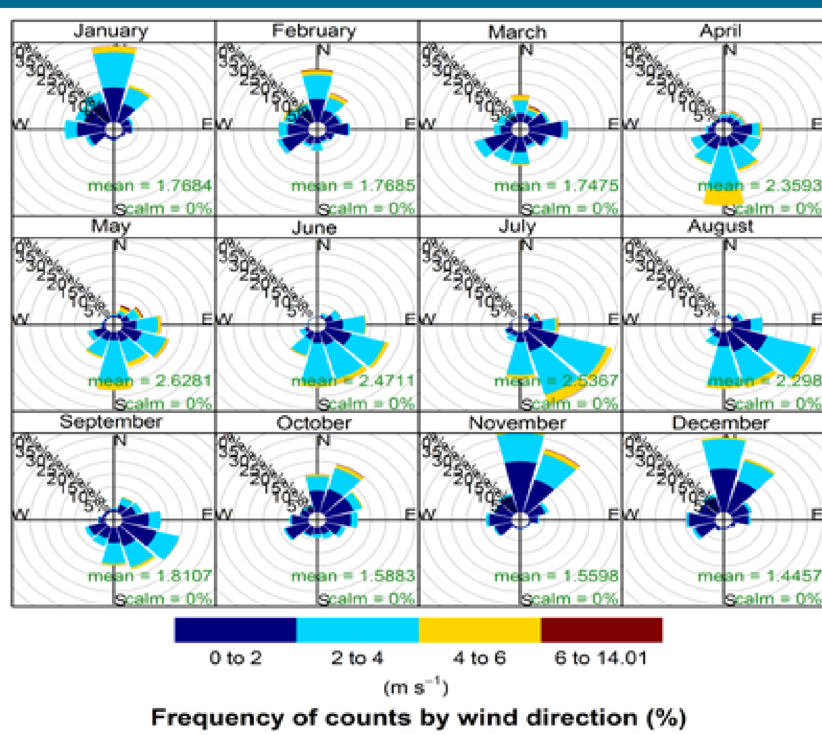
4.4 Chittagong

4.4.1 Meteorology

4.4.1.1 Wind roses

Monthly wind roses of Chittagong (Figure 41) differ slightly from those of Dhaka, especially for the month of October and for the winter season. Northern and northeastern winds prevail in October and throughout the winter season (November – January) in Chittagong. However, the wet seasonal wind resembles that in Dhaka – blows from the south and southeast directions.

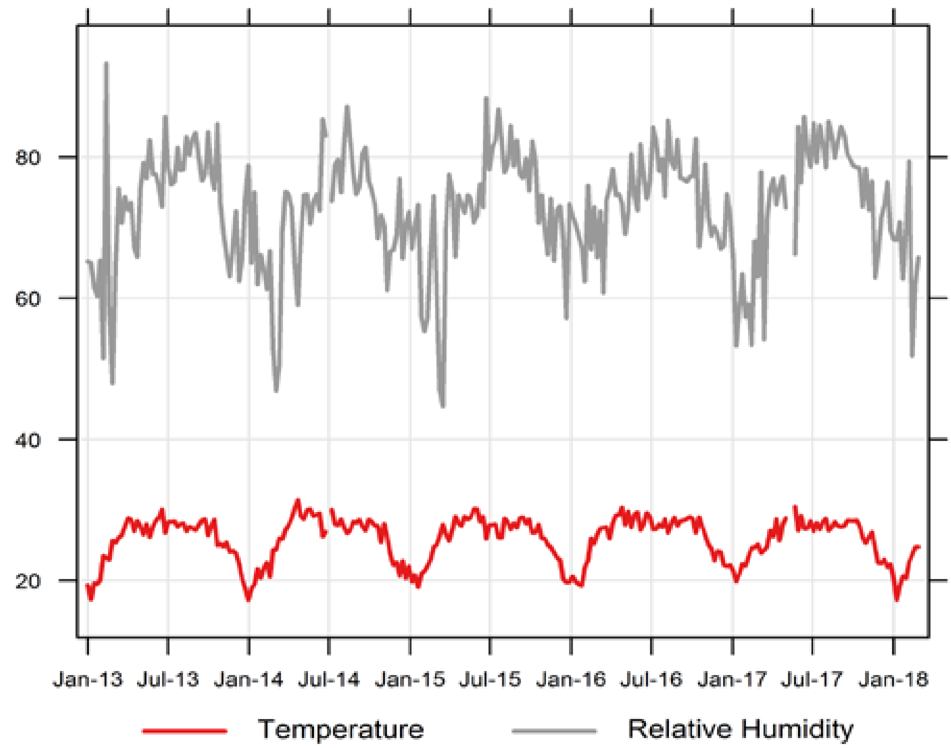
Figure 41 Monthly wind roses generated from wind data from 2013 to 2017 at Chittagong station



4.4.1.2 Temperature and Relative Humidity

Figure 42 shows the trends in temperature and relative humidity at the Chittagong station. The weather is little comfortable in Chittagong for its stance near the sea.

Figure 42 Trends in weekly temperature (ºC) and relative humidity (%) in Chittagong



4.4.2 Criteria Air Pollutants

4.4.2.1 Particulate Matters

The trend in PM concentrations in Chittagong is also influenced by seasonal changes; high pollution level prevails in dry season while that in wet season is compliant with the national standards. However, the intensity of PM pollution throughout the year in Chittagong is comparatively lower, to some extent, than that in and around the Dhaka city. The month of January tops for high PM_{10} concentrations, followed by February and December while for $PM_{2.5}$ concentrations, the month of January is followed by December and February (Figure 44). The city of Chittagong is situated by the Bay of Bengal, and sea salt is expected to have a good share in PM_{10} concentration in the city. The land-sea breeze motion and relatively warm winter may play good role in the characteristics of atmospheric pollution in Chittagong.

Diurnal and weekday variations of PM concentrations in Chittagong (Figure 45) differ little from those in Dhaka and its vicinity. The morning peak of $PM_{2.5}$ concentration at 9:00 am is not so remarkable in Chittagong, and that the pollution level during dry season lessens in Friday, the first official holiday, which was not found in and around Dhaka city. The diurnal variations (Figure 45) also reveal that contributions of coarse size particles (PM_{10} – $PM_{2.5}$) to PM outdo that of fine particles from the afternoon till 9:00pm during the dry season, and from noon to the midnight during the wet season. At night, the presence of fine particles is found to remain in high proportion (Figure 45).

The percentiles and mean values of the daily PM concentrations for each year are shown in Table 7. Annual daily PM concentrations are calculated when minimum 80% hourly data are present in a day – meaning that only those days with minimum 19 numbers of hourly data are considered for the statistics. The criterion of setting high threshold value for calculating daily average forces many days to be excluded from the determination of yearly statistical parameters in Table 7, which consequently lowers overall data numbers in some years. The trend in PM concentration (Figure 43) is also plotted with the days having 80% valid hourly data. Annual daily PM_{10} and $PM_{2.5}$ concentrations in Chittagong are found nearly 120 µg m^{-3} and 80 µg m^{-3} respectively which are about 25 and 13 % lower than those in Dhaka city.

Table 7 Overview of daily PM concentrations in Chittagong in recent years; daily concentrations are determined when minimum 80% valid hourly data available in that day

Year	PM_{10} Conc. (µg m^{-3})					$PM_{2.5}$ Conc. (µg m^{-3})				
	percentile				mean	percentile				mean
	25	50	75	95		25	50	75	95	
2013	46	87	190	297	123	24	52	115	191	75
2014	nc	nc	nc	nc	nc	30	81	128	175	88
2015	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
2016	45	82	162	254	107	21	36	111	175	67
2017	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

nc=not calculated for inadequate data capture

Figure 43 Trends in daily PM concentration (data threshold 80%) in Chittagong. The red and grey horizontal lines are standards for PM10 and PM2.5 respectively in Bangladesh

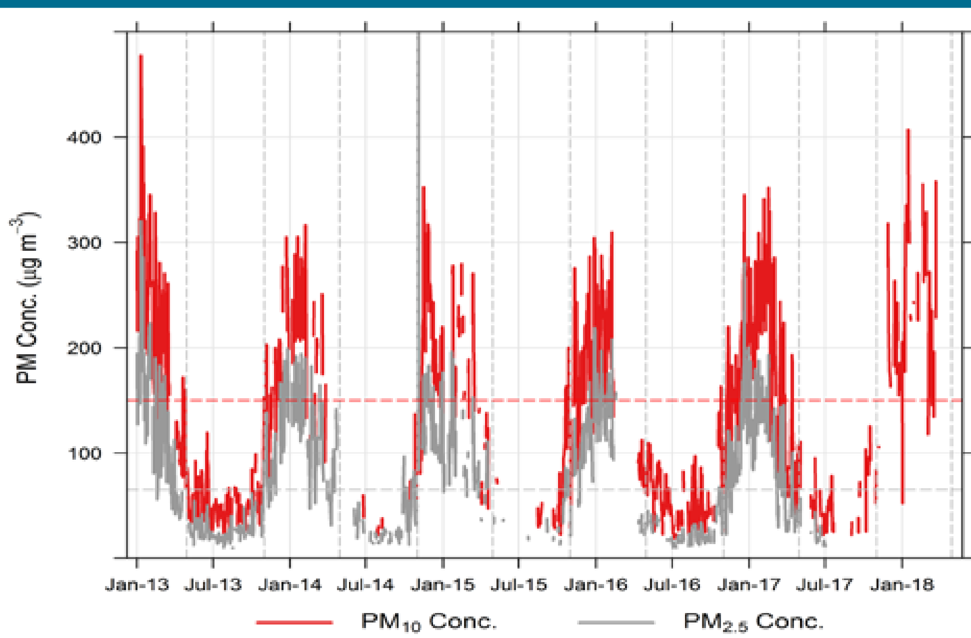


Figure 44 Box-whisker plots of PM concentrations in different months in Chittagong

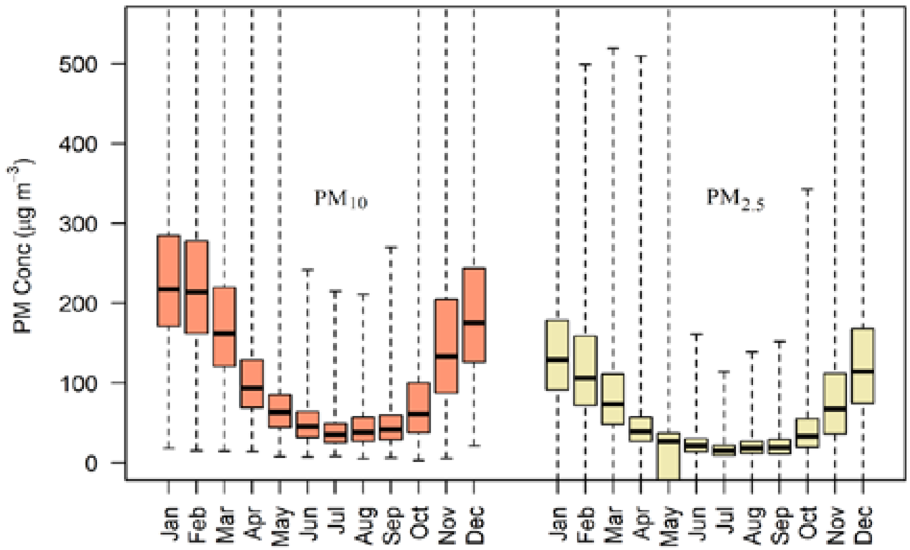
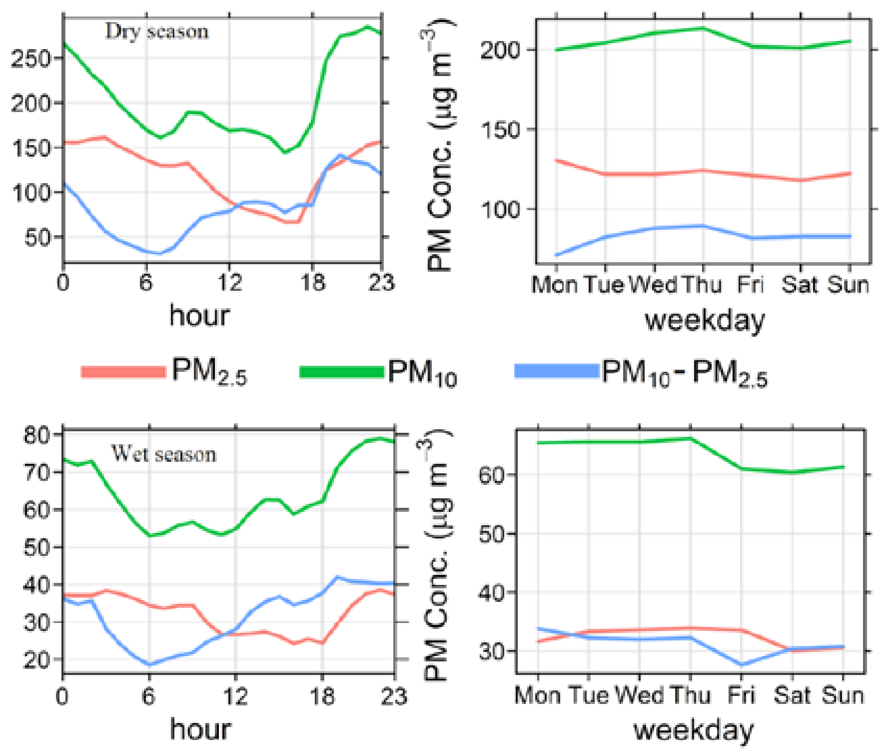
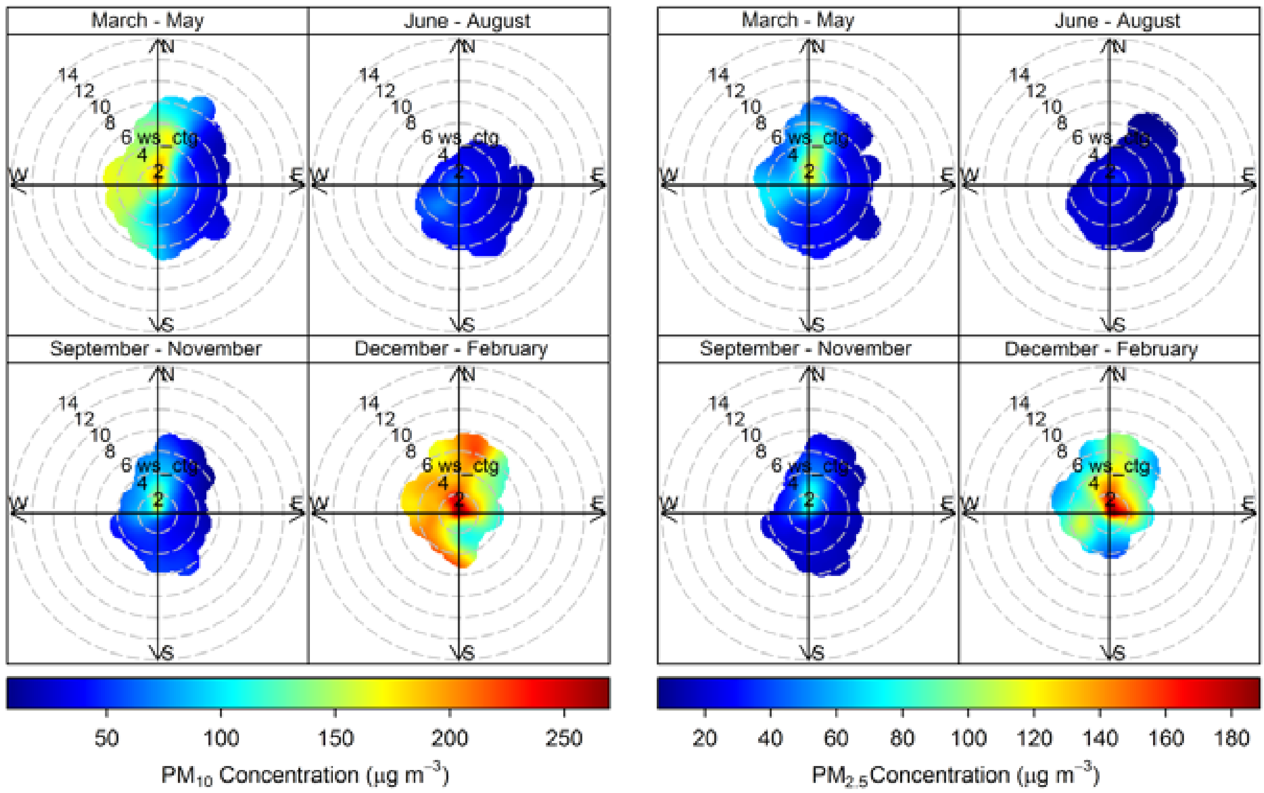


Figure 45 Variations of PM concentration in different time of day and in different day of week in both dry and wet season in Chittagong



Polar plots of PM_{10} and $PM_{2.5}$ concentrations in different seasons (Figure 46) show very high PM concentrations in winter time prevails with calm weather – indicating existence of local pollutions releasing near ground level, and the sources could be dusts, cooking, vehicles and/or open burning. High pollutions in dry season are also experienced from the northern and western directions.

Figure 46 Directional influences on the PM concentrations in different seasons in Chittagong



4.4.2.2 Gaseous Pollutants

The level of gaseous pollutants irrespective of the season in Chittagong is very compliant with the respective limit values (Figure 47&48), except some days in dry season when the NO_2 and O_3 concentrations remain very close to the permissible limits. The seasonal trends of the gaseous pollutants are as usual – up in dry season and down in wet season.

Diurnal variations of NO_x, NO_2 and NO concentrations (Figure 48a, inset) at the Chittagong site differ greatly from those in Dhaka station (Figure 26a). NO_2 concentrations all of the time of the day outdo the NO concentrations at this residential site of Chittagong, presumably for its location away from vehicular emissions and from any big industries with high thermal activities.

Figure 47 Trends in daily average SO_2 Conc. (left) and 8-h average CO Conc. (right) in Chittagong; BS = Bangladesh Standard

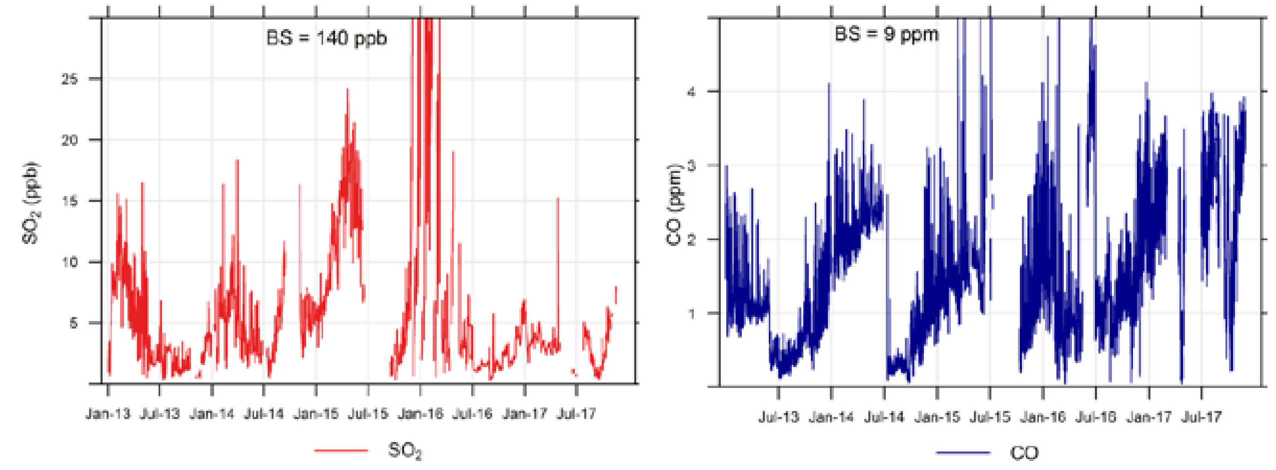
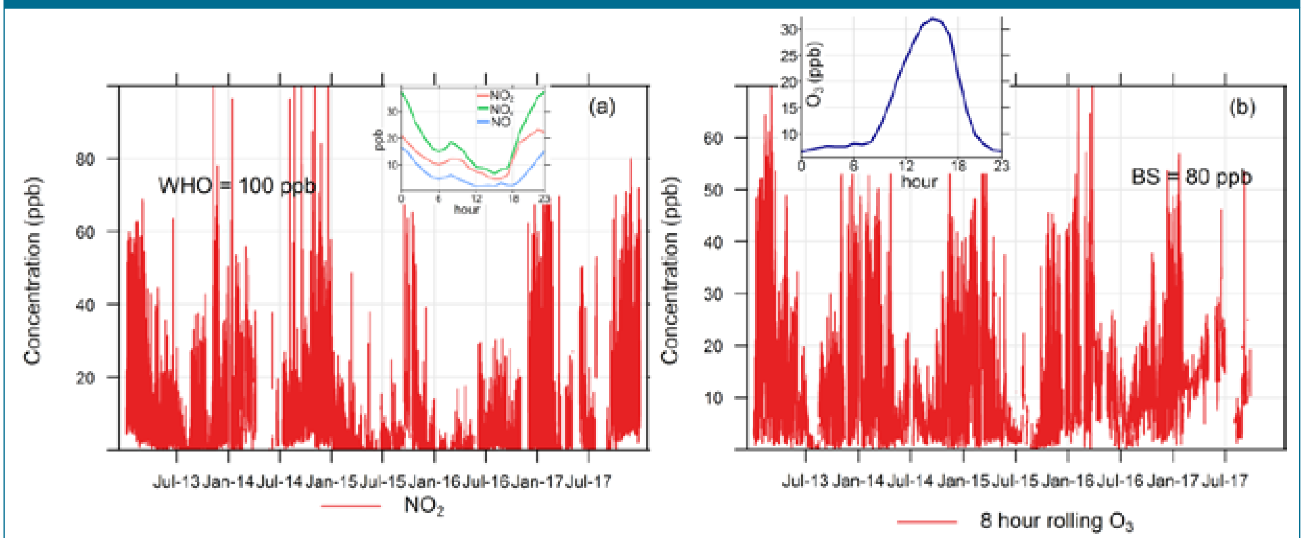


Figure 48 (a) Trends in hourly NO_2 Conc. in Chittagong with the diurnal variations of NO_2, NO_x and NO Conc. in dry season shown in inset. (b) Trends in 8-hour rolling average O_3 Conc. in Chittagong with the diurnal variations of O_3 conc. in dry season shown in inset. BS=Bangladesh Standard, WHO=World Health Organization guideline value.



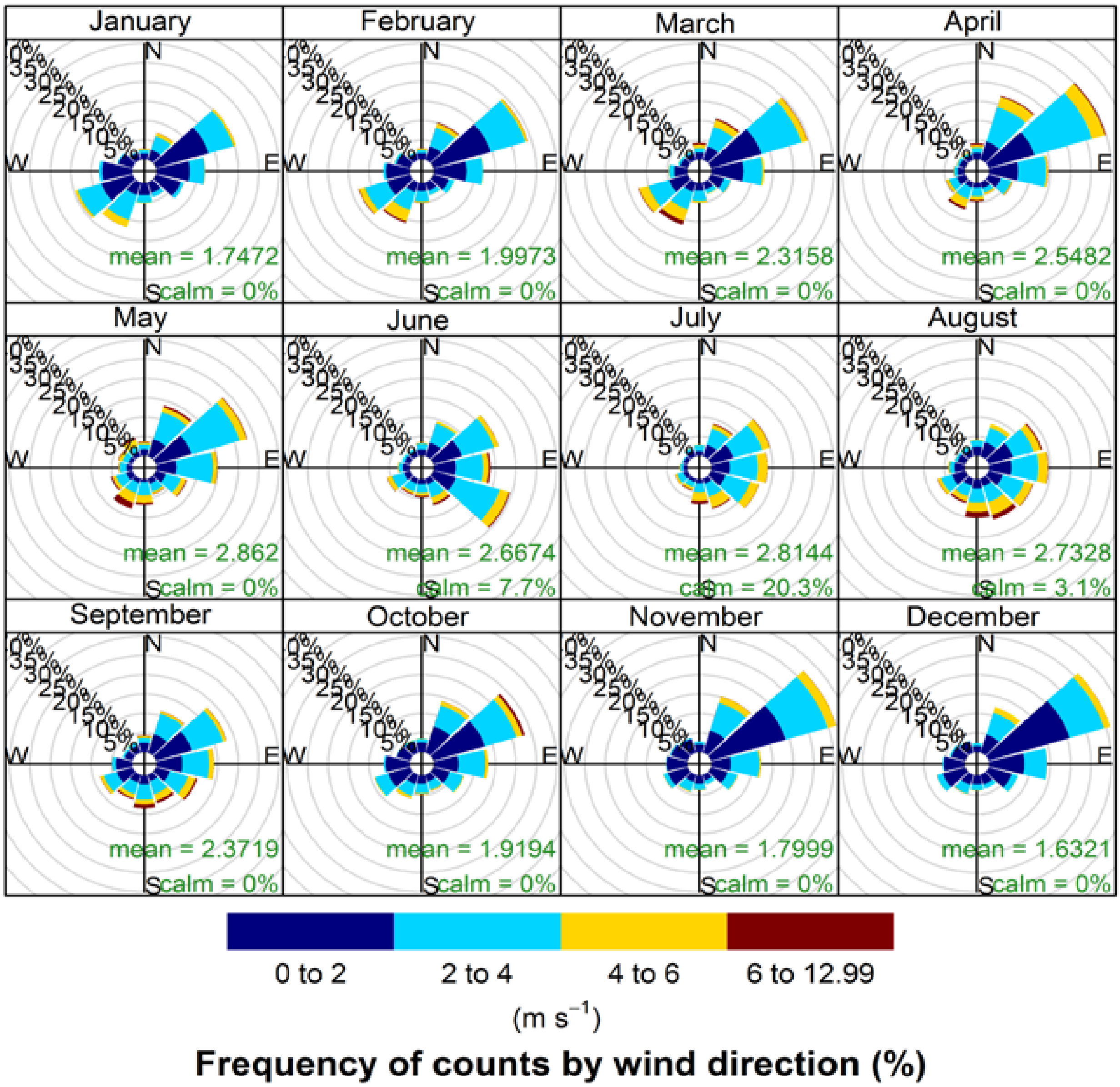
4.5 Sylhet

4.5.1 Meteorology

4.5.1.1 Wind roses

Wind pattern in Sylhet is different from other parts of the country. In lieu of the northwest and southeast dominancy of wind directions which is seen in other parts of the country, air blows majorly from the east and northeast directions throughout the year in Sylhet. In addition, a portion of wind comes from the southwest direction during dry season, and in wet season a fraction comes from the southeast direction (Figure 49).

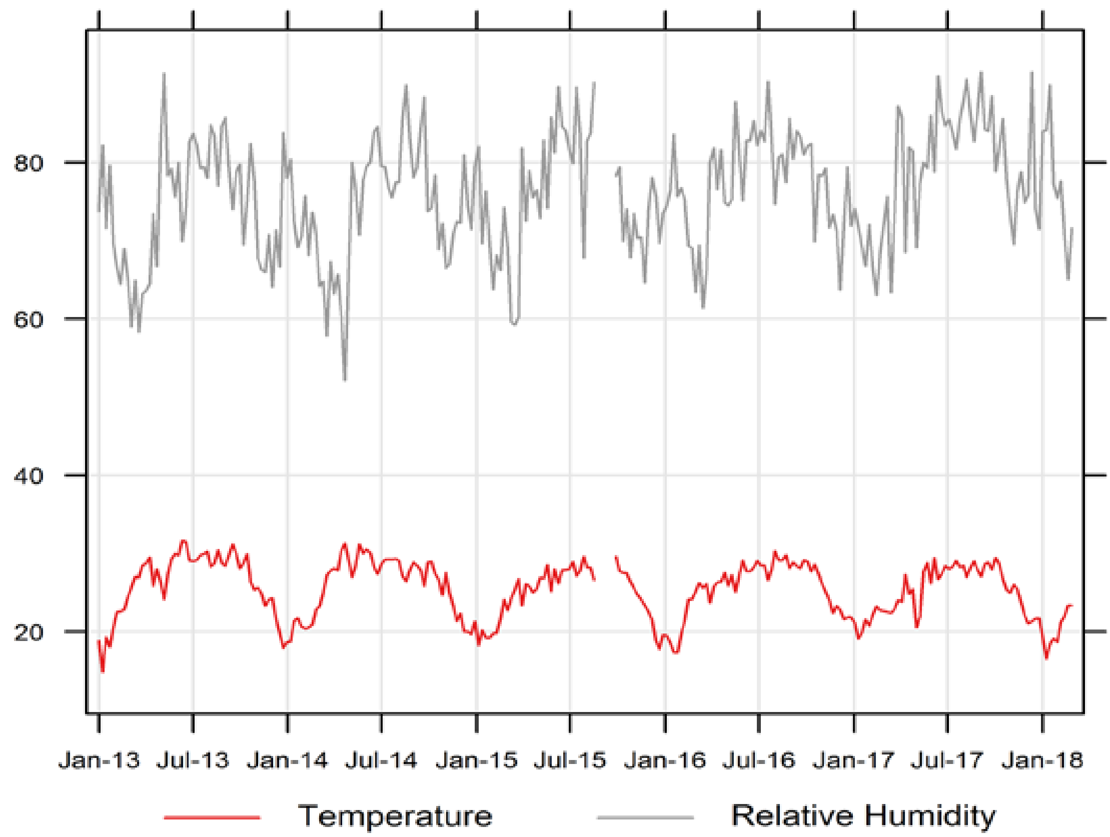
Figure 49 Monthly wind roses generated from wind data from 2013 to 2017 at Sylhet station



4.5.1.2 Temperature, Relative Humidity

Trends in temperature and relative humidity are mostly similar to those in other parts of the country although the level of temperature in Sylhet is little lower than Dhaka. Temperature starts to rise from February and gets it peak in April, remains at high level up to October after which it continues diving up to January, which is the coldest month. On the other hand, the relative humidity in Sylhet wanes from January, and comes to its lowest value in the month of April to May (Figure 50). During the month of June to October, the atmosphere remains soggy.

Figure 50 Trends in weekly temperature (oC) and relative humidity (%) in Sylhet



4.5.2 Criteria Air Pollutants

4.5.2.1 Particulate Matters

Air quality of Sylhet is found better than that of other urban areas of the country. Annual daily PM_{10} and $PM_{2.5}$ concentrations in Sylhet are found nearly 110 µg m^{-3} and 62 µg m^{-3} respectively (Table 8). On an average, this annual daily PM concentration in Sylhet is about 30% lower than that in Dhaka. The trend of PM concentration is as usually dependent on seasonal influences – high concentrations in dry season and low in wet season. However, the PM characteristics of individual month of dry season differ greatly in Sylhet. Unlike other parts of the country, the month of December in Sylhet is less polluted than the months of February and March in terms of PM concentrations (both fraction) (Figure 52). The atmosphere in November and April is also less polluted (Figure 52). PM concentrations in about 50% days of dry season in Sylhet are found compliant with the limit values (Figure 53) whereas for Dhaka city and its vicinity it was about 25% days only (Figure 22).

Diurnal and weekday variations of PM concentrations in Sylhet (figure 54) are also different from other cities. The morning peaks of PM_{10} and $PM_{2.5}$ concentrations at 9:00 am in both the seasons are obscure in Sylhet; rather, the concentrations are seen to hike a little at 11:00 am to 12:00 pm. PM concentrations at daytime in dry season undulate a little, and get an evening hike at 8:00 pm to 9:00 pm, but in wet season the daytime concentrations do not diminish at all. In both seasons, the PM concentrations fall sharply in Friday, the first official holiday in the country.

Table 8 Overview of daily PM concentrations in Sylhet in recent years; daily concentrations are determined when minimum 80% valid hourly data available in that day

Year	PM_{10} Conc. ($\mu g\ m^{-3}$)					$PM_{2.5}$ Conc. ($\mu g\ m^{-3}$)				
	percentile				mean	percentile				mean
	25	50	75	95		25	50	75	95	
2013	48	103	171	236	114	20	45	95	148	62
2014	51	94	167	221	110	23	50	95	140	62
2015	60	94	149	225	110	30	55	104	138	65
2016	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
2017	40	83	141	212	97	17	35	70	124	48

nc= not calculated for inadequate data capture

Figure 51 Trends in daily PM concentration (data threshold 80%) in Sylhet. The red and grey horizontal lines are standards for PM_{10} and $PM_{2.5}$ respectively in Bangladesh

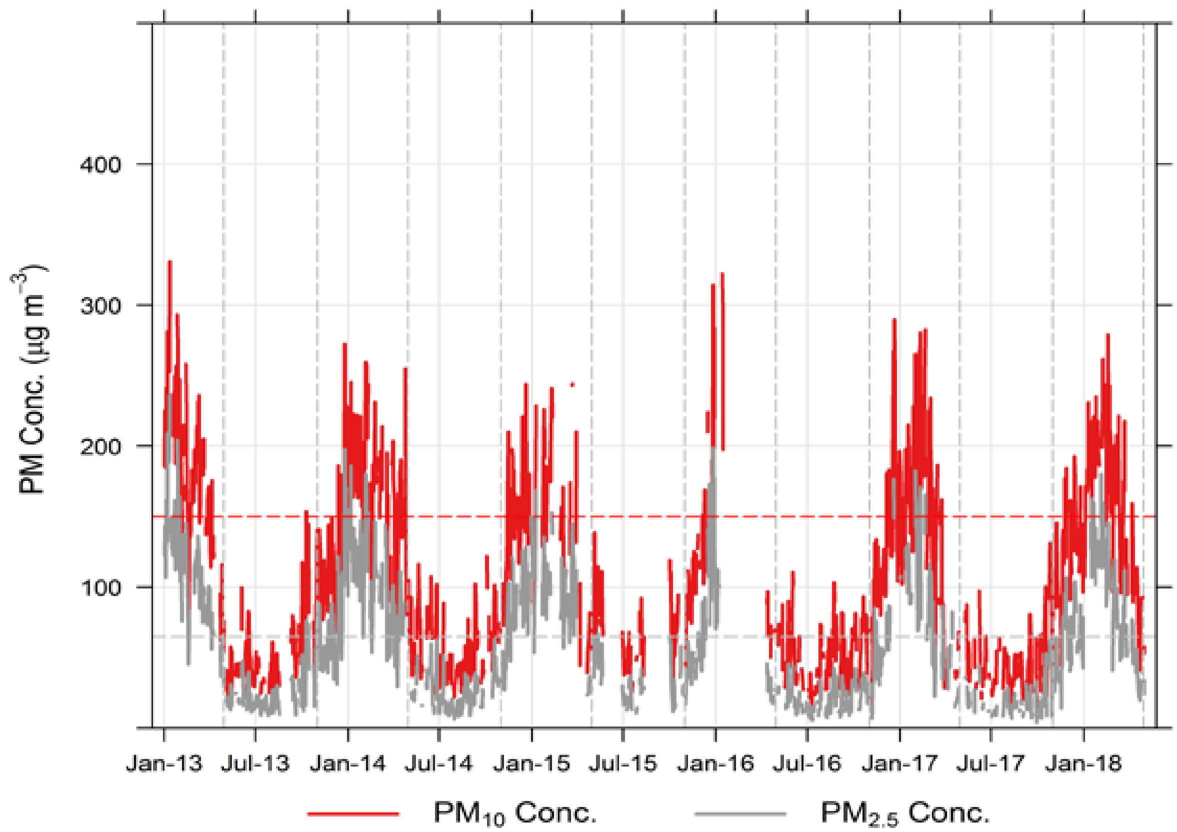


Figure 52 Box-whisker plots of PM concentrations in different months in Sylhet

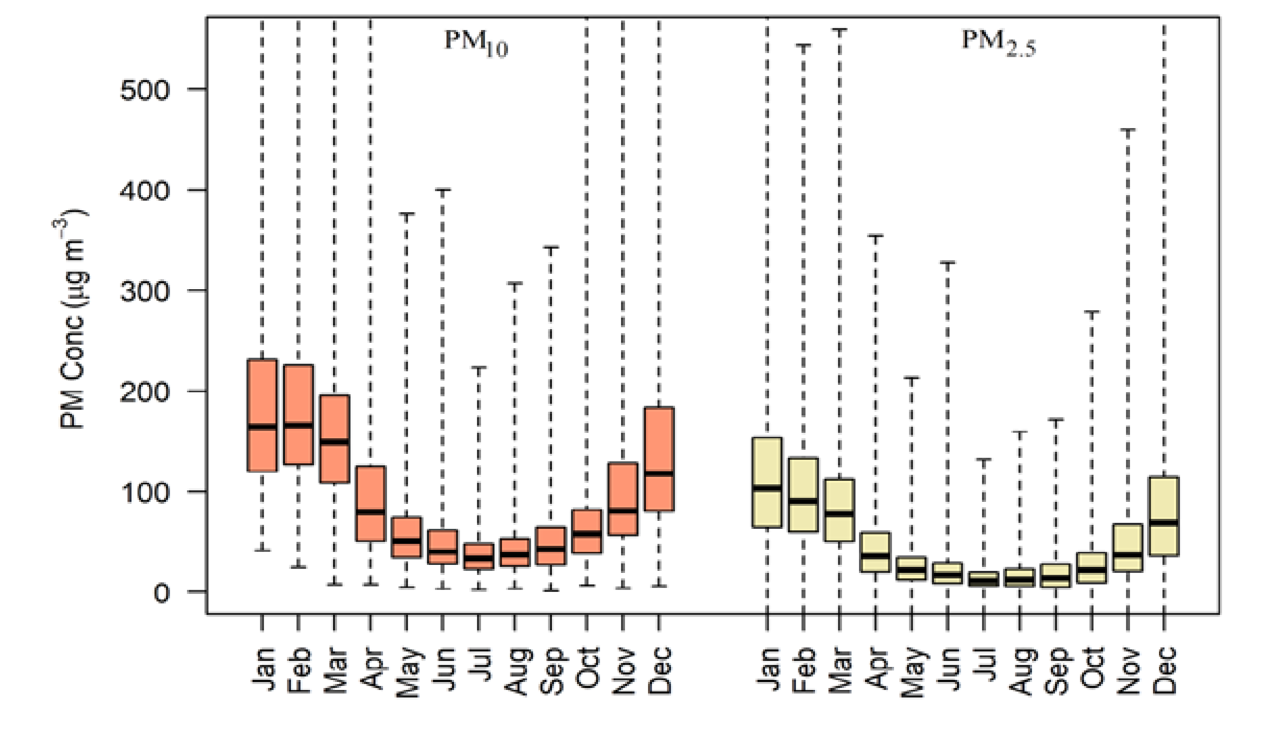


Figure 53 Box-whisker plots of daily PM concentration in dry season in Sylhet shown for different years; horizontal lines are standards for daily PM_{10} (maroon) and $PM_{2.5}$ (lemon) Conc. Dry season is measured from November (previous year) to April (current year)

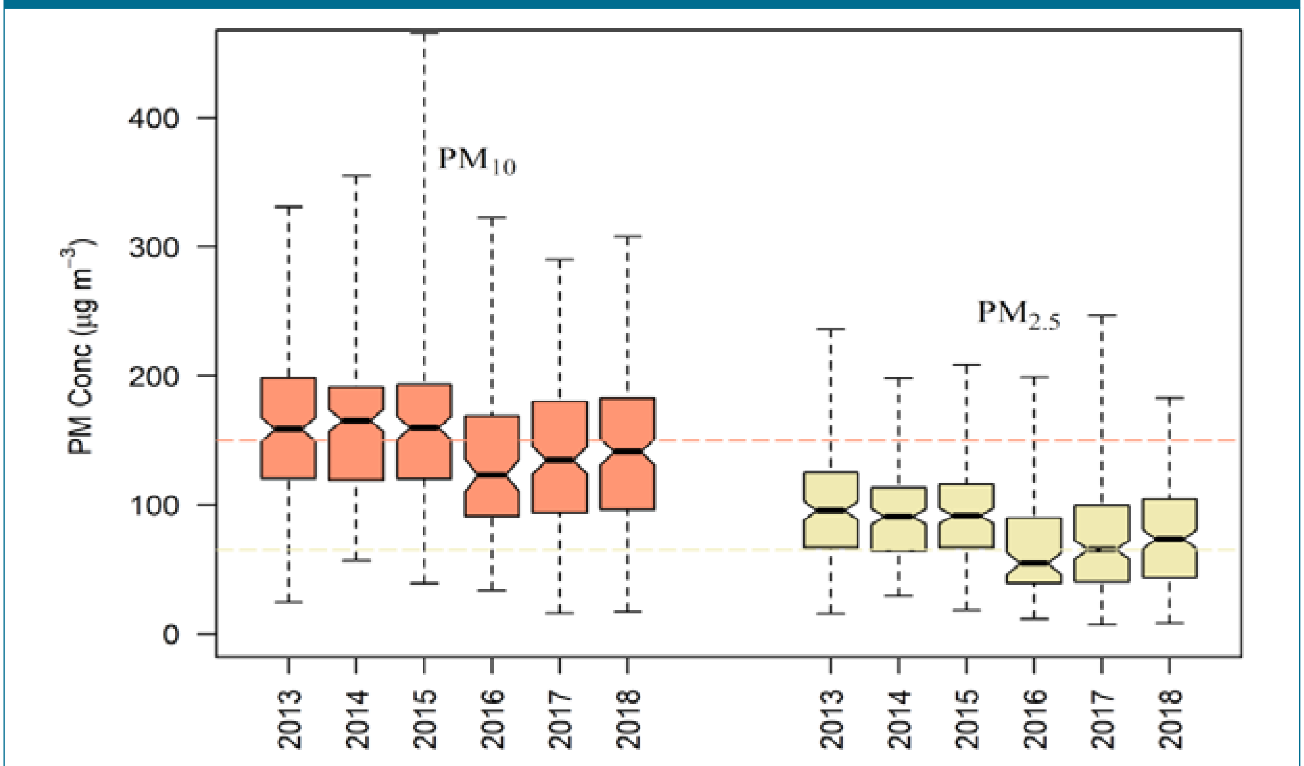
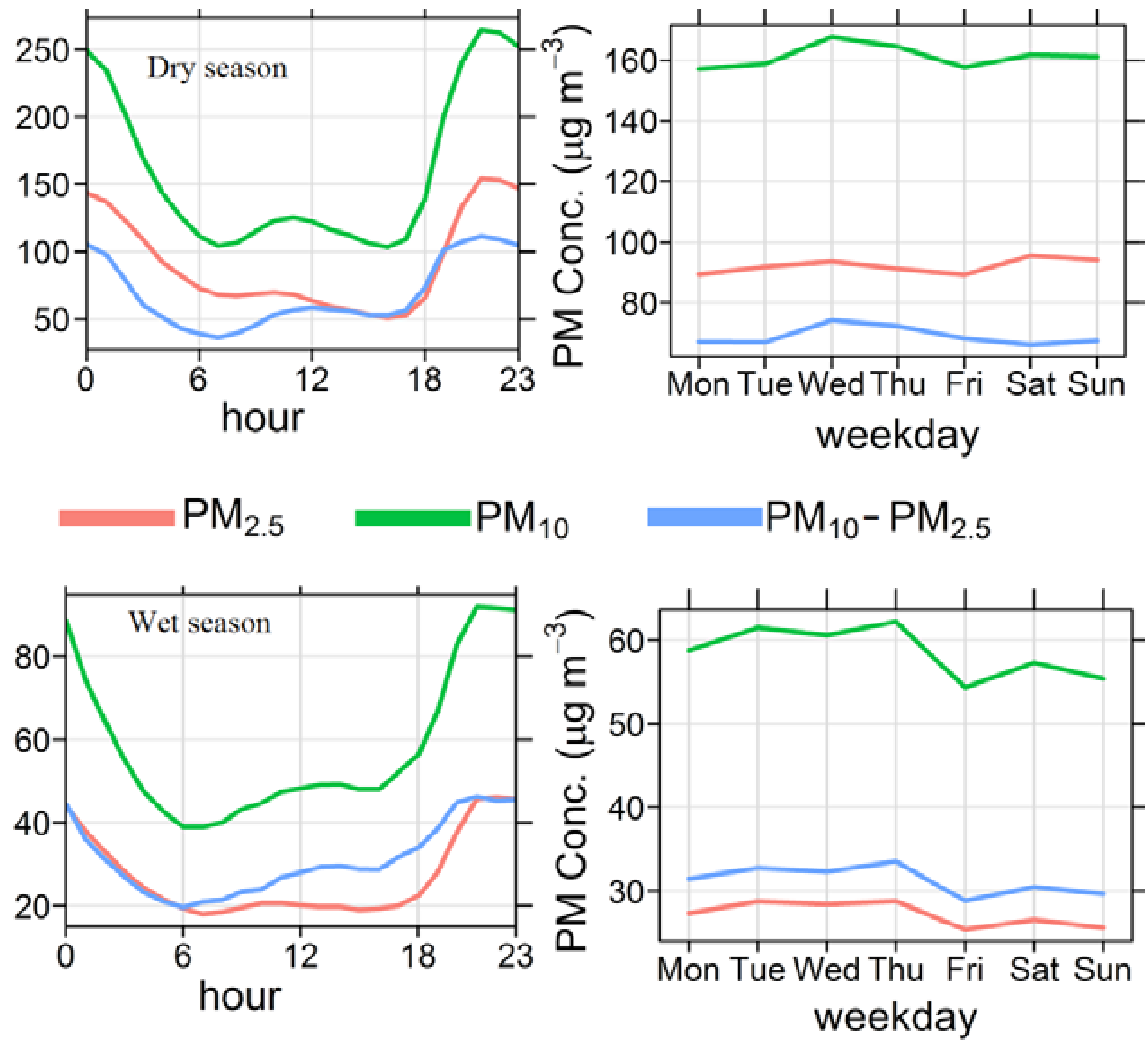
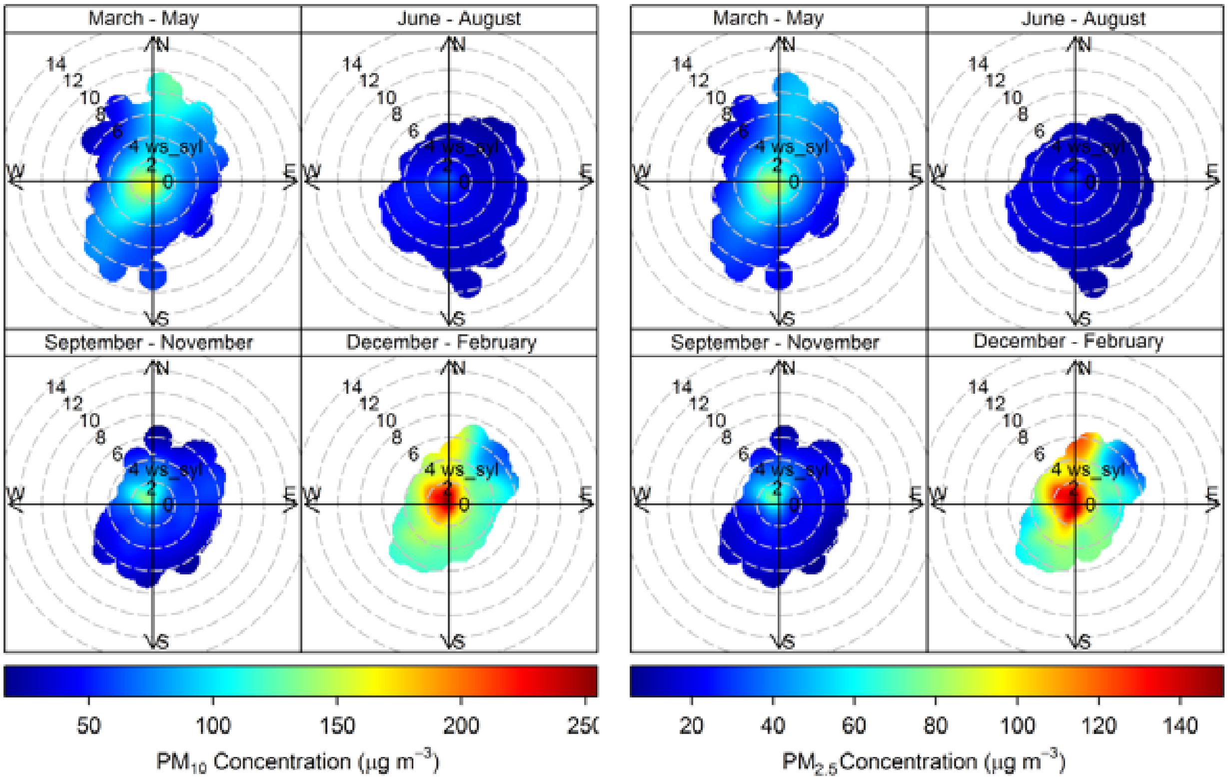


Figure 54 Variations of PM concentration in different time of day and in different day of week in both dry and wet season.



Directional variations of PM concentrations in Sylhet (Figure 55) reveal that high concentrations associate with calm weather in dry season – primarily indicates to the local sources releasing near ground (dusts, vehicles, open burning, etc.). In addition, the station experiences high PM from the southwest and northwest directions although most of the wind in dry season blows from the northeast direction (Figure 49). High PM concentrations from the north are also achieved at the station with high wind velocities.

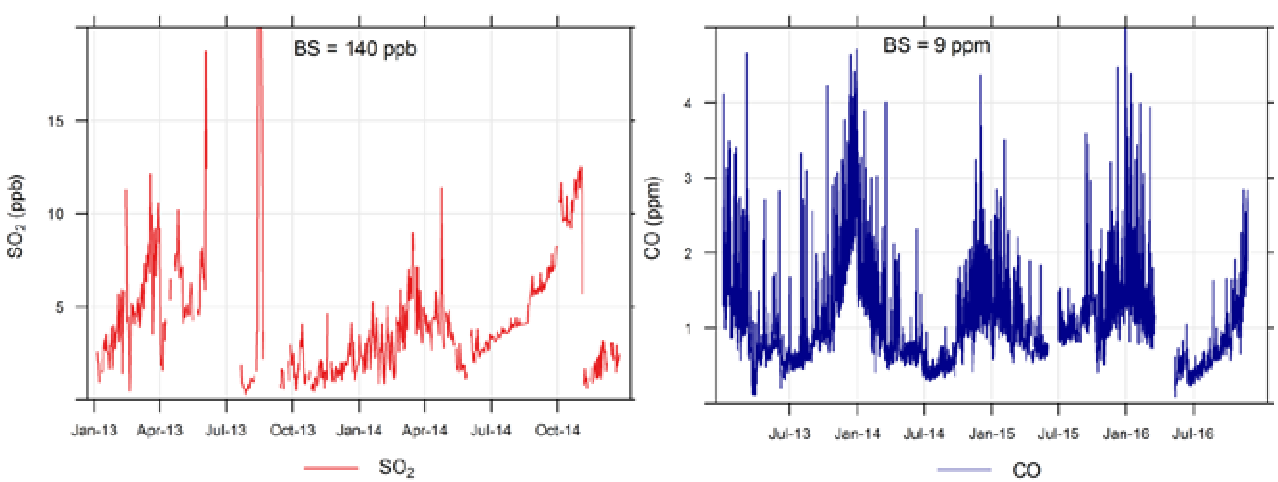
Figure 55 Directional influences on the PM concentrations in different seasons in Sylhet



4.5.2.2 Gaseous Pollutants

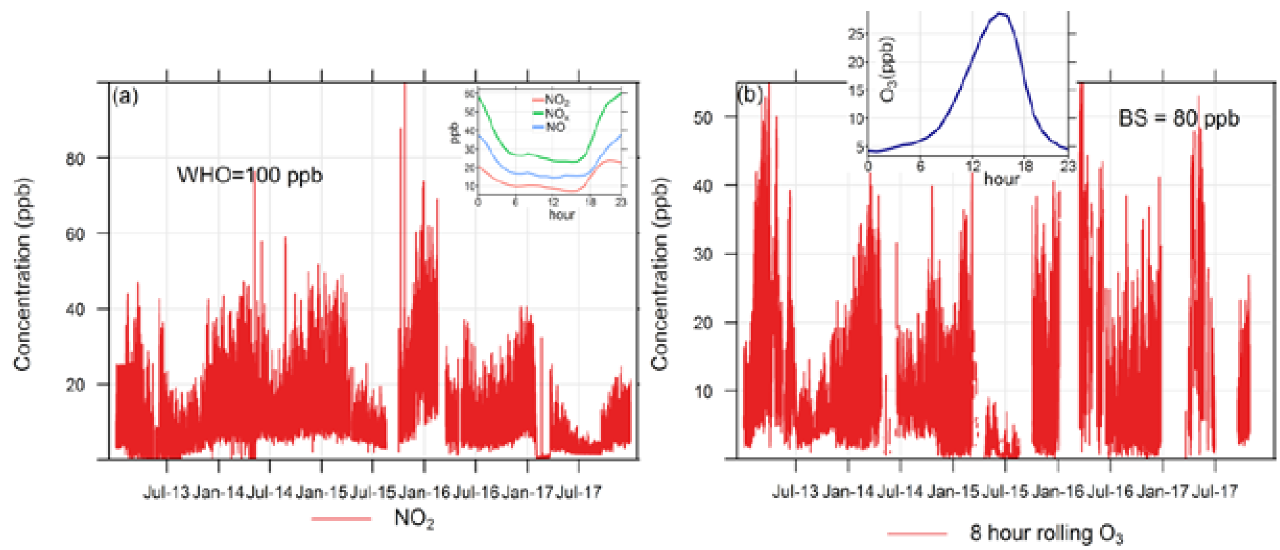
Gaseous pollutants are not so important in Sylhet city. Figure 56 shows the trends in SO_2 and CO concentrations recorded at the Sylhet station. Both the pollutants are much below the limit values set by the Government.

Figure 56 Trends in daily average SO_2 Conc. (left) and 8-h average CO Conc. (right) in Sylhet; BS = Bangladesh Standard



NO_2 and O_3 concentrations throughout the year in Sylhet are also compliant with the respective standard values (Figure 57 a&b).

Figure 57 (a) Trends in hourly NO_2 Conc. in Sylhet with the diurnal variations of NO_2, NO_x and NO Conc. in dry season shown in inset. (b) Trends in 8-hour rolling average O_3 Conc. in Sylhet with the diurnal variations of O_3 conc. in dry season shown in inset. BS=Bangladesh Standard, WHO=World Health Organization limit guideline value.



4.6 Barisal

4.6.1 Meteorology

4.6.1.1 Wind roses

Wind roses in Barisal are very similar to those in Dhaka – dry seasonal wind blows from the west and northwest directions whereas the wet seasonal wind comes mostly from the southeast direction. The atmosphere remains very calm from October to December, and is comparatively vigorous in April and May (Figure 58).

Figure 58 Monthly wind roses generated from wind data from 2013 to 2017 at Barisal station

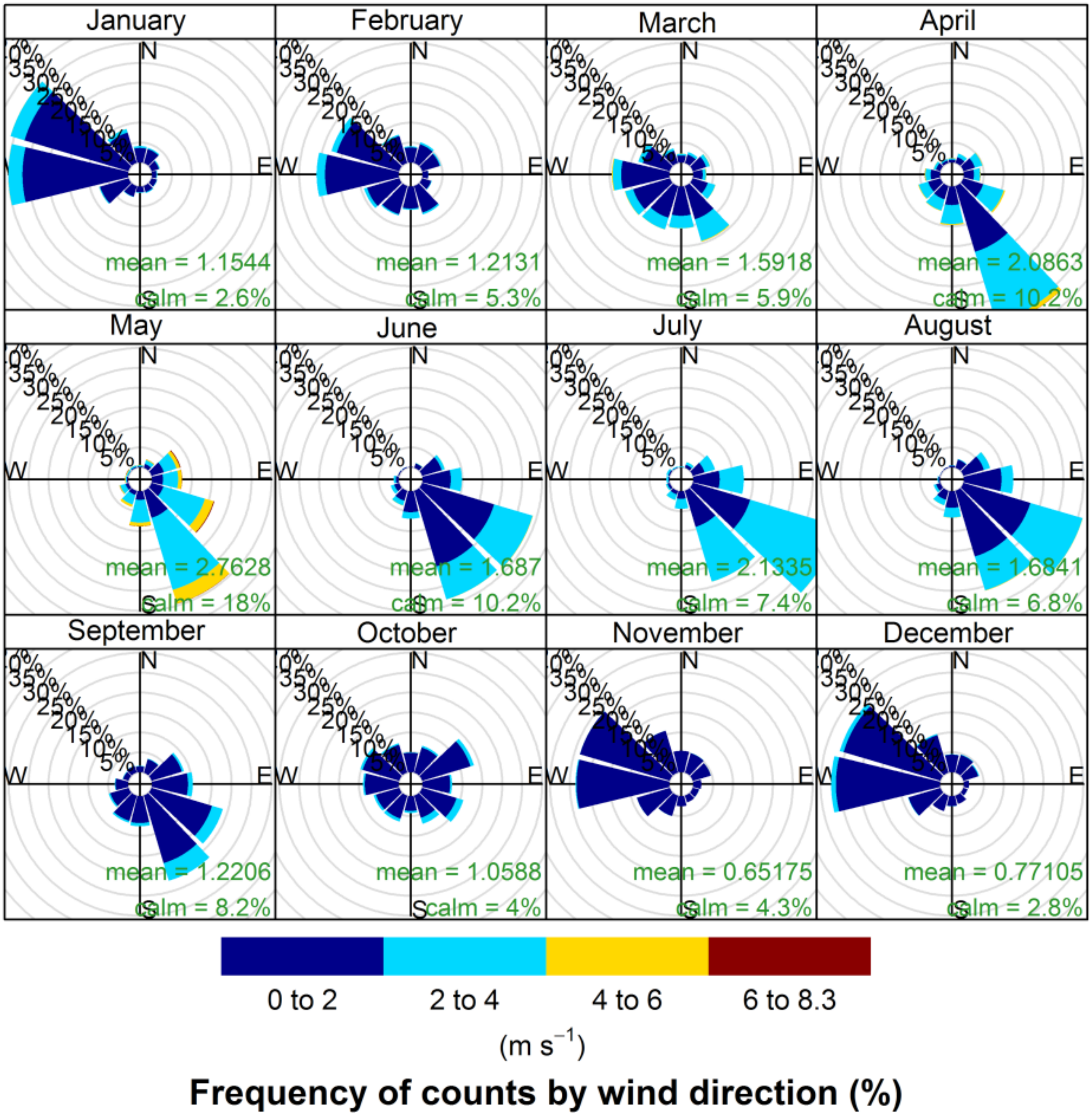
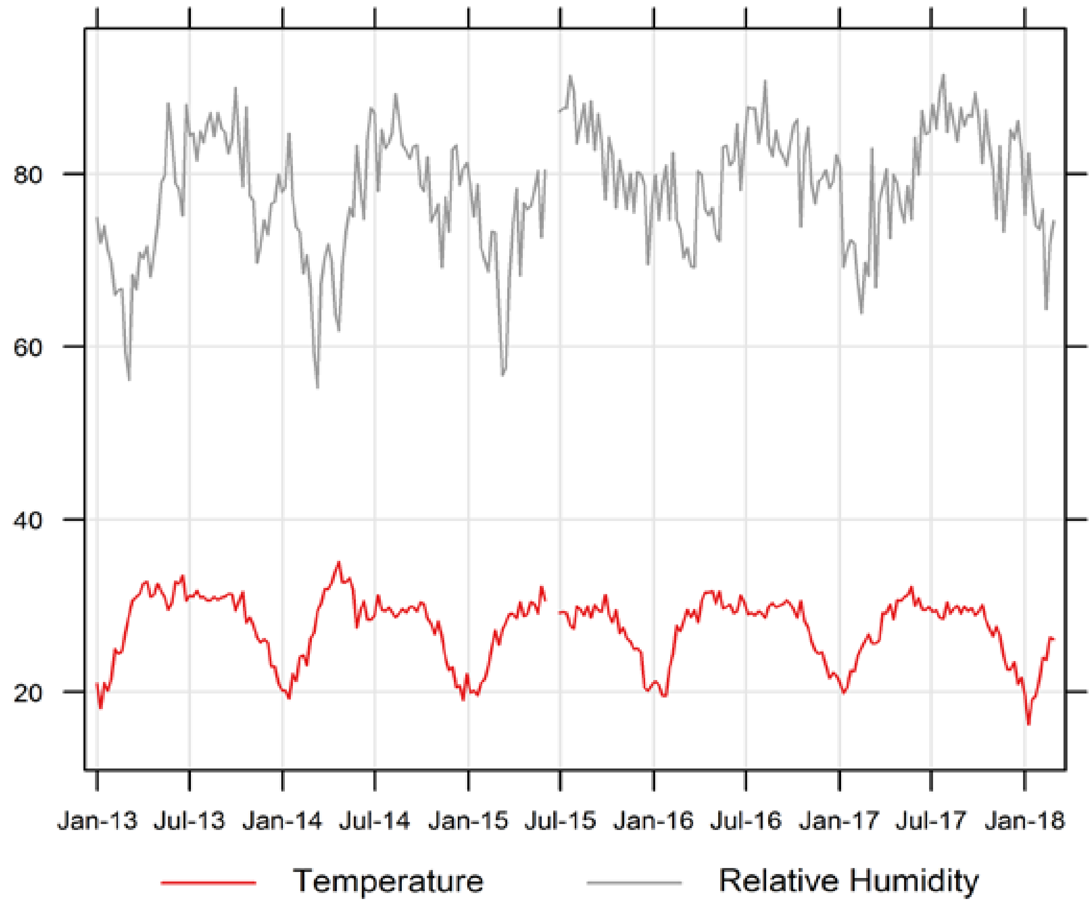


Figure 59 Trends in weekly temperature (°C) and relative humidity (%) in Barisal



4.6.1.2 Temperature and Relative Humidity

Compared to other cities the weather of Barisal is little comfortable – not extreme cold in winter and not extreme hot in summer. High temperature prevails from March to October (Figure 59) when rain washes the atmosphere frequently.

4.6.2 Criteria Air Pollutants

4.6.2.1 Particulate Matters

PM concentrations in Barisal, a serene and small divisional city, are found unexpectedly high. Compared to the status of Dhaka, annual PM_{10} concentration is about 25% lower, whereas annual $PM_{2.5}$ concentration is only 10% lower. The statistics shown in table 8 reveal comparatively higher fraction of fine particles in PM in Barisal. The trends in PM concentrations (Figure 60, 61) demonstrate strong seasonal variations in the city – higher pollutions in dry season (November – April) and relatively fresh air in wet season (May – October). Like Dhaka and its surroundings, the month of January tops for both fraction of PM concentrations followed by December, February and March (Figure 61). Diurnal trends in PM concentrations in dry season are also very similar to those in Dhaka – daytime pollution peak at 9:00 am from when downtrend continues up to 5:00 pm. The most polluted time within a day in dry season is 8:00 pm to 9:00 pm. Pollution level wanes throughout the night and again starts to hike from 6:00 am in the morning next (Figure 62).

The PM pollution in dry season in Barisal usually remains high in Wednesday and Thursday; the concentration tends to decrease in Friday and Saturday, the weekly holidays in the country (Figure 62).

Table 8 Overview of daily PM concentrations in Barisal in recent years; daily concentrations are determined when minimum 80% valid hourly data available in that day

Year	PM_{10} Conc. ($\mu g\ m^{-3}$)					$PM_{2.5}$ Conc. ($\mu g\ m^{-3}$)				
	percentile				mean	percentile				mean
	25	50	75	95		25	50	75	95	
2013	42	83	181	297	120	30	50	123	223	83
2014	nc	nc	nc	nc	nc	37	62	132	192	85
2015	55	118	187	249	123	39	83	130	182	89
2016	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc
2017	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc

nc = not calculated for inadequate data capture

Figure 60 Trends in daily PM concentration (data threshold 80%) in Barisal. The red and grey horizontal lines are standards for PM_{10} and $PM_{2.5}$ respectively in Bangladesh

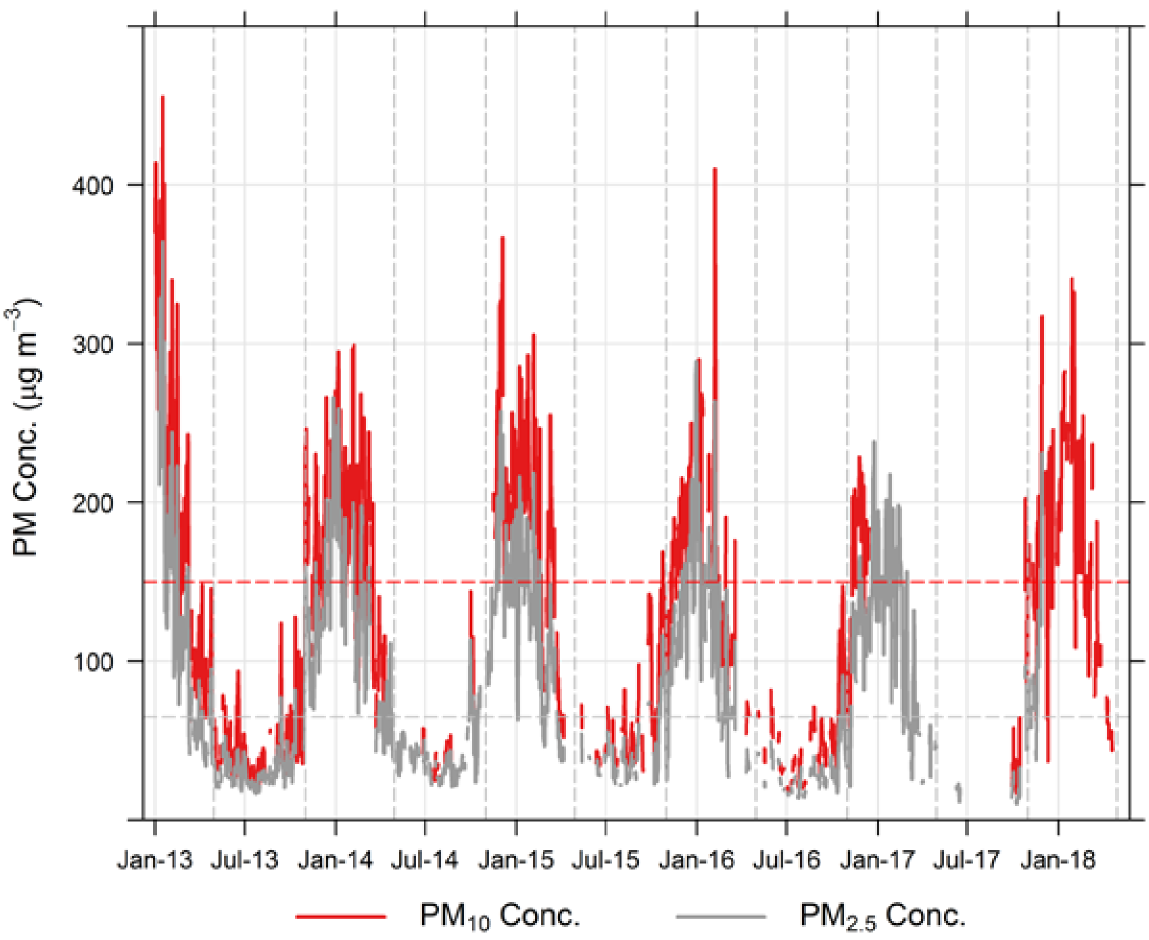


Figure 61 Box-whisker plots of PM concentrations in different months in Barisal from 2013 to 2018

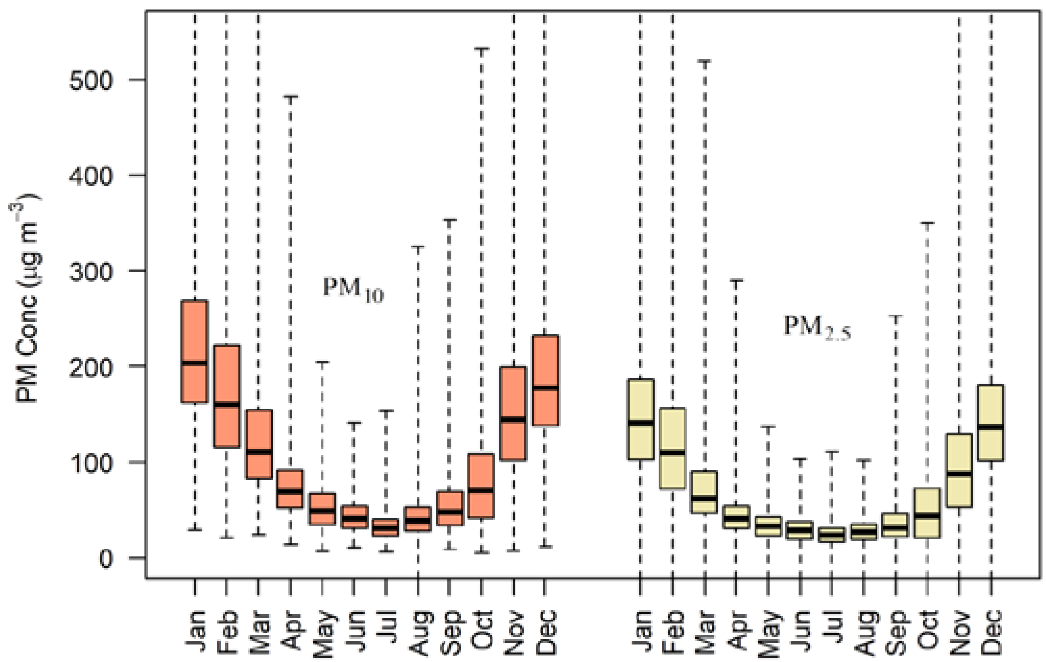
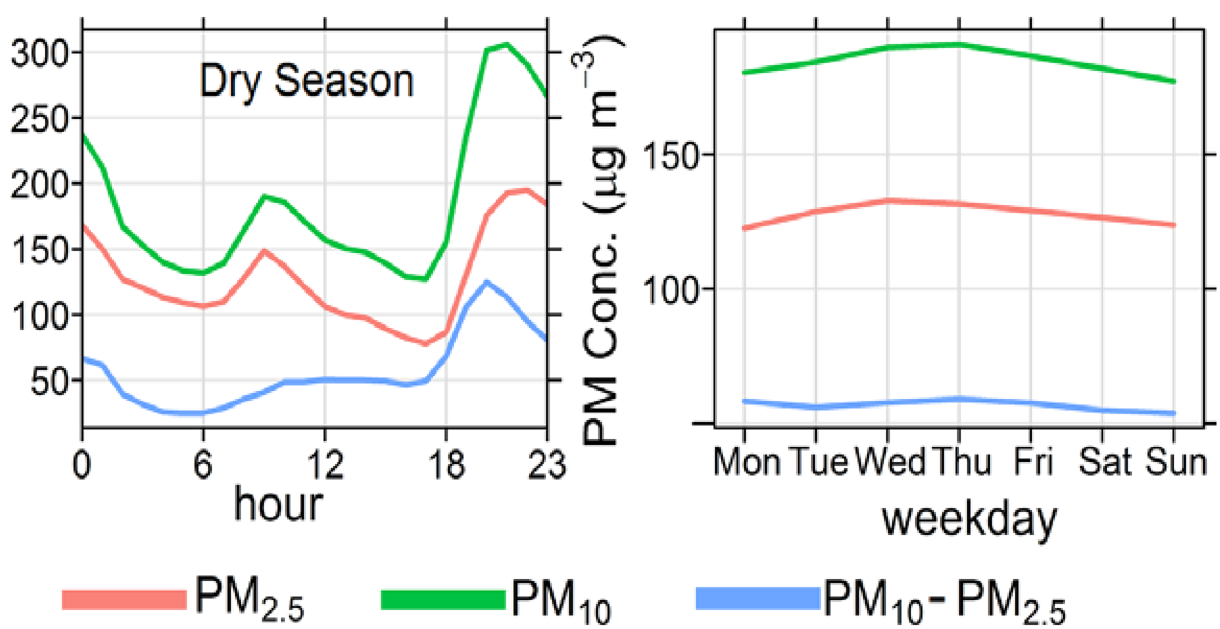
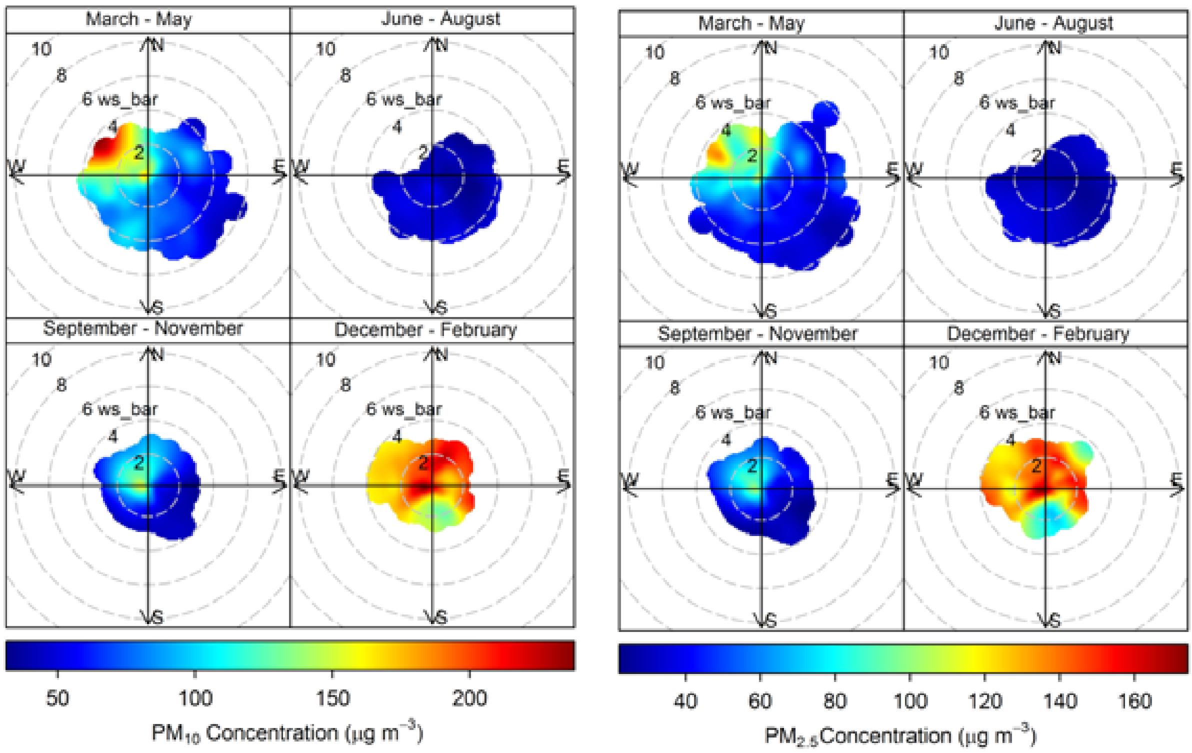


Figure 62 Variations of PM concentration in different time of day and in different day of week in dry season in Barisal



In winter, high levels of PM concentrations mostly associate with the northeast and northwest directions (Figure 63).

Figure 63 Directional influences on the PM concentrations in different seasons in Barisal



4.6.2.2 Gaseous Pollutants

The levels of gaseous pollutants in Barisal, irrespective of the seasons, are very compliant with the corresponding national limit values in Bangladesh (Figure 64&65).

Figure 64 Trends in daily average SO_2 Conc. (left) and 8-h average CO Conc. (right) in Barisal; BS = Bangladesh Standard

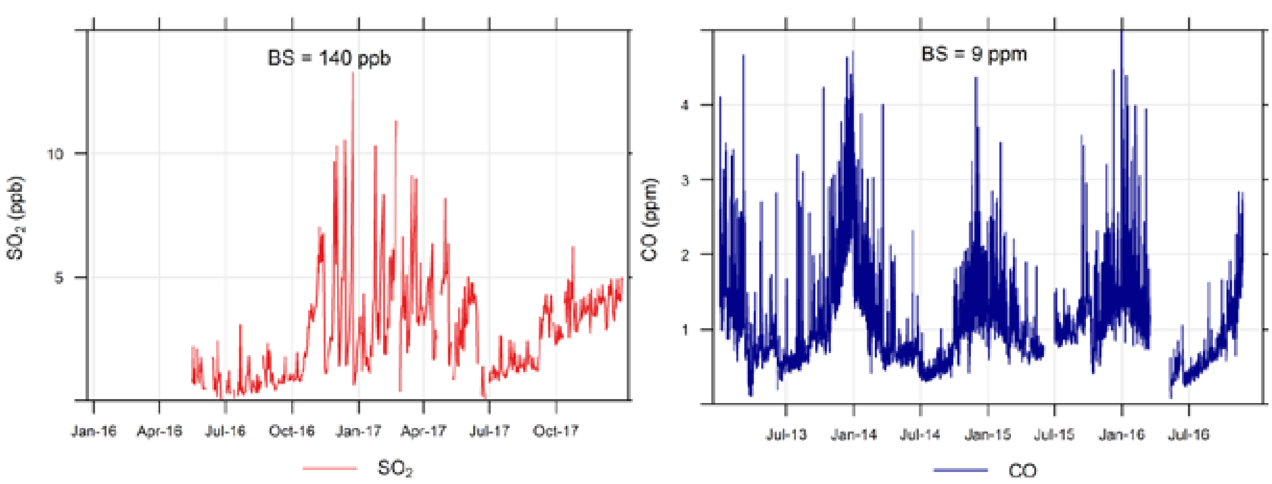
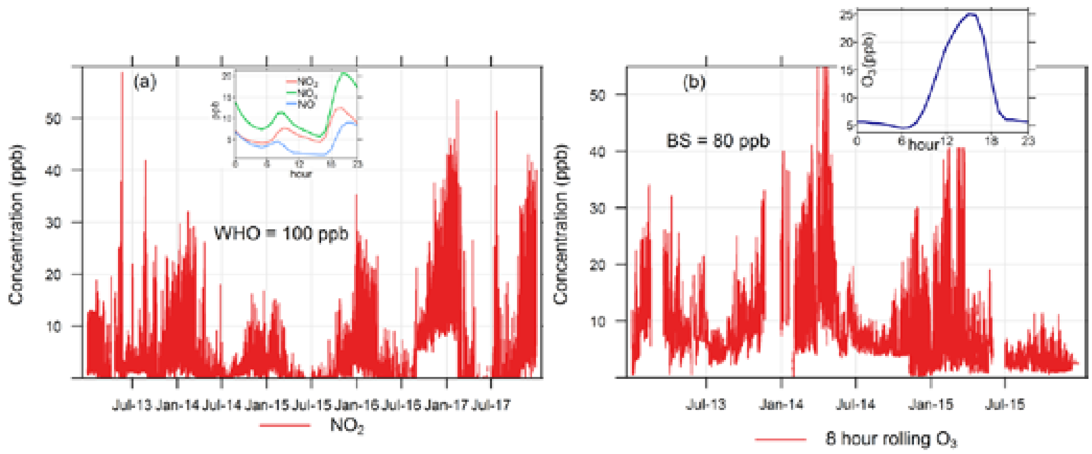


Figure 65 (a) Trends in hourly NO_2 Conc. in Barisal with the diurnal variations of NO_2, NO_x and NO Conc. in dry season shown in inset. (b) Trends in 8-hour rolling average O_3 Conc. in Barisal with the diurnal variations of O_3 conc. in dry season shown in inset. BS = Bangladesh Standard, WHO = World Health Organization guideline value



4.7 Khulna

Instead of detailed presentation of air quality status in khulna, a snapshot is demonstrated in the following for the poor data capture at Khulna station. Only those data and the period having adequate validity are presented here.

The trends in PM concentration are as usually influenced by the seasonal impacts – very high PM concentration in dry season and low concentration in wet season. Like other urban areas, December to January is the polluted time in Khulna followed by February, March and November (Figure 66).

The status of gaseous pollutants in air irrespective of the seasons in Khulna is found very accommodating (Figure 67 & 68).

Figure 66 Box-whisker plots of PM concentrations in different months in Khulna

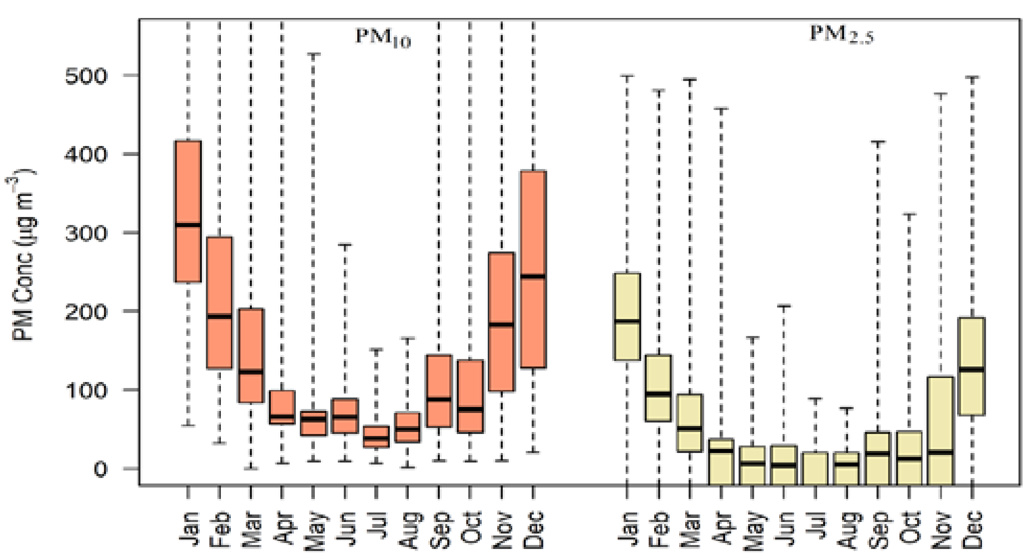


Figure 67 Trends in daily average SO_2 Conc. (left) and 8-h average CO Conc. (right) in Khulna; BS = Bangladesh Standard

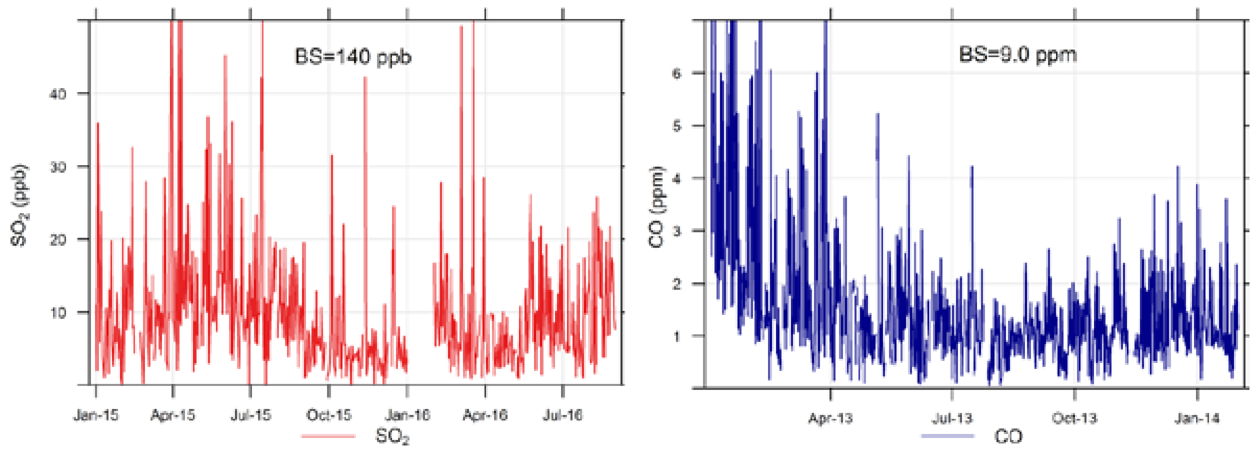
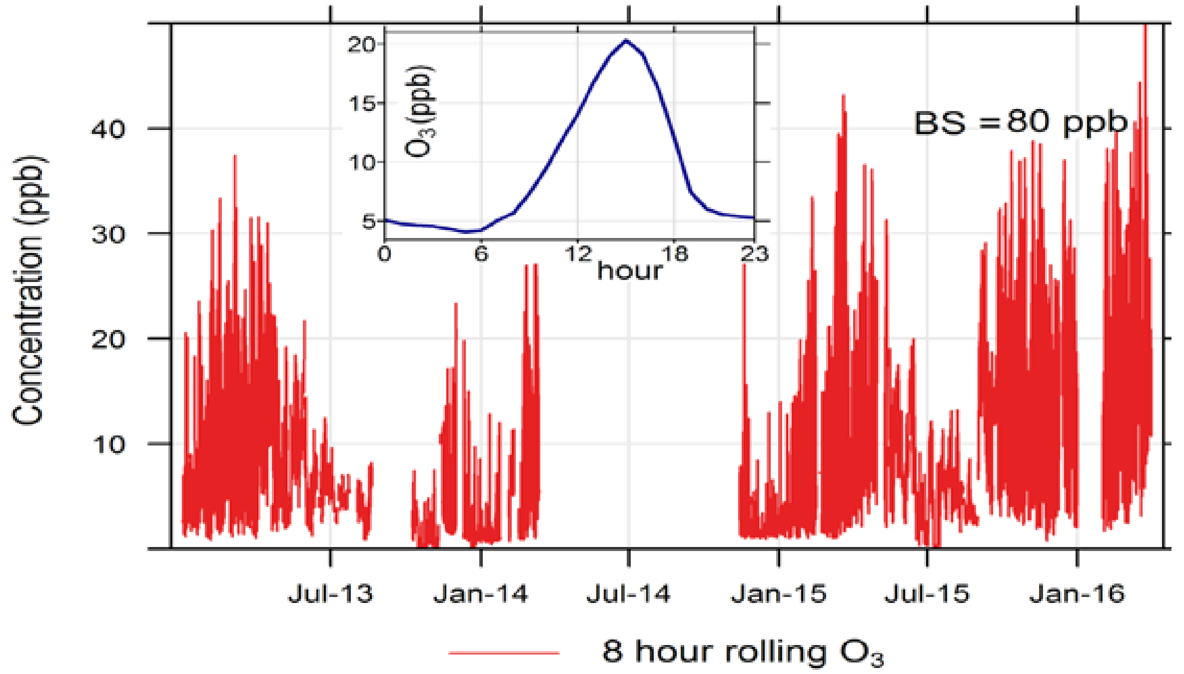


Figure 68 Trends in 8-hour rolling mean O_3 conc. in Khulna with diurnal variations of O_3 conc. in dry season in inset.



4.8 Rajshahi

Figure 69 and Figure 70 illustrate the status of air quality in Rajshahi. The month of January tops for the high PM pollution in the city followed by December, February and March (Figure 69). The figure 69 shows relatively high PM concentrations in wet season in Rajshahi compared to the usual characteristics found in other cities in the country. This heightened PM in wet season perhaps come from the wood burning in some small tea-stalls operating full time near the monitoring station.

SO_2 concentration throughout the year in Rajshahi is found very obedient, but the O_3 concentrations in dry season are sometimes observed little higher compared to other stations in the country, although it remains within the national standards (Figure 70).

Figure 69 Box-whisker plots of PM concentrations in different months in Rajshahi

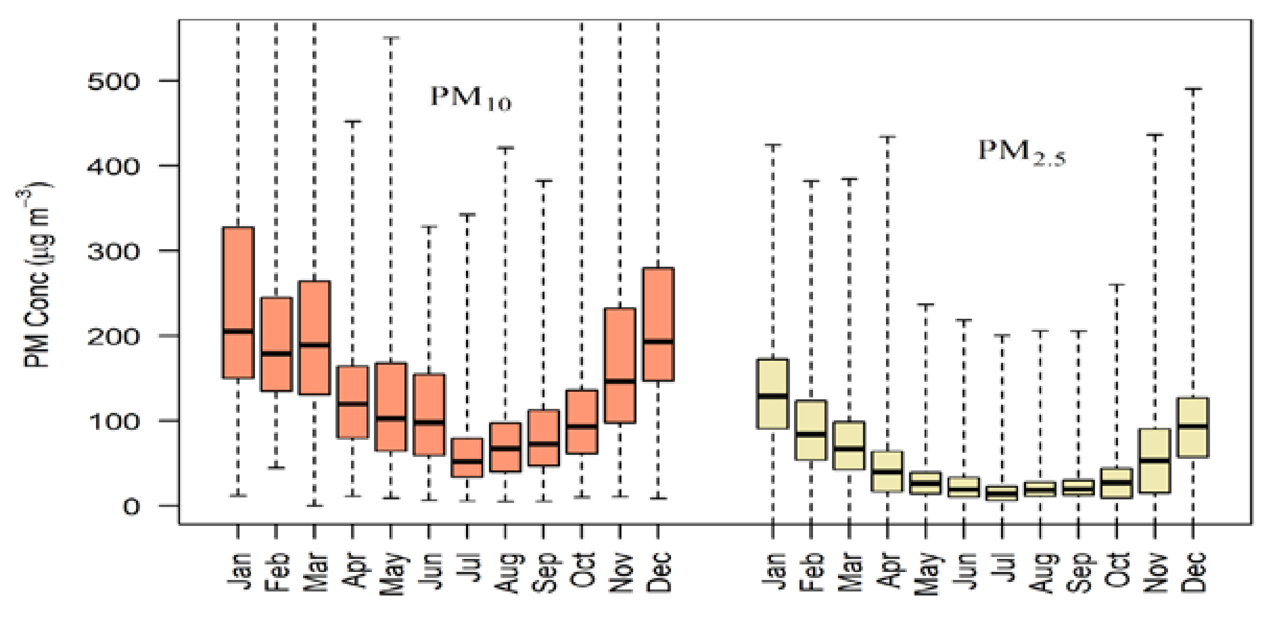
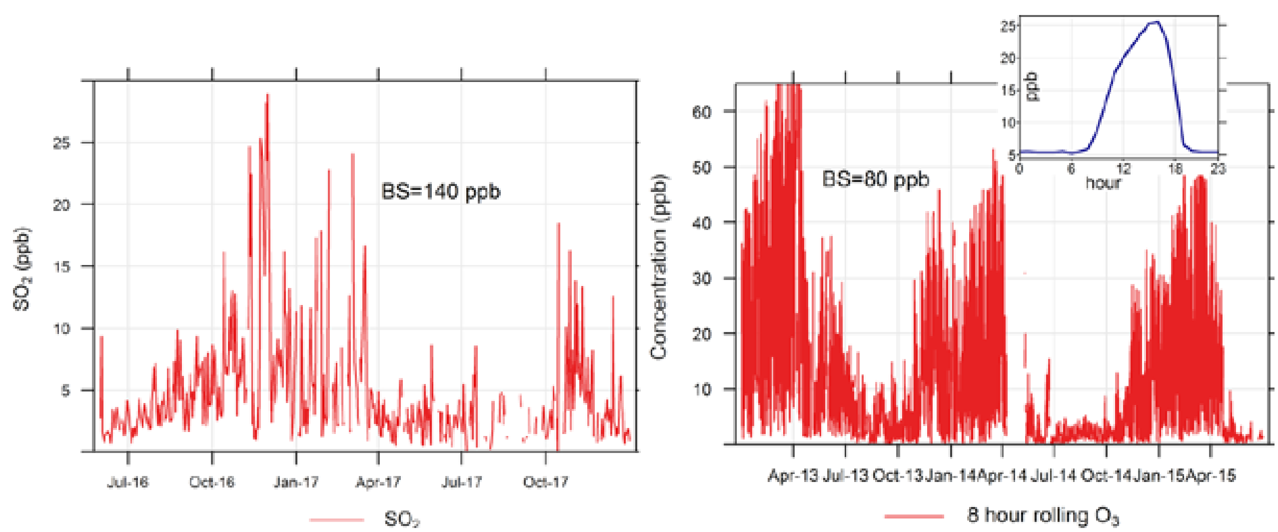


Figure 70 Trends in daily average SO_2 Conc. (left) and 8-hour rolling average O_3 Conc. (right) with diurnal variations of O_3 Conc. (inset) in Rajshahi



5 PROBLEM FACED DURING THE STUDY

Air quality monitoring is a new phenomenon in Bangladesh. Only in recent time the general people start to believe the serious consequences of inhaling polluted air. The first full-fledged monitoring station under the Department of Environment was set up in 2001; the number increased to five in 2005 and to eleven in 2011. Outside the DoE, only two/three stakeholders have established sensitive air monitoring equipment in very recent time. The coverage of AQ monitoring in the country is still inadequate. A list of major problems faced during the continuous air quality monitoring is provided below,

1. Managing a suitable site in populated and congested cities of Bangladesh for setting up equipment for monitoring ambient air is really challenging.
2. Unavailability of spares, consumables and calibration gases compel some equipment to remain shut off in some times. Worth to mention that the equipment manufacturers do not have direct business houses in Bangladesh.
3. The Department of Environment has to depend on the foreign engineers for the complicated maintenance of the instrument, for which the routine or emergency maintenances of the equipment sometimes get delay.
4. Power disruptions especially in summer time jeopardize the instrument stability and sensitivity, which causes to lose some data.

6 CONCLUSION

The Clean Air and Sustainable Environment (CASE) Project of the Department of Environment (DoE), Bangladesh has been continuously monitoring the ambient air quality of the major cities of Bangladesh. With the financial assistance from the World Bank, the project has established a countrywide network of 11 monitoring stations, and the network covers all the regions of the country. A very good number of new stations (both stationary and movable compact) are awaiting setup at different locations of the country. The existing monitoring stations in the cities of Dhaka, Chittagong, Narayanganj, Gazipur, Khulna, Rajshahi, Sylhet and Barisal are generating air quality and meteorology information every minute from 2013, based on the federal reference/equivalent methods of the USEPA. The data produced at the stations are transferred to the central server at the head office of the DoE at Agargaon, Dhaka where the data are stored in EnVIEW 2000 software at 15 minutes average. The project generates monthly air quality reports and calculates daily air quality index (AQI) for each city based on the USEPA prescriptions.

In this report air quality data are analyzed statistically to understand the seasonal, diurnal and directional trends of the components in the cities. Statistical parameters (mean, percentiles, etc.) of especially particulate matters (PM) are calculated for every year to observe year-wise and city-wise stances of the air quality in the country. The exhaustive analyses of AQ data characterize the air quality of the urban centers of the country as follows,

1. The trends of air quality in all the regions of the country are highly affected by the seasonal impacts, especially, frequent and excessive downpour in wet season (May – October) helps improve the air quality of the cities. Dry seasonal (November – April) PM pollution all over the country is the main concern.

2. The gaseous pollutants (i.e. SO_2, CO, NO_x, and O_3) in air of the cities, irrespective of the seasons, satisfy well the respective standards set by the

government. Only in several cases, NO_2 and O_3 concentrations at Chittagong station are found very close to the limit values.

3. During dry season, fine particles ($PM_{2.5}$) usually dominate contributions to PM concentrations all the time of the day in the cities except in the evening when coarse particles (PM_{10} – $PM_{2.5}$) are found equal to or sometimes greater than the fine particles. However, in Chittagong and Sylhet coarse fractions of PM get equal to or sometimes greater than the fine particles from noon to 9:00 pm.

4. The analyses reveal Narayanganj as the most polluted city in Bangladesh. PM concentrations in dry season in Dhaka and Gazipur are mostly similar although Dhaka site is urban, congested and the Gazipur site is urban background. Compared to Dhaka station, Chittagong, Sylhet and Barisal stations experience about 25, 30 and 25 % lower annual PM_{10} concentrations, and 13, 30 and 10 % lower annual $PM_{2.5}$ concentrations. Thus, Sylhet is found the least polluted city among the cities being monitored, and Chittagong and Barisal stations observe relatively higher $PM_{2.5}$ mass contribution to PM_{10} concentration.

5. A declining trend in annual PM_{10} and $PM_{2.5}$ concentrations in Dhaka is observed. Compared to 2013-14, the Dhaka station experiences about 12 and 14 % lower PM_{10} and $PM_{2.5}$ concentrations (annual) respectively in 2017. This reduction in yearly PM concentrations in air may be attributed to the ongoing reforms in the brick kiln sector.

6. Wind pattern in dry and wet season in Bangladesh is entirely opposite. Most of the country in dry season experiences wind from the west, north and northwest directions; only the northeast region (Sylhet) of the country acquires wind from the northeast and southeast directions in dry season.

However, ensuring data quality at the stations is a great challenge of this program since the instruments encounter frequent power disruptions, and problems in real time maintenance due to inaccessibility of spares and qualified engineers in the country. Increasing valid data capture rates at the stations are crucial and following measures may be taken for this,

1. Adequate arrangement must be taken to ensure uninterrupted power supply with steady voltage at the stations.

2. Trained and experienced technicians should be kept ready to serve immediately at any fault at the stations.

3. The performance of the stations must be monitored time to time, and immediate troubleshooting to be ensured upon a fault if perceived.

4. Available spares, accessories and qualified engineers must be ensured (at any cost) to heal the instrumental fault in short time, so that large data loss may not happen.

APPENDICES

APPENDIX – A

Gazette notification of Ambient Air Quality

রেজিস্টার্ড নং ডি এ-১

বাংলাদেশ গেজেট

অতিরিক্ত সংখ্যা
কর্তৃপক্ষ কর্তৃক প্রকাশিত

মঙ্গলবার, জুলাই ১৯, ২০০৫

গণপ্রজাতন্ত্রী বাংলাদেশ সরকার
পরিবেশ ও বন মন্ত্রণালয়
পরিকল্পনা শাখা-৫
প্রজ্ঞাপন

তারিখ, ১ শ্রাবণ ১৪১২/১৬ জুলাই ২০০৫

এস, আর, ও নং ২২০-আইন/২০০৫—বাংলাদেশ পরিবেশ সংরক্ষণ আইন, ১৯৯৫ (১৯৯৫ সনের ১ নং আইন) এর ধারা ২০ এ প্রদত্ত ক্ষমতাবলে সরকার পরিবেশ সংরক্ষণ বিধিমালা, ১৯৯৭ এর নিম্নরূপ সংশোধন করিল, যথা ঃ—

উপরি-উক্ত বিধিমালার—

(ক) তফসিল ২ এর পরিবর্তে নিম্নরূপ তফসিল ২ প্রতিস্থাপিত হইবে, যথা ঃ—

"তফসিল-২

বায়ুর মানমাত্রা (Air Quality Standards)*

[বিধি ১২ দ্রষ্টব্য]

বায়ু দূষণ	মানমাত্রা	গড় সময়
১	২	৩
কার্বন মনোঅক্সাইড	১০ মিলিগ্রাম/ঘনমিটার (৯ পিপিএম) (ক)	৮ ঘন্টা
	৪০ মিলিগ্রাম/ঘনমিটার (৩৫ পিপিএম) (ক)	১ ঘন্টা
লেড	০.৫ মাইক্রোগ্রাম/ঘনমিটার	বার্ষিক

(৭৫৬৭)
মূল্য ঃ টাকা ৪.০০

১	[illegible]	৩
নাইট্রোজেনের অক্সাইড	১০০ মাইক্রোগ্রাম/ঘনমিটার (০.০৫৩ পিপিএম)	বার্ষিক
প্রলম্বিত বস্তুকণা (এস পি এম)	২০০ মাইক্রোগ্রাম/ঘনমিটার	৮ ঘন্টা
বস্তুকণা ১০	৫০ মাইক্রোগ্রাম/ ঘনমিটার (খ)	বার্ষিক
	১৫০ মাইক্রোগ্রাম/ ঘনমিটার (গ)	২৪ ঘন্টা
বস্তুকণা ২.৫	১৫ মাইক্রোগ্রাম/ ঘনমিটার	বার্ষিক
	৬৫ মাইক্রোগ্রাম/ ঘনমিটার	২৪ ঘন্টা
ওজোন	২৩৫ মাইক্রোগ্রাম/ঘনমিটার (০.১২ পিপিএম) (ঘ)	১ ঘন্টা
	১৫৭ মাইক্রোগ্রাম/ঘনমিটার (০.০৮ পিপিএম)	৮ ঘন্টা
সালফার ডাইঅক্সাইড	৮০ মাইক্রোগ্রাম/ঘনমিটার (০.০৩ পিপিএম)	বার্ষিক
	৩৬৫ মাইক্রোগ্রাম/ঘনমিটার (০.১৪ পিপিএম) (গ)	২৪ ঘন্টা

শব্দ সংক্ষেপ ঃ

পিপিএম ঃ পার্টস পার মিলিয়ন।

নোট ঃ * এই তফসিলে বায়ুর মানমাত্রা বলিতে পরিবেষ্টক বায়ুর মানমাত্রা (Ambient Air Quality Standards) কে বুঝাইবে।

(ক) প্রতি বৎসরে একবারের বেশী অতিক্রম করিবে না।

(খ) বার্ষিক গড় মান ৫০ মাইক্রোগ্রাম/মি^{৩} হইতে কম বা উহার সমান হইতে পারিবে।

(গ) ২৪ ঘন্টার গড় মান বৎসরে ১ (এক) দিন ১৫০ মাইক্রোগ্রাম/ মি^{৩} হইতে কম বা উহার সমান হইতে পারিবে।

(ঘ) প্রতি ঘন্টার সর্বোচ্চ গড় মান বৎসরে ১ (এক) দিন ০.১২ পিপিএম হইতে কম বা উহার সমান হইতে পারিবে।

APPENDIX – B

Year-wise Statistics of Air Quality Index in the Cities

City	Year	Total Days	Number of Days with			
			AQI ≤100	AQI 101-200	AQI 201-300	AQI >301
Dhaka	2014	295	108	117	16	54
	2015	356	121	119	48	68
	2016	340	148	108	45	39
	2017	359	133	130	23	73
Gazipur	2014	285	118	100	23	44
	2015	354	130	112	47	65
	2016	344	158	78	50	58
	2017	320	142	80	29	69
Narayanganj	2014	272	146	65	21	40
	2015	332	138	70	50	74
	2016	335	165	69	31	70
	2017	348	136	98	34	80
Chittagong	2014	267	135	90	29	13
	2015	325	144	126	40	15
	2016	316	191	63	31	31
	2017	340	189	96	38	17
Sylhet	2014	282	169	100	13	0
	2015	290	138	100	43	9
	2016	276	213	51	10	2
	2017	365	220	124	16	5
Khulna	2014					
	2015	142	61	34	21	26
	2016					
	2017	139	79	40	16	4
Rajshahi	2014	232	135	57	24	16
	2015	157	62	72	15	8
	2016	315	154	115	32	14
	2017	338	158	122	39	19
Barisal	2014	279	112	119	18	30
	2015	338	127	119	54	38
	2016	323	171	84	47	21
	2017	343	168	106	37	32

APPENDIX – C

Analysis of Trends in Atmospheric Particulate Matters in major urban areas of Bangladesh: A detailed comparative study

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[2]Ministry of Environment, Forest and Climate Change

Abstract

The urban areas of Bangladesh suffer from severe air quality problem especially in dry season (November – April) when the PM concentrations frequently rise to 7-8 times of the WHO guideline value. The Clean Air and Sustainable Environment (CASE) Project of the Department of Environment has deployed countrywide continuous air monitoring systems to regularly monitor the air quality of the urban areas of Bangladesh. In this work hourly concentrations of PM_{10} and $PM_{2.5}$ captured using β-attenuation method from 2013 to April 2018 in six important cities located in different regions of the country were exhaustively analyzed. Besides statistical analyses, and seasonal and diurnal trends of PM concentrations, conditional bivariate polar functions were also calculated to examine directional source strength on the stations. Long range sources were spotted by Concentration Weighted Trajectory (CWT) method, where the trajectories were calculated using HYSPLIT-4 model. The analyses identified cities in the middle part of the country (Dhaka, Narayanganj, Gazipur) as the most polluted ones while the city to the northeast part (Sylhet) was the least polluted. Average PM_{10} concentrations at Dhaka, Chattogram, Narayanganj, Gazipur, Sylhet and Barisal stations in dry seasons (November – April) were found 238.7±155.4, 190.7±108.5, 303.6±161.4, 227.3±142.7, 151.7±105.0 and 170.7±108.4 µg m^{-3} respectively whereas those in wet seasons (May – October) were 75.0±51.6, 55.5±40.8, 102.4±84.4, 60.6±48.5, 52.7±38.3, and 54.4±41.6 µg m^{-3} respectively. Correlative study of diurnal variations in PM concentrations and meteorological parameters revealed that the congenial meteorology aided in developing higher concentrations of both PM_{10} and $PM_{2.5}$ during nighttime. Sources located to the northwestern districts (Naogao, Rangpur, Bogura) were traced by the CWT method contributing to the air pollution in other regions of the country. Outside the boundary, sources in Nepal, and Delhi-NCR and Uttar Pradesh regions of India could have contributed to fine particles at the middle of the country.

Keyword: Particulate Matter, Conditional Bivariate Polar Function, Diurnal Variation, Concentration Weighted Trajectory

Introduction

As provided in the main report

Monitoring sites (location, sources around, station capacity)

As provided in the main report

PM monitoring, Quality Control and analyses

As provided in the main report

Conditional bivariate polar function (CBPF)

According to Uria-Tellaetxe and Carslaw (2014), bivariate polar plots show how concentrations of a species vary jointly with wind speed and wind direction in polar coordinates. During the plotting, wind speed and direction bins are partitioned and concentrations of a pollutant associating with every bin are allocated. The wind components, u = ū.sin(2∏/), = ū.cos(2∏/), where ū is the mean wind speed and is the mean wind direction in degrees with 0° as being from the north, and concentration (C) provide a surface (Uria-Tellaetxe and Carslaw 2014). The concentration surface produced by u, and C is then modeled using a generalized additive model (GAM) (Wood 2006).

Conditional Probability Function (CPF) calculates the probability of a receptor to acquire from a particular wind direction sector a species greater than some specified concentration value (usually 90 percentile). The conditional bivariate probability function (CBPF) combines CPF with wind speed as a third variable. In this process, observed pollutant concentrations are allocated to bins defined by ranges of wind direction and wind speed. CBPF can be defined as equation 1 (Uria-Tellaetxe and Carslaw 2014):

$$CBPF_{\Delta\theta,\Delta u} = \frac{m_{\Delta\theta,\Delta u} \ \ (C\geq x)}{n_{\Delta\theta,\Delta u}} \qquad \text{Equation 1}$$

Where, is the number of samples in the wind sector with wind speed interval having concentration C greater than a threshold value *x*, is the total number of samples in that wind direction-speed interval. CBPF can also be calculated for an interval of concentration rather than only values greater than some threshold. In that case, CBPF is equated as equation 2,

$$CBPF_{\Delta\theta,\Delta u} = \frac{m_{\Delta\theta,\Delta u} \ \ (y\geq C\geq x)}{n_{\Delta\theta,\Delta u}} \qquad \text{Equation 2}$$

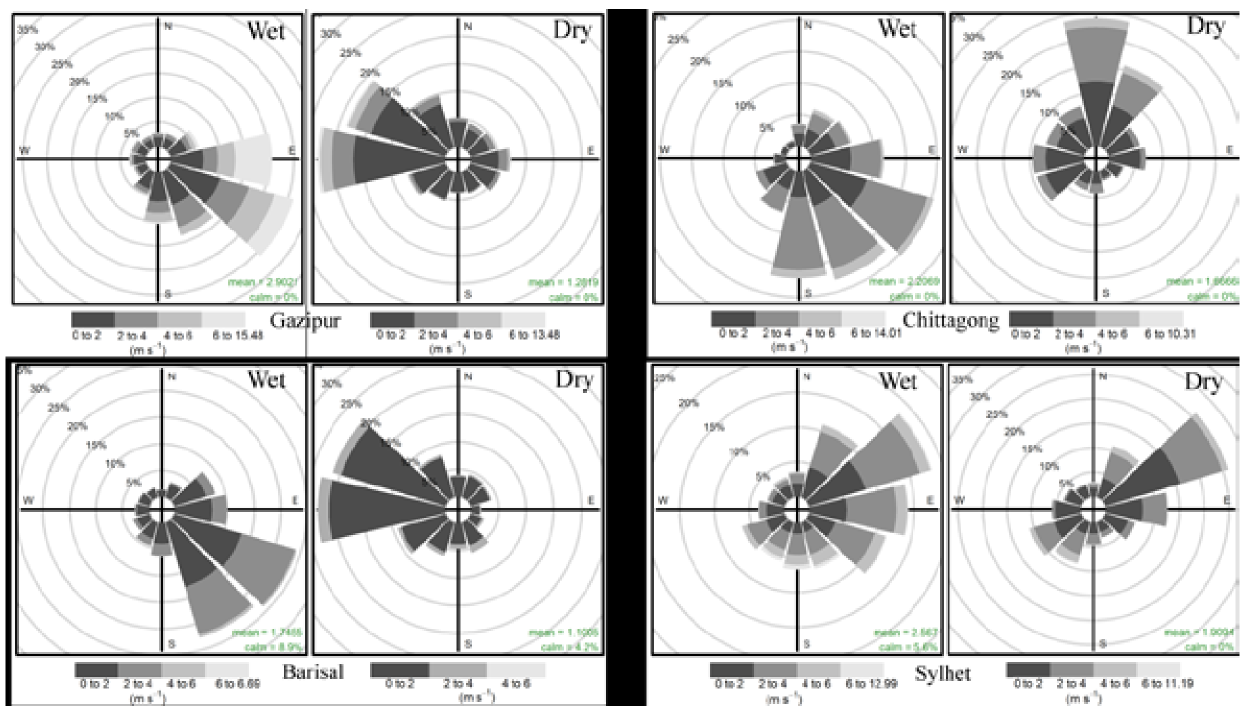
Where, is the number of samples in the wind sector with wind speed interval having concentration C between the value of *x* and *y*, is the total number of samples in that wind direction-speed interval (Uria-Tellaetxe and Carslaw 2014).

Meteorology of the cities

The meteorology of Bangladesh varies greatly in different times of the year. It is primarily divided into two seasons (**a)** dry season (November to April) and (**b)** wet season (May to October). For air quality study, Rana et al. (2016) divides the dry season further into two, (**i)** winter (November – January), and (**ii)** summer (February to April). Based on the data from the Department of Meteorology, Rana et al. (2016) showed that the atmosphere as a whole in the country remains very dry during the month of February to April and very wet from June to August. The wintertime is characterized with low temperature, wind speed and mixing height while the summertime is typified with high temperature, dryness and mixing height, and clear sky (Rana et al. 2016). The meteorology also differs regionally; the northeast region of the country experiences more rainfall (annually >4000mm) while the northwest region gets the less (annually <2300mm) (Shahid 2010). The climate of the northwest region is extreme (colder in winter time and hotter in summer and wet season) while that of the northeast, south and southeast regions is moderate.

The winter and wet seasonal winds are opposite; in general, the wind flows from the west and northwest directions during wintertime and from the south and southeast directions during summer and wet season (Rana et al. 2016). This study found most of the regions except the northeast (Sylhet) and southeast (Chattogram) regions of the country follow this pattern of wind flow (fig. 1). Sylhet experienced major wind from the northeast direction in dry season and from the east, northeast, and southeast directions in wet season (Fig. 1). However, the deviations of wind directions for Chattogram were not so major like Sylhet; the dry seasonal wind in Chattogram was observed from the north and northeast directions, and the wet seasonal wind from the south and southeast directions.

Figure 1 Wind- roses at different stations in wet and dry season



Results and Discussions

PM concentrations all over the country was found to follow a unique pattern of seasonal variations, high concentrations in dry season (November – April) and low in wet season (May – October) (Fig. 2). Average PM_{10} concentrations at Dhaka, Chattogram, Narayanganj, Gazipur, Sylhet and Barisal stations in dry seasons (November – April) during 2013 to 2018 were 238.7±155.4, 190.7±108.5, 303.6±161.4, 227.3±142.7, 151.7±105.0 and 170.7±108.4 $\mu g\ m^{-3}$ respectively whereas those in wet seasons (May – October) were 75.0±51.6, 55.5±40.8, 102.4±84.4, 60.6±48.5, 52.7±38.3, and 54.4±41.6 $\mu g\ m^{-3}$ respectively. On the other hand, the $PM_{2.5}$ concentrations in dry/wet seasons in Dhaka, Chattogram, Narayanganj, Gazipur, Sylhet and Barisal stations were respectively 139.3±94.9/38.4±27.4, 110.7±139.3/28.7±21.3, 168.4±105.6/35.4±34.8, 141.7±90.3/32.9±26.1, 84.9±68/23.5±21.1 and 116.4±77.9/36.2±24.3 $\mu g\ m^{-3}$. The ratios of $PM_{2.5}$ concentrations to PM_{10} concentrations were comparatively higher in wintertime (December – January) and lower in summertime (February – April). The ratios in winter/summer time in Dhaka, Chattogram, Narayanganj, Gazipur, Sylhet and Barisal cities were 0.67/0.56, 0.64/0.53, 0.60/0.46, 0.70/0.58, 0.58/0.53 and 0.76/0.64 respectively. Ratios in wet season were 0.52, 0.55, 0.37, 0.58, 0.42 and 0.72 respectively.

Thus, the cities located in the middle of the country (Dhaka, Narayanganj, Gazipur) were found more polluted compared to the cities in other parts of the country. Narayanganj was the topmost polluted city among those under study. Dhaka and Gazipur experienced almost the similar pollution level, although the Dhaka station was highly urban and was influenced by heavy traffic, and the Gazipur site was sub-urban background with rare nearby sources. The Narayanganj station although received the highest level of both PM_{10} and $PM_{2.5}$ concentrations (Table 1), it experienced comparatively lower contributions of $PM_{2.5}$ to PM_{10} concentrations – indicating massive sources of coarse particles near the station. Narayanganj station is about 25 km to the southeast direction from Dhaka city and is expected to experience pollution emitted from Dhaka city during dry season (Fig. 1). The PM concentrations captured at the Gazipur site especially during the dry season were too high (Table 1) for a sub-urban background station and the comparatively higher $PM_{2.5}$ contributions to PM_{10} concentrations indicate effects of the industries, brick kilns and open cooking. People of Gazipur are used to burn logs, straws and leaves for cooking, and both Gazipur and Narayanganj cities are highly industrialized. Number of battery manufacturing industries, steel mills, dye factories, garment manufacturing units, pharmaceuticals, cement industries, etc. operate within the boundary of those two districts. PM level in Barisal, a serene divisional city to the south of the country was somewhat astonishing; its $PM_{2.5}$ concentrations during this study period were even greater than that of Chattogram city which is bigger, busier, and more industrialized than Barisal city. $PM_{2.5}$ contributions to PM_{10} concentrations in wet season were found exceptionally higher (0.72) in Barisal city. Barisal is a big river port and the diesel driven water vessels could be a possible source of higher PM pollution in the city. Among the cities, Sylhet was found the least polluted in respect of both PM concentrations in air and fine particle contributions. Primary investigations reveal a relation between wind pattern and PM pollution level in the country – the northern, middle and southern part of the country (Dhaka, Narayanganj, Gazipur, Barisal) experienced similar wind pattern (mostly from the west and north-west directions) during dry season (Fig. 1) and were characterized with very high PM pollution as well as higher contribution of fine fraction to the PM concentrations. The southeast (Chattogram) and northeast (Sylhet) regions of the country having wind directions other than west and northwest in dry season (Fig. 1) experienced less pollution compared to the regions having wind from the west and north-west directions (Fig. 2; Table 1).

The statistics provided in Table 1 were calculated from daily average PM_{10} and $PM_{2.5}$ concentrations captured at the stations from 2013 to April 2018. Each data thus represents individual day. Fifty (50) percentile of $PM_{2.5}$ concentrations in winter in Dhaka city was 184 µg m^{-3} (Table 1) could thus be explained as, in 50% days of winter season in Dhaka city the $PM_{2.5}$ concentrations were within 184 µg m^{-3}. $PM_{2.5}$ concentrations in the rest 50% of the days of winter season in the city were thus greater than 184 µg m^{-3}, which is about 3 times greater than the national limit value of $PM_{2.5}$ concentration in Bangladesh or about 7 times greater than the WHO guideline value. Most of the days (~90%) of the winter season, especially during the month of December and January, the concentrations of both fractions of PM in the cities (except Sylhet) were greater than the national standard values; in case of Sylhet the conditions were little improved – in about 25% of the days in winter in Sylhet the PM levels were compliant. Compared to winter seasons, the summer seasons were less polluted although coarse particles dominated greatly in this season, causing nuisance to daily human life. On an average, the concentrations of PM_{10} and $PM_{2.5}$ in summer in Dhaka were respectively 27.7 and 41.0 % lower than those in winter season; in other cities the reductions in PM_{10} and $PM_{2.5}$ concentrations were as follows, Narayanganj (30.7 and 41.7 %), Gazipur (14.5 and 32.2 %), Chattogram (22.7 and 36.3 %), Sylhet (12.5 and 20.5 %) and Barisal (33.6 and 43.4 %). In all the cities, decrease in fine fraction of particle in summer with respect to winter were much greater than the reductions in

PM_{10} concentrations – indicating additional sources of $PM_{2.5}$, and congenial meteorology in winter season in the country, and one of this additional sources in wintertime could be long range $PM_{2.5}$ sources. The summertime PM concentrations (both PM_{10} and $PM_{2.5}$) in Gazipur did not wane much from the wintertime PM concentrations (Table 1) compared to those at the neighboring stations in Dhaka and Narayanganj cities.

The wet seasonal PM_{10} and $PM_{2.5}$ concentrations in the cities were highly compliant with the NAAQS; but the concentrations of PM_{10} and $PM_{2.5}$ still violated the WHO guideline values respectively in Dhaka by 75 & 75 % days, Narayanganj by 75 & 50 % days, Gazipur by 50 & 50 % days, Chattogram by 50 & 50 % days, Sylhet by 50 & 25 % days, and Barisal by 50 & 50 % days of the wet season (Table 1).

Figure 2 Time series graph of PM_{10} and $PM_{2.5}$ Concentrations at different cities of Bangladesh; horizontal lines are national limit values of PM_{10} (upper) and $PM_{2.5}$ concentrations (lower)

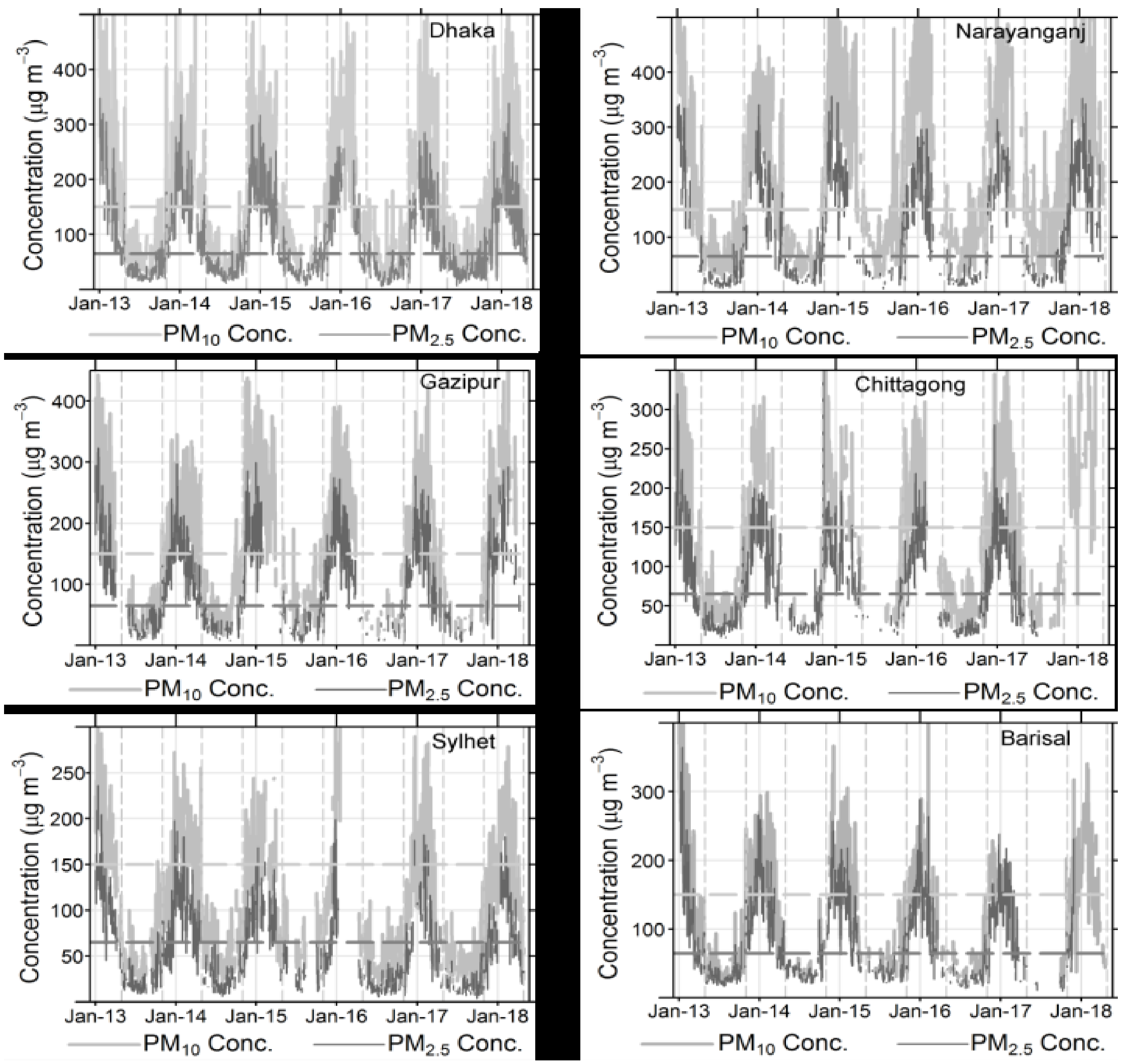


Table 1 Overview of the daily PM concentrations in different seasons in the cities of Bangladesh. Daily concentrations were calculated with minimum 80% data availability.

City	Season	PM_{10} Conc. (µg m^{-3})				$PM_{2.5}$ Conc. (µg m^{-3})			
		Percentiles				Percentiles			
		25	50	75	mean±sd	25	50	75	mean±sd
Dhaka	Winter	222.7	278.7	342.7	288.0±151.5	153.4	184.0	226.0	190.0±93.0
	Summer	128.6	192.0	273.9	208.6±152.0	65.7	97.8	147.6	110.0±85.0
	Wet	48.5	62.6	88.4	72.5±51.6	23.3	32.3	45.9	37.3±27.3
	Annual*	66.3	114.8	229.3	155.8±140.2	33.1	55.0	129.0	86.1±85.0
Gazipur	Winter	210.6	256.0	310.6	262.0±145.4	145.0	173.0	221.4	180.0±96.0
	Summer	165.7	231.0	282.0	224.0±132.2	83.5	121.1	157.6	122.3±76.1
	Wet	33.4	48.7	77.9	60.3±48.5	18.2	27.5	43.2	32.3±26.1
	Annual	59.3	153.0	244.0	161.3±136.0	34.8	88.8	155.4	100.7±86.8
Narayanganj	Winter	317.0	377.0	432.0	377.0±157.5	188.4	225.4	265.7	227.0±102
	Summer	156.7	250.6	349.4	261.0±156.4	68.5	125.0	187.8	132.3±93.2
	Wet	55.7	83.7	120.0	99.2±84.4	17.2	25.0	38.0	34.4±34.0
	Annual	86.7	160.2	310.8	203.0±163.2	26.0	57.4	173.0	108.0±103
Chattogram	Winter	182.0	216.0	260.0	224.0±113.0	116.6	138.5	167.8	143.3±76.0
	Summer	108.0	166.4	237.6	173.8±100.0	52.4	85.9	125.3	91.2±63.4
	Wet	34.4	45.7	61.6	53.7±40.8	17.6	22.3	31.3	28.4±21.3
	Annual	51.8	113.7	200.2	132.2±106.0	26.8	64.4	120.2	78.7±106.0
Sylhet	Winter	135.7	170.3	199.4	172.7±114.0	78.7	103.8	128.2	105.0±76.0
	Summer	101.7	160	192.5	151.0±92.0	56.8	84.0	110.5	83.4±55.0
	Wet	34.4	47.5	64.1	52.0±38.3	13.5	19.5	28.7	22.7±21.1
	Annual	47.5	83.1	149.1	102.5±91.2	19.8	38.8	83.6	54.6±57.3
Barisal	Winter	184.0	210.4	245.6	218.4±112.0	134.6	154.0	187.0	163.7±82.3
	Summer	87.0	129.6	190.6	145.0±97.0	52.0	83.5	124.5	92.7±64.0
	Wet	34.0	44.6	63.0	56.0±41.6	25.0	32.3	41.9	37.6±24.3
	Annual	50.9	112.7	190.6	126.7±102.7	34.0	66.7	130.7	85.6±71.5

* Annual mean was calculated with the data from 2013 to 2017.

Directional influences on the PM concentrations at the stations

The conditional bivariate polar functions (CBPF) of the PM at three percentile ranges (0 – 40, 41 – 70, and 71 – 98) were calculated for the stations particularly which had on-site meteorology data (Gazipur, Chattogram, Sylhel and Barisal). On-site meteorology data is crucial for modeling the CBPF. CBPFs at low percentile range (0 – 40) indicate possible source directions for the low PM concentrations which usually occur during the wet season (Table 1). Similarly, CBPFs at mid range percentiles (41 – 70) indicate source directions for moderate concentrations which occur immediately before and after rainy season (May & October – November) and the CBPFs at high percentile range (71 – 98) indicate source directions for high concentrations which occur during dry season (Fig. 2, Table 1). PM concentrations at the top two percentiles (99 – 100) were considered outliers and not included in the CBPF calculation.

The CBPFs of PM concentrations at Gazipur station (Fig. 3 a&d) show high probability of experiencing low concentrations of both PM_{10} (0 – 89 µg m^{-3}) and $PM_{2.5}$ (0 – 47 µg m^{-3}) from all the directions except the northwest side. Mid range PM_{10} (92 – 195 µg m^{-3}) and $PM_{2.5}$ (48 – 121 µg m^{-3}) concentrations at Gazipur station were highly probable from the west and northwest directions (Fig. 3 b&e); mid range PM at Gazipur was also probable from the northeast direction (Fig. 3 b&e). High PM concentrations (both PM_{10} and $PM_{2.5}$) at Gazipur station were highly probable from the west and northwest directions (Fig. 3 c&f) and in both cases high concentrations were associated with calm weather – indicating abundance of local pollutions emitted near ground.

Chattogram station was achieving high PM concentrations majorly from the area lying to the west to north directions (Fig. 3 i&l), and especially higher $PM_{2.5}$ was being experienced from the north (Fig. 3l). Sylhet station was experiencing PM from all the directions; but the greater concentrations were observed from the southwest direction (Fig. 3 m,n,o,p,q,&r). Barisal station also gained PM from all the sides, but higher concentrations were experienced from between north and west directions (Fig. 3 s,t,u,v,w,x).

The CBPFs of PM concentrations (Fig. 3) reveal that the stations were receiving PM from most of the sides, regulated by the wind directions. The meteorology played vital role in determining the levels of PM concentrations. Dry seasonal meteorology in Bangladesh is highly congenial for accumulating PM in the atmosphere; the dryness increases the residence time of the PM especially the fine particles in the atmosphere. Fig. 3 indicates local or regional area type sources (dust, vehicles, cooking, small/medium industries, etc.) of the PM around the stations. The southern sources could not impact high for its contributions got diminished by the wet seasonal influences; however in contrast, imbued by seasonal favorable weather in dry season the upwind sources impacted high on the ambient PM concentrations.

The CBPFs of PM_{10} concentrations mostly resemble those of $PM_{2.5}$ concentrations at each station (Fig. 3). Although CBPF is a phenomenon of the combined effect of source strength and wind direction, such resemblances primarily point to emissions of both PM_{10} and $PM_{2.5}$ from similar sources. The proportion of PM_{10} and $PM_{2.5}$ from a source may vary from time to time. Table 2 provides measures of correlation coefficient of PM_{10} and $PM_{2.5}$ concentrations at different season in the stations.

Figure 3 CBPFs of PM_{10} (left compartment) and $PM_{2.5}$ (right compartment) concentrations in three percentile ranges in the cities. The scale bar shows the probability of experiencing PM, the concentration range is shown in the bracket. gz=Gazipur (1st row), ctg=Chattogram (2nd row), syl=Sylhet (3rd row) and bar=Barisal (4th row)

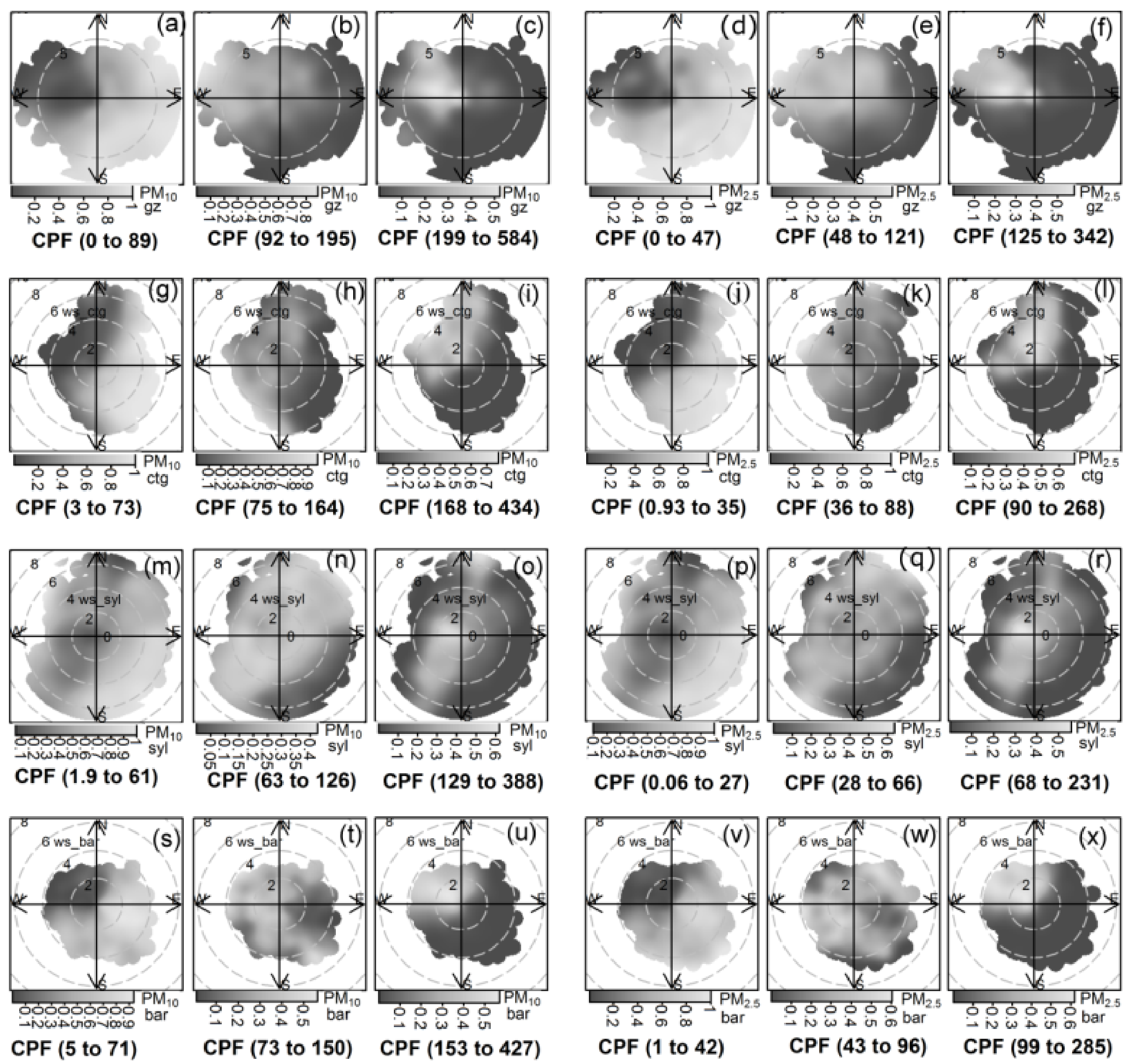


Table 2 Coefficient of correlation (r) between PM_{10} and $PM_{2.5}$ concentrations at different seasons at the stations

Season	Dhaka	Narayanganj	Gazipur	Chattogram	Sylhet	Barisal
Winter	0.83	0.70	0.82	0.76	0.91	0.88
Summer	0.81	0.76	0.81	0.72	0.88	0.88
Wet	0.72	0.59	0.69	0.69	0.85	0.85

Diurnal variations of PM concentrations

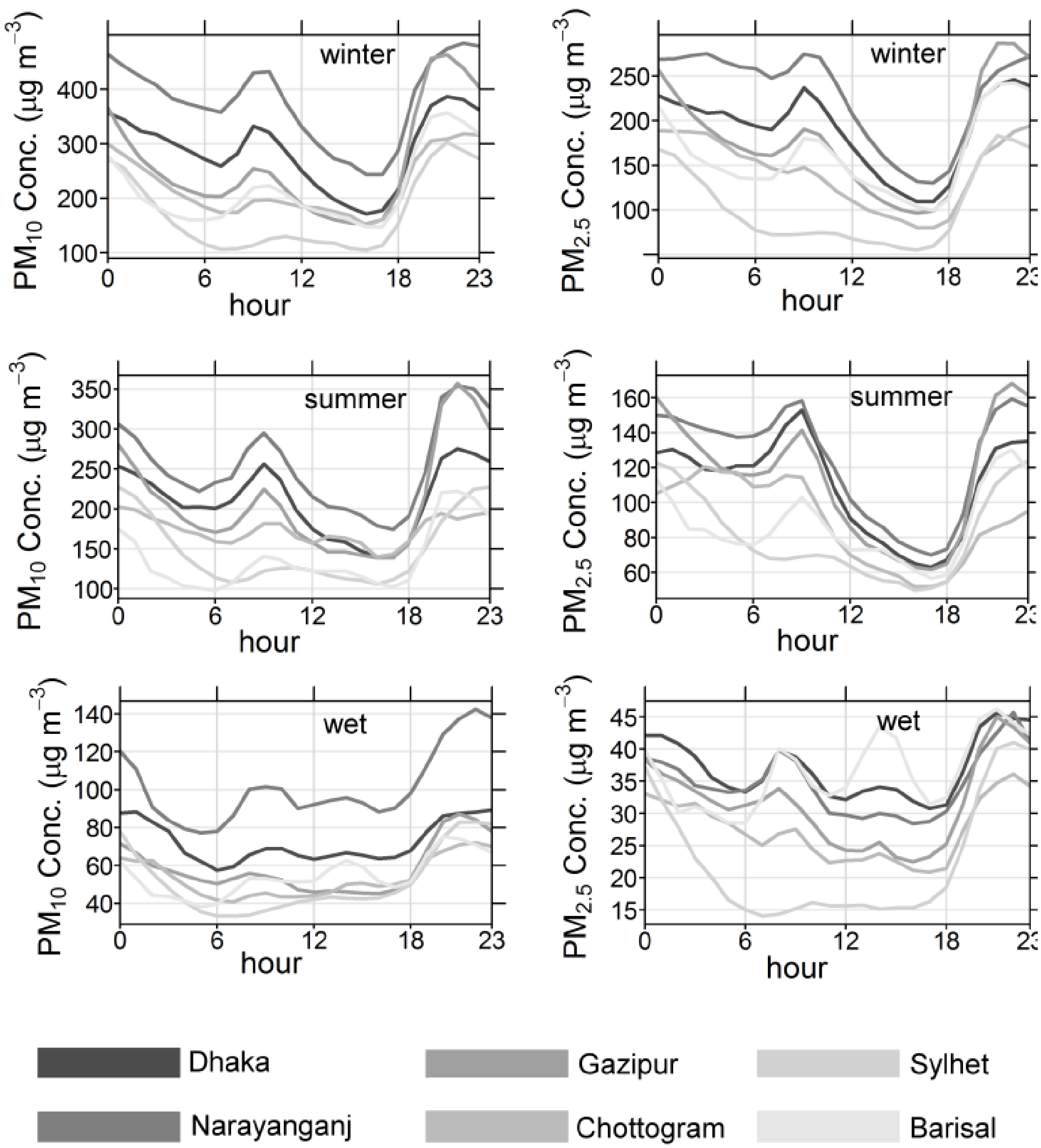
The diurnal variations of PM concentrations (both fractions) in Dhaka, Narayanganj, Gazipur and Barisal were mostly the same in winter and summer seasons (Fig. 4) – the variations were bimodal in pattern, having peaks at 9:00 am and 9:00 pm. After the concentration peak at 9:00 am, PM concentrations (both fractions) in all of the cities steeply went down throughout the day; the concentrations started to rise from 6:00 pm till the peak at 9:00 pm. The concentrations plummeted throughout the night and started to rise again from 6:00 am next morning (Fig. 4). The wet seasonal diurnal trends of PM in the upper mentioned four cities also experienced two pikes at 9:00 am and 9:00 pm, but the daytime variations of PM in this season were little different from the winter and summer seasons – tiny upward trend in the afternoon of wet season was noticed, and that the daytime trends of PM concentrations were little flat compared to those in winter and summer (Fig. 4). Diurnal variations of PM in the city of Chattogram and Sylhet were found little different from other cities, especially the PM peak in the morning in these two cities were less pronounced.

Although the cities of Chattogram, Sylhet and Barisal are located about 300 km away from the mid region of the country (Dhaka, Narayanganj, Gazipur) and have different type of source characteristics, the diurnal variations of the PM concentrations in all of the cities especially after 6:00 pm were the same (Fig. 4). This is perhaps for the similar kind of variations in the meteorology parameters in the cities (Fig. 5); the intensity of the meteorology was seasonally and spatially different though. The country of Bangladesh (except Sylhet and Chattogram regions) has a very flat terrain; climatic changes throughout the country are almost the same too.

A correlative movement of the normalized levels of the $PM_{2.5}$ concentrations and meteorological parameters are shown in Fig. 5. Normalized levels were calculated by dividing the real values of the parameters by the respective mean values – for example, the normalized level of $PM_{2.5}$ concentrations in winter of Gazipur was calculated by dividing the individual values of $PM_{2.5}$ concentrations in winter of Gazipur by the mean value of the concentrations in that season. Calculating and plotting the normalized level is a good means of plotting several parameters with different units and value-ranges (like $PM_{2.5}$ concentrations and wind speed, etc.) within the same diagram. Individual values of a parameter in a database may be inferred from the normalized plot if the mean value of the parameter is known.

Meteorology has profound impact on the air quality in a region (Schnell et al. 2018; Tiwari et al. 2014). The collective impacts of the local emissions, meteorology parameters, and boundary layer dynamics determine the trends in the PM concentrations in a region (Dumka et al. 2013, 2015). Stull (1988) suggests that the fumigation effect and evolution of the boundary layer height (BLH) just after the sunrise favor building up PM concentrations, which when combined with the rush hour emissions from especially motor vehicles result in the morning peaks. As Chattogram and Sylhet stations were far from the busy roads, and any other big local sources, the morning peaks of PM concentrations did not develop much at those stations (Fig. 4). However, nighttime hike in PM concentrations at 9:00 pm was very common in all the seasons in the cities (Fig. 4).

Figure 3 Diurnal trends in PM_{10} and $PM_{2.5}$ concentrations in different seasons in the cities



Although the source activities (vehicles, road dust, constructions, industries, etc.) in the cities run in large scale at daytime, the PM concentrations soared at nighttime (Fig. 4 & 5) and the average nighttime concentrations in all of the cities were greater than the average daytime concentrations (Table 3). Fig. 5 reveals that the daytime meteorology of the cities was characterized with comparatively greater solar radiation, wind speed and temperature, and lower relative humidity. Higher solar radiation induces higher convection that increases vertical depth of the atmosphere and therefore decreases the PM concentrations. Additionally, higher wind speeds at daytime assist in proper dispersion of the PM in the atmosphere. The nighttime PM_{10} and $PM_{2.5}$ concentrations at Dhaka stations in winter season were on average 33.5 and 26.4 % greater than the daytime concentrations respectively. Similarly, the nighttime PM_{10} and $PM_{2.5}$ concentrations were greater from the daytime concentrations in other cities in winter respectively by 26.2 and 22.0 % in Narayanganj, 63.8 and 54.6 % in Gazipur, 45.6 and 45.5 % in Chattogram, 85.4 and 98.7 % in Sylhet, and 38.2 and 35.2 % in Barisal. On the other hand, the increase in the nighttime PM_{10} and $PM_{2.5}$ concentrations compared to daytime concentrations in summertime in the cities were 23.2 and 16.7 % in Dhaka, 22.8 and 23.7 % in Narayanganj, 46.8 and 38.8 % in Gazipur, 13.6 and 21.5 % in Chattogram, 52.3 and 57.6 % in Sylhet, and 28.6 and 24.2 % in Barisal. Thus, the increase in nighttime PM_{10} concentrations compared to that in $PM_{2.5}$ concentrations during both winter and summer seasons were higher in Dhaka, Gazipur and Barisal. Narayanganj experienced mostly similar hikes in both fractions of PM concentrations at nighttime, and in contrast, Chattogram and Sylhel experienced greater increase in $PM_{2.5}$ concentrations at nighttime compared to daytime concentrations during both winter and summer seasons. Coarse particles ($PM_{10-2.5}$) have shorter residence time in the atmosphere compared to fine particles; thus the fine particles are usually expected to dominate at nighttime when major source activities are ceased off. However, the increase in PM_{10} concentrations compared to $PM_{2.5}$ concentrations at nighttime indicate not only meteorological impacts but also impacts of some sort of source activities at nighttime in Dhaka, Gazipur and Barisal. Chattogram and Sylhet stations are located far from major local sources and thereby experienced relatively higher $PM_{2.5}$ concentrations at nighttime.

Figure 5 Relationships among normalized level of diurnal variations of $PM_{2.5}$ and meteorology parameters; ws=wind speed, T= temperature, RH= relative humidity, SR= solar radiation. gz=Gazipur, ctg=Chattogram, syl=Sylhet, bar=Barisal

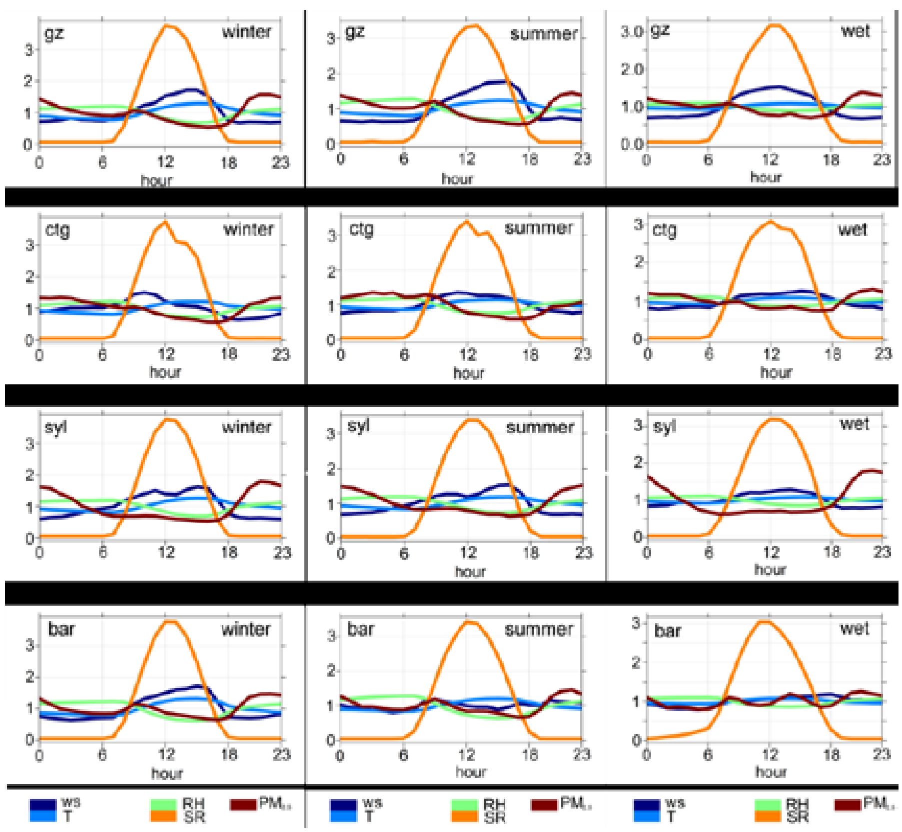


Table 3 Average PM concentrations (μg m^{-3}) at daytime and nighttime in different seasons in the cities

		Winter		Summer		Wet	
		day (avg±sd)	**night** (avg±sd)	**day** (avg±sd)	**night** (avg±sd)	**day** (avg±sd)	**night** (avg±sd)
DHK	PM_{10}	243.4±122.0	325.6±162.2	186.3±131.3	229.6±164.2	64.7±38.7	78.5±60.0
	$PM_{2.5}$	166.0±84.0	209.8±95.4	100.8±80.4	117.6±87.5	34.1± 23.1	39.5±30.2
NG	PM_{10}	331.3±143.8	418.2±155.5	224.5±127.5	275.8±173.3	93.0±66.2	107.0±96.5
	$PM_{2.5}$	203.9±105.0	248.6±96.0	110.0±85.2	136.1±97.7	32.1±29.0	37.0±39.2
GZ	PM_{10}	195.8±81.0	320.7±159.2	167.1±82.1	245.4±153.2	49.4±36.2	66.2±55.6
	$PM_{2.5}$	139.0±66.7	214.9±101.2	94.4±61.5	131.0±82.7	27.1±22.3	35.5±28.1
CTG	PM_{10}	178.8±71.7	260.3±127.0	162.0±82.2	184.0±111.5	46.0±26.0	59.6±49.3
	$PM_{2.5}$	114.8±59.4	167.0±81.6	80.8±57.7	98.2±67.0	23.8±15.2	30.8±25.2
SYL	PM_{10}	118.3±51.5	219.4±128.6	116.5±54.0	177.4±106.0	40.2±20.0	60.8±46.7
	$PM_{2.5}$	68.0±41.7	135.1±83.0	61.8±35.8	97.4±62.3	15.5±11.2	28.5±25.2
BAR	PM_{10}	180.2±58.6	249.0±133.4	118.0±57.0	151.8±118.0	52.1±30.7	55.6±48.7
	$PM_{2.5}$	135.0±49.8	182.5±96.4	76.3±44.5	94.8±74.8	35.5±20.0	36.1±27.1

DHK=Dhaka, NG=Narayanganj, GZ=Gazipur, CTG=Chittagong, SYL=Sylhet, BAR=Barisal

Long range PM sources

In dry weather PM gets longer residence time in atmosphere, especially the fine particles may have weeks of residence time and travel hundreds to thousands of kilometers before being removed from the atmosphere by dry deposition (Seinfeld and Pandis 1998). The entire south Asian region during the dry season suffers from increased level of PM in air. Not only the typical modern anthropogenic sources like industries and vehicles but also some primitive practices like open stubble burning and cooking, etc. infuse tons of PM into the atmosphere of south Asian countries. The PM so emitted during dry season disperses around thousands of kilometer over the south Asian countries (Begum et al. 2011; Lawrence and Lelieveld 2010). Several researches earlier have shown incursions of trans-boundary PM into Dhaka, and the source locations identified by those researches are Nepal and the Indian regions lying on the Himalayan Valley and on the Indo-Gangetic Plain (Rana et al. 2016a, Begum et al. 2010). In this work, long range PM pollution (both within and beyond the national boundary) was investigated around Dhaka, Chattogram, Sylhet and Barisal cities.

Ninety six (96)-hour backward trajectories with every 3-hours interval for the duration of 15 December 2015 to 15 January 2016 on Gazipur, Chattogram, Sylhet and Barisal stations were calculated using Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT-4) model (Draxler and Rolph 2003) on the platform of the analytical software "R" 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 analyzed with their association with station concentration data, starting points of the trajectories were kept at 10.0m high from the ground. PM concentrations in the cities usually remain at the highest level during this time period. Hourly $PM_{2.5}$ concentrations at the stations were associated with the trajectories arrived at the respective hours at the stations. Concentration weighted trajectory (CWT) method (seibert et al. 1994) was applied to identify possible long range regions responsible for contributing to PM pollution at the stations. CWT is calculated from the residence time of trajectories over a grid cell and the respective $PM_{2.5}$ concentrations the trajectories were associated with. In this method, for each cell of a domain, mean CWT or logarithmic mean concentration of a pollutant species was calculated according to the Equation1 as follows:

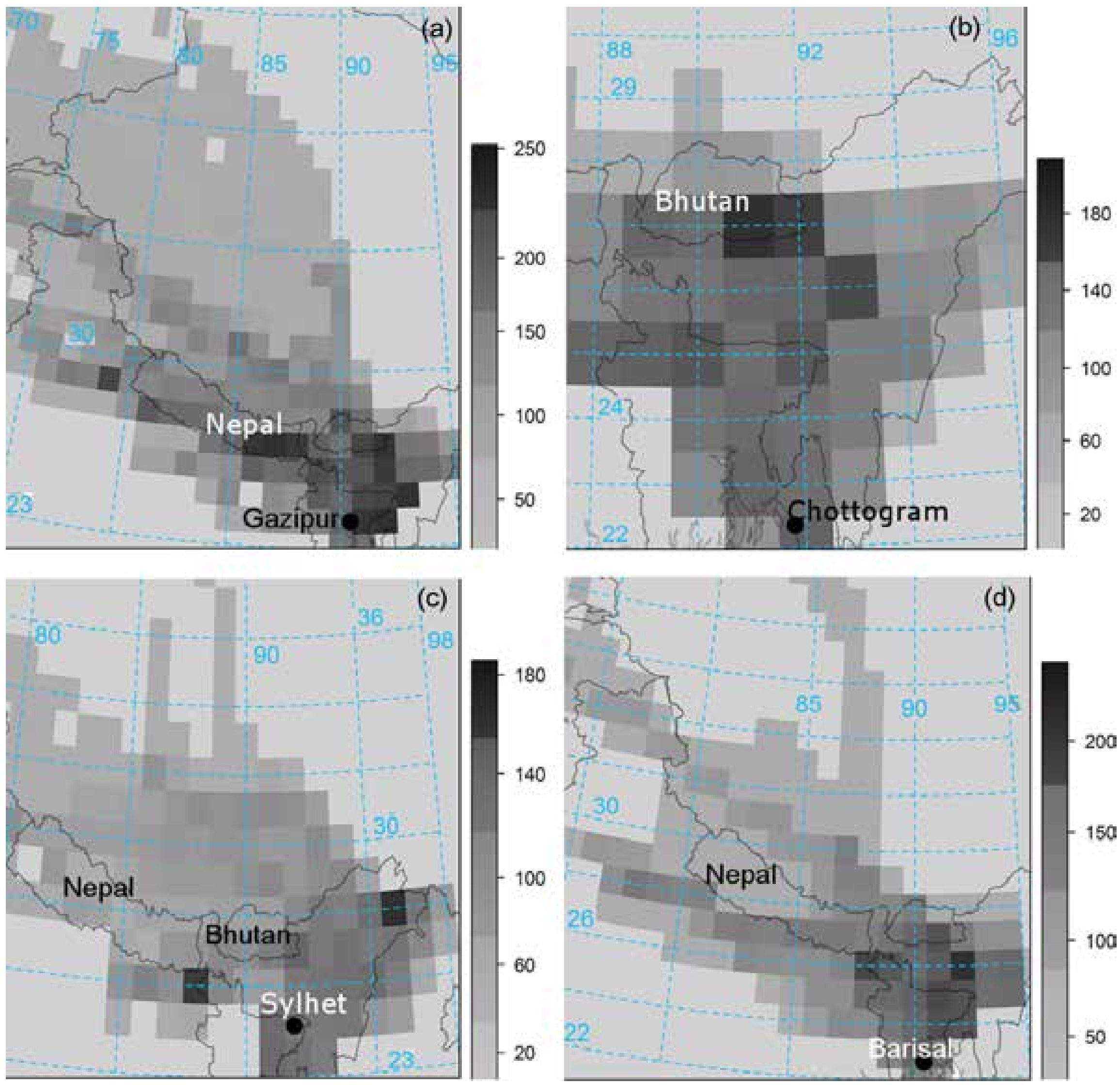
$$\ln(\overline{C}_{ij}) = \frac{1}{\sum_{k=1}^{n} \tau_{ijk}} \sum_{k=1}^{n} \ln(C_k)\tau_{ijk} \quad .... (1)$$

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

Gridded trajectory concentrations in Fig. 6 show that the stations were mostly polluted by the PM transported from long range sources present within the boundary. For example, sources of the northern districts Naogaon, Bogura and Rangpur were found to contribute to fine particles in the middle (Fig. 6a), south (Fig. 6d), and southeast (Fig. 6b) parts of the country. The south (Fig. 6d) and southeast (Fig. 6b) regions were also influenced by the sources operating in the middle part of the country (Dhaka, Gazipur, and Narayanganj). Sources in the eastern districts (Narsindhi and Bramhanbaria) and northeastern districts (Sylhet) were also found contributing to $PM_{2.5}$ concentrations at the south (Fig. 6d) and southeast (Fig. 6b) stations. Sylhet station was found to gain $PM_{2.5}$ from the sources located in the middle part of the country (Fig. 6c) during the time from December 2015 to January 2016. The northern districts possess a large number of rice mills and brick kilns; rice husks are widely used as fuel in those rice mills, and the brick kilns burn coals. Agricultural residue burning and open cooking are also broadly practiced in the northern districts. All of these are good sources of air pollution and are observed according to the Fig. 6 to contribute to the fine particles at the long range receptors within the country.

Sources of Nepal, and Delhi-NCR and Uttar Pradesh regions of India could have contributed fine particles at the Gazipur station (Fig. 6a). Delhi-NCR is currently the top ranked polluted city in the world (WHO 2018); Nepal and Pakistan are also heavily polluted (Gurung and Bell 2012; Khatum 2017). The stations could have also gained PM from the eastern state of Tripura and northeastern state of Assam/Meghalaya of India (Fig. 6).

Figure 6 Gridded back trajectory concentrations showing mean $PM_{2.5}$ concentrations using CWT method



CONCLUSION

Trend characteristics of PM concentrations in six cities of Bangladesh from 2013 to April 2018 were exhaustively studied. The cities were Dhaka, Gazipur and Narayanganj in the middle of the country, Chattogram to the southeast, Sylhet to the northeast and Barisal to the south of the country. The concentrations were monitored every minute with the continuous PM monitoring system BAM 1020 of the Met One Instrument Inc, USA. Two separate systems of the BAM 1020 were applied for monitoring PM_{10} and $PM_{2.5}$ concentrations in each city. After the study the following observations and findings were noted,

a) Atmospheric PM concentrations in all of the regions of the country were notably influenced by the seasonal variations. Average PM_{10} concentrations at Dhaka, Chattogram, Narayanganj, Gazipur, Sylhet and Barisal stations in dry seasons (November – April) were 238.7±155.4, 190.7±108.5, 303.6±161.4, 227.3±142.7, 151.7±105.0 and 170.7±108.4 μg m^{-3} respectively whereas those in wet seasons (May – October) were 75.0±51.6, 55.5±40.8, 102.4±84.4, 60.6±48.5, 52.7±38.3, and 54.4±41.6 μg m^{-3} respectively. The ratios of $PM_{2.5}$ concentrations to PM_{10} concentrations were comparatively higher in wintertime (December – January) and lower in summertime (February – April). The ratios in winter/summer time in Dhaka, Chattogram, Narayanganj, Gazipur, Sylhet and Barisal cities were 0.67/0.56, 0.64/0.53, 0.60/0.46, 0.70/0.58, 0.58/0.53 and 0.76/0.64 respectively. Ratios in wet season were 0.52, 0.55, 0.37, 0.58, 0.42 and 0.72 respectively.

b) The middle part of the country (Dhaka, Narayanganj and Gazipur) was found more polluted compared to other parts of the country while the northeast region (Sylhet) was found the least polluted. Primary investigations reveal a relation between wind pattern and PM pollution level in the country – the northern, middle and southern part of the country (Dhaka, Narayanganj, Gazipur, Barisal) experienced wind mostly from the west and north-west directions during dry season and were characterized with very high PM pollution as well as higher contribution of fine fraction to the PM concentrations. In contrast, the southeast (Chattogram) and northeast (Sylhet) regions of the country having wind directions other than west and northwest directions in dry season experienced less pollution.

c) The diurnal variations of PM concentrations (both fractions) in Dhaka, Narayanganj, Gazipur and Barisal were mostly the same in winter and summer seasons– the variations were bimodal in pattern, having peaks at 9:00 am and 9:00 pm. Diurnal variations of PM in the city of Chottogram and Sylhet were found little different from other cities, especially the PM peak in the morning in these two cities were less pronounced. The nighttime PM_{10} and $PM_{2.5}$ concentrations at Dhaka stations in winter season were on average 33.5 and 26.4 % greater than the daytime concentrations respectively. Similarly, the nighttime PM_{10} and $PM_{2.5}$ concentrations were greater from the daytime concentrations in other cities in winter respectively by 26.2 and 22.0 % in Narayanganj, 63.8 and 54.6 % in Gazipur, 45.6 and 45.5 % in Chattogram, 85.4 and 98.7 % in Sylhet, and 38.2 and 35.2 % in Barisal.

d) The Concentration Weighted Trajectory method applied to identify long range sources responsible for contributing PM to the cities primarily found that sources of one region (within the boundary) were contributing PM to other regions located downwind. For example, some hotspots in the northwestern districts (Naogaon, Bogura, Rangpur) were identified contributing PM to the middle and south part of the country. Outside boundary, sources of Nepal, and Delhi-NCR and Uttar Pradesh regions of India could have contributed fine particles at the Gazipur station. The stations could have also gained PM from the eastern state of Tripura and northeastern state of Assam and Meghalaya of India.

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