Air Quality Modeling and Health Risk Assessment of Air Pollutants Generating from Khulna Power Plant

by

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Declaration

This is to certify that the thesis work entitled as "Air quality modeling and health risk assessment of air pollutants generating from Khulna Power plant" has been carried out by Salma Alam in the Department of Civil Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above research work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

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To

My parents who show me the way of my life

ABSTRACT

Clean air is seriously affected by the atmospheric emissions generating from industrial sectors. Power plants contribute significantly among these emissions of air pollutants. This study describes the air pollutants emission from Khulna Power Company Limited (KPCL), the distribution of emitted pollutants with time and space, the contribution of power plant emission to the ambient air, and finally the estimation of health risk.

This Study reveals that KPCL (225 MW power generation capacity) using Heavy Fuel Oil (HFO) that contains C (83.42%), H (10.02%), S (0.7%), O (0.05%) and N (0.1%) by weight and the chemical formula of HFO was derived as $C_{2230}H_{3211}S_7N_{2.5}O$. The energy content of HFO was determined 17.76 MJ/kg and it contains Amino (-NH), Hydroxyl (-OH) and Aliphatic Carbon (-CH), Esters (S-OR) and Sulphate (S=O) bonds. The atmospheric emission from KPCL Power plants was estimated as 197.4 t/yr of SO_2, 84 t/yr of NO_X, 9 t/yr of CO, 12.46 t/yr of PM_{10}, 9.30 t/yr of $PM_{2.5}$ and 2.7 kg/yr of Lead compounds. The dominant air pollutants from KPCL were found SO_2 (62.04%) and NOx (26.35%).

This study also shows that the dispersion of air pollutants from KPCL during September month mostly travelled towards the northern direction in a long distance (>300 km) covering the area of Jessore, Chuadanga, magura, Jhenaidah in Khulna division; Pabna, Shirazgonj, Bogra in Rajshahi division and in some cases dispersed over Dinazpur, Rangpur, Thakurgaon in Rangpur division. During the period of November 2014 to February 2015 the plume travelled long distance of more than 200km covering the area of Mongla, Bagerhat Shundarbans, Potuakhali, Borguna, Gopalgonj, Pirozpur and over Bay of Bengal. Plume also travel over Sundarbans about one- fourth (4 months) period of a year. Back trajectory of long range transport showed that air pollutants from India, Bhutan and Nepal were also contributed to the airshed of Khulna city. Due to the location Himalayan Mountains the massive air pollution of china seems not transported to Khulna airshed.

Air Quality Index (AQI) results showed that during the September 2013the AQI for SO_2 (15) and NO_X (21) indicating the 'good' category (1-50) which pose little or no short term health risk. During this month comparing with the available local air quality monitoring station data, it was found that 18.5% of total ambient SO_2 and 12.36% of total ambient NO_X contributed by KPCL emission respectively. From dispersion modeling of November 2014 to February 2015, it was found that, 2km surrounding area of KPCL is mostly affected by SO_2 and NO_X. Average concentrations of SO_2in that area were 7.04µg/m^3 in November 2104, 7.7µg/m^3 in December 2014, 6.62µg/m^3 in January 2015 and 7.92µg/m^{3}and the average concentrations of NO_X were 2.94µg/m^3 in November 2014, 3.13µg/m^3 in December 2014, 2.81µg/m^3 in January 2015 and 3.42µg/m^3 in February 2015. Due to the exposure of SO_2 and NO_X in this area the DALYs for chronic respiratory disease obtained 0.15 and for cardiovascular disease it was obtained 0.35 per 10 Lac which indicates that 10 Lac inhabitants surrounding the KPCL area will lose their life expectancy by 128 days due to cardiovascular disease and 55 days due to chronic respiratory disease.

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ABBREVIATION

KPCL   :   Khulna Power Company limited

ADB   :   Asian Development Bank

SO_2 :   Sulfur di Oxide

NO_X :   Nitrogen Oxides

CO   :   Carbon Monoxide

O_3 Ozone

PM   Particulate Matter

PM_{10} :   Particulate Matter Having diameter of 2.5 to 10 micrometer

$PM_{2.5}$:   Particulate Matter Having diameter smaller 2.5 micrometer

AQI   :   Air Quality Index

WHO   :   World Health Organization

DALYs   :   Disability Adjusted Life Years

ALA   :   American Lung Association

CASE   :   Clean Air and Sustainable Environment

UNITS OF MEASUREMENTS

%	Percent
t/yr	Tons/ year
MW	Mega Watt
KW	Kilo Watt
gm	Gram
gm/KW	Gram per Kilo Watt
kg	Kilogram
kg/day	Kilogram per Day
kg/cap/day	Kilogram per Capita per Day
g/m^3	gram per Cubic Meter
$\mu g/m^3$	Micro gram per Cubic Meter
m	Meter
m^3	Cubic Meter
$g/m^2/month$	gram per Square Meter per month
Kcal/kg	Kilocalorie per Kilogram
cm	centimeter
cal/cm	Calories per centimeter
mL	milliliters
^{o}C	degree Celsius
ppm	Parts per million
PJ	Peta Joule

CHAPTER 1

INTRODUCTION

1.1   General

Air is an indispensable to all living being in this world. Poor air quality affects human health as well as environment. By reducing air pollution levels, the disease burden can be reduced from stroke, heart disease, lung cancer, and both chronic and acute respiratory diseases, including asthma. Industrial pollution is one of the most dominating sources among all anthropogenic sources of air pollution. Globally the power plant sector is considered as an increasing threat to the human health and the environment. For this, understanding of air pollutants emission from power generation sector is essential to ensure the clean and healthier air by reducing the air pollutants emission.

1.2   Problem Statement

Industrial and transportation sectors are the principle sources of outdoor air pollution in Bangladesh (Alam, 2009). The outdoor air quality pattern can be indexed and predicted using air quality monitoring and air dispersion modeling. The air quality monitoring stations in Bangladesh consists of eleven (11) fixed Continuous Air Monitoring Stations (CAMS) in Dhaka, Narayangonj, Gazipur, Chittagong, Khulna, Rajshahi, Barisal and Sylhet (CASE, 2015), monitored by Department of Environment (DoE) of Bangladesh Government, which provides the concentration of PM_{10}, $PM_{2.5}$, CO, SO_2, NO_X and O_3, of the surrounding areas. But due to poor data capture rate/malfunction of the analyzer/sensor, all the data were not available in the Khulna station in each month (CASE, 2015). The air dispersion modeling deals with the atmospheric conditions, chemical and physical processes and provides the archived and predicted air pollutants concentration of the surrounding areas from emission sources. Limited studies have been conducted on air dispersion modeling in Bangladesh (Guttikunda & Begum, 2012), among them most of the studies were focused on the air pollution from brick kiln and motor vehicles in Dhaka city.

Daily electricity demand in 2010 was 6,454 MW which became 10,283 MW in 2015 in Bangladesh. This increasing demand of electricity (Table 1.1) necessitates the establishment of power plant of available fuel depending on the location. Power generation contribute about 70% of sulfur dioxide (SO_2) and 30% of nitrogen oxides (NOx) (Arnab et al., 2013). In Bangladesh, as per the generation capacity by fuel type, 62.47% of power producing plants are gas based, 21.35% are Heavy Fuel Oil (HFO) based, 8.08% High speed diesel fuel based, 2.0% Hydro based, 1.74% are coal based (BPDB, 2016). With this increasing demand the contribution of air pollutants from power plants will increase day by day as well as will contribute impact global environment and health of people.

Table 1.1 Trend of electricity increment

Year	Peak Demand (MW)
2010	6,454
2011	6,765
2012	7,518
2013	8,349
2014	9,268
2015	10,283

Source: BPDB, 2016

The World Health Organization (WHO) considers clean air to be a basic requirement of human health and well-being. It recognizes ambient air pollution as a major environmental health problem affecting everyone in developed and developing countries. In 2012, 3.7 million deaths worldwide were attributed to ambient air pollution, with the greatest number occurring in the Western Pacific (1.67 million deaths) and South East Asian (936000 deaths) regions (WHO, 2013). Air pollution kills 15,000 Bangladeshis each year, (Ahmed and Mahmud, 2011). In 2001 a World Bank report released in Dhaka and according to the report, Bangladesh could save between $200 million and $800 million per year, about 0.7 to 3.0% of its gross national product, if air pollution in the country's four major cities were reduced (South Asia, 2001). So it is necessary to investigate emission level of air pollutants and their contribution to ambient air quality from power plant as well as the impact on human health.

The outcome of this study will evidently represent the level of emissions from power plants and the dispersion pattern of pollutants released from the KPCL plant. The study will be beneficial to prepare the national guideline for emission estimation from power plants having different fuel types. In addition, the dispersion modeling technique will assist to understand the air pollutants movement including their concentration and deposition from point source of existing/forthcoming industries.

1.3 Objectives and Scope of the Research Work

This study is aimed at to demonstrate the power plant emission and its distribution with change the space and time. The ultimate goal of this study is to find out the contribution of power plant emission to the ambient air quality and the health impact of emitted pollutants.

The specific objectives of this study are given below:

1   To characterize the fuel oil and estimate the air pollutants emission from Khulna Power Company Limited (KPCL) plant,
2   To determine the contribution of KPCL emission of Sulfur dioxide (SO_2) and Nitrogen Oxides (NO_X) to the ambient concentration in Khulna airshed,
3   To assess the spatial and temporal distribution of atmospheric SO_2 and NO_X emitted from KPCL, and
4   To evaluate the health risk due to the exposure of SO_2 and NO_X emitted from KPCL.

1.4 Structure of the Dissertation

The dissertation has been presented in following seven distinct chapters comprising different aspects of this study. The chapters describe the overall view of emissions from power plant in addition to the pollutants transmission pathway after emitted from specific source.

Chapter 1: This chapter gives a general overview of the background information, specific objectives and structure of the dissertation of this study.

Chapter 2: This chapter comprises of comprehensive literature review encompassing the air pollution, global air pollution due to power generation, dispersion modeling, Gaussian dispersion modeling, emission estimation and health effect of air pollutants.

Chapter 3: This chapter contains elaborate description of sampling and testing protocols that have performed for HFO characterization, emission estimation, HYSPLIT dispersion model development as well as data analysis and interpretation.

Chapter 4: This chapter represents the detailed characterization such as chemical composition, energy content, functional group analysis and combustion analysis of HFO used for the power generation in addition to the estimation of emitted air pollutants generated from power plant.

Chapter 5: This chapter describes the construction of windrose from meteorological data and validation of HYSPLIT model in addition to the contribution of power plant emission to the ambient air quality.

Chapter 6: This chapter shows the spatial and temporal distribution of pollutants, and identification of zone of maximum concentration and deposition. This chapter also assesses the health impact due to long term exposure of pollutants that are emitted from power plant.

Chapter 7: This chapter includes the summary the findings of this study and provides recommendations for further research.

References: Lists of relevant publications and reports cited in the texts are included in this section.

Appendices: This section provides the lists of appendices used in this study.

CHAPTER 2

LITERATURE REVIEW

2.1 General

The purpose of this chapter is to provide comprehensive literature review encompassing the air pollution, global air pollution due to power generation, Gaussian dispersion modeling, emission estimation and health effect of air pollutants.

2.2 Air Pollution

Air pollution is the introduction into the atmosphere of chemicals, particulates, or biological materials that cause discomfort, disease, or death to humans, damage other living organisms such as food crops, or damage the natural environment or environment. Atmosphere is a complex dynamic natural gaseous system that is essential to support life on planet Earth. Stratospheric ozone depletion due to air pollution has long been recognized as a threat to human health as well as to the Earth's ecosystems. Due to enhanced human activities producing increased emissions atmospheric pollution in urban area has become a major issue in many developing countries all over the world. The emission rates of increasing air pollutants in the cities of developing countries are higher than those of developed countries (Kato et al., 1991).

Climate change is the foremost environmental impact of global air pollution which is described as global warming or the greenhouse effect, most scientists now agree that the climate is warming up. The expert Inter-Governmental Panel on Climate Change (IPCC) has predicted a possible rise in the average global temperature of 1 degree Celsius by 2025 and 3 degrees Celsius before the end of the 21st century (EEA, 2008). As well as nitrogen and oxygen, the atmosphere also contains small amounts of water vapour, carbon dioxide, methane, nitrous oxide and ozone; these are sometimes referred to as "greenhouse gases" as

they keep the earth's surface about 30 degrees Celsius warmer than it would otherwise be (EEA, 2008). In the last few hundred years the rising human population and industrialization have increased the levels of these gases in the atmosphere. The global temperature changed to o.9 degree from 1880 to 2015 (figure 2.1) and this change is leading global warming (EEA, 2008).
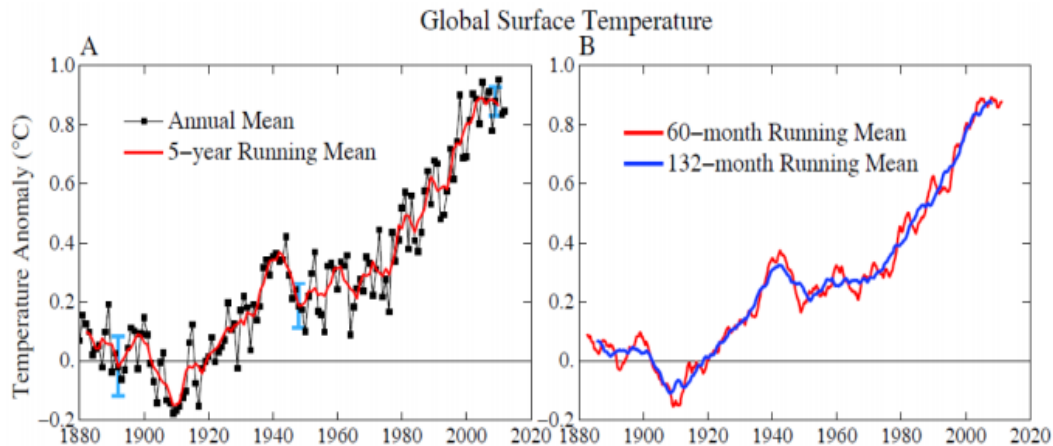
Figure 2.1 Global surface temperature changes relative to 1880–2020 (EEA, 2008)

In 2010, estimated worldwide emissions from human activities totaled nearly 46 billion metric tons of greenhouse gases, expressed as carbon dioxide equivalents (US EPA, 2014). This represents a 35 percent increase from 1990 (USEPA, 2014). These numbers represent net emissions, which include the effects of land use and forestry. Between 1990 and 2010, global emissions of all major greenhouse gases increased net emissions of carbon dioxide increased by 42 percent, which is particularly important because carbon dioxide accounts for about three-fourths of total global emissions (USEPA, 2014). Nitrous oxide emissions increased by 9 percent while emissions of methane increased by 15 percent (USEPA, 2014). Energy production sector represents the largest source of greenhouse gas emissions (71%) worldwide followed by agriculture (13%) in 2010 (USEPA, 2014)

The six largest emitting countries/regions in 2014 were: China (with 30%), the United States (15%), the European Union (EU-28) (9.6%), India (6.6%), the Russian Federation (5.0%)

and Japan (3.6%). Remarkable trends were observed in the top three emitting countries/regions, which account for 54% of total global emissions. In China and the United States, emissions are increased by only 0.9% (Olivier et al., 2015). Global emission of air pollutants in terms of carbon dioxide equivalent was around 34,000 million metric tons which turned in 2010 to around 46,000 million metric tons showing in figure 2.2 (WRI, 2014).
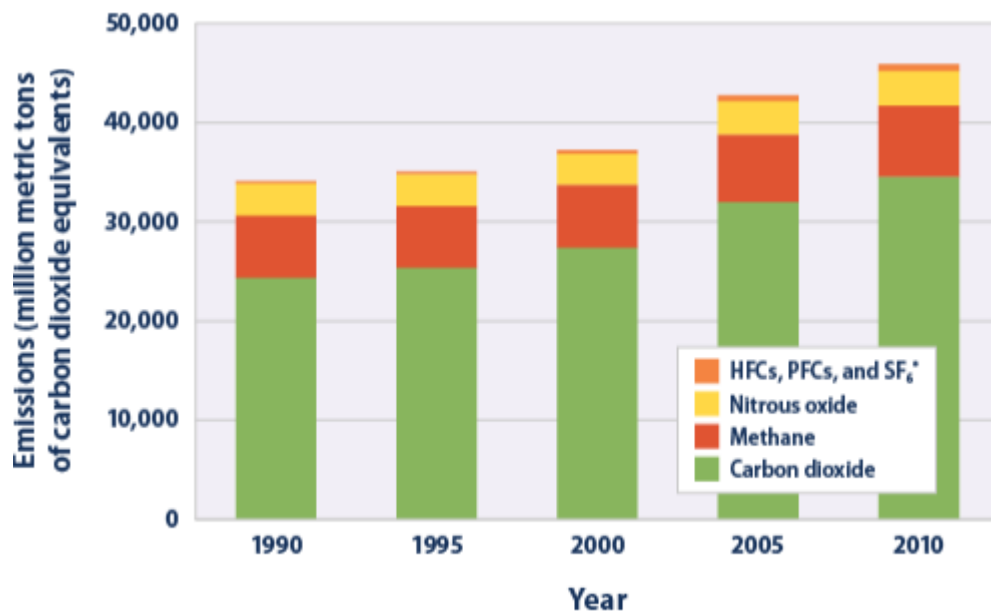
Figure 2.2 Global emission of air pollutants equivalent to CO_2 (WRI, 2014)

2.3 Air Pollution in Bangladesh

Air pollution is one of the major manmade environmental problems that had recently gained importance among environmental issues in Bangladesh (Ahmed & Hossain, 2008). Bangladesh has been ranked fourth among 91 countries with worst urban air quality in the latest air pollution monitoring report of World Health Organization (WHO, 2015). Moreover, three Bangladeshi cities such as Narayanganj, Dhaka and Gazipur have been put among the top 25 cities with poorest air. The 2014 version of the Ambient Air Pollution (AAP) database consists mainly of urban air quality data of 1600 cities from 91 countries. In the city-wise

assessment, Narayanganj has been marked as the 17th city with worst air quality whereas Gazipur and Dhaka have been ranked 21st and 23rd respectively (Daily star, 2014). According to the report almost 90 percent of people living in the cities are being exposed to dangerous levels of air pollution. Outdoor air pollution killed 3.7 million people in 2012 and the WHO says it is now the world's largest single environmental health risk (WHO, 2013). The report also states only 12 percent of people are living in cities that conform to the WHO air quality guideline levels. The report was more extensive than a similar database released by the WHO in 2011. The report was prepared on the basis of the monthly air quality monitoring data of 2013 of the Department of Environment (DoE), Bangladesh.

Table 2.1 Ambient air quality standards in Bangladesh from July 2005 and their comparison with WHO and US standards

Pollutants	Averaging period	Bangladesh Standard ($\mu g/m^3$)	WHO Guideline
Carbon Monoxide (CO)	8 hour	10,000 (9 ppm)	10,000
	1 hour	40,000 (35 ppm)	30,000
Lead (Pb)	Annual	0.5	0.5
Nitrogen Oxides (NO_x)	Annual	100 (0.053 ppm)	-
Suspended Particulate Matter (SPM)	8 hour	200	-
Coarse Particulates (PM_{10})	Annual	50	20
	24 hour	150	50
Fine Particulates ($PM_{2.5}$)	Annual	15	10
	24 hour	65	25
Ozone (O_3)	1 hour	235 (0.12 ppm)	-
	8 hour	157 (0.08 ppm)	100
Sulphur Dioxide (SO_2)	Annual	80 (0.03 ppm)	-
	24 hour	365 (0.14 ppm)	20

(Source: CASE, 2015)

The DoE has set up air quality monitoring stations in eight (8) cities, including Dhaka, Narayanganj, Gazipur, Rajshahi, Chittagong, Khulna and Sylhet. Though Narayanganj has the highest level of gaseous pollutants, the report shows the air of the northern metropolis

Rajshahi contains the highest level of dust particles (Daily Star, 2015). Among the gaseous pollutants which the DoE measures are carbon monoxide (CO), sulphur dioxide (SO_2), oxides of nitrogen (NOx) and ozone (O_3), methane and non-methane pollutants.

Brick manufacturing is the fastest growing industrial sector in Bangladesh and among the top three sectors, along with vehicle exhaust and suspended road dust, contributing to the air pollution and health problems in Dhaka. The total emissions from the brick manufacturing in the Greater Dhaka region, has been estimated and found 23,300 tons of $PM_{2.5}$, 15,500 tons of SO_2, 302,000 tons of CO, 6,000 tons of BC, and 1.8 million tons of CO_2 emissions from the clusters of brick kilns, to produce 3.5 billion bricks per year (Guttikunda et al., 2012). Emission of individual air pollutant from brick kilns varied significantly during a firing batch (seven days) and between kilns. Average emission factors per 1,000 bricks were 6.35 to 12.3 kg of CO, 0.52 to 5.9 kg of SO_2 and 0.64 to 1.4 kg of PM (Le and Oanh, 2010).

At present, air pollution from power generation sector is under investigation as the prevalence of different fuel options such as natural gas, coal, and HFO. Numerous diesel generators currently supplement the infrequent grid electricity supply in the residential, industrial and commercial sectors. These diesel generators currently pose risk to the surrounding environment. Like other developing countries, up to 10% of respiratory infections and disease in Bangladesh can be attributable to urban air pollution (World Bank, 2006). Heavy toxic trace metals carried by atmospheric particles may change the chemical composition of metals after settling on the superficial soil, thus changing their bio-availability in the soil and water (Hernandez, 2003). Particularly, industrial and automotive emissions contribute to a larger extent in this respect (Kakula, 2003).

2.4 Air Pollution and Power Generation Sector

According to the American Lung Association (ALA, 2015), 76% of U.S. acid gas emissions, which are known to irritate breathing passages, come from coal-fired power plants. Out of all industrial sources, these plants are also the biggest emitter of airborne mercury, which can become part of the human food chain through fish and wildlife-high mercury levels are linked to brain damage, birth defects, and damage to the nervous system. Overall, air

pollutants from coal plants can cause heart attacks, strokes, lung cancer, birth defects, and premature death. ALA reports on a study finding that coal-powered electricity caused over 13,000 premature deaths in 2010.

The Electricity sector involves the generation, transmission, and distribution of electricity. Carbon dioxide (CO_2) makes up the vast majority of greenhouse gas emissions from this sector, but methane (CH_4) and nitrogen oxide (NOx), sulfur dioxides (SO_2) are also emitted. These gases are released during the combustion of fossil fuels, such as coal, oil, and natural gas, to produce electricity. Less than 1% of greenhouse gas emissions from this sector come from is sulfur hexafluoride (SF_6), an insulating chemical used in electricity transmission and distribution equipment. Coal combustion is generally more carbon intensive than burning natural gas or petroleum for electricity.

2.5 Global Emission of Air Pollutants from Power Generation Sector

In 2005, power plants (2834 nos.) in North America emitted to the atmosphere around 9611608MT SO_2, 3489075 MT NO_X, 2419514935 MT CO_2, 33591MT CH_4, 35428 NO_2 and 936033MT Particulate matter (CEC, 2011). On the basis of study on 600 coal and oil-fired electric power plants, United States environment protection agency revealed that, those power plants are emitting harmful pollutants including mercury, non-mercury metallic toxics, acid gases, and organic air toxics including dioxin and their percentage which contribute to the ambient air quality. In 2005, China's power plants also emitted 55% of SO_2 and 38% of NOx (Wang et al., 2011).

In 2010, power plant SO_2 and NOx emissions were both 68 percent lower than they were in 1990 (US EPA, 2012). In 2010, power plant CO_2 emissions were 24 percent higher than they were in 1990 Between 2009 and 2010, power plant CO_2 emissions increased by 5 percent, and total US greenhouse gas emissions increased by over 3 percent (US EPA, 2012). This increase is primarily due to economic growth resulting in increased energy consumption across all sectors, and much warmer summer conditions resulting in an increase in electricity demand for air conditioning that was generated primarily by combusting coal and natural gas. CO_2 emissions from power plants are largely unregulated at the federal level. There are

greenhouse gas permitting requirements for new or modified power plants and EPA has proposed national emissions standards for new fossil fuel-fired power plants; however, no standards have been proposed for existing facilities Preliminary data from 2011 indicate that CO_2emissions declined by about 5 percent in 2011 This is in large part due to a shift away from coal between 2010 and 2011 coal based electricity production fell by more than 6 percent. Power plants have only recently begun to report their mercury emissions; therefore, long-term emissions trends are not available (USeia, 2014). Although coal accounts for about 77% of CO_2emissions from the sector, it represents about 39% of the electricity generated in the United States. About 27% of electricity generated in 2013 was generated using natural gas, although this percentage decreased relative to 2012 (USeia, 2014). Petroleum accounts for less than 1% of electricity generation. The remaining generation comes from nuclear (about 19%) and renewable sources (about 13%), which includes hydroelectricity, biomass, wind, and solar (USeia, 2014).

In 2013, the electricity sector was the largest source of U.S. greenhouse gas emissions, accounting for about 31% of the U.S. total. Greenhouse gas emissions from electricity have increased by about 11% since 1990 as electricity demand has grown and fossil fuels have remained the dominant source for generation (USEPA, 2014). In 2014 77% of acid gases were emitted from power plants in USA. Figure 2.3 showing the percentage of air pollutants that have emitted from power plants in 2014.

2.6 Fuel Types in Power Generation Sector

The choice of fuel types of which technology to use and the type of power plant depend on many factors, such as purpose of the plant, capacity required and fuel availability. The fuel is one of the most important elements to needed to consider in terms of air pollutants emission. Table 2.2 shows the most common fuels used, by type of power plant. The relative proportion of pollutants emitted during the combustion of fossil fuels is shown in figure 2.4. In this figure, coal has been taken as a reference; therefore, for each pollutant, emissions from coal are given a value of 100%. Natural gas is said to be the "cleanest" of the three types of fossil fuels, due to the significantly lower emissions generated before the post-combustion control equipment. Emissions of NO_X are highly dependent on firing

configuration, type of burners, flame temperature and to some extent on the nitrogen content of the fuel, although NO_X is formed even when the fuel contains no nitrogen.

Table 2.2 Types of fuel using in power generation sector

Types of plant	Fuel
Steam	Coal/Natural Gas
Combined cycle	Natural Gas
Turbine	Natural gas/Diesel
Dual	Coal
Internal combustion	Diesel
Nuclear	Uranium

(Source: EEA, 2013)

In addition to the pollutants shown in Figure 2.3, there are other pollutants emitted by fossil fuel power stations, such as organic compounds that include volatile organic compounds (VOCs), semi-volatile organic compounds, and condensable organic compounds.
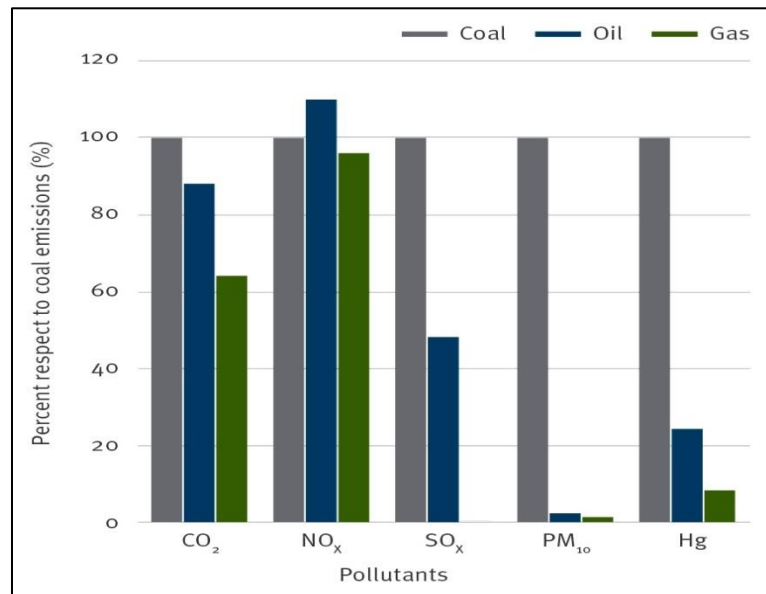
Figure 2.3 Comparative emissions of pollutants for different fuel in power generation (US EPA, 2015).

There are also emissions of some metallic compounds such as mercury and other greenhouse gases besides CO_2, such as methane and nitrous oxide; and some halogenated compounds. In 2014, the United States generated about 4,093 billion kilowatt-hours of electricity (US EPA, 2015). About 67% of the electricity generated was from fossil fuels such as coal, natural gas, and petroleum (US EPA, 2015).

2.7 Air Quality Index

The AQI is a tool for reporting daily air quality of any city or country. It provides information about how clean or polluted the air is, and what associated health effects might be a concern for public. The AQI focuses on health effects that one might experience within a few hours or days after breathing polluted air. The AQI value is a yardstick (Table 2.3) that runs from 0 to 300.The higher the AQI value, the greater the level of air pollution and the greater the health concern. For example, an AQI of 50 represents good air quality with little potential to affect public health, while an AQI value of 300 represents hazardous air quality.

An AQI value of 100 generally corresponds to the national air quality standard for the pollutant, which is the level that set by the mandated Environment Protection Agency (e.g., for Bangladesh Department of Environment) to protect public health. 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 main purpose of air quality index are Daily release of air quality conditions to the public, Convey the health implications of air quality, Protect public interest and take actions to reduce emissions and Forecast air pollution level.

In Bangladesh, the AQI is based on 5 criteria pollutants; Particulate Matter (PM_{10} and $PM_{2.5}$), NO_2, CO, SO_2 and Ozone (O_3). The Department of Environment (DoE) has also set national ambient air quality standards for these pollutants. These standards aim to protect against adverse human health impacts. The AQI standard for Bangladesh is given as under.

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Table 2.3 Approved Air Quality Index (AQI) for Bangladesh

Air quality index (AQI) Range	Category	Colour	Cautionary Statement
0-50	Good	Green	little potential to affect public health
51-100	Moderate	Yellow Green	Unusually sensitive individuals
101-150	Caution	Yellow	Identifiable groups at risk – different groups for different pollutants
151-200	Unhealthy	Orange	General public at risk; sensitive groups at greater risk
201-300	Very Unhealthy	Red	General public at greater risk; sensitive groups at greatest risk

(Source: CASE, 2015)

2.8 Air Quality Modeling

Air quality modeling uses mathematical equations, describing the atmosphere, dispersion and chemical and physical processes within the plume, to calculate concentrations at various locations (USEPA, 1996). Air pollution measurements provide information about ambient concentrations and deposition at specific locations and times, without giving clear guidance on the identification of the causes of the air quality problem. This makes air pollution models indispensable in regulatory, research, and forensic applications.

There have been various review papers on atmospheric modeling and their approaches to dispersion of pollutants (Vardoulakis et al., 2003) and comparisons between different models using test meteorological data (Ellis et al. 2001), these have focused on modeling gaseous dispersion. Unfortunately, only a few studies have simultaneously measured particle concentration with gases and the differences between the studies may be partially responsible for the differences observed. In open sites several studies have shown varying correlations between the concentrations of gases and particles. Monn et al. (1997) showed a poor correlation between the outdoor PM_{10} concentrations and NO_2 concentrations in an urban environment with a better correlation between PM2.5 and NO_2. Roorda-Knape et al. (1998)

observed that benzene, $PM_{2.5}$ and PM_{10} showed no significant decrease in concentration upto 300m from a major motorway. This was consistent with the small decrease in the $PM_{2.5}$ concentration observed by Hitchins et al. (2000). In that study the authors observed that particle number concentration decreased faster than NO_2 concentration from a motorway. Zhu et al. (2002) showed that number concentration of particles between 6 and 220nm correlated well with CO concentration from a motorway. All of these studies were made in an open environment where the wind direction was perpendicularly away from the road. However, differences have been observed between the local dispersion of gases and particles (Morawska 2003;Holmes et al. 2005). Simultaneous measurements of CO and particle number concentration showed that CO concentration was not significantly correlated to particle number concentration around the site and examination of between-site comparisons with the two pollutants showed different spatial and temporal trends. In another study of urban sites Harrison and Jones (2005) observed that particle concentrations correlated only weakly with NOx, with the highest correlation observed at a curbside monitoring location, where concentrations are less affected by dispersion. In addition, an examination of many urban studies (Morawska 2003) has shown that the vertical profiles of particle number concentration around buildings differed from that of gases. These studies differ from the previous studies in that they were conducted in a more complex environment where wind flows were heavily affected by turbulence and emissions were not limited to a single line source.

2.9 HYSPIT Dispersion Modeling

HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model developed jointly by National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) and Australian Bureau of Meteorology, is a computational tool designed to produce air parcel trajectories, and to carry out simulations on different spatial and time scales from local, regional and long-range transport, dispersion, and deposition of air pollutants (Stein et al. 2015).
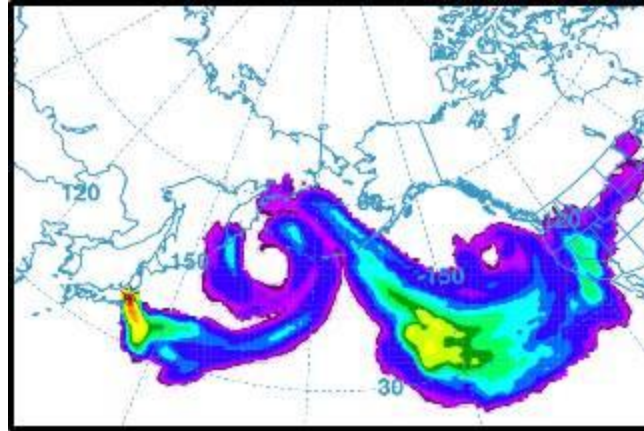
Figure 2.4 Dispersion of air pollutants from a point source developed by HYSPLIT (ARL, 2015)

Draxler (2006) used the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to predict transport and dispersion of trace plumes over Washington, DC. Myles et al. (2009) reported that sulfur and nitrogen oxides react in the atmosphere to form compounds which may be transported over long distances using HYSPLIT dispersion modeling. Challa et al. (2009) showed the mesoscale transport and dispersion of air pollutants in the Mississippi Gulf coastal region using HYSPLIT dispersion modeling.

2.9.1 Global Data Assimilation System (GDAS)

The Global Data Assimilation System (GDAS) is the system used by the National Center for Environmental Prediction (NCEP) Global Forecast System (GFS) model to place observations into a gridded model space for the purpose of starting, or initializing, weather forecasts with observed data. GDAS adds the following types of observations to a gridded, 3-D, model space: surface observations, balloon data, wind profiler data, aircraft reports, buoy observations, radar observations, and satellite observations. GDAS data are available through NCEI's NOAA National Operational Model Archive and Distribution System (NOMADS) as both input observations to GDAS and gridded output fields from GDAS. This system consists of a complex system of data analysis. It has spectral statistical interpolation (SSI) routine related to a three-dimensional variation analysis (3DVAR) (Parrish and Derber, 1992). In addition to SSI module, there are routines for decoding observation data, and

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quality controls based on the optimal interpolation (OI) and hydrostatic consistency check. Details for the GDAS are described in Kalnay et al. (1996). Gridded GDAS output data can be used to start the GFS model. Due to the diverse nature of the assimilated data types, input data are available in a variety of data formats, primarily Binary Universal Form for the Representation of meteorological data (BUFR) and Institute of Electrical and Electronics Engineers (IEEE) binary. The GDAS output is World Meteorological Organization (WMO) Gridded Binary (GRIB).

Table 2.4 Features of Global Data Assimilation System (GDAS)

Product	Grid/Scale	Period of record	Model cycle	Output time step	Data Access link
GDAS Snow, Ice, SST, Satellite, Ship, Aircraft (GRIB and BUFR)	1° by 1°, 0.5° by 0.5°,0.25° by 0.25°	01Jan2001– Present (approx. one year to present online)	4/day: 00, 06, 12, 18UTC	Anl, +00, +03, +06, +09 hours	FTP, HTTP
GDAS –Daily Tar File	1° by 1°	01Jan2001– 21Feb2012	4/day: 00, 06, 12,18UTC	Anl, +00, +03, +06, +09 hours	HAS
GDAS - Hourly Tar Files	1° by 1°, 0.5° by 0.5°,0.25° by 0.25°	13Feb2012– Present	4/day: 00, 06, 12, 18UTC	4/day: 00, 06, 12, 18UTC	HAS
GDAS - Daily BUFR Files	1° by 1°, 0.5° by 0.5°,0.25° by 0.25°	13Feb2012– Present	4/day: 00, 06, 12, 18UTC		HAS

2.9.2 *Back trajectory modeling*

Back-trajectory calculations have been one of the most attractive and prominent features by which HYSPLIT has been used in many studies (Fleming et al., 2012). Although trajectories offer a simple assessment of source–receptor relationships, a single trajectory cannot adequately represent the turbulent mixing processes that air parcels experience during transport. However, coupling the back-trajectory calculation with a Lagrangian dispersion component can produce a more realistic depiction of the link between the concentrations at the receptor and the sources influencing it (Lin et al. 2003).
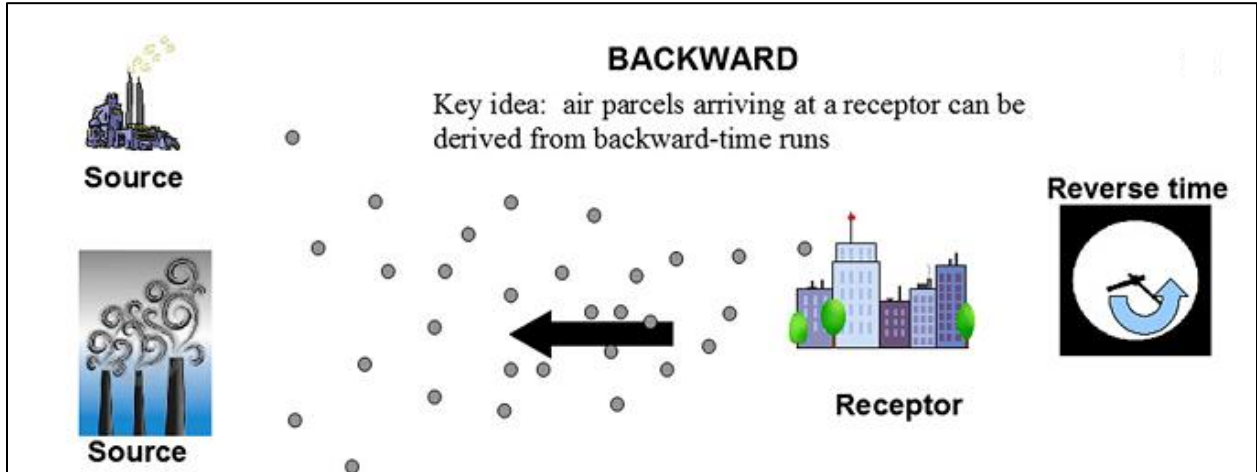
Figure 2.5 Backward-time stochastic Lagrangian particle simulated to describe atmospheric transport (Fleming et al., 2012)

Under this approach, the increasingly wider distribution of Lagrangian particles or puffs released from a receptor undergoing backward in time transport and dispersion represents the geographical extent and strength of potential sources influencing the location of interest. Nevertheless, this particular model application must satisfy the well-mixed criteria, include appropriate representation of the interaction between the wind shear and vertical turbulence (Lin et al., 2003). Ceballos et al. (2013) used HYSPLIT trajectory model to detect the source areas and calculate transport dynamics for airborne olive pollen observed in the city of Co´rdoba, southwest of Iberian Peninsula, Bella et al. (2015) characterized the pollution transport into Texas using HYSPLIT back trajectory model.

2.9.3 Limitation of HYSPLIT

Hence HYSPLIT simulate long range dispersion of air mass, it has some limitation. HYSPLIT do not consider the secondary chemical reactions, dense gases, byproducts from fires, explosions, or chemical reactions of gases released that are not neutrally-bouyant. HYSPLIT do not calculate deposition unless the user enters appropriate wet and dry deposition parameters and particulate transport unless the user enters information about the

particle (size, deposition rates, etc), at the varying emission rate with time (except for Controlled Burn simulation), varying emission rate with height HYSPLIT is unable to run.

2.9.4 Other considerations of HYSPLIT

HYSPLIT's minimum time step is 1 minute, so the model cannot be used for transport less than the distance it takes for the pollutant to move in 1 minute. However, keep in mind that the meteorology may not adequately represent the transport/dispersion at the point of release regardless of the model time step. For scales less than 1 km the CAMEO/ALOHA model is recommended.

For ground-based hazardous material releases, near-surface meteorological conditions, including the 10-meter winds, 2-m temperatures, and surface fluxes (which determine the stability and thus the vertical dispersion of material) are important determinants of the horizontal and vertical spread of the material. Numerical weather prediction (NWP) forecasts of these meteorological variables are inputs to the HYSPLIT model, but the NWP models are limited in a number of ways in their representation and forecast of near-surface conditions. Frequently, the meteorological forecast data available to run HYSPLIT has been spatially averaged, resulting in representativeness problems for modeling dispersion in, for example, areas of complex terrain.

Meteorological data used to force HYSPLIT is available at relatively coarse temporal resolution (1-6 hours), which can result in errors in rapidly changing conditions, even if the NWP model itself can faithfully emulate these conditions. NWP models also have limitations in their ability to accurately forecast the onset and spatial scales of phenomena that may affect dispersion, such as sea-breezes and mountain-valley circulations.

Finally, the meteorological data used by HYSPLIT is bi-linearly interpolated in space and linearly interpolated in time to the location and time of a pollutant release and during the forecast of the subsequent diffusion of materials. If important variations in the

meteorological fields occur between grid points or between meteorological data output times, concentrations errors may result.

2.9.5 Gaussian plume Distribution Model

The basic "Gaussian Model" which is included in typical air pollution courses is outlined below. Atmospheric dispersion of air pollutants from a point source is typically depicted in Figure 2.6. This model predicts an average concentration under steady state condition.
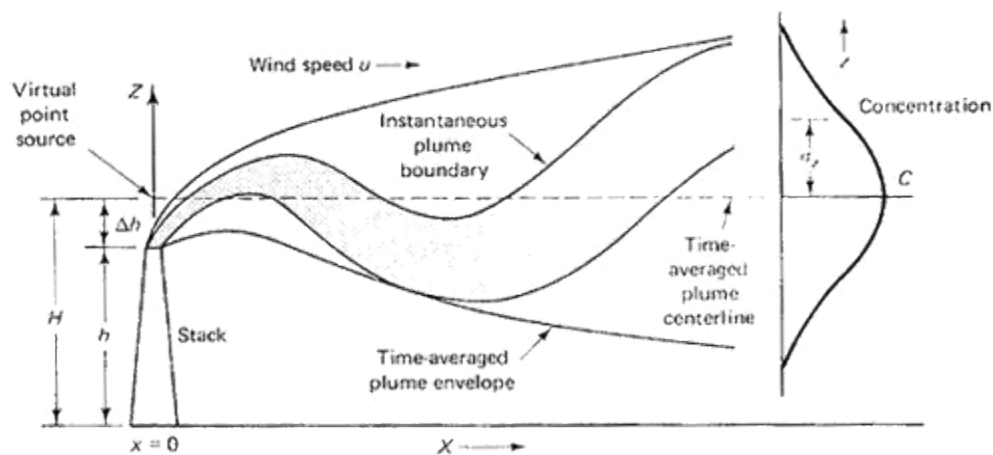
Figure 2.6 Plume Boundary and Time Averaged Envelope (Carl, 2013)

The coordinate systems in all teaching modules described in this chapter use coordinate systems as shown in Figure 2.7. The shape of the plume undergoing dispersion is a function of the wind speed, vertical temperature profile and atmospheric stability. These functional relationships are discussed in details in most textbooks adopted for air pollution courses.
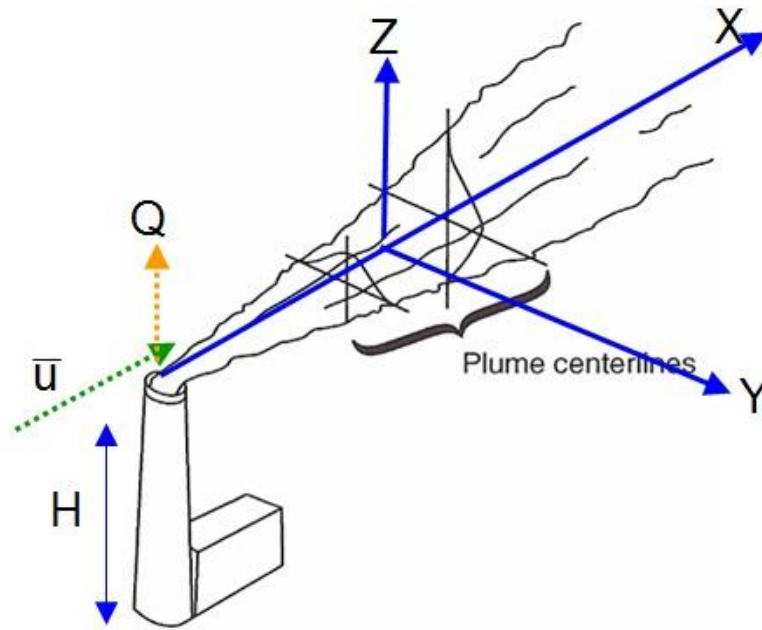
Figure 2.7 Plume Dispersion by Gaussian distribution and Coordinate System (Carl, 2013)

The general equation to calculate the steady state concentration of an air contaminant in the ambient air resulting from a point source is given by:

$$C(x, y, z) = \frac{Q}{2\pi u \ \sigma_y \sigma_z} \cdot \exp\left(\frac{-y^2}{2\sigma_y^2}\right) \cdot \left\{ \exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right] \right\}$$

where

$c(x,y,z)$ = contaminant concentration at the specified coordinate [ML^{-3}],

x = downwind distance [L],

y = crosswind distance [L],

z = vertical distance above ground [L],

Q = contaminant emission rate [MT^{-1}],

σ_y = lateral dispersion coefficient function [L],

σ_z = vertical dispersion coefficient function [L],

u = wind velocity in downwind direction [L T^{-1}],

H = effective stack height [L].

2.10 Health effects of Air pollution

2.10.1 Mortality due to air pollution

"Epidemiological studies suggest that more than 500,000 Americans die each year from cardiopulmonary disease linked to breathing fine particle air pollution" A study by the University of Birmingham has shown a strong correlation between pneumonia related deaths and air pollution from motor vehicles. Worldwide more deaths per year are linked to air pollution than to automobile accidents. A 2005 study by the European Commission calculated that air pollution reduces life expectancy by an average of almost nine months across the European Union. Causes of deaths include aggravated asthma, emphysema, lung and heart diseases, and respiratory allergies. The US EPA estimates that a proposed set of changes in diesel engine technology could result in 12,000 fewer premature mortalities, 15,000 fewer heart attacks, 6,000 fewer emergency room visits by children with asthma, and 8,900 fewer respiratory-related hospital admissions each year in the United States. The US EPA estimates allowing a ground-level ozone concentration of 65 parts per billion, would avert 1,700 to 5,100 premature deaths nationwide in 2020 compared with the current 75-ppb standard. The agency projects the stricter standard would also prevent an additional 26,000 cases of aggravated asthma and more than a million cases of missed work or school. The worst short term civilian pollution crisis in India was the 1984 Bhopal Disaster. Leaked industrial vapors from the Union Carbide factory, belonging to Union Carbide, Inc., killed more than 23,000 people outright and injured anywhere from 150,000 to 600,000. The United Kingdom suffered its worst air pollution event when the December 4 Great Smog of 1952 formed over London. In six days more than 4,000 died, and 8,000 more died within the following months.

An accidental leak of anthrax spores from a biological warfare laboratory in the former USSR in 1979 near Sverdlovsk is believed to have been the cause of hundreds of civilian deaths. The worst single incident of air pollution to occur in the US occurred in Donora, Pennsylvania in late October, 1948, when 20 people died and over 7,000 were injured. A new economic study of the health impacts and associated costs of air pollution in the Los Angeles Basin and San Joaquin Valley of Southern California shows that more than 3800 people die

prematurely (approximately 14 years earlier than normal) each year because air pollution levels violate federal standards. The number of annual premature deaths is considerably higher than the fatalities related to auto collisions in the same area, which average fewer than 2,000 per year. Effects on cardiovascular health: A 2007 review of evidence found ambient air pollution exposure is a risk factor correlating with increased total mortality from cardiovascular events (range: 12% to 14% per a 10 $\mu g/m^3$ increase). Air pollution is also emerging as a risk factor for stroke, particularly in developing countries where pollutant levels are highest. A 2007 study found that in women air pollution is associated not with hemorrhagic but with ischemic stroke. Air pollution was also found to be associated with increased incidence and mortality from coronary stroke in a cohort study in 2011. According to a estimates made by researchers from King's College London, almost 9,500 people in London alone died prematurely in 2010 due to pollution - 3,537 from the effects of nitrogen dioxide (NO_2), which is expelled by engines and power stations, and 5,879 from $PM_{2.5}$ (WHO, 2016)

2.10.2 Health impact of SO_2

The SO_2 is hygroscopic, when it is in the atmosphere it reacts with humidity and forms sulphuric and sulphurous aerosol acid that is later part of the so-called acid rain. The intensity in the formation of aerosols and the permanence of them in the atmosphere depend on the meteorological conditions and the quantity of catalytic impurities (substances that accelerate the processes) present in the air. But in general, the average time of permanence in the atmosphere is around 3-5 days, so it can transport long distance. The air pollution by SO_2 has the following effects on human beings are Corneal haze, Breathing difficulty, Airways inflammation, Eye irritation, Psychic alterations., Pulmonary oedema., Heart failure and Circulatory collapse

Sulphur dioxide is also associated with asthma, chronic bronchitis, morbidity and mortality increase in old people and infants. Sulfur is high noxious venom for people's health, although we can be more resistant than other creatures that live with us. For example, the level of 0.3 µg per cubic meter of air implies a potential risk for human health, but for trees, 0,2 µg is

extremely dangerous. Because of that, sulfur oxides (SOx) and sulfuric acid (H_2SO_4) are related with the damage and destruction of vegetation, soil deterioration, construction material and watercourses.

Several clinical studies reported signs and symptoms as observations concurrent to investigation of other effects. Healthy subjects reported nose and throat irritation, taste and odor complaints, and discomfort during single exposures (15 and 28 ppm for 10 minutes or less than 1 ppm for 40 minutes) as well as during multiple exposures (1 ppm for 4 hours/day, 3 days/week for 3 weeks and 1 to 25 ppm for 6 hours/day for 3 consecutive days). Some coughing was observed in the healthy subjects during forced mouth breathing.

2.10.3 Health impact of NOx

Exposure to high industrial levels of nitric oxide and nitrogen dioxide can cause death. It 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.

Industrial exposure to nitrogen dioxide may cause genetic mutations, damage a developing fetus, and decrease fertility in women. Repeated exposure to high levels of nitrogen dioxide may lead to permanent lung damage. Industrial exposure to nitric oxide can cause unconsciousness, vomiting, mental confusion, and damage to the teeth. Industrial skin or eye contact with high concentrations of nitrogen oxide gases or nitrogen dioxide liquid can cause serious burns. Long-term exposure to nitrogen oxides in smog can trigger serious respiratory problems, including damage to lung tissue and reduction in lung function. Exposure to low levels of nitrogen oxides in smog can irritate the eyes, nose, throat, and lungs. It can cause coughing, shortness of breath, fatigue, and nausea.

CHAPTER 3

RESEARCH METHODS

3.1 General

This chapter presents the research method that has been employed in this study to accomplish the research objectives as reported in section 1.3. This chapter describes the methods of chemical content test, functional group analysis, calorific value determination of Heavy Fuel Oil (HFO) used in KPCL plant. The emission estimation technique and HYSPLIT dispersion modeling in addition to the health risk assessment are also described here.

3.2 Study Location

Khulna the south-western divisional city in Bangladesh situated between 21.38^o north altitude and 88.58^o east longitude (Figure 3.1). In Khulna, Southerly wind blows from the Bay of Bengal during monsoon and Northwesterly wind from Himalayas during winter. Khulna's climate is classified as tropical. The summers here have moderate rainfall, while the winters have very little. The yearly average wind rose suggests that wind prevails flowing from south to north direction in most of the time in a year. During November to February, maximum prevailing wind flows from north and north-west to south and southeast direction. During March to April wind mostly flows from south and southwest to north and northeast, and during May to October it flows from south to north and southeast to northwest direction (Weather and Climate , 2015)

Khulna Power Company limited (KPCL), 225 MW Barge mounted power plant (Figure 3.2), is selected for this study for the assessment of atmospheric emissions and dispersion of air pollutants.   KPCL is located at Goalpara, Khalishpur, Khulna (Lat- 22.865370N, Long-89.536345E). In KPCL-I, two floating barges named Tiger I and Tiger II.
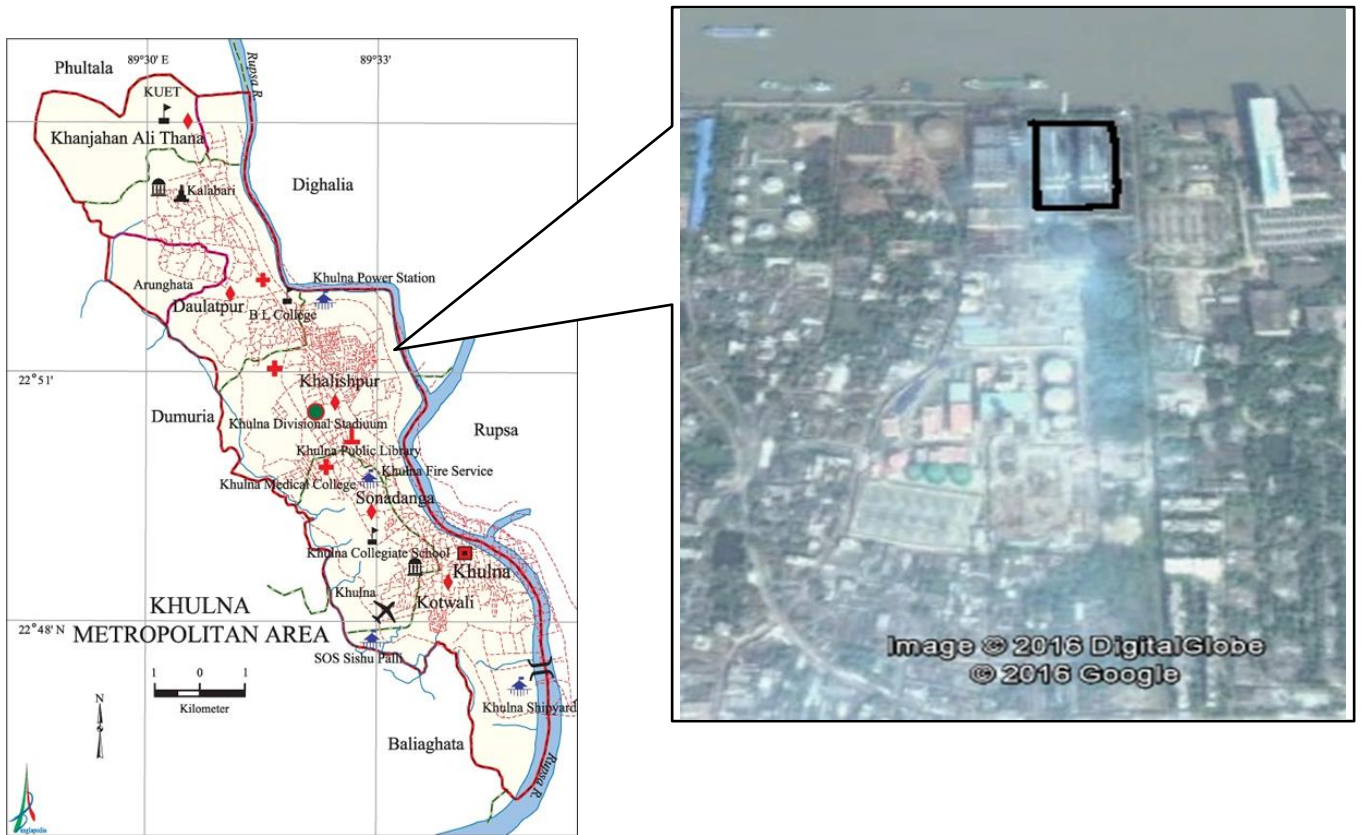
Figure 3.1 Study area (Khulna Metropolitan area)

Figure 3.2 Khulna Power Company limited (KPCL)

These two barge-mounted plants are connected to the national grid. The plant consumes about 600 MT of Heavy Fuel Oil (HFO) daily to generate 110 MW power by the 19 generators on the two barges. The barges shipped as deck cargo on submersible dry tow ship, are moored in a closed basin. Each barge is approximately 91 meters long and 24 meters wide. Generating Plants are 19 X Wartsila 18V32 DG Sets. Khulna Power Company Unit II Ltd. (KPCL-II) -115 MW Capacity which is Land based plant. Generating Plants are 7 X Wartsila 18V46 DG Sets and HFO based plant (KPCL, 2014)

3.3 Characterization of Heavy Fuel oil

The analysis of HFO used in KPCL plant was performed to characterize the HFO to have baseline data for emission estimation and quantification of dispersed pollutants concentration and deposition   generating from KPCL plant.

3.3.1 HFO sample collection

For the analysis of fuel oil used in KPCL, the fuel sample was collected from KPCL area (Figure 3.3). A typical HFO have a density, ρ=990 kg/m^3, high heating value= 43 MJ/kg, and the flash-point at 360-380 ℃. A typical HFO have a composition of 88% C, 10% H, 1% S, 0.5% H_2O, 0.1% ash by weight and may contain dispersed solid or semi-solid particles (asphaltenes, minerals and other leftovers from the oil source, metallic particles from the refinery equipment, and some dumped chemical wastes), plus some 0.5% water. HFO leaves a carbonaceous residue in the tanks, and may have up to 5% of sulfur (Energy.gov, 2015)

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Figure 3.3 Heavy fuel oil (HFO)

3.3.2 C,H,N,S,O Determination

The purpose of CHNSO determination is to estimate the air pollutants generating from KPCL using HFO and to calculate the calorific value in addition to the derivation of chemical formula. After collecting HFO samples, Carbon (C), Hydrogen (H), Nitrogen (N), Sulfur (S) and Oxygen (O) was determined from Bangladesh Council for Science and Industrial Research (BCSIR) to investigate the chemical composition of HFO. This analysis was carried out using CHNS/O analyzer.

3.3.3 Determination of Calorific Value

The calorific value of HFO is used for the activity rate calculation (Appendix C-2) of air pollutants emission estimation. The laboratory test for calorific value of HFO was performed in the Heat Engine Laboratory of Mechanical Engineering Department of Khulna University of Engineering and technology (KUET), Bangladesh. The calorific value of HFO was determined using oxygen bomb calorimeter.

Equipment:

1) Mass balance
2) Thermometer
3) Oxygen bomb calorimeter

Procedure

1 gm of fuel sample (Figuure 3.4) is accurately weighed into the crucible and a fuse wire (whose length is known) is stretched between the electrodes (Figure 3.5). It should be ensured that wire is in close contact with the fuel. To absorb the combustion products of sulfur and nitrogen 2 ml of water is poured in the bomb. Bomb is then supplied with pure oxygen through the valve (Figure 3.6). The bomb is then placed in the weighed quantity of water, in the calorimeter. The stirring is started after making necessary electrical connections, and when the thermometer indicates a steady temperature fuel is fired and temperature readings are recorded after 30 seconds intervals until maximum temperature is attained (Figure 3.7). The bomb is then removed; the pressure slowly released through the exhaust valve and the contents of the bomb are carefully weighed for further analysis. The heat released by the fuel on combustion is absorbed by the surrounding water and the calorimeter.

The generalized equation for calorific value determination using Oxygen bomb calorimeter

$$CX + C_1X_1 = (M+W)(\Delta\Theta + 0.5\Delta t\ r^o) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where,

C = calorific value of fuel oil (Kcal/kg)

X = Mass of fuel burnt, (gm)

C_1 = Calorific value of the fuse weir burnt (2.79 cal/cm)

X_1 = Length of fuse weir burnt (cm)

M = mass of water contained in the calorimeter, (mL)

$\Theta 1$ = Steady temperature before the combustion, (^{o}C)

$\Theta 2$ = Observed maximum temperature after the combustion, (^{o}C

$\Theta = \Theta 2 - \Theta 1$ = observed rise in temperature (^{o}C)

W = Water equivalent (206 g/^{o}C) of the oxygen bomb calorimeter

Δt = time elapsed to maximum temperature to reach

r^o = Time rate of the temperature drop after the maximum temperature was reached

Figure 3.4 Weighting of sample

Figure 3.5 Connecting fuse weir with bomb

Figure 3.6 Oxygen supplying to the Bomb

Figure 3.7 Final setting of Oxygen bomb calorimeter

3.3.4 Modified Dulong's Formula for Calorific value

Calorific value of HFO measured in the laboratory test was compared with the estimated calorific value using Modified Dulong's formula. Modified Dulong's formula is widely used for estimating calorific value which was derived from the heat liberated by the combustion of one pound of oil composed of carbon, hydrogen, oxygen and sulfur. The Modified Dulong's Formula is shown as below:

Energy content of fuel, MJ/kg $= 337C + 1419 (H_2 - 0.125O_2) + 93\ S + 23.26N$

where, C is the % carbon, H_2 is % hydrogen, O_2 is the % oxygen, S is the % sulfur and N is the % nitrogen,

3.3.5 Functional Group Analysis

Functional group analysis was performed to identify the presence of functional groups related to the air pollutants emission from KPCL. Functional analysis of HFO was performed by Fourier Transfer Infra-Red (FTIR) test which is a preferred method where IR radiation is passed through sample. Some portion of IR radiation is absorbed by the sample and the rest is transmitted through the sample. The resulting spectrum represents the molecular absorption and transmission, creating a molecular fingerprint of the sample. In this study, the spectrum of heavy fuel oil (HFO) was measured using Perkin- Elmer FT-IR system, Spectrum GX. The spectra were recorded from 4000 to 500 cm^{-1} with a resolution of 4 cm^{-1}.

3.3.6 Chemical Formula Derivation of HFO

Chemical formula for HFO was derived from C, H, S, N and O content using the following steps:

1) First the mass of individual component was derived.
2) Molar composition of individual component was computed and
3) Finally the molar ratio of components was computed to derive the chemical formula for HFO.

3.3.7 Combustion analysis of HFO

Combustion analysis of HFO was performed in the Transportation Engineering laboratory of Civil Engineering Department at KUET. The test was performed using HFO sample (79 g) and the concentration of SO_2 and NO_X were recorded by industrial combustion gas analyzer (Figure 3.9). The temperatures were also recorded 5 minutes interval during the entire combustion analysis. In this analysis the sample of HFO was combusted using cup combustion heater (Figure 3.8) and the flue of combusted HFO was emitted through a funnel. To measure gas concentration, probe of combustion gas analyzer was inserted into the exhaust flue and exhaust gas temperature is measured using a thermometer positioned to measure the highest exhaust gas temperature. The concentration of SO_2 and NO_X were directly measure by analyzer.

Figure 3.8 Combustion process set up

Figure 3.9 Industrial combustion gas analyzer

3.4 Emission Estimation of Air Pollutants

The emission estimation technique (EET) is applied in this study to estimate the air pollutants emission from KPCL following the emission estimation technique manual for fossil fuel electric power generation published by EPA Australia (2012). Air pollutants emission from KPCL was estimated using following equation:

$$E_{kpy,i} = AR \times EF_i \times [1 - (CE_i/100)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.2)$$

where

$E_{kpy,i}$ = emission rate of pollutant i, kg/yr

AR = activity rate (fuel use), t/yr

Ophrs = operating hours, hr/yr

EF_i = uncontrolled emission factor of pollutant i, kg/t

CE_i = overall control efficiency for pollutant i, %.

Emission factors (Appendix A) can be considered based on either fuel consumption data (kg/ton of fuel consumed) or energy consumption data (kg/PJ or ton/PJ of energy input). The emission factor method used in this study is based on energy consumption data using the following equation:

Energy = [fuel consumption (tones/year) x heating value (MJ/kg)]/10^6 consumption (PJ/year)………………………………………………………………………………(3.3)

Emission factors are developed from considering alternative fuel types and combustion processes which are independent to the location of power plant and can be applied in the case study of Bangladesh. For this study the emission factors were taken for residual fuel in generator based power generation. The KPCL plant consumes about 1200 MT of Heavy Fuel Oil daily to generate 225 MW power by the 19 generators on the two barges in plant -I and by 7 generators in plant-II (KPCL fundamental, 2015).

3.5 HYSPLIT Modeling

3.5.1 Dispersion Modeling

HYSPLIT dispersion modeling using archived meteorology was developed and the average concentration of SO_2 and NOx were simulated and compared with the local available air quality data to find out the contribution of KPCL to the ambient air quality. The month of September 2013 was selected for the availability of air quality monitoring data of SO_2 and NOx from Khulna station (CASE, 2015). HYSPLIT dispersion modeling in the period from November 2014 to February 2015 was also performed to determine the spatial and temporal distribution of SO_2 and NOx. The Dispersion modeling period of November 2014 to February 2015 was selected because of winter season having more stable wind speed with lower velocity than other seasons which can provide the maximum pollutants concentration in addition to availability of air quality monitoring data. During this period the wind mostly moves towards the south, south-west and south-east direction. The distribution of pollutants plume over Sundarbans was also shown. The important input parameters are as below:

Release type- Long duration

Source location - 22.865370 N   89.536345E

Stack height – 30m

Meteorology – GDAS

Dispersion direction - Forward

Release quantity – Emission from power generation

Release duration- 72 hours

Averaging period – 24 hours

Pollutant characteristic – Gas

Top of Averaged layer – 100m

Dispersion modeling was run in forward mode for the source location of KPCL (Lat-22.865370 N, Lon- 89.536345 E) using archived meteorology of GDAS (1 Degree, global, 2006-present). The GDAS archive is a latitude/longitude global grid with a resolution of 1

degree, is a weekly one-degree, pressure-level, Global Data Assimilation System (GDAS) model output (ARL's GDAS archive). Dispersion simulation is done over a range of 200 km around the sources. A horizontal grid of $0.02° \times 0.02°$ with resolution of $0.02° \times 0.02°$ (roughly 2×2 km) and with 30m above ground level is considered in HYSPLIT dispersion model. Pollutant concentrations are sampled every time step and averaged over every 24 hour. Averaging period indicate the sampling interval of pollutants concentration. The dispersion calculations were made for SO_2 and NO_X. The plume is treated as top-hat puffs in the horizontal. In dispersion modeling main dominating parameters are emission rate, averaging period and meteorological data such as wind direction, and wind speed. All the meteorological factors are assimilated in GDAS. GDAS meteorological data file was validated by constructing the windroses from HYSPLIT and with the regional meteorological data collected from air quality monitoring data by CASE study.

3.5.2 HYSPLIT Back Trajectory Model

Contribution of long range transported pollutants from outer region to the source location was also analyzed using HYSPLIT Archive backward trajectory modeling. In this study, back trajectory models were developed as the period of dispersion model period with the trajectory interval of 12 hours. From this back trajectory modeling the contribution air pollution from other country to the source location will be identified.

3.5.3 Validation of HYSPLIT Meteorology Data

The HYSPLIT particle dispersion model was widely used for dispersion modeling (Connen et al., 2013) which has been validated elsewhere (Wang et al. 2009a, 2009b). In this study the validation of meteorological data file used in HYSPLIT was done by developing windrose from regional air quality data and another from HYSPLIT. If both windroses assimilate nearly same direction then it would be the validation HYSPLIT meteorological data file.

3.6 Air Quality Index Calculation

AQI index value for this study was calculated for ambient concentration of SO_2 and NO_X to check the ambient air quality for these two air pollutants. Air quality index (AQI) is used by government agencies to communicate to the public how polluted the air currently is or how polluted it can become. As the AQI increases, an increasingly large percentage of the population is likely to experience increasingly severe adverse health effects. AQI values are derived from air quality data readings, which allows for more meaningful comparison of pollutants affecting air quality. The index is derived using the following formula:

$$AQI = \frac{Pollutants\ Data\ Reading}{Standard\ Limit} \times 100 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(3.4)$$

3.7 Health Risk Calculation

The effect of air pollution for the exposure of ambient pollutants concentration and exposure due to KPCL emission was calculated in terms of Disability Adjusted Life Years (DALYs). DALY is the sum of years of potential life lost due to premature mortality and the years of productive life lost due to disability. DALY due to the environment pollution is termed as Environmental Burden of Disease (EBD). Here the EBD for the pollutants exposure is the portion of total national DALYs for outdoor air pollution which is contributed by the specific pollutant for specific disease. WHO provides necessary formula to calculate the EBD in case of indoor air pollution as well as outdoor air pollution.

The calculation of environmental burden of disease (EBD) in DALYs was based on the formula

$$EBD\ (in\ DALYs) = PAF* BoD \dots\dots\dots\dots\dots\dots\dots\dots\dots..(3.5)$$

Where, PAF is size of the population attributable risk (proportion of the population exposed to Pollutants concentration). This value is calculated based on the relationship given below (equation- 3.4)

$$PAF = f. (RR-1)/ f.(RR -1)+1 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.6)$$

Where f is the conventional exposure unit and is 1 $\mu g/m^3$ and RR means the health risk arising in response to an increase in the concentration of SO_2 and NOx on a conventional unit of 1 $\mu g/m^{3.}$ According to the WHO methodology the value of RR should be calculated from the formula

$$RR = \exp [\text{ß} (X-Xo)] \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.7)$$

Where ß is the pollutant concentration response limit function (Appendix A-7), X is the annual average concentration in $\mu g/m^3$, Xo is the baseline concentration in $\mu g/m^3$.

For this Study the value of EBD in terms of DALYs were calculated for both ambient concentration of SO_2 and NO_X exposure and for the concentration of SO_2 and NO_X contributed by the KPCL emission. The baseline concentrations were selected as average concentrations for ambient and KPCL emission. All the ambient concentrations of baseline and annual average were collected from air quality monitoring station data of CASE study.

CHAPTER 4

CHARACTERISTICS OF HEAVY FUEL OIL AND ESTIMATION OF AIR POLLUTANTS FROM KPCL

4.1 General

This chapter describes the chemical composition, calorific value and FTIR anlysis of HFO using in KPCL plant. The estimated emission of pollutants from KPCL are also descrbed in this chapter.

4.2 Charaterization of Heavy Fuel Oil

The characterization of HFO was performed by determining the C,H,S,O,N content, energy content, FTIR, and combustion analysis.

4.2.1 Chemical Composition of Fuel

Heavy Fuel Oil (HFO) is the residue of crude oil distillation that still flows (the quasi-solid residue is asphalt); waste oil from other industries are often added. It is the fuel used in large marine vessels because of price (about half the price of distillates).

HFO using in power generation contains C (83.42%), H (10.02%), %S (0.7%), O (0.05%) and N (0.1%) by weight. At present the consumption of coal in power generation is increasing rapidly. Coal can contain up to 10% sulfur by weight, although values of 1-4% are more typical depending on the region where the coal was extracted (Engineering toolbox, 2015). In this regard the selection of HFO as fuel is more environment friendly in case of SO_2 emission. The chemical formula for HFO was derived as $C_{2230}H_{3211}S_7N_{2.5}O$

Table 4.1 Chemical composition of HFO using in KPCL

Test Parameters	C	H	N	S	O
Content (w/w%)	83.42	10.02	0.11	0.7	0.05

4.2.2 Calorific Value

Calorific value of HFO used in KPCL was determined by oxygen bomb calorimeter and estimate using the Dulong's formula. Table 4.2 shows the calorific value of tested sample of HFO using oxygen bomb calorimeter. The calorific value for funace oil were obtained 17.7662 MJ/kg and 17.7594 MJ/kg. From this test it was obtained that the fuel using in power genration is of low calorific value. As the the heavy fuel oil is resudual oil thus this lower calorific value indicates that the fuel oil is containing contaminants. The major contaminats of HFO can be water, sodium, sediment, alumina, sludge, fibers and oxidation products (American Bureau of Shipping, 2001). Inspite of having lower calorific value heavy fuel oil is using around 21.39% power plants in Bangladesh because of its higher storagability than coal and natural gas. In addition, Calorific value of HFO from laboratory test was comaperd with the calorific value estimated by modified Dulong's equation. The estimated value was 18.415 MJ/ kg which was close to the determined value using oxygen bomb calorimeter.

Table 4.2 Energy content of Heavy Fuel oil

Sample ID	Sample-I	Sample-II	Average
Calorific value (MJ/ kg)	17.7662	17.7594	17.7628

4.2.3 Functional Group Analysis

The spectrum of heavy fuel oil was measured by a Perkin- Elmer FT-IR system, Spectrum GX. The spectra were recorded from 4000 to 500 cm^{-1} with a resolution of 4 cm^{-1}. Figure 4.1 shows the FTIR scans of HFO. Table 4.3 and Table 4.4 represents the FTIR analysis of

furnace oil. The interpretation of spectra was limited to the selected organic absorbence group as mentioned below.
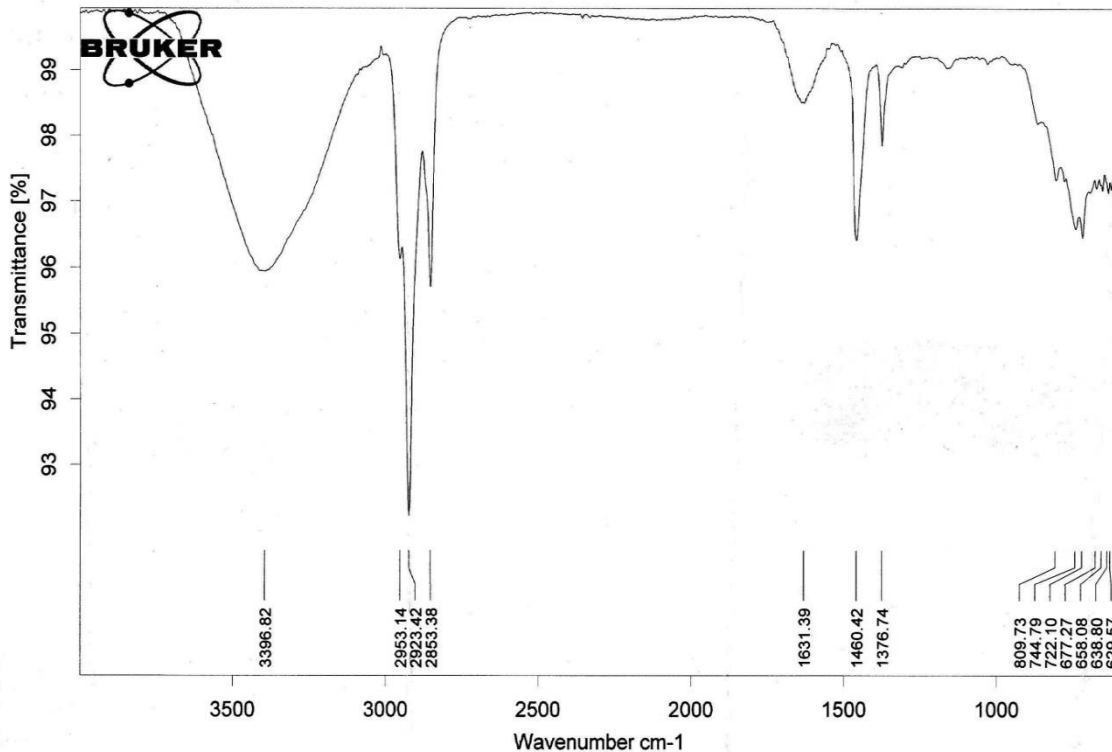
Figure 4.1 FTIR analysis of heavy Fuel oil using in power generation in KPCL

The characteristic IR spectra of aliphatic carbon bonds occur in the region of 2850-3000cm^{-1}. The aliphatic carbon molecules can constitute of –CH$_3$, -CH$_2$, and –Chcarbon bonds which may include n-alkines, branched alkanes, carbonylcontaining molecules, alkanes and arometics aliphatics substituents. The absorption at 2853 and 2923 cm^{-1} are attributed to –CH$_2$ assimetric vibration. Hydroxyl group of alchohol and phenols mainly occures at 3250-3650 cm-^{1} absorption range. Amino group can occur in different vibration from 3300-3500, 1550-1650, 660-900 cm^{-1}.

Table 4.3 The FTIR analysis of HFO

Pick (cm^{-1})	Intensity	Nature of peak	Range (cm^{-1})	Functional class	Assignment
629.57	Wk	Narrow	600-700	Alkenes	C-H deformation
638.80	Wk	Narrow	600-700	Alkenes	C-H deformation
658.08	Wk	Narrow	600-700	Alkenes	C-H deformation
677.27	Wk	Narrow	600-700	Alkenes	C-H deformation
722.10	Wk	Narrow	700-900	esters	S-OR
744.79	Wk	Narrow	700-900	esters	S-OR
809.73	Wk	Narrow	700-900	esters	S-OR
1376.74	med	Narrow	1330-1430	sulphate	S=O
1460.42	Str	Narrow	1350-1470	Alkenes	CH$_2$ & CH$_3$ deformation
1631.39	med	Broad	1590-1650	Amines	N-H (1i-amide)II bands
2853.38	wk	Narrow	2500-3300	Carboxylic acid & Derivatives	O-H (very broad)
2923.42	Str	Narrow	2500-3300	Carboxylic acid & Derivatives	O-H (very broad)
2953.14	Str	Narrow	2500-3300	Carboxylic acid & Derivatives	O-H (very broad)
3396.82	med	Broad	3200-3550	Alchohols & phenols	O-H (H-bonded) usually broad

Table 4.4 Organic functional Group of HFO

Functionality		Absorption Frequencies (cm-1)	Observed peaks	Presence
-CH	Aliphatic Carbon	2850-3000	2923.42	
			2953.14	Yes
-OH	Hydroxyl	3250-3650		
		1400-1450	3396.82	Yes
		1000-1050		
-NH	Amino	3300-3500	3396.82	
		1550-1650	1631.39	Yes
		660-900	809.73	

The spectrum analysis of HFO shows that it contains Alkenes of C-H, CH_2 & CH_3 deformation, esters (S-OR), sulphate (S=O), Amines (N-H) and Hydroxil (-OH) bonds. The presemce of these bonds ensure that the gassous pollutants emmited from HFO oil burning will contain the sulfur, nitrogen, carbon, hydrogen and oxygen.

4.2.4 Combustion Analysis of HFO

Emissions from fuel oil combustion depend on the grade and composition of the fuel, the type and size of the boiler, the firing and loading practices used, and the level of equipment maintenance. Because the combustion characteristics of distillate and residual oils are different, their combustion can produce significantly different emissions. Sulfur oxides (SOx) emissions are generated during oil combustion from the oxidation of sulfur contained in the fuel and Oxides of nitrogen (NOx) formed in combustion processes are due either to thermal fixation of atmospheric nitrogen in the combustion air, or to the conversion of chemically bound nitrogen in the fuel. The air pollutants (SO_2 and NO_X) concentration was recorded by the industrial combustion gas analyzer (Table A-6) The concentrations of SO_2 and NO_X were plotted with time (Figure 4.2). For first 30 minutes the concentration of SO_2 was not observed and the concentration of NOx was about $2mg/m^3$. After 35 minutes the concentration started to increase and reached the maximum concentration of SO_2 and NO_X of $443mg/m^3$ and $209mg/m^3$, respectively after 55 minutes.
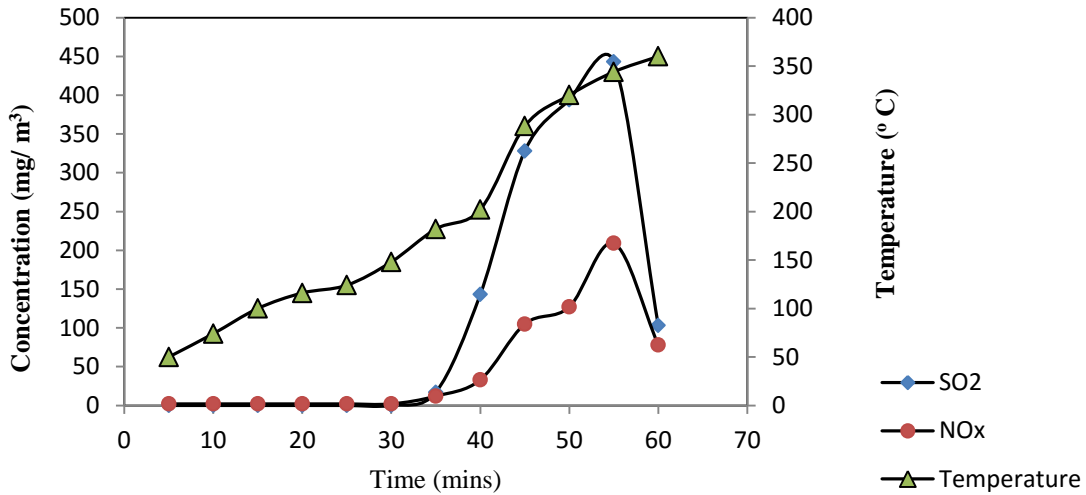
Figure 4.2 Combustion analysis of HFO

From this combustion analysis it can be conclude that the concentration at the combustion point was found very high which can have negative impact on human health and environment.

4.3 Emission Estimation from KPCL

Using emission estimation technique the amount of SO_2, NO_X, CO, $PM_{2.5}$, PM_{10} and lead compounds were calculated from KPCL plant of 225MW generation capacity. Emission estimation technique was applied for five criteria pollutants; the pollutants whose national ambient air quality standards were established to show the contribution of power plant emission to the ambient air quality. Table 4.5 provides the mass of air pollutants released from KPCL plant due to the electricity generation using HFO. Emission results show that significant amount of air pollutants are emitting daily from the KPCL plant. Using the emission estimation technique (Article 3.4), it can be concluded that the power plant is releasing 197.4 t/annum of SO_2, 84t/annum of NO_X, 9t/yr of CO, 12.4 t/yr of PM_{10}, 9.3t/yr of $PM_{2.5}$ and 2.7 kg/yr of Lead compounds. The dominant air pollutants from KPCL were found SO_2 (62.04%) and NOx (26.35%). In addition, KPCL emits 2.92 gm of SO_2/KW, 1.24gm NO_X/KW, 0.26gm CO/KW, 0.16gm PM_{10}/KW, 0.106gm $PM_{2.5}$/KW and $4X10^{-5}$gm Lead compounds to generate per KW electricity using HFO. Here from table 4.5 we can see that

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the emission of SO_2 and NO_X are more than that of CO, but the HFO characterization showed that HFO contains 83.42 % Carbon whereas the Sulfur and Nitrogen content are 0.7% and 0.11% by weight respectively. The emission of CO is less because in case of electricity generation the carbon present in fuel converted in electricity. The emission of less CO indicates the higher efficiency of electricity generation of fuel.

Table 4.5 Estimated Emission from KPCL using HFO

Compounds	Emission	
	Ton/year	gm/KW
SO_2	197.4	2.92
NO_X	84.0	1.24
CO	9.0	0.27
PM_{10}	12.5	0.16
$PM_{2.5}$	9.3	0.11
Leadcompounds	2.7×10^{-3}	4.0×10^{-5}

According to the EURELECTRIC, 2003; from a power plant of 1,000 MW generation capacity, using the fuel oil emits SO_2 and NOx of 8.7 gm/KW, though the diversity of fuel mixes in each country gives different average values.In India, the new standards are aimed at reducing emission of PM_{10} (0.98 kg/MWh), sulphur dioxide (7.3 Kg/MWh) and Oxide of nitrogen (4.8 kg/MWh), which will in turn help in bringing about an improvement in the Ambient Air Quality (India Environment Portal, 20016).

The emitted sulfur dioxide and nitrogen oxides arise into the atmosphere, where they come in contact with water vapor and they form sulphuric acid, sulfurous acid, nitric acids etc. Those acids then fall to the ground mixed with rain and damage plants, which affects animals and pollutes the environment, as well as cities, because those acids react with some metals and other materials that are commonly found on buildings or monuments. Another process occurs

on fine and cloudy days. Airborne acids come directly through winds, and deposit themselves on trees, buildings, and even human respiratory systems. These deposited acids may increase the acidity in soil, lake and water bodies.

CHAPTER 5

CONTRIBUTION OF POWER PLANT EMISSION TO
THE KHULNA AIRSHED

5.1 General

According to the environmental and aesthetic point of view the location of any anthropogenic emission source should be far away from the locality. This chapter describes the surrounding environment of KPCL power plant; validation of GDAS meteorology data file and the HYSPLIT dispersion model results in addition to the contribution of power plant emission to the ambient pollutants concentration of available local air quality data.

5.2 Surrounding Environment of KPCL

The location of KPCL is bank of the Bhairab River, but within 1 km of source location there are School, collage, stuff quarter, central mosque, Cinema hall, market, power station, jute mill and other medium size industries are located. Figure 5.1 is showing the location of KPCL plant. Within the 1 km area of KPCL word no 7, 8, 10 and 11 of Kahlishpur Thana are located having total population of 71269 (BBS, 2016). According to the public Service commission of Wisconsin state, the location of power plant should be selected by considering the criteria of Degradation of local air quality, Dust, Noise, Operational odors, Traffic safety, and Aesthetics. Also considering the public exposure to air emissions is regulated through the National Ambient Air Quality Standards (NAAQS) for major air pollutants including sulfur dioxide, oxides of nitrogen, carbon monoxide, ozone and particulates.

Figure 5.1 Surrounding environment of KPCL power plant

The location of power plant should be far enough from densely populated area due to the smoke, stem noise, vapor etc. Total population of Khalishpur thana is about 1,72000 and from this point of view the location of KPCL is hazardous for surrounding environment

5.3 Construction of Windrose and Validation of HYSPLIT Model

The HYSPLIT particle dispersion model was widely used for dispersion modeling (Connen et al., 2013) which has been validated elsewhere (Wang et al. 2009). Dispersion in the mesoscale (>10 km) is determined by the prevailing wind (speed, direction), atmospheric stability, mixing layer height, and the diurnal and spatial variation in these quantities in every

modeling system. GDAS meteorological data file in the HYSPLIT dispersion model was used to run the model. To verify the GDAS data file with local meteorology data, windrose for 1st September 2013 to 3rd September 2013 was formed by HYSPLIT and with regional air monitoring data (Figure 5.2). Both windrose assimilate the same direction of wind movement with nearest wind speed. Figure 5.2 showing both windrose from HYSPLIT and raw data. Both Windrose shows that wind in these three days mostly moved towards north and north-east directions. Assimilation of these two windrose validates the meteorological data used in HYSPLIT dispersion model.

(a)   (b)
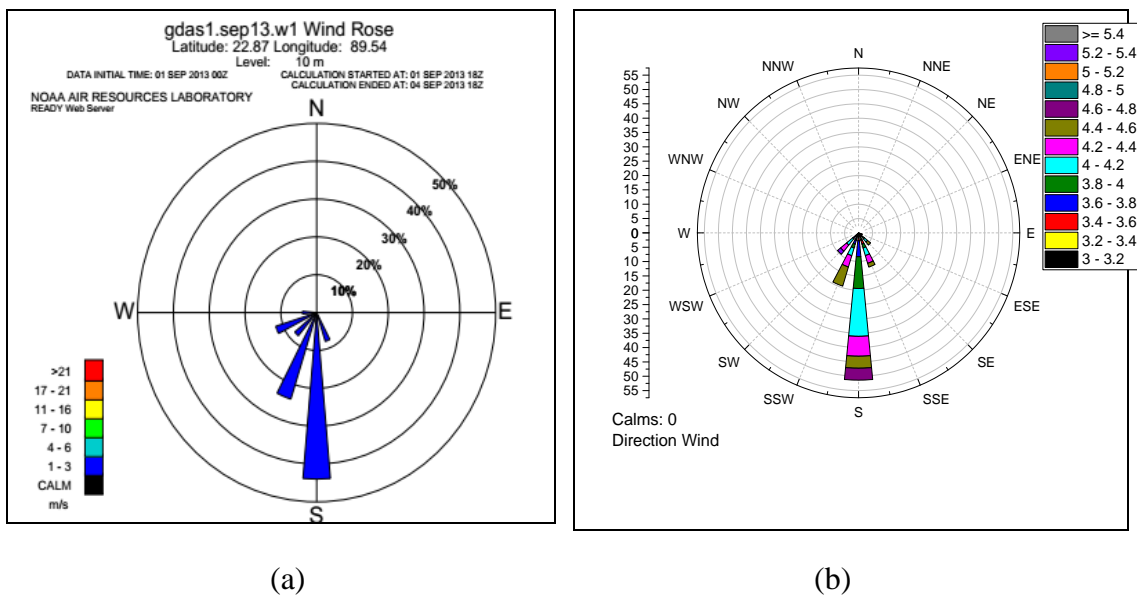
Figure 5.2 Windrose for 1st September 2013 to 3rd September 2013; (a) generated by HYSPLIT, (b) windrose with regional air monitoring data

To graphically represent the validation of HYSPLIT plume distribution with Gaussian plume distribution, a long section along the direction of plume distribution and a cross section transverse to the long section of a dispersion modeling result was selected and the value of pollutant concentrations were plotted against distance.

(a)

(b)
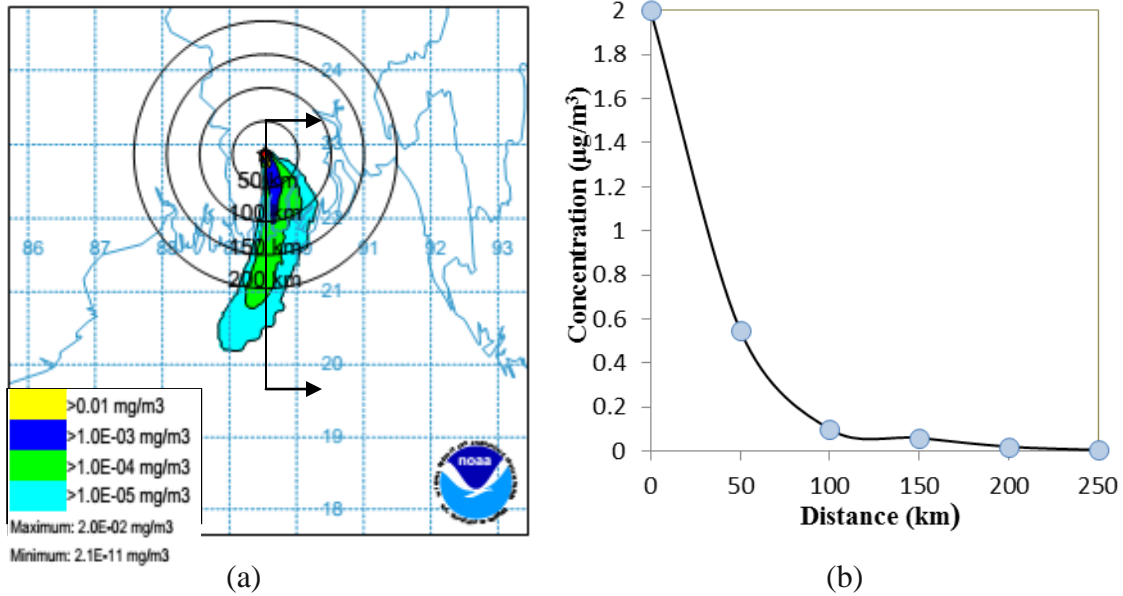
Figure 5.3 Spatial distribution of plume; (a) Dispersion map of 1st December of 2014, (b) plume distribution along the distance

(a)

(b)
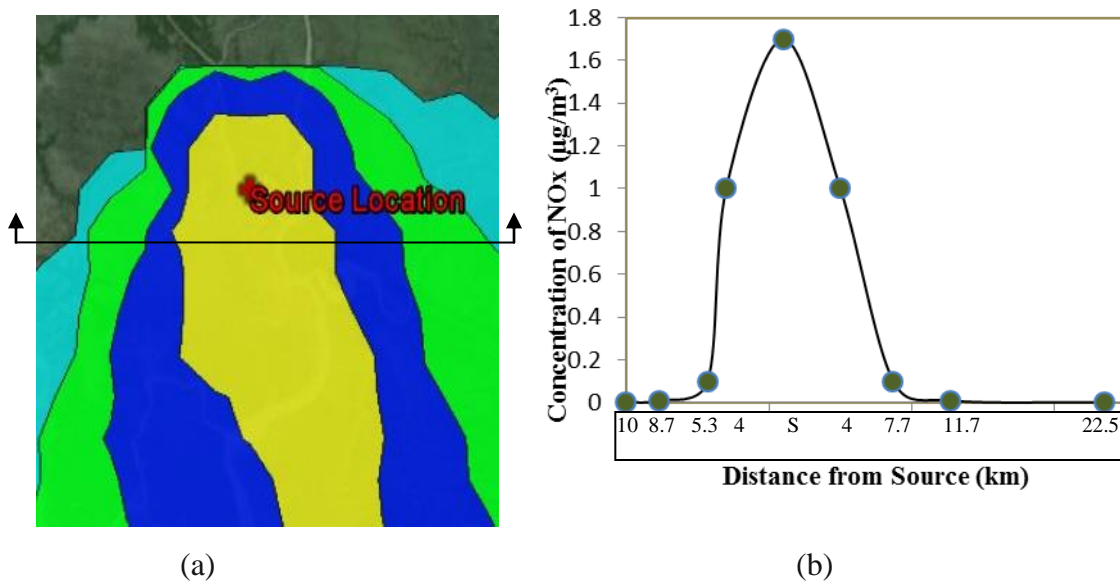
Figure 5.4 Gaussian plume distribution; (a) Top view of pollutant dispersion, (b) Cross-section of plume distribution

Figure 5.3 and 5.4 showing the plume distribution of pollutants after emission. Here the concentration of NOx is continuously decreasing with the increasing of distance. Highest

concentration along the plume was $2\mu g/m^3$ and at the distance 100 km away from the source the concentration was $o.1\mu g/m^3$. The concentration continuously decreased and at the distance 250 km away from source it became $0.005\mu g/m^3$. The mass of pollutants after emission started to get dispersed with Brownian motion and started to travel along with the direction of wind movement. By this time of travelling some pollutant mass get deposited on earth surface. Thus with the passage of time the covering areas of dispersion increase and the pollutant concentration decrease. Both plume distribution simulated from HYSPLIT model results shows the similarity with Gaussian plume distributions (Article 2.9.5).

5.4 Dispersion of SO_2 and NOx

In HYSPLIT, the plume dispersion for every pollutant is constant under the same meteorology and time as the model run under certain mathematical formula simulated in the model. The generated dispersion models for the air pollutants emitted from power plant showing their path of dispersion after emission. The dispersion map in figure 5.5 to 5.7 showing the plume dispersion is concurrent with the meteorology that is wind speed and wind direction. In this approach, the plume spread more than the range of 200 km from the source and the time of evolution of the area exposed above a particular concentration limit are considered. Dispersion results from different simulations show variation in plume distribution pattern and concentration with the variation of time and distance. Differences are seen in both plume movement and its aerial spread in each case. The plumes traveled considerable distance to the north and further downwind the plume moved towards north-east and north-west as well. The cross-wind spread of the plume was also comparatively high in the simulation. The highest concentration was near to the source in all cases and within 2km of radial distance.

Simulation from model results shows that for 01 September to 06 September the pollutant plume moved towards north direction (Figure 5.5a) with the maximum concentration of $5.7\mu g/m^3$ and the plume emission dispersed to a long distance more than 300 km from source covering the area of Jessore, Chuadanga, magura, Jhenaidah in Khulna division; Pabna,

Shirazgonj, Bogra in Rajshahi division mostly and in some cases dispersed over Dinazpur, Rangpur, Thakurgaon in Rangpur division.

(a)	(b)	(c)
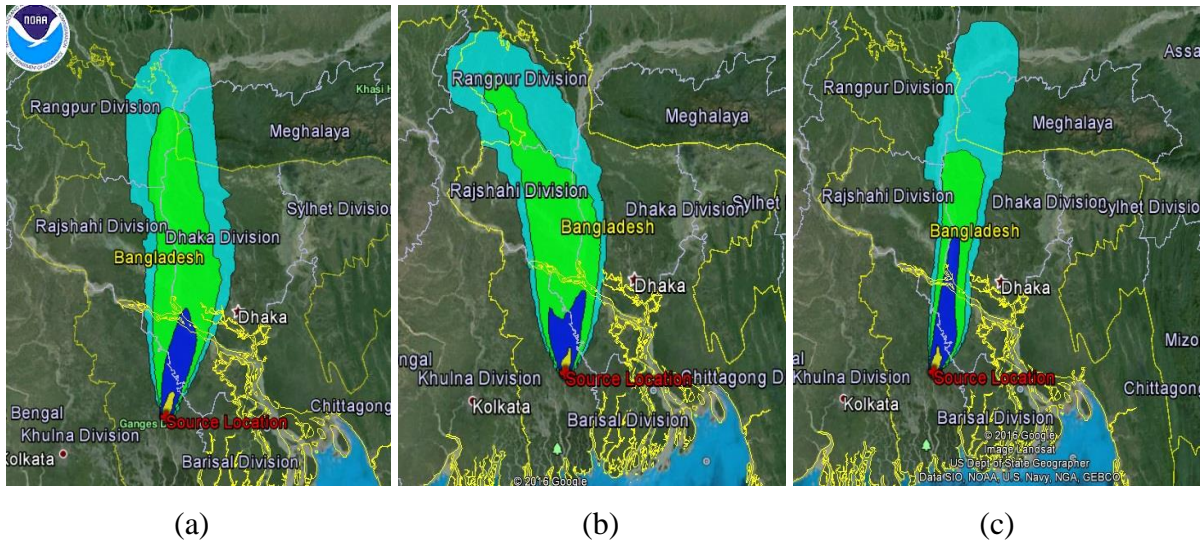
Figure 5.5 HYSPLIT-generated SO_2 concentration ($\mu g/m^3$) averaged between 0 and 30 m levels and integrated for 24-h period (a) 1st September 2013 (b) 3rd September 2013 (c) 6th September 2013

(a)	(b)	(c)
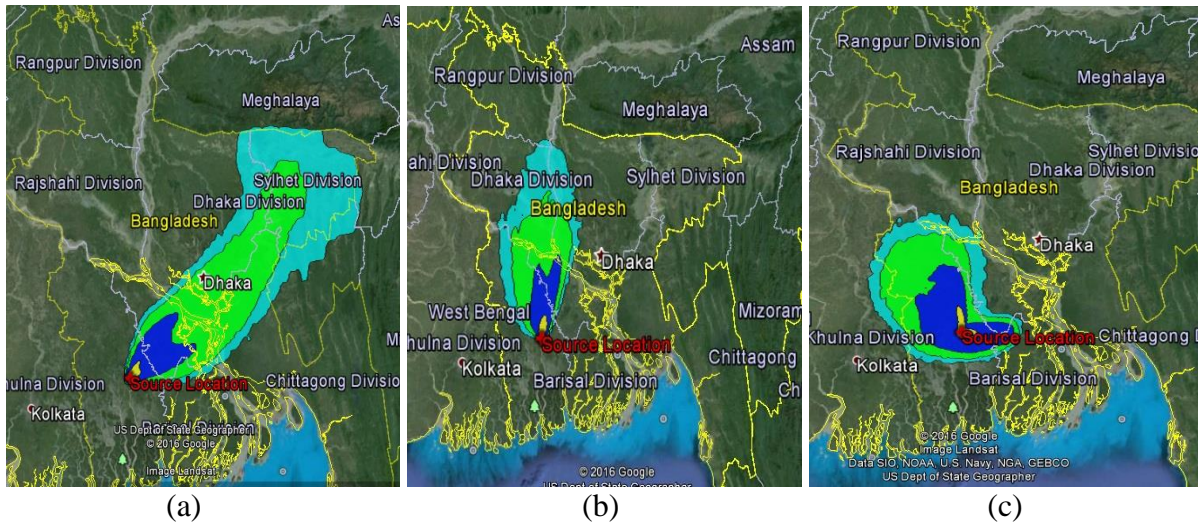
Figure 5.6 HYSPLIT-generated SO_2 concentration ($\mu g/m^3$) averaged between 0 and 30 m levels and integrated for 24-h period (a) 7th September 2013 (b) 10th September 2013 (C) 13th September 2013

The plume direction for 07 to 13 September changed to north-east and north west direction due to the result of cross wind (Figure 5.6c) the plume emission scattered in several direction at the same time with maximum concentration ranged from 2.3 to 9.7 µg/m^3 at the distance within 150km covering the area of Jessore, Chuadanga, magura, Jhenaidah Pabna, Ishwardy and Shirazgonj. For 14 September to 22 September the plume dispersion moved toward north-west direction with the maximum concentration ranged from 9.1 to 5.6 µg/m^3 (Appendix A-5) at a distance more than 300 km covering the area of Jessore, Chuadanga, magura, Jhenaidah in Khulna division; Pabna, Shirazgonj, Bogra in Rajshahi division mostly and in some cases dispersed over Dinazpur, Rangpur, Thakurgaon in Rangpur division. Using the Gaussian plume distribution model the maximum concentration obtained 14.2µg/m^3 whereas from HYSPLIT dispersion modeling, the maximum concentration obtained 9.7µg/m^3. From plume dispersion it is obtained that the concentration is inversely proportional to the wind velocity that is with the increase of wind velocity the plume dispersion was longer than relatively lower velocity. At the same time with the longer plume dispersion the concentration get decreased due to increased wind velocity.

5.5 Long Range Transported Pollutants

The emission from plume not alone contribute for the dispersion path, some other sources from long range distance also contribute to source point at the same time. To show how the other sources from long range distance contributing to the source point two archive Back trajectory model for several month of 2013 were done. Figure 5.7 is showing that most of air masses were come from eastern and southern part of India and also from bay of bangle. The potential sources of air pollutants which are travelling to Bangladesh from Bay of Bengal are emission from ships. During the travelling period the air masses entered in Khulna through the southern and western part of Bangladesh that is the direction was concurrent with the local wind direction. The dominance of the southern and south- western origins of air masses arriving at Khulna throughout the year. In between the experimental days, long range air masses were mainly originated from east Bengal, south India and from Bay of Bengal and had a long pathway through the southern India, before entering Khulna from south. This continental pathway explains the dry weather. During post monsoon, air masses were also

originated from the west but over Indian Ocean, they passed India and entered the domain from south. Directions of long range transported air masses to Khulna showed similarity with the local wind
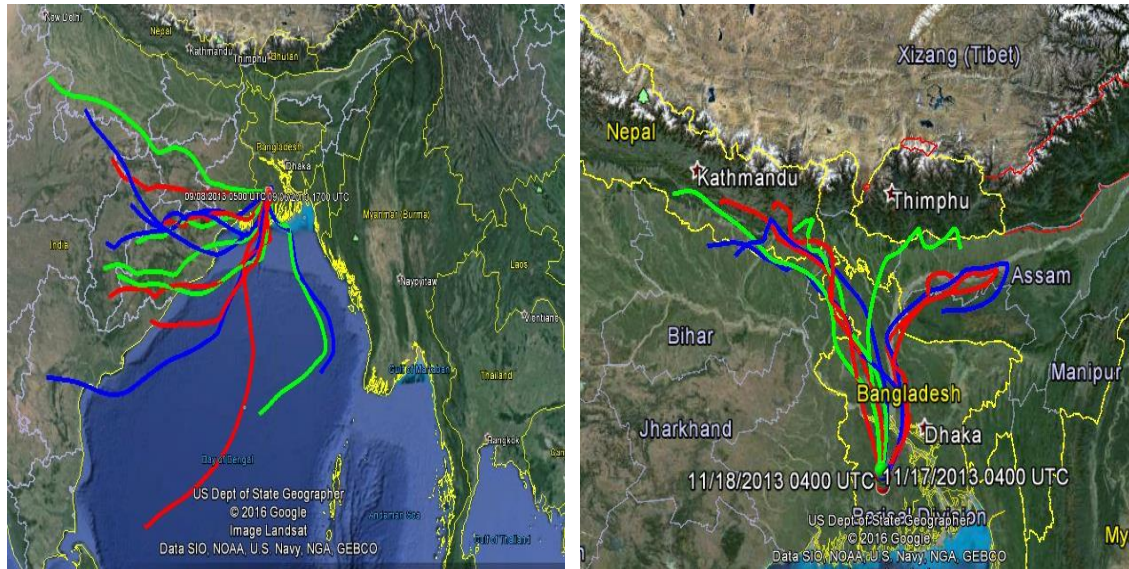
Figure 5.7 Back trajectories produced by HYSPLIT model

The pathways of air masses reflect the topography of the country with the long Himalaya range situated in the northern part of Bangladesh and hilly regions on the eastern, northeastern and southeastern parts (Figure 5.7). Analyzing the path of long range transported pollutants it was found that due to presence of Himalayan mountains in Nepal the emission from china cannot contribute to airshed of Khulna as well as Bangladesh.

5.6 Contribution of KPCL Emission to the Ambient Air Quality

5.6.1 Ambient Air Quality

The dispersion modeling of 1st to 22nd September 2013 was performed to compare with the available air quality monitoring data and to find the contribution of KPCL emission to the ambient air quality, because due to poor data capture rate/malfunction of the analyzer/sensor, all the air quality data are not available in the Khulna station in each month (CASE, 2015).

To analyze the local ambient air quality the collected raw air quality data for the month of september 2013 is tabulted (Table 5.1). Only SO_2 and NO_X are main concern of this study because from estimated emisssion it was found that the major portion of emission were SO_2 and NO_X. The average concentration of SO_2 and NO_X were 55.35μg/m^3 and 21.25μg/m^3 respectively the maximum ambient concentration of SO_2 and NO_X were recorded 236.56 μg/m^3 and 33.66μg/m^{3}respectively. According to national ambient air quality standard for maximum 24-hr average concentration of SO_2 and NO_X are 365 μg/m^3 and 100 μg/m^3. In this regard the ambient air quality was quite below to the standard limits.The average concentration of SO_2 and NO_X were 55.35μg/m^{3}and 21.25μg/m^3 and these average concentrations were used to calculate the Air Quality Index of Khulna for September 2013.

Table 5.1 Ambient concentration of SO_2 and NO_X

Date	SO_2 (μg/m^3)	NO_X (μg/m^3)	Date	SO_2 (μg/m^3)	NO_X (μg/m^3)
01.09.13	15.37	12.68	12.09.13	56.89	18.05
02.09.13	14.6	13.67	13.09.13	13.32	20.03
03.09.13	27.71	13.62	14.09.13	14.82	17.1
04.09.13	23.85	13.21	15.09.13	176.85	31.86
05.09.13	37.16	15.59	16.09.13	236.56	32.1
06.09.13	28.73	13.19	17.09.13	113.02	32.18
07.09.13	22.8	13.47	18.09.13	60.35	33.66
08.09.13	43.28	14.68	19.09.13	78.09	32.81
09.09.13	45.66	13.81	20.09.13	49.39	32.59
10.09.13	16.86	14.27	21.09.13	74.47	32.68
11.09.13	41.75	13.92	22.09.13	26.18	32.31

5.6.2 Air Quality Index (AQI)

Air Quality Index (AQI) provides the understanding of air pollution level at which air can be polluted and the associated health effects that might concern. In Bangladesh the AQI is calculated based on five criteria pollutants such as Particulate Matter (PM$_{10}$ and PM$_{2.5}$), NO_2, CO, SO_2 and Ozone (O_3). The Department of Environment (DoE) has also set national

ambient air quality standards for these pollutants. These standards aim to protect against adverse human health impacts has established national air quality standards to protect public health.

Data obtained from monitoring of ambient air was used to calculate the AQI values for 24 hourly averages SO_2 and NO_X concentrations. In this month AQI due to the maximum concentration of SO_2 and NO_X were 64 and 34 respectively which fall in moderate and good category. The AQI for average SO_2 and NO_X was obtained 15 and 21, respectively. AQI value for both SO_2 and NO_X fall in good category (0-50) which pose little or no short term exposure.

5.6.3 Contribution of SO_2 and NOx from KPCL

HYSPLIT dispersion modeling results of September 2013 (22 nos, 24-hr avg) were simulated to calculate the average concentration of SO_2 and NO_X. The simulated concentrations of SO_2 and NO_X for both ambient and from KPCL were tabulated (Apendix- A5) and the contribution of KPCL emission was calculted for each day and finally the contribution for 22 days were averaged to show the average contribution of KPCL emission to the ambiet airshed. Figure 5.8 and figure 5.9 shows the contribution of power plant mission to the ambient air quality Comparing with local air quality monitoring station data, it was found that 18.5% of total ambient SO_2 contributed by KPCL emission and12.36% of total ambient NO_X contributed by KPCL emission.
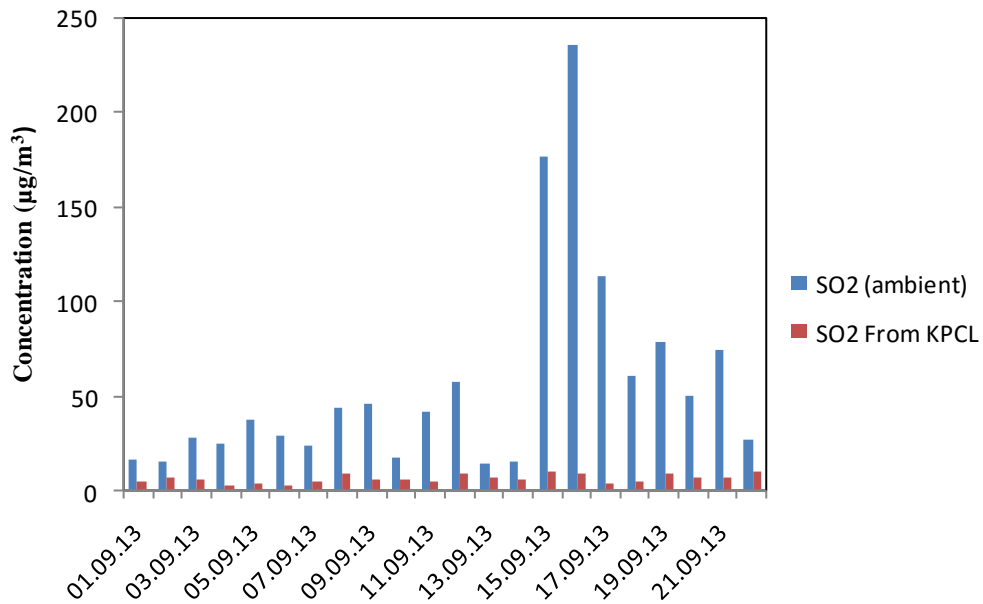
Figure 5.8 Contribution of KPCL SO_2 emissions to the ambient SO_2 concentration
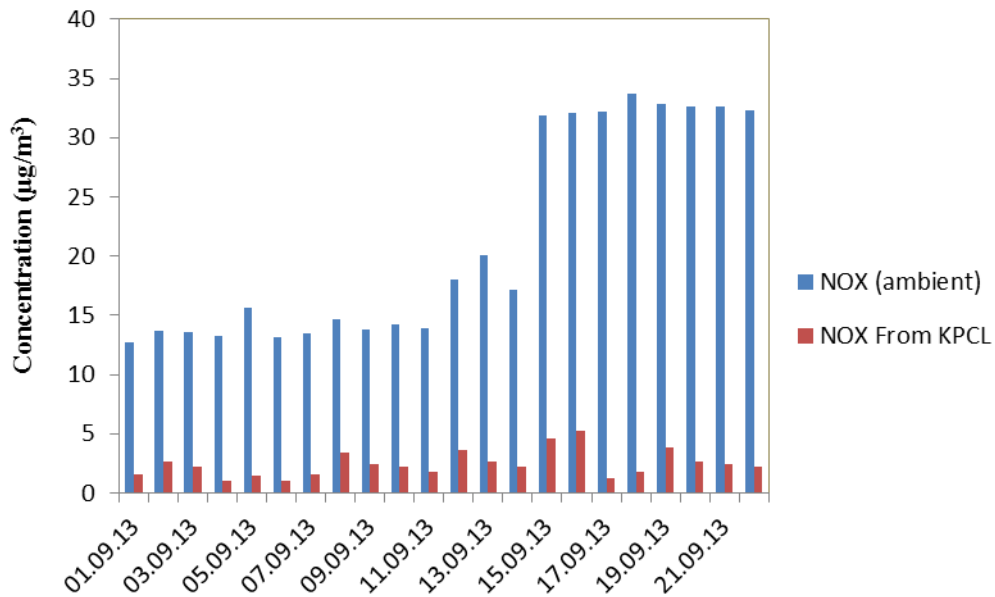
Figure 5.9 Contribution of KPCL NO_X emissions to the ambient NO_X concentration

The anthropogenic emissions are mainly due to fossil fuel combustion from both stationary sources, such as power generation sector (21%) and mobile sources like transportation sector

44% (AQO, 2016). The sources of SO_2 and NO_X emission can be contributed from transportation sector and other industries such as Khulna GT Power plant, Padma Oil, and Jute mills which are situated in the surrounding areas of KPCL in addition to the release of SO_2 and NOx from KPCL plant. Lightning can be the natural source of NO_X which can also contribute to the air pollution. In addition, long range transport pollutants may also contribute to the atmospheric air pollution in the Khulna region.

CHAPTER 6

SPATIAL AND TEMPORAL DISTRIBUTION OF SO_2 AND NO_X EMMITED FROM KPCL AND THEIR HEALTH IMPACT

6.1 General

The atmospheric pollutants get dispersed from the source and deposited over a certain distance depending on the pattern of wind movement and wind speed. This chapter describes the variation of plume distribution with the time and space, the concentration and deposition of SO_2 and NOx in some point of interests, the zone of maximum exposure concentration and health impact due to long term SO_2 and NOx exposure in different zones.

6.2 Windrose Construction

The windrose of November 2014 to February 2015 (winter season) is constructed and shows the direction of wind movement in Khulna (Figure 6.1). According to the Gaussian plume dispersion, the concentration is inversely proportional to the wind speed. Through the whole year, average monthly wind speed varies from 0.2 to 1.5 m/s in the month of November to February and from the month of March to October it varies from 1.5 to 4.5m/s (Weather and Climate, 2016). Thus the winter season is selected to show the maximum concentration level of pollutants emitted from power generation. During the winter season, the predominant windrose was found towards southern direction. Hence, the plume can travel towards SE, S and SW direction.
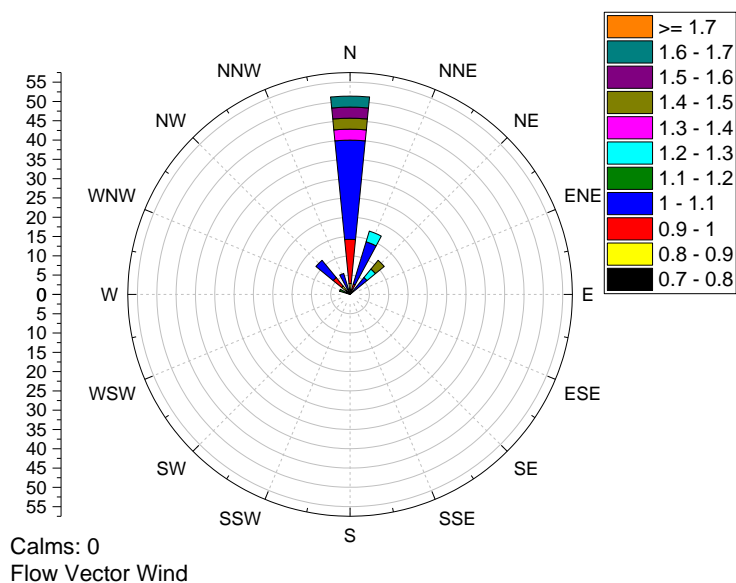
Figure 6.1 Windrose for Khulna for the period of November to February

6.3 Dispersion of SO$_2$ and NO$_X$ emission

The temporal distribution of SO$_2$ and NOx pollutants is presented (Figure 6.2-6.4) by performing the dispersion modeling of SO$_2$ and NO$_X$ released from KPCL during November 2014 to February 2015 and the concentration of SO$_2$ and NO$_X$ were tabulated (Appendix- A1, A2, A3 and A4). The dispersion modeling results shows that the pollutants are travelling towards the southern direction over Sundarbans. From the beginning of November 2014 mostly plume travelled towards the south direction and travel long distance more than 200 km from the source and covering the area of Khulna, Mongla, Bagerhat, Sundarbans, Potuakhali, Borguna and over Bay of Bengal. Maximum concentration surrounding the source varied from 4.51μg/m^3 to 17.43μg/m^3 of SO$_2$ and 1.87μg/m^3 to 7.23μg/m^3 of NOx. From 7th November to 13th November plume started to change the direction towards south and south-west direction. Then the plume is dispersed and become wider covering more area of Khulna, Mongla, Bagerhat, Sundarbans, Gopalgonj, Potuakhali, Borguna and Barisal with maximum concentration ranging from 3.6μg/m^{3}to 7μg/m^3 of SO$_2$ and 1.7μg/m^3 to 3.82μg/m^3.

Figure 6.2 HYSPLIT-generated Dispersion pathway of pollutants averaged between 0 and 30 m levels and integrated for 24-h period (a) 1st November 2014; (b) 3rd November 2014; (c) 7th November 2014; (d) 10th November 2014; (e) 14th November 2014; (f) 18th November 2014; (f) 21st November 2014; (g) 24th November 2014; (h) 27th November 2014 and (i) 30th November 2014

Figure 6.3 HYSPLIT-generated Dispersion pathway of pollutants averaged between 0 and 30 m levels and integrated for 24-h period (a) 1st December 2014; (b) 3rd December 2014; (c) 7th December 2014; (d) 10th December 2014; (e) 14th December 2014; (f) 18th December 2014; (f) 21st December 2014; (g) 24th December 2014; (h) 27th December 2014 and (i) 30th December 2014

During these days the cross-wind effect was also observed. After that the plume again moved towards north direction for the rest of the month. The average concentration of SO_2 was 7.04μg/m^3 and for NO_X was 2.92μg/m^3. The wind speed during the entire November month varied from 0.4m/s to 0.6 m/s thus plume dispersion were more stable and similar. The typical variations of plume movement in three days of November 2014 are showed in Figure 6.2.

In December 2014, the plume started to travel towards south west direction and chronologically travelled towards south, covering the area of Bagerhat, Mongla and Sundarbans with the maximum concentration changing from 4.92μg/m^3 to 14.57μg/m^3 of SO_2 and 2.04μg/m^3 to 6.4μg/m^3 of NO_X. Maximum concentration of SO_2 and NO_X were recorded as 15.17μg/m^3 and 8.21μg/m^3, respectively. During this month, the variations of SO_2 concentration were varied from $1.9X10^{-12}$μg/m^3 to maximum 15.17μg/m^3 and similar for NO_x from $1.9X10^{-14}$μg/m^3 to maximum 8.21μg/m^3. The average concentration of SO_2 during this month was 7.7μg/m^3 and for NO_X was 3.13μg/m^3. The average wind speed during the entire December month was 0.5m/s thus the plume was found having similar pattern. During this month the pathway of plume dispersion was also stable and no effect of cross wind was shown the plume of pollutants mostly travel over Sundarbans and contribute to the airshed of Sundarbans. The typical variation of plume movement in three several days of December 2014 are showed in Figure 6.3.

The plume dispersion for the month of November and December 2014 were almost similar and stable, however, the plume dispersion started to move in several directions from January 2015. From the beginning of this month the plume dispersed in west direction for first 4 days covering the area of Khulna and Shatkhira with the concentration varied from 4μg/m^3 to maximum 15μg/m^3 of SO_2 and from 1.7μg/m^3 to 6.38μg/m^3 of NOx. Then for 5th January to 8th January the plume travel towards south–east direction covering the area of Khulna, Bagerhat and Pirozpur. The plume also traveled over the Bagerhat Shat Gambuj Mosque, an ancient mosque of Bangladesh.

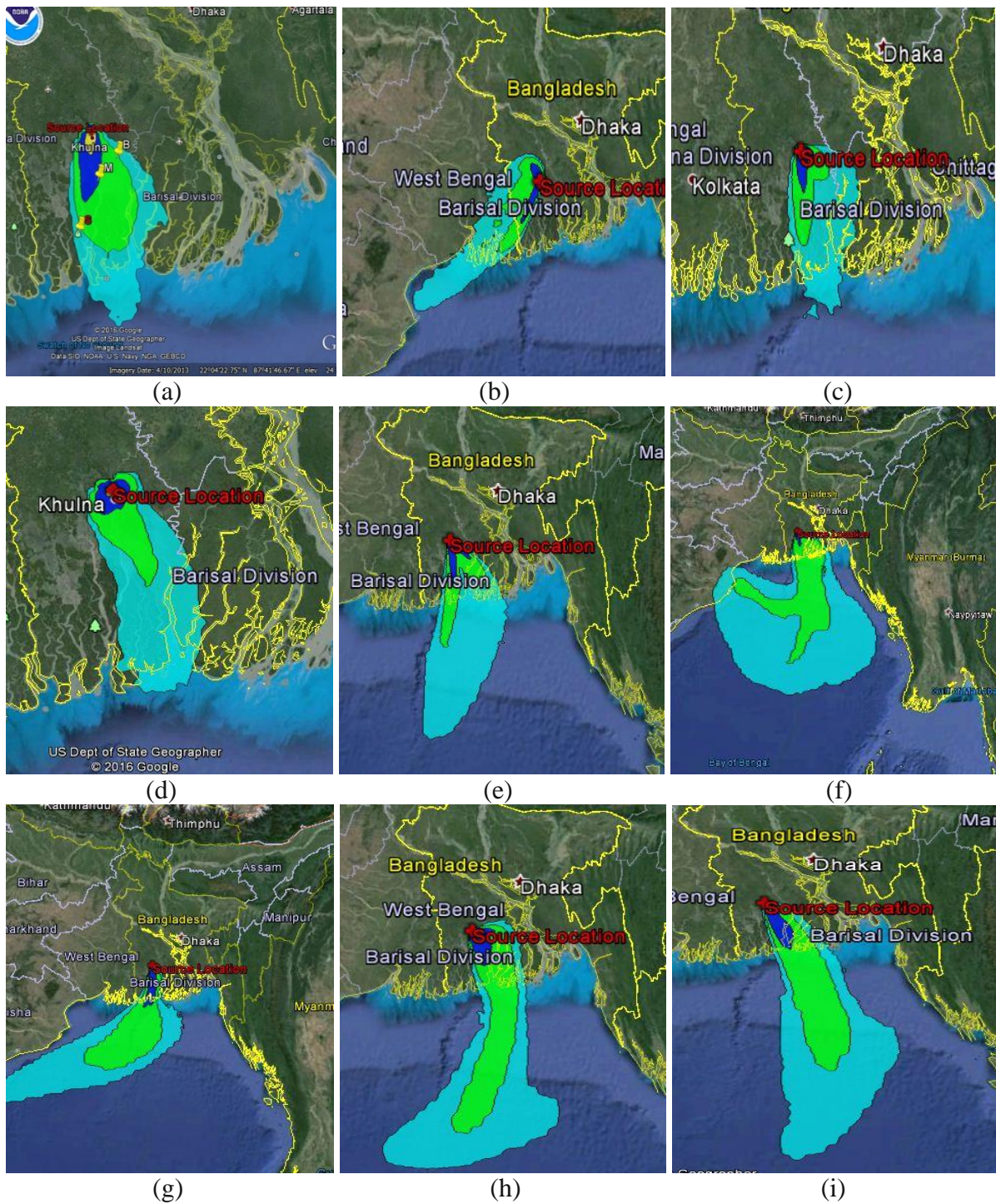Figure 6.4 HYSPLIT-generated Dispersion pathway of pollutants averaged between 0 and 30 m levels and integrated for 24-h period (a) 1st January 2015; (b) 3rd January 2015; (c) 7th January 2015; (d) 10th January 2015; (e) 14th January 2015; (f) 18th January 2015; (f) 21st January 2015; (g) 24th January 2015; (h) 27th January 2015 and (i) 30th January 2015

From 9th January plume started to travel towards south and south-west direction covering the area of Bagerhat, Mongla, Sundarbans and Potuakhali. The typical variation of plume movement in three several days of January 2015 are showed in Figure 6.4. The effect of cross wind was minor in this month. The plume did not spread wider as well along the transverse direction of the path of plume. During the entire month the plume moved from west to south-east direction and the plume distribution over Sundarbans were less than previous two months. In this month, the variations of SO_2 concentration were varied from $3.12X10^{-12}$ μg/m^3 to 15μg/m^3 and similar of NO_x varied from $6.7X10^{-14}$μg/m^3 to 6.38μg/m^3.

The direction of plume dispersion were started to show the changing of season from winter to spring. For the first ten days the plume travels towards the south direction covering the area of Bagerhat, Mongla, Sundarbans and over the Bay of Bengal. From the 13th February to 18th February 2015, the plume started to travel east direction covering the area of Khulna, Fokirhat and Gopalgonj. From 19th February the plume started to move towards north and north east direction covering the Jessore, Jhenaidah, Chuadanga and Kushtia. The effects of cross wind were several in this month and during the entire month the plume travel mostly all the directions and the effect over Sundarbans were minor comparing to the previous three months. The typical variation of plume movement in three several days of February 2015 are showed in Figure 6.5. In this month, the variations of SO_2 concentration were varied from $9.18X10^{-12}$μg/m^3 to 22μg/m^3 and for NO_x varied from $2.74X10^{-14}$μg/m^{3}to 9.36μg/m^3.

During modeling period, the plume had dispersed over a larger portion of the computational domain. Differences are seen in both plume movement and its aerial spread in each case. The plumes traveled considerable distance towards south and further downwind of south-east and south-west as well. Almost all dispersion maps indicate the movement of plume over Sundarbans during this period. Simulation results show that the plume dispersed over Sundarbans for about one-fourth period of a year (3 months).
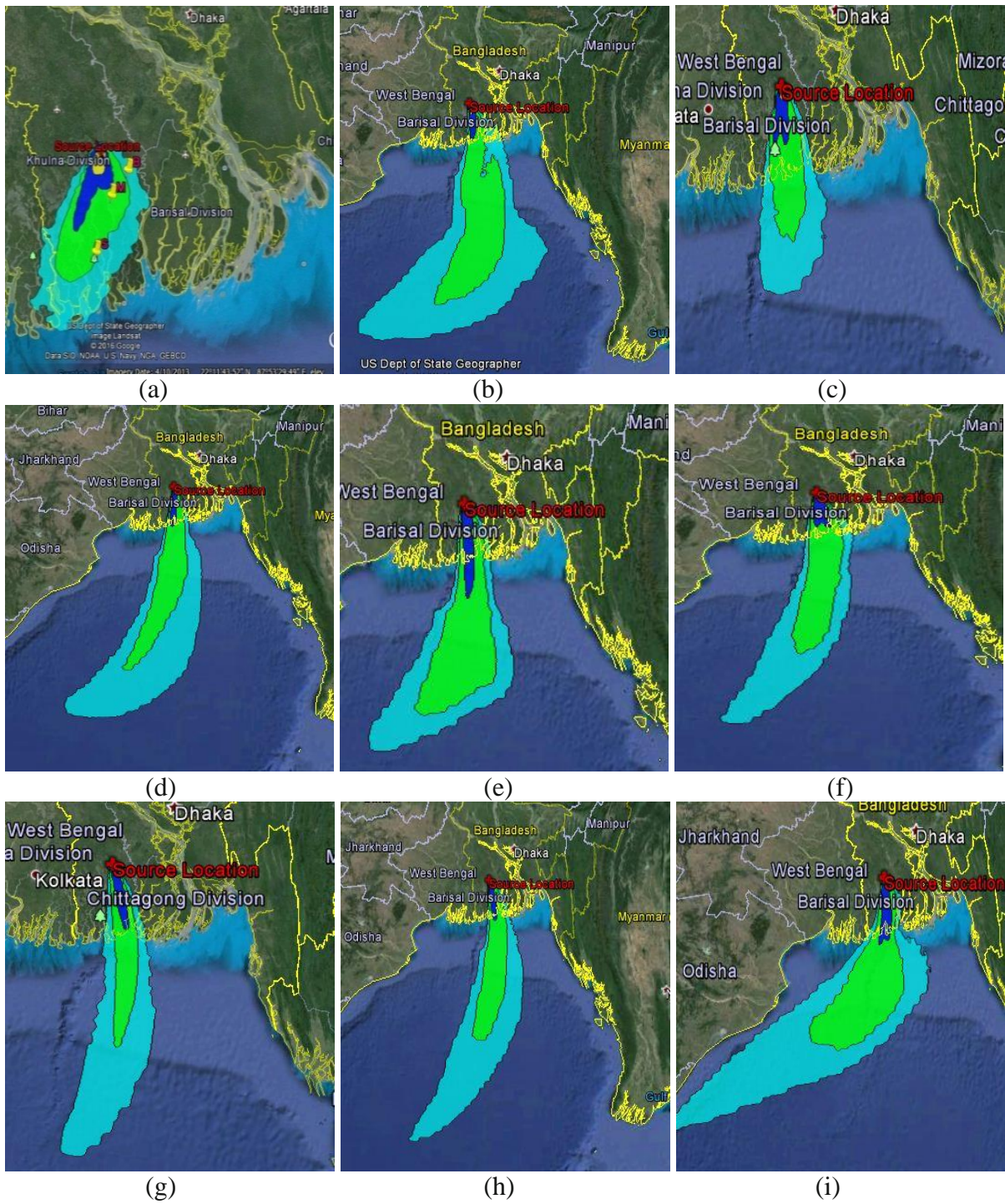
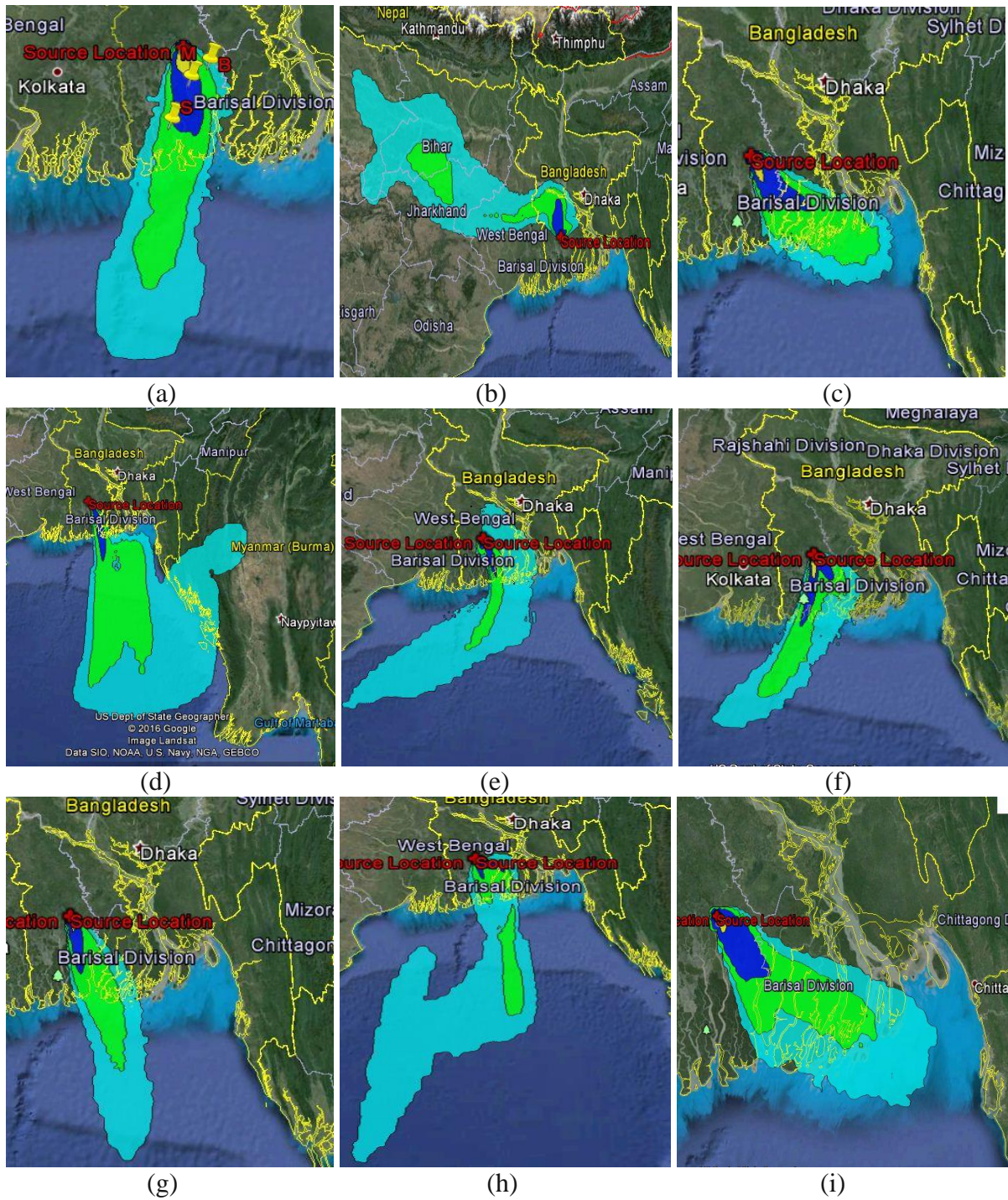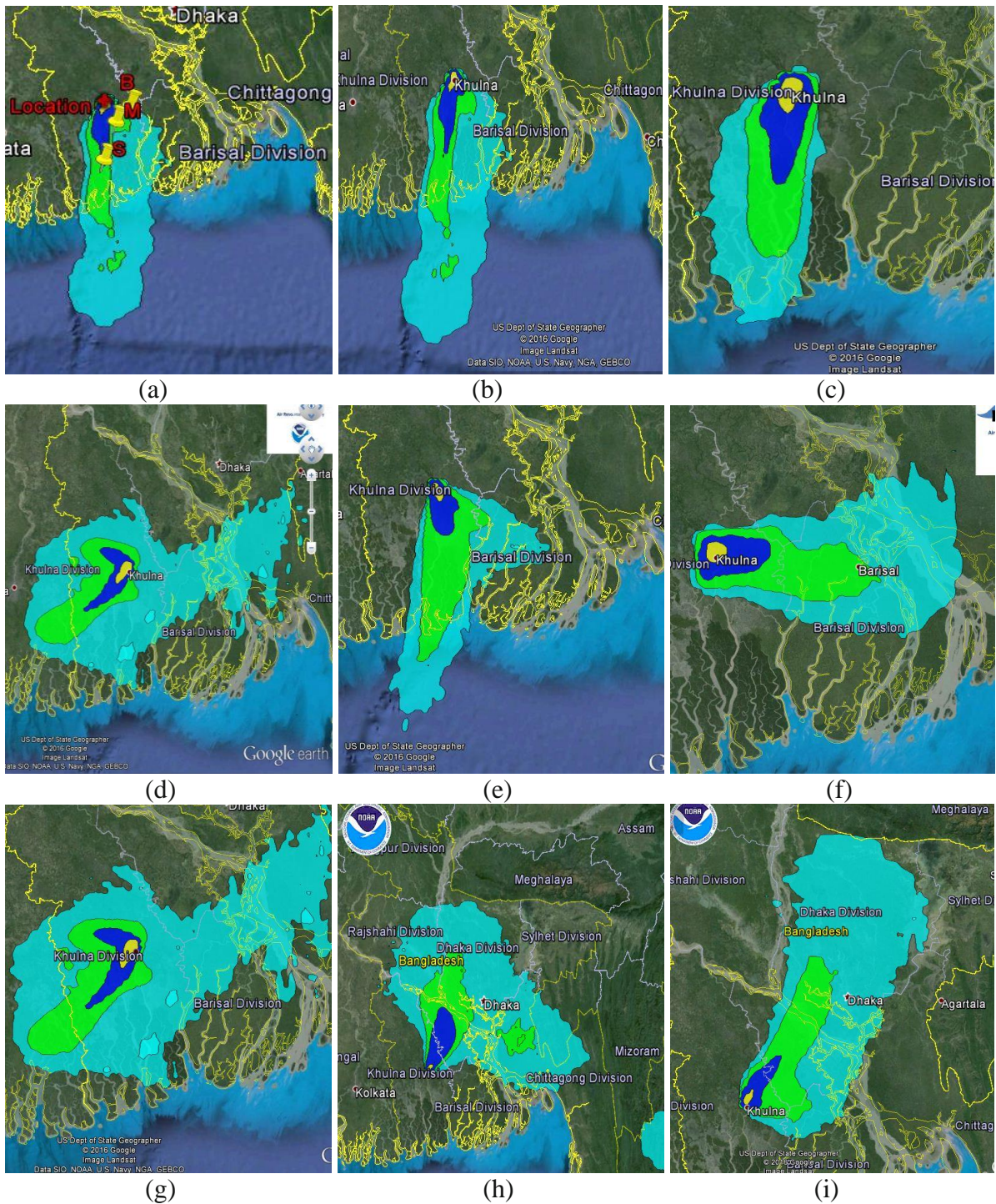Figure 6.5 HYSPLIT-generated Dispersion pathway of pollutants averaged between 0 and 30 m levels and integrated for 24-h period (a) 1st February 2015; (b) 3rd February 2015; (c) 7th February 2015; (d) 10th February 2015; (e) 13th February 2015; (f) 16th February 2015; (f) 19th February 2015; (g) 22th February 2015; (h) 25th February 2015 and (i) 28th February 2015

6.4 Concentration of SO_2 and NO_X at Different Locations

Six important locations in Khulna city in addition to the Sundarbans were selected for determining the SO_2 and NO_X concentration for the dispersion of pollutants from KPCL. These locations are: KUET (Khulna University of Engineering and Technology); Shonadanga area where the location of bus stand, School, Hospital and residential area; Thaana More near the commercial offices and market places; Royal More near the collage, international hotels, residential area and hospital; Khulna University (KU) area; Khulna Medical (KMC) collage area; and Sundarbans, the great mangrove forests. All the locations were selected concerning people having maximum exposure of pollutants except Sundarbans. Table 6.1 shows the average concentrations of SO_2 and NO_X at the selected locations simulated from HYSPLIT dispersion model results.

Table 6.1 Concentrations of SO_2 and NO_X at different locations

Location	Aerial Distance from Source (km)	Concentration ($\mu g/m^3$)							
		November 2014		December 2014		January 2015		February 2015	
		SO_2	NO_X	SO_2	NO_X	SO_2	NO_X	SO_2	NO_X
KUET	4.52	2.74	1.15	2.86	1.19	2.67	1.16	2.90	1.20
Shonadanga	5.28	2.54	1.08	2.75	1.12	2.46	1.04	2.82	1.15
Thanaa More	6.34	1.40	0.88	1.48	0.82	1.34	0.75	1.50	0.96
Royal more	6.95	1.07	0.74	1.1.8	0.94	1.1	0.66	1.27	0.88
KU	7.65	1.12	0.80	1.15	0.90	1.05	0.60	1.2	0.95
KMC	4.43	2.94	1.05	3.00	1.16	2.65	0.84	3.10	1.20
Sundarbans (Hiron point)	117.5	0.005	0.003	0.0045	0.0025	0.0040	0.0035	0.0060	0.004

The simulation of SO_2 and NO_X concentration from dispersion model results of every month showed that the air shed of Khulna city was covered by the SO_2 concentration of $> 1\mu g/m^3$ and NO_X concentration of $>0.1\mu g/m^3$ emitted from KPCL. The concentration of SO_2 and

NO_X at different locations are showing that the concentration decreasing with the increase of distance. Several studies reported signs and symptoms as nose and throat irritation, taste and odor complaints, and discomfort during single exposures (Alberta, 2006).

6.5 Zone of maximum concentration

Average concentration of SO_2 attributed to the ambient air quality of hotspot was simulated as 7.04μg/m^3 in November 2014, 7.7μg/m^3 in December 2014, 6.62μg/m^3 in January 2015 and 7.92μg/m^3.Average concentration of NO_X attributed to the ambient air quality of hotspot was 2.94μg/m^3 in November 2014, 3.13μg/m^3 in December 2014, 2.81μg/m^3 in January 2015 and 3.42μg/m^3 in February 2015.The zone of maximum concentration of pollutants can be identified within 2 km area of the source (concentration $\geq$ 1μg/m^3) emitted from power plant in every month of modeling. Maximum concentrations of SO_2 for every month of selected period were plotted and shown in Figure 6.6.

| (a) | (b) |
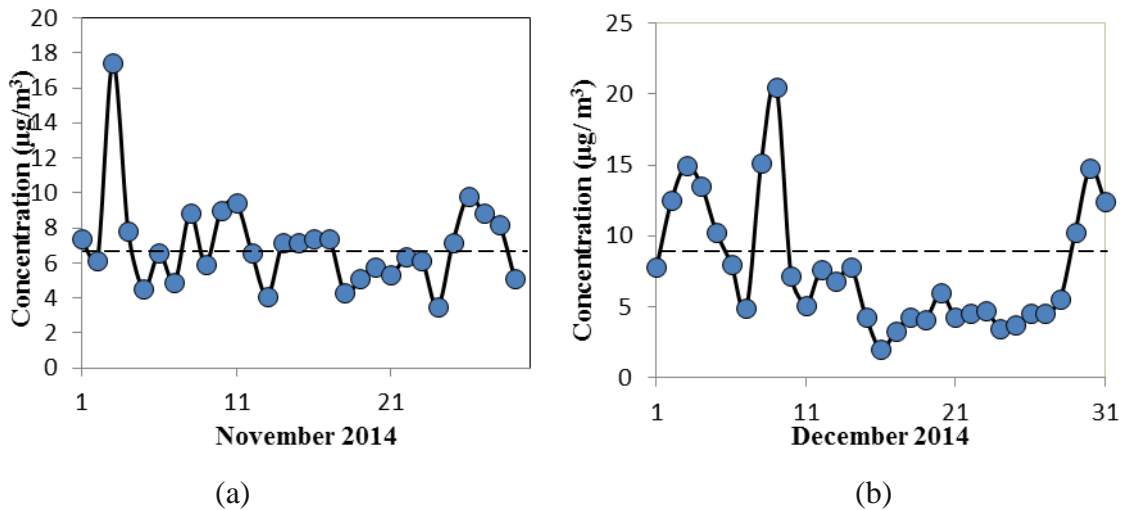
Figure 6.6 Maximum SO_2 concentration simulated from HYSPLIT, (a) November 2014 and (b) December 2014
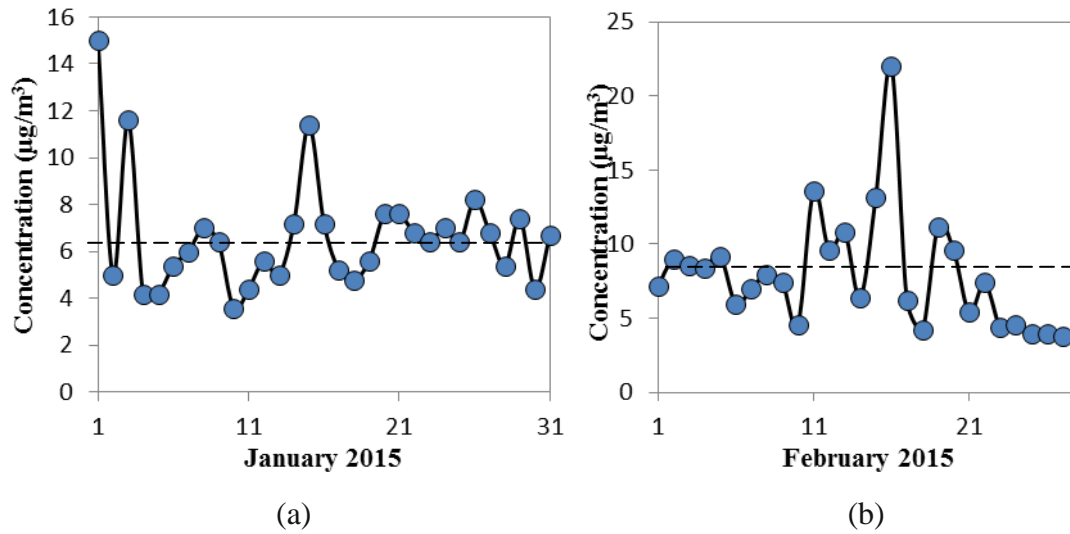
Figure 6.7 Maximum SO$_2$ concentration simulated from HYSPLIT, (a) January 2015 and (b) February 2015

The zone of maximum concentration within the 2km of source location can be identified as mostly concentrated zone (Z-1) which is 2km radial area near the source with the concentration of SO$_2$ >4.71µg/m^3 and NO$_X$>1.5 µg/m^3. Z-2 is 4km radial area surrounding the source with the concentration of SO$_2$>3.14 µg/m^3 and NO$_X$>1.25 µg/m^3). Z-3 is 6km radial area surrounding the source with the concentration of SO$_2$>1.57 µg/m^3 and NO$_X$>1 µg/m^3. Z-4 is 8km radial area with the concentration of SO$_2$>1.00µg/m^{3}and NO$_X$ >0.75 µg/m^3. Among the selected locations KUET, Shonadanga and KMC are within the zone-3 and Thanaa More, Royal more and KU are within the zone-4.
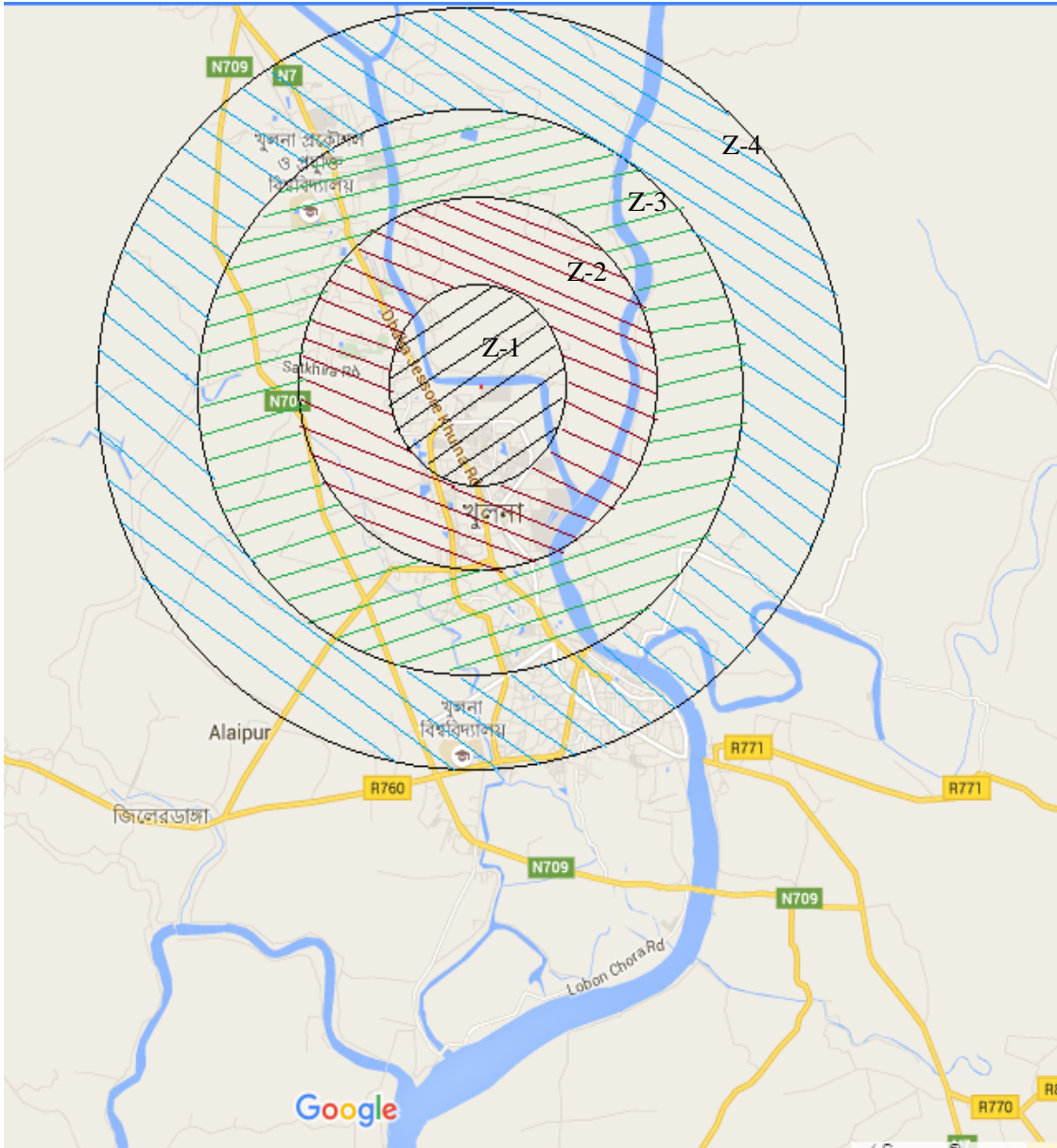
Figure 6.8 Exposure zone of SO_2 and NOx emitted from KPCL

= Z-1(SO_2>4.5 $\mu g/m^3$, NO_X>1.5$\mu g/m^3$)		= Z-3 (SO_2>1.5 $\mu g/m^3$, NO_X>1$\mu g/m^3$)
= Z-2 (SO_2> 3.0 $\mu g/m^3$, NO_X>1.25$\mu g/m^3$)		= Z-4 (SO_2>1.00$\mu g/m^3$, NO_X>0.75$\mu g/m^3$)

6.6 Deposition of SO_2 and NO_X

The air pollutants can be deposited on water and soil to pollute the water and soil during the movement of plume. The deposition of SO_2 and NO_X in atmosphere forming acid rain is the main effect of emission of acid forming pollutants. The deposition of SO_2 and NO_X are shown in Figure 6.10. Due to the emission from KPCL power plant, the maximum deposition of SO_2 on November 2014 was 20.14 mg/m^2, on December 2014 was 23.75mg/m^2, on January 2015 was 28.39 mg/m^2 and on February 2015 was 26.32mg/m^2 in the area of zone-1.Similarly the maximum deposition of NO_X on November 2014 was 9.57mg/m^2, on December 2014 was 8.8mg/m^2, on January 2015 was 12.34mg/m^2 and on February 2015 was 13.12mg/m^2 in the area of zone-1. During dry season mainly dry deposition of acid forming pollutants occurred and about half of the acidity in the atmosphere falls back to earth through dry deposition. The wind blows these gases onto buildings, cars, homes, and trees. Dry deposited gases and particles can also be washed from trees and other surfaces by rainstorms. When that happens, the runoff water adds those acids to the acid rain, making the combination more acidic than the falling rain alone. Bangladesh is yet highly concerned with acid rain effect however, it can be considerable in future depending on increasing emission of $S0_2$ and NOx.
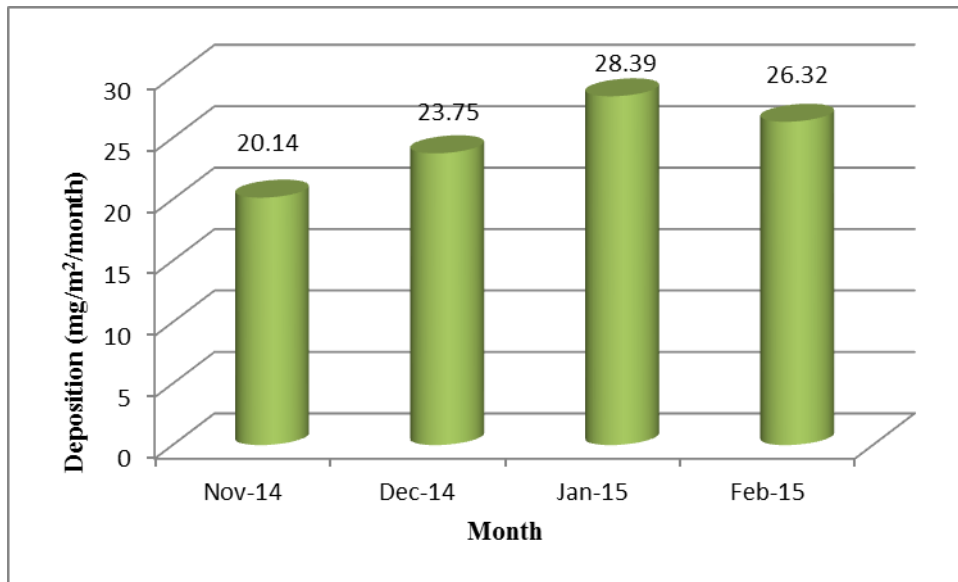
Figure 6.9Maximum Deposition of SO_2 in zone-1

6.7 Health Risk Assessment

Health risk assessment was performed in this study by estimating the number of the number of disability adjusted life years (DALYs) associated with the exposure of SO_2 and NOx concentration having limited focus on single risk factors and selected types of disease. The necessary parameters such as population size, exposure data and associate health effects, dose-response criteria were considered here and describe in Article 3.7.

This assessment describes the concept of the environmental burden of disease (EBD) related to SO_2 and NO_X exposure emission from KPCL in the ambient air, and health problems due to cardio-respiratory diseases and cardiovascular diseases in Khulna city of Bangladesh. DALY method is increasingly used in public health for improved understanding of health risk. Using this method the environmental burden of selected diseases were calculated in response to SO_2 and NO_X concentration in ambient air and expressed it in the form of disability-adjusted life years (DALYs) is presented in Table 6.2.According to WHO (2013) DALYs were found for outdoor air pollution is 0.7 per 1000 capita/year and chronic respiratory disease attributed for 1.5% and similar for cardiovascular disease (5%) of total disease burden.

Table 6.2 Attributable burden of respiratory mortality cases in DALYs calculated for Khulna due to power plant emission of SO_2 and NO_X

Area	Environmental Burden of Disease (DALYs/ 10 lac capita)			
	Cardiovascular		Chronic Respiratory	
	From KPCL	Ambient	From KPCL	Ambient
Z-1	0.35		0.15	
Z-2	0.31		0.093	
Z-3	0.28	1.989	0.083	0.811
Z-4	0.21		0.064	

In case of chronic respiratory disease DALYs for SO_2 and NO_X obtained 0.35 and for cardiovascular disease it was obtained 0.15 per 10lac people. This DALYs indicates that 10lac population surrounding the source of maximum pollutants concentration exposure can

lose their life expectancy by 128 days due to cardiovascular disease and 55 days due to chronic respiratory disease.

It has been estimated that exposure to the simulated concentrations of SO_2 and NOx leads to a shortening of the average life expectancy of inhabitants of zone-1 to zone-4. It is worth noting that the proposed by WHO methodology of EBD calculation takes into account the differences in current exposure which reflects different levels of concentrations in selected area. The place of residence and related specific socio-economic and environmental conditions are significant for the value of estimated EBD rate. It is well known that the preferred life style, with registered high frequency of tobacco smoking, is an important determinant of health. The proposed DALYs indicators are useful in further research and policy related to human health for the determination of prioritize actions aimed at improving the health of people exposed to SO_2 and NOx pollution.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusion

The comprehensive study on air quality modeling and health risk assessment of air pollutants generating from Khulna Power plant reveals that:

1) Khulna Power Company Limited (KPCL) of 225 MW power generation capacity using Heavy Fuel Oil (HFO) contains C (83.42%), H (10.02%), S (0.7%), O (0.05%) and N (0.1%) by weight. Functional group analysis of HFO shows that the HFO contains Amino (-NH), Hydroxyl (-OH) and Aliphatic Carbon (-CH), esters (S-OR) and Sulphate (S=O) bonds. The atmospheric emission from KPCL Power plants was estimated as 19.74 t/yr of SO_2, 8.4 t/yr of NO_X, 900 kg/yr of CO, 1.246 t/yr of PM_{10}, 930 kg/yr of $PM_{2.5}$ and 0.27 kg/yr of Lead compounds..

2) Comparing with the available local air quality monitoring station data, it was found that 18.5% of total ambient SO_2 contributed by KPCL emission and 12.36% of total ambient NO_X contributed by KPCL emission. The zone of maximum concentration of pollutants can be identified within 2 km area of the source ($SO_2 \geq 4.5\mu g/m^3$ and $NO_X \geq 1.5\ \mu g/m^3$) emitted from power plant in every month of modeling period

3) Dispersion modeling of pollutants released from KPCL plant showed long range dispersion more than 200km towards downwind direction and this plume dispersion have distinct effect over Sundarban in winter season. The back trajectory model showed that the air pollution from India, Nepal and Bhutan contribute to the local airshed of KPCL area and the pollutants from Bay of Bengal mainly originated from ship emission also had a contribution to the source area.

4) In case of chronic respiratory disease DALYs for SO_2 and NO_X obtained 0.15 and for cardiovascular disease it was obtained 0.35. This DALYs indicates that total population surrounding the source of maximum pollutants concentration exposure will lost their life expectancy by 0.15 year (55 days) due to chronic respiratory and 0.35year (128 days) due to cardiovascular disease.

7.2 Recommendation for Future Studies

From the above given conclusions, the following recommendations could be implied for further studies:

1. Determining the emission factors for different fuel types and combustion processes.

2. Dispersion analysis applying different modeling systems for comparison.

3. Establishing the national reporting process and threshold limit for emission from power generation sector.

4. Long term monitoring of air pollutants in the downwind and upwind areas of power plants.

5. Comprehensive assessment of environmental and health risks due to exposure of criteria pollutants generating from power plants.

REFERENCES

Ahmed, S., & Hossain I. (2008). "Applicability of air pollution modeling in a cluster of brickfields in Bangladesh", Chemical Engineering Research Bulletin pp.28-34.

Ahmed, S. & Mahmud, I. (2011). "Air pollution kills 15,000 Bangladeshis each year: The role of public administration and government's integrity" Journal of Public Administration and Policy Research Vol. 3(4), pp. 129-140, May 2011 ISSN 2141-2480 ©2011 Academic Journals.

ALA (2015). "Toxic Air: The Case for Cleaning Up Coal-Fired Power Plants," Retrieved from http://ala1-old.pub30.convio.net/healthy-air/outdoor/resources/toxic-air-report/

Alam, G. M. (2009). "Environmental pollution of bangladesh – it's Effect and control", International Conference on Mechanical Engineering (ICME2009) 26- 28 December 2009, Dhaka, Bangladesh.

Alberta Health & Wellness Health Surveillance, (2006). "Health Effects Associated with Short-term Exposure to Low Levels of Sulphur Dioxide (SO_2) - A Technical Review",

American Bureau of Shipping (2001). Notes on "Heavy Fuel Oil", Retrieved from www.eagle.org/eagleExternalPortalWEB/ShowProperty/BEA%20Repository/Rules&Guides/Current/31_HeavyFuelOil/Pub31_HeavyFuelOil

ARL (2015). Retrieved from http://www.arl.noaa.gov/HYSPLIT_info.php

Arnab, I. Z., Ali, T.,Sahidujaman, M., Hossain, M. (2013)."Consideration of Environmental Effect of Power Generation: Bangladesh Perspective". Energy and Power Engineering, 1521-1525 doi:10.4236/epe.2013.54B288.

BBS (2016). "Population of Khalishpur thana"., Retrieved from http://en.banglapedia.org/index.phpa

Bella, D., Culpepper1. J., Khaimova, J.(2015). "Characterization of pollution transport into Texas using OMI and TES satellite, GIS and in situ data, and HYSPLIT back trajectory analyses: implications for TCEQ State Implementation Plans" Air QualAtmos Health DOI 10.1007/s11869-015-0363-2

BPDB (2016). "demand Forecast" Retrieved from http://www.bpdb.gov.bd/bpdb/index.php?option=com_content&view=article&id=12 &Itemid=126

Carl, Y. H. (2013). "Effect of Terrain on Mass and Heat Transport of Smoke Plume Based on Geometric Properties of Digital Elevation Model and Satellite Imagery" American Journal of Geographic Information System, p-ISSN: 2163-1131 e-ISSN: 2163-114X 2013; 2(4): 67-81 doi:10.5923/j.ajgis.20130204.01

CASE (2015). "Monthly Air Quality Monitoring Report Reporting Month: August, 2015", Government of the People's Republic of Bangladesh Ministry of Environment and Forests.

Ceballos M.A., Soares, J., Mozo, H., Sofiev, M., Bolivar, J.P. & Galan, C. (2013). "Analysis of atmospheric dispersion of oliv pollen of southern Spain using SILAM and HYSPLIT", Aerobiologia DOI 10.1007/s10453-013-9324-0

CEC (2011). "North American Power Plant Emission". page-14. Retrieved from http://www3.cec.org/islandora/en/item/10236-north-american-power-plant-air-emissions

Challa, V. JayakumarIndracan, J. M Baham, R. Hughes, C. Patrick, J. Young, M. Rabbarison, S. Swanier, Hardy M. G. and Anjaneyulu, Y. (2009) "A Simulation Study of Meso-Scale Coastal Circulations in Mississippi Gulf coast for Atmospheric Dispersion". Atmos. Res., 91, 9-25.

Coates, J. (2000). "Interpretation of Infrared Spectrum, Apartical Approach", Johhn Wiley and Sons, Inc., U.S.A

Connan, O., Smith, K., Organo, C., Solier, L., Maro, D. & Hébert, D. (2013). "Comparison of RIMPUFF, HYSPLIT, ADMS atmospheric dispersion model outputs, using emergency response procedures, with 85Kr measurements made in the vicinity of nuclear reprocessing plant". Journal of environmental radioactivity, 124, 266-277.

Daily Star (2015, March 08). "Bangladesh 4th most polluted in world" Retrieved from http://www.thedailystar.net/bangladesh-4th-most-polluted-in-world-23348

Draxler, R.R., Taylor, A.D. (1982). "Horizontal dispersion parameters for long-range transport modeling". Journal of Applied Meteorology 21, 367e372.

Draxler R.R. (2006). "The Use of Global and Mesoscale Meteorological Model Data to Predict the 632 Transport and Dispersion of Tracer Plumes over Washington, D.C"., Wea. Forecasting, 21, 383- 633 394.

EEA (2008). "Air pollutants and global effect'. Retrieved from http://www.eea.europa.eu/publications/259/page009.html

EEA (2013). "Electricity production by fuel" Retrieved from http://www.eea.europa.eu/data-and-maps/indicators/electricity-production-by-fuel

Ellis, K., C. McHugh, et al. (2001). "Comparison of ADMS-Roads, Caline4 and UK DMRB Model Predictions for Roads." 7th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes

Energy.gov (2015). "Oil-Fired Boilers and Furnaces" Retrieved from http://energy.gov/energysaver/oil-fired-boilers-and-furnaces

Engineering toolbox (2015). "Classification of coal based on volatile matter and cooking power of clean material" Retrieved from http://www.engineeringtoolbox.com/classification-coal-d_164.html

Fleming Z.L., Monks P.S. and, Manning A.J., (2012). Review: "Untangling the influence of air-mass history in 663 interpreting observed atmospheric composition", Atmospheric Research, Volumes 104–105, 664 February 2012, Pages 1-39, ISSN 0169-8095,

Guttikunda, S,K., Begum, B.A., & Wadud, Z. (2012). "Particulate pollution from brick kiln clusters in the Greater Dhaka region, Bangladesh". Air Quality, Atmos. Health, 6(2): 357-365.

Guttikunda, S. K.,& Begum, B. A. (2010). "Particulate pollution from brick kiln clusters in the Greater Dhaka region, Bangladesh". Air Qual. Atmos. Health DOI 10.1007/s11869-012-0187-2.

Harrison, R. N. and Jones, A. M. (2005). "Multisite study of particle number concentrations in urban air." Environmental Science & Technology 39(16): 6063-6070.

Hernandez, L., Probst, A., Probst, J. L., and Ulrich. E., (2003). "Heavy metal distribution in some French forest soils:evidence for atmospheric contaminant". Science of the Total Environment 312, 195.

Hitchins, J., L. Morawska, et al. (2000). "Concentrations of sub-micrometre particle from vehicle emissions near a major road." Atmospheric Environment 34: 51-64.

Holmes, N. S., L. Morawska, et al. (2005). "Spatial distribution of sub-micrometre particles and CO in an urban microscale environment." Atmospheric Environment 39(22): 3977-3988.

India Environment Portal (2016). "Revised standards for Coal-based Thermal Power Plants" Retrieved from http://www.indiaenvironmentportal.org.in/content/423111/revised-standards-for-coal-based-thermal-power-plants/

Kakula, S. E., (2003). "Trace metal concentration in roadside surface soil and tree back: Ameasurement of local atmospheric pollution in Abuja, Nigera". Envronmental Monitoring Assessment- 89, 233

Kalnay, E., and Coauthors, (1996). "The NCEP/NCAR 40-Year reanalysis project". Bull. Amer. Meteor. Soc., 77, 437-471.

Kato, N., Ogawa, Y., Koike, T., Sakamoto, T., Sakamoto, S., & Group, R. (1991). "Analysis of the structure of energy consumption and the dynamics of emissions of atmospheric species related to the global change (SOx, NOx and CO_2) in Asia". NISTEP Report no 21, 4th Policy-oriented Research Group, National Institute of Science and Technology Policy, Tokyo

KPCL:Khulna Power Company Limited (2014). "Annual Report" Retrieved from http://www.khulnapower.com/wp-content/uploads/2015/12/Annual-Report-2014.pdf

Le, H.A. & Oanh, N.T., (2010). "Integrated assessment of brick kiln emission impacts on air quality". Environ. Monit.Assess., 171: 381-394

Lin, J. C., C. Gerbig, Wofsy, S. C., Andrews, A. E., Daube, B.C., Davis, K. J. & Grainger, C. A. (2003). "A near-field tool for simulating the upstream influence of atmospheric observations: The Stochastic TimeInvertedLagrangian Transport (STILT) model". J.Geophys. Res., 108, 4493, doi:10.1029/2002JD003161.

Lin, A., Dylan, B., Millet, B., Ariel F. Stein, C., and Draxler, R. (2012). "A backward-time stochastic Lagrangian air quality model" 2012, Atmospheric Environment 54: 373-386

Monn, C., A. Fuchs, et al. (1997). "Particulate Matter less than 10 μm (PM_{10}) and Fine Particles less than 2.5 μm ($PM_{2.5}$): Relationship between Indoor and Outdoor and Personal Concentrations." The Science of the Total Environment 208: 15-21.

Morawska, L. (2003). "Motor vehicle emissions as source of indoor particles". Indoor Environment. XVII:297-319.

Moti, M. L. (2006). "Estimates of Emissions from Coal Fired Thermal Power Plants in India. Retrieved from http://www.air-quality.org.uk/04.php

Myles L, Dobosy RJ, Meyers TP, Pendergrass W.R. (2009). "Spatial variability of sulfur dioxide and sulfate over complex terrain in East Tennessee, USA". Atmos Environ 43:3024–3028

Olivier, Jos, G.J(PBL)., Janssens-Maenhout, Greet (IES-JRC)., Muntean, Marilena (IES-JRC)., & Peters, Jeroen, A.H.W. (2015). Trends in global CO_2 emissions.Prepared for PBL Netherlands Environmental Assessment Agency.

Parrish, D. F., and Derber, J. C. (1992). "The National Meteorological Center's spectral statistical interpolation analysis system". Mon. Wea. *Rev*., 120, 1747-1763.

Roorda-Knape, M. C., N. A. H. Janssen, et al. (1998). "Air Pollution from Traffic in City Districts near Major Motorways." Atmospheric Environment 32: 1921- 1930.

Sharan, M., A. K. Yadav, et al. (1996). "Plume dispersion simulation in low-wind conditions using coupled plume segment and Gaussian puff approaches". Journal of Applied Meteorology 35(10): 1625-1631.

South Asia. (2001). "Pollution Causes 15,000 Deaths Annually. Number 395". Retrieved from http://southasia@yahoogroups.com

Stein, A.F., Draxler, R.R, Rolph, G.D., Stunder, B.J.B., Cohen, M.D., and Ngan, F. (2015). "NOAA's HYSPLIT atmospheric transport and dispersion modeling system, Bull. Amer". Meteor. Soc., 96, 2059-2077

USEIA (2014). "Electricity in the Uinited States" Retrieved from www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states

USEPA (1996). "Requirements for preparation, adoption and submittal implementation plan". Final rule, Republishing the US guidelines for Air Quality Models, 61 Fed. Reg. 41837-418934.

USEPA (2012). "U.S. Power Plant Emissions Report Reflects Industry's Transition to Cleaner Energy". Retrieved from http://www3.epa.gov/mats/powerplants.html

USEPA (2014). "Climate Change Indicators in the United States: Global Greenhouse Gas Emissions". Retrieved from www.epa.gov/climatechange/indicators

USEPA (2015). "Cleaner Power Plants". Retrieved from http://epa.gov/mats/powerplants.

Vardoulakis, S., B. E. A. Fisher, et al. (2003) "Modelling air quality in street canyons: a review." Atmospheric Environment 37(2): 155-182.

Weather and Climate (2015). "Average weather in Bangladesh" Retrieved from www.Weather-and-climate.com/average-monthly-rainfall-temperature.

Wang, J., Hiscox, A. L., Miller, D. R., Meyer, T. H. & Sammis, T. W. (2009). "A comparison of Lagrangian model estimates to light detection and ranging (LIDAR) measurements of dust plumes from field tilling". Journal of the Air & Waste Management Association, 59, 1370-1378.

Wang, J., Sammis, T. W., Miller, D. R., Hiscox, A. L., Granucci, D., Holmén, B., Kasumba, J., Shukla, M. K., Dennis, S. O. & Zhang, X. (2009). "Simulate Regional PM10 Dispersion from Agricultural Tilling Operations Using HYSPLIT4". Journal of the Air & Waste Management Association, 59.

Wang, Y., Stein, A. F., Draxler, R. R., De La Rosa, J. D. & Zhang, X. (2011). "Global sand and dust storms in 2008: Observation and HYSPLIT model verification". Atmospheric Environment, 45, 6368-6381.

WHO (2013). "Review of evidence on health aspects of air pollution – REVIHAAP project". Technical Report. Retrieved from http://www.euro.who.int/data/assets/pdf_file/0004/193108/REVIHAAP-Final-technical report-finalversion.pdf.

WHO (2016). "Air pollution is now a global 'public health emergency", Retrieved from http://www.independent.co.uk/environment/air-pollution-public-health-emergency-who-world-health-organisation-a6821256.html.

World Bank (2006) Bangladesh. "Country Environmental Analysis", Bangladesh Development Series. Paper No: 12.

WRI: World Resources Institute (2014). "Climate Analysis Indicators Tool (CAIT) 2.0" WRI's climate data explorer. Retrieved from http://cait.wri.org.

Zhu, Y., W. C. Hinds, et al. (2002). "Concentration and Size Distribution of Ultrafine Particles Near a Major Highway." Journal of Air and Waste Management Association 52: 1032-104.

APPENDIX –A (Table)

Table A-1 Maximum concentration and deposition of SO_2 in November 2014 and December 2014

Month	Concentration ($\mu g/m^3$)	Deposition (mg/m^2)	Month	Concentration ($\mu g/m^3$)	Deposition (mg/m^2)
1(Nov)	7.79	0.64	1 (Dec)	7.79	0.88
2	7.38	0.80	2	12.51	1.12
3	6.15	0.76	3	14.97	1.60
4	17.43	1.64	4	13.53	1.86
5	7.79	0.62	5	10.25	1.34
6	4.51	0.38	6	8.00	1.00
7	6.56	0.62	7	4.92	0.46
8	4.92	0.42	8	15.17	1.28
9	8.82	0.82	9	20.50	0.66
10	5.95	0.54	10	7.18	0.62
11	9.02	1.10	11	5.13	0.34
12	9.43	1.00	12	7.59	0.56
13	6.56	0.60	13	6.77	0.46
14	4.10	0.40	14	7.79	1.02
15	7.18	0.76	15	4.31	1.34
16	7.18	0.74	16	2.03	0.18
17	7.38	0.58	17	3.28	0.48
18	7.38	0.38	18	4.31	0.92
19	4.31	0.40	19	4.10	0.38
20	5.13	0.22	20	5.95	0.34
21	5.74	0.38	21	4.31	0.38
22	5.33	0.52	22	4.51	0.40
23	6.36	0.56	23	4.72	0.34
24	6.15	1.06	24	3.49	0.30
25	3.49	0.30	25	3.69	0.28
26	7.18	0.62	26	4.51	0.38
27	9.84	1.08	27	4.51	0.44
28	8.82	1.00	28	5.54	0.40
29	8.20	0.76	29	10.25	1.12
30	5.13	0.44	30	14.76	1.68
			31	12.43	1.19

Table A-2 Maximum concentration and deposition of SO$_2$ in January 2015 and February 2015

Month	Concentration ($\mu g/m^3$)	Deposition (mg/m^2)	Month	Concentration ($\mu g/m^3$)	Deposition (mg/m^2)
1(jan)	15	1.14	1 (Feb)	5.6	0.70
2	5	1.66	2	7.2	0.88
3	11.6	3.20	3	9	1.22
4	4.2	0.42	4	8.6	1.02
5	4.2	0.38	5	8.4	0.96
6	5.4	0.56	6	9.2	1.22
7	6	0.46	7	6	0.64
8	7	0.74	8	7	0.72
9	6.4	0.62	9	8	1.04
10	3.6	0.32	10	7.4	0.54
11	4.4	0.30	11	4.6	0.88
12	5.6	0.42	12	13.6	1.38
13	5	0.60	13	9.6	0.92
14	7.2	0.84	14	10.8	1.32
15	11.4	1.40	15	6.4	0.76
16	7.2	0.80	16	13.2	0.54
17	5.2	0.54	17	22	1.50
18	4.8	0.58	18	6.2	0.72
19	5.6	0.44	19	4.2	0.38
20	7.6	0.68	20	11.2	1.24
21	7.6	0.78	21	9.6	1.22
22	6.8	0.80	22	5.4	0.44
23	6.4	0.70	23	7.4	1.18
24	7	0.70	24	4.4	1.62
25	6.4	0.60	25	4.6	0.38
26	8.2	1.58	26	4	0.76
27	6.8	2.40	27	4	1.18
28	5.4	0.44	28	3.2	1.11
29	7.4	1.30			
30	4.4	1.62			
31	5.7	1.49			

Table A-3 Maximum concentration and deposition of NO_X in November 2014 and December 2014

Month	Concentration ($\mu g/m^3$)	Deposition (mg/m^2)	Month	Concentration ($\mu g/m^3$)	Deposition (mg/m^2)
1(Nove)	3.23	0.37	1 (Dec)	3.23	0.27
2	3.06	0.48	2	5.19	0.34
3	2.55	0.68	3	6.21	0.32
4	7.23	0.79	4	5.62	0.70
5	3.23	0.57	5	4.26	0.26
6	1.87	0.43	6	3.32	0.16
7	2.72	0.20	7	2.04	0.26
8	2.04	0.54	8	6.30	0.18
9	3.66	0.28	9	8.51	0.35
10	2.47	0.26	10	2.98	0.23
11	3.74	0.14	11	2.13	0.47
12	3.91	0.24	12	3.15	0.43
13	2.72	0.20	13	2.81	0.26
14	1.70	0.43	14	3.23	0.17
15	2.98	0.57	15	1.79	0.32
16	2.98	0.07	16	0.84	0.31
17	3.06	0.20	17	1.36	0.25
18	3.06	0.39	18	1.79	0.16
19	1.79	0.16	19	1.70	0.17
20	2.13	0.14	20	2.47	0.09
21	2.38	0.16	21	1.79	0.16
22	2.21	0.17	22	1.87	0.22
23	2.64	0.14	23	1.96	0.24
24	2.55	0.13	24	1.45	0.45
25	1.45	0.12	25	1.53	0.13
26	2.98	0.16	26	1.87	0.26
27	4.09	0.19	27	1.87	0.46
28	3.66	0.17	28	2.30	0.43
29	3.40	0.48	29	4.26	0.32
30	2.13	0.71	30	6.13	0.19
			31	3.23	0.27

Table A-4 Maximum concentration and deposition of NO_X in January 2015 and February 2015

Month	Concentration ($\mu g/m^3$)	Deposition (mg/m^2)	Month	Concentration ($\mu g/m^3$)	Deposition (mg/m^2)
1(jan)	6.38	0.49	1 (Feb)	2.38	0.35
2	2.13	0.71	2	3.06	0.44
3	4.94	1.36	3	3.83	0.61
4	1.79	0.18	4	3.66	0.51
5	1.79	0.16	5	3.57	0.48
6	2.30	0.24	6	3.91	0.61
7	2.55	0.20	7	2.55	0.32
8	2.98	0.31	8	2.98	0.36
9	2.72	0.26	9	3.40	0.52
10	1.53	0.14	10	3.15	0.27
11	1.87	0.13	11	1.96	0.44
12	2.38	0.18	12	5.79	0.69
13	2.13	0.26	13	4.09	0.46
14	3.06	0.36	14	4.60	0.66
15	4.85	0.60	15	2.72	0.38
16	3.06	0.34	16	5.62	0.27
17	2.21	0.23	17	9.36	0.75
18	2.04	0.25	18	2.64	0.36
19	2.38	0.19	19	1.79	0.19
20	3.23	0.29	20	4.77	0.62
21	3.23	0.33	21	4.09	0.61
22	2.89	0.34	22	2.30	0.22
23	2.72	0.30	23	3.15	0.59
24	2.98	0.30	24	1.87	0.81
25	2.72	0.26	25	1.96	0.19
26	3.49	0.67	26	1.70	0.38
27	2.89	1.02	27	1.70	0.59
28	2.30	0.19	28	3.32	0.44
29	3.15	0.55			
30	1.87	0.69			
31	6.38	0.49			

Table A-5 Ambient concentration and Simulated concentration from HYSPLIT from 1st September 2013 to 22nd September 2013

Date	SO_2 (ambient) $(\mu g/m^3)$	SO_2 From KPCL $(\mu g/m^3)$	NO_X (ambient) $(\mu g/m^3)$	NO_X From KPCL $(\mu g/m^3)$
01.09.13	15.37	3.8	12.68	1.6
02.09.13	14.6	6.3	13.67	2.6
03.09.13	27.71	5	13.62	2.2
04.09.13	23.85	2.3	13.21	1
05.09.13	37.16	3.6	15.59	1.4
06.09.13	28.73	2.4	13.19	1
07.09.13	22.8	4.2	13.47	1.6
08.09.13	43.28	8.6	14.68	3.4
09.09.13	45.66	5.8	13.81	2.4
10.09.13	16.86	5.6	14.27	2.2
11.09.13	41.75	4.7	13.92	1.8
12.09.13	56.89	8.8	18.05	3.6
13.09.13	13.32	6.4	20.03	2.6
14.09.13	14.82	5.5	17.1	2.2
15.09.13	176.85	9.1	31.86	4.6
16.09.13	236.56	8.7	32.1	5.2
17.09.13	113.02	3.2	32.18	1.2
18.09.13	60.35	4.5	33.66	1.8
19.09.13	78.09	8.2	32.81	3.8
20.09.13	49.39	6.3	32.59	2.6
21.09.13	74.47	5.9	32.68	2.4
22.09.13	26.18	9.7	32.31	2.2

Table A-6 Combustion Analysis of HFO

Time elapsed (mins)	Pollutant concentration (mg/m^3)		Temperature (^{o}C)
	SO$_2$	NO$_X$	
05	0	2	50
10	0	2	74
15	0	2	100
20	0	2	116
25	0	2	124
30	0	2	148
35	17	12	182
40	143	33	202
45	328	105	288
50	394	127	320
55	443	209	344
60	103	78	360+

Table A-7 Pollutants response function (β)

Pollutants	Disease	β
PM2.5	Total Mortality	0.058
	Chronic Bronchities	0.091
	Non Fatal Stroke	0.025
CO	Asthma	0.033
	Lung Disease	0.025
	Dysrhthmias	0.058
	Heart Failure	0.034
NO$_X$	Respiratory Disease	0.004
	Heart Failure	0.003
	Ischemic Heart Disease	0.003
O$_3$	Mortelity	0.001
	Asthma	0.003
	Lung Disease	0.003
	Respiratory Infection	0.002
	Dysrhthmias	0.002
SO$_2$	Respiratory Infection	0.002
	Heart Disease	0.0028

APPENDIX –C (Calculation)

C-1 <u>CALCULATION OF CALORIFIC VALUE</u>

$$CX + C_1X_1 = (M+W)(\Delta\Theta + 0.5\Delta t\ r^o)$$ ……………………(1)

Where,

      C = calorific value

      C_1= 2.79 cal/cm

      X_1= fuse length after burnt

      M= mass of water

      W= 206 g/^{o}C

      Δt= time elapsed

      r^o= 0.008

<u>Test-1</u>

Initial Temperature of the fuel= 29°C

Initial fuse length =14 cm

Time elapsed(sec)	30	30	30	30	30	30
Temp (^{o}C)	30.5	31	31.2	31.3	31.4	31.5

Final length of fuse = 13 cm

Fuse burnt = 1 cm

From equation (1) we get

$$CX + C_1X_1 = (M+W)(\Delta\Theta + 0.5\Delta t\ r^o)$$

$C*1 + 2.73*13 = (1500 + 206)(2.5 + 0.5*3*0.008)$

C = 4249.202 cal/gm   x 4.18

  = 17761.664 Kj/kg

  = 17.761 Mj/ kg

C-2 EMSSION ESTIMATION

The generalized equation for estimating emission from fossil fuel power generation

$E_{kpy,i}$= AR x EF_{ix} [1 - (CE_i/100)]

where :$E_{kpy,i}$= emission rate of pollutant i, kg/yr

AR = activity rate (fuel use), t/yr

EF_i= uncontrolled emission factor of pollutant i, kg/t

CE_i= overall control efficiency for pollutant i, %.

For KPCL Power plant (considering uncontrolled emission)

Activity rate for the used fuel oil = fuel usage * calorific value/$1E^6$

$$= 600 * 17.761/1E6$$

$$= 0.01 \text{ Pj/ day}$$

SO_2 Emission:

E_{SO2}= AR x EF [1-(CE/100)]

$\quad$ = 0.01 *4.7X10^5S [1-(0/100)]

$\quad$ =**329 kg/day**

> For residual fuel oil, EF= 4.7X10^5S
>
> Where, S= sulfur content = 0.7

NO_X EMISSION:

E_{NOX}= 0.01 *1.4X10^4 [1-(0/100)]

$\quad$ = **140 kg/day**

> For residual fuel oil, EF=1.4X10^4

CO Emission

E_{CO}= 0.01 *1.5X10^3[1-(0/100)]

$\quad$ = **15 kg/day**

> For residual fuel oil, EF=1.5X10^3

PM_{10}Emission:

E_{PM10}= 0.01*1.8X10^3A *[1-(0/100)]

$\quad$ = **20.77 kg/day**

> Particulate emission factors for residual fuel oil combustion without emission control are, on average, a function of fuel oil grade and sulfur content (S)
> A = 1.12 x (S) + 0.37
> $\quad$ = 1.154
> EF= 1.8X10^3A

PM$_{2.5}$ Emission:

E$_{PM2.5}$ = 0.01*1.2X10^{3}A *[1-(0/100)]

      = **13.834 kg/ day**

Lead compounds Emission:

E$_{Lead}$ = 0.01* 4.51-(0/100)]

    = 0.0045 kg/day

For residual fuel oil, EF=4.5

[**Source**: Australia Government, Department of sustainability, environment, water pollution and communities (2012), Emission Estimation Technique Manual for fossil fuel electric power generation. Retrieve from http://www.npi.gov.au]