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IMPACT OF EMISSIONS RESULTS FROM POWER GENRATION ON THE AIR QUALITY OF SELECTED URBAN AREAS IN KUWAIT

By

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Abstract

Air pollution in urban areas is a problem affecting many countries in the world and has important implications for health and environmental management. However, air quality prediction plays an important role in the controlling air pollution problem. Air-quality models are also extensively used in all aspects of air pollution control and to predict spatial and temporal dispersion of pollutants in the atmosphere. The main objectives of this work are to provide an overview of the pollutant levels and their trends in the study area (Rabia) and to predict the ground level concentrations of sulphur dioxide (SO_2) and nitrogen oxide (NOx) mainly emitted from power generation stations by using Source Complex model for Short-term Dispersion (ISCST4.5) for years 2001 and 2004.

The hourly air pollutants concentrations were measured continuously by fixed ambient air stations located over the polyclinics in Rabia area in Capital Governorate in the State of Kuwait. The first objective of this research is to determine the pollution levels of sulphur dioxide (SO_2), nitrogen oxide (NOx), consisting of nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO) and ozone (O_3) in year 2001 and 2004 in order to assess the pollution trends. However, the pollutants levels were found to exceed of Kuwait Environmental Public Authority (K-EPA) standards. The recorded data are used in identification of the most probable sources of these pollutants. The diurnal patterns were observed and analyzed for different seasons for two years 2001 and 2004. Weekdays and weekend variation on ozone pollution has been thoroughly investigated. It is observed that SO_2 and O_3 monthly levels were higher in year 2001 as compared to year 2004 due to prevalent meteorological conditions that has high wind speed and dusty weather in year 2004 as compared to year 2001, providing an adequate dispersion. The monthly average concentrations of NOx, NO_2 and CO in year 2004 are higher than year 2001. This is mainly due to high urbanization and increases industrial emissions caused by industrial growth other than increase in number of cars over the years and operation of power generation plants at full capacity to cover the skyrocketing demand of utilities with expanding urbanization. The O_3 levels of the daytime hours from April to September

period have shown high buildup on weekends as compared to weekdays due to low NO generation as a consequence of decrease in traffic density on the roads.

In Kuwait, two main power stations, one comprising of seven-300MW steam generators at Doha and other with eight-300MW steam generators at Subyia cover the major power requirement of Kuwait city. These stations used different types of fuel oil as the prime source of energy that has different sulpher contents (S %). Comprehensive emission inventories for the year 2001 and 2004 were used to execute Source Complex model for Short-term Dispersion (ISCST4.5) to predict ambient ground level concentrations of sulphur dioxide (SO_2) and nitrogen oxide (NOx) at selected receptors. A yearlong meteorological data were used in conjunction with the dispersion model to compute SO_2 and NOx levels in and around the power stations. Contributions of each power station to the highest predicted values were assessed. Significance of the fifty highest hourly, daily and annual ground level concentration values under existing meteorological conditions was analyzed.

For validation of the model, computed results were compared with the measured daily average values at a fixed Kuwait EPA air quality monitoring station located at the roof of polyclinic in Rabia residential area. The model results have been compared with the observed values at Kuwait EPA air quality monitoring station at Rabia using it as a discrete receptor. Top fifty daily average values showed a slope of 0.806 for 2001 under predicting 20% and 0.96 for 2004 under predicting 4% which is predicting more accurately than the previous run of year 2001. The slope of the daily predicted ground level concentration of NOx against the observed values was equal to 0.52 for 2001 under predicting 48% and 0.71 for 2004 under predicting 29%. Validation of the model results showed a greater discrepancy in case of NOx as compared to SO_2.

The results for 2001 revealed that daily and annual mean predicted SO_2 concentrations had exceedence about 16.5% and 0.57% while for 2004 increased to 40.8% and 0.3% respectively of the total area under investigation. In case of NOx there is no violation exceeding the standards limits of Kuwait EPA.

The emission inventories for the years 2001 and 2004 have been used in Source Complex model for Short-term Dispersion (ISCST4.5) to predict ambient ground level concentrations of sulphur dioxide (SO_2) and nitrogen oxide (NOx) at selected receptors for years 2001 and 2004 to compare the influence of increase in emission rates due to urban and industrial growth. For both years, the respective meteorological data were used in conjunction with the dispersion model to compute SO_2 and NOx levels in and around the power stations. The five highest hourly, daily and annual ground level concentration values under prevailing meteorological conditions were compared for year 2001 to 2004. It was found that the hourly mean concentrations were strongly influenced by prevailing meteorological conditions resulting into higher values as compared to year 2004. The effect of meteorological conditions have not been that dominant for daily and annual mean values and the predicted values for year 2004 were higher than year 2001 based on high emission rates in summer months.

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Chapter 1

General Introduction

1.1: Introduction

Air pollution is one of the world's major urban environmental problems. Resulting from industrialisation and rapid urban growth, the air pollution problem is caused by emissions from fixed, mobile, area and biogenic sources (Peavy, *et al.,* 1985). However, there are several sources of air pollution that strongly influence the air quality and industrial emissions, such as power plants, transportation and natural sources. Air pollution can have negative impacts on the health of humans, animals, vegetation and architecture (Larsen *et al.*, 1991; Laurance, 1998), and increasing levels of air pollution can erode materials (Brunekreef, *et al.*, 2002). However, air pollution is not only an emissions problem; it is also considered to be a weather hazard that is influenced by weather conditions or other weather-related phenomena (Pielke, 1979). Furthermore, many studies have shown that high concentrations of air pollutants are associated with increases in mortality and morbidity caused by respiratory conditions (USA- EPA, 1996).

Increases in population size with the rise of standards of living due to industrialisation have created strains on the environment. However, the importance of preventing air pollution has increased in recent years due to increasing knowledge of pollution sources and the trends and levels of air pollution. All cities of the world are facing an acute problem of air quality, and pollutants are continuously monitored at many locations to provide up to date information about air quality indices. However the pollutants are divided into primary pollutants, which are emitted directly from the source of pollution, and secondary pollutants, which are formed in the atmosphere as a result of photochemical reactions (Bizjak *et al.*, 1988; Valeroso *et al.*, 1992).

Economic development in the world has been achieved very successfully, reaping rich benefits that can be gauged by factors such as luxurious and comfortable living, which also come with a heavy price tag. Uncontrolled use of natural resources has resulted in the depletion and reduced availability of these resources. Nature has the ability to regenerate the resources over a given time span, but when this drive to extract these resources to ensure personal economic development occurs at the cost of the environment, many problems are created. Unfortunately the costs of the treatment procedures are substantial and require equal amounts of dedication and expertise.

The world today, marching in the direction of progress with little care for the environment, creates a variety of problems of considerable magnitude. In addition, there have been a large number of calamities and accidents such as all of the wars that have taken place to date and the disaster at the Chernobyl nuclear power plant in the Ukraine on April 1986.

The problem over the world is not the technology but the people using the technology and the level of environmental information being used. Technology allows people to see to the various aspects of any situation, including the pros and cons; problems generally arise when one exploits the benefits while not considering the potential complications. To be more precise, it is usually the decision-making step that brings problems to our environment. There are incidents that have resulted from attempts to curb waste disposal requirements, which include the London smog incident, the Ganga river case history, the Taj Mahal case history, etc. The London smog incident during the winter of 1952 resulted from the combustion of rich sulphur coal for domestic heating and consisted of a mixture of SO_2 and acidic sulphate fog. The formation of the London smog was mainly due to higher emissions from the use of coal together with critical weather conditions. Numerous environmental complications today resemble this sad saga, such as the Global Warming Issue, the Ozone Hole problem, the Acid Rain issue, and the Arabian Gulf fish kill issue. Judicious

decisions that conservatively dictate where to draw the line are needed when dealing with these issues.

Sustainable development can be helpful in these issues, and it is aimed at controlling the use of resources, cleaner production technologies, developing environmentally friendly manufacturing processes, lowering the volumes of waste generated, lowering profit margins, and using resources more thoughtfully so as to safeguard these resource banks for the future generations. This ensures a moderate income, a modestly flourishing economy, reduced pollutant burdens on nature, a simplified recovery to a normal state and a bright future for the younger generations, with safer and healthier environments to live in.

None of this can be achieved without a large amount of resolve and hard work. It involves a sense of responsibility and hard work directed towards both safeguarding nature and instilling this responsibility in future generations. However, addressing the overall problem is vital, and achieving this task is only possible if tackled righteously at all levels of society by people in all walks of life and if every obstacle is dealt with using the necessary team spirit. In addressing the problem, the authorities and other key figures or institutions that keep track of such issues play key roles. The authorities in this case are the local Environmental Protection Authority (EPA) or the environmental ministry in a given country that tracks environment pollution and establishes rules and regulations to keep the pollution under check.

Air pollution can be judged by the presence of certain characteristic gaseous and particulate species that act as indicators of the level of pollution in the atmosphere. They have a special significance with respect to their effects on human health and the environment as a whole. The most significant among these include hydrocarbons, nitrogen oxides, sulphur oxides, hydrogen sulphide, ozone and particulate dust. Hydrocarbons such as polycyclic aromatic hydrocarbons (PAH's) and Volatile Organic Compounds (VOC's) are mainly considered to be

hazardous due to recent reports of their carcinogenic effects and the contributions of methane to global warming. The major sources of pollution in mega-cities are power plants, oil production plants, refineries and transportation, all of which are associated with sulphur dioxide (SO_2), nitrogen oxide (NOx), carbon oxide (CO), carbon monoxide (CO_2), ozone (O_3), VOCs, lead and particular matter (PM) (Seinfeld, 1986).

Nitrogen oxides (NOx) are formed mainly due to the combination of atmospheric oxygen and nitrogen at high temperatures and are considered to be a vital indicator of air pollution as they aggravate asthmatic conditions, can form nitric acid on reacting with water and contribute to the acid rain issue, and by themselves are precursors to the formation of ozone. Sulphur dioxides (SO_2) are formed mainly due to the burning of fuel containing sulphur and also contribute to the acid rain problem, while hydrogen sulphide is a potential hazard by itself. Carbon monoxide (CO_2) is formed due to incompletely burned fuel. Large amounts of SO_2, NOx, VOCs and PM have been released into the atmosphere, bringing about a series of environmental problems, such as degradation of air quality, increases of acid deposition, as well as damages to the ecosystem (Zhiwei Han *et al.*, 2007). Ozone (O_3) is another hazard that is considered to be a serious air pollution problem for many industrialised countries as it causes detrimental human health problem and also damages vegetation, architecture and ecological systems (Spektor *et al.*, 1991; Kinney *et al.*, 1996). Its function is limited to the upper atmosphere, where it filters out the harmful UV radiation from the sun, while its harmful effects are primarily felt at ground level, where it is the key component of photochemical smog, and it is also an eye irritant and interferes with photosynthesis and plant growth. Particulate dust is also an issue in terms of air pollution, and particles of 2.5 microns or less are the most concerning. Particles of this size cannot be filtered by the respiratory tract and find their way into the lungs, where they cause a variety of asthmatic complications. However, there is a global effort to study, detect and find solutions to reduce the concentrations of these potential hazards.

The United States Clean Air Act of 1970 established a set of national standards of ambient air quality to protect humans and the environment from harmful effects of air pollution. In establishing air quality standards, regulations have been introduced in order to set limits on the emissions of pollutants so that they cannot exceed certain prescribed maximum limit values. For this purpose, it is required by the local regulatory authorities that monitoring stations are set up at various locations. Locations are selected based on prevalent activities that are potential threats, and activities at these stations are evaluated through monitoring networks that keep a track of these activities.

There are two main air quality assessment tools that assist in determining air quality: ambient air monitoring and atmospheric dispersion models. In order to create a strategy to control the air pollution problems in industrial countries, it is imperative to establish ambient air quality monitoring stations as monitoring networks. These stations are established to determine the spatial and temporal variation of the pollutant concentrations at residential and study areas. In the beginning of the 1950's, urban air pollution monitoring networks were established in many large developed cities of the world. However, the first major review for the air pollution monitoring programmes took place in Leicester, England in 1937-1939 to measure the pollutant concentrations at sources (Meetham and Monkhouse, 1945). In addition, the objectives of a monitoring network were to detect violations of the ambient air quality standards and to validate the air pollution diffusion models. The design of an air quality monitoring network for monitoring ambient air has been the subject of several publications (USA-EPA, 1971, Noll and Miller, 1977 and Liu *et al.*, 1986). Computer techniques used in conjunction with both deterministic and statistical approaches provide powerful tools to study the impact of pollutants on the environment. They also enable the prediction of likely outcomes and help to develop environmental safe guards. Models are used to calculate the spatial and temporal concentrations of pollutants at study areas and are validated with actual data to verify both the authenticity of novel approaches and their compatibility

with the Environmental Public Authority (EPA) criteria. Air pollution models such as Industrial Source Complex Short Term (ISCST) (USA-EPA, 1995) were used to predict the hourly pollution concentrations for a period of up to a year in order to calculate the ground level concentrations of specific pollutants at Discrete Cartesian and Uniform Cartesian Receptors.

The State of Kuwait is considered to be one of the top fifteen developed countries in the world in terms of the emission of SO_2 with 5% emission of SO_2 (see Figure 1.1). Kuwait has high emissions of SO_2 due to petroleum industrials and the large amount of fossil fuel oil containing high sulphur used in power stations to cover the energetic demands of electricity and water desalination. However, Figures (1.2) and (1.3) show respectively the SO_2 and NOx emissions per populated area in the highest twenty countries around the world. The State of Kuwait has been identified as one of the top twenty countries for the emission of SO_2 with 5% and NOx with 3% per populated area (thousand metric tons / Square km). (www.NationMaster.com).

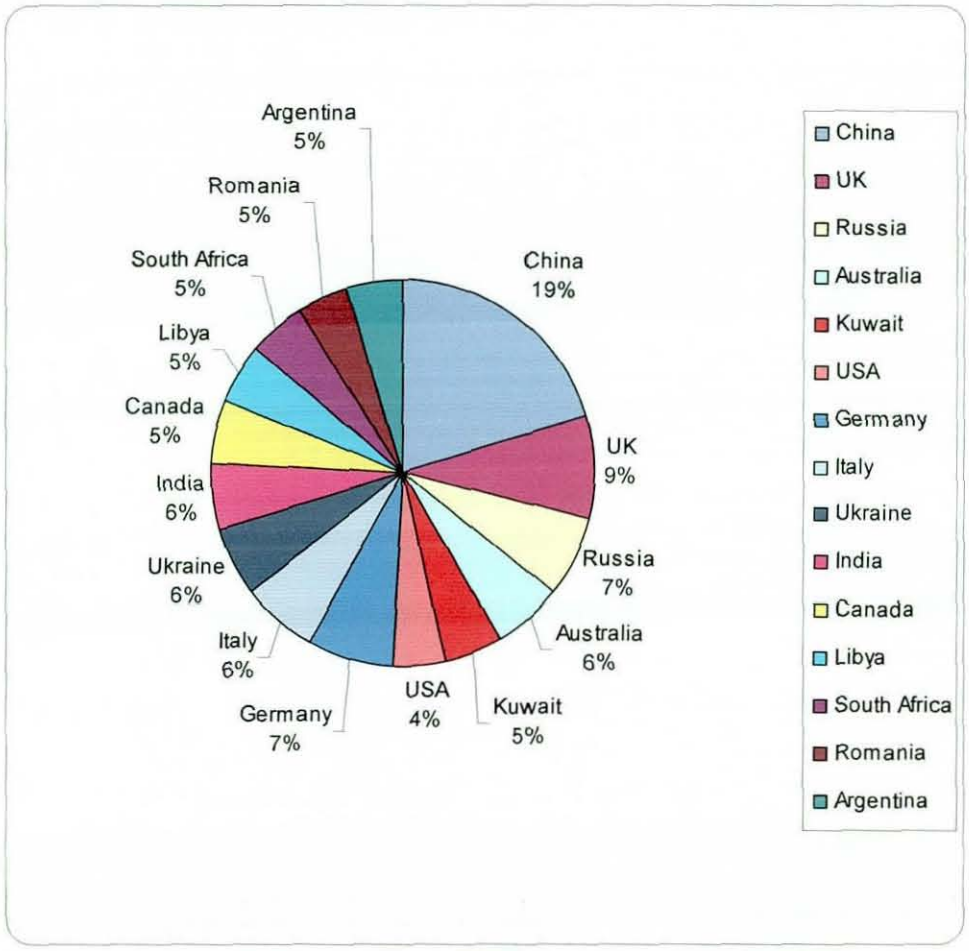


Figure 1.1: Percentage of SO_2 emission in Kuwait compared with the highest fifteen countries in the world (www.NationMaster.com).

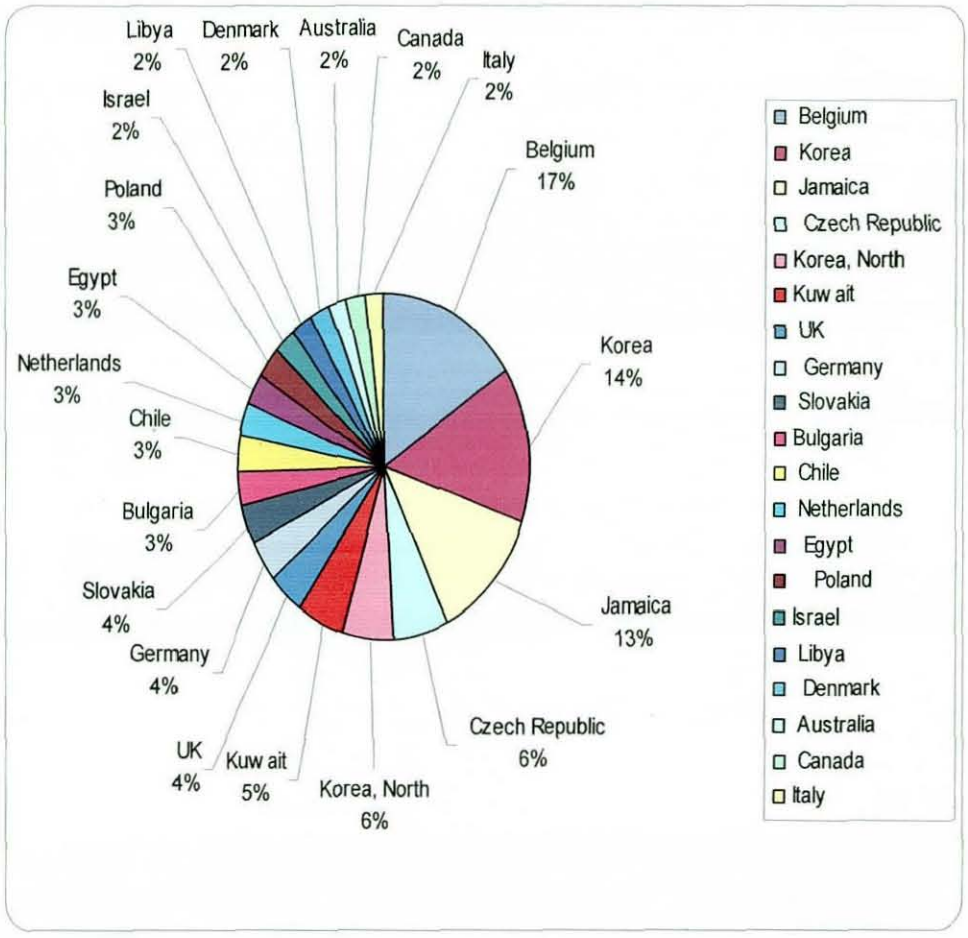


Figure 1.2: Percentage of SO_2 emissions per populated areas in Kuwait in comparison with highest twenty countries in the world (www.NationMaster.com)

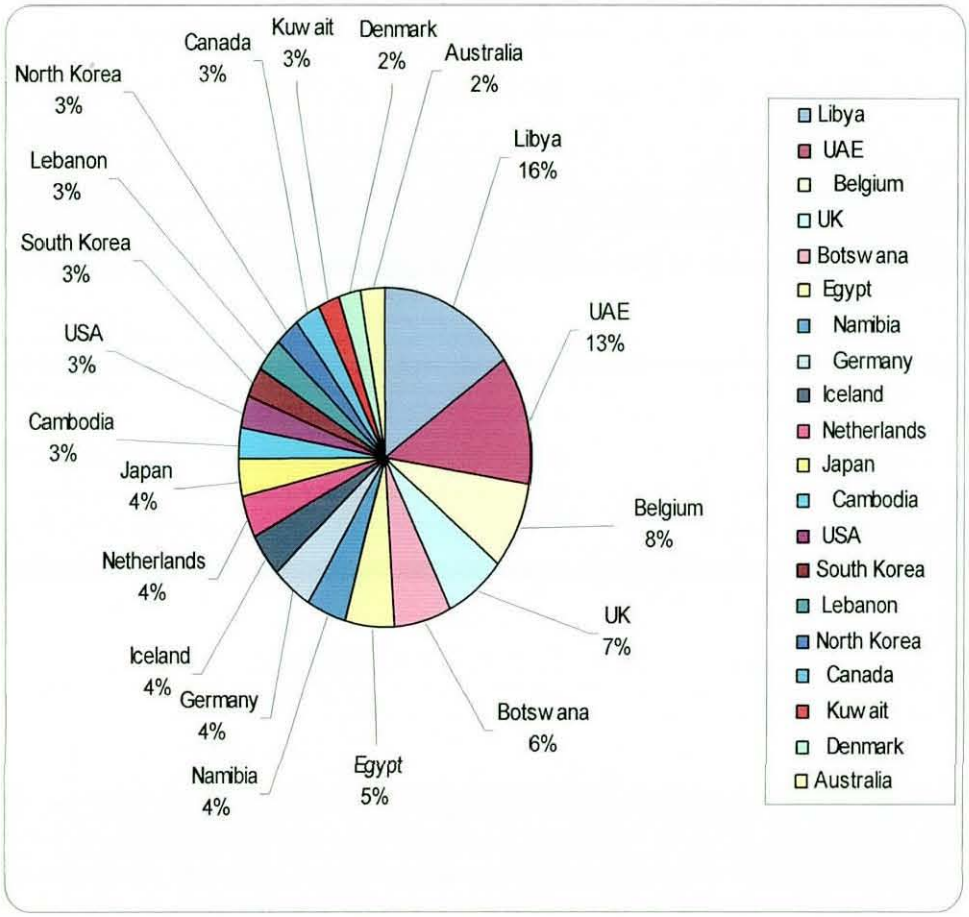


Figure 1.3: Percentage of NOx emissions per populated area in Kuwait in comparison with highest twenty countries in the world (www.NationMaster.com).

1.2: Kuwait's Position on the Issue of Air Pollution

The impact of economic and industrial activities on the environment and human health is an ever increasing concern around the world. This is particularly important considering the inevitable rise of the living standards in many parts of the world. There is a very fine line between meeting the demands of economic growth and safeguarding the environment. Kuwait is not an exception to these worldwide trends, and its environment requires protection in the face of significant rise in its prosperity.

Kuwait, as a budding developing nation, is on the global map due to its advancement after the discovery of oil. The economic development has brought about a radical change in the lives of the people in terms of improved lifestyles, but this has had its drawbacks. The state of Kuwait is an oil-producing country and has invested heavily in petroleum and petrochemical industries. Kuwait is an OPEC member, produces almost 2.5 million barrels of oil per day, and has numerous petroleum refineries, petrochemical plants, petroleum dispensing centres, power stations, and oil-related industries. In addition, Kuwait has highly congested roads with a heavy flux of traffic. However, the air pollution problem in the state of Kuwait resulted from the emissions of toxic compounds emitted from industrial areas, and particularly from the oil production, petroleum refineries, petrochemical plants and power stations. The petroleum refineries and petrochemical plants are the largest sources of air pollution in the region. However, their operation is associated with the emission of various organic compounds into the atmosphere (Cetin *et al.*, 2003). There are examples of accidents related to the process of oil production: the Ahmadi refinery explosion of 2000, the fish kill incident of 2001, the Gathering centre (GC-15) explosion of 2002, and the Um Al-Haiman incident of 2003.

Power stations are the primary source of energy from which the state of Kuwait obtains the electrical energy, covering the demand of electricity for water

desalination (Al-Rashdi *et al.*, 2005). In Kuwait, both electricity and water are produced from seawater by employing thermal steam turbines and multistage flash desalination units.

These power stations use fossil fuel oil with different sulphur contents as a main source for energy production. The fossil fuel provided by the Kuwait Oil Company (KOC) to these stations is mainly gas oil, crude oil, and heavy oil. The total sulphur contents by weight in these fuels are 1, 2.5, and 4%, respectively. Therefore, the emissions of pollutants from these power stations vary with the sulphur content of the fuel and the amount of the fuel consumed during a year. The power stations are considered to be the major source of SO_2 emitted to the atmosphere in the state of Kuwait (AL-Ajmi and abdal, 1987). However, during the Iraqi invasion of Kuwait in 1990, many oil wells were destroyed, and consequently, many pollution problems were recorded in Kuwait. The resulting pollution occurred in all forms: air, water, solid waste, etc. Numerous oil wells were set ablaze by the retreating Iraqi forces and emitted thick black smoke for months on end. Thousands of barrels of crude oil were dumped into the sea, and there were numerous other oil lakes formed inland as well. The damage to the ecosystem was colossal, both on land and in aquatic habitats; numerous species of birds, fish, and other aquatic life forms were killed, and their populations experienced a tremendous blow. The damage to human health was proportional with the amount of hazardous chemicals prevalent in the atmosphere. These chemicals were released from burning oil wells, and the oil lakes created by the gushing oil from the damaged well heads were laden with the toxins described above.

As a result of these environmental issues, the government of Kuwait established the Kuwait Environmental Public Authority (K-EPA) in 1995 to safeguard the environment from air pollution due to heavy industrialisation. Similar to other environmental agencies around the world, the Kuwait EPA established a number of fixed monitoring stations (eight stations) to record the air quality in urban

areas through a monitoring network. These stations continuously measure the levels of pollutants such as SO_2, NO_2, CO, NO, CO_2, H_2S, O_3, and TSP (Total Suspended Particles) that affect human health at high levels and erode certain materials. However, these monitoring stations will be beneficial in making decisions in the state of Kuwait regarding any new projects.

1.3: Study Area

The State of Kuwait is located in the north-western corner of the Persian Gulf and is bounded on the east by the sea, on the south and the southwest by the Kingdom of Saudi Arabia, and on the north and the northwest by the Republic of Iraq. Figure (1.4) shows that the distance between the farthest northern and southern points of the state boundaries is about 200 km and from farthest east to west is about 175 km. The total length of the border is about 690 km, and about 200 km of these borders to the east are maritime borders along the Gulf. The land borders are about 490 km in length, 250 km of which represents frontiers with the Kingdom of Saudi Arabia in the south and west, and 240 km of which borders the Republic of Iraq in the north and west.

As shown in Figure (1.5), the power stations chosen for this research were the Doha and Subyia power stations. However, the study area selected for this research covered all residential areas, and particularly the Rabia area and the areas that surround these two power stations, with a total study area of 2400 km^2. The Rabia residential area is located to the southwest of Kuwait city and is 16.5 km from Doha East and 17.1 km from Doha West in a southeast direction, and about 39.4 km from Subyia power station in a southwest direction. The polyclinic that caters to the medical requirements of this area is located in the centre of Rabia.

Figure 1.4. Map of the State of Kuwait showing the location of the Doha and Subyia Power stations (www.Unimaps.com).

The fixed ambient air monitoring station of the Kuwait Environmental Public Authority (K-EPA) is located on the roof of this building, and it collects the meteorological data of this area and its surroundings. For the purposes of our study, we have chosen the monitoring station located at Rabia, a serene residential area in the heart of the city that is located closest to the power stations, the major source of SO_2 emission in Kuwait.

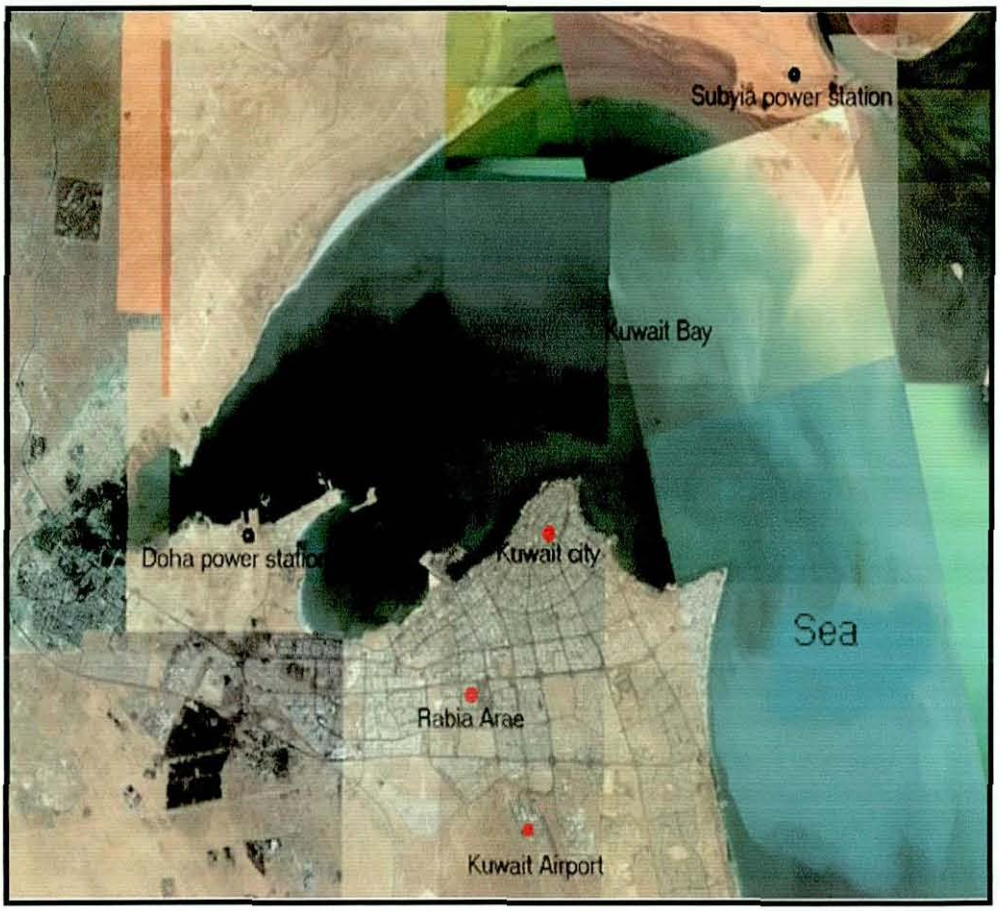


Figure 1.5: Location of the Rabia area and the Doha and Subyia Power stations (www.Google Earth.com).

1.4: Importance of this Research

Air quality is considered to be one of the most important issues around the world. This has led many countries to monitor their ambient air quality and to ensure that the pollutant levels are within the standard limits of their environmental protection authorities. However, air pollution is one of the key issues for the Government of Kuwait, especially after the increase in demand for crude oil by consumer countries and the need to provide fossil fuel for the operation of power plants. As a result, the government of Kuwait established the Kuwait Environmental Public Authority (K-EPA) in 1995 to control the emissions of pollutants into the atmosphere. This research will provide actual air quality data

and meteorological data that are needed to activate emergency control procedures during episodes of high emissions. Furthermore, this study will allow the trends of pollution to be evaluated throughout urban and non-urban areas and will allow the effects of pollution in these areas to be determined. Also, this work will provide data for the validation and evaluation of the diffusion models used to predict air quality. All of these objectives make this research an important issue for most environmental agencies throughout the world.

1.5: Research Objective

The aim and objective of this work is to study the air pollution problem in the state of Kuwait resulting from various sources such as industrial emissions and road traffic. The focus of this research is mainly on the emissions from the power stations and the other combustion sources through analysing data collected from the Kuwait Environmental Protection Authority (K-EPA) and Kuwait Airport. In addition, for modelling purposes, hourly meteorological data were collected for the years 2001 and 2004 from the Kuwait International Airport and were analysed to provide upper air data files compatible with the ISCST4.5 model. The dispersion model ISCST4.5 has been used to investigate the influence of the emission rates of sulphur dioxide (SO_2) and nitrogen oxide (NOx) from the two major power stations at Doha and Subyia. The computed ground level concentrations of these two pollutants were compared with the measured values in the Rabia area in order to validate the model, and all the computed results were later interpreted and discussed in detail. These results can provide a guide for environmental decision making by the K-EPA through various pollution episodes.

1.5.1: The summarised objectives of this work are

a- To determine the pollution levels of pollutants over the state of Kuwait, and particularly the Rabia residential area for the years 2001 and 2004;

b- To compare the pollutant levels with standards in order to evaluate whether they exceeded limits from the Kuwait Environmental Authority Standard;

c- To investigate the weekday and weekend variation of ozone pollution in the Rabia area;

d- To evaluate the ISCST4.5 model results by comparing the daily predicted ground level concentrations with the observed data from the ambient air quality monitoring station of the Kuwait Environmental Protection Authority (K-EPA) located above the polyclinic of the Rabia area under the meteorological conditions in the State of Kuwait;

e- To validate the computed output results from the ISCST4.5 model by comparisons with measured monitored ambient air data.

f- To assess the impacts of sulphur dioxide and nitrogen oxides released from the power stations (Doha and Subyia) into the surrounding urban area in the state of Kuwait.

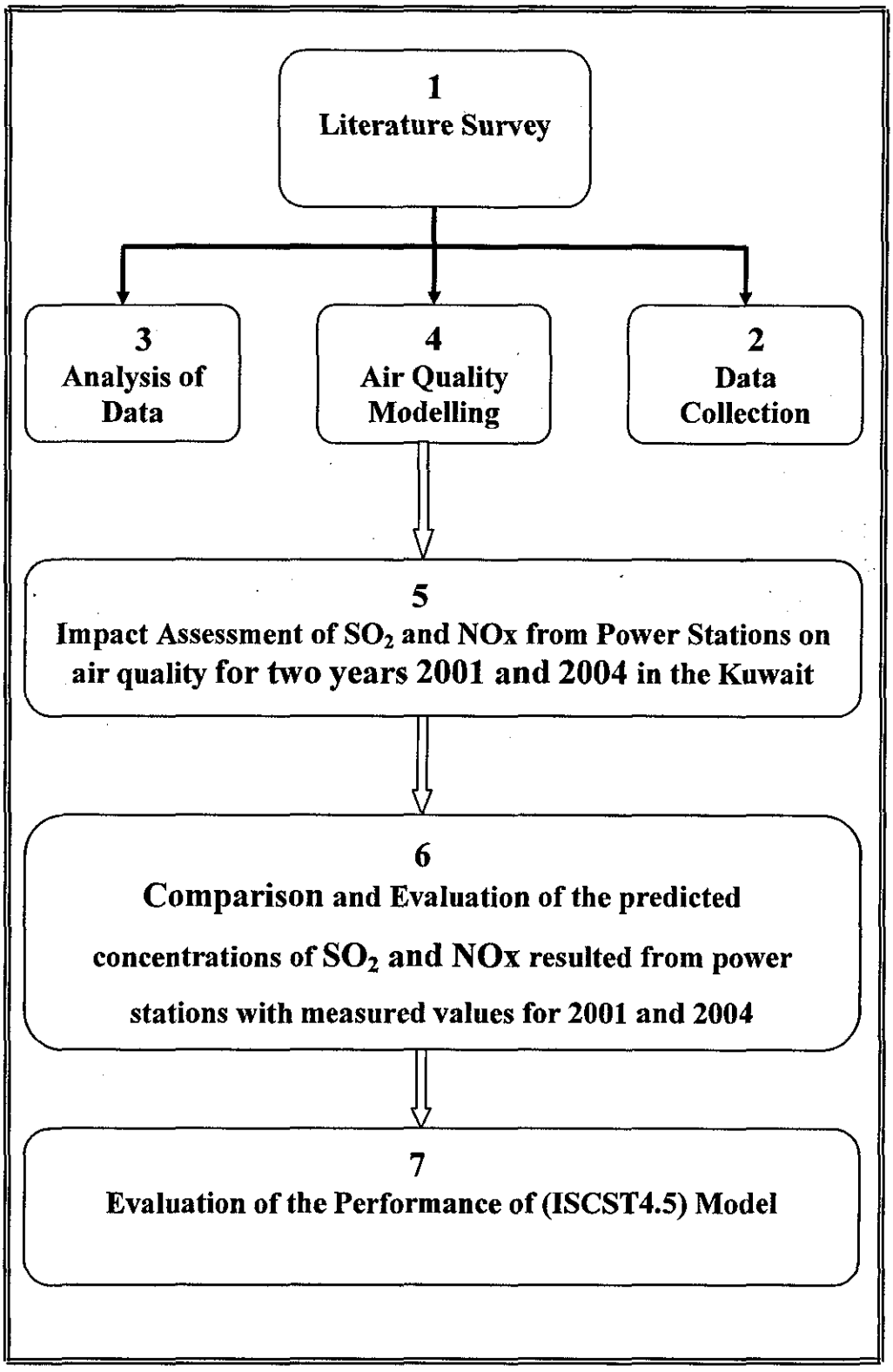


Figure 1.6: A schematic showing the steps and output of the research study

1.6: Research Methodology

The aim of this research was to investigate the pollution levels over an urban area and to determine the sources of the pollution. In addition, this study aimed to determine the dispersion process of sulphur dioxide and nitrogen oxide emitted from the following two major power stations and to evaluate their influence on the neighbouring residential area by using ISCST4.5 model: Doha, located in the northwest, and Subyia, located in the northeast of the Rabia area. This model was used to compute ground level concentrations of these pollutants for different scenarios based on the available meteorological data in order to determine the extremes that can be expected in terms of pollutant dispersion under the prevalent conditions.

1.6.1: The specific tasks in this research:

Literature Review

A preliminary objective of this study in highlighting previously conducted research was to indicate the inadequacies and shortcomings of those endeavours, particularly in terms of the impacts and emphasis of meteorological parameters on air quality monitoring in residential areas. Another key approach was the applicability of air quality modelling using programmes such as ISCST4.5 as an investigation tool in order to evaluate impact of various industrial activities on metropolitan areas.

Data collection and Analysis

For the purpose of this study, various kinds of data related to the state of Kuwait were used in order to obtain the optimum benefits of modelling. These data included terrain data of the state of Kuwait related to all entities under analysis in this study. Demographic data in study areas also played a vital role in this study. Another key data set was the dimensional and operational details of the power station under review. Of equal importance were the detailed meteorological data,

as well as the measured concentrations of SO_2 from the K-EPA air monitoring stations.

Modelling and Simulation

In this study, the Industrial Source Complex for Short-term Dispersion Model (ISCST4.5) (U.S. EPA, 1995) was used, which has been approved by the U.S. Environmental Protection Agency, and which effectively justifies the purpose of related studies, as seen in most of the previous research. This model has been appropriately justified in attempts to study the nature of dispersion of SO_2 and NOx released from power stations and their impacts on residential areas in different scenarios.

1.7: Novelty of Thesis

This research has led to the generation of new quantitative predictions for the impact of sulphur dioxide (SO_2) and nitrogen oxide (NOx) emissions from two major power plants at Doha and Subyia under existing meteorological conditions for different years 2001 and 2004 in the state of Kuwait. The modelling tool used for this purpose has been the Industrial Source Complex Short-term Dispersion model (ISCST4.5) which in the cases of (NOx) has been its first use to study the situation in Kuwait. The model predictions have been compared with available observed data to evaluate the measure of their reliability. A further achievement of this research has been the evaluation of the influence of meteorological conditions which has been shown to be complex. To evaluate the influence of prevailing yearly meteorological conditions, the emission rates of SO_2 and NOx were fixed and on this basis the ISCST4.5 model was executed for the years 2001 and 2004 for each month independently. In particular effects of prevailing wind direction have been shown to be non-uniform as far as dispersion of main pollutants from different power stations is concerned. In conjunction with the main pollutants, variations of the levels of ozone (O_3) concentration on the study area has been investigated by calculating O_3 and NOx concentrations for

weekdays and weekends for both years. This has shown, for the first time, the effects of increase in car traffic in Kuwait and its impact in comparison to the pollutants emitted from the power plants.

1.8: Overview of the Thesis Structure

This thesis consists of seven chapters, as follows:

Chapter 1: General Introduction

An overview of the pollution problem in the state of Kuwait is presented, and the need for this research is justified along with the aims and objectives and the research methodology.

Chapter 2: Literature review

This chapter offers insight into the achievements of previously conducted research studies and their limitations.

Chapter 3: Pollutions status

This chapter covers the prevailing pollutant levels in the form of measured data and the impacts of diurnal and seasonal variations in concentration. The data used for the purpose of this study were obtained from the local Kuwait EPA monitoring stations along with the meteorological conditions.

Chapter 4: Pollution Modelling and Simulation

This chapter focuses emission inventories and meteorological data used in the dispersion model to predict the spatial and temporal ground level concentrations of SO_2 and NOx. The results from model were described the peak load events in power production and related scenarios using simulation software.

Chapter 5: Data Interpretation

This chapter presents the output of the dispersion model and examines the validity of the model by comparing measured data from the KEPA monitoring station. The results are discussed in detail and present all probable explanations for these high predicted concentrations in the context of time and location.

Chapter 6: Conclusion

The results of this research are summarised with the validation of the model and its applicability and authenticity in representing real-time situations, and further suggestions and recommendations are offered for future work.

Chapter 7: References

All the relevant references are listed in this chapter.

Chapter 2
Literature Survey

2.1 Introduction:

In literature survey chapter the air pollution and the history of ambient air monitoring stations and the modelling tools used to predict the air pollutants concentrations will be described. In addition, to show some of historical pollution studies related to the field measurement analysis and dispersion models in some cities in the world. The problem of air pollution received attention since the beginning of last century and it is considered as a major problem resulting from the industrialization and economic growth of nations. This problem is created because of unplanned industrial growth and progress in technology, which makes damages on our ecosystem. These damages include the destruction of nature, the environment as a whole, and the loss to human lives. These are the damages that cannot be reimbursed monetarily and neither can they be annulled. There are several steps to control the air pollution problem by defining the air pollution problem, determining the source of pollution, monitoring the Pollutants emitted from these sources, assessing the pollution by computer and finally designing the suitable solution for the pollution problem.

A worldwide awareness movement has curbed these activities with every new venture demanding detailed elucidation. The concerns generated worldwide with each venture revolve round the pollution levels that can be anticipated, and their impact on human health and the environment and the remedial measures available, their viability, and the costs involved. The pollutants differ based on the part of the environment they effect air, water, soil, or the type of damage that they cause allergic, carcinogenic, etc, or simply the chemical nature they possess, and likewise, their impacts vary. There have been numerous studies done previously to gauge the

damage by various kinds of pollutants in various countries of the world, but the damage to human health and lives is comparable to none.

The monitoring programmes of air pollution have been evolving since last century with first survey taking place in Leicester, UK in 1937. Many cities in the world established urban air quality networks to monitor the pollution level in early 1950. One of the first studies was recorded in USA (Keagy *et al.*, 1961 and Stalker *et al.*, 1962) and in UK (Clifton *et al.*, 1959). These researchers tried to develop a method that can specify the number of sampling stations and the sampling frequency to estimate the concentration levels of pollutants. The most favourable design for an Air Quality Monitoring Network (with respect to the location, numbers, design) for monitoring the ambient air has been the topic of research for many years (Noll et al. and Liu *et al.*, 1986). In the design of a permanent air quality monitoring network, the key considerations include the conclusion on the number and location of the sampling sites, selection of the appropriate instrumentation, resolving the frequency and sampling schedule, confirming the instrument and probe setting criteria, (USA-EPA, 1976).

Kuwait is a country no different from others in the developing world. The privilege of being one of the leading economies of the world fuelled by petroleum revenues does not come without its share of problems. The government of Kuwait established the Kuwait Environmental Public Authority (K-EPA) in 1995, to protect the environment from air pollution due to heavy industrialization. The pollutants under mentoring were mainly related to the oil production, petrochemical refineries and power generation plants. Kuwait Environmental public Agency possesses eight such stations positioned at different industrial and residential areas in order to keep a track of the activities in the country. Considering the environmental consequences resulting from the emissions of SO_2 and NO_x, there is strong need in ensuring compliance with environmental legislation. Hence, it is obligatory that emissions

form power stations be monitored by an Environment Protection Authorities, or related agencies (Civerolo *et al.*, 2001a,b), and corrective actions be taken in all areas where their concentrations surpass the statutory limits in order to limit the impacts to the environment as well as human life.

The main objective in air pollution problems is to estimate at what point and in what concentration pollutants will contact the ground level from their sources. The dispersion model is used to achieve this objective. In 1970 the United State Clean Air Act produced and applied mathematical models to control and monitored the air quality problems. Models have many different structures and different levels of complexity depending on the underlying theory and the set of assumptions (USA-EPA, 1996). However, the models should be as simple as possible to avoid high cost and time consuming. The most recommended models by the US-EPA and European Environmental protection agency are Gaussian dispersion model.

2.2: Air pollution and metrology

The atmosphere is the medium by which air pollution is transported away from their sources. However, the air pollution cycle can be considered to consist of the release of air pollutants at the source, transport and dispersion in the atmosphere, and finally reception of air pollutants in reduced concentrations by human, animal, plants, etc. The influence of metrology is greatest during the diffusion phase since it's determines the atmosphere's ability to transport and dilute pollutants in passage between the source and target (Turner, 1973). The most important metrological factors controlling the levels of pollution in the atmosphere are the wind speed and wind direction. Wind speed determines the travel time from the source point to a given receptor and the total area over which the plume will be dispersed. The wind direction determines the course the effluents will take or the area to which the plume will be directed. For high wind speed the dispersion process will be very quickly

while in the calm winds the dispersion process will be small. Other important metrological parameters affecting the transport and dispersion of pollutants comprise cloud cover, relative humidity.

2.3: Air Quality Monitoring Network

Although many large developed cities of the world had established urban air pollution monitoring networks since the beginning of the 1950's, the first programme to be evaluated was in Leicester, England, between 1937, and 1939 (Meetham, 1945). A total of fifteen monitoring sites were designed, installed, and operated, and yet, back then it was realized that these sites needed to be representative in quality, in order to ensure that the actual trend of measured pollutant concentrations was aptly represented. Then began with reticent plans at first growing into more complex ventures, with the number of pollutants and the station densities growing many fold, with examples of studies like (Clifton *et al.*, 1959) in Great Britain, and (Keagy *et al.*, 1961, Stalker and Dickerson, 1962) in the USA.

Then there was a phase of almost ten years where such studies were carried out. This was followed by a new wave, with an increasing interest in monitoring objectives to the extent that the focus diversified into issues like citing criteria, estimation of regional mean, detection of statutory violations, and the validation of air pollution diffusion models. The dedication can be reflected in the publications like those of Noll and Miller (1977), and guidelines such as USA Environmental Protection Agency (US-EPA 1971), and World Health Organisation (WHO, 1977).

Air pollutants, emitted from an array of sources, and capable of atmospheric transport and dispersion, vary with respect to locations as well as time frames, and can only be described statistically. Apparently, in order to understand and design

successful and quality air monitoring systems, with insight into the number and location of the monitoring sites, is imperative to comprehend the factors that govern temporal and spatial distribution of air pollutant concentration like the ambient weather at various locations of the world, etc. This section, therefore, is aimed at providing the background information into design methodology with a critical literature review of the shortcomings of past studies conducted on similar grounds.

2.3.1 Objectives of the Ambient Air Quality Monitoring Network

It is obvious that to assess and control air pollution it is imperative to monitor the ambient air quality. This is due to the fact that without reliable measured data, no quantitative relationship between pollutant levels and source emissions can be deduced, and neither can one assess the impacts of these pollutants on health of humans and animals, vegetation, materials and weather.

Miller and Noll (1976) realised in their investigation that site selection is a very important criteria in the survey design, where the objectives of a study remain incomplete on the selection of wrong site or omission of an acute site in spite of having volumes of accurately measured data. Ludwig (1978) emphasized that poor citing procedures would simply enhance the costs way beyond the actual cost of establishing and operating of monitoring stations if sites were located in areas inappropriate for the utilisation of their data.

The 1977 amendments and the passage of Clean Air Act made ambient air monitoring programs a prerequisite of state implementation plans. Even the United States Environment Protection Agency's (US-EPA) 1975 document stressed on the consideration to the allocation of greater resources, both manpower and monetary, to the citing of monitoring facilities; as against the common practice. This meant that undertaking a monitoring effort involving thousands of dollars was incoherent

without conducting a smaller study focused on the proper citing of the instruments (US-Environmental Protection Agency, 1975).

The World Health Organization (WHO, 1977) developed general design guidelines for an Air Quality Monitoring Network (AQMN) for urban and industrial areas which are as follows:

- Assess long-term trends- Stations should be located with this view in mind, where either the concentrations can be anticipated to be highest or temporal and spatial variations can be assessed most accurately.
- Evaluate control strategies
- Provide data during episodes
- Evaluate risk to human health.
- Investigate risk to the damage of the environment.
- Provide data base for land use planning.
- Validate dispersion models accurately.
- Investigate complaints
- Carry out an initial assessment or locate stations at areas of high violation.

2.3.2 Number of the Ambient Air Quality Monitoring Stations

In designing an AQMN, the primary step would be to decide the number of monitoring stations required. Modak and Lohani (1985), found two ways to determined the number of monitors. The first approach is analytical and the second approach is empirical which is the most often used to find the number of monitoring stations needed for area study. The USA-EPA (1971), WHO (1977) and Noll and Miller (1977) developed the most frequency empirical approaches to find number of monitoring stations.

USA-EPA (1971), presents the relationship between number of network stations sophistication of the equipments and the population in urban area In addition, this relation provides a good estimate for a number of monitoring stations to the population related to the pollutants that result from vehicles traffic such as carbon monoxide, nitrogen oxide and hydrocarbons. For the pollutants emitted from other sources such as sulphur dioxide and total suspended particles matter this relation is not applicable. Therefore, the USA-EPA has issued standards for monitoring pollutants from sources and they suggest at least three monitoring stations for monitored these pollutants (USA-EPA, 1976).

The population is the most criteria should be considered when designing an urban ambient air quality monitoring network. The World Health Organization (WHO, 1977) was suggested the average numbers of monitors in urban areas of given population. For sulphur dioxide and Total Suspended Particles matter they suggest 5 monitors for population between 1 to 4 millions, 8 monitors for 4 to 8 millions and 10 monitors for more than 8 millions. However, they suggest for Nitrogen oxide and Carbon Monoxide 2 monitors for population between 1 to 4 millions, 4 monitors for 4 to 8 millions and 5 monitors for more than 8 millions. Based on the guidelines developed by US-EPA, WHO, and Noll and Miller (1977), they deduced that it

would be totally based on the population, pollution patterns, and the geographical location of the sources, and hence, developed these modifications:

- The number of stations for monitoring of total suspended particles and sulphur dioxide should be increased in cities having high industrialized areas.
- Similarly, the number of stations for monitoring sulphur dioxide need to be increased in areas using high amounts of heavy oil.
- The number of stations should be increased in areas of irregular terrain.
- Double the number of stations for nitrogen oxides, oxidant and carbon monoxide stations in areas of heavy traffic.
- The stations for nitrogen oxide, and oxides and carbon monoxide may be reduced in areas of population greater than 4.0 million, and comparatively less traffic.

The pollution dose to population approach is developed to locate the designated monitoring sites in locations where the higher population areas are expected to receive high pollution dose. Darby *et al.* (1974) have examined the effectiveness of an air quality monitoring network in Boston urban area, in terms of its capability to supply maximum protection against health effects. The urban selected area was divided into squares grid points such as 2 km by 2 km and the population in each square was calculated. As a result the network effectiveness function, which is the probability of the pollutant concentration exceeded air quality standard for a given length of time at a higher population area.

Godfrey *et al.* (1975) developed a new approach, which is the potential violations method to use in the air pollution dispersion models. This method is applied a Gaussian-type dispersion model, in conjunction with one year air meteorological data to simulate the dispersion of sulphur dioxide (SO_2) ground level concentrations emitted from two stacks in a coal-fired power plant in USA over selected mesh area that contain 180 grid points. In this approach, at each of the grid location in the area under study, the frequency of the number of violations over an ambient air quality standards were calculated. The monitoring network was selected depend on these calculations which have different sizes and configurations. The grid receptors that have repeatedly violated locations on the mesh were selected as monitoring sites. However, the Godfrey *et al.* (1976) show that, the relationships between the percentages of violations of the 24-hourly average concentrations of sulphur dioxide (SO_2) as a function of the number of monitoring stations.

2.4: Dispersion Modelling

In the process of developing befitting regulations to keep these environmental issues at bay, models played an important role in making expensive, important decisions (Maynard, 1984). Hence, the next step would include the selection of an appropriate modeling tool, in order to help predict the anticipated outcome of such pollutant concentrations to help decision makers in arriving to conclusions in either improvising on the legislation or the industrial operations to ensure the perceived threats are kept at Bay. The United State Clean Air Act of 1970 and its amendments have established national standards of ambient air quality to protect humans and the environment. Also, the Clean Air Act of 1970 produced a strongly motivation for the application of mathematical models to air quality problems. Scupholome *et al.* (1977), reported that the successful application of a model relies on detailed emission inventory of all sources and the metrological data applicable to the study area.

However, for planning purposes, models should be simple as possible, otherwise the application of the model might be time consuming and expensive.

There is various modelling software available in the market for this purpose, the recent trend is to use statistical models rather than the traditional deterministic ones (Kolehmainen *et al.*, 2001). Among the commonly used statistical models are time-series analysis (Hsu, 1992), Artificial neural networks (Gardner and Dorling, 1998; Abdul-Wahab, 2001; Elkamel *et al.*, 2001; Abdul-Wahab and Al-Alawi, 2002; Nunnari *et al.*, 2004), Regression analysis (Abdul-Wahab *et al.*, 1996, 2003, 2005). Overall, air quality models in the recent years have proved to be crucial tools in evaluating the impacts of pollutants on the urban environment and more importantly human health (Gokhale and Khare, 2004). Air pollution basically contains a set of formulae taking into consideration a quantified record of the pollutant sources of a given area, the transitions involved in the ensuing chemical reactions, the various meteorological and topographical features, along with other features that come into play during the dispersion of these pollutants. Hence, a successful application of such a model, weighs heavily on a detailed emission inventory of all pollutant sources, and the accurate meteorological data applicable to the area (Scupholome *et al.*; 1977, Fox, 1981). Zanetti (1994) described the process of computer modelling of air pollution as the method of using computers in solving the basic equations that govern and portray metrological dynamics and air pollution phenomena, and most importantly on the adverse effects of air pollution.

The harsh weather conditions in Kuwait results in temperatures approaching mid 50°C in summer. To counteract the difficult living conditions resulting from this very high power consumption are normal during these months in Kuwait. This in turn gives rise to high air pollutants emissions from power stations. However, these months are characterized by high winds causing severe dust storms that disperse the high pollutant emissions. These two factors will increasing the ground level

concentration of pollutants dominated by meteorological conditions. Computer modelling can hence be used as a convenient method for the prediction of the effects of using various types of fuel under various meteorological conditions to minimize the impact of high gaseous pollutants emissions.

2.4.1: Classification of Models

Air quality models are divided into two approach's physical and mathematical. The first approach which is physical models is built for experimentation on the small-scale. Therefore, the physical approach has problems associated with properly duplicating the actual atmospheric scales of turbulent motion making the model of limit uses. However, the mathematical or numerical models are based on a set of equations that describe the physical and chemical aspects of the air problem.

Seinfeld (1975), Zanetti (1990) and Topcu *et al.* (1993), reported that the mathematical models are divided into two approaches:

- Statistical Models: The ambient air qualities in these models are based on an empirical statistical analysis of the available air monitoring data.
- Deterministic Models: This approach is based on fundamental physical laws and mathematical descriptions at atmospheric processes to predict the ground level concentrations of air pollutant.

2. 4.2: Industrial Source Complex-Short Term (ISCST4.5) model

The Industrial Source Complex-Short Term (ISCST4.5) model is the approved air quality model by the U.S. EPA for its regulatory work. ISCST4.5 model is a steady state plume dispersion model, based on the Gaussian plume simplification of the three-dimensional convective-diffusion equation to enable the calculation of hourly, daily, monthly, annual and study period averages of ground level pollutant concentrations, or total deposition from multiple continuous sources under varying conditions of meteorology. It is a very handy tool, able to evaluate pollutant concentrations ensuing from a wide variety of sources, related to industrial complexes (Law *et al.*, 2006). The model is quite descriptive elaborating on a vital number of details including area, line and volume sources, downwash, dry deposition and settling of particles, plume rise, as a function of downwind distance, separation of point sources, and limited terrain adjustment, topographic effects, pollutant decay, and the effect of building aerodynamic wake on plume dispersion (US EPA, 1995). These characteristics are making it a popular option among the modelling community for a variety of applications. The model assumes time independence in the input meteorology, and source concentration, and can even handle polar or Cartesian coordinates (ISC3-1995a). The model uses Briggs formulae to compute plume rise, and for representing horizontal and vertical dispersion parameters with options for rural or urban backgrounds (Briggs, 1973). The wind profile law is used for the estimation of wind speed at stack height (ISC-3, 1995b). The model has the option of focusing on the effect due to pollutants around a particular source and one or multiple receptors by sketching three super imposed grids around the source. These grids can be of variable areas- one larger grid, and two smaller finer grids with a variable number of receptor points for the accurate evaluation of the pollutant concentrations, around the power stations.

There are two types of models that were developed- the short term model (ISCST), which is applicable to predict for sources within a 25 km radius and long term model (ISCLT) which can be used to cover greater distances, and even greater time intervals, like a seasonal, or annual ground level concentrations. It is pointed out that the ISC model is comprised of two codes, one for short-term (ISCST) impact analysis, and one for long-term (ISCLT) (Bowers *et al.*, 1982), and likewise the subject of numerous publications. Among the dispersion options that form the prerequisites of the model are the stack-tip downwash, buoyancy induced dispersion and final plume rise in order to enable the calculation of averages during the prevalence of calm conditions. For simplifying the understanding of the lateral dispersion of the plume, we need to add those factors that have a relative effect on it, namely the wind profile exponents, and the upper bound estimates for the super squat buildings. The model requires three major input data namely, source data, meteorological data, and receptor data. Turner (1970) stated that stability class is determined based on Pasquill categories and mainly is a function of the hourly pollutant measurements, sky cover and the wind speed. Short-term air quality dispersion models like ISCST4.5 use National Weather Service data in order to derive hourly stability class and mixing height using a meteorological pre-processor like PCRAMMET (U.S. EPA, 1999).

2.5: Field Measurements

Many studies have carried out the analysis of the trends of air pollutants over different areas in the world. Bower *et al.* (1991), show that the analysis of urban nitrogen dioxide (NO_2) and nitrogen oxide (NOx) concentrations during summer and winter periods in London, (UK). In addition, in Johannesburg, the concentrations of nitrogen oxide (NOx) and non-methane hydrocarbon (NMHC) over inland areas were analyzed and show that two maximum values over 24-hours period. The first value occurred in the mourning at time 8:00 am while the second value occurred at

time 5:00 pm (Stevens, 1987). Abdul-wahab and Bouhamra (2004) have presented a study for analysis of ozone (O_3) variation over 24-hours period in Khaldyia city in the state of Kuwait. This study shows that two maximum values occurred over study period. The first value occurred at early mourning between 4:00 and 5:00 am, while the second value occurred at the midday between 11:00 am and 4:00 pm. Bizjak *et al.* (1988), found that the variation of sulphur dioxide (SO_2) over Ljubljana in the Yugoslavia have two maximum values, the first value occurred at time 9:00 am and the second value at time 9:00 pm.

Bouhamra *et al.* (1999) presented a statistical analysis study of the collected data by laboratory mobile for air pollution which fixed in mansouriya residential area for one month period (May-1994) in state of Kuwait. The selection of this area to study the impact of pollution sources mainly heavy traffic into and out of Kuwait city on air quality. The pollutants monitored for analysis in this study are nitrogen oxide (NOx), nitrogen dioxide (NO_2), carbon monoxide (CO) and ozone (O_3) and most of these pollutants are resulted from traffic movement in any urban area. In addition, sulphur dioxide was monitored during the same period, which is resulted from power stations. The metrological parameters such as wind speed, wind direction, temperature and relative humidity were also recorded at the same time. The investigation of this study was to measure the levels of pollutants in atmosphere and to compare it with the standard limits of Kuwait environmental protection authority (K-EPA), and in addition, to study the diurnal variations of these pollutants over the area study. The results of this study show that the levels of pollutants not exceed the standards limits the recommended range for residential areas according to environmental protection agency standards. It is found that the trend concentration of CO was correlated with heavy traffic movements during the rush hours. In addition, the trend concentration of SO_2 has the same trend of CO. This was attributed to the transportation process by heavy diesel trucks through and around area study and other sources such as power stations. Also, the hourly distribution of CO, NO and

NO_2 were compared over the days of the week. The results show that in the weekend there were no morning peaks detected for these gases. The correlation between O_3 concentrations and NO and NO_2 was analyzed over the area study. It was shown that the concentration levels of O_3 have a high peak at midday.

Luis *et al.* (2001) conducted a study on CO and NO_x measurements from mobile sources at two urban locations in Cordoba City, Argentina; they used a very simple method to estimate emission from these sources. This development was possible because primary urban air pollution in Cordoba comes mostly from mobile sources and because a field measurement campaign was conducted by the city government during 1995–1996 that has allowed to have a complete and valuable data bank. Air concentrations of CO, NOx as well as physical and meteorological variables were measured at two urban sites with two monitoring stations. They compared the measured CO and NOx air concentration data with the predictions of a method that uses regression analysis to estimate the emission factor from the mobile sources.

The method presented here can be very useful in the underdeveloped countries, where no emission inventories exist, or the existent ones turn quickly out of date. Accuracy in models, that simulate primary pollution as well as in those that calculate ozone formation, is directly related to the existence of a reliable CO and NOx emission value. Besides, an emission inventory is a key factor for the development of a public program aimed at reducing urban primary air pollution. However, they have presented a simple method to estimate CO and NOx car emissions in countries where there is not enough funding to do field measurements or it is difficult to establish regulations to limit emissions from mobile sources. This method is not intended to replace more complete and reliable studies, but to have an inexpensive and simple alternative. The major advantage of this method is that a CO and NOx monitors and any traffic flow measurement instrument are the only tools needed to estimate mobile sources emission values. Although simple and limited, they believe that this

kind of method is a feasible tool to estimate non-reactive compound concentrations in urban regions presenting arteries considered as a street canyon. The method is easy to set up. It has very low computational demand and low worker requirements to compile data related to daily traffic cycles. No special meteorological equipment is required besides that available at any nearby location.

Pont (2001) and his coworker examined ozone data from five large French cities (Marseilles, Lyon, Paris, Strasbourg and Toulouse) in spring and summer over a three-year period and studied the possible influence of local primary pollutant emissions. In these cities, the level of traffic emission varies according to the day of the week. There is a decrease of about 25% in traffic emissions between non-consecutive Tuesdays and Sundays. Traffic emissions on Fridays are about 40% more than on non-consecutive Sundays whereas they seem to be similar for non-consecutive Tuesdays and Thursdays. Despite this variation in traffic emissions between Fridays and Sundays, 85% of daily ozone maxima are identical for all days compared; in 15% of cases, percentiles of daily ozone maxima vary by about 20% at the most. This difference was observed for the highest values of daily ozone maxima that they could found both in rural and urban sites. Marseilles is the most pollution-sensitive city; every site of this area is concerned, which gives a regional origin to ozone variability. In the less-populated Toulouse area, differences between ozone on Fridays and Sundays are less significant. Our results show the importance of advection phenomena of ozone. It calls into question strategies of local reductions in traffic during ozone episodes.

The traffic levels vary by more than 40%, especially between Fridays and Sundays. They found an important decrease in the CO concentrations between Sundays and Fridays in Marseilles, which lets us suppose a similar decrease in all traffic emissions. About 85% of ozone values in each city studied showed little difference between Fridays and Sundays, while all CO values are concerned by the 40%

decrease. Only about 15% of ozone values were higher than standards limits and these highest values, were influenced by the variations in traffic emissions. It reveals the chemical non-linearity of ozone and overall an important background level of ozone, which is adverted over these, urbanized areas, to which is added the local production. Only the city of Marseilles shows a more significant decrease in its concentrations of ozone when traffic levels are lower.

This study highlights the predominant role of advection in the origin of ozone pollution. Moreover, not only have they seen that a decrease of 40% of the traffic intensity in cities does not have a striking impact on ozone levels, as they compared Fridays and Sundays percentiles distributions, but also they can notice that daily ozone maxima levels on Sundays are as great as those on Tuesdays and Thursdays. On a regional scale, differences between primary pollutant concentrations are difficult to study, as concentrations are low out of urban areas and the sensitivity of measurements devices used in monitoring networks is not enough to properly bring out these differences. Thus, this study would seem to suggest that strategies of local reduction in traffic levels during episodes of ozone pollution are insufficient at the scale of the town and its suburbs, to lead to significant effects. Sudden high reductions in emissions, which start when ozone concentrations are already high, will not be successful

Cogliani (2001) had developed air pollution indexes the daily index studied here are highly correlated with meteorological variables and this index is capable of identifying those variables that significantly affect the air pollution. The index is connected with attention levels of NO_2, CO and O_3 concentrations. A law proposed by the Italian Ministries of Health and Environment fixes the attention levels. He analyzed the relation of that index with some meteorological variables by the linear multiple partial correlation statistical method. He selects Florence, Milan and Venice to show the correlation among the air pollution index and the daily thermic

excursion, the previous day's air pollution index and the wind speed. During the January-March period, the correlation coefficient reaches 0.85 at Milan. The deterministic methods of forecasting air pollution concentrations show very high evaluation errors and are applied on limited areas around the observation stations, as opposed to the urban areas. The global air pollution, instead of the concentrations at specific observation stations, allows the evaluation of the level of the sanitary risk regarding the urban population.

In the operative application, the knowledge of the previous day's air pollution index and the day's lowest temperature, and the forecast of the day's highest temperature and wind speed, enables the forecast of the day's air pollution to be done in the morning. An increase in the forecasting reliability of the air pollution index can be obtained by increasing the urban observation stations, where both the pollutant concentrations and the meteorological parameters are measured. He obtained correlation value difference at Milan and at Vicente, and depend either on the different number of the stations, or on their different location. Some locations might represent better than others the average urban air pollution. It is then desirable to take better care of locations and the number of observation stations. On the other hand, a better characterization of the total urban air pollution is obtained by considering other pollutants in addition to NO_2, CO and O_3, namely, the particulate matters or benzene; increasing that characterization will also increase the forecasting reliability of the air pollution index . The exposed method allows him to easily increase the number of the pollutants, which are likely to be considered.

Elbir (2004) and his coworker carried out an air pollutant emission inventory of primary pollutants for Izmir, which is a highly industrialized area situated in the western part of Turkey. A proper emission inventory is very important for planning pollution control programs, particularly in coastal sites like Izmir, where environmental quality is of growing concern owing to their typical meteorological

conditions. The sources were broadly classified as point, line and area sources in a systematic way. The data on activity levels of industries, fuel consumption in vehicles and domestic activities along with the respective emission factors were used for estimating the emissions for the year 2000. The results that they obtained showed that industry is the most polluting sector for sulphur dioxide (SO_2) in the study area contributing about 88% of total emissions. On the other hand, domestic heating is the most polluting sector contributing about 56% of total particulate PM emissions while traffic has the highest portion for NO_X emissions. Especially, emissions from industries located outside the metropolitan city centre are much higher in amount. Industries located around the Izmir metropolitan centre contribute to the industrial SO_2 emissions by 93%, PM emissions by 59% and NO_X emissions by 80% of the total.

They conclude that unless immediate technical measures such as in a control policy plan are promulgated in accordance with some realistic target values for reducing the emissions, Turkish industrial and urban sites will undergo very severe air pollution problems. Therefore, emission reduction programs including control technology implementation, energy conservation planning and pollution prevention techniques must be urgently prepared and implemented. In this planning work, priorities of contributing source categories must be taken into account. In the Izmir, study area it is expected that two such developments will largely affect the emission inventory: recent gradual replacement of industrial fuels with imported natural gas beginning from 2003 and the national purchase tax incentives in effect aiming at the renewal of the car fleet since summer 2003. Natural gas is presently available for use in the industrial at the peripheral zones of the city of Izmir. Moreover, the tax-driven car renewal campaign backed up by the prohibition of leaded-gasoline sales in the country will possibly increase the use of catalytic converters in cars. It is expected that a better maintenance capacity will be developed in the near future. However, a policy plan involving regular follow-ups for air pollutant emission inventory and

pollution reduction strategies is seriously and urgently needed aiming at protection of the natural resources, agricultural production, community health and cultural archaeological heritage in Izmir.

Antonia-Nelly (2005) analyzed air quality data (O_3, NO_2, NO, CO and SO_2) of two Greek coastal cities, Patras and Volos, and compared to evaluate: (a) the exceedances of air quality EU threshold values, (b) the diurnal patterns of air pollutants and (c) the "weekend effect" on ozone levels. High ozone levels, close to the thresholds for human health and clearly above the threshold for the protection of plants and ecosystems, were observed in Volos. O_3 levels in Volos were higher than those in Patras. NOx levels in Patras were significantly higher than the limits for human health and plants protection. Both, NOx and SO_2 levels were higher in Patras than in Volos. The Patras harbour high traffic seems to drive the diurnal pattern of SO_2 in the city.

The examination of the rate of ozone accumulation, during the high O_3 period (Apr.–Sep.), revealed the occurrence of two phases, a fast and a slow one, with different durations in each city. They suggest that the occurrence of such two phase's patterns should be considered in relevant ozone studies. In both towns, the O_3 levels were higher during weekends in comparison to midweek days, although NO levels were lower. Our results support the hypothesis that the weekend O_3 effect is due to a combination of VOC sensitivity of the studied areas and the reduced NOx emissions during weekends. Based on the comparison of the weekend effect in the two cities, they suggested that the occurrence of a feedback mechanism between peri-urban natural ecosystems (forests) and the polluting anthropogenic ones (cities).

The primary pollutants NO, NO_2 and SO_2 occurred at higher levels in Patras than in Volos, while the inverse was observed for O_3. There were no significant levels noticed for CO between two cities. Concerning the exceedance of O_3 and CO, for

human health in Patras and Volos, there is not any exceedance in those two cities. Yet, the inhabitants of the two cities are subjected to low but different levels of chronic and acute exposures to SO_2 and NO_2. In terms of vegetation protection, exceedance of O_3 levels was observed in Volos but not in Patras. For the protection of ecosystems, there were not exceedance of SO_2 levels in any of the two cities, but they found exceedance of the annual limit value of NOx in both cities.

A strong weekend effect was observed in Patras, but less intense in Volos. Both cities seem to be VOCs limited. The causes of the weekend O_3 effect are probably the weekend/weekday differences in NOx emissions and the complex non-linear photochemistry of ozone. The relatively lower NO_2 concentrations on weekend result in less OH radical loss and more O_3 formation. Lower NOx emissions on weekends decrease NO titration of the O_3 newly formed at the surface and the ozone transported. Besides, the forest of Pelion Mt., near Volos, may contribute to the enrichment of the atmosphere of the city with biogenic VOCs and this is another reason that the weekend effect is stronger in Patras than in Volos.

Genikhovicha (2005) has measured the bi-annual data set of concentrations of several traffic-related air pollutants, continuously in street canyons in St. Petersburg and Copenhagen. He analyzed jointly using different statistical techniques. Annual mean concentrations of NO_2, NOx and, especially, benzene are found systematically higher in St .Petersburg than in Copenhagen but for ozone, the situation is opposite. In both cities probability distribution functions (PDFs) of concentrations and their daily or weekly extreme are fitted with the Weibull and double exponential distributions, respectively. Sample estimates of bivariate distributions of concentrations, concentration roses, and probabilities of concentration of one pollutant being extreme given that another one reaches its extreme are diacuaws in this publication as well as auto- and co-spectra. It is demonstrated that there is a

reasonably high correlation between seasonally averaged concentrations of pollutants in Petersburg and Copenhagen.

However, he concluded that the trend of air pollutants in two big European cities located in the Baltic Sea region have not varied too much from year to year. Therefore, these results have a certain predictive value, at least, in the short run. When validating dispersion models, especially those with street-canyon options and the simulated the probability distribution functions of concentrations and their extreme in agreement with empirical data presented. Such simulation took into account actual regimes of variations of the wind speed, wind direction and other governing meteorological parameters as well as traffic intensity, structure and so on. A significant level for correlation of air pollution registered in Petersburg and Copenhagen can be considered as an indication of possibility for development of schemes for prediction of the regional air pollution. Such a possibility does not look too surprising because the regional air pollution should be governed by large (regional)-scale meteorological and synoptic processes. Therefore, similar correlations could be expected for air pollution in other cities if the distance between them is inside the synoptic scale.

Venegas *et al.* (2005) have conducted a study on estimations of horizontal distributions of carbon monoxide (CO) and nitrogen oxides (NOx) background concentrations in Buenos Aires City. They applied the urban atmospheric dispersion model to estimate the contribution of area and point source emissions, respectively. They used an emission inventory with a resolution of 1 km x 1 km, which includes the major sources located in the city (residential; commercial; small industries; road traffic; power plants and aircraft landing, taxi and take off at the Domestic Airport). They compared estimated concentrations with observed values at four locations. Statistical analysis has been carried out to assist in the comparison of model estimations and observations. Estimations were in good agreement with CO and

NOx observed data. For both pollutants, estimated hourly average (averaged over a year) background concentration patterns showed a large spatial variability related to the distribution of emissions. At evening, during rush hour, hourly average CO concentrations may reach 4.5 ppm and NOx concentrations 0.42 $\mu g\ m^{-3}$.

The results that obtained show good agreement with observational data registered at four sites in the city. For both air pollutants, more than 90% of model estimates are within a factor of two and the values of the fractional bias are low. For both pollutants, concentration distribution pattern shows a large spatial variability across the city with higher values in areas with dense traffic. They identified the different areas in the city with higher concentration levels, most of them are near the main train stations. In these areas, CO background concentrations may reach values near 4 ppm and NOx background concentrations may be approximately 0.4 $\mu g\ m^{-3}$.

Vardoulakis (2005) has investigated the variation of air pollution in different European cities. They carried out a 7 month sampling campaign on a major road axis (Avenue Leclerc) leading to a very busy intersection (Place Basch) in central Paris, covering the surroundings of a permanent air quality monitoring station. This station has recorded the highest CO and NOx concentrations during recent years in the region of Paris. Diffusive BTX samplers as well as a mobile monitoring unit equipped with real time CO, NOx and O_3 analyzers and meteorological instruments were used to reveal the small-scale pollution gradients and their temporal trends near the permanent monitoring station. The diffusive measurements provided 7 day averages of benzene, toluene, xylene and other hydrocarbons at different heights above the ground and distances from the kerb covering summer and winter periods. Relevant traffic and meteorological data were also obtained on an hourly basis. Furthermore, three semi-empirical dispersion models (STREET-SRI, OSPM and AEOLIUS) were tested for an asymmetric canyon location in Av. Leclerc. The

analysis of this comprehensive data set has helped to assess the representative ness of air quality monitoring information.

Although there was no marked seasonal variation in the observed street-level values, higher pollutant concentrations were mainly associated with periods of relatively low southerly winds, which probably transported polluted air masses Concern was created over the long term NO_2 and benzene concentration averages, which seemed to exceed the annual EU limit values at all roadside sampling locations. However, the BG benzene concentrations remained below the EU limit value during the same period. The AIRPARIF monitoring station has recorded the highest CO and NOx concentrations during recent years in the region of Paris. The AIRPARIF values were generally much higher than the concentrations observed within the asymmetric canyon segment of Leclerc during an intensive 1 week monitoring period. Given the sitting of the permanent monitoring station and the pronounced spatial variability of air pollution in its vicinity, it can be concluded that the measurements from this site do not give a representative picture of air quality in the surrounding area and are thus inappropriate for population exposure studies.

Jo *et al.* (2005) have performed a roadside data analysis study over last five to six years in Korea to provide baseline data for exploring associations between environmental exposure to four gaseous pollutants and health effects on residents living near roadways. The yearly roadside concentrations of CO and SO_2 showed a well-defined decreasing trend, whereas those of NO_2 and O_3 exhibited the reverse trend. In most cases, the diurnal trends of the roadside concentrations were well defined for all seasons, and the daytime concentrations were higher than the night time concentrations. In contrast to the other target pollutants, the daytime O_3 concentrations observed at the roadside sites were lower than those observed at the residential site, likely due to high-levels of fresh NO from traffic emissions that rapidly react with O_3, thereby reducing the O_3 roadside level. The Sunday roadside

concentrations of CO, NO_2, and SO_2 were similar to or somewhat lower than the weekday concentrations. Conversely, for O_3, the Sunday roadside concentrations were similar to or somewhat higher than the weekday concentrations. The higher O_3 concentrations on Sunday may be due to the reduced titration from a decrease in NOx emissions under VOC-limited conditions (low VOC/NOx conditions). The monthly averages of O_3 concentrations exhibited the reverse seasonal variation to the other target compounds, with peak O_3 concentrations between April and June, and the second peak between August and October. They also suggested that for O_3, the 8-hr standard is more stringent than the 1-hr standard, while for NO_2 and SO_2, the 1-hr standard is more stringent than the 24-hr standard. They obtained multiple regression equations from the relationship between the concentrations and five meteorological parameters, which indicated that the number and type of meteorological variables in the equations varied according to the pollutant, monitoring station, or season.

Shuenn-Chin Chang et al. (2006), collected data from the five air-quality monitoring stations established by the Taiwan Environmental Protection Administration from 1994 to 2003 in Taipei City. These data were analyzed to assess the temporal variations of air quality in this city. They found that the primary pollutants such as SO_2, NOx and CO show an obvious decrease over the last 10 years while the secondary pollutants such as O_3, display a yearly increase over the time period when a reduction of primary pollutants is obvious. However, the monthly variations of primary pollution are significant from January to April, while O_3 increases from April to August.

2.6: Studies using ISCST model

There are many of studies carries out on related areas of interest. Zanetti (1983) simulated the dispersion of SO_2 from the Shuaiba Industrial area (SIA) in Kuwait from all stacks in the area, comparing the predicted values against the observed

concentrations. However, the evaluation of the dispersion model with SO_2 measured concentrations were carried out at more than one monitoring station located at (SIA).

Al-Sudairawi and Mackay (1988) also evaluated the performance of the model based on the fifty highest values of the hourly averages of SO_2 concentration at Shuaiba Industrial Area (SIA), in Kuwait, finding that the model under-predicted as compared to real-time values and was found to be due to use of meteorological data from Kuwait International Airport (KIA) rather than from the Shuaiba Industrial Area which is some 30 km away. Also, Al-Ajmi *et al.* (1988) carried out a statistical comparison between the ISCLT model prediction concentrations and the measured concentrations for the same industrial are. They found a good agreement for the winter season but not for the summer season.

Honaganahalli *et al.* (2000) conducted a field study in September 1995 by measuring the ambient methyl bromide (MeBr) concentrations in the Salinas valley in California. The measurements taken at 11 sites located on the adjacent mountains, valley floor, and at the Pacific Ocean coast for a 4-day period measured up to 9 $\mu g\ m^{-3}$. With the help of two published flux values, and estimated source strengths for fumigated fields, dispersion model simulation was performed with ISCST3 and CALPUFF. When comparing the immediate downwind concentrations of methyl bromide from a single tarped field with the predicted ISCST3 model values, it was found that ISCST3 is capable of back calculating a flux term, when the downwind concentrations were known. In this study, the ISCST3 model under predicted concentrations for 76% of data and averaged 66% of measured while the CALPUFF model under predicted concentrations for 67% of observation and averaged 84% of measured. The coefficient of determination (R^2) for ISCST3 model was 0.7 and for CALPUFF was 0.55 between the models predicted and measured concentrations.

Abdul-Wahab *et al.* (1999) performed a similar evaluation for the same area comparing the ground level concentrations of SO_2 to measured ones, and found that model fared extremely well for seven months (January, June, August, September, October, November, and December), over-predicted in February, March, April, and May, and under-predicted in July.

R. Sivacoumar *et al.* (2001), used the Industrial Source Complex Short-Term Gaussian dispersion model (ISCST) to evaluate the impact of NOx emissions resulting from various air pollution sources, viz. industries, vehicles and domestic in Jamshedpur, the steel city of India. The contribution of NOx concentration from industrial, vehicular and domestic sources was found to be 53, 40 and 7%. In addition, the model performance was evaluated by comparing the measured and predicted NOx concentrations and they found good agreement with an accuracy of about 68%.

Santis *et al.* (2003) conducted a study to determine the air quality and spatial dispersion of certain pollutants (NOx, SO_2, NO_2, NH_3, and BTX- butane, toluene, and xylene) in an area surrounding an oil refinery in Italy, using diffusive samplers. The main results drawn form this study were vehicle exhaust registered as a primary contributor as compared to industrial sources, and that diffusive samples proved to be a comparatively useful and cost effective tool.

Hajraf *et al.* (2005) used the ISCST-3 model for a parametric study of a thermal plant, exploring the alteration of the stack features in order to lower ground level concentrations of SO_2 and NOx, and found stack height, diameter, fuel type, are all vital features that govern pollutant emissions. The use of low sulphur fuel, as well as the increasing of the stack height facilitated effective pollutant dispersion.

A.D. Bhanarkar *et al.* (2005), investigated the pollution from different types of sources in Jamshedpur, the steel city of India, in winter 1993. They used two approaches to determine the levels of pollution in this area. The first approach was to evaluate the emission inventory and estimated the spatial distribution of pollution loads in terms of SO_2 and NO_2 from different types of industrial, domestic and vehicular sources in this area. The results indicate that industrial sources account for 77% and 68% of the total emissions of SO_2 and NO_2, respectively while the vehicular emissions contributed to about 28% of the total NO_2 emissions. In the second approach, the levels of pollutions were assessed through air pollution dispersion modeling. They used the ISCST3 model to predict the ambient air concentration levels of SO_2 and NO_2 in winter season. The analysis indicates that emissions from industrial sources are responsible for more than 50% of the total SO_2 and NO_2 concentration levels. Vehicular activities contributed to about 40% of NO_2 pollution and domestic fuel combustion contributed to about 38% of SO_2 pollution. However, for evaluated the performance of the model they used the predicted 24-hr concentrations to compare with measured concentrations at 11 ambient air monitoring stations and they found a good agreement between the two values.

Venegas *et al.* (2005) used the ISCST3 model to urban background pollution in Buenos Aires City using an emission inventory with a 1 km x 1 km resolution taking into account the major pollutant contributors (residential, commercial, industrial, traffic, power station, air traffic, etc). It was discovered that the CO concentration during rush hour reached 4.5ppm, while the NOx concentration reached 0.42 $\mu g\ m^{-3}$. For the purpose of this study, the area sources were divided over a grid area of 17 x 19 grid cells with a 1 km x 1 km resolution. It was observed that in a city like Buenos Aires, 45.57% of the NOx emissions can be attributed to vehicular traffic, while 48.74% to power plants. The model in use here, ISCST3 is quite versatile, in that it is capable of providing ground reflection, ceiling dispersion, stack-tip downwash, wind profile, buoyancy-induced dispersion, urban and rural dispersion,

terrain adjustment algorithms, etc. The dispersion parameter formulas are derived from the Pasquill-Gifford, and McElroy-Pooler data. The model to define plume rise, transport and diffusion conditions uses hourly meteorological data. In each hour of input meteorological data, the model estimates source and receptor concentration combinations and these values summed to give total concentration by a combined source. The grid resolution considered for this study is a 100 m x 100 m covering the entire city. The contribution of the point sources in the background concentration values can be obtained by averaging the estimated hourly concentrations over each 1 km^2 grid. This study was the first of its kind is successfully achieving the background concentrations of CO and NOx in study area. The results obtained showed considerable agreement between predicted and observed values, hinting at the success of the model.

Alrashidi *et al.* (2005) were used the ISCST-3 model to investigate the efficiency of the existing monitoring sites for the impact of SO_2 emissions from power stations in the state of Kuwait. In addition, to study the variations of SO_2 over residential areas; both temporally, and spatially, with a statistical comparison of the maximum values showing an effective accuracy of 60-94% depicted by the model. In Kuwait, electrical and power generation stations can be registered as the major sources of SO_2 emissions. The power stations use three different types of fossil fuels, namely gas oil, crude oil and heavy oil, in which the total sulphur content by weight is 1%, 2.5%, and 4% respectively. Since the power stations at Shuwaikh, and Shuaiba use natural gas as fuel registering a sulphur content of zero, they can be exempted from the calculation. The total SO_2 emission rate from the power stations depends on fuel type and its total monthly consumption. A major portion of the SO_2 emissions, 49% comes from the Doha complex, which comprises Doha west and Doha east. The model, based on the simplification of three dimensional diffusion equation is able to generate ground level pollutant concentrations in terms of hourly, daily, and annual averages in terms of meteorology conditions being released from elevated sources.

The model is capable of justifying a lot of crucial pollutant and dispersion related factors, like settling criteria, line and point sources, emission rate variations for various pollutants, topographic effects, Building aerodynamic wake and its effect on plume dispersion. The grid receptors considered in this study were 2500, which was divided into smaller sections of 2km in order to cover the study area of 87 km x 87 km. From the result it was observed that the model over predicted in the case of the maximum average daily ground level SO_2 concentration by at least 600 $\mu g\ m^{-3}$. The highest predicted concentration was observed on the 20th of August 2001, occurring at a distance of 3.175 km form the centre of the Doha complex. The coordinates of this receptor are X = 775328.2, Y = 3248972, a spot on the coastline in the near vicinity of the residential areas. The current location of the power stations, that is, along the coast is most ideal, as long as the islands of Kuwait remain uninhabited. This is due to the observation of the pollutants being washed out at the Bay and further into the Arabian Gulf. This will have an adverse effect on the marine life. Also, they concluded from this study highlighted the inability of these stations to measure the actual impact of the SO_2 emissions because of their inappropriate placement. Hence, there was a strong recommendation to reposition these stations in order to adequately address the problem.

Rama Krishana *et al.* (2005) presented the impact of SO_2 emitted from an industrial complex on the ambient air of Jeedimetla in the outskirts of Hyderabad city in India from 38 elevated point sources, and 11 area sources. They were used the Industrial Source Complex Short Term (ISCST-3) model to obtain the predicted ground level concentrations of SO_2 around the study area. In addition, they used meteorological data for two months (April and May 2000) representing the summer season and for one month (January 2001) representing the winter season and these data are obtained from the India Meteorological Department, Hyderabad for Airport station. The spatial distribution of the SO_2 concentrations has been examined over an area of 10 km x 10 km surrounding the industrial complex. They were selected two mesh area

study the first one was considered up to a distance of 5 km, with a spacing distance of 250 m, while the second one considered between 5 km to 10 km was done so using a spacing distance of 500 m. The 8-hr and 24-hr averaged model-predicted ground level concentrations of SO_2 have been calculated over study period. In both seasons, it was observed that the distribution of SO_2 concentrations over the study area is in the a summer and winter month was found that the levels of SO_2 are within the limits in comparison to the National Ambient Air Quality Standards except near the industrial area. However, the SO_2 concentrations are greater closer to the industrial complex, slightly exceeding the national standard because of the pollutants are not transported any further than the industrial complex and its close vicinity due to low stack height and comparable height of buildings in close vicinity. The concentrations observed in winter are slightly lower than summer due to high prevalent wind speeding. A 90 pairs of the predicted and observed concentrations of SO_2 have been used for validation the model and it is found that the predicted ground level concentrations are relatively close to those observed values and the model performance is found to be satisfactory.

In another study by Alrashidi *et al.* (2005) were presented an application of the (ISCST3) model to quantify the impact of SO_2 released from four power plants for different sulphur contents in state of Kuwait. The sulphur contents in the fuel used in this study are 4%, 2.5%, 1% and 0.5%. In addition, they used metrological data for full one year (2001) with emission rates of SO_2 emitted from these power stations to consider the distribution of predicted SO_2 over the study area. Based on the sulphur content in the fuel used in the power stations, four different scenarios were simulated with their corresponding real case scenarios to analyze the impact of SO_2 over the study area. The selected mesh area in this study was 63 km x 75 km with 441 uniform grid receptors is used to predict the ground level concentrations of SO_2 released from power stations. The resulted predict concentrations of SO_2 were compared with standard limits of Kuwait Environmental Agency (K-EPA). The

objective of this study to select the best scenario that give the best fuel provide lower impact of sulphur dioxide as well as minimize the fuel cost to achieve the energy requirements by the domestic. It is found that in case of real scenario the hourly maximum predicted ground level concentration is about 2244 $\mu g\ m^{-3}$ which is exceeding the allowable limit (K-EPA) of SO_2 (hourly limit of SO_2 is 445 $\mu g\ m^{-3}$). If they used the fuel with low content of sulphur (0.5%) the hourly maximum predicted ground level concentration of SO_2 was 370 $\mu g\ m^{-3}$ which is with the limit of K-EPA.

Also, AL-Rashidi *et al.* were studied the effects of sulphur dioxide (SO_2) emissions in the residential areas of Kuwait from the Doha complex which consist of west and east Doha power generation plants and located in the northwest. This study was presented in the Kuwait first International Petrochemical Conference and Exhibition, 12-14 December 2005. They used the industrial source complex short term (ISCST3) model to investigate the effects of sulphur dioxide under the metrological conditions of the State of Kuwait. Also, the validation of the model was presented in this work. The hourly metrological data was colleted for full one year (2001) from the Kuwait international airport (KIA) and used it as an input data for running the model in this study. In addition, for the validation of the model they select Rabia area which consists of an ambient air monitoring station and it is located exactly in down wish direction and about 16 km from Doha complex. The period used for this study was two month August and September of year 2001. The results show that the most of the residential areas are affected by the SO_2 plume emitted from the Doha complex, especially when the wind is from northwest direction. They conclude that the comparison between the daily predicted ground level concentrations of SO_2 and measurements at Rabia station for the study period show that the model is can predicted the observed daily concentrations of SO_2 with any accuracy of about 90%.

Abdul Wahab (2006) developed correlations for predicting the maximum hourly as well as the overall SO_2 ground level concentrations within the vicinity of a petroleum

refinery, depending on the meteorological conditions in the Oman. It was found that none of the major meteorological conditions like the mixing height, wind direction or the temperature had an impact on the predicted SO_2 concentrations apart from the wind speed and the atmospheric stability class. These predictions were made using the ISCST model, a plume dispersion model, based on the simplification of the Gaussian equation, developed originally by the U.S.EPA during the 1970s. In this study, they used the short-term version model (ISCST3). It is most apt for regulatory purposes, often used for assessing the effects of pollutants on local air quality, and is the focus of this study. The input data would therefore, be required to describe both the emission source as well as the prevalent meteorology. The emission source data would outline both the physical stack dimensions like the height, internal diameter, location, etc, as well as the physical characteristics of the discharge, that is the velocity and temperature of the emitted gases, as well as the SO_2 emission rates, which were calculated in this study by chemical mass balance.

The area under study is the Mina-Al-Fahal refinery of Oman. When the fuel is burned, reactions generally take place at around 1800°C, where carbon, present in the fuel is converted to CO and or CO_2, hydrogen forms H_2O, sulphur forms SO_2, and nitrogen forms nitric acid (NOx). It was found that wind speed determines the extent of initial dilution of SO_2 (at the point of release by ambient air), the travel time (from source to a given receptor), total area of plume dispersion, as well as the dilution in the downwind direction. They found that the model under-predicted in case of the average measure concentration by approximately 36.8%, while remained in agreement with the observed values. It was found that the decrease in the maximum SO_2 concentration was non-linear as wind speed increased. This meant that with a wind speed greater than 3 m s^{-1}, it was unlikely to have a high SO_2 concentration. Lastly, it was also concluded that for the estimation of the spots that depicted maximum SO_2 concentrations, the essential parameter was wind direction.

Ramadan *et al.* (2007) aggregated the total SO_2 emissions from power stations and used ISCST3, an air quality model that is based on the simplification of the Gaussian plume of the diffusion equation to study the impact of these emissions in the state of Kuwait. They pointed out to the fact that the sulphur content of fuel was among the deciding factor in the ground level SO_2 concentration released by the power stations. Therefore, they expressed the emission rate for SO_2 as a function of the specified fuel consumption rate and the sulphur content. The ISCST3 model or short-term model, since it predicts results within a radius of 25 km from the point source, used the existing scenario for the power stations in Kuwait. In the interest of the effects of the SO_2 ground level concentrations due to power stations, a few assumptions were made that the background SO_2 concentration (all other sources) was considered as zero. In addition, they considered that the power stations were the sole source, the fuel oil used was solely heavy fuel oil, flue gas desulphurization, building downwash, or plume depletion were exempted from the scenario, and that steam energy was totally steam turbine generated.

A variety of scenarios were taken into consideration, where the sulphur content in the fuel varied between 1, and 4%, and similarly, the load under which these power stations operated was considered on a seasonal, hourly, and devoid of any load, as well as a combination of various scenarios were used to assess the effects of the load cycle. The results obtained form these assumptions showed that though the annual SO_2 concentrations for all scenarios and in the case of 1% sulphur remained below the K-EPA standard, all other scenarios violated the K-EPA standard. The input data used for the purpose of this study was derived from Kuwait International Airport for the period of 1999-2003. The other findings from this study include the fact that all K-EPA violations occurred in the maximum load period, i.e., summer between 11:00 am and 2:00 pm, when the maximum demand is the highest and the meteorological conditions provide an appropriate match-up to cause chaos throughout the system. The findings confirm northwest (NW) being the predominant wind direction, and

that the current citing of all the power stations is most ideal with respect to pollutant dispersal. However, over the years, the feasibility of this decision comes under question as the power loads increase, and the marine environment comes under threat. Also, in this study they calculated the ratio of the area affected by the exceedance to the calculation-domain area, i.e. $A\ r$, is affected by two factors: sulphur contents and the emission cycle and they found that the $A\ r$ increases with sulphur contents (SC).

2.7: Present Work

In the present work the data obtained from the Kuwait environmental public authority (K-EPA) station located at urban area for two complete years 2001 and 2004 have been analyzed in great depth to determent the air quality. The influences of urbanization, population growth, commercial and recreational activities have been evaluated in great depth. Emission inventories from two major power generation facilities at Doha and Subyia have been analyzed with seasonal variation in their power output. Meteorological data for years 2001 and 2004 were obtained from Kuwait Environmental Protection Authority (K-EPA) and used as input in PCRAMMET software to determine stability class and upper air data to generate compatible data file for implementation of the dispersion model. This data with all other specifications from Power stations, stack characteristics, flue gas flow, exit temperature and exit velocity at stack tip with local terrain detail were fed to the Source Complex for Short-term Dispersion (ISCST4.5). However, Industrial Source Complex, ISCST4.5 model is used for parametric study for a 2400 MW generation power plant using local fossil fuel oil of different sulphur containing. The environmental impact of two major power production facilities using ISCST4.5 model has been assessed the hotspots predicting hourly, daily and annually. The highest fifty values were identified with their location and time of occurrence.

Chapter 3
Ambient Air quality in the selected study area for years 2001 and 2004 in the State of Kuwait

3.1: Introduction

In order to control the air pollution or perform an impact assessment study for such industrial activities it is necessary to have an accurate knowledge of the spatial and temporal trends of the pollutants concentrations. Air pollutants, especially SO_2, NO_2, NOx and the major secondary photochemical oxidant, O_3 strongly influence plants, and human health, and so the emphasis in the current study will focus on them.

The focus of this chapter is to determine the pollution levels of measured SO_2, NOx, NO_2, O_3 and CO in year 2001 and 2004 to assess the pollution trends and to found the most probable sources of these pollutants. The pollutants levels were compared to evaluate exceedence of Kuwait Environmental Authority Standards. The diurnal patterns were also analyzed in great depth for different seasons for two years 2001 and 2004. Weekdays and weekend variation on Ozone pollution has been thoroughly investigated.

The state of Kuwait is an OPEC member, and the economy of Kuwait is predominantly supported by petroleum industry, one of the key natural resources of the country. Kuwait has the third largest oil reserves in the world after Saudi Arabia kingdom and Iraq public. However, the petroleum industrials account over 90% of Kuwait's export ravenous. Most industries of Kuwait are connected to petroleum. Considering the size of this industry in Kuwait significant impact to the environment can be expected as an obvious outcome. With such a soaring economy, there was a considerable influx of people to help support the infra-structure surrounding this economy. In order to accommodate this population boom, the areas of the desert had to be taken to task and groomed into residential

zones with the basic amenities which also include cooling in a desert like Kuwait. This inflicted a significant load on the power grid to cater to these requirements, which meant that the power stations would be running on full capacity, especially during the summer, the months of July, August, and September. The power requirement of Kuwait has been seen to be growing at an alarming rate of 7.7% as compared to other developing countries (Al-Tameemi, 1995). Since the state of Kuwait depends mainly on the desalination of seawater to provide its citizens with drinking water, and fulfill the growing demand of electrical power, five major power stations were set up, which work continuously. As a result, the most important activities investigated in this research are the power generation plants.

Bouhamra (1995), have reported VOCs concentrations in ambient air after the largest manmade environmental disaster occurred in Kuwait, exploding over six hundred wellhead by the retreating Iraqi army. He reported low concentration but prolonged exposure of these compounds has substantial health risk to Kuwaiti population. Bouhamara *et al.* (1997) have identified large number of organic compounds in indoor and outdoor air of various Kuwaiti houses using GC/FID with Tenax TA cartridge. The concentrations of various contaminants were reported between 100 and 5000 $\mu g\ m^{-3}$. In another study, Bouhamra and Abdul-Wahab (1999), have not reported any violation of residential standards set by Kuwait Environment Public Authority (K-EPA) over mansouryia area, for one-month duration, May 1994.

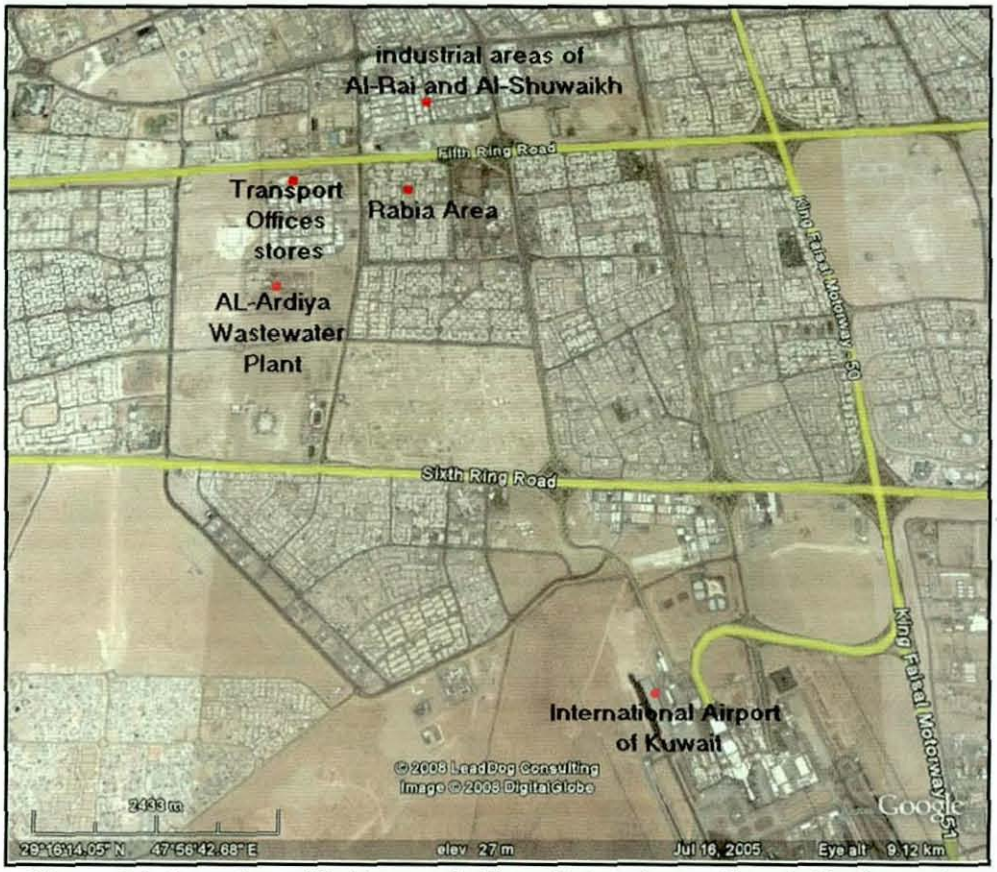


Figure 3.1: Location of Rabia area in Kuwait state (www.Google Earth.com).

3.2:Description of the Study Area (Rabia area) and graphical data

The State of Kuwait is boarded in the east by the sea, by the Kingdom of Saudi Arabia in the south and southwest and in the north and the northwest by the Republic of Iraq (Figure 1.4). Kuwait is a flat and arid desert country located at the end of the Arabian Gulf coastline. Kuwait has four distinct seasons- summer, winter, spring, and autumn. However, its summer is quite long and hot in comparison with the relatively short and mild winter. The weather in winter is comfortably cool and during nights sometimes can be cold with temperature dropping blow 5°C while in summer, the outstanding features are heat and the dryness of the air. The mean temperature in July to August ranges from 30°C to 50°C with an average mean daily maximum of nearly 35°C.

Most of the Kuwait population (approximately 2.5 million inhabitants) lives in Kuwait city, which extends over 100 km next to the Gulf shores. In addition, most of its power plants and industrial sites are located in the vicinity of urban areas.

Figure (1.4) shows the distance between the farthest northern and southern points of the state boundaries is about 200 km and from farthest east to west is about 175 km. The total length of the border lines about 690 km, about 200 km of these borders to the east is maritime borders along the Gulf. The land frontiers are 490 km of which 250 km from the frontiers with the Kingdom of Saudi Arabia in the south and west 240 km with the Republic of Iraq in the north and west.

The total area of the State of Kuwait is 17,818 km^2. The highest concentration of residential areas is arranged among the southeast edge of the Kuwait Bay and occupying only 7% of the total area of the country. The earth surface slopes down gently from west to east. The prevailing winds in Kuwait are from the northwesterly quadrant throughout the year, about 60% of the time, the prevailing wind in summer is northwesterly, so that they are more frequently in summer.

Figure (3.1) show that he Rabia area is located in the south-west of central Kuwait, with a total area of 2.5 km^2 and is mainly flat land. Figure (3.2) show that the fixed monitoring station for Rabia is located above the polyclinic, in the centre of the area. There are two major highways passing adjacent to it, Fifth ring road to the north, and Sixth ring road from the south. There is an industrial area, Shuwaikh industrial consisting mainly of garages and workshops for the repair of cars, located to the north of Rabia. The International Airport of Kuwait located to the southeast, has a daily traffic of planes that take off and land at regular intervals. Rabia is flanked by two power stations; Doha complex to the northwest, and Subyia to the northeast, and a wastewater treatment plant located to the southwest, in Ardiya. The total inhabitation of Rabia ranges between 30,000-35,000, divided into five blocks, consists of 320 houses, 7 schools, a

polyclinic, a police station, and 14 co-operative stores. In addition, there are 20 main electrical distribution stations, 2 petrol stations, 1 to the east, and the other to the west, a wedding hall, a restaurant and a training institute of the public authority for agriculture and fish resources, which is located to the east (Kuwait Municipality, 2003). Traffic moves in and out of Rabia through many main streets, to the centre of the city. The rush hours are 7:00 to 9:00 am in the morning, and around 5:00 to 8:00 pm in the evening. Most of the pollution resulting form traffic is due to heavy vehicles that use diesel as fuel, and light vehicles using gasoline as fuel.

Figure 3.2: The fixed ambient air monitoring station above the polyclinic in Rabia

Wind rose is considered as a graphical tool used by meteorologists to give a succinct view of how wind speed and direction are distributed at a particular location. The directions of the rose with the longest spoke show the wind

direction with the greatest frequency. The length of each spoke around the circle is related to the frequency that the wind blows from a particular direction per unit time. Each concentric circle represents a different frequency, starting from zero at the centre to increasing frequencies at the outer circles. Wind roses were used in this work divided to 16 cardinal directions, such as north (N), NNE, NE, etc.

Figure (3.3) reveals that the majority of the prevailing winds are from northwest direction (NW) were about 18% is from NW and about 40% from the N-W sectors for years 1995 to 2005. Moreover, Figure (3.4) presents the frequency distribution of the winds class were about 31.9% of wind speed record is in between 3.6-5.7 m s^{-1} and about 30.5% is in between 2.1-3.6 m s^{-1}. The wind speed and wind direction can indeed play an important role in the outcome of the strength of any possible air pollution. Low to Medium winds blowing from the direction of power stations towards highly populated residential areas can in no doubt increase the possibility of pollution that can eventually affect the health of the local people living within such areas.

The effects of the wind speed are a very important parameter in the dispersion process of pollutants. The relationships between the wind speed and the concentrations of pollutants downwind a source is of inverse proportional. This means when the wind speed reaches its highest level it actually helps in reducing the concentration of any air pollutant, and thus serves to reduce its hazardous effects on the residential areas. On the other hand, slow wind can be considered as disadvantage since it allows for the formation of high concentrations of pollutants moving slowly over residential areas and thus increasing the pollutants and their hazardous effects.

Winter in Kuwait is characterized by low temperature, low inversion layers, lesser wind movements, which do not promote the dispersion of pollutants as compared to summers, which have high temperature, high inversion layers, high wind movements and effective distribution and dilution of pollutants.

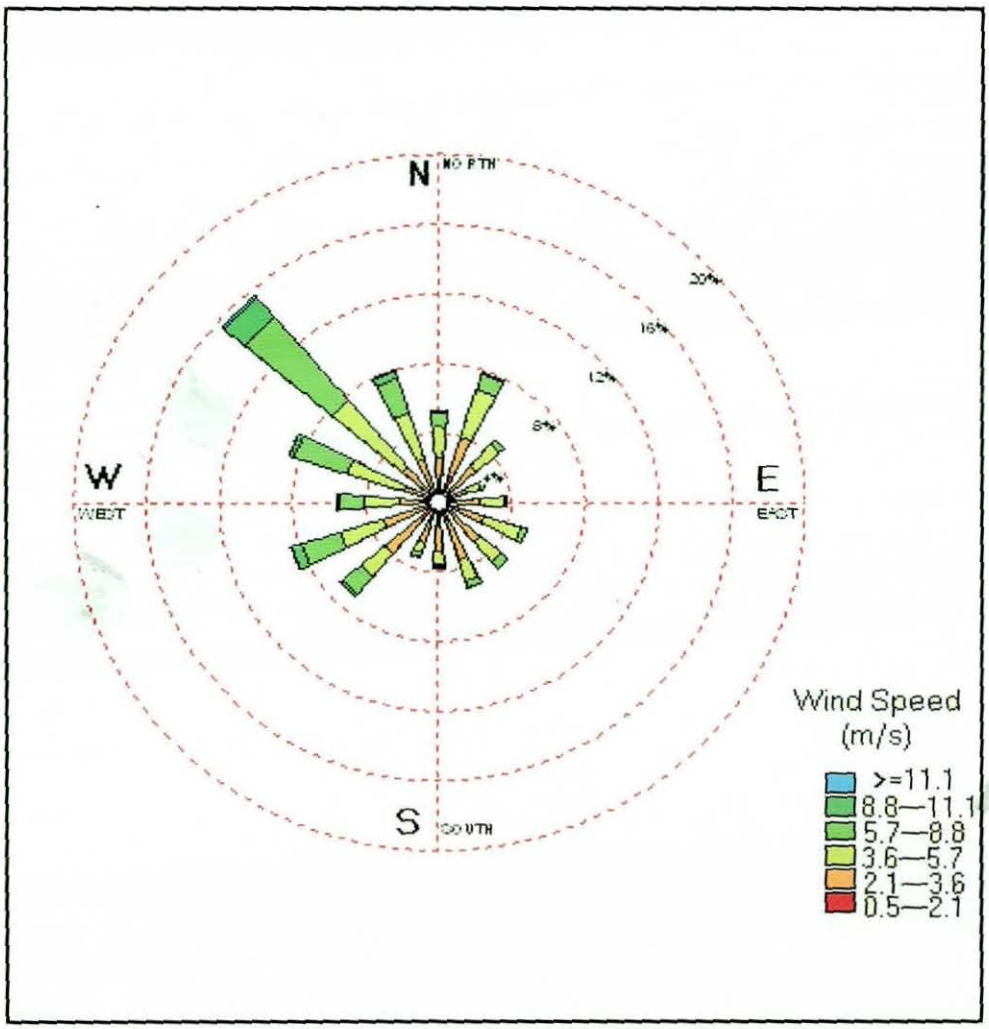


Figure 3.3: Wind Rose Plot for years 1995 to 2005

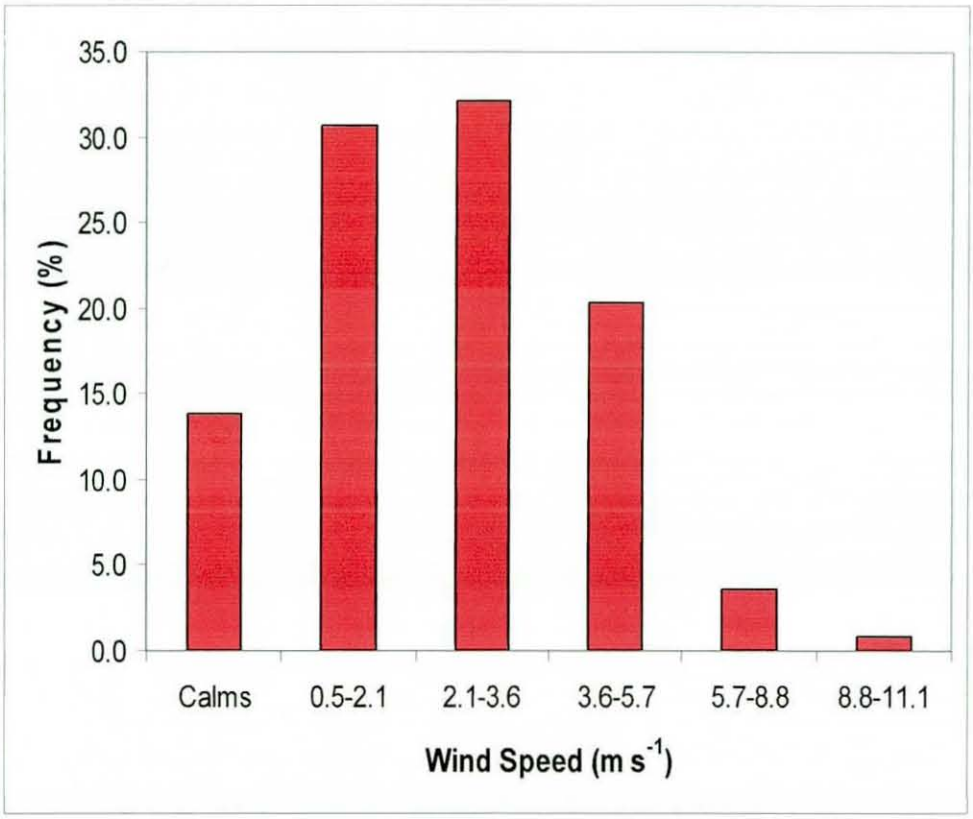


Figure 3.4: Wind class frequency distribution for year 1995 - 2005

3.3: Meteorological Data and methods

The Kuwait Environmental Public Authority (K-EPA) fixed an ambient air pollution monitoring (APM) station that consists of direct reading instruments for measuring major air pollutants as well as meteorological parameters. These monitoring stations are equipped with an automatic analyzer and metrological sensors (Noll, K.E. and Miller, T.L., 1977). The APM station constantly monitored the ambient air pollution and accumulated and stored raw data in an onboard computer that subsequently processes and analyze in hour and minute detail. The APM station is equipped with analyzers for the continuous monitoring of ambient air to determine the concentrations of various pollutants (Table 3.1). The sampling system consists of an aspirated glass tube with individual outlets for each analyzer. The air sample is slightly de-humidified prior to its entry into the analyzer. A Teflon filter is used at the input of each analyzer to trap dirt and other small suspended particles. The filter is usually changed every week (SO_2 and NOx Analyzer Operation Manual, 2006).

A multi-gas dilution calibration system is used to calibrate each analyzer for zero and span values (Chrisman, K.F. and Foster, K.E., 1963). Room air is scrubbed to remove all contaminants and is passed over a heated catalyst to oxidize the hydrocarbons. The purity of the generated zero air is generally acceptable to calibrate the zero-point of each analyzer. High concentration certified calibration gases, either as single components or as multi-components, are diluted in precise ratios to generate span gases at around 80% of the used measurement range for each analyzer. Multi-point calibration, if desired, is accomplished by varying the dilution ratio of the certified gas. The frequency of routine calibration is at least once a week. Additionally, each analyzer is re-calibrated every short period and maintained (SO_2 and NOx Analyzer Service Manual, 2006).

The sulphur compounds analyzer use fluorescence detection to measure sulphur dioxide (SO_2) over high level ranges (0-400 ppm). The fluorescence detection

system is also used in the measurement of total sulphur (TS) over a range of 0-20 ppm and in the measurement of sulphur compounds (SO_2, H_2S, TRS & TS) over a range of 0-2000 ppb. However, SO_2 analyzer incorporates UV fluorescence spectrometry with microprocessor control for accurate and reliable measurement of sub-ambient levels of SO_2. The SO_2 measured concentration is automatically corrected for gas temperature and pressure changes and can be displayed in units of ppb, ppm, $\mu g\ m^{-3}$ or $mg\ m^{-3}$. in case of the oxides of nitrogen analyzer use microprocessor control and chemiluminescence's technology to measure oxides of nitrogen (NO_X, NO_2 & NO) over high level ranges (0-1000 ppm) in the ambient air. The oxides of carbon group of analyzers use IR gas filter correlation photometry to measure carbon monoxide (CO) and carbon dioxide (CO_2) over high level ranges (0-3000 ppm). In addition, this measurement system is also used in conjunction with converters as an Ammonia analyzer (NH_3) in the ambient air. The ozone (O_3) analyzer combines microprocessor control with ultraviolet (UV) photometry to provide accurate measurements in the range of 0-50 ppb and 0-20 ppm with a detection limit of 0.5 ppb.

To obtain more precise information, the meteorological conditions are taken into account. The meteorological instruments in the APM station provided localized meteorological data, including wind speed, wind direction, temperature and relative humidity. Effects of various meteorological parameters on measured pollutant concentrations will be examined individually and in combination.

Table (3.1): Monitored Parameters and Analyzer Specifications

(www.epa.org.kw)

S.N	Monitored Parameter	Analyzer Model	Detection Principle	Measurement Range (ppm)
1.	Carbon Monoxide, CO Carbon Dioxide, CO_2	CO 11 M - LCD	IR Correlation	0 – 50 0-3000
2.	Sulfur compounds: SO_2, H_2S, TRS	AF 21 M - LCD	UV Fluorescence	0 – 10 0 - 400
3.	Nitrogen Compounds: NO, NO_2, NOx	AC 31 M - LCD	Chemiluminescence's	0 – 10 0 - 1000
4.	Hydrocarbons: CH_4, non-CH_4	AC 51 M - LCD	Flame Ionization Detector	0 – 50
5.	Ammonia: NH_3	AC 31 M – LCD with Converter	Chemiluminescence's	0 – 10 0 - 1000

The collected meteorological data are for hourly and every 5 minutes and will be utilized to determine the correlation between different weather phenomena and the measured concentration of pollutants emitted from various emissions sources like power plants, road traffic and other industrial activities. In our study area, the ambient air monitoring station is located over the polyclinic Building in Rabia. The government of Kuwait established the Kuwait Environmental Public Authority (K-EPA) in 1995, to safeguard the environment from air pollution due to heavy industrialization. Kuwait EPA established a number of fixed ambient air monitoring stations (eight stations), to be updated with the air quality in the urban areas, through a monitoring network (Figure 3.5). These stations continuously measure the levels of pollutants such as SO_2, NO_2, NO, NOx, CO, CO_2, H_2S, O_3, N-MHC and TSP (Total Suspended Particles) in the atmosphere for each hourly and five minutes. The data were obtained from K-EPA for year 2001 and year 2004 and consisted of the hourly averages of continuous measurements of the concentration of the pollutants SO_2 (ppm), NO_2 (ppm), CO (ppm), NO (ppm) and O_3 (ppm) and meteorological data. Kuwait Environmental Public Authority (K-EPA) has set hourly, daily and annual limits for NO_2 concentrations in the ambient area but there is no specific limit for NOx. They are considered that the limit of NOx as limit of summation of NO and NO_2.

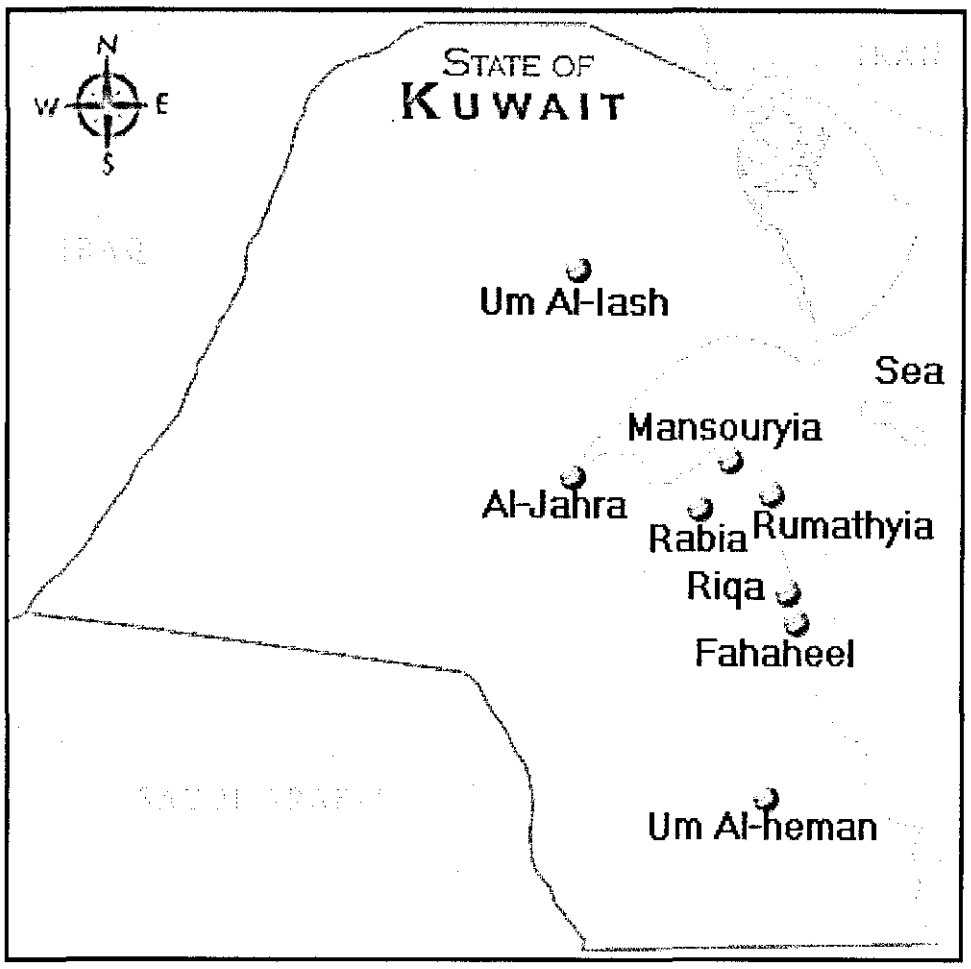


Figure 3.5: Location of fixed ambient air monitoring stations in Kuwait (www.epa.org.kw)

Table (3.2): Kuwait Standards for Ambient Air pollutants (K-EPA)

Pollutants	Units	Standards		
		Annual	24 hours	Hourly
Nitrogen Dioxide (NO_2)	ppb ($\mu g\ m^{-3}$)	30 (67)	50 (112)	100 (225)
Sulphur Dioxide (SO_2)	ppb ($\mu g\ m^{-3}$)	30 (80)	60 (157)	170 (444)
Hydrogen Sulphide (H_2S)	ppb ($\mu g\ m^{-3}$)	6 (8)	30 (40)	140 (200)
Carbon Monoxide (CO)	ppb ($\mu g\ m^{-3}$)	--------- ---------	8,000 (9,000)	30,000 (34,000)
Ozone (O_3)	ppb ($\mu g\ m^{-3}$)	---------- ----------	---------- ----------	80 (157)
Nitrogen oxide (NOx)	ppb ($\mu g\ m^{-3}$)	60 (134)	100 (224)	200 (450)

3.4: Results and Discussion

The investigation of this study shows the comparison between the trend of three primary and secondary pollutants SO_2, NOx, NO_2 and O_3 using a fixed monitoring station located above the polyclinic at a height of about 6 m in the Rabia residential area in Kuwait state using hourly data for the four seasons in two years 2001 and 2004 (Figure 3.1). This work covers a thorough analysis of the trends in air pollution levels of SO_2, NO_2 and O_3 and their most probable sources in Rabia area in the State of Kuwait. In order to assess the air quality in this area, measured concentration values of these pollutants have been analyzed and compared with the specified limits and guideline published by the Kuwait Environmental Protection Authority (K-EPA).

It should be noted that, in general, each year data is mainly valid only for that year. The reason is that condition my change year to year. However, the degree of similarity between the conditions, for one year (2001 or 2004) to another year periods an indicate regarding the validity of concentration for these years. In this work the selection of data for years 2001 and 2004 are based mainly on the fact that these were good quality data which covered all of the months of these years that could be used to make the investigation of the suitability of the adopted methodology. The analyses of data for this work have been started on 2005 and the only good quality data was found for full years are these data.

3.4.1 Sulphur dioxide (SO_2) sources and analysis of measured concentrations

Sulphur dioxide (SO_2) is primary pollutant and it is released in the air during the exploration, power generation plants, transportation, and consumption of fuel. The main contribution is from the power generation plants and oilfields, during exploration, production and transportation of oil, to refineries and other related

industries, during refining, processing, flaring, and transport industry, which is one of the end users, and power stations that use oil to generate electric power. These sources and their emissions are directly related to the operational conditions of the machinery involved, and the prevailing weather conditions that ultimately determine the fate of sulphur dioxide released to the environment. The transport industry releases are mainly related to vehicle emissions, based on the type of fuel used by trucks, buses, large heavy-duty vehicles, trucks, buses, cranes.

A- Winter season analysis

In more than 93.13% of cases it was possible to obtain hourly measured concentration of SO_2 for the winter season (January to March). There was no observed violation for hourly data exceeding 170 ppb, the specified limit of K-EPA for SO_2 concentration. The maximum hourly SO_2 measured concentration in this period was around 6.58 ppb at 19:00 hr on 31st March where the corresponding temperature was 27.9°C, relative humidity 11.4%, wind speed 3.69 m s^{-1} from WNW direction (265°) confirming the predominant emission source, the Doha power station. The maximum daily measured mean SO_2 concentration for this period was 3.18 ppb corresponding to 31st of March. Overall, the monthly average SO_2 measured concentration for January was $0.57 \pm 0.88\sigma$ ppb, where standard deviation (σ) = 0.5, for February was $0.47 \pm 0.79\sigma$ ppb, where σ = 0.435 and for March was $0.69 \pm 0.75\sigma$ ppb, where $\sigma = 0.82$.

In year 2001, the winter season show that the hourly data of SO_2 measured concentration was recorded around 99.77 % of total cases, with no violations in this period either, exceeding 170 ppb, the specified limit of K-EPA for SO_2 concentration. The maximum hourly SO_2 measured concentration for this period was around 141.1 ppb at 21:00 hr on 7th March where the corresponding temperature was 26°C, relative humidity 61.38%, wind speed 1.03 m s^{-1} from SSE direction (171°). The probable sources are the heavy transport vehicles that

used diesel fuel, which passed through AL-Gazalli expressway and a restaurant café, which is located to the southeast of our monitoring stations in Rabia area that uses charcoal fire for roasting meat, generously augmenting the prevalent SO_2 concentrations. The maximum daily mean SO_2 measured concentration for this period was 38.95 ppb, corresponding to 7th March. The monthly average SO_2 measured concentration was $2.5 \pm 0.786\sigma$ ppb, in January where $\sigma = 0.25$, February $4.4 \pm 0.789\sigma$ ppb, where $\sigma = 0.41$ and March $4.6 \pm 0.53\sigma$ ppb, where $\sigma = 0.7$ respectively.

B- Spring season analysis

The recorded hourly measured concentrations data of SO_2 during the spring (April to June) of 2004 was 67%. This is due to continuous malfunction of the SO_2 monitor. There was no observed violation, exceeding 170 ppb specified limit of K-EPA for SO_2 concentration. The maximum measuring hourly SO_2 concentration for this period was around 8.1 ppb at 11:00 hr on 3rd April where the corresponding temperature was 28.7°C, relative humidity 0.87%, wind speed 3.1 m s^{-1} from SSE direction (143°). In this location, the most probable source is a café restaurant and heavy transport vehicles. The maximum daily mean SO_2 measured concentration for this period was 4.22 ppb, corresponding to 27th May. The monthly average SO_2 measured concentration for April was $1.2 \pm 0.73\sigma$ ppb, where $\sigma = 0.934$, May $1.25 \pm 0.765\sigma$ ppb, where $\sigma = 0.91$.

The available measured data for hourly recorded SO_2 concentrations in spring period for year 2001 was 92.58% from the total case, with a violation of around 0.046% exceeding 170 ppb specified limit of K-EPA for SO_2 concentration which occurred one time. The maximum hourly SO_2 measured concentration for this period was around 171.25 ppb at 19:00 hr on 3rd April where the corresponding temperature was 34.85°C, relative humidity 45.3%, wind speed 2.22 m s^{-1} from SSE direction (138°), validating the above explanation of the heavy transportation vehicles over AL-Gazalli expressway and a restaurant as a

high contributor of SO_2. The maximum measuring daily mean SO_2 concentration for this period was 16.62 ppb, corresponding to 3rd April. The monthly average measured SO_2 concentration was $4.8 \pm 0.77\sigma$ ppb, where $\sigma = 0.393$ for the month of April, May $1.75 \pm 0.7\sigma$ ppb, where $\sigma = 0.148$ and in June was $1.2 \pm 0.83\sigma$ ppb, where $\sigma = 0.963$.

C- Summer season analysis

The hottest temperature in the state of Kuwait is recorded in this period (July to September) and is identified as the summer season. The available measured data for hourly SO_2 concentrations in this period were recorded about 98 % for 2004. There was no apparent violation exceeding 170 ppb, the specified limit of K-EPA for SO_2 concentration in this period. The maximum hourly SO_2 concentration was around 87.7 ppb at 11:00 hr on 18th August 2004 where the corresponding temperature was 41.1°C, relative humidity 1.94%, wind speed 3.41 m s^{-1} from WSW direction (253°). The most probable sources are the numerous transport offices, in Ardiya area, which has that use heavy transport to mobilize goods, heavily contributing to the high SO_2 levels and AL-ardiya wastewater plant. The maximum daily mean SO_2 concentration for this period was 15.34 ppb, corresponding to 29th July. The monthly average measuring SO_2 concentration was $1.8 \pm 0.56\sigma$ ppb, where $\sigma = 0.28$, for July, $1.5 \pm 0.595\sigma$ ppb, where $\sigma = 0.26$, for August and in September was $1.2 \pm 0.95\sigma$ ppb, where $\sigma = 0.76$.

The available hourly data recorded for SO_2 measured concentrations in this period was about 91.75% for 2001. There was no observed violation exceeding 170 ppb, the specified limit of K-EPA for SO_2 concentration in this period. The maximum hourly SO_2 concentration was around 134 ppb at 11:00 hr on 5th September where the corresponding temperature was 47.6°C, relative humidity 13.78%, wind speed 2.43 m s^{-1} from NW direction (299°). The most probable source was the Doha power station, confirming the fact that the power plants run at peak loads during summer. The maximum daily mean SO_2 concentration for

this period was 16.02 ppb, corresponding to 5th September. The monthly average SO_2 measured concentration in July was 1.4 ± 0.62σ ppb, where σ = 0.175, August 1.3±0.7σ ppb, where σ = 0.163 and in September was 3.7±0.66σ ppb, where σ = 0.395.

D- Autumn season analysis

The available measured data for hourly recorded SO_2 concentrations in autumn period (October to December) for 2004 was 63.53 % from the total case and there was no obvious violation exceeding 170 ppb specified limit of K-EPA for SO_2 concentration in this period. The maximum hourly SO_2 concentration was around 23.25 ppb at 11:00 hr on 27th December where the corresponding temperature was 12.6°C, relative humidity 55.2%, wind speed 3.01 m s^{-1} from WNW direction (290°). The most probable source is the Doha power station, working in peak load in the summers, using heavy fuel containing 4% sulphur. The maximum daily mean SO_2 concentration for this period was 9.53 ppb, corresponding to 11th December. The monthly average SO_2 concentration in October was 2.8 ± 0.91σ ppb, where σ = 0.166, and in December was 3.4 ± 0.81σ ppb, where σ = 0.279, for month of November there was no data recorded in year 2004.

The data available in 2001 for hourly recorded SO_2 concentrations in the autumn season was approximately 98.45%, and there was no observed violation exceeding 170 ppb specified limit of K-EPA for SO_2 concentration in this period. The maximum hourly SO_2 concentration was around 114.7 ppb at 20:00 hr on 21st November where the corresponding temperature was 20.7°C, relative humidity 52.5%, wind speed 0.73 m s^{-1} from SE direction (142.5°). The most probable source is the high traffic load at the junction of the Gazalli expressway, and 6th ring road. The maximum daily mean SO_2 concentration for this period was 35.7 ppb, corresponding to 21st November. The monthly average SO_2 concentration in October was 2.8 ± 0.63σ ppb, where σ = 0.307, November 4.2 ±

0.35σ ppb, where $\sigma = 0.68$ and in December was $1.4 \pm 0.84\sigma$ ppb, where $\sigma = 0.97$.

Overall, it can be seen that from the results the overall monthly SO_2 measured concentrations for 2001 were greater than 2004. This observation has justification mainly due to prevalent meteorological conditions that has high wind and dusty weather in 2004 as compared to 2001, providing very good dispersion. This can be credited to the growing environmental awareness that has prompted changes like the use of lower sulphur content fuel for power generation plants, cleaner fuel, and treatment prior to discharge. In addition, the average measuring concentrations of SO_2 in the summer period are higher than the other seasons and the lower season in the winter for both years. This is explained by the growing demand of power to meet the requirements of the nation. The summer temperatures escalate the need for comparative cooling causing the power stations to be running at peak loads, with fuel contains high sulphur content and in spite of the favorable dispersion conditions the concentration noticed are comparatively high.

There are a number of ways in which the concentration distribution around a source of emission can be presented. Analysis of the ambient air pollutants concentrations according to wind direction at a source location considered as one of main factors in ambient air pollution monitoring study. When air pollutants released from one or array of point sources such as stacks, then the wind direction determines the paths effluents will take or the area to which the plumes will be directed. The correlation of wind direction and air pollution concentrations at any location can help to identify the sources mainly responsible for the pollution measured at the site. In meteorology it is conventional to consider the wind direction as the direction from which the wind blows, therefore in our case a northwest wind will move pollutants to southeast of the source. In this thesis, as shown in the Figure 3.6, 3.7, 3.8 and 3.9 measured concentration distribution of pollutant such as SO_2 in rose charts which include geographic directions with respect to the meteorological conditions are shown.

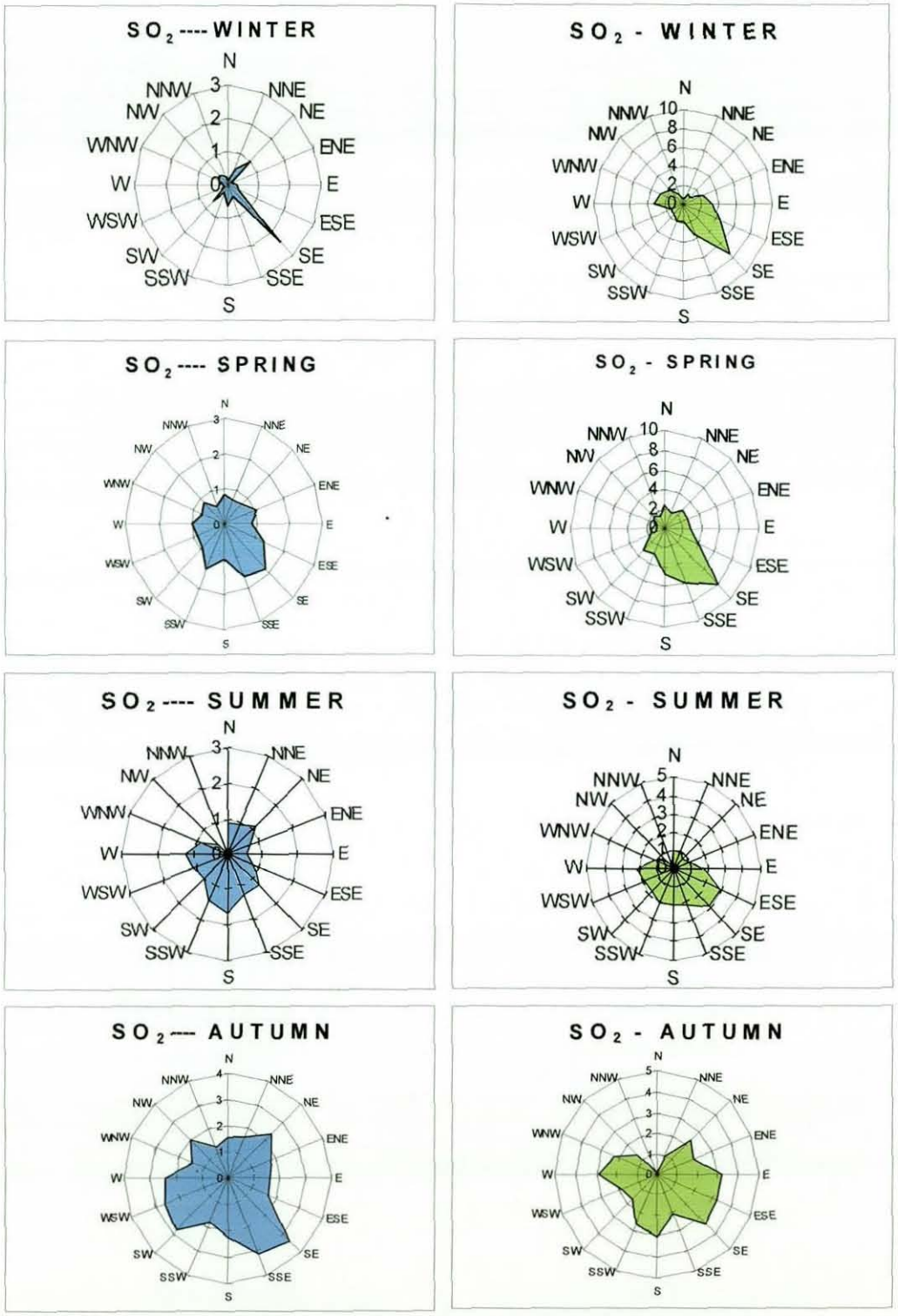


Figure 3.6: The seasonal wind rose mean variation of measured SO_2 (ppb) at Rabia station according to wind direction for year 2001 (right) and 2004 (left).

Figure (3.6) shows that the seasonal mean distribution of SO_2 measured concentrations using wind rose diagram for both years at Rabia monitoring station. From this figure, we can see that the measured high mean concentration of SO_2 is almost in the sector of southeast of the monitoring station for all seasons and the low mean concentration in the opposite sector, which is northwest for both years. This mean that the main source of SO_2 comes from Doha power station, which is located in the northwest of our study area and this wind direction sector is agrees with our results.

3.4.2 Nitrogen oxide (NOx) sources and analysis of measured concentrations

Nitrogen oxide ($NOx = NO + NO_2$) is a primary pollutant. They are formed because of combustion processes, mainly when fuel burns at a high temperature, and, therefore, the chief sources would industrial such as power generation plants, commercial and residential areas using fuel, and motor vehicles. These oxides react to produce nitrates and nitric acid, that cause smog and acid rain, and they catalyze the formation of harmful ground-level ozone.

A- Winter season analysis

The measured data collection of NOx had been carried out for the winter 2004 (January-March) about 98.6% data for the season, had been determined by a data monitor on hourly basis. On analyzing the data, it was observed that, the specified limit of K-EPA (200 ppb) was found to be violated 150 times with 6.87% beyond the limit. The maximum hourly measured NOx concentration in this period was around 802.3 ppb at 21:00 hr on 19th February, where the corresponding temperature was 15.6°C, relative humidity 34%, and wind speed 1.6 m s^{-1} from NW direction (304°). On detailed investigation it was proved that, the most probable source for this, was the emissions from Doha power station and local traffic road. The maximum NOx measured concentration (recorded on daily basis) for this period was 209.3 ppb, corresponding to 2nd March. The

average measuring NOx concentrations (recorded on monthly basis) were 74.26 ± 0.92σ ppb (σ = 3.23), 65.03 ± 0.74σ ppb (σ = 3.9), 73.99 ± 0.82σ ppb (σ = 5.45) for the months January, February and March respectively.

Previous data collection records revealed that, 2001 winter (January – March) 94% data had been collected for measured NOx concentration and the violations exceeding 200 ppb specified limit of K-EPA was about 60 times with 2.78%. On hourly basis analysis the highest hourly NOx measured concentration in this period was 543.2 ppb at 20:00 hr on 24th February. The atmospheric conditions were as follows, temperature 22°C, relative humidity 61%, and wind speed 0.7 m s^{-1} from SW direction (222°). The possible causes stated for this was the road traffic and the emissions released form Al-Ardiya wastewater plant that located to the southwest of Rabia area with distance of 2 km. The maximum daily NOx measured concentration for this period was 125.9 ppb, corresponding to 28th February. The monthly average NOx measured concentration in January was 71.6 ± 0.82σ ppb, where σ = 2.9, February 63.25 ± 0.71σ ppb, where σ = 3.2 and in March was 61.74 ± 1σ ppb, where σ = 1.9.

B- Spring season analysis

The spring season analysis (April – June, 2004) showed comparatively better results. The prior data available for NOx measured concentrations for this season 2004, (95.5% data had been collected by the monitor on hourly basis), infringes the toleration limit 200 ppb (K-EPA) about 38 times with 1.72%. The peak hourly NOx measured concentration recorded in this period was 513 ppb at 23:00 hr on 29th April. Consequent weather conditions were temperature 27.6°C, relative humidity 7.7%, and wind speed 0.83 m s^{-1} from SE direction (154°). The heavy traffic congestion at the Gazalli expressway, which is aligned to the Rabia area from the east, was the possible reason for this. The maximum daily NOx measured concentration for this period was 170.7 ppb, corresponding to 16th June. The monthly average measuring NOx concentration in April was 74.12 ±

0.77σ ppb, where σ = 2.7, May 73.95 ± 0.82σ ppb, where σ = 1.9 and in June was 74.35 ± 0.65σ ppb, where σ = 3.1.

In year 2001 the measuring NOx concentrations (about 88%) obtained on hourly basis was found to violate 7 times exceeding the specified limit of K-EPA (200 ppb) 0.32% beyond the toleration. The maximum hourly NOx measured concentration in this period was around 389.8 ppb at 21:00 hr on 13th May, where the corresponding temperature was 39.5°C, relative humidity 46.6%, wind speed 1.24 m s^{-1} from WNW direction (274°). The most probable sources identified were, the Doha power station and the numerous transport offices in Ardiya area. The maximum daily NOx measured concentration for this period was 135.5 ppb, on 15th May. On monthly basis determination, the average measured NOx concentration in April was 62.07 ± 0.98σ ppb, where σ = 1.68, May 61.7 ± 0.77σ ppb, where σ = 2.51 and in June was 62.02 ± 0.87σ ppb, where σ = 0.82.

C- Summer season analysis

The NOx measured concentrations data collected during summer 2004 (July – September) is as follows. Out of 98.8% data collected, violations exceeded specified limit of K-EPA happened 37 times with 1.67% beyond the toleration. The hourly monitoring of NOx measured concentration in this period showed a highest value 416.6 ppb at 23:00 hr on 24th July, where the corresponding temperature was 36.4°C, relative humidity 8.5%, wind speed 1.77 m s^{-1} from W direction (271°). The most probable source is the Doha power station, running at peak load in summers enhancing the pollution load. The maximum measured daily mean NOx concentration for this period was 106.7 ppb, corresponding to 6th July. The monthly average measured NOx concentrations were 73.97 ± 0.78σ ppb, (σ = 2.4), 73.86 ± 0.82σ ppb, (σ = 2.2), 74.59 ± 0.94σ ppb, (σ = 2.4) during July, August and September respectively.

Former NOx measured concentrations data collection during this period, noted on hourly basis (2001, 89% data) surpassed 200 ppb (specified limit of K-EPA) 8 times with 0.36% beyond the toleration. The maximum hourly NOx measured concentration noted during this season was around 353.75 ppb at 20:00 hr on 6th September with following weather conditions. Temperature was 43.5°C, relative humidity 39%, and wind speed 1.52 m s^{-1} from SW direction (206°). Major source responsible for this pollutant level was the emissions released form Al-Ardiya wastewater plant which is located to the southwest of Rabia area with distance of 2 km. When monitored on daily basis the maximum NOx measured concentration for this period was 106.7 ppb, corresponding to 26th September. The monthly average NOx measured concentration in July was 61.75 ± 0.895σ ppb, where σ = 0.98, August 61.81 ± 0.78σ ppb, where σ = 1.22 and in September was 62.03 ± 0.8σ ppb, where σ = 2.72.

D- Autumn season analysis

About 67% data was available for the autumn season (hourly determined data, 2004, October - December). From the collected data of NOx concentrations, 5.8% were found violated 87 times, beyond the specification (200 ppb) of K-EPA. The hourly recorded data of NOx measured concentration in this period showed a peak value of 623.75 ppb at 21:00 hr on 6th December where the corresponding temperature was 13.6°C, relative humidity 25.8%, wind speed 0.43 m s^{-1} from SSE direction (172°). The most probable source was the heavy traffics from Gazalli expressway. The maximum NOx measured concentration for this period (daily basis) was 196.1 ppb, on 30th December. The monthly average NOx measured concentration in October was 75.61 ± 0.84σ ppb, where σ = 3.2, in November there was no data recorded in year 2004, and in December was 75.74 ± 0.72σ ppb, where σ = 4.3.

98% previous data was available for (recorded hourly) NOx concentrations during this period, (year 2001). It was noted that, 6.6% values exceeded 97 times,

the specified limit of K-EPA (200 ppb). The hourly NOx measured concentration in this period showed a maximum around 690.1 ppb at 20:00 hr on 11th October, where the corresponding temperature was 36.6°C, relative humidity 55%, and wind speed 1 m s^{-1} from SSW direction (200°). The emissions from Al-Ardya sewage treatment plant and the prevalent traffic of heavy vehicles are the sources. The peak NOx measured concentration for this period was 215.6 ppb, corresponding to 11th October. When assessed monthly basis the average measuring NOx concentrations in October was 54.87 ± 0.73σ ppb, (σ = 5.3), November 61.9 ± 0.83σ ppb, (σ = 3.12) and in December was 54.71 ± 0.84σ ppb, (σ = 2.8).

Overall, the monthly average measured concentrations of NOx in 2004 are higher than 2001. This is mainly due to high emission rate of NOx emitted from power stations to cover the demand of utilities required for residential areas and increase in number of vehicles over the years. In areas of high motor vehicle traffic, such as in Rabia, the amount of nitrogen oxides emitted into the atmosphere can be quite significant. Jia Li *et al.* (2004) show that in Shanghai city in the China the emissions of NOx have increased dramatically between years 1990 and 1999, as result of the rapid growth in the number of vehicles.

As shown in the Figure (3.7), the highest mean distribution of NOx measured concentrations extending from sector ESE to SSW for year 2001. This result indicates that the main sources of NOx measured concentrations are the Doha and Subyia power stations, which located in the northwest and northeast respectively. In addition, for year 2004 the highest seasonal mean distribution of NOx measured concentrations extending from sector WNW to NNE at Rabia monitoring station. This means that the main source of NOx for this year is the traffic movements at the study area, which is also considered as the main source of NOx in residential areas. The traffic movement in the residential areas is responsible for the emissions of 95% of carbon monoxide (CO) and 26% of nitrogen oxide (NOx) in the state of Kuwait (Bouhamra and Abdulwahab, 1999).

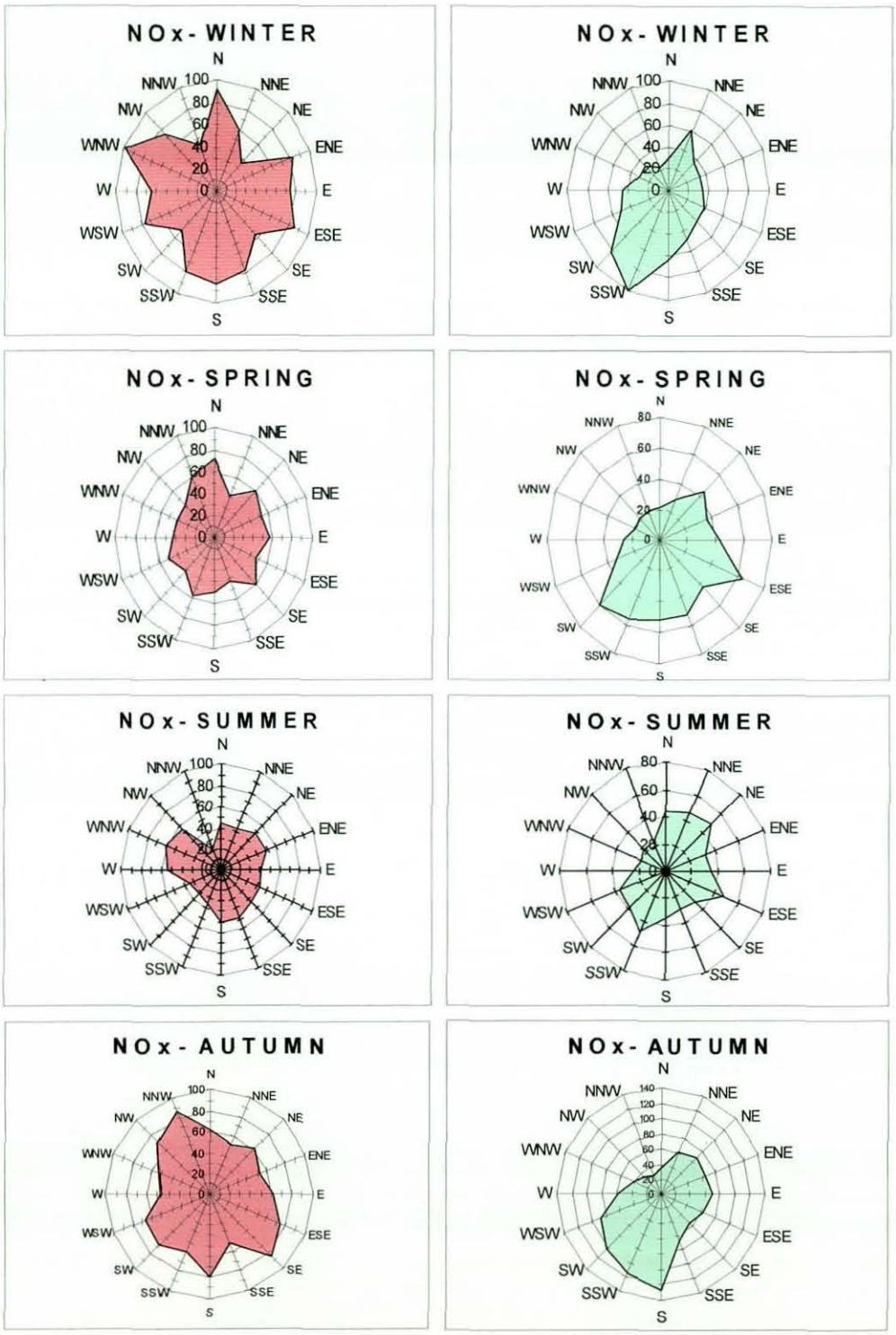


Figure 3.7: The seasonal wind rose mean variation of measured NOx (ppb) at Rabia station according to wind direction for year 2001 (right) and 2004 (left).

3.4.3 Ozone (O_3) sources and analysis of measured concentrations

It is a secondary pollutant, created in the presence of sun light, NOx and a pre-curser VOCs. It is complimentary in its action along with NOx, in that in the presence of sunlight, the available concentration of NOx is consumed and used in generation of ozone, while in the absence of sunlight, the reversible reaction prevails, reducing the O_3 concentrations, and enhancing the NOx concentrations. The analysis of ozone during the daytime was found to be significantly due to high O_3 precursor concentrations generating substantial O_3 levels than that of nighttime where only neutralization occurs due to fresh NO production (Abdul-Wahab *et al.*, 2002).

A- Winter season analysis

On analyzing 95%, O_3 measured concentrations collected data recorded by the data monitor on hourly basis (2004 winter, January – March); it was found to be in conformation with the regulations, and never found to violate the specified limit of K-EPA (80 ppb). The peak value obtained on hourly determination of O_3 measured concentration in this period was around 39.42 ppb at 15:00 hr on 1st of February, where the corresponding temperature was 18°C, relative humidity 52.2%, wind speed 2.6 m s^{-1} from SE direction (115°). Traffic congestion, diverging towards the junction of the Gazalli expressway and 6th ring road should be the reason behind this level of O_3. In addition, increasing number of cars this will lead to increase the emission of NOx in the ambient air so that the level of O_3 concentration will lowered due to neutralizing. However, 20 ppb recorded as the maximum daily O_3 measured concentration for this period, which was on 30th of March. The monthly average of O_3 measured concentration in January was 7.8 ± 0.92σ ppb, (σ = 0.39), February 11.1 ±0.81σ ppb, (σ = 0.35) and in March was 12.1 ± 1.1σ ppb, (σ = 0.37).

Concentrations of O_3 in the preceding data collected for the same season during the year 2001 were about 99.82% (hourly basis). This data collection showed no noticeable violations exceeding 80 ppb specified limit of K-EPA. Hourly recorded data, in this period showed a peak measured value of 53 ppb at 16:00 hr on 24th March where, the corresponding temperature was 28°C, relative humidity 74%, wind speed 5.5 m s^{-1} from SE direction (112°). This confirms the fact that road traffic at the junction of Gazalli expressway, and 6th ring road considerably contributes to this O_3 pollution level. The peak value of O_3 concentration for this period was 25.94 ppb, corresponding to 24th March (monitored on daily basis). The monthly average O_3 concentration in January was $7.9 \pm 0.786\sigma$ ppb, where $\sigma = 0.32$, February $11.7 \pm 0.81\sigma$ ppb, where $\sigma = 0.4$ and in March was $11.9 \pm 0.74\sigma$ ppb, where $\sigma = 0.42$.

B- Spring season analysis

The monitored data on hourly basis (O_3 measured concentrations) in this period, 2004 spring April to June was about 88 %, with no violations exceeding 80 ppb specified limit of K-EPA. The maximum measured (hourly) O_3 concentration in this period was around 43.1 ppb at 13:00 hr on 28th May, where the corresponding temperature was 355°C, relative humidity 4.4%, wind speed 3.16 m s^{-1} from E direction (81°). The probable cause was the traffic congestion at the Gazalli expressway. The highest daily O_3 concentration for this season was 28 ppb, corresponding to 16th April. The monthly average O_3 concentration in April was $14.4 \pm 0.77\sigma$ ppb, ($\sigma = 0.533$), May $12.2 \pm 0.8\sigma$ ppb, ($\sigma = 0.36$) and in June was $11.9 \pm 1.5\sigma$ ppb, ($\sigma = 0.3$).

On investigating the available measured data recorded in 2001 (92.6% Hourly monitored O_3 concentrations) for this period, observed to have no violations exceeding 80 ppb specified limit of K-EPA. Hourly peak O_3 concentration in this period was around 51 ppb at 15:00 hr on 11th April where the corresponding temperature was 38°C, relative humidity 30.5%, and wind speed 1.8 m s^{-1} from

W direction (272°). Operational violations of the numerous transport offices and heavy vehicles in Ardiya and local cars traffic, were the reason for this pollution. The maximum daily O_3 concentration for this period was 33.1 ppb, corresponding to 18th May. The monthly average O_3 concentration in April was 15.3 ± 1.026σ ppb, where σ = 0.594, May 15.6 ± 0.86σ ppb, where σ = 0.59 and in June was 20.2 ± 0.92σ ppb, where σ = 0.38.

C- Summer season analysis

The available hourly monitored data (2004) for O_3 measured concentrations in summer season (July to September) was about 92 %. On detailed observations, violation of exceeding 80 ppb specified limit of K-EPA had happened 0.095%. The maximum (hourly monitoring) O_3 concentration in this period was around 90.6 ppb at 14:00 hr on 18th September where the corresponding temperature was 36.7°C, relative humidity 2.31%, wind speed 1.88 m s^{-1} from NE direction (46°). This level of O_3 was due to the Subyia power station emissions (NOx), which run at peak load in summers and local car traffic. Peak (daily) O_3 concentration for this period was 26 ppb, corresponding to 17th September. The monthly average O_3 concentration in July was 14.4 ± 0.87σ ppb, where σ = 0.34, August 16.1 ± 0.86σ ppb, where σ = 0.45 and in September was 17.9 ± 1.1σ ppb, where σ = 0.48.

The data observation revealed that the hourly monitored O_3 measured concentrations in 2001 were about 91.88% and showed a violation of 0.091% exceeding 80 ppb specified limit of K-EPA for O_3 concentration. The violation occurred twice during this season. The maximum (hourly) O_3 concentration in this period was around 112 ppb at 13:00 hr on 25th July with a temperature of 49.9°C, relative humidity 29%, wind speed 2.33 m s^{-1} from ENE direction (68°). This value of O_3 concentration was due to the Subyia power station, which was running at peak load in summers exerted a sizeable stress on the environment by emitted NOx to the atmosphere. The maximum (monitored daily) O_3

concentration for this period was 38.2 ppb, corresponding to 3rd July. The monthly average O_3 concentration in July was 20.5 ± 0.85σ ppb, where σ = 0.793, August 17.7 ± 0.86σ ppb, where σ = 0.546 and in September was 17.4 ± 0.77σ ppb, where σ = 0.484.

D- Autumn season analysis

The O_3 measured concentrations available data for 2004, October to December which was monitored on hourly basis was about 92 %, with no violations exceeding 80 ppb specified limit of K-EPA. O_3 concentration in this period recorded a peak value around 60 ppb at 15:00 hr on 1st October where the corresponding temperature was 37.4°C, relative humidity 6.9%, wind speed 1.5 m s^{-1} from NNE direction (12°) when monitored on hourly basis. The most probable source for this level of O_3 was the traffic congestion, at the 5th ring road, enhanced the pollution load. Peak daily O_3 concentration for this period was 22 ppb, corresponding to 10th October. The monthly average O_3 measured concentration in October was 11.6 ± 0.85σ ppb, where σ = 0.54, and in December was 9.1 ± 0.8σ ppb, where σ = 0.26.

The data recorded for hourly O_3 measured concentrations for this period, in the 2001 was about 91.88% with a violation of 0.091% exceeding 80 ppb specified limit of K-EPA for O_3 concentration. The maximum hourly O_3 concentration in this period was around 59.3 ppb at 15:00 hr on 13th October where the corresponding temperature was 40.6°C, relative humidity 54%, wind speed 2.22 m s^{-1} from ENE direction (82.5°). The most probable source is the prevalent traffic congestion, at the junction of Gazalli expressway, and 5th ring road, enhancing the stress on the environment. The maximum daily mean O_3 concentration for this period was 38.2 ppb, corresponding to 4th October. The monthly average O_3 concentration in October was 12.1 ± 0.846σ ppb, where σ = 0.4, November 10.8 ± 0.83σ ppb, where σ = 0.349 and in December was 9.4 ± 0.83σ ppb, where σ = 0.36.

From the above results it can be seen that the monthly measured concentrations of O_3 in 2001 were comparatively higher than year 2004. This was because of increasing in the emission of NOx emitted from power stations and increasing number of cars supports this very well over the years that have escalated the NOx concentrations over the years, and NOx being hostile to O_3, neutralizing the concentrations by reacting and forming NO_2.

The seasonal distributions of ozone (O_3) according to the wind rose diagram in the Figure (3.8) show that the high mean measured concentrations of O_3 extending between WNW and ENE for both years. It is interesting to note that the O_3 considered as a secondary pollutant so that the concentrations of O_3 are not emitted from local sources but it is a results of photochemical reactions due to the availability of NOx, NMHC in present of sunlight. Lorenzini *et al.* (1994) have presented a study in Italy that show the formation of O_3 was depended on the photochemical reactions of NOx, NMHC, Oxygen and solar radiation energy. However, the highest concentration of O_3 is always related to the low concentrations of NOx, CO and NMHC. In addition, the average mean measured concentrations of O_3 in year 2001 are higher than 2004 Figure (3.8). This is because of increasing number of cars that increase the emissions of NOx which will neutralize O_3 resulting in lower values.

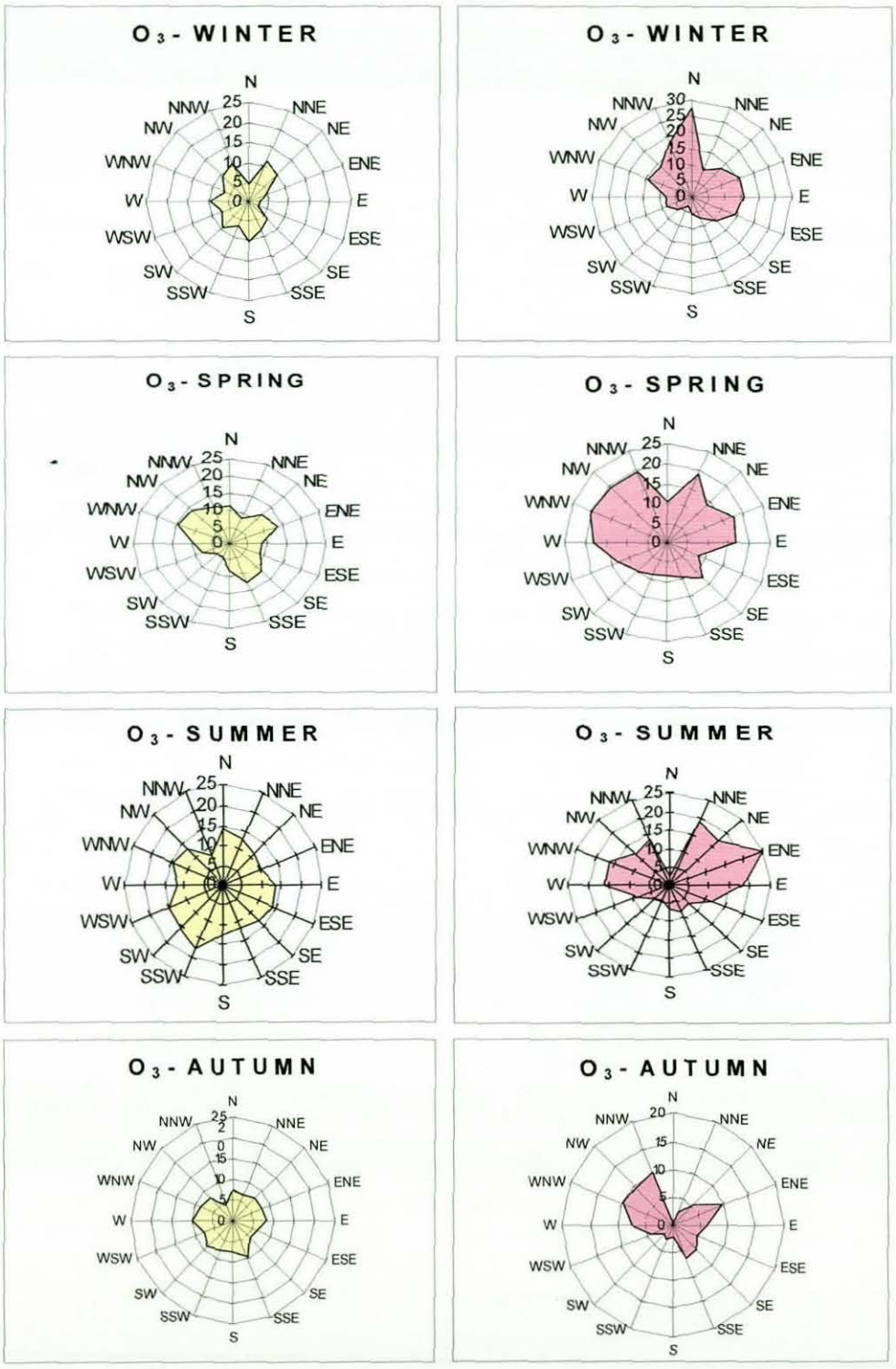


Figure 3.8: The seasonal wind rose mean variation of measured O_3 (ppb) at Rabia station according to wind direction for year 2001 (right) and 2004 (left).

3.4.4 Nitrogen dioxide (NO_2) sources and analysis of measured concentration

Nitrogen dioxide (NO_2) is a secondary pollutant. The most obvious sources are cars, combustion sources, power stations, flares, etc. In addition, under normal temperatures, and the presence of an oxidizing agent like O_3, OH- the oxidation of NO to NO_2 takes place.

A- Winter season analysis

A detailed analysis of compiled data (98.6%) of NO_2 measured concentrations (hourly basis) during January to March 2004 showed no violations exceeding 100 ppb (the specified limit of K-EPA). The maximum NO_2 measured concentration in this period (hourly basis) showed a peak value of 64.17 ppb at 17:00 hr on 15th March, where the corresponding temperature was 20°C, relative humidity 7.14%, wind speed 2.6 m s^{-1} from WNW direction (300°). The reasons for the observed level of NO_2 were the traffic congestion, at the junction of 5th ring road and Ardiya area enhanced the level of NO_2. The peak concentration of NO_2 observed when monitored on daily basis was 36.35 ppb, on 5th January. The monthly average NO_2 measured concentration in January was $18.3 \pm 0.88\sigma$ ppb, where $\sigma = 0.57$, February was $18.4 \pm 0.77\sigma$ ppb, where $\sigma = 0.41$ and in March was $22 \pm 0.82\sigma$ ppb, where $\sigma = 0.61$.

Earlier measured data (93.7%) available for this season for the year 2001 for the same pollutant showed no violation exceeding 100 ppb specified limit of K-EPA for NO_2 concentration. The highest hourly NO_2 concentration in this period was around 53.1 ppb at 14:00 hr on 2nd January, where the corresponding temperature was 25.13°C, relative humidity 68.5%, wind speed 0.66 m s^{-1} from SE direction (146°). The root cause of resultant pollutant level of NO_2 was the prevalent traffic congestion at the junction of Gazalli expressway, and 6th ring road, enhancing the stress on the environment. The maximum daily NO_2 concentration for this period was 38.2 ppb, corresponding to 2nd January. The

monthly average NO_2 concentration in January was 17.6 ± 0.77σ ppb, where σ = 0.37, February was 17.4 ± 0.82σ ppb, where σ = 0.428 and in March was 17.3 ± 1.46σ ppb, where σ = 0.417.

B- Spring season analysis

NO_2 concentrations data monitored on hourly basis for the spring season of 2004 showed no failure to the regulations K-EPA. (100 ppb). 95.5% collected data had been analyzed for the season, found to be in conformation with the standard regulations. The maximum hourly of NO_2 measured concentration in this period was around 55.6 ppb at 18:00 hr on 19th June with following weather conditions. Temperature recorded was 38.95°C, relative humidity 1.14%, and wind speed 2.33 m s^{-1} from NW direction (307°). The presence of NO_2 concentrations was justified by the emissions from Doha power plant, which is working at near peak load and the car traffic. The maximum daily NO_2 measured concentration for this period was 35.5 ppb, corresponding to 3rd April. The monthly average NO_2 concentration in April was 18.5 ± 0.96σ ppb, (σ = 0.61) and in May was 17.9 ± 0.77σ ppb, (σ = 0.4) where as, in June it was 23.7 ± 0.87 ppb, (σ = 0.5).

On investigating the 88.55% collected data in same season of 2001 (hourly recorded) NO_2 measured concentrations showed no violation exceeding 100 ppb specified limit of K-EPA. The peak hourly NO_2 concentration in this period was around 88.7 ppb at 10:00 hr on 1st April, where the corresponding temperature was 39.7°C, relative humidity 33.7%, and wind speed 0.86 m s^{-1} from ESE direction (117°). The most probable source of the resulted level of NO_2 concentrations was due to the traffic congestion at the junction of Gazalli expressway and Farwaniya, enhanced the stress on the environment. The maximum daily NO_2 measured concentration for this period was 31.83 ppb, corresponding to 24th April. The monthly average NO_2 concentration of in April was 18.6 ± 1.1σ ppb, where σ = 0.565, May was 15.8 ± 0.99σ ppb, where σ = 0.426 and in June was 15.7 ± 0.91σ ppb, where σ = 0.346.

C- Summer season analysis

The available data of NO_2 measured concentrations monitored on hourly basis during 2004, July to September was about 99%. On examining the collected data this data never exceeded 100 ppb specified limit of K-EPA. The maximum hourly NO_2 measured concentration in this period was around 86.6 ppb at 17:00 hr on 25th September where, the corresponding temperature was 34.6°C, relative humidity 3.8%, wind speed 1.4 m s^{-1} from NE direction (47.5°). The reason for this pollution level of NO_2 is the Subyia power plant emissions, which is working at peak load in summer and the local traffic in the study area. The maximum NO_2 concentration when determined everyday, for this period was 40.6 ppb, corresponding to 26th September. The monthly average measured concentration of NO_2 in July was as given 26.6 ± 0.86σ ppb, (σ = 0.0052), August was 20.3 ± 0.72σ ppb, (σ = 0.00343) and in September was 24.3 ± 1.06σ ppb, (σ = 0.0068).

On inspecting the older data (89.43 %) available for the same season which had been monitored on hourly basis for the year 2001, this data was not in conformation with the specified limit of K-EPA for NO_2 concentration, 0.045% exceeded 100 ppb. The maximum measured (hourly basis) NO_2 concentration in this period was around 100.75 ppb at 11:00 hr on 25th September where the corresponding weather conditions are as follows: temperature was 47.6°C, relative humidity 15.9%, and wind speed 1.13 m s^{-1} from ENE direction (73°). Origin of this NO_2 concentration was due to the traffic congestion, at the junction of Gazalli expressway, 5th ring road, and boosted the stress on the environment. The highest daily NO_2 concentration for this period was 50.85 ppb, corresponding to 26th September. The monthly average NO_2 concentration in July was 16.8 ± 0.94σ ppb, (σ = 0.49), August was 14.2 ± 0.79σ ppb, (σ = 0.513) and in September was 17.9 ± 0.76σ ppb, (σ = 0.125).

D- Autumn season analysis

Year 2004 autumn season (October to December) showed interesting data. When analyzed the 67% data collected, it was found that there were no violation of exceeding 100 ppb specified limit of K-EPA for NO_2 concentration. The data were recorded on hourly basis. The peak measured value of NO_2 concentration in this period was around 61 ppb at 19:00 hr on 1st October 2004 (recorded on hourly basis). The corresponding temperature was 31.7°C, relative humidity 15.9%, and wind speed 1.2 m s^{-1} from NE direction (40°). Subyia power plant emissions were the most probable source, which is working at near peak load. The maximum daily NO_2 measured concentration for this period was 25.81 ppb, corresponding to 12th October. The monthly average NO_2 concentration in October was 14.8 ± 0.83σ ppb, (σ = 0.47) and in December was 15.1 ± 0.78σ ppb, (σ = 0.31).

The monitored previous data available in 2001 autumn (98.5%) for NO_2 measured concentrations found to violate 100 ppb specified limit of K-EPA. 1.9% data exceeded the toleration limit. The maximum hourly NO_2 measured concentration in this period was around 161.4 ppb at 10:00 hr on 15th October 2001 with atmospheric conditions: temperature 41.5°C, relative humidity 50.1%, wind speed 0.98 m s^{-1} from ESE direction (104°). The possible reasons for this pollution were the developing traffic congestion at the junction of Gazalli expressway, and 6th ring road, responsible for the enhanced pollutant load. The maximum daily NO_2 measured concentration for this period was 79.58 ppb, corresponding to 10th October. The average NO_2 measured concentrations determined on monthly basis were: October 13.4 ± 0.85σ ppb, (σ = 0.199), November 15.9 ± 0.796σ ppb, (σ = 0.51) and in December 14.3 ± 0.96σ ppb, (σ = 0.381).

In the case of NO_2, the overall monthly measured concentrations were higher in 2004, as compared to 2001. This is because of the emissions of NO_2 having

increased dramatically between these years, as result of the rapid growth in the number of vehicles.

In the Figure (3.9), the high mean measured concentration is found for NO_2 in the sector extending from N to SE. This is agreeing with our observation that the Doha power station is the main source of pollutants. Beside the power stations, the heavy traffic is considered as a main source of NO_2. In addition, as shown from rose diagram the mean measured concentration of NO_2 in year 2001 is higher than year 2004. However, in year 2001 the high mean measured concentration of NO_2 occurred in autumn season while in the year 2004 the high mean concentration happens in summer season.

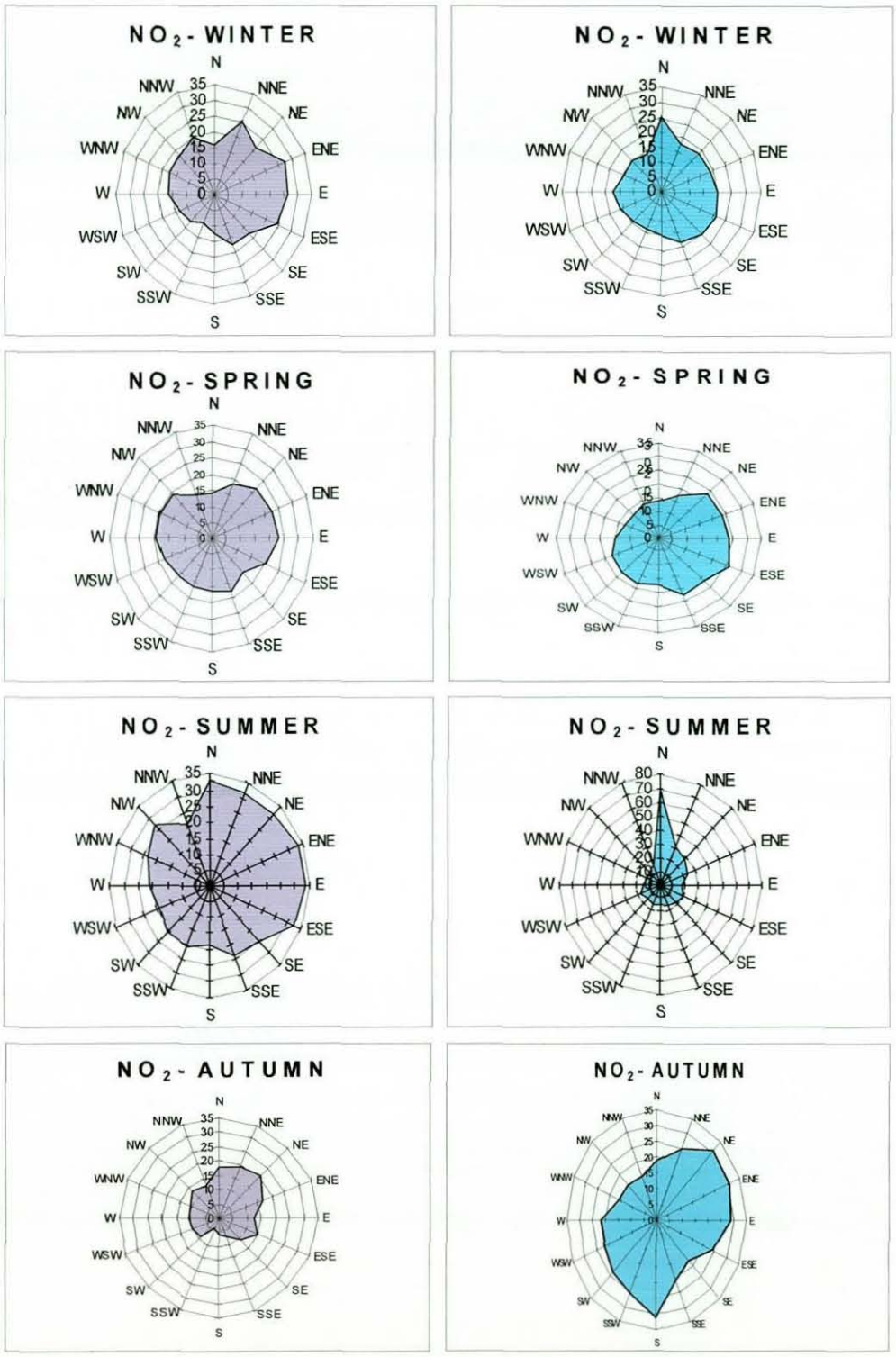


Figure 3.9: The seasonal wind rose mean variation of measured NO_2 (ppb) at Rabia station according to wind direction for year 2001 (right) and 2004 (left).

Table (3.3): The number and percentage of exceedence of the pollutants hourly concentration measurements in (ppb) with respective of Kuwait- EPA standards limits at Rabia area for years 2001 and 2004.

Rabia 2001						
Pollutants	**Existing number of data (%)**	**Maximum Over year**	**Average Over year**	**Minimum Over year**	**NO. of Exceedances**	**% Exceedance**
SO_2	99.8	171.25	2.39	0.00	1	0.0114
NO_2	93.7	161.42	18.3	0.00	29	0.331
NOx	92.3	690.1	45.7	1.70	198	2.26
CO	90.2	14525	1183.7	125	0	0.00
O_3	99.8	112	11.7	0.00	2	0.023
Rabia 2004						
Pollutants	**Existing number of data (%)**	**Maximum Over year**	**Average Over year**	**Minimum Over year**	**NO. of Exceedances**	**% Exceedance**
SO_2	93.2	87.7	1.13	0.00	0	0.00
NO_2	95.5	86.75	18.53	0.00	0	0.00
NOx	98.6	802.3	57.1	0.00	309	3.52
CO	96.8	14983	1005	150	0	0.00
O_3	92.1	90.6	10.1	0.00	2	0.023

With respect to the standards set by the Kuwait EPA Table (3.3), show that all the pollutants come within the set limits with no observations of any violations during the study period. Except in the case of SO_2 that occurred one time in year 2001 with 0.0114% exceeding and in case of O_3 that happen two times in year 2001 and also two times in year 2004 with 0.023% exceeding for both years. In addition, NO_2 has been exceeding 29 times the standard limits of K-EPA for year 2001 with 0.331% exceeding the limits and there is no violation observed for year 2004.

To asses the air quality in Rabia area, air pollution data for two years, 2001 and 2004 for this area in the state of Kuwait were obtained from a monitoring station located at the top of polyclinic. The pollutants under observation were O_3, SO_2, NO_2, CO and NOx. When considering the sources of these pollutants, the location of Rabia is very crucial. Three major highways flank it on three of its sides, fifth ring road to the north, sixth ring road to the south, and Gazalli highway to the east, while the fourth side is shared with Ardiya area, which houses transport offices that have come up substantially over the years. These offices mobilize goods using heavy transport vehicles and trailers, which used diesel fuel. Further north, is the industrial areas of Al-Rai and Al-Shuwaikh, which house numerous garages, and metal processing workshops. There are two large power plants, Doha complex 16 km to the northwest and Subyia power plant 25 km to the northeast, which use heavy oil for the production of power that contains about 2.5 - 4% sulphur. In addition, there is airport 8 km to the southeast. The east and west boundaries accommodate two fuel dispersing stations. In the close vicinity of the monitoring station is also located a restaurant that use coal fires for the roasting of meat as part of its daily activities. Taking all these sources into consideration, the stress on the air quality in this area is quite significant. In order to understand the impact on the environment a detailed examination of the seasonal and diurnal variations was carried out, the results of which are quite crucial.

Most of the research studies indicate that a general features in the diurnal variations of primary pollutants, which are emitted directly from there; sources such as SO_2, NOx, CO and hydrocarbons (HCs) have two maxima in urban and suburban areas. While for secondary, pollutants such as O_3 and NO_2 were formed because of the photochemical reactions of the primary ones have a single maximum in diurnal variations. However, there are some exceptions of these features in the diurnal variations of the pollutants concentrations and these exceptions are mainly due to the metrological conditions or the location of the sources to the monitoring location (Bouhamra, *et al.*, 1999 and Abdul-Wahab, *et al.*, 2004). Valeroso *et al.* 1992, have presented a study for the diurnal variations of O_3 at five urban sites in Manila. This study shows three locations out of five that have single maxima at midday over 24-hour and two maxima during a day at other two locations.

Primary pollutants are emitted from different sources into atmosphere, mixed with the wind stream of the lower layer of atmosphere and transformed via various chemical and physical pathways to produce the secondary pollutants (oxidants) such as O_3 and NO_2. As a result, the oxidants are not emitted directly to the ambient air but they are formed as results of a series of chemical reactions in atmosphere. Hsu (1992) mentioned that the transformations of the primary pollutants to the secondary ones in the atmosphere are very complex. Lorenzini *et al.*, (1994) have used six years data for ozone to study the formation of O_3 in Pisa, Italy. This study show that the formation of O_3 found as a results of photochemical reaction of oxygen, non-methane hydrocarbon and nitrogen oxide. In addition, the metrological conditions such as wind speed; wind direction, temperature and solar radiation are effected on formation process of O_3.

Kuwait is ranking as one of the highest oil producing countries in the world also has a large number of related industries for the refining and processing of this oil and its various fractions. The major sources of SO_2 emission in Kuwait are the electrical power generation plants and water desalination plants. The prevailing

wind in Kuwait is almost comes from northwest, so that the Doha complex, which consists of Doha east and Doha west power stations located near the residential areas, makes the highest contribution of about 49% of the total SO_2 emitted in Kuwait (Al-Rashidi *et al.*, 2005).

As shown in the figures (3.10, 3.11) the SO_2 have high measured concentrations in the summer, when the power stations that use fossil fuel are running at full load to meet the power needs of the country and low concentrations at winter period for both years. In case of NO_2, the high concentration occurred in autumn period for year 2001. This is because the winters in Kuwait portray a low temperature, low inversion layers, lesser wind movements, which do not promote the dispersion of pollutants, as compared to summers, which have high temperature, high inversion layers, high wind movements and effective distribution and dilution of pollutants. For year 2004, the trends of NO_2 have the high measured concentration in summer season. The trends of CO and NOx are the same for both years and the high season occurred in winter and low measured concentrations in summer. This can be attributed to the fact that high temperatures, high winds, high inversion layer, and a very significant dispersion rate of pollutants characterize the summer in the state of Kuwait especially for the pollutants that resulted from the traffic or sources inside the study area. However, for pollutants that resulted from the power generation plants the metrological conditions will take the main effecting factor.

However, in the Figures (3.10, 3.11), there are two distinct peaks, which is a characteristic feature of primary pollutants occurred in urban regions. In case of SO_2, it has two maxima over 24-hour period, the first peak occurs at midday between 11:00 am and 12:00 pm and the second occurred at evening between 8:00 pm and 10:00 pm for both years. In addition, for NO_2 it has one maximum happens at 6:00 pm. For CO and NOx they have two maxima peaks over a day time, the first highest peak occurred at 7:00 am, which represents the traffic congestion caused by people commuting to work, and children commuting to

school and at time 8:00 pm, which represents people driving out there home to visiting, shopping malls, or just out for some fresh air. Bouhamra *et al.* (1999), they have finding the same result of CO and NOx in the residential area in Kuwait. Also, it is shown from Figures (3.10, 3.11) in both years the highest peak of O_3 occurred at 2:00 pm and second small peak occurred at 3:00 am early morning. As we said that, there is an exception case for some of secondary pollutants in case of diurnal variations due to metrological conditions and the photochemical reactions. Ozone is considered as secondary pollutant so that it has one maximum peak over 24-hour and it is considered as the main index substance of the photochemical smog that was recognized as one of the principle pollutant degrading air quality. Ozone on the other hand, being a secondary pollutant, with a high dependence on photochemical oxidation shows a single stretched peak limited to the daytime, and two characteristic troughs. This is linked to the antagonistic behavior of O_3 towards NOx, where the NOx concentrations are depleted in the presence of sunlight and O_3 precursor gases. The reverse is true in the absence of sunlight. The highest measured concentration of O_3 is always related to the low measured concentrations of NOx, CO and NMHC. NOx concentrations become decreasing after the first morning peak, with increasing sunlight, remains dormant until 4:00 pm and then begin to climb of the second peak. These concentrations remain elevated with fresh emissions from vehicles and reverse conversion of ozone to nitrogen oxide, until 7:00 am the next day morning. It is interesting to observe that the diurnal curves of O_3 are exactly opposite to the curves found for NOx and CO for both years.

Another characteristic feature in the observations for the two years data is the average measured concentrations of SO_2 in the year 2001 is higher as compared to the year 2004. This is due to the rising awareness towards the environment that has brought about radical changes, which can be seen in the use of better quality of oil such as fuel oil that has low sulphur contents (1%) in all the various processes, as well as treatment processes to curb the discharges. In the case of NOx, the trend of average measured concentrations of this pollutant in year 2004

is higher that year 2001. This is because of the increase in the number of vehicles over the years, personal, as well as commercial, which is of importance to this area, since numerous transport offices with strong fleets of goods carriers have come up in neighboring Ardiya. This increase is reflected quite strongly in the case of NOx, where the concentrations have nearly doubled. The average measured concentrations remain unchanged in the case of O_3, considering that it thrives totally on photochemical oxidation, and there are no alterations in the prevalent climatic conditions in this region.

However, Figures (3.10, 3.11) present the trends of SO_2 in the year 2001, the highest measured concentration detected was in the summer season, followed by autumn, and then spring and lastly winter. For year 2004, the trend is similar to year 2001, with the highest measured concentration detected in summer, followed by autumn, spring and lastly winter. These results are in full agreement with our previous results in our research that the main source of SO_2 was the power generation plants such as Doha and Subyia power stations, which they working in full capacity in summer season.

In the case of NOx and CO, Figures (3.10, 3.11) show that the highest measured concentration measured in year 2001 was in the winter period, followed by autumn, and then spring and lastly summer. For year 2004, the trend is similar to year 2001, with the highest measured concentration detected in winter, followed by spring, and summer. This is because the winters in Kuwait portray a low temperature, low inversion layers, lesser wind movements, which do not promote the dispersion of pollutants as compared to summers, which have high temperature, high inversion layers, high wind movements and effective distribution and dilution of pollutants.

For the case of O_3, the highest measured concentration in 2001 was recorded in spring, summer and followed by winter, and lastly autumn (Figure 3.10). The highest measured concentration in 2004 were seen in spring, followed by

summer, autumn, and finally winter (Figure 3.11). This is because O_3 being a product of photochemical oxidation, is highly dependant on solar radiation, and winters have shorter day hours, and are more cloudy, leading to poor solar radiation, hence winter and autumn have a poor show with respect to O_3 concentrations.

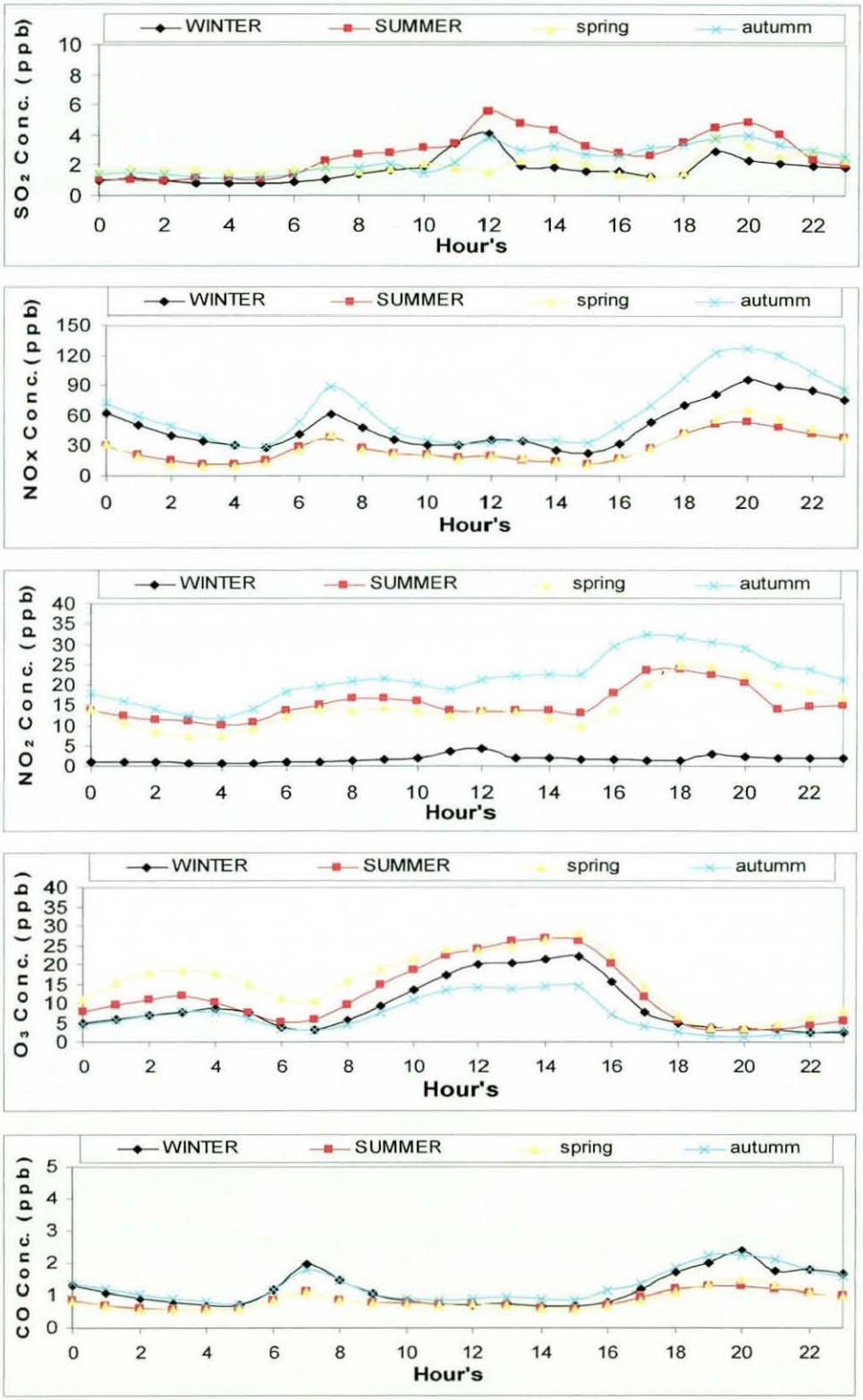


Figure 3.10: Hourly diurnal patterns of air pollutants for Rabia area in 2001

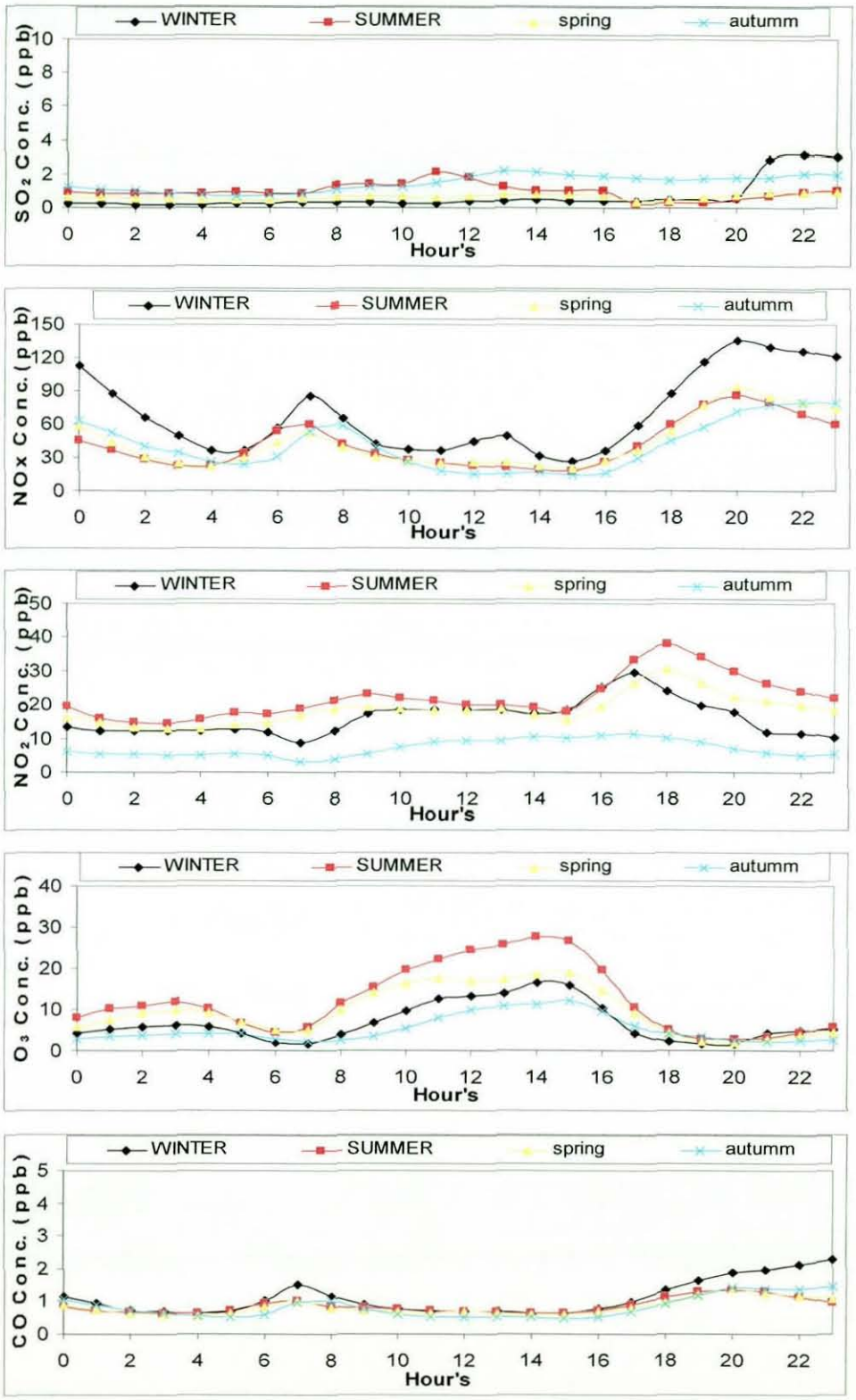


Figure 3.11: Hourly diurnal patterns of air pollutants for Rabia area in 2004

In the year 2001, the highest measured concentration of NO_2 was seen in autumn, followed by summer, winter, and lastly spring (Figure 3.10). In addition, the highest measured concentration of NO_2 in year 2004 was observed in summer, followed by winter, then spring, and lastly autumn (Figure 3.11).

3.5: Weekday/weekend Variations

Daily changes in the emissions are directly related to human activities and weekly cycle of ambient pollutants concentrations is strong function of weekday and weekend actions. There are contradictory reports about the emission-concentration relationship in urban and rural sites (Pun *et al.*, 2003). The difference in the ambient concentration of air pollutants NOx, CO, SO_2 and ozone for weekdays to weekend has been investigated and reported elsewhere (Marr *et al.*, 2002, and Vandaele *et al.*, 2002). The emissions of anthropogenic pollutants especially of ozone precursors during weekend are lower than normal weekday emissions due to lower traffic rush and less production industrial activities. Pont and Fontan (2001), present a comparative study of variation in daily ozone maxima between the different days of the week in big French cities over the summer period of 1994 - 1996. This study indicates a difference of almost 20% between the highest values of ozone concentration measured on weekdays and over the weekend, while traffic levels vary by more than 40% especially between Friday's and Sunday's (2001).

The occurrence of high concentration of ozone and low NO concentration during weekend has been reported as weekend effect. Fujita *et al.* (2003), have reported strong weekday/weekend variation in NO and O_3 levels and nearly constant during the weekdays. The monthly averages of the hourly mean ozone and NO measured concentrations for each daylight hour between 07:00 and 21:00 during midweek (Sunday-Tuesday) versus the corresponding measured concentrations of both pollutants (O_3 and NO) on Wednesday, Thursday, Friday and Saturday recorded for two years 2001 and 2004 were plotted. Weekdays and weekend

depict different pollution pattern in urban areas. Weekdays reflect offices, schools/colleges and other commercial activities while weekends have the least official activities but high commercial activities spread throughout the day. On weekdays, morning offices opening hours and later in the day closing hours have ascertained the diurnal concentration behavior related to mobile sources mainly traffic. Ozone in troposphere is an indication of the urban pollution resulting into smog formation and other harmful effects to life (plants and animal). Ozone formation is dependent on ultraviolet light, and presence of ozone precursors emitted from mainly fixed and mobile sources. In this research, six summer months (April to September) data have been averaged for daytime 10 hours for weekdays and weekends and are compared to investigate respective pollution levels in urban areas.

Figure (3.12) and (3.13) represents the mixing ratio for weekday/weekend of measured O_3 and NO in study area (Rabia) for 2001 and 2004 . The linear regression equations and the corresponding correlation coefficients, R^2 values are tabulated in Table (3.4).

In year 2001, the slopes of linear regressions showed that during Wednesdays and Thursdays, O_3 levels were similar to those existing during midweek days. During Fridays, O_3 levels were higher compared to midweek days by about 15% but on Saturdays O_3 levels dropped almost 16% lower than midweek days. In year 2004, O_3 levels for Wednesdays, Thursdays, Fridays and Saturdays were recorded 12-14% lower than the midweek days.

For year 2001, Wednesdays and Saturdays NO levels were similar to those experienced during midweek days, while Thursdays and Fridays NO levels were 45% lower than the midweek NO concentrations. In year 2004, Wednesdays and Fridays NO levels were similar to those occurring during midweek days. During Thursdays, NO levels increased by 17% than midweek concentrations while Saturdays NO levels showed 48% increase over midweek levels.

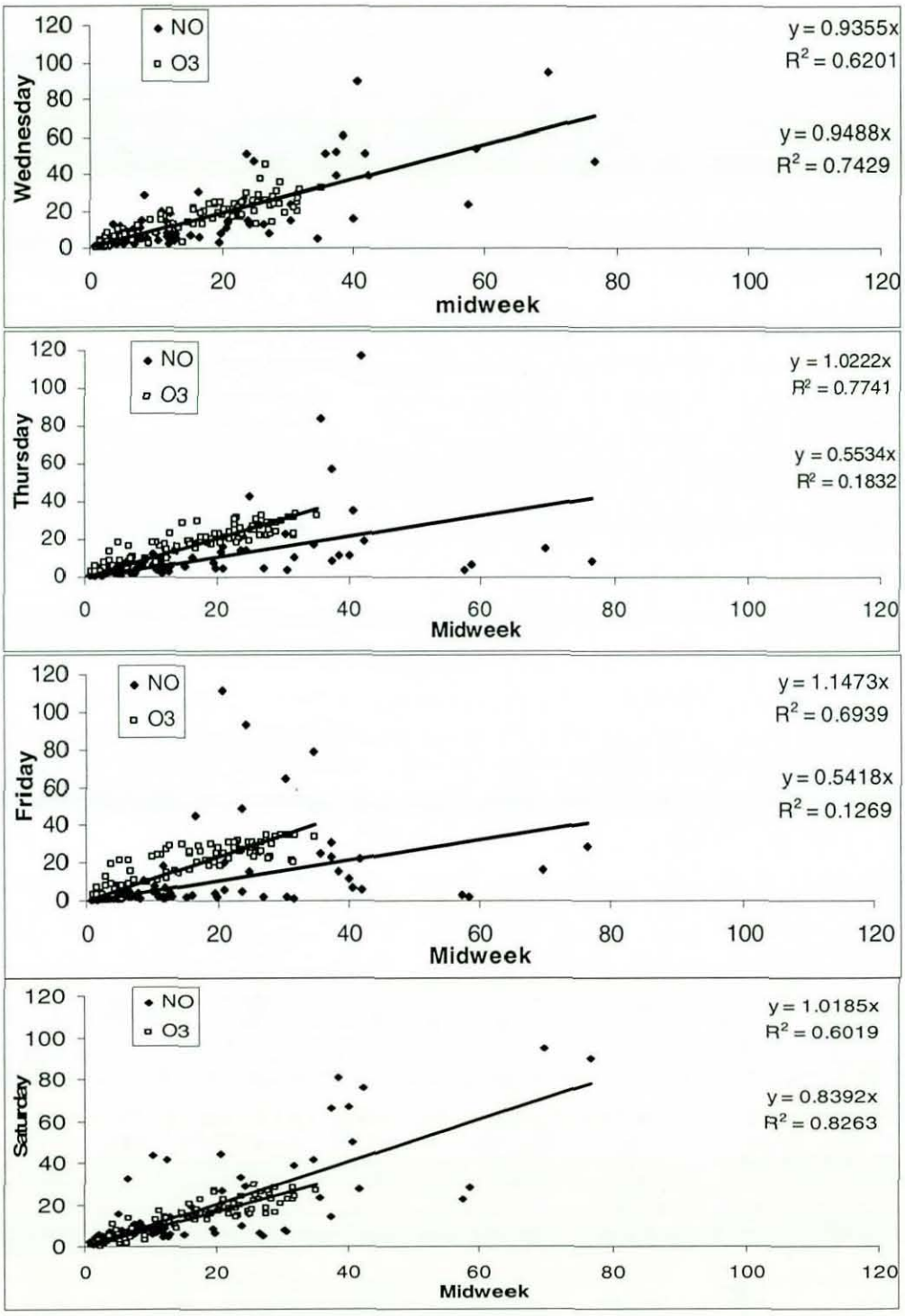


Figure 3.12: Correlation plots of the monthly average of the mean hourly measured O_3 and NO mixing ratios on Saturday, Wednesday, Thursday and Friday versus the corresponding mixing ratios, for each daylight hour between 7:00 and 21:00, during midweek (Sunday, Monday and Tuesday) occurred in year 2001

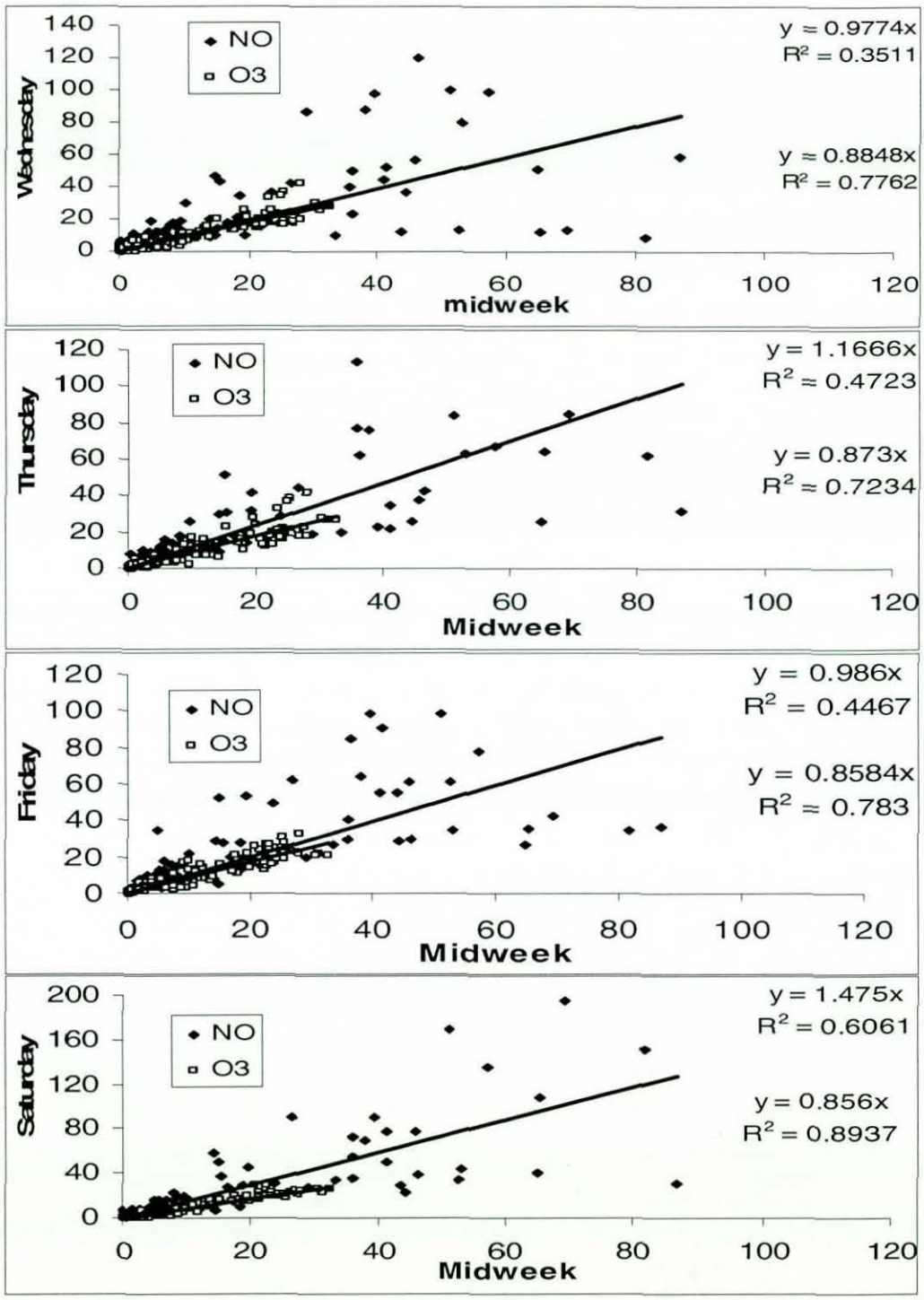


Figure 3.13: Correlation plots of the monthly average of the mean hourly measured O_3 and NO mixing ratios on Saturday, Wednesday, Thursday and Friday versus the corresponding mixing ratios, for each daylight hour between 07:00 and 21:00, during midweek (Sunday, Monday and Tuesday) occurred in year 2004.

The variation in NO levels as high as 15% is not considered significant due to diurnal and seasonal disparity (Riga-Karandinos and Saitanis, 2005). These results indicate well-pronounced weekend effect in year 2001, reflecting a 45% decrease in NO levels on Thursdays and Fridays, which is explained in the following section. In year 2004, an increase of 48% in NO levels on Saturdays had been recorded, while weekend effect is not that conspicuous. Based on O_3 measured concentrations there is a 14-16% decrease on weekends as compare to weekdays.

O_3 and NO behavior is very complex, high NO levels restrain the O_3 formation due to NO titration of O_3 and reaction of NO_2 and OH to result in HNO_3 deposition that acts as a sink for both radicals. O_3 levels are not linearly related to the concentrations of precursors. The abundance of VOCs relative to NO in the NOx sensitive region results into decrease in O_3 levels with reduction in NO emissions as compare to VOCs. In VOCs sensitive region, (abundance of NO relative to VOCs) O_3 levels show an increase with the decrease in NO levels due to reduced titration and HNO_3 deposition reactions.

Blanchard and Tanenbaum (2003) have discussed O_3 levels increase in VOCs limited zone and is supported from the results of Riga-Karandinos *et al.*, (2005), al for VOCs sensitive locations, Patras and Volvos, coastal cities in Greece. In the present study, O_3 levels for year 2001 showed an increase on Fridays similar to the reported results for all mega-cities, Los Angeles, San Francisco etc. while in year 2004, O_3 levels decreased with a recorded increase in NO levels on Saturdays. It is obvious that due to oil production, refining and dispensing activities, VOCs levels are high and NOx sensitive regions are prevailing. NO emissions from power plants and high traffic density have strong influence on the O_3 levels for weekday/weekend. On Saturdays, NO levels increase almost 48% due to the above-mentioned reasons. There is no apparent deviation of O_3 and NO concentrations for Fridays to weekend for daytime hours 7:00 hr to 19:00 hr for April to September Month for 2001.

Table 3.4: Regression equations of the summer mean hourly O_3 and NO mixing ration at Rabia during midweek (X) versus the corresponding mean hourly O_3 and NO on Wednesday, Thursday, Friday and Saturday (Y) for each daylight hour between 7:00 and 19:00.

Year	**2001**		**2004**	
	Equation	**R^2**	**Equation**	**R^2**
Wednesday, O_3	Y = 0.9488 X	0.7429	Y = 0.8848 X	0.7762
Wednesday, NO	Y = 0.9355 X	0.6201	Y = 0.9774 X	0.3511
Thursday, O_3	Y = 1.0222 X	0.7741	Y = 0.8730 X	0.7234
Thursday, NO	Y = 0.5534 X	0.1832	Y = 1.1666 X	0.4723
Friday, O_3	Y = 1.1473 X	0.6939	Y = 0.8584 X	0.7830
Friday, NO	Y = 0.5418 X	0.1269	Y = 0.9860 X	0.4467
Saturday, O_3	Y = 0.8392 X	0.8263	Y = 0.8560 X	0.8937
Saturday, NO	Y = 1.0185 X	0.6019	Y = 1.4750 X	0.6061

3.6: Rate of Ozone accumulation

Ozone (O_3) concentration is governed by its precursor concentration in the presence of sufficient sunlight. The nitrogen oxide (NO) is the most influencing pollutant that controls the concentration of ozone (O_3) before sunrise and it neutralizes the concentration of ozone present in the ambient air. The concentration of ozone gradually increases due to the photo dissociation of nitrogen dioxide (NO_2), mainly coming from automobile exhaust and because of combination of atomic oxygen (O) and molecular oxygen (O_2) which is present abundantly in the atmosphere (1998).

The building up of ozone (O_3) commences when the mixing ratios of ozone (O_3) and nitrogen oxide (NO) are equal and is known as termination of the morning inhibition period (Pun *et al.*, 2003 and Fujita *et al.*, 2003). The accumulation rate of ozone (O_3) can be calculated from the slope of ozone (O_3) concentration profile reacting to the highest value.

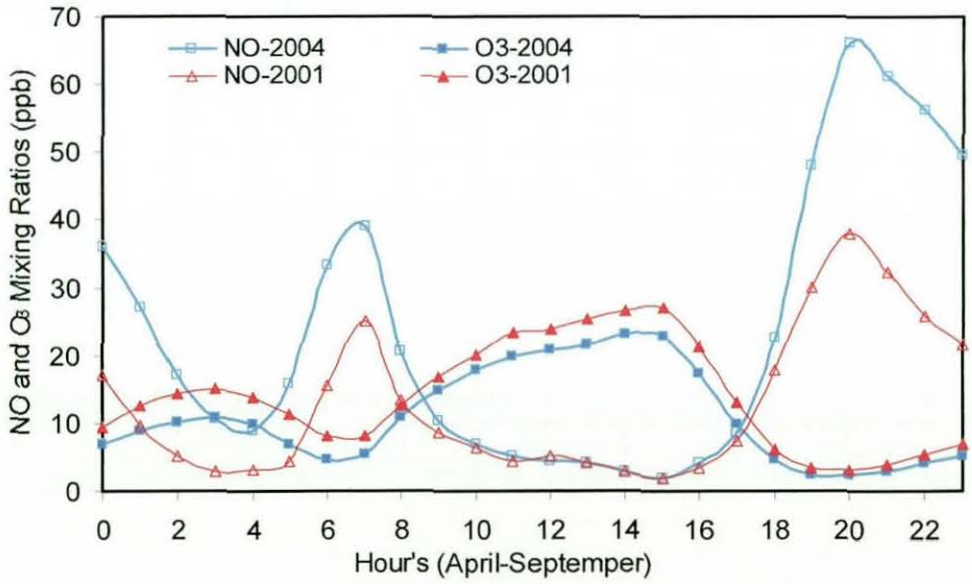


Figure 3.14: The average diurnal pattern of measured O_3 and NO in 2001 (triangles) and 2004 (square) in summer period (April to September)

This measured data analysis for ozone (O_3) and nitrogen oxide (NO) showed that, the high rate of ozone accumulation (O_3) was in summer period (April - September) in both years Figure (3.14). As shown in Figure (3.14), the crossover in year 2001 occurs about 45 minutes earlier than year 2004 for Rabia area. Riga-Karandinos and Saitanis (2005) have presented O_3 and NO mixing ratio in two Mediterranean coastal cities. The crossover in Volos area has occurred about one hour earlier than Patras area. The difference in the crossover time between two years came from the high rate of NO in year 2004 compared to year 2001. The reduction of NO from its peak value to the corresponding point took a longer time but in year 2001, the value of NO is lower than year 2004 hence taking lesser time to reduce NO to crossover point.

As shown in the Figure (3.14), the high rate of accumulation of O_3 value for year 2001 occurred faster between 8:00 hr and 11:00 hr and followed by a slow increase between 11:00 hr to 15:00 hr, reaching to the highest value at 15:00 hours. For year 2004, the O_3 accumulation was identical to year 2001 reaching the maximum value at 15:00 hours. The rate of accumulation of Ozone in year 2001 was slightly higher than year 2004. The accumulation rate of ozone (O_3) and nitrogen oxide (NO) showed similar trend as observed by Riga-Karandinos and Saitanis (2005).

3.7: Conclusions

The monthly measured concentrations levels of SO_2 and O_3 were higher in year 2001 as compared to year 2004 due to the application of various mitigation strategies such as using fuels that have low sulphur content for generating power plants and relocation of car auction market and transport depot, which were located in the northwestern side of Rabia area with distance of 2 km. In case of NOx, NO_2 and CO the levels of measured concentration in year 2001 are lower than 2004. This is because of the number of vehicles has been increasing over the

years and as a result the emission rates of NOx, NO_2 and CO also increased. In addition, the emission rates of NOx from the power stations were increased.

The O_3 levels of the daytime hours from April to September period has shown high buildup on weekend as compared to weekdays due to the least traffic density on the roads.

The highest measured concentration of SO_2 detected was in the summer season for both years. This can be explained by the highest demand of power generated from power plants to meet the requirements of the nation resulting into high emissions.

In the case of NO_2, the overall measured concentrations were higher in 2004, as compared to 2001. In 2004, the highest measured concentration detected was in summer and in year 2001; the highest measured concentration was in autumn. This is because the increase in the number of vehicles over the years.

The measured concentration of ozone in 2001 is greater than 2004 so that the increasing number of cars increase NO emissions that neutralize O_3 resulting to lower values. In 2001, the highest measured concentration of O_3 was in summer and for year 2004; the highest measured concentration recorded was in spring. This is because O_3 being a product of photochemical oxidation, is highly depend on sufficient of sun light, and O_3 precursor concentrations. In winter, days are short and are cloudier, leading to lower photo-oxidation reactions.

Weekdays/weekend effect on O_3 and NO has been investigated for both years 2001 and 2004 for the day hours from 7:00 hr to 21:00 hr for April to September periods. It was found that on weekend, O_3 levels are high due to lower volumes of traffic while on weekdays O_3 was neutralized by the excessive NO produced by high traffic density.

The wind rose diagram show that the high mean measured concentration of SO_2 is almost in the sector of southeast of the monitoring station for all seasons and the low mean measured concentration in the opposite sector, which is northwest for both years. Since, the prevailing winds from northwest direction (N-W sectors) is about 60% for year 2001 and for year 2004 are about 46% from the N-W sector so that the main source of SO_2 comes from Doha power station, which is located in the northwest of our study area and this wind direction sector is agrees with our results.

The metrological conditions such as wind speed, wind direction, temperature and solar radiation are considered as the main factor in the dispersion process of the pollutants over the state of Kuwait.

The highest mean measured concentrations of NOx extending from sector ESE to SSW for year 2001. This result indicates that the main sources of NOx concentrations are the Doha and Subyia power stations, which are located in the northwest and northeast respectively. However, for year 2004 the highest mean measured concentrations of NOx extending from sector WNW to NNE at Rabia monitoring station. This means that the main source of NOx for this year is the traffic movements at the study area.

The diurnal variations for the primary pollutants such as SO_2, CO and NOx show those two maxima during a day, one in early morning and a second in the evening. However, the secondary pollutants usually show that a single maximum around afternoon such as O_3.

In the case of O_3, the relation between O_3 and NOx and CO is negative. As shown in previous results the measured concentration of O_3 reached its minimum value in the early morning, the concentration of NOx and CO reached their morning maximum peak. This is also for the afternoon period.

Chapter 4

Air Quality Modelling of Sulphur Dioxide (SO_2) and Nitrogen Oxide (NOx) over Kuwait

4.1: Introduction

The study of air pollution requires complete insight into the nature, behaviour, and characteristics of a pollutant along with the prevalent meteorological characteristics of the environment into which it is released. This basic data determines its impact on the environment and enables the development of effective measures to mitigate the potential damage to nature. Gokhale and Khare (2004) have established an empirical relationship between pollutant concentrations in the air and meteorological parameters, which has facilitated the construction of design methodologies for environmental protection. However, statistical models have been used more in the last decade than the traditional deterministic models (Kolehmainen *et al.*, 2001).

Computer techniques used in conjunction with both deterministic and statistical approaches are powerful tools to study the impact of pollutants on the environment. They also enable the prediction of likely outcomes and help to develop environmental safeguards. These models, validated with actual field and laboratory data, help verify the authenticity of novel approaches as well as their compatibility with the Kuwait Environmental Protection Authority (K-EPA) criteria. Air quality models are therefore indispensable tools for evaluating the impact of air pollutants on urban environments and human health (Gokhale and Khare, 2004).

Among the pollutants that have emerged as problematic are the oxides of sulphur, generally referred to as sulphur dioxide (SO_2), and the oxides of nitrogen, generally referred to as nitrogen oxide (NOx). Both categories of pollutants have

a sizeable impact on human health and the environment, and are therefore used as indices in monitoring air quality. In today's scenario, air quality modelling has emerged as an established tool for nearly all air pollution monitoring studies; in fact, the introduction of statutory standards for these pollutants has made model use obligatory for studying their spatial and temporal distribution and identifying trouble areas.

The state of Kuwait can be considered a representative case of rapid industrialization leading to deterioration of the ambient air quality. Therefore, this chapter has been dedicated to evaluating the application of an industrial source complex model (ISCST4.5) as a viable tool for the short-term prediction of sulphur dioxide (SO_2) and nitrogen oxide (NOx) behaviour released from power generation plants under the meteorological conditions prevalent over the study area. Although the sources of these pollutants are quite varied, especially in the case of NOx, a single source of power generation plants has been considered for the purpose of this study. The main objectives governing the use of the ISCST4.5 model are determining the viability of the model and assessing the impact of these pollutants released from power stations on residential areas in the state of Kuwait. In addition, this study has investigated the performance of the ISCST4.5 model under prevailing meteorological conditions in Kuwait. Successful application of any mathematical model depends on the quality of the emission inventory data for all sources and meteorological data (Fox, 1981). In addition, the predicted results from the ISCST4.5 model are compared with measured data collected at the station located above the polyclinic in the Rabia area.

4.2: Description of the Study Area (graphical data)

The State of Kuwait is located in the northeastern corner of the Arabian Peninsula, bordered by the Kingdom of Saudi Arabia to the south and west, by the Republic of Iraq from the north, and by the Persian Gulf in the east (Figure 3.2). The weather in winter is comfortably cool, though during the night the temperature sometimes drops to around 0°C. In the summers months the weather is hot, with daytime temperatures approaching 50°C. The mean temperature in the summer season, especially in July and August, ranges from 30°C to 50°C with an average mean daily maximum of nearly 41°C.

Figure (4.1) shows the location of the Doha and Subyia power stations and the Rabia air pollution monitoring station. The Rabia area was chosen as the most appropriate location for the purpose of this study. Kuwait municipality's 2003 records describe Rabia as a relatively run down residential suburb of central Kuwait, covering a total area of 2.5 km^2. Rabia area lies between three major highways: 5th ring road at the northern end, 6th at the south, and Gazalli expressway stretching along its eastern border. Kuwait International Airport is located further southeast of Rabia. The main sources of pollutants are the power stations of the Doha complex in the northwest and the Subyia complex in the northeast; they are the closest to our study area and therefore represent the most prominent impact. The Doha power station, also referred to as the Doha Complex, is a combination of two stations: Doha East and Doha West. Doha East is in turn made up of two chimneys, one with four stacks and the other with three, while Doha west is made up of two chimneys that each have four stacks.

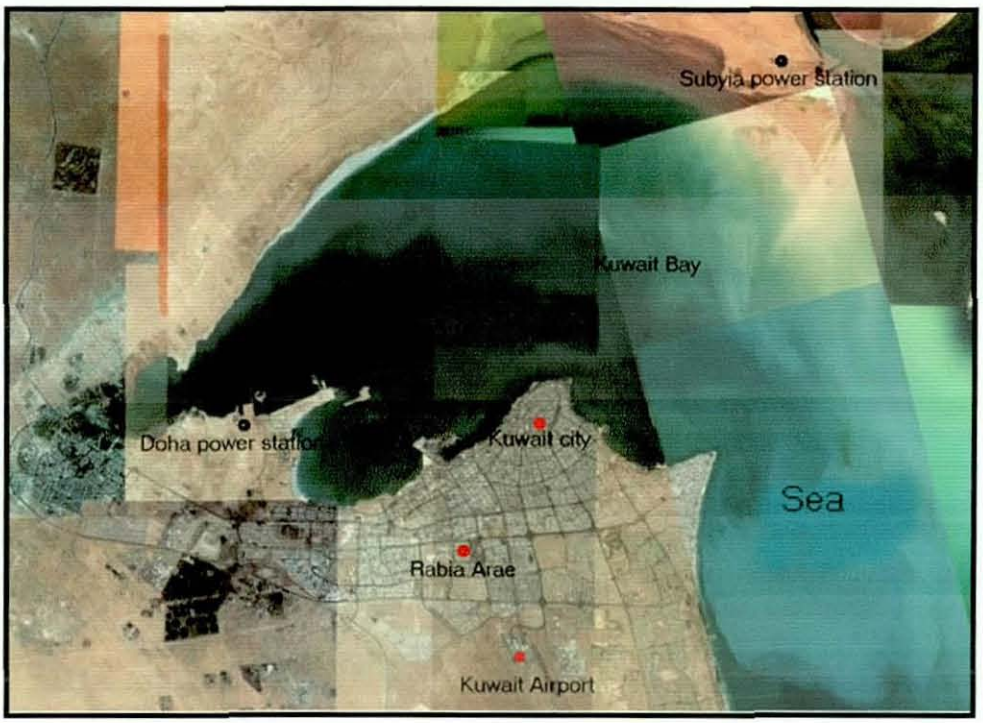


Figure 4.1: Location of Doha and Subyia Power stations and Rabia air pollution monitoring station. (www. Google Earth.com)

The Doha residential area is the closest populated area in the vicinity of the Doha complex, at a distance of 6 km, followed by Sulaibikhat at 8 km, where both lie to the southeast of the complex. The closest residential area to the Subyia power station is Kuwait city, at a distance of 25.4 km across the Kuwait Bay. For the purpose of this study, the official distance between Rabia and Doha east is taken to be 16.5 km east and 17 km west of Rabia, while that of Subyia is 39.5 km from Rabia.

An important reason for selecting Rabia as a study area was the presence of an air quality monitoring station on the roof of the Rabia polyclinic. Data taken at five minute increments from this station, meteorological conditions, and subsequent one–hour averages are collected with an excel based macro. These measured ground level concentrations of SO_2 and NOx were then used to validate the model output.

In addition to the power plants, the other main source of air pollution in Rabia is traffic, partly from the highways surrounding the area and partly from the transport offices located in nearby Ardiya, which have large trailer convoys, offering goods and services on a cross-country basis. Another transport activity contributing to air pollution is the Kuwait International Airport, which is located southeast of Rabia and has significant air traffic volumes. A relatively minor source of pollution is the Al-Rai industrial area in the north, with numerous garages offering automobile repair services and workshops for manufacturing paints, chemicals and welding works. Other sources are the Ardiya sewage treatment plant and a small restaurant that uses charcoal fires in its kitchen. However, the most significant source of air pollution in Rabia is the power plants.

4.3: Model Details

In this study, the Industrial Source Complex for Short-term Dispersion (ISCST4.5) model approved by U.S. EPA (USA-EPA, 1995) is used. The model was initially developed in 1970 by the US-EPA and modified numerous times to enable this type of study of pollution. The ISCST model is considered suitable for predicting pollutant concentrations from the wide variety of sources associated with industrial complexes. The success of the model lies in the precision of the input data, i.e., the emission inventory pertaining to the pollutant source, the meteorological data, and the topographical data related to the study area. In addition, this system offers options to model emissions from a wide range of sources that might act as pollution sources. The model incorporates reflection from the ground, elevated dispersion ceiling, the dispersion parameter formulas derived from Pasquill and McElroy-Pooler data, and the plume rise formula of Briggs. It also takes into account stack-tip downwash, wind profile, buoyancy-induced dispersion, urban and rural dispersion, and terrain adjustment algorithm. The model calculates pollutant ground level concentrations from multiple point sources at a specified grid receptor. A detailed description of the ISCST4.5 model can be found in U.S. EPA (1995).

The ISCST model is based on a straight line, steady state bi-Gaussian plume simplification equation. Gaussian plume models are the most widely used for air pollution projects due to their simplicity and versatility. This model uses the Gaussian plume simplification of the three dimensional convective-diffusion equation to calculate hourly, daily, monthly and annual averages of the ground level concentrations of a pollutant released from elevated sources under varying realistic meteorological conditions. A three-dimensional axis system is used to provide downwind, crosswind and vertical resolution of the pollutants continuously emitted from a point source. The Gaussian dispersion equation for predicting a ground level concentration directly downwind of an elevated source is given by (4.1):

$$C(x,y,z)=\left[\frac{Q}{2\pi\sigma_y\sigma_x u}\right].\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)\right]\bullet\left[\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_Z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\left(\frac{z+H}{\sigma_Z}\right)^2\right)\right]\right] \quad (4.1)$$

Where:

C = Concentration of pollutant at down wind distance (x) and cross wind distance (y) in metres ($\mu g\ m^{-3}$)

Q = Source strength or emission rate of pollutant ($g\ s^{-1}$)

$\sigma_{y,z}$ = Dispersion coefficients of the concentration in the crosswind direction (m)

u = Mean wind speed at stack height ($m\ s^{-1}$)

H ($h + \Delta h$) = Source height or effective stack height (m)

The dispersion coefficients (σ) are of the most important key factors in the Gaussian equation since it is measured the dispersion process. The dispersion coefficients ($\sigma_{y,z}$) of the concentration in both the crosswind and vertical

directions are dependent on the distance (X) from the source and the atmospheric stability. The crosswind dispersion coefficient (σ_y) is given by equation (4.2):

$$\sigma_y = 1000 \cdot X \cdot \tan\left(\frac{L}{2.15}\right) \tag{4.2}$$

L is a function of the atmospheric stability class (S) and the downwind distance (X) from the source in km. The coefficient L is calculated for different stabilities from the appropriate empirical function in Table (4.1).

In addition, the vertical dispersion coefficient (σ_z) is given by equation (4.3):

$$\sigma_z = aX^b \tag{4.3}$$

The coefficients (a) and (b) are functions of the distance downwind (X) from the source and the atmospheric stability class (S); they are listed in Table (4.2).

Table (4.1): Equations for (L)

Stability	Equation for L (function of (X) in km)
A	$L = 24.167 - 2.5334 \ln(x)$
B	$L = 18.333 - 1.8096 \ln(x)$
C	$L = 12.5 - 1.0857 \ln(x)$
D	$L = 8.3333 - 0.72382 \ln(x)$
E	$L = 6.25 - 0.54287 \ln(x)$
F	$L = 4.1667 - 0.36191 \ln(x)$

Table (4.2):.Values for (*a*) and (*b*)

Stability Classes (*S*)	**X (km)**	(*a*)	(*b*)
A	>3.11	σ_z = 5000 (m)	
	0.5-3.11	453.85	2.1166
	0.4-0.5	346.75	1.7283
	0.3-0.4	258.89	1.4094
	0.25-0.3	217.41	1.2644
	0.2-0.25	179.52	1.1262
	0.15-0.2	170.22	1.0932
	0.1-0.15	158.08	1.0542
	<0.1	122.8	0.9447
B	>35	σ_z = 5000 (m)	
	0.4-35	109.30	1.0971
	0.2-0.4	98.483	0.98332
	<0.2	90.673	0.93198
C	all	61.141	0.91465
D	>30	44.053	0.51179
	10-30	36.650	0.56589
	3-10	33.504	0.60486
	1-3	32.093	0.64403
	0.3-1	32.093	0.81066
	<0.3	34.459	0.86974
E	>40	47.618	0.29592
	20-40	35.420	0.37615
	10-20	26.970	0.46713
	4-10	24.703	0.50527
	2-4	22.534	0.57154
	1-2	21.628	0.63077
	0.3-1	21.628	0.75660
	0.1-0.3	23.331	0.81956
	<0.1	24.260	0.83660

The height of the plume rise (Δh) is considered the height to which an emission will initially rise as a result of the thermal buoyancy and vertical momentum. Figure (4.2) shows that the effective stack height (*H*) is equal to the sum of the stack height (*h*) and plume rise height (Δh) (K., Noll, T., Miller, 1977). The effective stack height (*H*) is given by:

$$H = h + \left[\frac{\left[1.6 \exp\left(\ln \frac{F_0}{3} \right) \exp\left(2 \ln \left(\frac{3.5 X_0}{3} \right) \right) \right]}{U} \right] \tag{4.4}$$

Where

h = Physical height of the stack (m)

U = Mean wind speed (m s^{-1})

F_0 and X_0 are given by the formulas

$$F_0 = 2.45 \cdot v_0 \cdot d^2 \cdot \left[\frac{(t_0 - t_1)}{t_0} \right] \tag{4.5}$$

If $F_0 > 55$, then

$X_0 = 34 \cdot \exp(0.4 \cdot \ln(F_0))$

If $F_0 \leq 55$, then

$X_0 = 14 \cdot \exp(0.625 \cdot \ln(F_0))$

Where

v_0 = Gas exit velocity (m s^{-1})

d = Stack diameter (m)

t_0 = Gas exit temperature (K)

t_1 = Ambient air temperature (K)

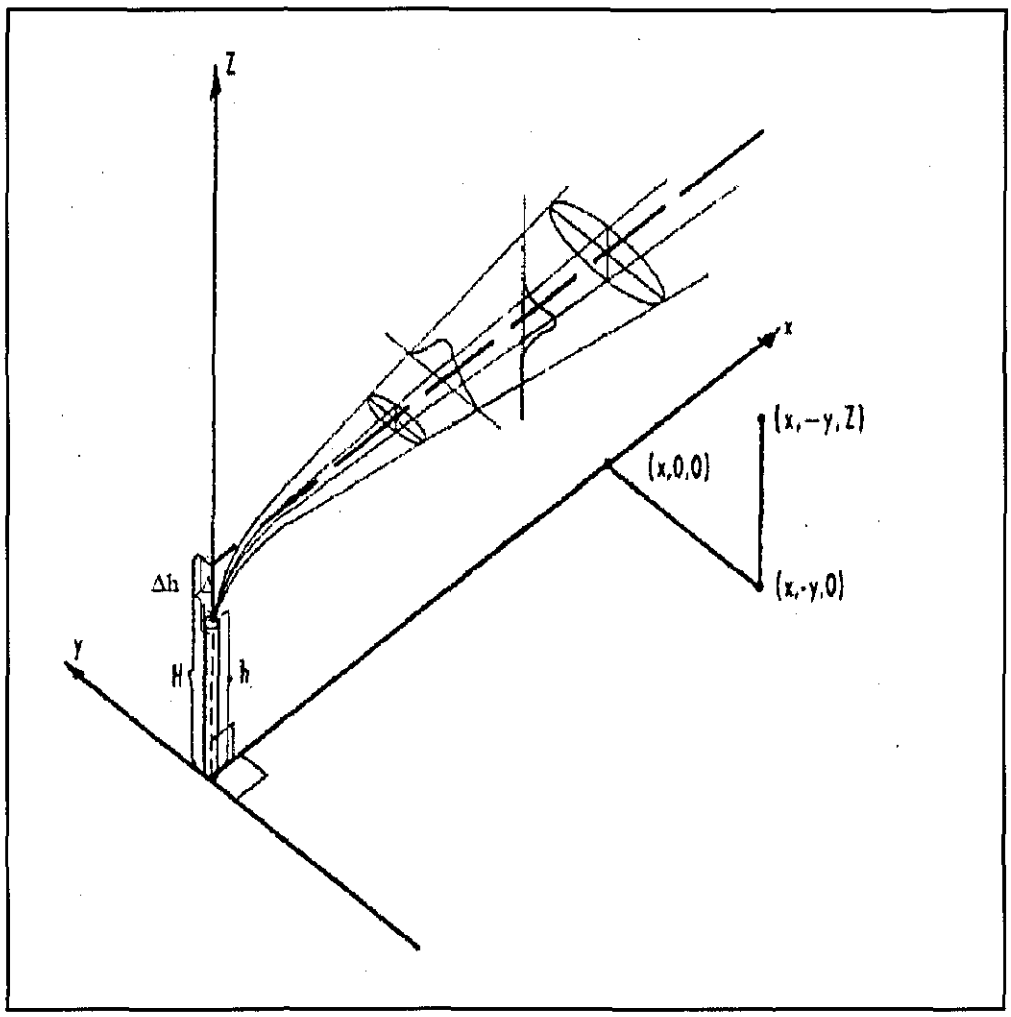


Figure 4.2: Coordinate system of the Gaussian plume theory
(Air Monitoring Survey Design, 1977)

The Gaussian dispersion equation for predicting ground level concentrations of air pollutants directly downwind from an elevated continuous point source is based on the following assumptions:

(1) Uniform and time invariant emission sources.

(2) No atmospheric chemical reactions.

(3) Perfect reflection of the plume at the underlying surface.

(4) Non-zero wind speed.

(5) No gravitational settling of the pollutant.

(6) Homogenous and time invariant metrological condition within the study area.

The present study is focused on ISCST4.5, a short-term model used to predict the temporal and spatial ground-level concentrations of sulphur dioxide (SO_2) and nitrogen oxide (NOx). It is applied herein to model the impact of emissions from the Doha and Subyia power plants.

Previous modelling studies are also revaluated in this chapter, such as the one presented by Al-Rashidi *et al.* (2005) on predicting the dispersion of SO_2 from the power stations and investigating the efficiency of existing SO_2 level monitoring stations in the state of Kuwait. In addition, many previous modelling studies are also critically evaluated; these include the work of Zannetti (1983), Al-Sudairawi and Mackay (1988), and Abdul-Wahab *et al.* (1999), which use different ISC models to predict the dispersion of SO_2 from the Shuaiba Industrial Area (SIA) in Kuwait. In most previews work the topographical effects are not taken into account, an oversight that may result in poor modelling simulation accuracy. Details of the ISCST environmental model are given elsewhere (e.g.,

US EPA, 1995 and Malmaeus and Håkanson, 2003) and will not be repeated here. Rama Krishna *et al.* (2004) have studied the assimilative capacity and dispersion of air pollutants, namely sulphur dioxide and nitrogen oxide from industrial sources in the Visakhapatnam bowl area, using an ISCST3 model.

The present model considers the impact of settling criteria, sources (line and point), pollutant decay, emission rate alterations, and landscape details on plume dispersion. The model has three main input data requirements (see Figure 4.3):

1. Source information (emission rate, stack height, inner exit diameter, gas discharge speed, exit temperature, height above sea level) as obtained from the Ministry of Electricity and Water (see Figure 4.4).
2. Meteorological information (wind speed, wind direction, air temperature, mixing height, stability class, with which measurement the conditions are coincident) as obtained from direct measurements (see Figure 4.5).
3. Receptor information (location coordinate in order to forecast pollutant concentration at various points on the mesh) (see Figure 4.6).

Two types of receptor coordinates are used in the present model:

1. Discrete Cartesian Receptors.
2. Uniform Cartesian Receptors.

The selection of receptors is based on their actual site in terms of UTM (Universal Transverse Mercator) location coordinates in Kuwait. Meteorological data were obtained from the Kuwait Environmental Protection Authority (K-EPA) for this model, which provided data about relative humidity, wind speed, wind direction, temperature, and inversion layer, all based on hourly measurements. These data include stability class, which is an index based on hourly measurements of wind speed and cloud cover, as Pasquills categories (Turner, 1970). This information, along with the mixing height, is used in model.

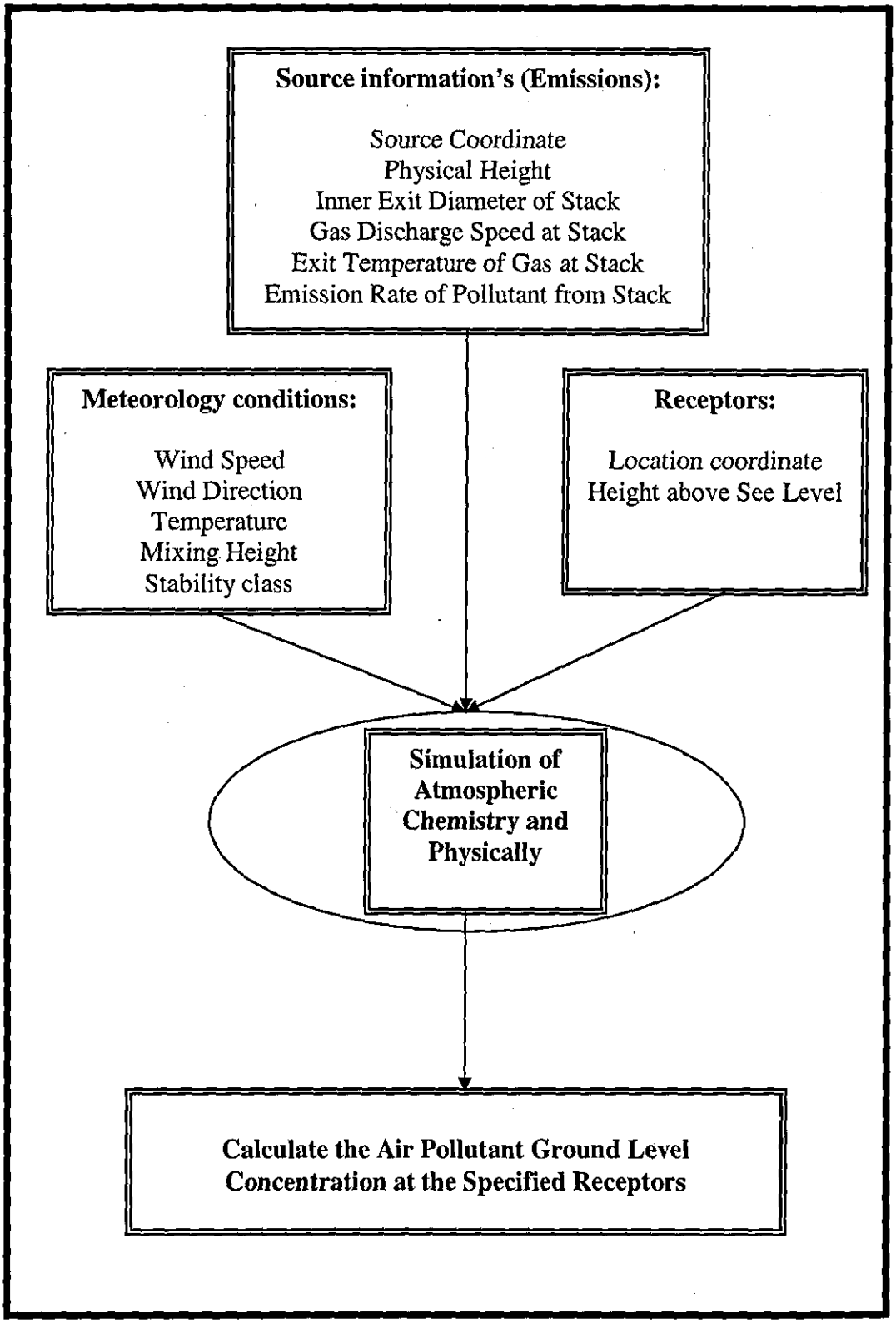


Figure 4.3: Structure of a Dispersion ISCST4.5 Model

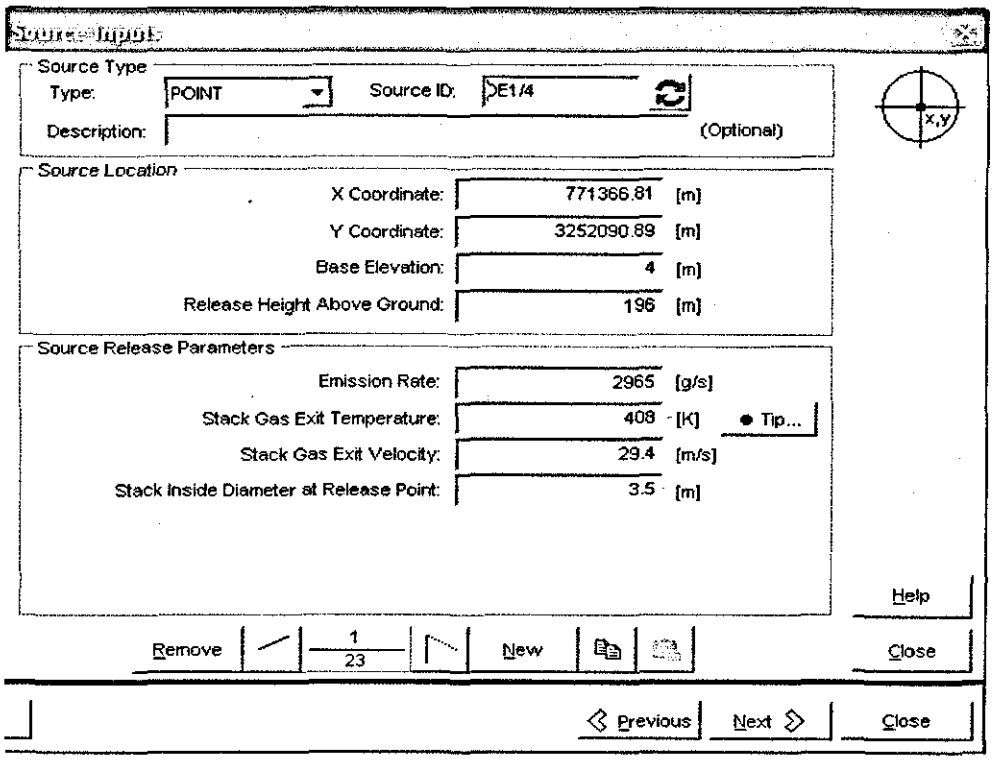


Figure 4.4: Sample screen of source inputs data

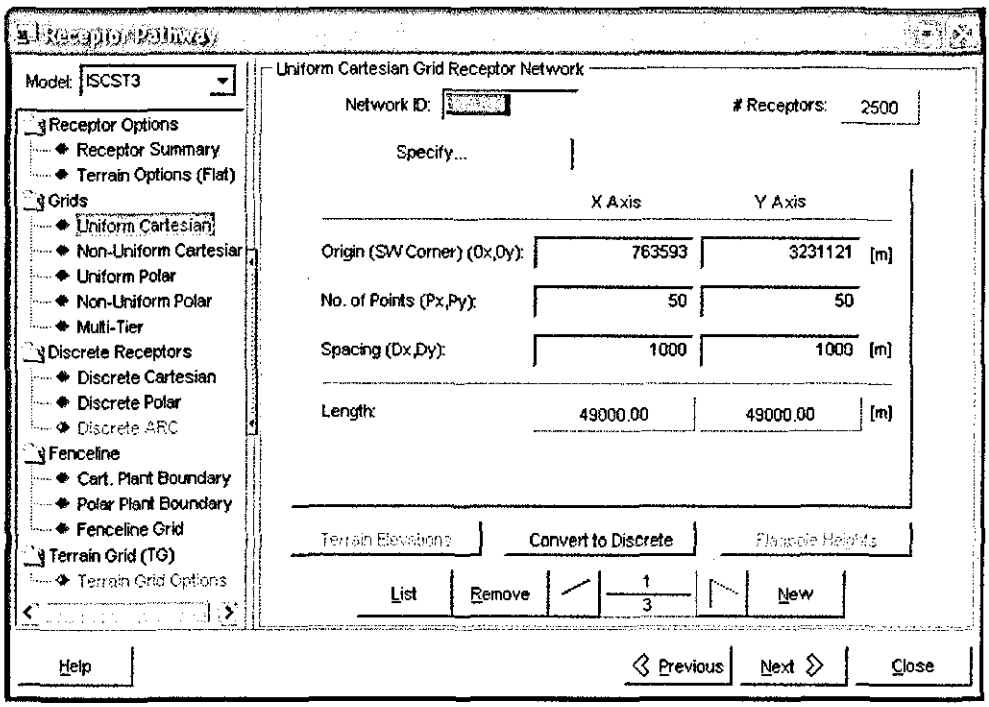


Figure 4.5: Sample screen of uniform Cartesian grid receptor network

The ISCST model is used in conjunction with PCRAMMET, which is a metrological pre-processor for preparing National Weather Service (NWS) data (U.S. EPA, 1999). The PCRAMMET is used to estimate the hourly stability class and hourly mixing height. Meteorological data obtained from the Kuwait environmental public authority (K-EPA) and Kuwait International Airport (KIA) for the year 2001 and 2004 is used to run PCRAMMET to generate the meteorological input file for running the ISCST4.5 model.

The outputs available in the ISCST4.5 model are:

- High ground level predicted concentration values (highest, second highest, third highest, etc.) by receptor for each averaging period and source group combination (see Figure 4.7).
- Maximum ground level predicted concentration values for each averaging period and source group combination with their locations and time.
- Tables of concurrent predicted concentration values summarized by receptor for each averaging period and source group combination for each day of data processed.
- Isopleths plot (contour) of the maximum hourly, daily, monthly, annually and seasonally ground level predicted concentrations of pollutants in $\mu g\ m^{-3}$ (see Figure 4.8)

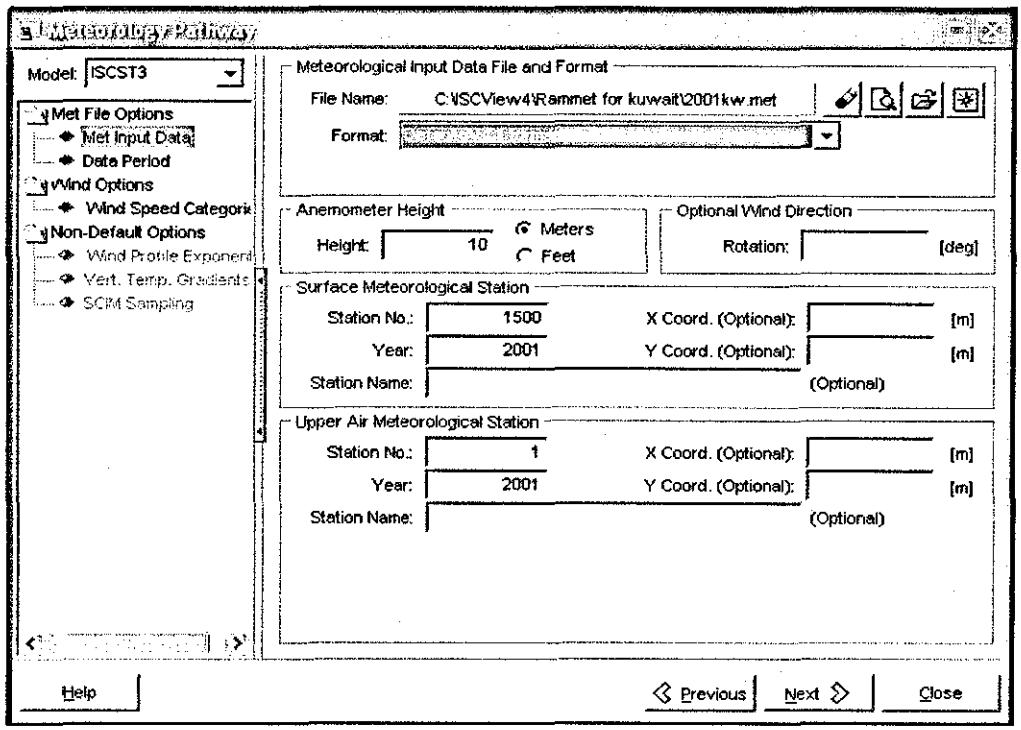
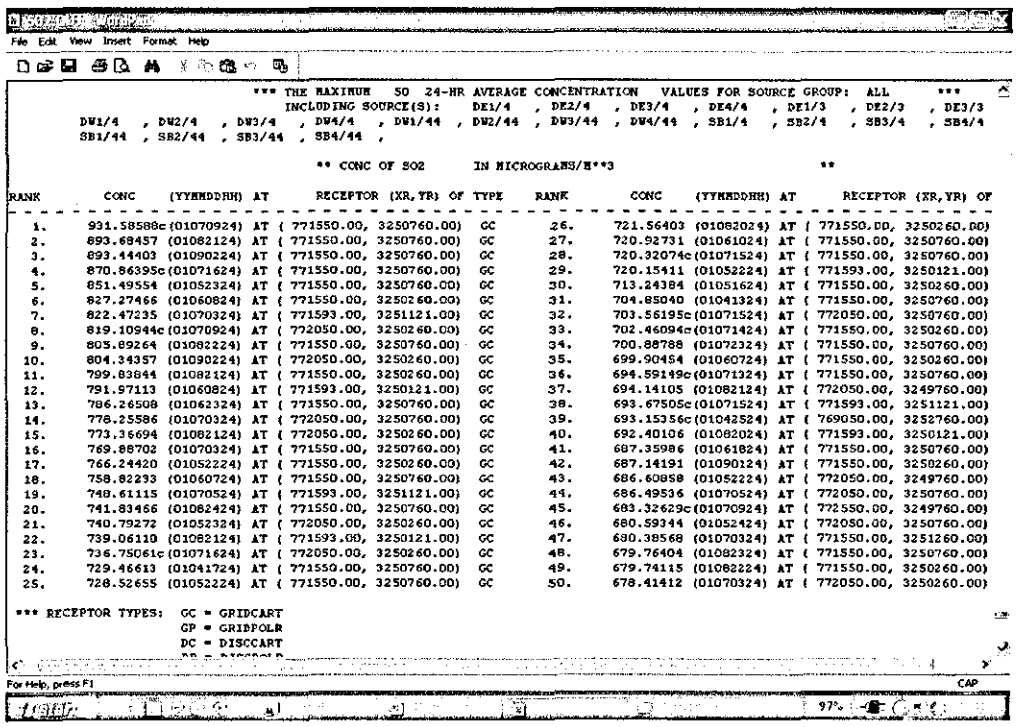


Figure 4.6: Sample screen of meteorology input data file.



```
*** THE MAXIMUM  50  24-HR AVERAGE CONCENTRATION   VALUES FOR SOURCE GROUP:  ALL      ***
                    INCLUDING SOURCE(S):   DE1/4   , DE2/4   , DE3/4   , DE4/4   , DE1/3   , DE2/3   , DE3/3
     DW1/4   , DW2/4   , DW3/4   , DW4/4   , DW1/44  , DW2/44  , DW3/44  , DW4/44  , SB1/4   , SB2/4   , SB3/4   , SB4/4
     SB1/44  , SB2/44  , SB3/44  , SB4/44  ,

                    ** CONC OF SO2      IN MICROGRAMS/M**3                    **

RANK      CONC     (YYMMDDHH) AT     RECEPTOR (XR,YR) OF TYPE   RANK      CONC     (YYMMDDHH) AT     RECEPTOR (XR,YR) OF
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  1.   931.58588c (01070924) AT ( 771550.00, 3250760.00) GC    26.   721.56403 (01082024) AT ( 771550.00, 3250260.00)
  2.   893.68457 (01082124) AT ( 771550.00, 3250760.00) GC    27.   720.92731 (01061024) AT ( 771550.00, 3250760.00)
  3.   893.44403 (01090224) AT ( 771550.00, 3250760.00) GC    28.   720.32074c(01071524) AT ( 771550.00, 3250760.00)
  4.   870.86395c (01071624) AT ( 771550.00, 3250760.00) GC    29.   720.15411 (01052224) AT ( 771593.00, 3250121.00)
  5.   851.49554 (01052324) AT ( 771550.00, 3250760.00) GC    30.   713.24384 (01051624) AT ( 771550.00, 3250260.00)
  6.   827.27466 (01060824) AT ( 771550.00, 3250260.00) GC    31.   704.85040 (01041324) AT ( 771550.00, 3250760.00)
  7.   822.47235 (01070324) AT ( 771593.00, 3251121.00) GC    32.   703.56195c(01071524) AT ( 772050.00, 3250760.00)
  8.   819.10944c (01070924) AT ( 772050.00, 3250260.00) GC    33.   702.46094c(01071424) AT ( 771550.00, 3250260.00)
  9.   805.89264 (01082224) AT ( 771550.00, 3250760.00) GC    34.   700.88788 (01072324) AT ( 771550.00, 3250760.00)
 10.   804.34357 (01090224) AT ( 772050.00, 3250260.00) GC    35.   699.90454 (01060724) AT ( 771550.00, 3250260.00)
 11.   799.83844 (01082124) AT ( 771550.00, 3250260.00) GC    36.   694.59149c(01071324) AT ( 771550.00, 3250760.00)
 12.   791.97113 (01060824) AT ( 771593.00, 3250121.00) GC    37.   694.14105 (01082124) AT ( 772050.00, 3249760.00)
 13.   786.26508 (01062324) AT ( 771550.00, 3250760.00) GC    38.   693.67505c(01071524) AT ( 771593.00, 3251121.00)
 14.   778.25586 (01070324) AT ( 772050.00, 3250760.00) GC    39.   693.15356c(01042524) AT ( 769050.00, 3252760.00)
 15.   773.36694 (01082124) AT ( 772050.00, 3250260.00) GC    40.   692.40106 (01082024) AT ( 771593.00, 3250121.00)
 16.   769.88702 (01070324) AT ( 771550.00, 3250760.00) GC    41.   687.35986 (01061824) AT ( 771550.00, 3250760.00)
 17.   766.24420 (01052224) AT ( 771550.00, 3250260.00) GC    42.   687.14191 (01090124) AT ( 771550.00, 3250260.00)
 18.   758.82293 (01060724) AT ( 771550.00, 3250760.00) GC    43.   686.60858 (01052224) AT ( 772050.00, 3249760.00)
 19.   748.61115 (01070524) AT ( 771593.00, 3251121.00) GC    44.   686.49536 (01070524) AT ( 772050.00, 3250760.00)
 20.   741.83466 (01082424) AT ( 771550.00, 3250760.00) GC    45.   683.32629c(01070924) AT ( 772550.00, 3249760.00)
 21.   740.79272 (01052324) AT ( 772050.00, 3250260.00) GC    46.   680.59344 (01052424) AT ( 772050.00, 3250760.00)
 22.   739.06119 (01082124) AT ( 771593.00, 3250121.00) GC    47.   680.38568 (01070324) AT ( 771550.00, 3251260.00)
 23.   736.75061c (01071624) AT ( 772050.00, 3250260.00) GC    48.   679.76404 (01082324) AT ( 771550.00, 3250760.00)
 24.   729.46613 (01041724) AT ( 771550.00, 3250760.00) GC    49.   679.74115 (01082224) AT ( 771550.00, 3250260.00)
 25.   728.52655 (01052224) AT ( 771550.00, 3250760.00) GC    50.   678.41412 (01070324) AT ( 772050.00, 3250260.00)

*** RECEPTOR TYPES:  GC = GRIDCART
                     GP = GRIDPOLR
                     DC = DISCCART
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Figure 4.7: Sample screen of the output maximum average concentration values

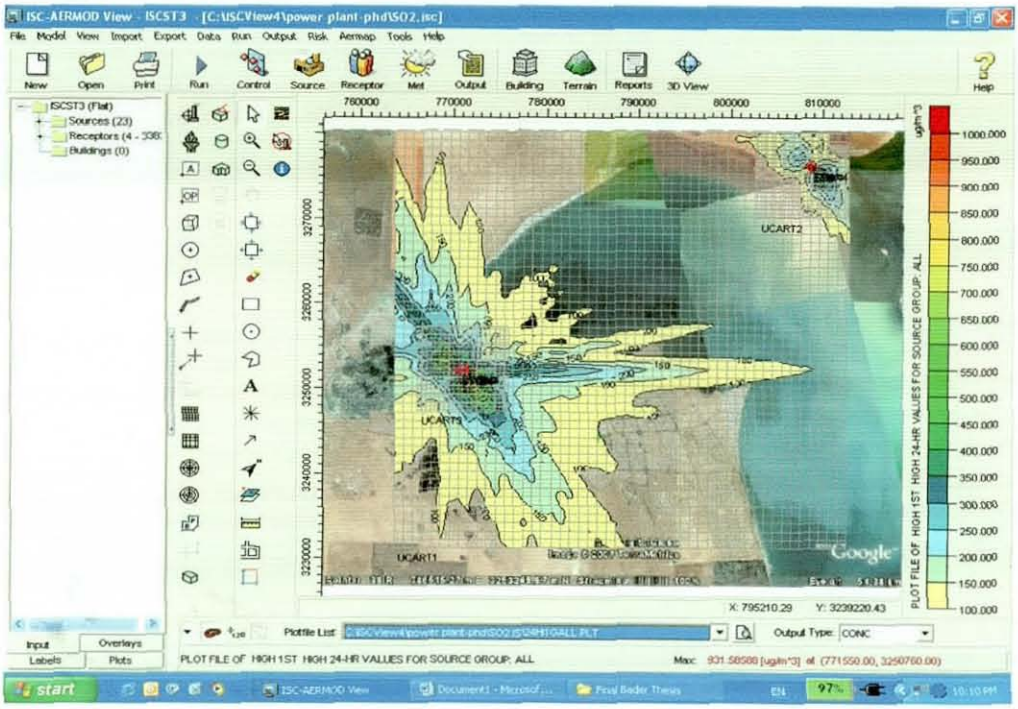

Figure 4.8: Sample screen of output isopleths plot (contour) of the maximum ground level concentrations

4.4: Meteorological conditions

In the Chapter (2), it was mentioned that the metrological conditions play a primary role in the dispersion of air pollution. However, the metrological conditions in the state of Kuwait have only two distinct seasons, summer and winter, each lasting for almost six months. However, for the purpose of this study, these two representative seasons are broken down further into the four time periods of summer, autumn, winter and spring, which are divided into three months each. Summers are dry and harsh, with day mean temperatures of about 41°C. Summer months are almost intolerable without significant air conditioning, which leads to high rates of power consumption. Summer winds are considerably turbulent, and are predominantly in the northwest direction. This favours effective pollutant dispersion accompanied with a high inversion layer. In autumn, conditions become much more bearable. Winters are cold and damp with rains causing

further drops in temperature, which falls on occasion to 0°C during the night. Wind conditions in winters are calm, and hence, are accompanied with a low inversion layer that gives rise to poor pollutant dispersion. Spring represents the transition from winter to summer, and is the most pleasant season in Kuwait. There is no observable change in the wind direction, either diurnally or seasonally. As expected, the meteorological conditions play a pivotal role in pollutant dispersion and affect ground level concentrations in residential areas. The meteorological parameters that are expected to affect SO_2 and NOx concentrations are wind speed, wind direction, mixing height, ambient temperature, and inversion layer. In addition, measured concentrations of SO_2 and NOx were assessed for a period of 8760 hours, which is equivalent to one full year.

The significant effects of wind speed make this a very important parameter in the dispersion process of pollutants. The relationship between wind speed and pollutant concentrations downwind of a source is inverse proportional. This means when the wind speed reaches its highest level, there is a reduction in the concentration of any air pollutant that in turn reduces hazardous effects on the residential areas. On the other hand, slow wind can be considered disadvantageous, since it allows for the formation of high pollutant concentrations that move slowly over residential areas, and thus increases the pollutants and their hazardous effects.

Winters in Kuwait are characterized by low temperature, low inversion layers, decreased wind movement that promote less dispersion of pollutants as compared to summers. In contrast, summers have high temperatures, high inversion layers, strong wind movements, and effective distribution and dilution of pollutants.

Figures (4.9) and (4.10) reveal that the majority of the prevailing wind is from the northwest direction (NW); in 2001, about 20.1% came from the NW and about 60% from the N or W sectors, while, in 2004, about 17.8% came from the NW

and 46% from the N or W sectors. However, as shown in Figures (4.9) and (4.10), the prevailing wind direction is NW, so the frequency distribution of the wind speed class for the N and W sectors is higher than the other sectors.

As shown in Figures (4.9) and (4.10) the prevailing wind is nearly always from northwest in both years and therefore there is a strong mechanism to carry the pollutants along this direction. However, as far as maintaining air quality is concerned this may not be the best direction for the dispersion of pollutants, especially for emissions from Doha power station. This is because that northwesterly wind moves the pollutants to the urban areas located in direction of the downwash. In contrast, the emissions from Subyia power station are carried to sections outside of the urban areas and over the bay of Kuwait by the wind from northwest direction. Therefore, the effect of prevailing wind direction on the air quality in Kuwait is complicated and should be considered carefully for every situation. As a result, the best direction for dispersion of the pollutants is southwest direction, which the plumes will be directed to the see.

Moreover, Figures (4.11) and (4.12) present the frequency distribution of the wind classes. For 2001, about 31.1% of the wind speed record fell between 3.3-5.4 m s^{-1} and about 20.6% fell between 0.5-2.1 m s^{-1}, while for 2004 46% fell between 3.6-5.7 m s^{-1} and 17.7% fell between 5.7-8.8 m s^{-1}. Both wind speed and wind directions are important factors in measuring any possible air pollution problem. However, low to medium wind speeds blowing from the direction of power stations toward residential areas can increase the possibility of pollution, which will affect the human health in these areas.

Table (4.3): Pasquill Stability Categories of Atmospheric Conditions

Category Conditions	**Atmospheric Stability (*S*)**
A	Very Unstable
B	Unstable
C	Slightly Unstable
D	Neutral
E	Stable
F	Very Stable

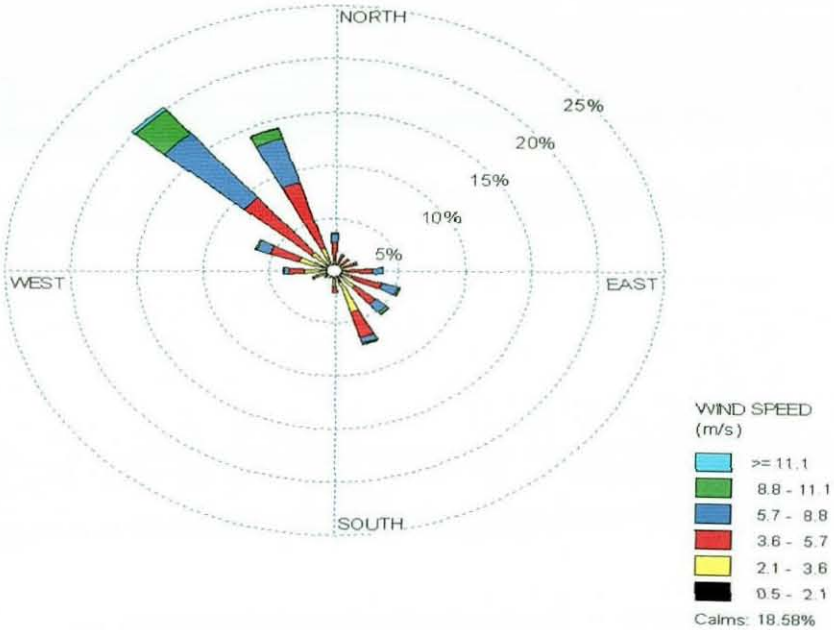

Figure 4.9: Wind Rose Plot for 2001

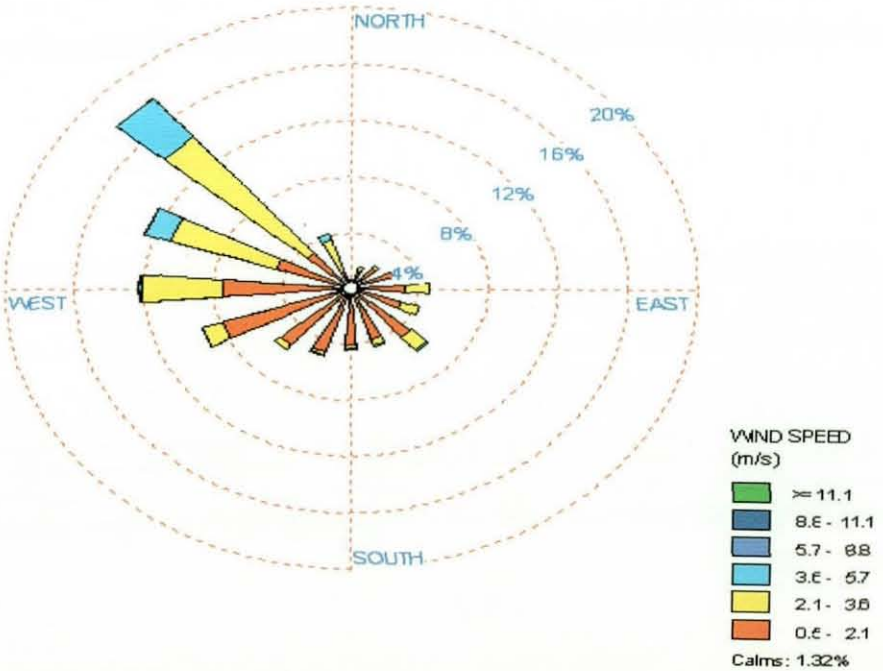

Figure 4.10: Wind Rose Plot for 2004

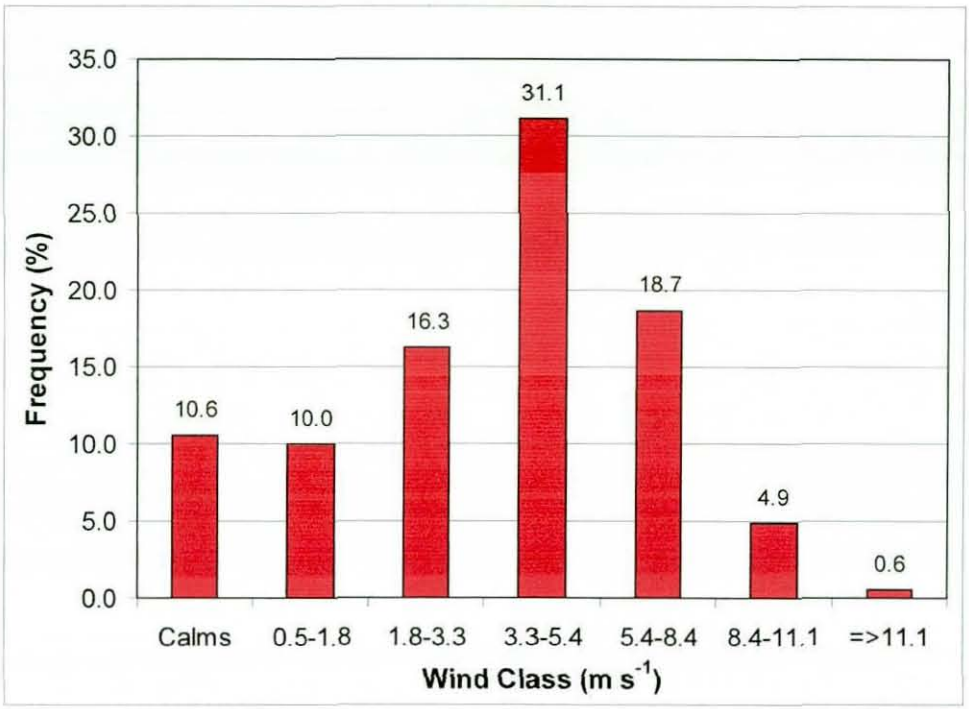

Figure 4.11: Frequency Distribution of Wind Speed Class during 2001

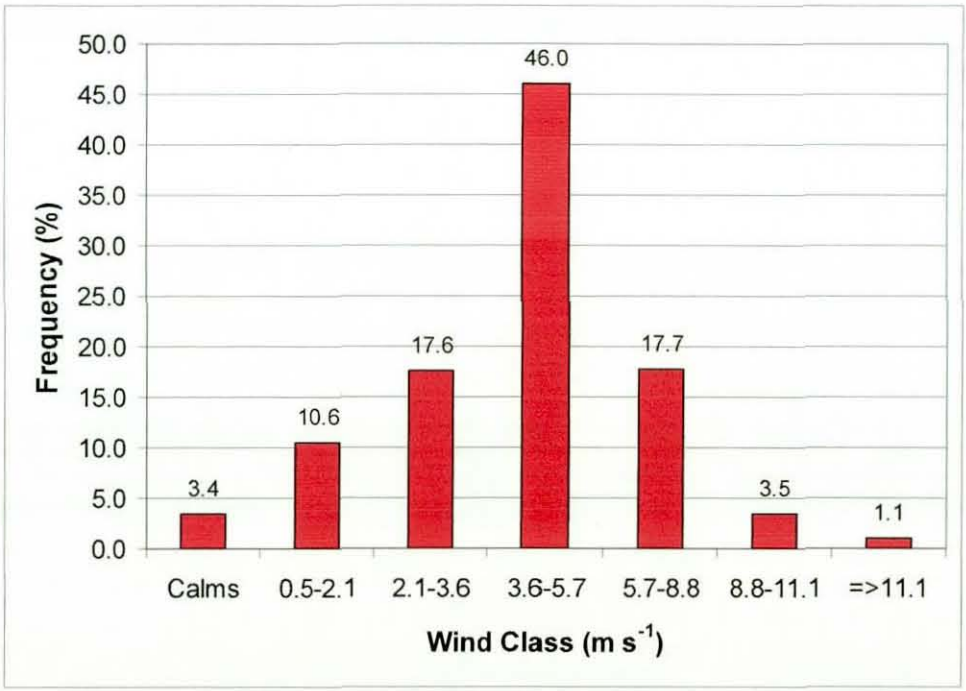

Figure 4.12: Frequency Distribution of Wind Speed Class during 2004

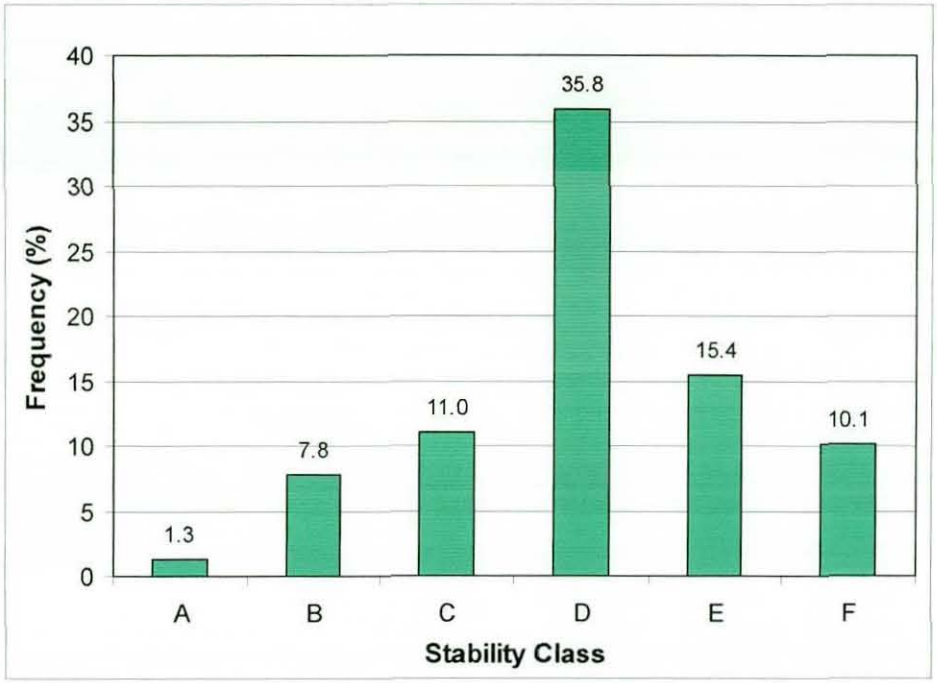

Figure 4.13: Frequency Distribution of Stability Class during 2001

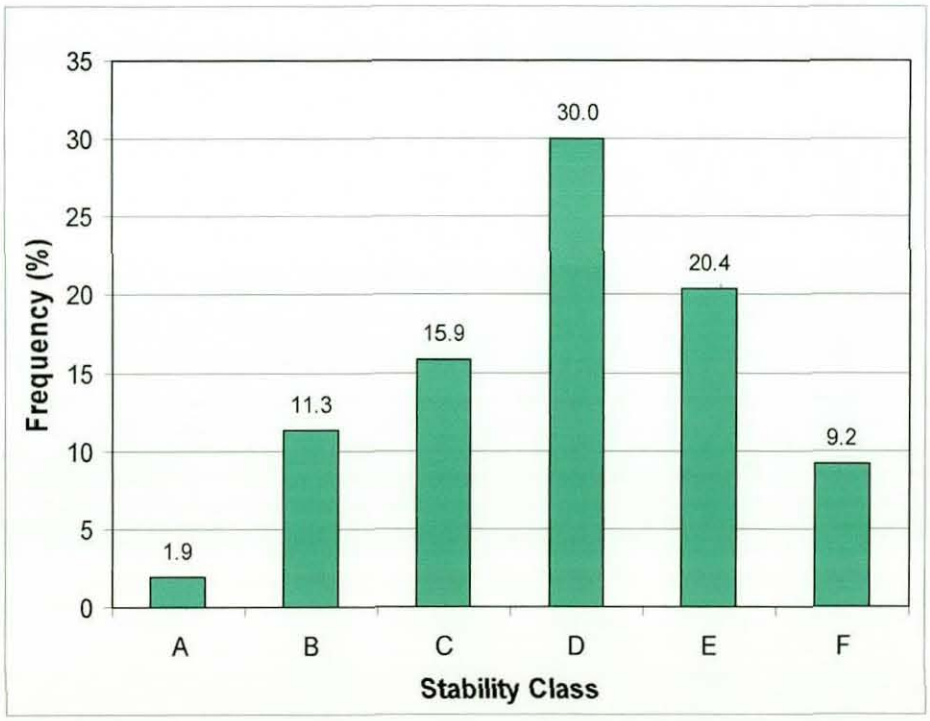

Figure 4.14: Frequency Distribution of Stability Class during 2004

The conditions for different atmospheric lapse rates were presented in Table (4.3). The normal lapse rate is positive when the atmospheric stability is strongly stable (E - F) and negative when the atmospheric stability is unstable (A - C). Figures (4.13) and (4.14) present the frequency distribution of the stability class for years 2001 and 2004. In 2001, the highest frequency stability class was neutral (D) with 35.8%, followed by stable (E) with 15.4%. For 2004 the highest stability class was neutral (D) with 30%, again followed by stable (E) with 20.4%.

Tables (4.4) and (4.5) present the mean, minimum, and maximum monthly wind speed and monthly ambient air temperature for 2001 and 2004. These meteorological data were computed from the hourly records from each day of both years from the K-EPA. In 2001, the annual mean wind speed was 3.7 m s^{-1} and the annual mean temperature is 27.3°C; in 2004, the values were 4.4 m s^{-1} and 29.8°C, respectively. The highest monthly mean wind speed and monthly mean temperature for 2001 occurred in June (5.39 m s^{-1}) and August (40.4°C), and the minimum values occurred in January (2.66 m s^{-1}) and December (11.8°C). For 2004 the highest monthly mean wind speed and monthly mean temperature came in June (5.98 m s^{-1}) and August (43.7°C), and minimum values came in December (2.81 m s^{-1}) and January (15.48°C).

Table (4.4): Monthly (Mean, Minimum, Maximum) Wind Speed and Temperature for 2001

Month	Mean Wind Speed ($m\ s^{-1}$)	Minimum Wind Speed ($m\ s^{-1}$)	Maximum Wind Speed ($m\ s^{-1}$)	Mean Ambient Temp. (ºC)	Minimum Ambient Temp. (ºC)	Maximum Ambient Temp. (ºC)
January	2.66	0.17	4.9	14.87	7.8	22.47
February	2.84	0.37	5.7	15.5	7.5	27.1
March	3.51	0.45	5.6	21.7	11.7	33.5
April	3.94	0.45	5.7	24.76	13.4	35.6
May	4.96	0.67	5.67	33.1	21.7	40.1
June	5.72	0.94	5.97	38.4	27.3	45.4
July	5.53	0.97	5.7	39.3	28.3	48.7
August	4.72	0.79	5.1	40.4	29.7	51.4
September	3.63	0.51	5.4	36.6	23.4	44.4
October	3.14	0.39	5.2	29.1	21.4	38.9
November	2.94	0.17	5.9	23.2	7.6	34.8
December	2.81	0.17	4.4	11.8	2.4	20.3

Table (4.5): Monthly (Mean, Minimum, Maximum) Wind Speed and Temperature for 2004

Month	Mean Wind Speed ($m\ s^{-1}$)	Minimum Wind Speed ($m\ s^{-1}$)	Maximum Wind Speed ($m\ s^{-1}$)	Mean Ambient Temp. (ºC)	Minimum Ambient Temp. (ºC)	Maximum Ambient Temp. (ºC)
January	2.93	0.47	4.37	15.48	9.38	30.6
February	3.01	0.5	4.56	18.1	10.5	30.6
March	4.21	0.6	4.86	23.3	18.2	35.3
April	5.22	0.65	5.5	28.6	22.9	38.4
May	5.91	0.73	6.14	35.8	28.7	44.6
June	5.98	0.87	6.22	39.7	32.8	48.5
July	5.87	0.67	6.07	42.89	35.2	51.7
August	5.61	0.48	5.81	43.7	35.2	53.97
September	4.34	0.29	4.32	38.6	31.3	47.2
October	3.71	0.22	3.8	31.1	27.1	40.2
November	2.98	0.21	3.77	23.4	12.6	36.4
December	2.81	0.15	4.24	17.4	12.2	27.1

4.5: Pollutants of Interest in this Study

Sulphur dioxide (SO_2) belongs to the SOx family. Elemental sulphur is abundant in nature, and SO_2 is formed mainly during the burning of sulphur containing fuels (69%), industrial activities like the extraction of gasoline from oil (13%), and from vehicular emissions (2-6%) (Ramadan *et al.,* 2007). A less consistent but still important source is volcanic activity. SO_2 remains a cause of concern due to its predominance as a health hazard; it contributes significantly to various respiratory ailments in young and old alike, some of the main symptoms of which are asthma and laboured breathing. The compound also contributes to worldwide acid rain, since it is a highly reactive species that combines with moisture to form acid. Acid rain is formed by the reaction of sulphur dioxide with water and atmospheric oxygen; it is a globally acknowledged problem that causes the destruction of landscape, property, and merchandise, and enhances the acidification of natural water resources, lowering their productivity and ability to sustain life forms. It can take place either by wet deposition, in which case the problems manifest much faster, or by dry deposition, in which case the pollutants are deposited in dust or smoke and their effects emerge over a longer period. In its ability to persist and be transported over long distances, SO_2 projects an increasing threat to areas beyond the vicinity of its production.

Nitrogen oxide generally referred to as NOx according to the United States Environmental Protection Agency (USA-EPA), is a generic term used to represent a group of highly reactive gases. All of them contain nitrogen and oxygen in varying proportions, and most of them tend to be colourless, odourless, and toxic. One species, nitrogen dioxide, can generally be seen as a reddish-brown layer over most urban areas. Nitrogen oxides are formed when fuel is burned at high temperatures, and are primarily emitted from power stations generating electrical power, followed by motor vehicles and other commercial and residential fuel burning activities. Nitrogen and oxygen gases will not react with each other in the atmosphere at ambient temperatures. It prevails as a cause

of concern because in addition to posing a respiratory hazard on its own, NO_2 is also involved in the formation of other respiratory hazards such as ground-level ozone (O_3). Secondly, this reactive species interacts with moisture to form acid rain, or with water resources to degrade their quality through nutrient enhancement. Of further concern is the contribution of NOx to global warming, to the formation of compounds that impair vision, and to the formation of other toxins. NOx is also known for its prevalence and potential to be transported over long distances, extending its threat to an entire region rather than remaining restricted in a particular area. In order to curb the problem, the U.S. EPA has taken a firm stand by issuing standards for vehicles and power stations to reduce pollution emissions.

4.6: Emission Inventory

Sulphur and sulphur dioxide are prevalent in most types of fossil fuels including oil and coal, and in ores containing metals such as copper, zinc, aluminium, iron, and lead. Therefore, when sulphur-containing fuels are used for power generation or during metal extraction processes, sulphur dioxide is released into the atmosphere. The major sources of SO_2 and NOx emissions in the state of Kuwait are power stations and water desalination plants, which are responsible for 69% and 22% of the total load, respectively (Ramadan *et al.*, 2007). The emissions from power plants include SO_2, NOx, and VOCs, which are transformed to acid rain and TSP in the form of ash; in dry weather, these substances are then deposited on surfaces. It is reported that the SO_2 and NO_x emissions from power stations in the UK sum to around 70% and 25% of the total emission loads, respectively (www.environment-agency.gov.uk).

Tables (4.6) and (4.7) show the amount of oil consumed by the main power stations during 2001 in Kuwait. The fuel provided to these stations by the Kuwait Oil Company (KOC) is mainly gas oil, crude oil, and heavy oil. The total sulphur content (*SC*) in these fuels by weight is 1, 2.5, and 4%, respectively. However,

the Ministry of Electricity and Water (MEW, 2002) rarely uses the low sulphur fuel oil for economic reason. The following formula relates the fuel consumption volumes to the SO_2 emissions,

$$Q(SO_2) = \sum \left[\frac{F \cdot S \cdot MW\ (SO_2)}{MW\ (SC)} \right] \tag{4.6}$$

Where,

$Q\ (SO_2)$ = SO_2 emission rate (g s^{-1})

F = Fuel consumption (g s^{-1})

SC = Sulphur content weight fraction in fuel

$MW(SO_2)$ = Molecular weight of Sulphur Dioxide = 64 g mol^{-1}

$MW(S)$ = Molecular weight of Sulphur = 32 g mol^{-1}

Table (4.6): Consumption of oil in barrels per month during 2001

2001	Gas oil consumption		Crude oil consumption		Heavy oil consumption		
Month	**Doha East**	**Subyia**	**Doha East**	**Subyia**	**Doha East**	**Doha West**	**Subyia**
January	0	0	0	0	330923	814867	432026
February	150	0	0	0	261903	790490	341509
March	0	0	209241	0	100657	1019186	436866
April	164	0	295882	0	112297	1328635	555425
May	0	0	0	0	498323	1487229	835965
June	9	0	772205	0	28189	1577459	1087167
July	0	0	557214	0	277076	1707170	1167712
August	0	4340	430966	732534	411504	1764804	683261
September	0	0	406286	1418522	298151	1340515	0
October	0	0	0	830657	560747	1361848	0
November	130	450	0	96020	388949	1090725	255170
December	115	0	0	0	294303	912929	489714

Table (4.7): Consumption of oil in barrels per month during 2004

2001	Gas oil consumption		Crude oil consumption		Heavy oil consumption		
Month	**Doha East**	**Subyia**	**Doha East**	**Subyia**	**Doha East**	**Doha West**	**Subyia**
January	0	0	0	823	0	0	496308
February	0	16269	6614	276424	561625	0	148409
March	0	12604	66022	497505	683795	0	0
April	145	0	1519	108895	0	564270	518601
May	0	0	8930	473892	0	364355	349753
June	0	0	2387	940178	0	1766659	0
July	0	0	0	924361	0	1971908	0
August	0	0	0	965539	0	1938006	0
September	0	0	7334	138226	0	363407	587379
October	135	0	0	0	0	0	639688
November	0	0	0	0	0	0	520490
December	140	0	0	0	0	0	546743

These oxides react to produce nitrates and nitric acid, which cause smog and acid rain, and act as a catalyst in the formation of harmful ground-level ozone. Oxygen and nitrogen react at high temperatures to form NO and NO_2; and NOx formation increases exponentially as temperature rises. Bouhamra and Abdul-Wahab (1999) reported that traffic in the residential areas of Kuwait is responsible for 26% of total NOx emissions and 96% of the total CO present in ambient air.

The modelling tool used in this study was the short term version of the Industrial Source Complex ISCST4.5, which is an modelling tool approved of and used by the U.S. Environmental Protection Agency (USA-EPA, 1995) for regulatory purposes. The model proves to be an appropriate tool for the study of temporal and spatial variations in ground level concentrations of SO_2 and NOx after being discharged from power station stacks. The fundamental input parameters for a given point source include emission rate of the pollutant (g s^{-1}), stack height (m), inner diameter at the exit stack (m), gas discharge rate (m s^{-1}), temperature (K), location coordinates in UTM (m), and elevation of the base from sea level (m).

Table (4.8) presents the physical stack properties for each power plant. The power station at Subyia has 8 stacks, Doha west has 8, and Doha east has 7. Therefore, the total emissions are divided equally between the 23 stacks to obtain the rate per stack. In addition, the emission rates represent the total amount of the monthly variations for 2001 and 2004, which reflect oil consumption at the power stations and indicate the greatest consumption during the summer.

Table (4.8): Source parameters input to the ISCST4.5 model

Station	Doha East	Doha West	Subyia
Number of Stacks	7	8	8
Location Coordinate in UTM E-W(X) (m)	771416.8	770561.3	808643.5
Location Coordinate in UTM N-S(Y) (m)	3252100.7	3251990.5	3276032.3
Base Elevation from Sea Level (m)	4	4.5	4.1
Stack Height (m)	196	190	192
Exit Temperature (K)	408	403	426
Exit Velocity (m s^{-1})	29.4	29.4	28.8
Exit Diameter (m)	3.5	4.3	4.3

High temperatures and resulting high demand for electricity in the summer forced the Kuwait Ministry of Electricity and Water to construct a new 2400 MW power plant (Subyia power station) in northern Kuwait in 2005. In addition, a new power plant is being constructed in southern Kuwait (Zour power station) with a total capacity of 2500 MW to cover the surge in electricity consumption during the summer.

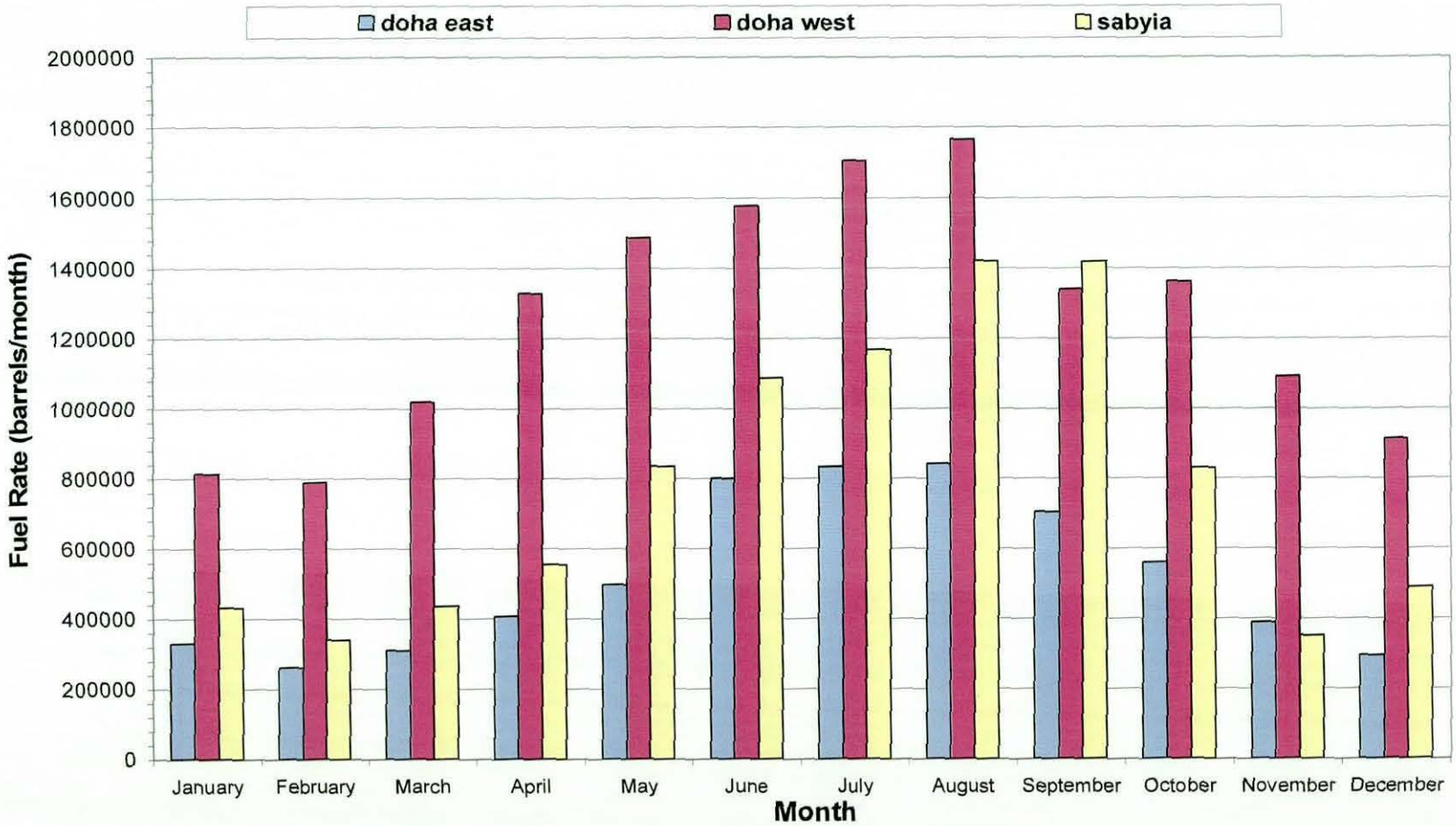

Figure 4.15: Monthly average consumption of fuel feed (barrels/month) for Doha and Subyia power stations during 2001

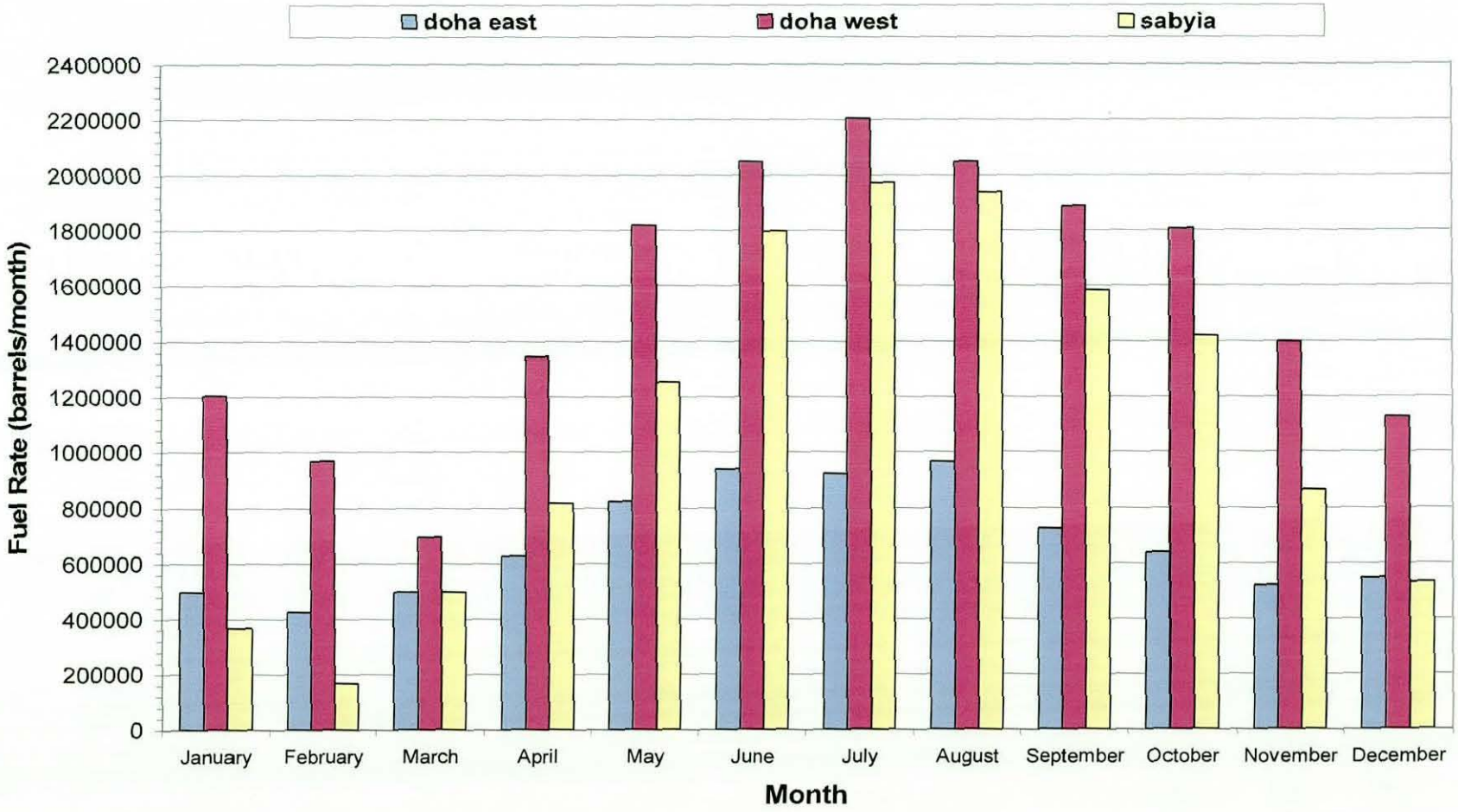

Figure 4.16: Monthly average consumption of fuel feed (barrels/month) for Doha and Subyia power stations during 2004

Figures (4.15) and (4.16) show the consumption of oil (barrels/month) during 2001 and 2004. The highest fuel consumption was in the summer period, driven by the high demand for power from the power stations.

Figures (4.17) and (4.18) show the SO_2 emission rates from the power stations for the 2001 and 2004 in Kuwait. The highest overall emission rates of SO_2 were recorded in the summer season due to the heavy load during this period, and the lowest were seen during winter. The oil consumption at the three power stations bears witness to this, with the consumption greatest in the summer. For August of 2001, Doha west consumed 1.75 million barrels, Subyia consumed 1.42 million barrels, and Doha east consumed 0.82 million barrels. In July of 2004, Doha west used 22 million barrels, Subyia used 1.9 million barrels, and Doha east used 0.95 million barrels. The lowest consumption levels for 2001 are reported in February, when Doha west used 0.79 million barrels, Subyia 0.36 used million barrels, and Doha east used 0.26 million barrels. For 2004, the lowest consumptions for Doha west are reported in March, with 0.7 million barrels, for Subyia in February with 0.18 million barrels, and for Doha east in February with 0.42 million barrels. Similar agreement is observed with respect to emissions, with Doha west ranking highest in emissions, followed by Subyia and then Doha east. The highest recorded emission rate from Doha west in 2001 was 7000 g s^{-1} in August, while, for 2004, the maximum was 8800 g s^{-1} in July, followed by the months of August and June. The lowest emission rate was in February for 2001 and March for 2004. At the Subyia station, the highest emission rate in 2001 of 4700 g s^{-1} was seen in July, followed by August and June, while the lowest emission rate was in November. For 2004, the highest emission rate in Subyia station was seen in September at 5700 g s^{-1}, followed by October and August, and the lowest emission rate occurred in February. For Doha east, the 2001 highest emission was 2700 g s^{-1} in August, followed by July, September, and October, and the lowest occurred in March. For 2004, the highest emission rate was 2700 g s^{-1} in September, followed by May and August, and the lowest emission rate occurred in March.

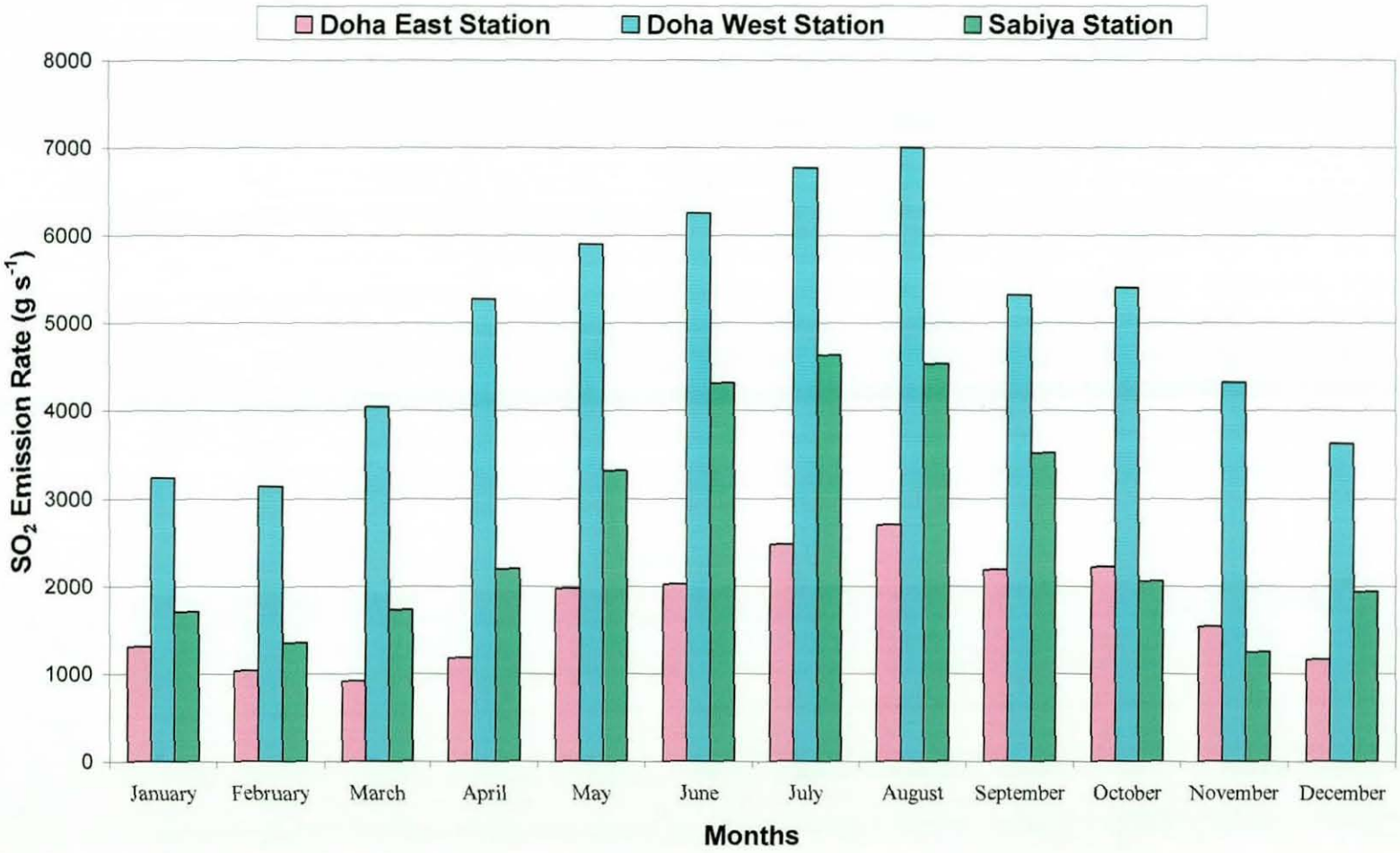

Figure 4.17: The emission rate of SO_2 in ($g\ s^{-1}$) from two power stations for 2001

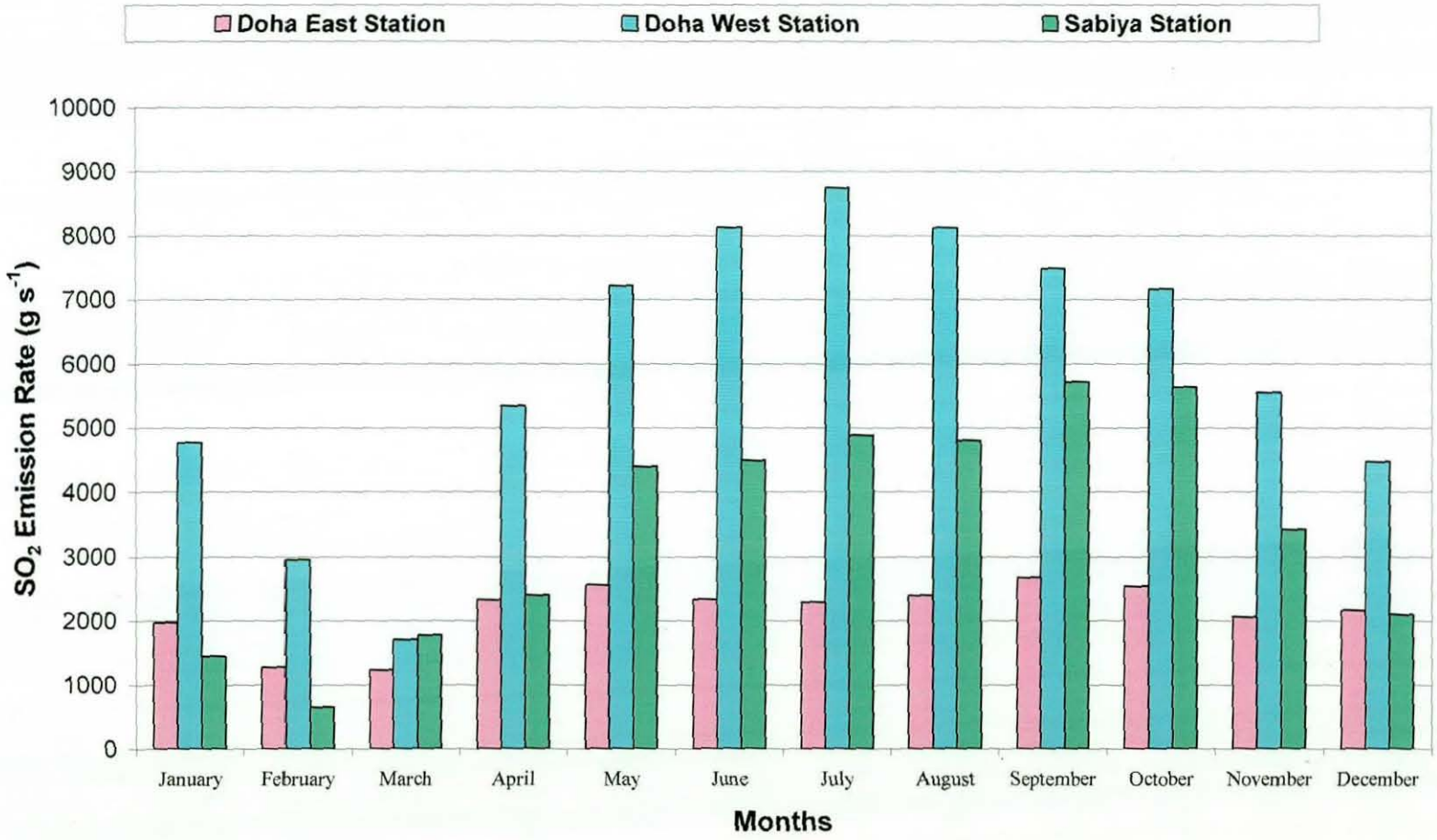

Figure 4.18: The emission rate of SO_2 in (g s^{-1}) from two power stations for 2004

Figures (4.19) and (4.20) represent the NOx emission rates in 2001 and 2004. These figures show that the highest emission rates of NOx occurred during the summer. Another interesting observation seen in the study of the NOx concentrations is the fact that Subyia registers consistently high emissions throughout the summer, a phenomenon that was it really masked and hidden in the case of SO_2 emissions. The highest recorded emission rate of NOx in 2001 was 595 g s^{-1} in August at Doha west. This is followed by 590 g s^{-1} at Subyia in August. The emissions from Doha east are far less significant, with the maximum value recorded at 305 g s^{-1} in August. The lowest emission rate recorded at Subyia was 110 g s^{-1} in the month of November, while the lowest value recorded at Doha west was 285 g s^{-1} in the month of January. The lowest emission rate recorded at Doha east was 80 g s^{-1} in the month of April. This agrees with the oil consumption at the three sources. Consumption is greatest at Doha west, which exhibits the three highest values in the summer with 1.78, 1.75 and 1.59 million barrels for June, July and August, respectively, followed by 1.41 at Subyia in August. The highest consumption values at Doha east, 0.82 and 0.81 million barrels, are also observed during the summer. The lowest consumption values at all three sources are documented in the winter, specifically in February, with 0.79 million barrels at Doha west, 0.27 at Subyia, and 0.23 at Doha east.

The highest recorded emission rate in 2004 at Doha west was 760 g s^{-1} in July followed by 640 g s^{-1} in August. At Subyia, the maximum emission rate was 730 g s^{-1} in July. The emissions from Doha east were far lower, with the maximum value recorded at 310 g s^{-1} in August. The lowest emission rate recorded at Doha west was 285 g s^{-1} in February, while the lowest value recorded at Subyia was 95 g s^{-1} in February. The lowest emission rate recorded at Doha east was 100 g s^{-1} in March. This finding agrees with the oil consumption at the three sources, which was greatest at Doha west and lowest at Doha east in the summer of both years.

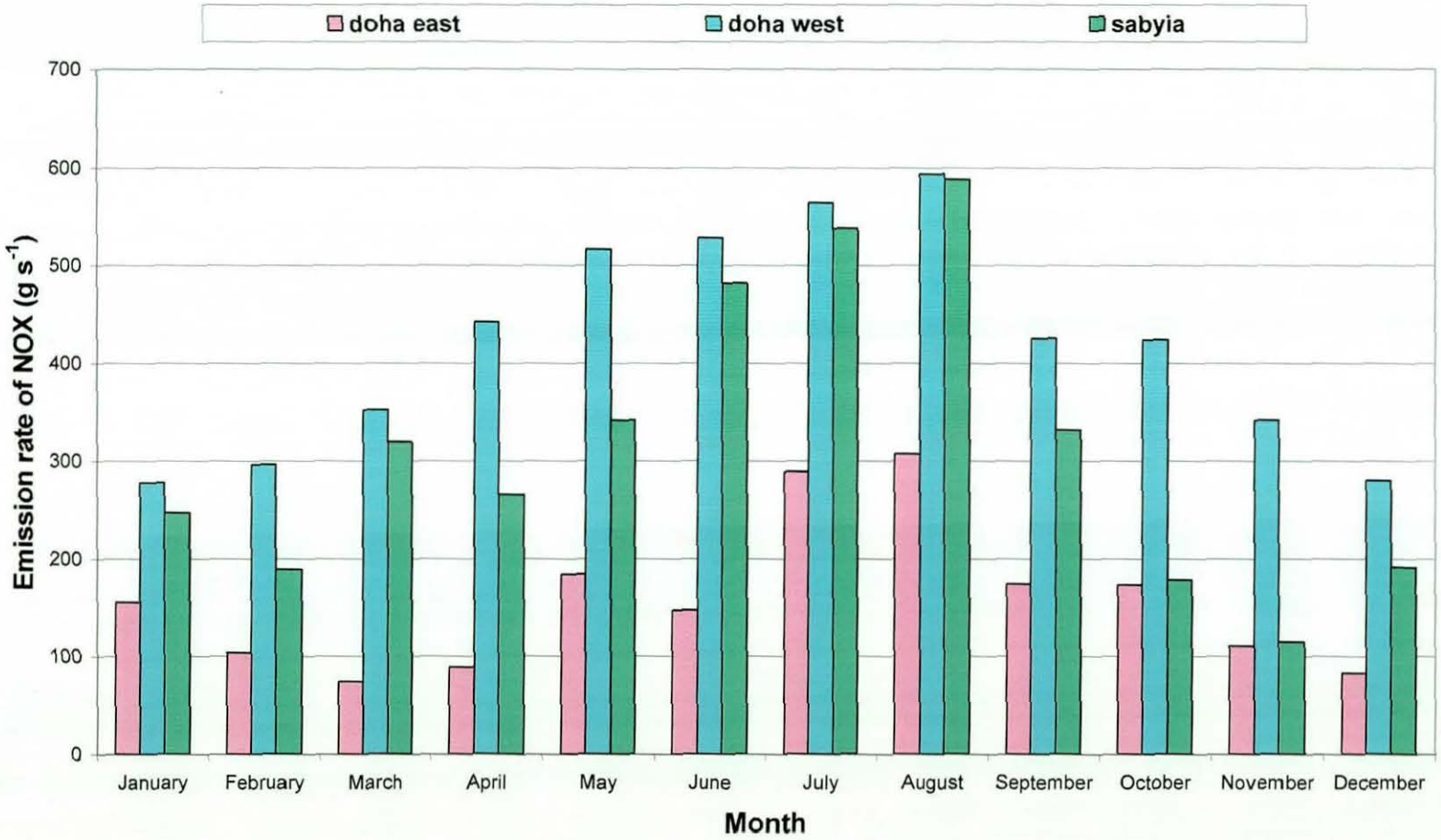

Figure 4.19: The emission rate of NOx in (g s^{-1}) from two power stations for 2001

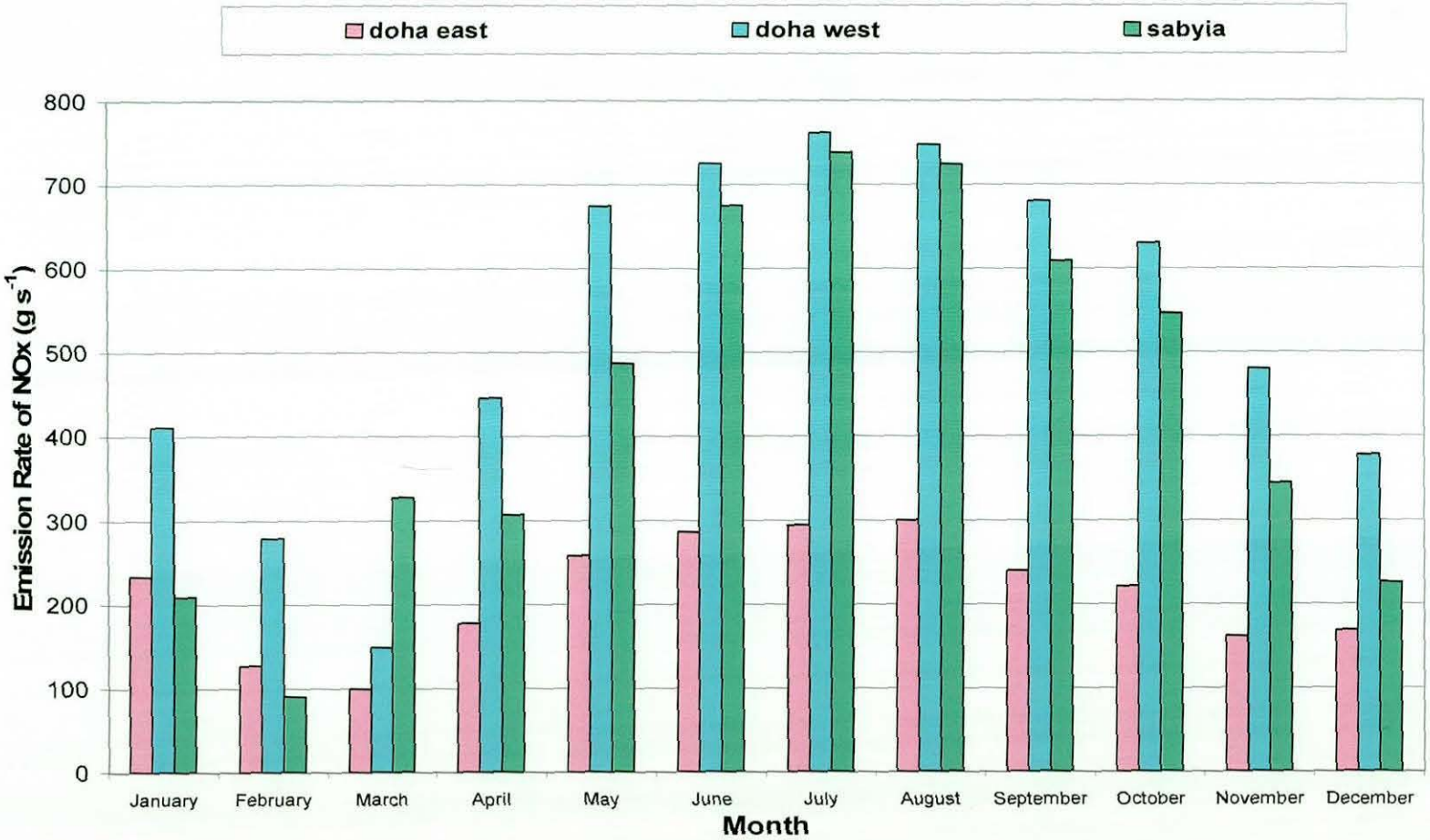

Figure 4.20: The emission rate of NOx in (g s^{-1}) from two power stations for 2004

4.7: Results and Discussions

The ISCST4.5 model was run (See Appendix (B)) to predict the emissions from the stacks of two main power stations, one comprised of seven 300 MW steam generators at Doha and the other of eight 300 MW steam generators at Subyia, that together satisfy the majority of the power requirement of Kuwait city. The Doha power station has two stacks: east and west. The east stack consists of three chimneys, while the west stack consists of four; they are collectively referred to as the Doha Complex. The Subyia station has two stacks, each consisting of four chimneys.

The ISCST4.5 model used three selected mesh areas to cover the study area (Fig.4.21). The first area covers the total selected mesh area of 2400 km^2 with 2500 receptors, comprised of single cells of 1 km^2. The second mesh covers only the Doha power station area of 100 km^2, with single cells of 0.25 km^2. The third mesh covers only the Subyia power station area of 100 km^2, again with single cells of 0.25 km^2. The mesh areas had defined coordinates in terms of X and Y-axes and contained selected source and receptor location. As discussed above, the sources of various pollutants are many, but for the purpose of this work, we have considered only the impact of the power stations. Fifty points were considered for the first mesh on the X-axis, which has a total length of 49 km, with a spacing of 1km between each two points; fifty points were also used on the Y-axis, which also has a total length 49 km and a spacing of 1 km between points. Collectively, this makes up 2500 receptors in a Uniform Cartesian Grid. The single receptor of interest, Rabia, is referred to as the Discrete Cartesian. The second and third mesh areas have 21 points on the x-axis and 21 points on the y-axis. These axes have total lengths of around 10 km in both x and y directions, each with spacing of 0.5 km between two points. Therefore, 441 receptors are considered for each station area's mesh. Thus, the total number of receptors in the three mesh areas is 3383. In designing the described mesh arrangements, the geographical shape of Kuwait was also taken into account. The closest residential areas to the Doha

Complex are the Doha residential area, located at a distance of 6.5 km, and the Sulaibikhat residential area, located at a distance of 8 km, both southeast of the complex. The closest residential area to Subyia is Kuwait city, located 25.4 km in the southwest direction, on the other side of the Kuwait Bay.

Emission inventories from two major power generation facilities at Doha and Subyia have been analyzed with seasonal variation in their power output. Meteorological data for 2001 and 2004 were obtained from the K-EPA and used as input in the PCRAMMET software to predict ground level concentrations of SO_2 and NOx.

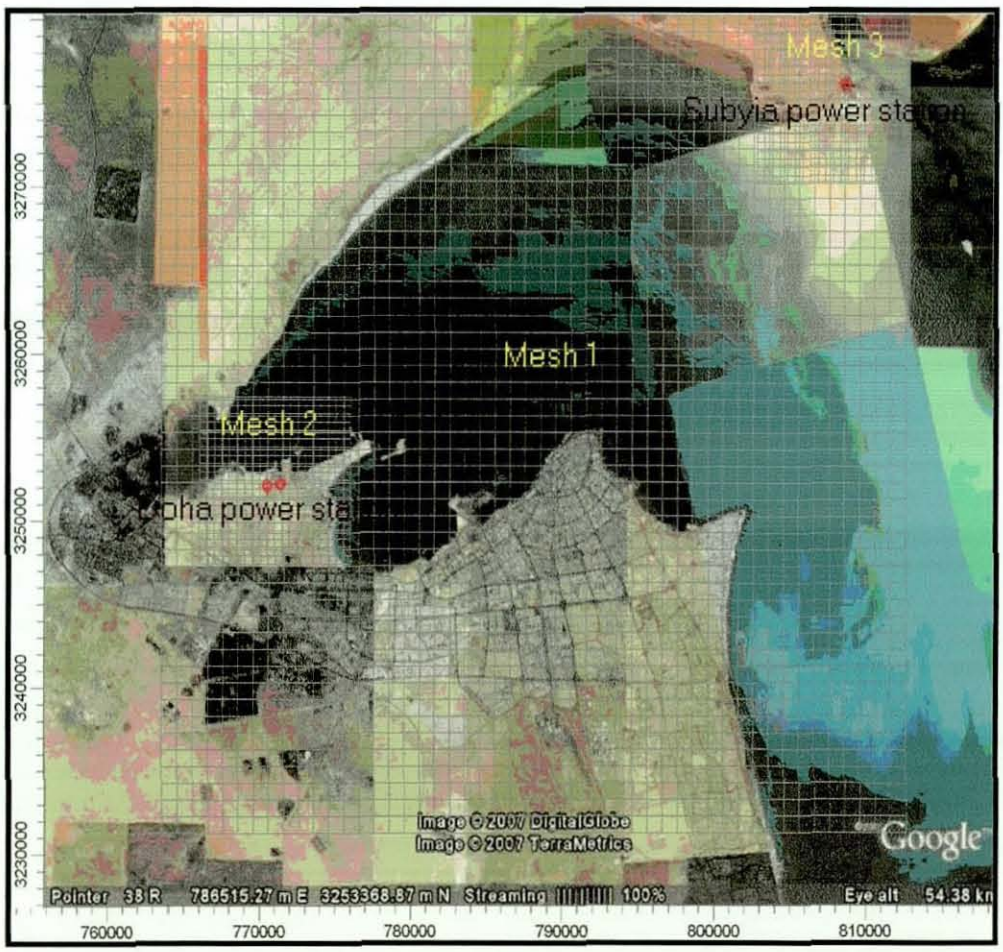

Figure 4.21: Location of selected mesh areas covering the study area (www. Google Earth.com).

4.7.1: Validation of the (ISCST4.5) Model

The air quality monitoring station, located on the top of the polyclinic in Rabia, provides measured data for studying the impacts of ground level pollutants concentrations. This data is also used to evaluate the predicted concentration values obtained from the mathematical model, in order to validate the model. In some cases, model parameters such as the dispersion coefficients can be adjusted within a theoretically acceptable range to calibrate the model. The validity of the model is tested by comparing observed and predicted data (Seinfeld, 1975).

To evaluate the performance of the model, the predicted values were compared with the measured values. In this study, the measured values have been obtained for SO_2 and NO from the monitoring station located on the polyclinic roof in the Rabia area. Figures (4.22) and (4.23) show that the slope of the daily predicted ground level SO_2 concentration against the measured values is equal to 0.81 for 2001 and 0.96 for 2004. Figures (4.24) and (4.25) show that the slopes comparing NOx values are 0.55 for 2001 and 0.76 for 2004. The lower slope value in 2001 was mainly due to the contribution from other combustion sources, such as vehicles coming and going from a cargo depot and auction market that were located 1.5 km northwest of the monitoring station. In 2004, the cargo depot was moved to a faraway location. The vehicle auction market was also closed down. However, there is annual growth in the number of cars on the road. In addition, the emission rates of SO_2 and NOx in 2004 were higher that 2001. It should be noted that the results presented in this study do not take into account SO_2 and NOx background concentrations. The validity of the model is quite satisfactory.

There is a strong influence of background NOx concentration, due to the many fixed and mobile sources; this results in different measured concentrations at EPA monitoring stations.

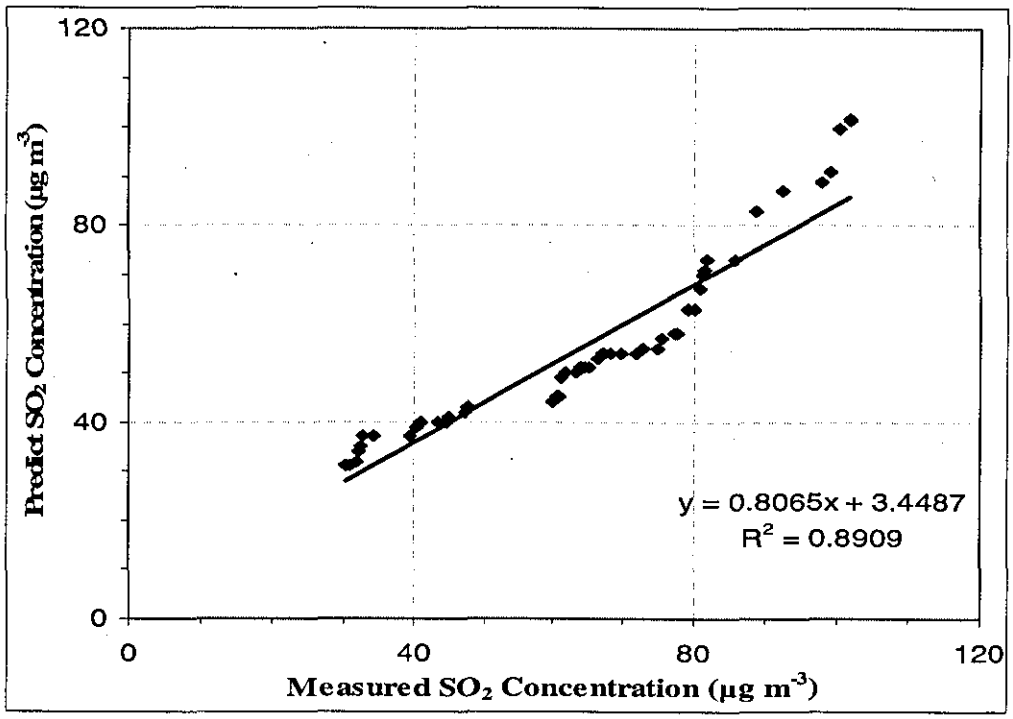

Figure 4.22: The fifty highest values of the predicted daily SO_2 concentration (µg m^{-3}) versus the fifty highest values of the observed daily SO_2 concentration (µg m^{-3}) in 2001 at Rabia

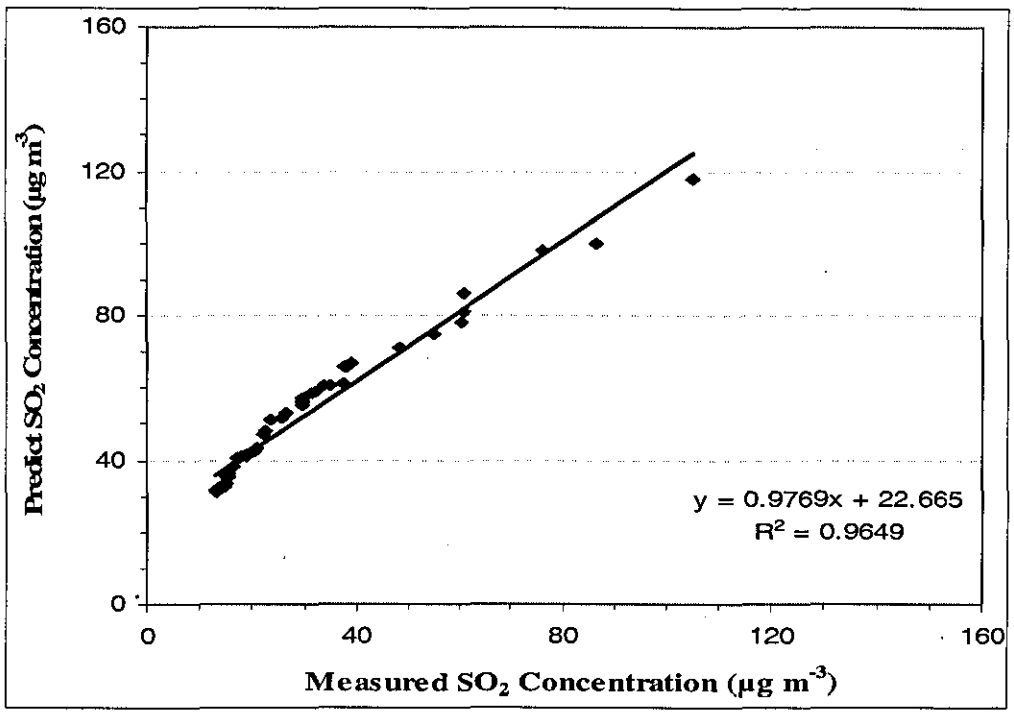

Figure 4.23: The fifty highest values of the predicted daily SO_2 concentration (µg m^{-3}) versus the fifty highest values of the observed daily SO_2 concentration (µg m^{-3}) in 2004 at Rabia

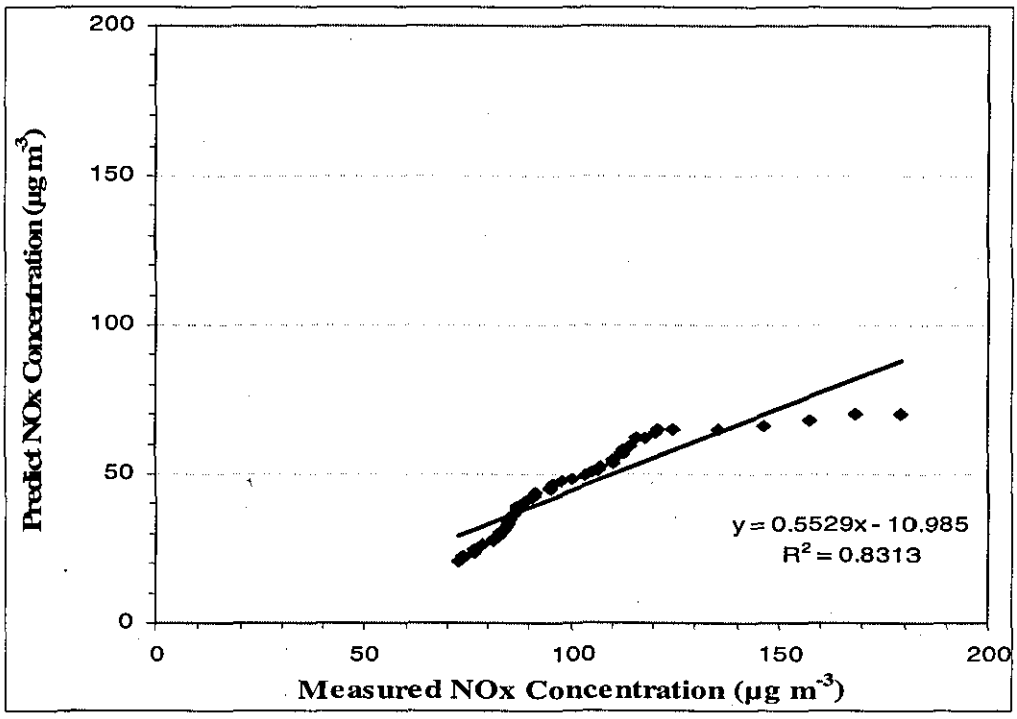

Figure 4.24: The fifty highest values of the predicted daily NOx concentration ($\mu g\ m^{-3}$) versus the fifty highest values of the observed daily NOx concentration ($\mu g\ m^{-3}$) in 2001 at Rabia

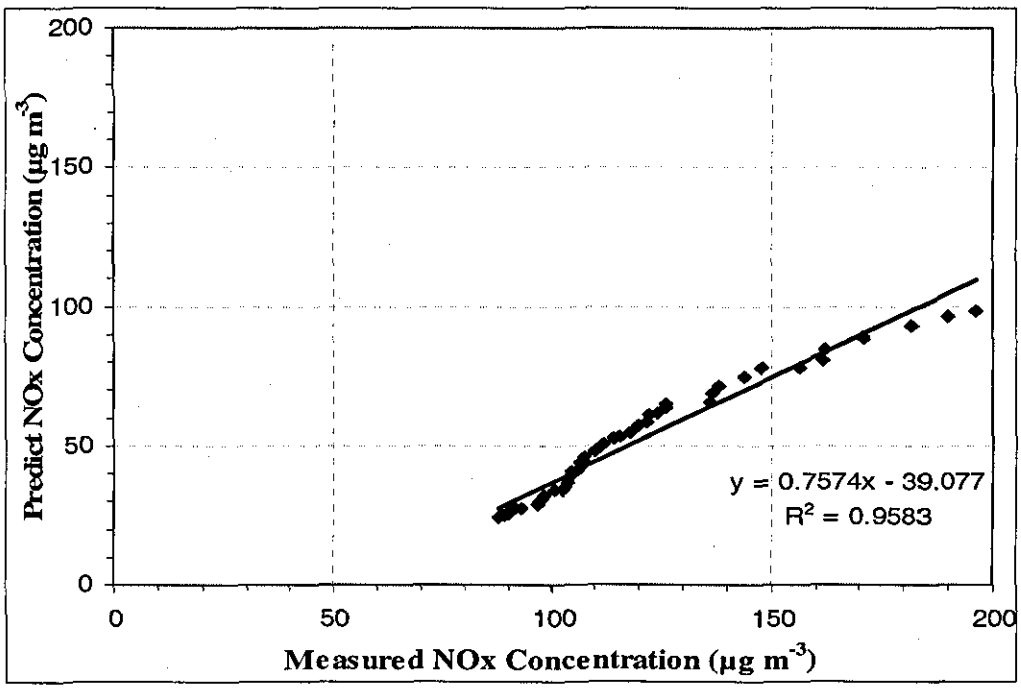

Figure 4.25: The fifty highest values of the predicted daily NOx concentration ($\mu g\ m^{-3}$) versus the fifty highest values of the observed daily NOx concentration ($\mu g\ m^{-3}$) in 2004 at Rabia

4.7.2 Monthly analysis of predicted results from the ISCST4.5 model for 2001 and 2004

In the first study, the maximum hourly and daily ground level predicted concentrations were calculated for each month at uniform grid receptors for the entire year based on the prevalent meteorological conditions for 2001 and 2004. For the prevalent pollutant values, we have used the K-EPA air monitoring station from the roof of the polyclinic in the centre of the Rabia area.

Table (4.9) shows the highest hourly ground level predicted concentrations of sulphur dioxide (SO_2) for each month of 2001. The highest monthly predicted concentration was recorded in August; a predicted concentration of 4421 $\mu g\ m^{-3}$ was noted on the 3rd at 4:00 am at a distance of 1.7 km from the Doha Complex, in the E direction, and 43.1 km from the Subyia station in the SW direction, with receptor coordinates of the X-axis 772592 and Y-axis 3252120. The corresponding temperature at that time was 37.5°C, relative humidity was 49.4%, and wind speed was 1.6 m s^{-1} in the W direction. The total area with predicted concentration values exceeding the K-EPA limit of 444 $\mu g\ m^{-3}$ was 1731.68 km^2. The second highest monthly value in the hourly ground level predicted concentration of SO_2 was recorded in June; a concentration of 3402 $\mu g\ m^{-3}$ was noted on the 3rd at 2:00 am, at a distance of 2.7 km from the Doha Complex in the E direction, and at 42.3 km from the Subyia station in the SW direction, with receptor coordinates of X-axis 773050 and Y-axis 3252260. The corresponding temperature at that time was 36.6°C, relative humidity was 35.2%, and wind speed was 1.96 m s^{-1} in the WNW direction. The area where the predicted concentration exceeded the K-EPA limit of 444 $\mu g\ m^{-3}$ was 1242.6 km^2. The lowest monthly ground level predicted concentration of SO_2 was recorded in January; a concentration of 1268.6 $\mu g\ m^{-3}$ was measured on the 8th at 5:00 am, at a distance of 1.8 km from the Doha Complex in the SW direction, and 46.5 km from the Subyia station in the SW direction. The corresponding temperature at that time was 16.53°C, relative humidity was 99.7%, and wind speed was 1.33 m s^{-1} in the NW direction, with receptor coordinates of X-axis 769618 and Y-axis

3250679. The total area where the predicted concentration exceeded the K-EPA limit of 444 μg m^{-3} was 861.2 km^2. The next lowest value was noted in the month of December, with a ground level predicted concentration of 1529 μg m^{-3}.

With respect to the daily ground level predicted concentration, Table (4.9) shows the highest ground level concentrations for each month in 2001. The highest ground level concentration was recorded in July; a predicted concentration of 931 μg m^{-3} was noted on the 9th at a distance of 1.6 km from the Doha Complex in the SE direction, and 44.9 km from the Subyia station in the SW direction, with coordinates of X-axis 771550 and Y-axis 3250760. The corresponding temperature at that time was 42.3°C, relative humidity was 33%, and wind speed was 3.7 m s^{-1} in the NWN direction. The area of land registering predicted concentrations exceeding the K-EPA limit of 157 μg m^{-3} was 181.5 km^2. The second highest daily depicted value occurred in August, with a ground level predicted concentration of 894 μg m^{-3} measured on the 21st at a distance of 1.6 km from the Doha Complex in the SSE direction and 44.9 km from the Subyia station was 44.9 km in the SW direction, with coordinates of X-axis 771550 and Y-axis 3250760. The corresponding temperature at that time was 44.1°C, relative humidity was 36.4%, and wind speed was 3.9 m s^{-1}. The area with predicted concentration values exceeding the K-EPA limit of 157 μg m^{-3} was 223.32 km^2. The lowest ground level predicted concentration occurred in January, with a concentration of 267 μg m^{-3} being measured on the 24th, at a distance of 1.55 km from the Doha Complex in the SE direction, and at 44.9 km from the Subyia station in the SW direction, with coordinates of X-axis 771583 and Y-axis 3250679. The corresponding temperature at that time was 18°C, relative humidity was 75%, and wind speed was 2.98 m s^{-1} in the W direction. The total area where the predicted concentration exceeded the K-EPA limit of 157 μg m^{-3} was 9.472 km^2.

On the other hand, Table (4.10) presents the highest predicted results of the ground level concentrations of SO_2 for each month in 2004. For year 2004, the

month with the highest predicted ground level concentration was August, with 3436 μg m^{-3} predicted on the 2nd of August 2004 at 12:00 pm, at 3.5 km from the Doha station in the SE direction, and at 47 km from the Subyia station in the SW direction, with the coordinates of X-axis 768702 and Y-axis 3251020. The temperature at 50°C recorded at this hour, relative humidity was 11.7%, and wind speed was 4.15 m s^{-1} in the NW direction. The area exceeding the K-EPA limit of 444 μg m^{-3} in August was 2151.8 km^2. The second highest predicted concentration was in July, with 3302 μg m^{-3} measured on the 24th at 7:00 am at 9.5 km from the Doha station in the WNW direction, and 36 km from Subyia in the SW direction with X-axis 779702.25 and Y-axis 3248020. The corresponding temperature at that time was 36.1°C, relative humidity was 6%, and wind speed was 1.23 m s^{-1} in the SE direction. The total area with predicted concentration levels exceeding the K-EPA limit in this month was 2351 km^2. The highest value of the month with the lowest overall predicted value occurred in March, with a ground level concentration of 814 μg m^{-3} occurring at 6:00 am on the 13th, at 10.9 km from Doha station in the SEE direction and 33.2 km from Subyia in the SW direction, with X-axis 780702 and Y-axis 3257020. The corresponding temperature at that time was 19°C, relative humidity was 36%, and wind speed was 1.1 m s^{-1} in the SE direction. The area exceeding the K-EPA limit in March was 1503 km^2 over the selected mesh area.

Table 4.9: The highest predicted first values of hourly and daily average of SO_2 concentrations per month for 2001

Month	Hourly / Daily	Conc. SO_2 ($\mu g\ m^{-3}$)	Time	Distance from Doha (km)	Direction from Doha	Distance from Subyia (km)	Direction from Subyia
January	H	1268.6	8th @ 5 am	1.8	SW	46.5	SW
	D	267	24th	1.55	SE	44.9	SW
February	H	1051.4	24th @ 9 am	2.2	NNE	43	SW
	D	278.7	14th	2.4	NW	44.6	SW
March	H	1984.3	23rd @ 3 am	0.6	ENE	43.9	SW
	D	391	18th	1.6	SE	44.9	SW
April	H	3083	8th @ 3 am	1.4	NW	45.6	SW
	D	729	17th	1.6	SE	44.9	SW
May	H	3026	25th @ 1 am	2.7	E	42.3	SW
	D	851	23rd	1.6	SE	44.9	SW
June	H	3402	3rd @ 2 am	2.7	E	42.3	SW
	D	827	8th	1.6	SE	44.9	SW
July	H	3235	2nd @ 3 am	2.9	SE	43.3	SW
	D	931	9th	1.6	SE	44.9	SW
August	H	4421	3rd @ 4 am	1.7	E	43.1	SW
	D	894	21st	1.6	SE	44.9	SW
September	H	2267.3	8th @ 3 am	5	NE	43.1	SW
	D	893	2nd	1.6	SE	44.9	SW
October	H	2209.9	1st @ 4 am	2.4	NE	44.6	SW
	D	463.1	30th	1.6	SE	44.9	SW
November	H	2054	22nd @ 5 am	1.4	NW	45.6	SW
	D	532.7	28th	1.6	SE	44.9	SW
December	H	1529	13th @ 7 am	4.5	E	40.6	SW
	D	392.8	17th	1.6	SE	44.9	SW

The daily predicted ground level concentrations of SO_2 for each month within the study area in 2004 are shown in Table (4.8). The highest recorded daily predicted concentration was seen in June, with 1224 μg m^{-3} observed on the 26th of June, at 1.4 km from the Doha power station in the SE direction and 45 km from the Subyia station in the SW direction, with coordinates of X-axis 771550 and Y-axis 3250760. The temperature on this day was 36.5°C, relative humidity was 3.6%, and wind speed was 3.2 m s^{-1} in the NW direction. The area exceeding the K-EPA limit for this month was 2041.2 km^2. The next highest predicted value was in June, with a concentration of 1054.3 μg m^{-3} recorded on the 18th of July, at distance of 1.7 km from the Doha station in the ESE direction and 46.1 km from the Subyia station in the SW direction, with X-axis 769702.25 and Y-axis 3251020. The corresponding temperature on that day was 38.5°C, relative humidity was 3.3%, and wind speed was 1.6 m s^{-1} in the NWN direction. The area exceeding the K-EPA limit in July was 2217.6 km^2. In addition, the highest value in the month with the overall lowest predicted concentration occurred in March, with 177.2 μg m^{-3} recorded on the 14th, at 2.3 km from Doha station in the SE direction and 44.1 km from the Subyia station in the SW direction, with coordinates of X-axis 772550 and Y-axis 3250260. The corresponding temperature at that time was 19.8°C, relative humidity was 21.8%, and wind speed was 3.6 m s^{-1} in the WNW direction. The total area exceeding the K-EPA limit in this month was 1214.7 km^2.

The highest predicted hourly ground-level concentrations of NOx for each month in 2001 are presented in Table (4.11). The highest monthly concentration was recorded in August, with a maximum value of 421 μg m^{-3} recorded on the 3rd at 4:00 am, at a distance of 4.5 km from the Doha Complex in the ESE direction, and 40.6 km from the Subyia station in the SW direction, with coordinates of X-axis 772592 and Y-axis 3252120.

Table 4.10: The highest first predicted values of hourly and daily average SO_2 concentrations per month for 2004

Month	Hourly / Daily	Conc. SO_2 ($\mu g\ m^{-3}$)	Time	Distance from Doha (km)	Direction from Doha	Distance from Subyia (km)	Direction from Subyia
January	H	2081.3	18th @ 4 am	10.5	ENE	34	SW
	D	582.4	2nd	2.1	SE	45.9	SW
February	H	1338.7	26th @ 13 pm	3.12	ENE	41.5	SW
	D	337.2	25th	2	ESE	43.9	SW
March	H	814	13th @ 6 am	10.9	SEE	33.2	SW
	D	177.2	14th	2.3	SE	44.1	SW
April	H	2238.8	12th @ 7 am	9.9	WNW	38	SW
	D	533.8	17th	1.7	ESE	43.5	SW
May	H	3019.5	17th @ 7 am	9.2	ENE	35.8	SW
	D	645.3	23rd	1.4	SE	44.9	SW
June	H	2650.4	14th @ 14 pm	2	W	45.9	SW
	D	1224.7	26th	1.4	SE	45	SW
July	H	3302.1	24th @ 7 am	9.5	WNW	36	SW
	D	1054.3	18th	1.7	ESE	46.1	SW
August	H	3436.4	2nd @ 12 pm	3.5	SE	47	SW
	D	1017.6	22nd	1.25	SE	45.3	SW
September	H	2525	28th @ 17 pm	1.5	SES	46.1	SW
	D	1025.5	8th	1.4	SE	44.9	SW
October	H	2879.5	13th @ 8 am	8.7	W	37.5	SW
	D	922.3	23rd	1.75	SE	45.3	SW
November	H	2464	26th @ 13 pm	2.3	SES	46.5	SW
	D	693.9	30th	1.6	ESE	43.5	SW
December	H	1760.2	8th @ 4 am	9.5	ESE	43.3	SW
	D	499.1	1st	1.6	ESE	43.9	SW

The corresponding temperature at that time was 39.5°C, relative humidity was 58%, and wind speed was 1.81 m s^{-1} in the W direction. Since the highest predicted concentration recorded in this month did not exceed the standard limit of K-EPA, there is no area affected by excessive concentrations. This was followed by July, with a maximum predicted concentration of 308 μg m^{-3} found at 3:00 am on the 2nd, at a distance of 46 km from the Doha Complex in the NE direction and 2.3 km from the Subyia station in the N direction, with coordinates of X-axis 772550 and Y-axis 3252260. The corresponding temperature at that time was 39.9°C, relative humidity was 46.3%, and wind speed was 1.79 m s^{-1} in the SWS direction. Again, there is no area affected by concentrations exceeding the K-EPA standard limit. The lowest predicted concentration was seen in February, the highest value in this month was measured as 149 μg m^{-3} on the 15th at 3:00 am, at a distance of 2.2 km from the Doha Complex in the ESE direction and at 43 km from the Subyia station in the SW direction. The corresponding temperature at that time was 20.6°C, relative humidity was 65.5%, and wind speed was 1.34 m s^{-1} in the WNW direction, with coordinates of X-axis 769050 and Y-axis 3250760. Again, there was no area that exceeded the K-EPA limit. The second lowest monthly predicted concentration was recorded in December, with a value of 157 μg m^{-3}.

Of daily predicted concentrations, the highest value reached was 79 μg m^{-3} on the 9th of July, at a distance of 1.6 km from the Doha Complex in the SE direction and 44.9 km from the Subyia station in the SW direction, with coordinates of X-axis 771550 and Y-axis 3250760 (Table 4.11). The corresponding temperature at that time was 42.3°C, relative humidity was 33%, and wind speed was 3.7 m s^{-1} in the NW direction. There was no area that exceeded the K-EPA standard limit of 224 μg m^{-3} within the selected mesh area in this month. The next highest monthly value occurred in August, with the maximum predicted concentration of NOx measured at 75 μg m^{-3} on the 21st, at 1.6 km from the Doha Complex in the SE direction, and 44.9 km from the Subyia station in the SW direction, with coordinates of X-axis 771550 and Y-axis 3250760. The corresponding

temperature at that time was 44.1°C, relative humidity was 36.4%, and wind speed was 3.9 m s^{-1} in the NW direction. No area exceeded the K-EPA limits over the study area in August. The month with the lowest ground level concentrations of NOx was January, with the month's maximum predicted concentration recorded as 28 μg m^{-3} on the 24th, at a distance of 1.6 km from the Doha Complex in the SES direction, and 44.9 km from the Subyia in the SW direction, with coordinates of X-axis 771550 and Y-axis 3250760. The corresponding temperature at that time was 18°C, relative humidity was 75%, and wind speed was 2.98 m s^{-1} in the W direction. This was followed by the month of December with maximum ground level predicted concentration of 35 μg m^{-3}. In neither month was there any area exceeding the K-EPA limits.

Similarly, Table (4.12) presents the high ground level predicted concentrations of nitrogen dioxide (NOx) for each month in 2004 from both power stations. The highest predicted hourly concentration in the highest concentration month was observed in July of 2004, with a value of 395 μg m^{-3} recorded on the 18th at 5:00 am, at 10.4 km from the Doha power station in the ENE direction and 36.5 km from the Subyia station in the SW direction, with coordinates of X-axis 780593 and Y-axis 3256121. The corresponding temperature at that time was 34.4°C, relative humidity was 3.8%, and wind speed was 1.7 m s^{-1} in the WNW direction. The month with the next highest concentration was August, with a max value of 357.9 μg m^{-3} observed on the 2nd at 12:00 pm, at 3.2 km from the Doha station in the SW and 47.7 km from the Subyia station in the WSW direction, with coordinates of X-axis 768050 and Y-axis 3250760. The temperature on this day was 43.3°C, relative humidity was 1.3%, and wind speed was 4.1 m s^{-1} in the NW direction. The month of March showed the lowest predicted ground level NOx concentration, with 114.2 μg m^{-3} observed on the 13th at 7:00 am. This predicted concentration was measured at 36.6 km from the Doha station in the NE direction and 13.2 km from the Subyia station in the NW direction, with coordinates of X-axis 795593 and Y-axis 3279121. No part of the selected study area exceeded the K-EPA NOx limits for any months in 2004.

Table 4.11: The highest first predicted values of hourly and daily average NOx concentrations per month for 2001

Month	Hourly / Daily	Conc. SO_2 ($\mu g\ m^{-3}$)	Time	Distance from Doha (km)	Direction from Doha	Distance from Subyia (km)	Direction from Subyia
January	H	160	29th @ 7 am	1.8	SW	46.5	SW
	D	28	24th	1.6	SE	44.9	SW
February	H	149	15th @ 3 am	2.2	ESE	43	SW
	D	36	14th	2.4	ENE	44.6	SW
March	H	169	15th @ 3 am	0.6	ENE	43.9	SW
	D	37	15th	1.6	SE	44.9	SW
April	H	258	8th @ 3 am	1.4	SW	45.6	SW
	D	61	17th	1.6	SE	44.9	SW
May	H	265	25th @ 5 am	2.7	E	42.3	SW
	D	71	23rd	1.6	SE	44.9	SW
June	H	283	13th @ 2 am	2.7	E	42.3	SW
	D	70	7th	1.6	SE	44.9	SW
July	H	308	2nd @ 3 am	46	NE	1.6	N
	D	79	9th	2.3	SE	44.9	SW
August	H	421	3rd @ 4 am	4.5	ESE	41.6	SW
	D	75	21st	2.6	SE	43.9	SW
September	H	216	9th @ 3 am	4.9	NE	39.8	SW
	D	66	2nd	1.8	SE	44.9	SW
October	H	206	1st @ 4 am	2.4	ENE	44.6	SW
	D	44	12th	1.6	SE	44.9	SW
November	H	199	26th @ 9 am	1.4	NW	45.6	SW
	D	46	28th	1.6	SE	44.9	SW
December	H	157	4th @ 7 am	1.6	SE	44.9	SW
	D	35	17th	1.6	SE	44.9	SW

Table (4.12) presents daily ground level NOx predicted concentrations of for each month in 2004. The highest predicted daily concentration in 2004 were recorded in June, with a concentration of 109.5 μg m^{-3} observed on the 26th at a distance of 1.4 km from the Doha Complex in the SE direction and 45 km from the Subyia station in the SW direction, with coordinates of X-axis 771550 and Y-axis 3250760. The corresponding temperature at that time was 46.5°C, relative humidity was 3.6%, and wind speed was 3.1 m s^{-1} in the NW direction. The next highest daily value was measured in September, with a concentration of 100.6 μg m^{-3} observed on the 8th at distance of 1.4 km from the Doha station in the SE direction and 45 km from the Subyia station in the SW direction, with coordinates of X-axis 771550 and Y-axis 3250760. The corresponding temperature at that time was 35.8°C, relative humidity was 10.3%, and wind speed was 1.5 m s^{-1} in the WNW direction. The month with the lowest predicted ground level NOx concentration was March, with the maximum concentration of 30.3 μg m^{-3} observed on the 14th at a distance of 44.8 km from the Doha Complex in the ESE direction and at 2.3 km from the Subyia station in the SE direction, with coordinates of X-axis 809816 and Y-axis 3274505. The corresponding temperature at that time was 20.1°C, relative humidity was 21.8%, and wind speed was 3.6 m s^{-1} in the WNW direction. However, there was no part of the study area that exceeded the K-EPA limit for daily NOx in 2004.

Overall, most of the highest hourly and daily predicted values for each month occurred in the early morning. The highest predicted concentrations were recorded in the summer season between June and September, with maximum values observed in August. Most of these highest values were observed at distances of less than 2 km to the southeast of the Doha power station and about 30 to 40 km to the southwest of the Subyia power station.

Table 4.12: The highest first predicted values of hourly and daily average NOx concentrations per month for 2004

Month	Hourly / Daily	Conc. SO_2 ($\mu g\ m^{-3}$)	Time	Distance from Doha (km)	Direction from Doha	Distance from Subyia (km)	Direction from Subyia
January	H	223.3	5th @ 10 am	11.4	NE	35.5	SW
	D	47.1	2nd	2.1	SW	45.9	SW
February	H	142.8	17th @ 7 am	10.8	ENE	34.8	SW
	D	30.7	25th	1.9	ESE	43	SW
March	H	114.2	13th @ 7 am	36.6	NE	13.2	NW
	D	30.3	14th	44.8	ESE	2.3	SE
April	H	236	12th @ 7 am	9.8	ESE	37.6	SW
	D	45.9	17th	1.7	ESE	43.5	SW
May	H	362.5	17th @ 7 am	12.3	ESE	32.8	SW
	D	63.7	23rd	1.4	SE	45	SW
June	H	276.5	14th @ 4 am	11	ESE	35	SW
	D	109.5	26th	1.4	SE	45	SW
July	H	395.3	18th @ 5 am	10.4	ENE	36.5	SW
	D	99.3	18th	1.7	SW	46.1	SW
August	H	357.9	2nd @ 12 pm	3.2	SW	47.7	WSW
	D	99.3	22nd	1.3	SE	45.3	SW
September	H	265.2	5th @ 9 am	7.5	SW	52.1	SW
	D	100.6	8th	1.4	SE	45	SW
October	H	327.7	13th @ 8 am	10.6	ESE	34.7	SW
	D	82.4	23rd	1.7	S	45.3	SW
November	H	248.7	4th @ 6 am	10.9	ESE	38.2	SW
	D	59.8	21st	1.8	SES	45	SW
December	H	184.2	12th @ 6 am	13.2	SW	56.8	SW
	D	44.3	1st	1.5	SE	43.5	SW

4.7.3: The highest fifty hourly and daily predicted values of SO_2 and NOx from two power stations for 2001 and 2004

Tables (4.13) and (4.14) summarise the predicted model results for the highest fifty hourly and daily ground level concentrations of SO_2, resulting from the Doha and Subyia power stations and predicted at the uniform grid receptors as described, including data on time, date, and X and Y coordinates for 2001 over the study area covered by the three mesh grids. The maximum predicted hourly ground level concentration was 4421 $\mu g\ m^{-3}$ at 4:00 am on August 3rd, with the coordinates on the X-axis of 772592 and Y-axis of 3252120. This value was measured at a distance of 1.7 km from the Doha Complex in the E direction and 43.1 km from the Subyia station in the SW direction. This is because the prevailing wind in Kuwait is from the North West (NW), so that the highest hourly value was located southeast of the Doha power station. Overall, the majority of these high values occur at the early morning and in the summer, especially in the month of August, which is the when the high temperatures are seen in Kuwait. As a result of high temperatures during the months of June, July, August, and September, the power stations are operating at full capacity to cover the demand for electricity. Even when people have returned from their summer vacations in late summer, the weather is still too hot so the power demand continues and results in violating pollutant concentrations. The maximum predicted daily ground level concentration was 931 $\mu g\ m^{-3}$, recorded on the 9th of July at coordinates of X-axis 771550 and Y-axis 3250760. The second daily value was 894 $\mu g\ m^{-3}$, observed on the 21st of August at coordinates of X 771550 and Y 3250760. These two daily values were located southeast of the Doha station. However, the coordinates of the highest 50 recorded daily concentrations are located in the uninhibited area within 1.55 km of the Doha station in the southeast direction. Overall, the majority of these values occur in summer months of June, July, and August, in the early morning.

Table 4.13: The highest fifty hourly average values of SO_2 predicted concentrations for 2001

No	Conc. SO_2 ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate	No	Conc. SO_2 ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate
1	4421	4:00 am on 3rd August	772592	3252120	26	3136	2:00 am on 17th August	771592	3250120
2	3944	4:00 am on 3rd August	772550	3252260	27	3131	4:00 am on 3rd August	772050	3252260
3	3782	4:00 am on 3rd August	773050	3252260	28	3083	3:00 am on 8th April	769550	3252260
4	3731	2:00 am on 6th August	769592	3253120	29	3080	3:00 am on 10th August	770050	3254760
5	3663	4:00 am on 3rd August	772550	3251760	30	3077	5:00 am on 25th August	772050	3250760
6	3631	2:00 am on 6th August	769050	3253760	31	3075	3:00 am on 1st August	769550	3251760
7	3629	2:00 am on 6th August	769550	3253260	32	3053	2:00 am on 6th August	768550	3253760
8	3565	4:00 am on 3rd August	773050	3251760	33	3044	3:00 pm on 31st July	771050	3253760
9	3488	4:00 am on 3rd August	773592	3252120	34	3026	1:00 am on 25th May	773550	3252260
10	3402	2:00 am on 3rd June	773050	3252260	35	3021	5:00 am on 25th August	771550	3250760
11	3364	3:00 am on 8th August	770050	3253260	36	3006	5:00 am on 28th August	772592	3252120
12	3362	2:00 am on 6th August	769050	3253260	37	3002	3:00 am on 2nd July	772550	3252760
13	3350	2:00 am on 6th August	768592	3254120	38	2995	5:00 am on 31st August	771550	3250260
14	3333	3:00 am on 6th August	770050	3253260	39	2992	1:00 am on 8th August	769050	3254260
15	3333	4:00 am on 3rd August	773550	3252260	40	2990	5:00 pm on 25th May	772550	3252760
16	3284	3:00 am on 10th August	770050	3254260	41	2985	3:00 am on 10th August	770050	3253760
17	3235	3:00 am on 2nd July	772550	3252260	42	2969	4:00 pm on 3rd August	774050	3252260
18	3233	4:00 am on 3rd August	772050	3251760	43	2966	2:00 am on 13th June	772592	3252120
19	3218	2:00 pm on 6th August	768550	3254260	44	2961	1:00 am on 25th May	773050	3252260
20	3208	4:00 am on 3rd August	773550	3251760	45	2953	5:00 am on 31st August	771592	3250120
21	3166	2:00 am on 17th August	771550	3250260	46	2935.	3:00 am on 2nd July	772050	3252260
22	3159	2:00 am on 13th June	773550	3252260	47	2923	5:00 am on 9th August	770050	3253760
23	3158	2:00 am on 2nd August	769550	3253760	48	2921	2:00 am on 24th July	776050	3250260
24	3158	3:00 am on 2nd July	773050	3252760	49	2919	2:00 am on 14th July	773050	3251260
25	3147	2:00 am on 13th August	772550	3252260	50	2914	2:00 am on 24th July	774550	3250760

Table 4.14: The highest fifty daily average values for SO_2 predicted concentrations for 2001

No	Conc. SO_2 ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate	No	Conc. SO_2 ($\mu g.m^{-3}$)	Time	X Coordinate	Y Coordinate
1	931	9th July	771550	3250760	26	721	20th August	771550	3250260
2	893	21st August	771550	3250760	27	720	10th June	771550	3250760
3	893	2nd September	771550	3250760	28	720	15th July	771550	3250760
4	870	16th July	771550	3250760	29	719	22nd May	771592	3250120
5	851	23rd May	771550	3250760	30	713	16th May	771550	3250260
6	827	8th June	771550	3250260	31	704	13th April	771550	3250760
7	822	3rd July	771592	3251120	32	703	15th July	772050	3250760
8	819	9th July	772050	3250260	33	702	14th July	771550	3250260
9	805	22nd August	771550	3250760	34	700	23rd July	771550	3250760
10	804	2nd September	772050	3250260	35	699	7th June	771550	3250260
11	799	21st August	771550	3250260	36	694	13th July	771550	3250760
12	791	8th June	771592	3250120	37	694	21st August	772050	3249760
13	786	23rd June	771550	3250760	38	694	15th July	772592	3251120
14	778	3rd July	772050	3250760	39	693	25th April	769050	3252760
15	773	21st August	772050	3250260	40	692	20th August	771592	3250120
16	769	3rd July	771550	3250760	41	687	18th June	771550	3250760
17	766	22nd May	771550	3250260	42	687	1st September	771550	3250260
18	758	7th June	771550	3250760	43	686	22nd May	772050	3249760
19	749	5th July	771592	3251120	44	686	5th July	772050	3250760
20	741	24th August	771550	3250760	45	683	9th July	772550	3249760
21	740	23rd May	772050	3250260	46	680	24th May	772050	3250760
22	738	21st August	771592	3250120	47	680	3rd July	771550	3251260
23	736	16th July	772050	3250260	48	679	23rd August	771550	3250760
24	729	17th April	771550	3250760	49	679	22nd August	771550	3250260
25	728	22nd May	771550	3250760	50	678	3rd July	772050	3250260

Since the Doha power station is considered a main source of pollutant emissions in Kuwait, it makes sense that the coordinates of these top hourly and daily values occurred in areas that are very close to the Doha power station; this desert area surrounding the power station and encompassing the top value measurement locations has a diameter of 5 km.

Tables (4.15) and (4.16) present the maximum fifty hourly and daily ground level predicted concentrations of NOx for 2001, also calculated from Doha and Subyia power stations in southwest Kuwait based on grid uniform receptors in the ISCST4.5 model, including parameters of time, date, and X and Y coordinates. The maximum predicted hourly NOx concentrations of 421 $\mu g\ m^{-3}$ was observed at 4:00 am on the 3rd of August, with coordinates X-axis 772592 and Y-axis 3252120, at a distance of 4.5 km from the Doha Complex in the ESE direction and at 40.6 km from the Subyia station in the SW direction. The majority of these hourly values occurred in the early morning, and all of them occurred in July and August. In addition, none of the fifty highest hourly ground level NOx concentrations exceeds the standard K-EPA limit. The maximum predicted daily ground level NOx concentration was 79 $\mu g\ m^{-3}$ on the 9th of July, with X-axis 771550 and Y-axis 3250760. Most of the fifty daily values were measured within the desert area within 1.55 km of the Doha complex in the southeast direction. In addition, the majority of the highest daily values occur in the summer between June and August. Since the weather in this period is very hot, with mean temperatures reaching 45°C, that the power stations work at full capacity to meet the electricity and water desalination demands. In addition, none of the highest fifty daily predicted values exceed the K-EPA limit; thus, there is no subset of the study area that exceeds the standards for either hourly or daily NOx concentrations. The coordinates of these top hourly and daily values occurred in very closed to the Doha power station, most of which were in a desert area within a 6 km diameter surrounding the power station, and some of which were located in the Kuwait bay that separates the two power stations.

Table 4.15: The highest fifty hourly average values of NOx predicted concentrations for 2001

No	Conc. NOx ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate	No	Conc. NOx ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate
1	421	4:00 am on 3rd August	772592	3252120	26	283	2:00 am on 24th July	776592	3250120
2	374	4:00 am on 3rd August	772550	3252260	27	283	4:00 am on 3rd August	774050	3251760
3	368	4:00 am on 3rd August	773050	3252260	28	283	2:00 am on 13th June	773050	3252260
4	342	4:00 am on 3rd August	773592	3252120	29	283	3:00 am on 2nd July	773550	3252760
5	341	4:00 am on 3rd August	773050	3251760	30	281	3:00 am on 2nd July	772550	3252760
6	339	4:00 am on 3rd August	772550	3251760	31	281	2:00 am on 24th July	775550	3250260
7	328	2:00 am on 6th August	769050	3253760	32	280	2:00 am on 14th July	773050	3251260
8	327	4:00 am on 3rd August	773550	3252260	33	280	2:00 am on 24th July	774550	3250760
9	326	2:00 am on 6th August	769592	3253120	34	280	3:00 am on 1st August	769550	3251760
10	323	2:00 am on 6th August	769550	3253260	35	279	4:00 am on 3rd August	772050	3251760
11	311	4:00 am on 3rd August	773550	3251760	36	277	3:00 am on 31st July	771050	3253760
12	308	3:00 am on 2nd July	772550	3252260	37	276	2:00 am on 24th July	775050	3250760
13	307	3:00 am on 2nd July	773050	3252760	38	276	5:00 am on 31st August	771550	3250260
14	303	2:00 am on 6th August	768592	3254120	39	275	4:00 am on 8th August	774592	3252120
15	301	3:00 am on 31st July	808816	3277505	40	275	3:00 am 10th August	770050	3254760
16	295	2:00 am on 6th August	768550	3254260	41	273	5:00 am on 31st August	771592	3250120
17	293	4:00 am on 3rd August	774050	3252260	42	273	4:00 am on 3rd August	772050	3252260
18	291	2:00 am on 24th July	776050	3250260	43	271	2:00 am on 2nd August	769550	3253760
19	290	3:00 am on 8th August	770050	3253260	44	271	2:00 am on 17th August	771550	3250260
20	290	2:00 am on 6th August	769050	3253260	45	271	3:00 am on 31st July	808816	3278005
21	287	3:00 am on 6ndAugust	770050	3253260	46	271	3:00 am on 2nd July	773050	3252260
22	286	5:00 am on 8th August	772592	3252120	47	269	2:00 am on 14th July	773550	3250760
23	286	3:00 am on 10th August	770050	3254260	48	269	2:00 am on 17th August	771592	3250120
24	286	3:00 am on 2nd July	810316	3276505	49	268	2:00 am on 6th August	768550	3253760
25	285	5:00 am on 25th August	772050	3250760	50	268	5:00 am on 25th August	772550	3250260

Table 4.16: The highest fifty daily average values of NOx predicted concentrations for 2001

No	Conc. NOx ($\mu g\ m^{-3}$)	Time	X coordinate	Y coordinate	No	Conc. NOx ($\mu g\ m^{-3}$)	Time	X coordinate	Y coordinate
1	79	9th July	771550	3250760	26	66	2nd September	771550	3250760
2	78	3rd July	809592	3275120	27	66	15th July	809592	3275120
3	75	21st August	771550	3250760	28	66	8th June	771550	3250120
4	74	9th July	809316	3275005	29	66	9th July	809592	3275120
5	74	9th July	809816	3274505	30	65	23rd June	771550	3250760
6	74	5th July	809592	3275120	31	65	23rd June	809816	3274505
7	74	3rd July	809816	3275005	32	65	3rd July	771550	3250760
8	73	16th July	771550	3250760	33	64	22nd May	771550	3250260
9	72	9th July	772050	3250260	34	63	9th June	809316	3275005
10	71	23rd May	771550	3250760	35	63	8th June	809316	3274505
11	71	16th July	809816	3274505	36	63	7th June	771550	3250760
12	71	5th July	809816	3275005	37	63	15th July	772050	3250760
13	70	7th June	809316	3275005	38	63	15th July	809816	3275005
14	70	3rd July	771592	3251120	39	62	23rd May	772050	3250260
15	69	8th June	809816	3274005	40	62	5th July	771592	3251120
16	69	8th June	771550	3250260	41	62	24th August	771550	3250760
17	69	3rd July	772050	3250760	42	62	21st August	772550	3249760
18	68	21st August	772050	3250260	43	62	16th July	772050	3250260
19	67	22nd August	771550	3250760	44	62	24th August	772050	3250760
20	67	8th July	809316	3275005	45	62	21st August	771592	3250120
21	67	7th June	809816	3274505	46	61	9th July	772550	3249760
22	67	8th June	809592	3274120	47	61	23rd June	809592	3275120
23	67	21st August	771550	3250260	48	61	22nd August	809316	3275005
24	66	21st August	809816	3274505	49	61	3rd July	810316	3274505
25	66	21st August	809316	3275005	50	61	9th July	772050	3250760

Tables (4.17) and (4.18) present the top fifty hourly and daily predicted ground level SO_2 concentrations for 2004 as calculated at the uniform grid receptors over the chosen study area, including data on time, date, and X and Y coordinates. These top values are predicted based on Doha and Subyia power station emissions. The highest predicted hourly ground level concentration was 3436.4 $\mu g\ m^{-3}$ at 12:00 pm on August 2nd, with coordinates of X-axis 768702 and Y-axis 3251020, located at 3.5 km from the Doha station in the SE direction, and 47 km from the Subyia station in the SW direction. This is because the prevailing wind in Kuwait is almost from the northwest (NW), so the highest hourly values are located southeast of the Doha power station and southwest of the Subyia station. Since the average wind speed in 2004 was higher than in 2001, the locations of the highest hourly values in 2004 are farther from the source than in 2001 (Tables 4.9, 4.10). The majority of these values occurred in the early mornings in July and at midday in August, which is considered the summer season with its high temperatures. The maximum predicted daily ground level SO_2 concentration was 1224.7 $\mu g\ m^{-3}$ on June 26th, at distance of 1.4 km from the Doha power station in the SE direction and at 45 km from the Subyia station in the SW direction, with coordinates of X-axis 771550 and Y-axis 3250760. Just as this daily value was located southeast of the Doha power station and southwest of the Subyia power station, the coordinates of the top 50 highest daily predicted concentrations were measured in the desert area within 1.6 km southeast of the Doha station. Overall, the majority of these values occur in the summer season between June and October, in the early morning. All fifty of the highest predicted hourly and daily SO_2 values exceed the standard limits set by K-EPA. This is because of the power stations would have been running at full capacity to cover the demand for electricity in the summer season.

Table 4.17: The fifty highest hourly average values of SO_2 predicted concentrations for 2004

No	Conc. SO_2 ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate	No	Conc. SO_2 ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate
1	3436.38	12:00 pm on 2nd August	768702	3251020	26	3011.89	12:00 pm on 18th July	767702	3251020
2	3415.87	12:00 pm on 2nd August	768050	3250760	27	3005.33	12:00 pm on 11th August	771050	3249760
3	3396.79	12:00 pm on 13th August	771050	3250260	28	2977.99	12:00 pm on 3rd August	770050	3249260
4	3302.09	7:00 am on 24th July	779702	3248020	29	2976.29	12:00 pm on 18th July	768550	3251260
5	3289.89	12:00 pm on 11th August	771050	3249260	30	2974.67	12:00 pm on 2nd August	769050	3251260
6	3288.62	12:00 pm on 11th August	770050	3249260	31	2956.00	12:00 pm on 2nd August	767050	3250260
7	3221.28	6:00 am on 18th July	783702	3253020	32	2953.72	5:00 am on 18th July	784702	3258020
8	3212.02	6:00 am on 18th July	782702	3253020	33	2949.86	12:00 pm on 13th August	771050	3249760
9	3207.07	5:00 am on 18th July	777702	3255020	34	2924.32	12:00 pm on 2nd August	768550	3250760
10	3193.91	12:00 pm on 14th August	770702	3250020	35	2919.88	12:00 pm on 18th July	768050	3251260
11	3190.78	5:00 am on 18th July	782702	3257020	36	2897.26	12:00 pm on 11th August	771050	3248260
12	3170.54	7:00 am on 24th July	781702	3247020	37	2892.34	12:00 pm on 30th July	768050	3251260
13	3168.23	12:00 pm on 11th August	771050	3248760	38	2890.30	6:00 am on 18th July	786702	3253020
14	3165.32	12:00 pm on 1st August	770050	3249760	39	2880.35	6:00 am on 18th July	780702	3253020
15	3158.49	5:00 am on 18th July	779702	3256020	40	2879.46	8:00 am on 13th October	779702	3252020
16	3157.47	6:00 am on 18th July	784702	3253020	41	2878.36	12:00 pm on 10th of August	770550	3249760
17	3140.31	5:00 am on 18th July	780702	3256020	42	2876.46	8:00 am on 13th of October	780702	3252020
18	3129.27	12:00 pm on 11th August	770702	3250020	43	2873.53	7:00 am on 24th of July	783702	3246020
19	3106.18	6:00 am on 18th July	781702	3253020	44	2867.65	7:00 am on the 17th of May	782702	3256020
20	3093.09	12:00 pm on 31st July	768550	3251760	45	2863.34	7:00 am on 30th of July	764702	3253020
21	3080.21	12:00 pm on 31st July	768050	3251760	46	2848.16	3:00 pm on 21st of July	769702	3252020
22	3041.43	6:00 am on 18th July	785702	3253020	47	2846.79	12:00 pm on 31st of July	767550	3251760
23	3031.54	12:00 pm on 1st August	770050	3248760	48	2839.02	12:00 pm on 13th August	771550	3248760
24	3025.76	7:00 am on 24th July	777702	3249020	49	2832.07	8:00 am on 13th of October	781702	3252020
25	3019.53	7:00 am on 17th May	779702	3255020	50	2828.28	4:00 pm on 22nd of July	769702	3252020

Table 4.18: The fifty highest daily average values of SO_2 predicted concentrations for 2004

No	Conc. SO_2 ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate	No	Conc. SO_2 ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate
1	1224.74	26th June	771550	3250760	26	885.2	23rd August	771550	3250760
2	1054.28	18th July	769702	3251020	27	872.12	22nd July	769702	3252020
3	1052.7	26th June	771550	3250760	28	867.88	23rd August	771050	3251260
4	1045.26	24th June	771550	3250760	29	866.79	27th June	772050	3250260
5	1025.52	8th September	771550	3250760	30	864.93	22nd July	768702	3252020
6	1017.65	26th June	771050	3250760	31	862.68	29th June	771550	3250760
7	1012.5	26th June	772050	3250260	32	860.1	24th October	771550	3250260
8	1001.45	7th July	771550	3250760	33	859.62	24th October	771550	3249760
9	990.31	3rd September	771550	3250760	34	859.6	1st July	772050	3250760
10	983.68	25th June	771702	3251020	35	858.7	24th October	771050	3250260
11	982.67	12th July	771702	3251020	36	854.01	22nd August	771550	3250260
12	935.67	1st July	771702	3251020	37	851.66	24th October	771050	3250760
13	926.23	13th July	771702	3251020	38	846.2	8th September	772050	3250260
14	922.92	11th July	771702	3251020	39	845.08	11th July	772050	3250760
15	922.3	23rd October	771050	3250260	40	841.2	24th October	771702	3250020
16	919.5	12th July	771550	3251260	41	838.8	1st July	771550	3250760
17	916.6	18th July	769550	3251260	42	838.43	23rd October	771050	3250760
18	914.14	18th July	769550	3250760	43	835.65	13th July	772050	3250760
19	910.57	25th June	772050	3250760	44	831.35	28th June	771550	3250760
20	901.09	12th July	769550	3251760	45	827.66	3rd September	772050	3250260
21	900.18	12th July	772050	3250760	46	822.24	1st July	771550	3251260
22	897.24	8th July	771550	3250760	47	822.17	11th June	771550	3250760
23	893.22	24th June	772050	3250260	48	821.88	9th September	771550	3250760
24	886.55	9th July	771550	3250760	49	812.13	8th July	772050	3250760
25	885.78	22nd July	769050	3251760	50	807.68	18th July	770050	3251260

Tables (4.19) and (4.20) present the maximum fifty hourly and daily predicted ground level NOx concentrations for 2004, as calculated based on the Doha and Subyia power stations located in southwest Kuwait using grid uniform receptors of ISCST4.5 model, including parameters of time and date, location and coordinates. The maximum predicted hourly NOx concentration in 2004 was recorded in July at 395.3 $\mu g\ m^{-3}$ on the 18th at 5:00 am, at 10.4 km from the Doha power station in the ENE direction and 36.5 km from the Subyia station in the SW direction, with coordinates of X-axis 780593 and Y-axis 3256121. Also, because of the average wind speed of year 2004 was higher than year 2001, the locations of the 2004 top hourly values farther away from the source than in 2001 (Tables 4.11, 4.12). The majority of these hourly values occurred in the early morning, and all occurred between July and September during the highest temperatures of the year. The coordinates of these top values are very close to the Doha power station or in the sea that separates the two stations. However, some of these higher values, which are near the K-EPA limits, occurred in the Doha and Sulybikhat residential areas located 6.5 km southeast of the Doha power station. Strictly speaking, though, none of the fifty highest hourly ground level NOx concentrations exceeded the K-EPA standards limit in the selected mesh areas. The maximum predicted daily value of ground level NOx concentration was 109.5 $\mu g\ m^{-3}$, recorded on the 26th of June at a distance of 1.4 km SE of the Doha Complex and 45 km SW of the Subyia station, with coordinates of X-axis 771550 and Y-axis 3250760. Most of the fifty highest predicted daily values have coordinate within desert areas with an average distance of only 1 to 2 km SW from the Doha complex. In addition, the majority of maximum daily values occurred in the summer season between June and August, when the high temperature and dusty conditions force the power stations in Kuwait to work at full capacity to meet increased electricity and water desalination demands. There is no area that exceeds the K-EPA limits in the case of predicted daily NOx concentrations.

Table 4.19: The fifty highest hourly average values of NOx predicted concentrations for 2004

No	Conc. NOx ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate	No	Conc. NOx ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate
1	395.27	5:00 am on 18th July	780593	3256121	26	347.13	7:00 am on 17th May	785593	3257121
2	390.44	5:00 am on 18th July	782593	3257121	27	345.93	5:00 am on 18th July	778593	3255121
3	389.54	6:00 am on 18th July	785593	3253121	28	345.27	5:00 am on 18th July	783593	3257121
4	388.51	6:00 am on 18th July	784593	3253121	29	343.83	6:00 am on 18th July	789593	3253121
5	384.13	6:00 am on 18th July	786593	3253121	30	343.77	7:00 am on 24th July	788593	3244121
6	382.42	7:00 am on 24th July	781593	3247121	31	343.03	3:00 am on 24th July	783593	3264121
7	379.25	6:00 am on 18th July	783593	3253121	32	337.96	5:00 am on 18th July	789593	3260121
8	376.42	7:00 am on 24th July	779593	3248121	33	337.17	7:00 am on 24th July	785593	3245121
9	373.84	6:00 am on 18th July	787593	3253121	34	333.59	7:00 am on 24th July	782593	3247121
10	367.86	3:00 am on 24th July	780593	3261121	35	331.81	12:00 pm on 13th August	771050	3250260
11	366.04	3:00 am on 24th July	779593	3260121	36	330.88	5:00 am on 30th July	763593	3253121
12	364.97	5:00 am on 18th July	785593	3258121	37	330.82	5:00 am on 17th May	777593	3260121
13	364.79	7:00 am on 24th July	783593	3246121	38	330.09	3:00 am on 24th July	784593	3265121
14	363.24	3:00 am on 24th July	781593	3262121	39	329.2	3:00 am on 24th July	777593	3258121
15	362.48	7:00 am on 17th May	782593	3256121	40	328.95	12:00 pm on 2nd August	768593	3251121
16	360.04	6:00 am on 18th July	788593	3253121	41	328.93	6:00 am on 18th July	781593	3253121
17	359.92	6:00 am on 18th July	782593	3253121	42	327.67	8:00 am on 13th October	781593	3252121
18	359.34	5:00 am on 18th July	784593	3258121	43	327.23	5:00 am on 17th May	778593	3261121
19	359.13	5:00 am on 18th July	787593	3259121	44	326.19	8:00 am on 13th October	782593	3252121
20	357.89	12:00 pm on 2nd August	768050	3250760	45	326.09	6:00 am on 18th July	790593	3253121
21	354.69	7:00 am on 24th July	786593	3245121	46	326.02	12:00 pm on 1st August	770050	3249260
22	354.59	3:00 am on 24th July	778593	3259121	47	326.01	7:00 am on 24th July	790593	3243121
23	354.44	3:00 am on 24th July	782593	3263121	48	325.74	8:00 am on 13th October	780593	3252121
24	353.74	7:00 am on 24th July	784593	3246121	49	325.39	12:00 pm on 11th August	771050	3249260
25	353.39	5:00 am on 17th May	779593	3255121	50	324.76	7:00 am on 17th May	788593	3258121

Table 4.20: The fifty highest daily average values of NOx predicted concentrations for 2004

No	Conc. NOx ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate	No	Conc. NOx ($\mu g\ m^{-3}$)	Time	X Coordinate	Y Coordinate
1	109.5	26th June	771550	3250760	26	82.46	23rd October	771050	3250260
2	100.64	8th September	771550	3250760	27	81.97	13th July	771593	3251121
3	99.32	18th July	769593	3251121	28	81.91	12th July	771550	3251260
4	99.27	22nd August	771550	3250760	29	81.68	24th June	772050	3250260
5	97.23	3rd September	771550	3250760	30	81.62	22nd July	769593	3252121
6	93.98	27th June	771550	3250760	31	81.55	8th September	809816	3274505
7	93.53	24th June	771550	3250760	32	81.53	26th June	809593	3275121
8	91.67	26th June	772050	3250260	33	81.34	25th June	809816	3275005
9	89.46	7th July	771550	3250760	34	81.25	11th July	771593	3251121
10	89.3	18th July	769550	3250760	35	81.09	24th June	769593	3251121
11	88.4	23rd August	771550	3250760	36	81.08	3rd September	772050	3250260
12	88.1	26th June	809816	3274505	37	80.73	9th September	771550	3250760
13	87.6	12th July	771593	3251121	38	80.67	12th July	772050	3250760
14	86.97	18th July	769550	3251260	39	80.25	18th July	770050	3251260
15	86.82	22nd July	769550	3251760	40	80.24	8th July	771550	3250760
16	86.08	25th June	771593	3251121	41	79.86	25th June	809593	3275121
17	85.76	23rd August	809316	3275005	42	79.76	1st July	772050	3250760
18	85.27	22nd August	771550	3250260	43	79.37	27th June	809816	3274505
19	85.11	22nd July	769050	3251760	44	79.33	9th July	771550	3250760
20	84.53	23rd August	771050	3251260	45	79.25	2nd August	769050	3251260
21	84.03	22nd August	809316	3274505	46	78.99	27th June	772050	3250260
22	83.81	1st July	771593	3251121	47	78.86	8th July	772050	3250760
23	82.75	8th September	772050	3250260	48	78.79	24th October	771593	3250121
24	82.72	25th June	772050	3250760	49	78.18	24th October	771550	3249760
25	82.63	22nd August	771593	3250121	50	78.18	24th October	771550	3250260

4.7.4: The highest predicted tenth percent of annual SO_2 and NOx concentrations from two power stations for 2001 and 2004

Table (4.21) presents the highest tenth of predicted annual ground level SO_2 concentrations for 2001 from the ISCST4.5 model. The highest annual value was 230 μg m^{-3}, with coordinates of X-axis 771550 and Y-axis 3250760, and located 1.6 km SSE of the Doha Complex and 44.9 km SW of the Subyia station. This is followed by the second highest value of 205 μg m^{-3}, at coordinates of X-axis 772050 and Y-axis 3250260, located 2.7 km from the Doha Complex in the SE direction and 44.6 km from the Subyia station in the SW direction. The third highest value was 192 μg m^{-3}, at coordinates of X-axis 772050 and Y-axis 3250760, and at 1.8 km from the Doha Complex in the SE direction 44.5 km from the Subyia station in the SW direction. The total area within the study region experiencing concentrations that exceeded the K-EPA limit of 80 μg m^{-3} was 11.5 km^2. The locations of the highest annually values were in desert areas southeast of both power stations, with coordinates within a 6 km radius of the Doha and Subyia power stations (see Figure 4.28).

Table (4.22) shows the model output predicting annual NOx concentrations for 2001, where the maximum annual NOx concentrations remained restricted below the standard limits of (K-EPA) (134 μg m^{-3}). The highest value was 19.41 μg m^{-3}, with equivalent coordinates on the X-axis of 771550 and on the Y-axis of 3250760. This site was 1.6 km SSE of the Doha Complex and 44.9 km SW of the Subyia station. The next highest value was 17.43 μg m^{-3}, with the equivalent coordinates of X-axis 772050 and Y-axis 3250260. The distance of this site was 2.7 km from the Doha Complex in the SE direction and 44.6 km from the Subyia station in the SW direction. This was followed by 16.5 μg m^{-3}, with equivalent coordinates of X-axis 772050 and Y-axis 3250760, and located 1.8 km SE of the Doha Complex and 44.5 km SW of the Subyia station.

Table 4.21: The highest ten values of annual average SO_2 predicted concentrations for 2001

No:	Conc. of SO_2 ($\mu g\ m^{-3}$)	X Coordinate	Y Coordinate
1	230	771550	3250760
2	205	772050	3250260
3	192	772050	3250760
4	184	771550	3250260
5	176	771592	3251120
6	174	772550	3249760
7	173	772050	3249760
8	172	772550	3250260
9	172	772952	3250120
10	171	771592	3250120

Table 4.22:The highest ten values of annual average NOx predicted concentrations for 2001

No:	Conc. of NOx ($\mu g\ m^{-3}$)	X Coordinate	Y Coordinate
1	19.41	771550	3250760
2	17.43	772050	3250260
3	16.51	772050	3250760
4	15.54	771550	3250260
5	14.94	772550	3250260
6	14.92	772550	3249760
7	14.90	771592	3251120
8	14.85	772592	3250120
9	14.71	772050	3249760
10	14.47	771592	3250120

There is no record of predicted concentrations exceeding the K-EPA limits when documented on an annual basis, so there is no area in excess of the standards in 2001. These coordinates are very close to the Doha and Subyia power stations, with distances of less than 6 km away in the SE direction (Figure 4.31).

The highest ten percent of predicted annual ground level SO_2 concentrations in 2004 are presented in Table (4.23). The maximum value was 276.4 μg m^{-3}, with coordinates of X-axis 771550 and Y-axis 3250760, at a distance of 1.6 km from the Doha Complex in the SSE direction and 44.9 from the Subyia station in the SW direction. The second highest annual value was 248.1 μg m^{-3}, with coordinates of X-axis 771702 and Y-axis 3251020, at a distance of 1.2 km from the Doha Complex in the SE direction and 44.6 km from the Subyia station in the SW direction. The third highest value was 226.6 μg m^{-3}, with coordinates of X-axis 772050 and Y-axis 3250760, at 1.8 km SE of the Doha Complex and 44.5 km SW of the Subyia station. The total area that exceeded the K-EPA limit of 80 μg m^{-3} was 7.1 km^2. The coordinates of the highest annual values were located southeast of both power stations in desert areas very close to the Doha and Subyia power stations, within a 6 km radius of these locations (Figure 4.34).

However, Table (4.24) shows the annual outcome from the model as predicted for 2004, where the maximum annual concentrations of NOx remained restricted below 100 μg m^{-3}. The highest value was 23.5 μg m^{-3}, with coordinates of X-axis 771550 and Y-axis 3250760, at a distance of 1.6 km from the Doha Complex in the SSE direction and 44.9 km from the Subyia station in the SW direction. The next highest value was 21.4 μg m^{-3}, with equivalent coordinates of X-axis 772050 and Y-axis 3250760, at a distance of 1.8 km SE of the Doha Complex and 44.5 km SW of the Subyia station. This was followed by 19.7 μg m^{-3}, with the equivalent coordinates of X-axis 771593 and Y-axis 3251121, located at 1.1 km SE of the Doha Complex and 44.5 km SW of the Subyia station. There is no record of any area exceeding the K-EPA limits as documented on an annual basis. In the case of NOx, these coordinates relate to areas that very close to the Doha and Subyia power stations, within 6 km in the SE direction (Figure 4.37).

Table 4.23: The ten highest annual average values of SO_2 predicted concentrations for 2004

No:	Conc. of SO_2 ($\mu g\ m^{-3}$)	X Coordinate	Y Coordinate
1	276.4	771550	3250760
2	248.1	771702	3251020
3	226.6	772050	3250760
4	224.5	772050	3250260
5	218.9	771550	3250260
6	201.4	771550	3251260
7	193.6	772050	3251260
8	177.4	771050	3250760
9	160.67	771702	3250020
10	152.98	772550	3250260

Table 4.24:The ten highest annual average values of NOx predicted concentrations for 2004

No:	Conc. of NOx ($\mu g\ m^{-3}$)	X Coordinate	Y Coordinate
1	23.5	771550	3250760
2	21.4	772050	3250760
3	19.7	771593	3251121
4	19.3	772050	3250260
5	17.8	771550	3250260
6	16.6	772050	3251260
7	14.7	771550	3251260
8	14.6	771050	3250760
9	14.2	771593	3250121
10	13.1	772550	3250260

4.7.5: Isopleth's figures for the predicted maximum hourly, daily and annually average ground level concentrations of SO_2 and NOx ($\mu g\ m^{-3}$)

Isopleth's plots (contours) were generated to show the hourly, daily, and annual average ground level predicted concentrations of SO_2 and NOx from the Doha and Subyia power stations in northwest Kuwait for the years 2001 and 2004. These plots describe the spatial distribution of hourly, daily, and annual maximum predicted ground level concentrations of SO_2 and NOx, respectively, from the two existing power stations in Kuwait.

Figure (4.26) presents the isopleth plot of predicted hourly ground level SO_2 concentrations, with 2378.1 km^2 of the area violating the K-EPA standards for predicted average hourly SO_2 in 2001 from both power stations; this represents about 99.1% of the total mesh area (2400 km^2). The maximum predicted hourly concentration in this contour was 4421 $\mu g\ m^{-3}$, observed at 4:00 am on the 3rd of August at receptor coordinate of X-axis 772592 and Y-axis 3252120, at a distance of 1.7 km east of the Doha Complex. It is clear from the hourly plot that the violation resulted from both power stations and covered most of the mesh area, so it is confirmed that the hourly standard specified by K-EPA is exceeded.

As is clear from Figure (4.27), the total area that violated the K-EPA limits for predicted average daily SO_2 in 2001 from both power stations is equal to 395.8 km^2, which in about 16.5% of the total mesh area (2400 km^2). The highest predicted daily ground level concentration of SO_2 was 931 $\mu g\ m^{-3}$, measured on July 9th of 2001 at a receptor with coordinates of X-axis 771550 and Y-axis 3250760, at 1.6 km SE of the Doha Complex. The predicted daily K-EPA limit for SO_2 is 157 $\mu g\ m^{-3}$. Therefore, the Rabia residential area, with its maximum predicted concentration of 100 $\mu g\ m^{-3}$, is at a safe distance away from the influence of the Doha and Subyia stations. In the case of the Subyia power station, some predicted high concentrations exceeded the K-EPA limits, but were in areas evenly distributed over the bay of Kuwait.

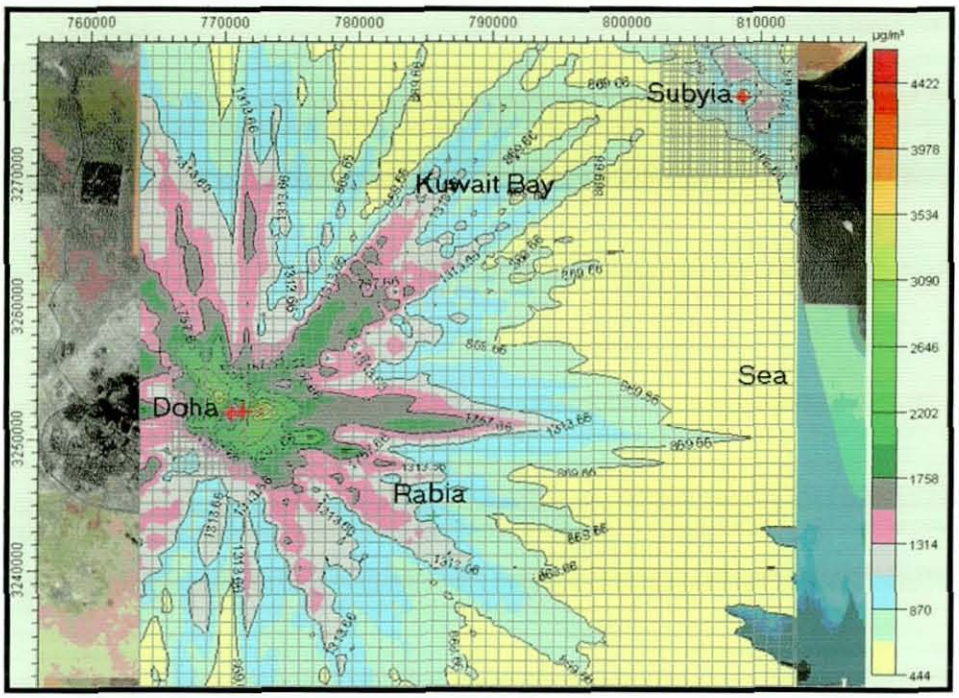

Figure 4.26: Isopleth plot for maximum hourly average ground level predicted concentrations of SO_2 ($\mu g\ m^{-3}$) for 2001

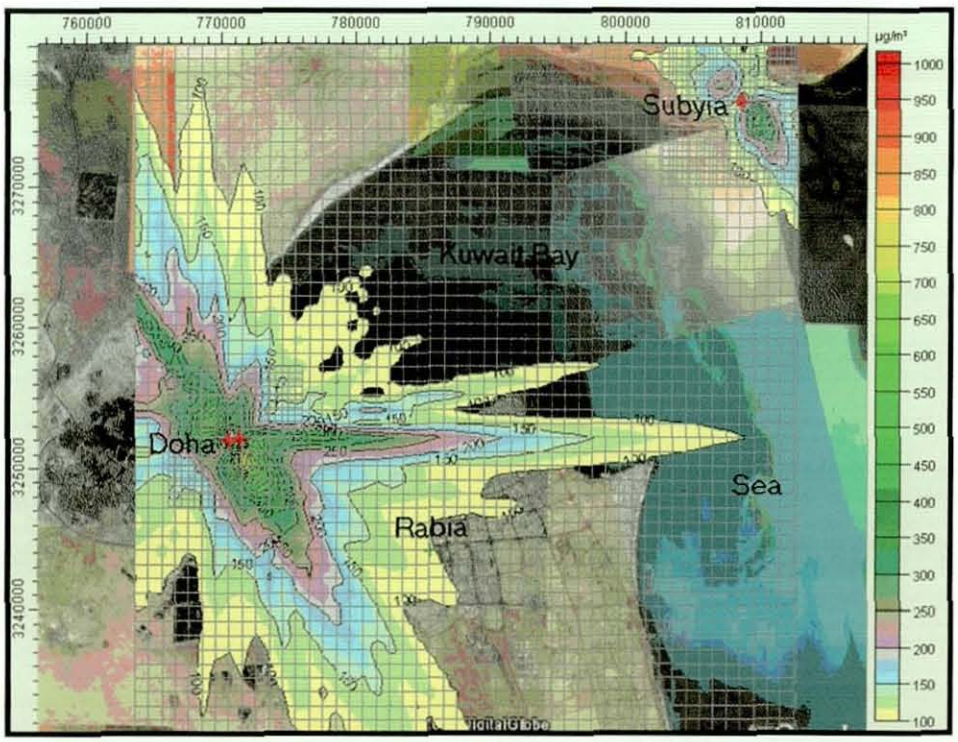

Figure 4.27: Isopleth plot for the maximum daily average ground level predicted concentrations of SO_2 ($\mu g\ m^{-3}$) for 2001.

In addition, Figure (4.28) shows that the isopleth plot of the annual area in violation of standards, based on predicted SO_2 in 2001, is about 11.5 km^2; these values in excess of the limits thus represent only 0.5% of the total area under study. The maximum annual predicted value was 230 $\mu g\ m^{-3}$, with coordinates of X-axis 771550 and Y-axis 3250760, at a distance of 1.6 km from the Doha Complex in the SSE direction. However, as is shown in Figure (4.28), this area includes the Doha residential area at a distance of 6.5 km SE of the Doha power station. Annual predicted concentration levels reached 80-120 $\mu g\ m^{-3}$ in this residential area (represented by the light blue colour band). High predicted concentrations of up to 200 $\mu g\ m^{-3}$ have been observed in the uninhabited area between the Doha power station and Doha residential area. For the Subyia station, the excess pollutant concentration is distributed over the sea. However, it is clear from Figure (4.28) that the metrological conditions (wind direction-NW) represent the primary factor affecting the distribution of pollutants from the sources.

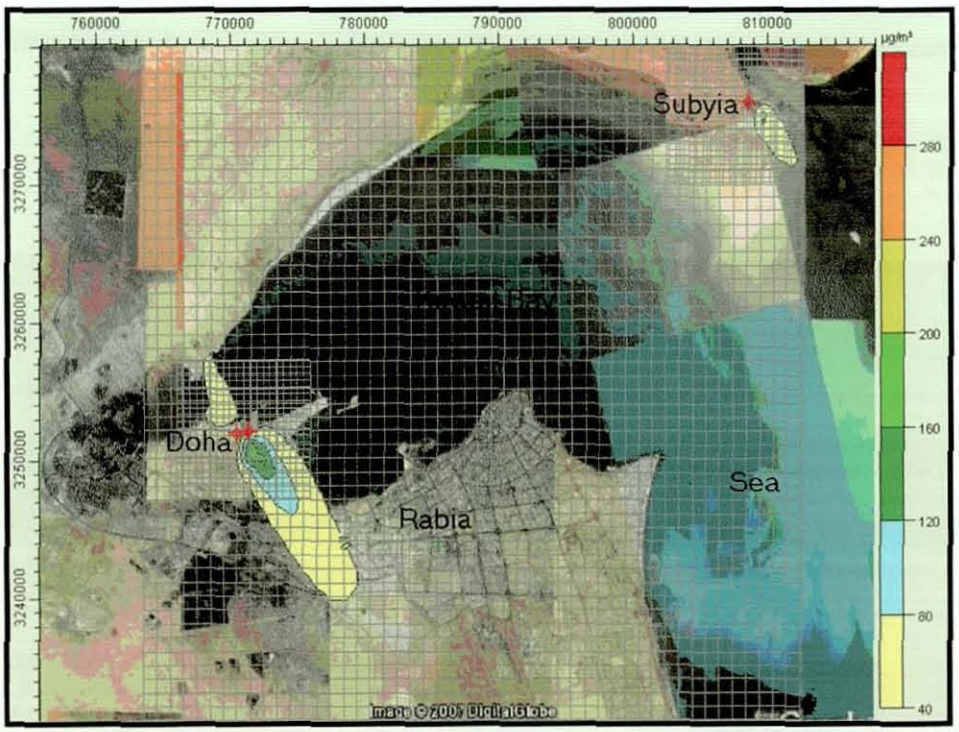

Figure 4.28: Isopleth plot for maximum annual average ground level predicted concentrations of SO_2 ($\mu g\ m^{-3}$) for 2001.

Figures (4.29), (4.30), and (4.31) present the isopleths of NOx in hourly, daily and annual predicted values from the ICSCT4.5 model for 2001. There is no violation that exceeds the standard limits in the hourly case, for which the maximum predicted concentration of 421 μg m^{-3} was measured at 4:00 am on August 3rd, with coordinates of X-axis 772592 and Y-axis 3252120. The maximum daily predicted concentration, also below limits, was 79 μg m^{-3} on the 9th of July, with coordinates of X-axis 771550 and Y-axis 3250760. The highest mean annual predicted concentration was 19.41 μg m^{-3}, with coordinates of X-axis 771550 and Y-axis = 3250760. The set K-EPA NOx limit on the hourly scale is 450 μg m^{-3}, on the daily scale is 224 μg m^{-3}, and on the annual scale is 134 μg m^{-3}. The predicted high concentrations surround the Doha power station, dropping off quickly with increasing distance from the source and reaching a safe hourly and daily mean concentration of 100 μg m^{-3} and 10 μg m^{-3} at Rabia, respectively. For the Subyia power station, the pollution is distributed over the sea.

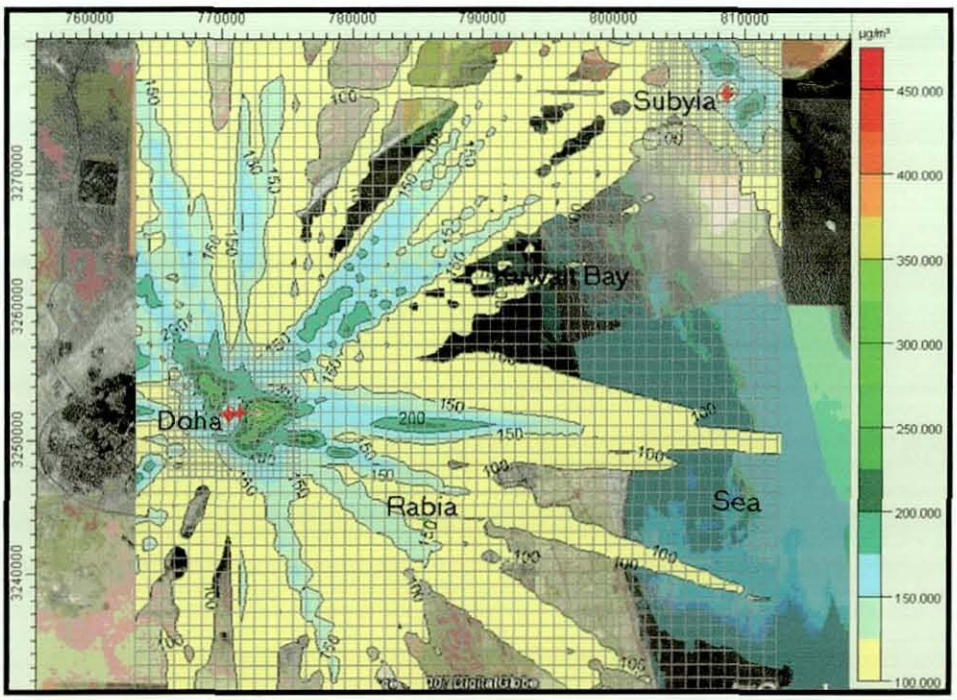

Figure 4.29: Isopleth plot for the maximum hourly average ground level predicted concentrations of NOx (μg m^{-3}) for 2001

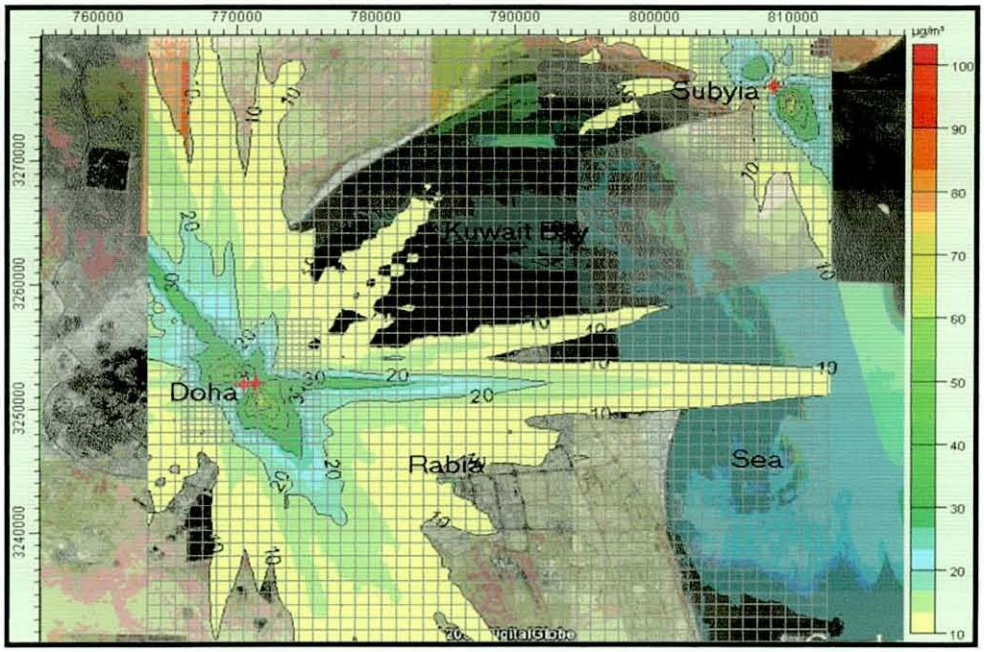

Figure 4.30: Isopleth plot for the maximum daily average ground level predicted concentrations of NOx ($\mu g\ m^{-3}$) for 2001

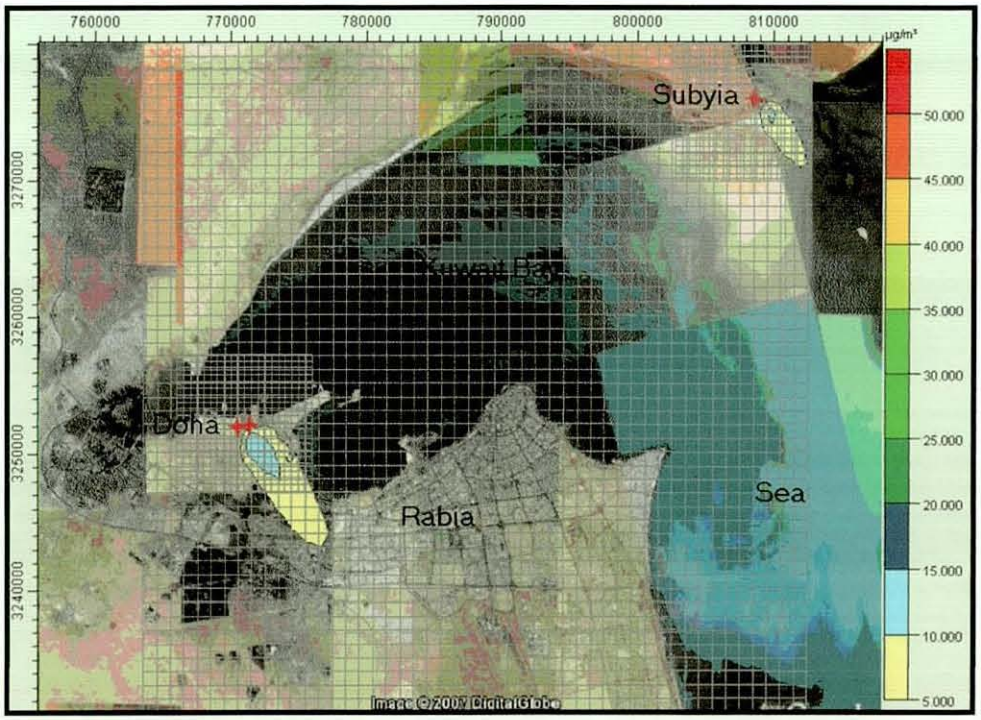

Figure 4.31: Isopleth plot for the maximum annual average ground level predicted concentrations of NOx ($\mu g\ m^{-3}$) for 2001

The isopleth plot in Figure (4.32) shows the highest predicted hourly ground level concentration of SO_2 with 100% of the total mesh area exceeding the K-EPA standards limit for average hourly predicted SO_2 in 2004 from both power stations (2400 km^2). The maximum predicted hourly concentration in this isopleths was 3436.4 $\mu g\ m^{-3}$, observed at 12:00 pm on August 2nd, with coordinates of X-axis 768702 and Y-axis 251020, located 3.5 km SE of the Doha station. In addition, it is clear from the hourly isopleth plot that the concentrations throughout the entire selected mesh area exceed the hourly standard specified by K-EPA.

As shown in Figure (4.33), the total violated area exceeding the K-EPA limits for average daily predicted SO_2 in 2004 from both power stations is 978.7 km^2, which is about 40.8% of the total 2400 km^2 area under consideration. The maximum predicted daily ground level concentration of SO_2 was 1224.7 $\mu g\ m^{-3}$, observed on the 26th of June at 1.4 km SE of the Doha station, with coordinates of X-axis 771550 and Y-axis 3250760. However, the Rabia residential area is among the locations subject to the pollution influence from the Doha and Subyia power stations, with maximum values between 150-250 $\mu g\ m^{-3}$. In the case of the Subyia power station, the predicted high concentration exceeded the K-EPA limits, but the pollution was evenly distributed over the sea and the bay of Kuwait.

Figure (4.34) shows that the isopleths plot of the annual violated area of predicted SO_2 in year 2004 was 7.1 km^2; this means areas in excess of the annual limits represented only 0.3% of the total area under study. The maximum annual predicted value was 276.4 $\mu g\ m^{-3}$, with coordinates of X-axis 771550 and Y-axis 3250760, at a distance of 1.6 km from the Doha Complex. However, as is shown in Figure (4.29) the violated area covers an uninhabited desert area between the Doha power station and Doha residential area; the annual predicted concentration levels in this area reached 80-100 $\mu g\ m^{-3}$ (represented by the light green colour band).

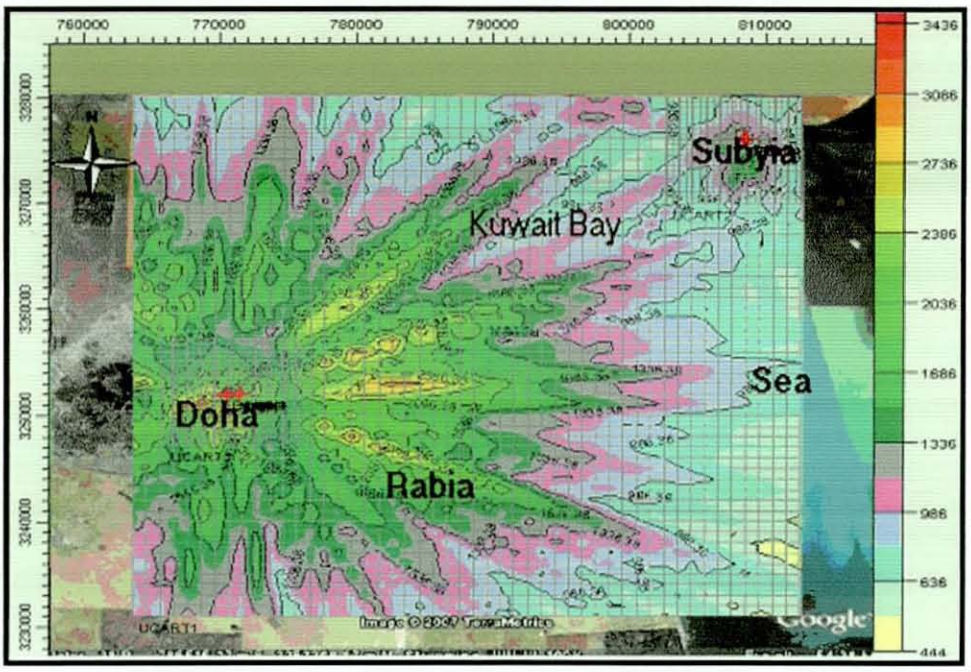

Figure 4.32: Isopleth plot for the maximum hourly average ground level predicted concentrations of SO_2 ($\mu g\ m^{-3}$) for 2004

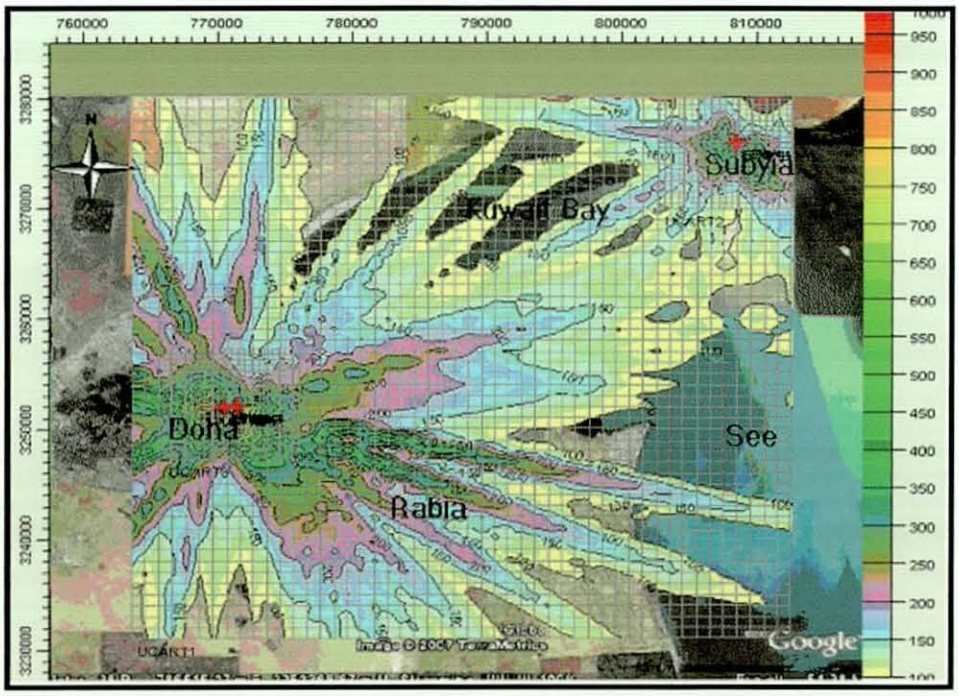

Figure 4.33: Isopleth plot for the maximum daily average ground level predicted concentrations of SO_2 ($\mu g\ m^{-3}$) for 2004

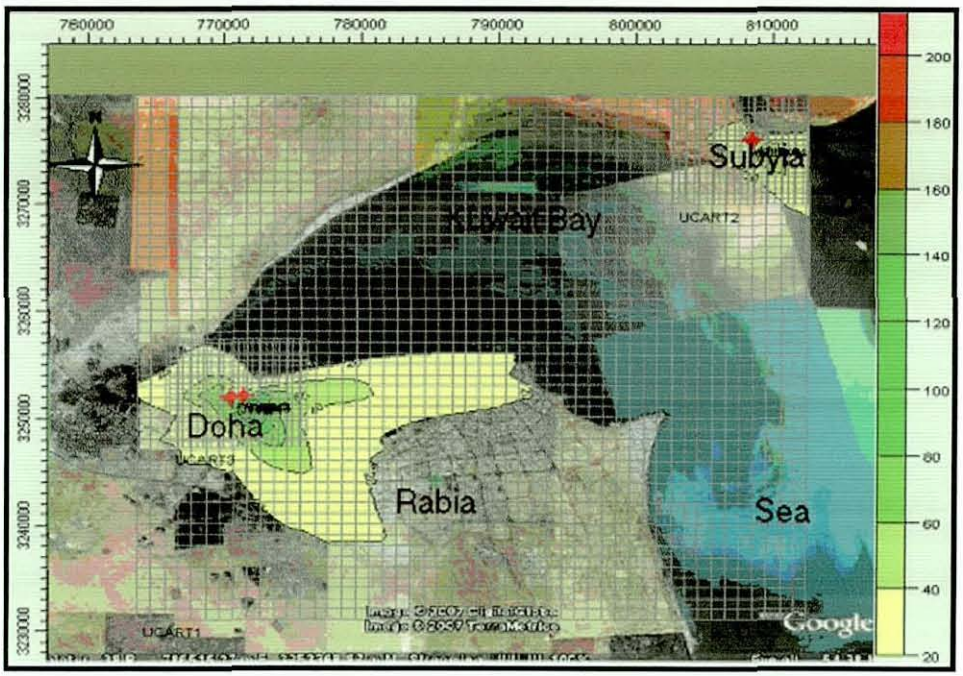

Figure 4.34: Isopleth plot for the maximum annually average ground level predicted concentrations of SO_2 ($\mu g\ m^{-3}$) for 2004

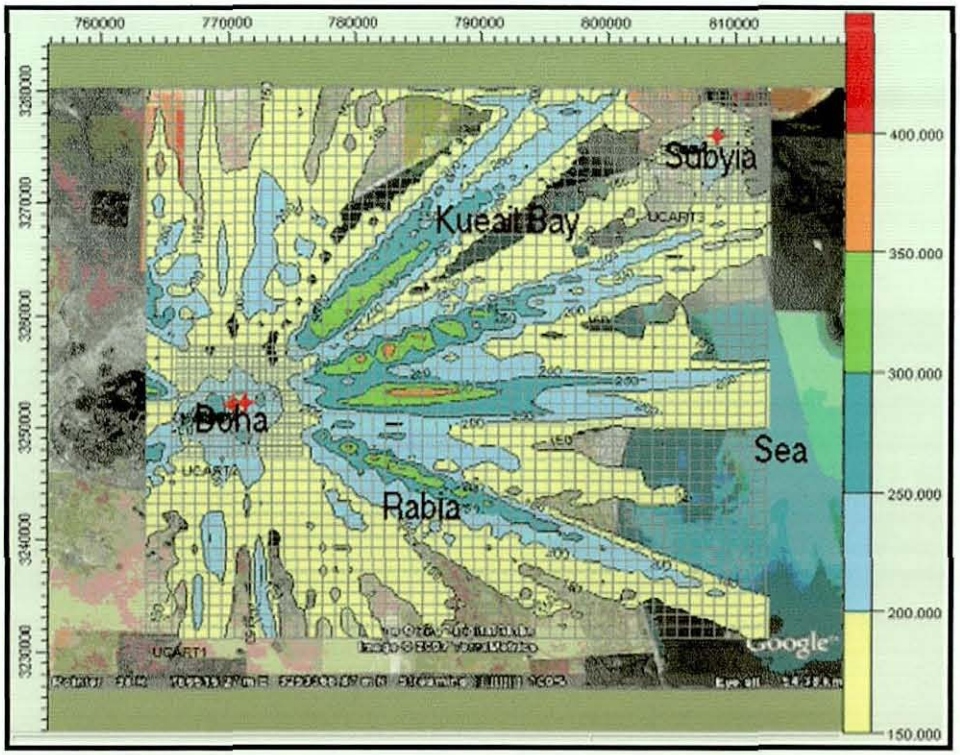

Figure 4.35: Isopleth plot for the maximum hourly average ground level predicted concentrations of NOx ($\mu g\ m^{-3}$) for 2004

Figures (4.35), (4.36) and (4.37) present the isopleths of NOx in hourly, daily and annual predicted values, respectively, generated by the ICSCT4.5 model for 2004. There are no violations that exceed the standard limits of K-EPA in the hourly case, with the maximum predicted concentration of 395.3 $\mu g\ m^{-3}$ observed on the 18th at 5:00 am, at 10.4 km distance from the Doha power station in the ENE direction and 36.5 km from the Subyia station in the SW direction. The coordinates of the maximum concentration was 780593 in X-axis and 3256121 in Y-axis; this location is located in the sea. The predicted hourly concentration reaching our area of interest (Rabia) is between 200-250 $\mu g\ m^{-3}$. There is also no violated area when considered on a predicted daily concentration basis; the maximum daily value was 109.5 $\mu g\ m^{-3}$, observed on June 26th at a distance of 1.4 km SE of the Doha Complex, with coordinates of X-axis 771550 and Y-axis 3250760. The daily predicted concentration reaching the Rabia area is between 20-30 $\mu g\ m^{-3}$. There is also no violation of limits based on annual predicted concentration values, with the highest concentration of 23.5 $\mu g\ m^{-3}$ having coordinates of X-axis 771550 and Y-axis 3250760. The predicted high concentrations are very near the Doha power station, at a distance of 1.6 km in the SE direction. In case of predicted annual concentrations, no significant pollution reached the considered Rabia area, but concentrations of 5 to 15 $\mu g\ m^{-3}$ are reached in the Doha residential area. As shown in the isopleths plots, the annual distribution over the selected mesh area from both power stations is toward the SE direction, which is in the same direction as the wind. The distributions of pollutants drop quickly as the distance from the source increases.

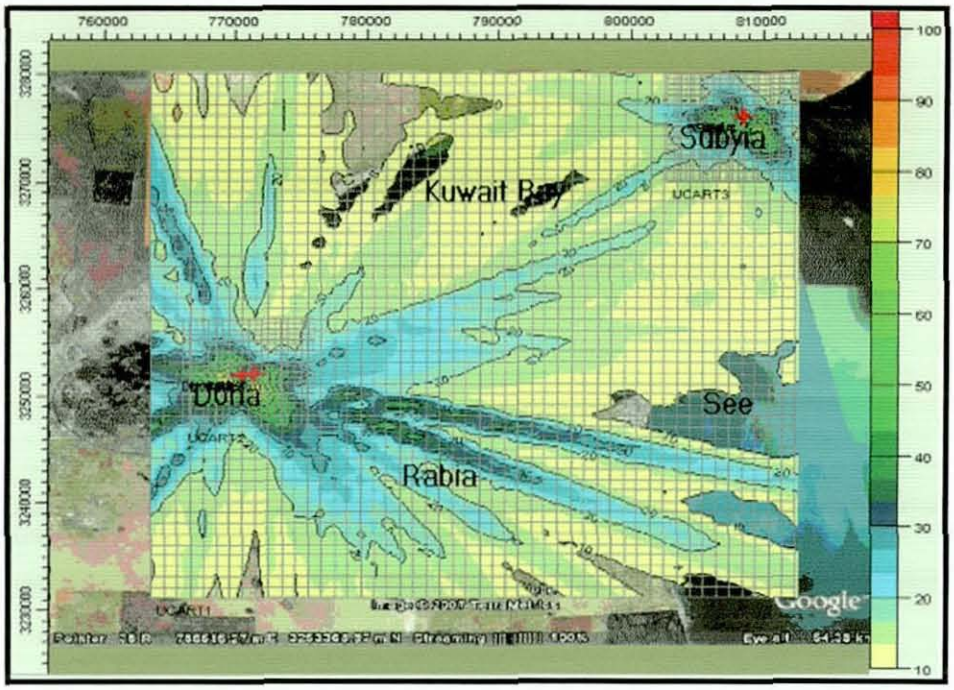

Figure 4.36: Isopleth plot for the maximum daily average ground level predicted concentrations of NOx ($\mu g\ m^{-3}$) for 2004

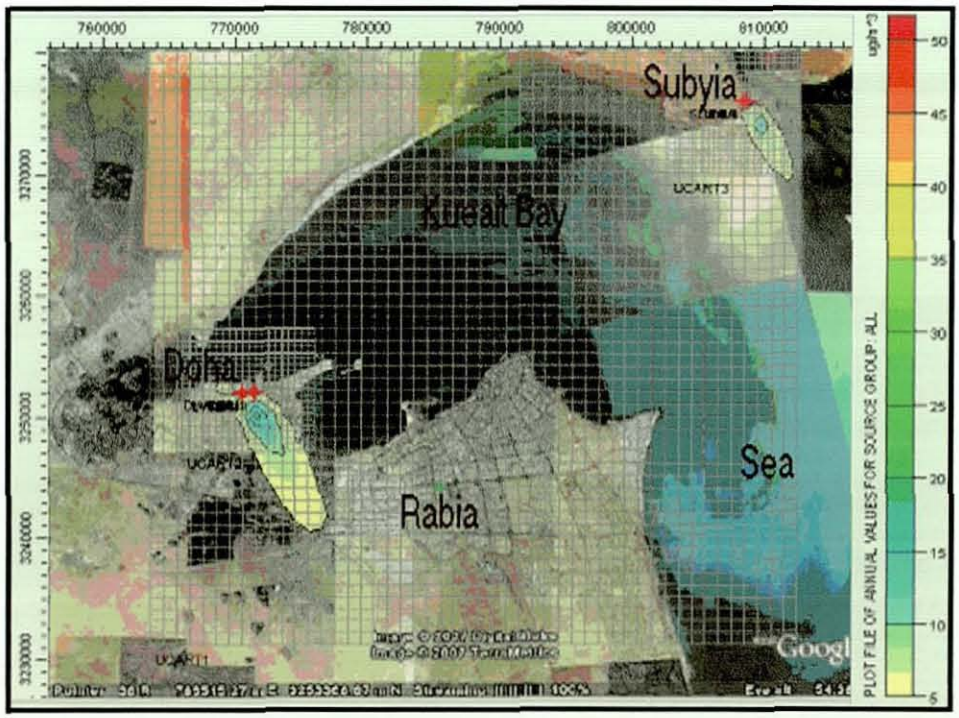

Figure 4.37: Isopleth plot for the maximum annually average ground level predicted concentrations of NOx ($\mu g\ m^{-3}$) for 2004

4.8: Conclusions

The Industrial Sources Complex for Short–Term (ISCST4.5) was used in this research as a mathematical model; this system is widely used in air pollution studies under existing meteorological conditions, to analyze the dispersion of sulphur dioxide (SO_2) and nitrogen oxide (NOx) released from the two existing power plants in Kuwait.

Two different grid receptors were used in the calculations of the ISCST4.5 model. These receptors are the discrete Cartesian receptor and the uniform grid receptors. The use of discrete Cartesian receptors is to evaluate the ISCST4.5 model and to investigate the air quality over the study areas; the uniform grid receptors are used to produce an overview of the spatial distribution of SO_2 and NOx predicted concentrations over the study area.

The hourly meteorological conditions used in this research were obtained from the Kuwait Environmental Protection Authority (K-EPA) for years 2001 and 2004. In addition, the emissions inventory data and the topographical data were used together with metrological data to predict the hourly, daily and the annual maximum average ground level concentrations of SO_2 and NOx.

The highest predicted hourly and daily concentrations were recorded in the summer season between June and September, with maximum values observed in the month of August. This agreed with our observations that the power stations work at full capacity during the summer to cover the increased demand for electricity and water desalination.

Most of the highest predicted hourly and daily values for each month occurred in the early morning. In addition, the location of most of the highest values are very close to the sources, at less than 2 km SE of the Doha power station and 2 km SW of the Subyia power station.

The hourly isopleths plots of SO_2 show that 2378.1 km^2 of the selected area exceeds the K-EPA standards limit for the average hourly predicted SO_2 in 2001 from pollution from both power stations; this is about 99.1% of the total selected mesh area (2400 km^2). The total area in violation of the K-EPA limits for average daily predicted SO_2 in 2001 due to pollution from both power stations is equal to 395.8 km^2, which is about 16.5% of the total selected mesh. The total area in violation for the annual predicted SO_2 in 2001 is about 11.5 km^2, meaning that areas in excess of the limit represented only 0.5% of the total area under study.

The area with the K-EPA standards violations for average hourly predicted SO_2 in 2004 due to pollution from both power stations is equal to 2400 km^2, which is 100% of the total mesh area (2400 km^2). The total area exceeded the K-EPA limits for average daily predicted SO_2 in 2004 from both power stations is 978.7 km^2, which is about 40.8% of the total area under consideration. The total area in violation of K-EPA limits for annual predicted SO_2 in 2004 was 7.1 km^2, meaning that areas in excess of the standard represented only 0.3% of the total area under study.

There is no area where predicted NOx exceeded the standards of the K-EPA in hourly, daily or annual predicted concentrations as a result of the Doha and Subyia power stations for either 2001 or 2004.

It was concluded that hourly SO_2 predicted concentrations have large areas subject to excess pollution from the Doha Power plant, including many residential and urban communities, for both years. Daily and annual mean predicted SO_2 concentrations had exceedances in only 16.5% and 0.5% of the total investigated area for 2001, respectively. For 2004, the daily and annual mean predicted SO_2 concentrations had exceedances in only 40% and 0.3% of the study areas, respectively.

The model results have been compared with the values observed at the Kuwait EPA air quality monitoring station at Rabia, which was used as t as a discrete receptor to validate the model. Comparing top fifty daily average values of predicted and measured SO_2 concentrations yielded a slope of 0.81 for 2001. For 2004, the slope value was 0.96, representing a more accurate prediction the previous run in 2001.

The slope of the daily predicted ground level concentration of NOx compared against observed values was equal to 0.55 for 2001 and 0.76 for 2004, which represents 48% and 29% under-prediction, respectively.

Chapter 5
Comparison and Evaluation of the Impacts of SO_2 and NOx Emissions from Kuwait Power Stations on Air Quality in 2001 and 2004

5.1: Introduction

In this chapter, the Industrial Source Complex Short Term (ISCST4.5) dispersion model is used to compare and evaluate the impacts of SO_2 and NOx emitted from Kuwait power stations. Locally produced heavy fuel oil used in Kuwait for power generation contains about 4% sulphur. Therefore, increased use of heavy fuel oil in Kuwait is a major source of SO_2 emissions. However, to predict the effects of continuously increasing use of electricity in Kuwait, the ISCST4.5 model (U.S. EPA, 1995) was used in this study. In conjunction with the SO_2 emissions, we also modelled NOx distribution and compared our results with previously published data of Al-Rashidi *et al.* (2005), whose study investigated the efficiency of existing stations that monitor the levels of SO_2 in the state of Kuwait.

Comprehensive emission inventories were prepared for Kuwait's main power stations located at Al-Doha and Al-Subyia in 2001 and 2004. These inventories were inserted, in conjunction with meteorological data, into the Source Complex model for Short Term Dispersion (ISCST4.5) to predict ambient ground level concentrations of sulphur dioxide (SO_2) and nitrogen oxides (NOx) at selected receptors for the years 2001 and 2004.

The presented simulations are based on three super-imposed uniform Cartesian grids with coinciding centres representing the sources (stations) of interest. The selected mesh area covers 2400 km^2 in addition to the Rabia area. The sole sources of emissions for sulphur dioxide and nitrogen oxides are assumed to be the main power stations in Kuwait, though there are also a variety of lesser

sources. The first mesh area covers an area of 49 km x 49 km with a grid spacing of 1 km consisting of 2500 grid points as receptors. The second and third uniform mesh areas each represent 10 km x 10 km sections with a grid spacing of 0.5 km and 441 grid points as receptors. The total grid points covered all three mesh areas, with a total area of 3382 km^2.

The essential input requirements for dispersion modelling are: (i) the source information, consisting of the locations, height, emission rate, inner diameter (at the exit point), and gas temperature (at the exit point) of the stack; (ii) the receptor information, consisting of the location and the distance from source; and (iii) the meteorological data, consisting of the wind speed and direction, temperature, inversion layer, mixing height and stability class. Stability class is a category index that uses cloud cover and wind speed, and it is ranging from 1, referring to extremely unstable, to 6, indicating very stable conditions (Turner, 1970).

In the present study, we used the short term version ISCST 4.5 to obtain temporal and spatial ground-level concentrations of SO_2 and NOx as indicators for the deterioration of air quality. Most of the previously published studies (e.g., see Al-Sudairawi and Mackay, 1988 and Abdul-Wahab *et al.*, 1999) have used different versions of the ISCST model. Where appropriate, we compared our predicted results from different years.

5.2: Description of Power Stations

In this study, the influence of different pollutants emitted continuously from the Doha and Subyia power stations at neighbouring residential areas was investigated in depth. Sulphur dioxide (SO_2) and nitrogen oxide (NOx) emissions from power stations are major contributors to air pollution in many parts of the world. Sulphur dioxide emissions result from the combustion of sulphur containing fossil fuels used in power generation. Kuwait is an arid desert with a harsh summer that lasts almost half the year. From July to September,

temperatures can reach 50°C in the daytime. The climatic conditions, combined with the rapid urbanization seen in recent years, pose a real challenge for air conditioning and refrigeration industries in Kuwait and put a very heavy load on its power generation and infrastructure. It is important to note that per capita energy consumption in Kuwait has increased during the last decade.

Boilers with steam turbines with a capacity of 300 MWH were considered in each power station. The Doha power generating facilities were composed of two thermal power stations. The power station on the east had eight boilers of 2400 MW capacity and two chimneys with four stacks each (Figure 5.1). The stack height was 196 m, the exit diameter was 3.5 m, and the exit velocity of the gas was approximately 29.4 m s^{-1} at 408K. The second thermal power station was located to the west and consisted of seven boilers with a 2100 MW capacity and two chimneys with seven stacks (Figure 5.2). The stack height was 190 m, the exit diameter was 4.3 m, and the exit velocity of the gas was 29.4 m s^{-1} at 403K. Therefore, the Doha complex has a total of fifteen stacks in four chimneys. The Subyia power station has the same capacity (2400 MW) as the Doha station had eight stacks in two chimneys. The stack height was 192 m, the exit diameter was 4.3 m, and the exit velocity of the gas was 28.8 m s^{-1} at 426K. The power stations operate on a different type of fossil fuel with a sulphur content (*SC*) of 1%, 2.5% and 4% by weight.

The Doha residential area is the closest residential area in the immediate neighbourhood of the Doha complex at a distance of 6 km, while the Sulaibikhat residential area is located 8 km from the south-eastern direction of the Doha complex. The Subyia power station is about 25.4 km from Kuwait city in the north-eastern direction. There is a continuous air quality monitoring station in the Rabia residential area that is about 16.5 km from Doha East, 17.1 km from Doha West and about 39.4 km from the Subyia power station. However, the emissions from these power stations mainly result from the burning of fossil fuels that discharge various pollutants into the atmosphere. Sulphur is prevalent in most types of fossil fuels, which are used for power generation and result in the release

of large quantities of sulphur dioxide into the atmosphere. SO_2 and NOx are further oxidised and are deposited through either wet or dry processes resulting in sulphuric and nitric acids or sulphate and nitrate particulates. All of these substances are harmful to various life forms, particularly humans, and to the environment. Power stations in Kuwait use four different types of fossil fuels, all of which contain varying amounts of sulphur. The emissions from the power plants include SO_2 and NOx, which are transformed to acid rain or dry deposition and particulate matter in the form of ash.

The fuel used in the power stations is provided by the Kuwait Oil Company (KOC) and consists mainly of gas oil, crude oil, and heavy oil. The total sulphur contents by weight in these fuels are 1, 2.5, and 4%, respectively. However, the Ministry of Electricity and Water (MEW, 2002) typically uses the heavy fuel oil that contains high sulphur contents. Al-Rashidi *et al.* (2005) presented the emission rate of SO_2 as a function of fuel consumption and sulphur content of the fuel.

In order to establish the SO_2 and NOx emissions to input into the ISCST model, the SO_2 and NOx emissions rates were calculated for each boiler stack. The total emission rates were divided by the number of stacks to obtain the emission rate per stack (boiler) for each station. Therefore, the actual emission rate for each stack (the source) was multiplied by the emission factor for the variation in the monthly emission rate. The ISCST4.5 model requires meteorological data to be used on an hourly basis for the entire year.

Figure 5.1: Doha power station (www.Google Earth.com).

Figure 5.2: Subyia power station (www.Google Earth.com).

5.3: Results and Discussion

The US EPA approved dispersion model was applied to assess the impacts of the power sources located to the north of the urban areas. Year-long emission inventories of major pollutants (sulphur oxides and nitrogen oxide) were prepared based on daily fuel consumption. Meteorological data for 2001 and 2004 were obtained from civil aviation authorities at the Kuwait Public Authority and the Kuwait Airport. However, the comprehensive emission inventories for 2001 and 2004 for Kuwait's main power stations located at Al-Doha and Al-Subyia have been prepared. These inventories are inserted, in conjunction with meteorological data, into the Source Complex model for Short Term Dispersion (ISCST4.5) to predict ambient ground level concentrations of sulphur dioxide (SO_2) and nitrogen oxides (NOx) at selected receptors for years 2001 and 2004. To run the model, steady state conditions were assumed with equal amounts of SO_2 and NOx emissions from each stack based on monthly emission inventories. There was no provision for flue gas desulphurization units at the Doha and Subyia power stations. In addition, neither dry nor wet plume depletion was used. The Doha power station stack is considered to be a reference for locating the hotspots in the regular grid for predicted ground level concentrations.

The analyses of predicted results from the ISCST4.5 model were divided into four study steps in this chapter. In the first study step, the emission rates were fixed to evaluate the effect of meteorological conditions on the dispersion of pollutant processes. The maximum predicted hourly and daily ground level concentrations were calculated every month at uniform grid receptors for the entire year over the entire study area, using the prevalent meteorological conditions for year 2001 and 2004. For the prevalent values of the pollutants, we used data from the K-EPA. The second study step was to compare hourly, daily and annual predicted ground level concentrations from both power stations with the meteorological conditions for 2001 and 2004. This study compared the five highest hourly, daily and annual ground level concentration values under their prevailing meteorological conditions of 2001 and 2004. The third study step was

to evaluate the exceedance fraction area limit, which is the area that exceeds the standard limits of K-EPA for hourly and daily values of SO_2 and NOx for 2001 and 2004 from both power stations. Finally, in the forth study step, the rose plots concentrations of the highest fifty values of the hourly and daily average predicted concentrations of SO_2 and NOx were generated for 2001 and 2004.

5.3.1: Analysis of Fixed and Real Emission Rates

To evaluate the influence of prevailing yearly meteorological conditions, the emission rate was fixed and the ISCST4.5 model was run for the years 2001 and 2004 for each month independently.

Figure (5.3) presents the highest predicted hourly ground level concentrations of SO_2 ($\mu g\ m^{-3}$) for fixed and real emission rates for 2001 and 2004. Using a fixed emission rate in 2001, the maximum hourly predicted concentrations were found to occur in the winter, with a peak monthly value of 2926 $\mu g\ m^{-3}$ (on the 8th of January at 3:00 am, at a distance of 1.3 km SE from the Doha Complex and 42.1 km SW of the Subyia station). The corresponding temperature, relative humidity and wind speed were 16.3°C, 99.7%, and 1.1 m s^{-1}, respectively. However, the lowest predicted value of 1428.4 $\mu g\ m^{-3}$ was recorded in the summer months on the 2nd of August at 4:00 am.

In case of real emission rates for 2001, Figure (5.3) shows that the maximum predicted concentration of 4421 $\mu g\ m^{-3}$ was observed in the summer (observed on the 3rd of August at 4:00 am, 1.7 km E of the Doha Complex and 43.1 km SW of the Subyia station). The corresponding temperature, relative humidity and wind speed were 37.5°C, 49.4% and 1.6 m s^{-1}, respectively. However, the lowest predicted concentration observed in real emissions was observed in the winter on January 24th (9:00 am) with a value of 1028.6 $\mu g\ m^{-3}$.

In addition, for the fixed emission rates the maximum hourly predicted concentrations for 2004 occurred in the winter, and the highest monthly value

was 2342 μg m^{-3}, observed on the 7th of February at 7:00 am, 10.3 km E of the Doha Complex and 35.1 SW of the Subyia station). The corresponding temperature at that time was 10.8°C, the relative humidity was 58.7%, and the wind speed was 2.1 m s^{-1}. The lowest predicted value in 2001 was observed on the 2nd of August at 6:00 am, with a concentration of 1289.8 μg m^{-3}.

For the real emission rates, the maximum hourly predicted concentrations for 2004 also occurred in the summer. The highest predicted ground level concentrations were in August, with a concentration of 3436 μg m^{-3} (predicted on the 2nd of August 2004 at 12:00 pm, 3.5 km SE of the Doha station and 47 km SW of the Subyia station). The temperature recorded at this time was 50°C, the relative humidity was 11.7%, and the wind speed was 4.15 m s^{-1}. However, the lowest concentration in real emissions was 1081.3 μg m^{-3}, observed in the winter on the 13th of January at 6:00 am. The observed results from both emission rates for the maximum hourly predicted concentration levels due to met conditions will be explained in more detail later in this section.

Figure (5.4) shows the highest predicted daily concentrations of SO_2 (μg m^{-3}) for fixed and real emission rates for 2001 and 2004. In the case of fixed emission rates, the maximum daily predicted concentrations were recorded in the months of December, January and February of 2001 with values of 663 μg m^{-3}, 771 μg m^{-3} and 673 μg m^{-3}, respectively. In 2004, the highest predicted concentrations occurred in February, January and December, with values of 863 μg m^{-3}, 831 μg m^{-3} and 780 μg m^{-3}, respectively. These months are in the winter season of the state of Kuwait. The lowest predicted values were observed in August of 2001, with a value of 317.5 μg m^{-3}, and in July of 2004, with a value of 355.2 μg m^{-3} (these months are in Kuwait's summer season).

For real emission rates, the maximum predicted daily concentrations were observed in the summer season for both years. The highest daily ground level predicted concentration in 2001 was recorded in the month of July with concentration of 931 μg m^{-3}, while the second and third highest values for 2001

were 894 μg m^{-3} (observed in August) and 893 μg m^{-3} (observed in September). In 2004, the maximum predicted daily ground level concentration was recorded in June, with a concentration of 1224.7 μg m^{-3}, while the second highest value of 1054.3 μg m^{-3} was observed in July and the third highest value of 1025.5 μg m^{-3} was observed in September. However, the lowest predicted values were 267.3 μg m^{-3} in 2001 (recorded in January) and 277.4 μg m^{-3} in 2004 (recorded in March).

Figures (5.5) and (5.6) present the highest predicted hourly and daily ground level concentrations of NOx (μg m^{-3}) for monthly fixed and real emission rates in 2001 and 2004. In the case of fixed emission rates, it is very clear that the maximum concentrations for both years were recorded in the winter season and the lowest concentrations were in the summer season. Figure (5.5) shows that the highest predicted hourly value for fixed emission rates for 2001 was 234.9 μg m^{-3} on the 12th of January at 7:00 am, at a distance of 2.1 km E of the Doha Complex and 43.8 km SW of the Subyia station. The corresponding temperature at that time was 14.6°C, the relative humidity was 96%, and the wind speed was 0.8 m s^{-1}. The lowest hourly predicted value for 2001 was 138.4 μg m^{-3}, observed on August 6th at 2:00 am. For 2004, the maximum predicted concentration of fixed emission rates was 2744 μg m^{-3}, observed on the 13th of January at 8:00 am at a distance of 11.1 km E of the Doha Complex and 33.8 km WS of the Subyia station.

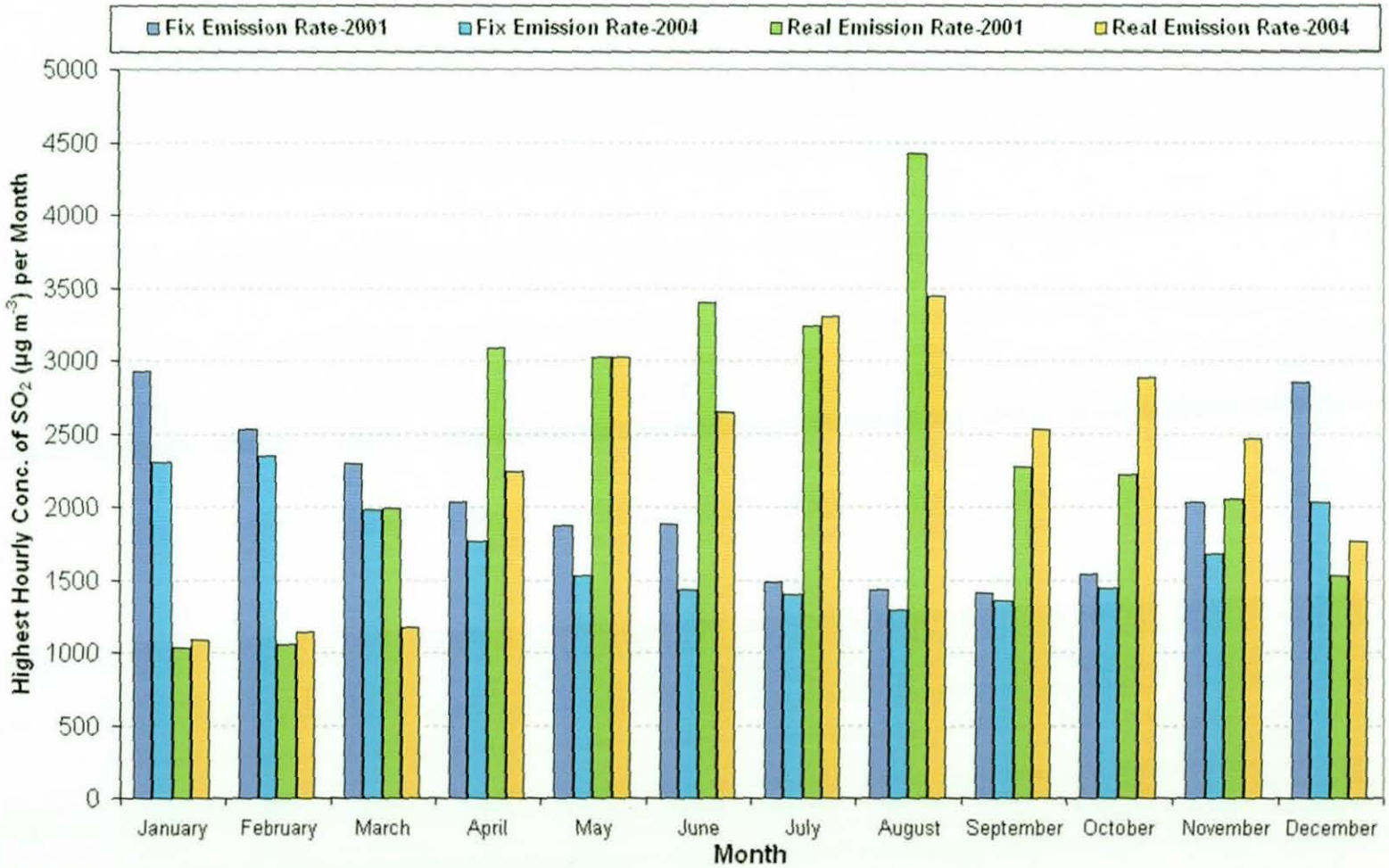

Figure 5.3: The highest predicted hourly concentrations of SO_2 ($\mu g\ m^{-3}$) for fix and real emission rates for 2001 and 2004

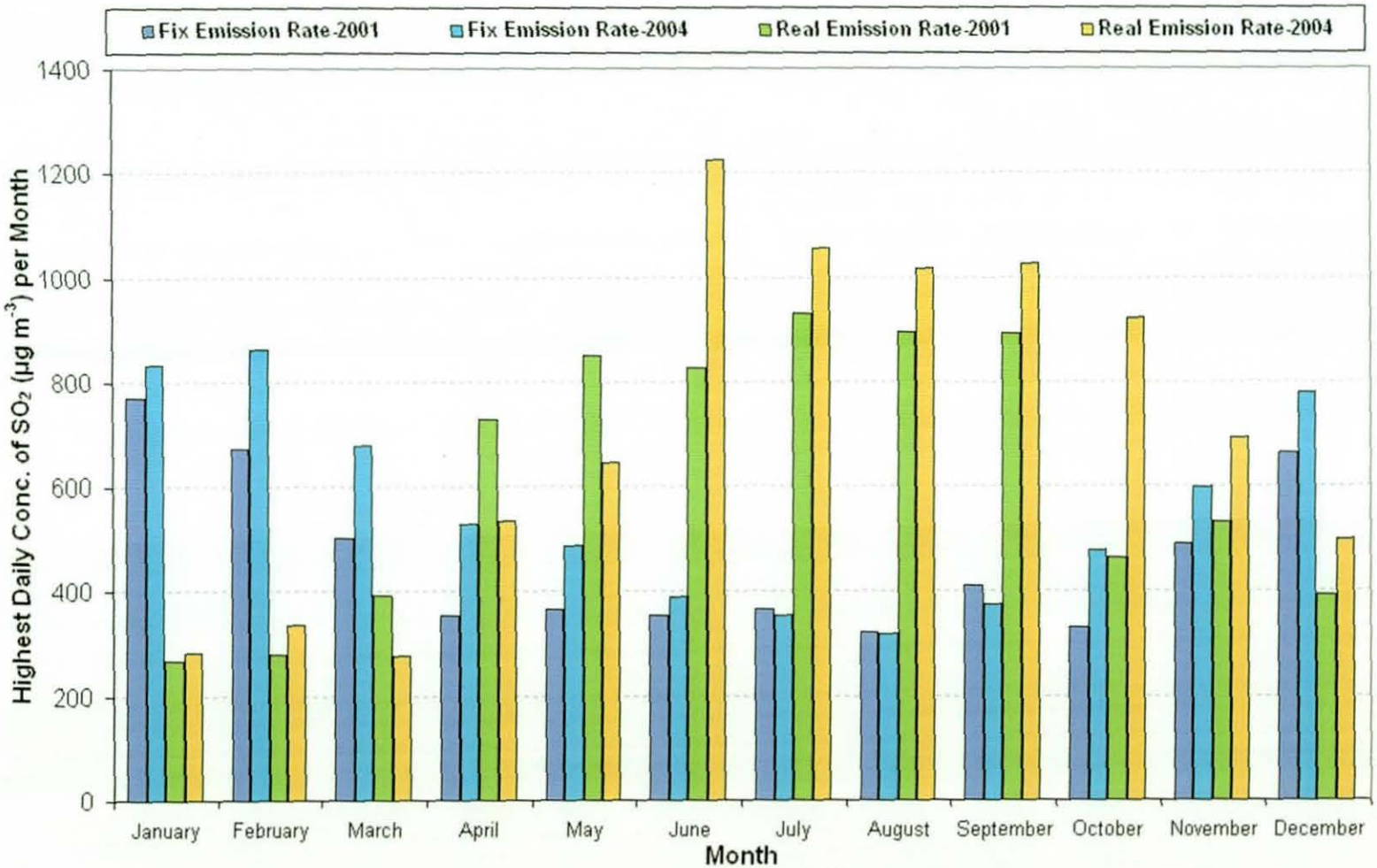

Figure 5.4: The highest predicted daily concentrations of SO_2 ($\mu g\ m^{-3}$) for fix and real emission rates for 2001 and 2004

The corresponding temperature at that time was 18.3°C, the relative humidity was 98.8%, and the wind speed was 1.5 m s^{-1}. In addition, the lowest predicted hourly value for 2004 was 144.2 μg m^{-3}, observed on the 2nd of August at 9:00 am. However, the maximum concentrations for real emission rates in 2001 were recorded in summer months, with highest monthly predicted concentration recorded in the month of August at a value of 421 μg m^{-3} (recorded on August 3rd at 4:00 am, at a distance of 4.5 km ESE from the Doha Complex and 40.6 km SW of the Subyia station). The corresponding temperature at that time was 39.5°C, the relative humidity was 58%, and the wind speed was 1.81 m s^{-1}. The lowest predicted concentration for 2001 in real emission rates was in February, with a concentration of 149 μg m^{-3}, observed on the 15th of February at 3:00 am. The month with the highest concentration in 2004 was July, with a concentration of 395 μg m^{-3} observed on the 18th at 5:00 am 10.4 km ENE of the Doha station and 36.5 km SW of the Subyia station. The corresponding temperature at that time was 34.4°C, the relative humidity was 3.8%, and the wind speed was 1.7 m s^{-1}. However, the lowest predicted concentration in real emissions was 114.2 μg m^{-3}, observed on the 13th of March at 6:00 am.

It is clear from Figure (5.6) that the highest predicted daily concentrations of NOx (μg m^{-3}) for fixed emission rates in both years were recorded in winter seasons while the lowest concentrations were recorded in the summer seasons. In case of fixed emission rates, the maximum daily predicted concentrations were recorded in the months of January, February and March in 2001 with values of 57 μg m^{-3}, 55.1 μg m^{-3} and 47.4 μg m^{-3}, respectively. For 2004, the highest daily predicted concentrations also occurred in January, February and March with values of 67.4 μg m^{-3}, 64.3 μg m^{-3} and 52.6 μg m^{-3}, respectively. These months are in the winter season in the state of Kuwait. The lowest values were recorded in the month of August for both years, with a value of 33.1 μg m^{-3} in 2001 and 34.7 μg m^{-3} in 2004.

For the real emission rates, the maximum predicted daily concentrations were observed in the summer season, while the lowest concentrations were recorded in the winter season for both years. The highest daily ground level concentration for real emission rates was recorded in the month of July, with a concentration of 79 $\mu g\ m^{-3}$, while the second highest value was 75 $\mu g\ m^{-3}$, observed in August, and the third highest value was 71 $\mu g\ m^{-3}$, observed in May 2001. In 2004, the maximum daily ground level concentration was recorded in June, with a concentration of 109.5 $\mu g\ m^{-3}$, while the second highest value was 100. 6$\mu g\ m^{-3}$, recorded in September, and the third highest value was 99.4 $\mu g\ m^{-3}$, recorded in August. However, the lowest predicted values were 28 $\mu g\ m^{-3}$ in 2001 and 30.7 $\mu g\ m^{-3}$ in 2004, recorded in January and February, respectively.

In reality, Kuwait has only two distinct seasons, summer and winter. Summers are dry and harsh, with daytime maximum temperatures reaching approximately 45°C on average. Summer months are almost intolerable without significant air conditioning, which leads to high rates of power consumption. In the summer, winds are turbulent and are predominantly from the north-west. This favours effective pollutant dispersion accompanied with a high inversion layer. Winters are mild and damp, with occasional rains, during which time the temperature can fall to 0°C at night. Wind conditions in the winters are calm and are hence accompanied with a low inversion layer that gives rise to a high pollutant concentration due to low dispersion. As a result, the winters in Kuwait are characterized by low temperatures. In addition, low inversion layers and lower wind movements in the winter adversely affect the dispersion of pollutants as compared to summers in which a high temperature, high inversion layers, high wind movements and effective distribution facilitate the dilution of pollutants. There is no observable change in the wind direction, either diurnally or seasonally for all months.

As expected, meteorological conditions play a pivotal role in pollutant dispersion and affect ground level concentrations of pollutants in residential areas. The meteorological parameters that are expected to affect SO_2 and NOx concentrations are wind speed, wind direction, mixing height, ambient air temperature and the inversion layer. The mixing height is the height above the ground surface where meticulous vertical mixing takes place (Manju *et al.*, 2002).

Wind speed and the concentrations of pollutants from a source are inversely related. The perfect dispersion process of pollutants in the atmosphere was accomplished based on the frequency distribution of wind direction and wind speed (Manju *et al.*, 2002). Therefore, when the wind speed reaches its highest level, it helps to reduce the concentration of any air pollutant and thus serves to reduce its hazardous effects. On the other hand, slow wind or calm conditions can cause a build up of pollutants, resulting in high concentrations in the immediate vicinity of the sources. However, low to medium winds blowing from the direction of power stations towards highly populated residential areas can increase the possibility of pollution, which can eventually affect the health of the local people living within such areas.

These metrological conditions and emission rates were the main cause of the trends shown in Figures (5.3, 5.4, 5.5 and 5.6). However, to examine the influence of meteorological conditions on pollutant concentrations in Kuwait, ISCST4.5 model was executed for fixed emission rates for two years, and the predicted ground level concentrations revealed that the peak values occurred in the early hours of the cold months of winter. The inversion layer due to low temperatures and slow wind speeds reduced the mixing height to a few hundred metres and facilitated the build-up of high concentrations of pollutants. There was an increase in the concentration of pollutants of 48% and 41% in one winter month (January) from summer month (July) for 2001 and 2004, respectively. The lowest predicted ground level concentration of SO_2 was observed in an extremely dry summer month (July) where

the mixing height increased to a few km due to intense temperatures and strong winds with high particulate concentrations. All of these factors facilitated excellent dispersion resulting in low ground level concentrations. As a result, the corresponding meteorological conditions in the winter season (low temperature and a low wind velocity that resulted in a low inversion layer) were considered to be the main factor affecting the dispersion process of pollutants under fixed emission rates.

Also, in case of real emission rates for both years, the evaluated ground level concentrations for major pollutants are a function of the emission rates and prevailing meteorological conditions. Power demand is minimal in the winter in Kuwait, which results in low emissions but adverse meteorological conditions that cause certain values of ground level concentrations. In the summer, the weather is very hostile, and power demand peaks, causing power stations to operate at their maximum capacity to cover the demand of electricity and water desalination at high emission rates. The computed ground level concentration shows that these high emission rates remain regardless of whether the prevalent meteorological parameters (high temperatures, high wind velocities and high inversion layer) are suppressed. There was a 2.5-fold increase in the month of July in predicted concentrations based on emissions in January in the year 2001, while a 2.9-fold increase was observed based on predicted concentrations in 2004. For both cases, the highest concentrations were located near the Doha power station, which is an uninhabited area.

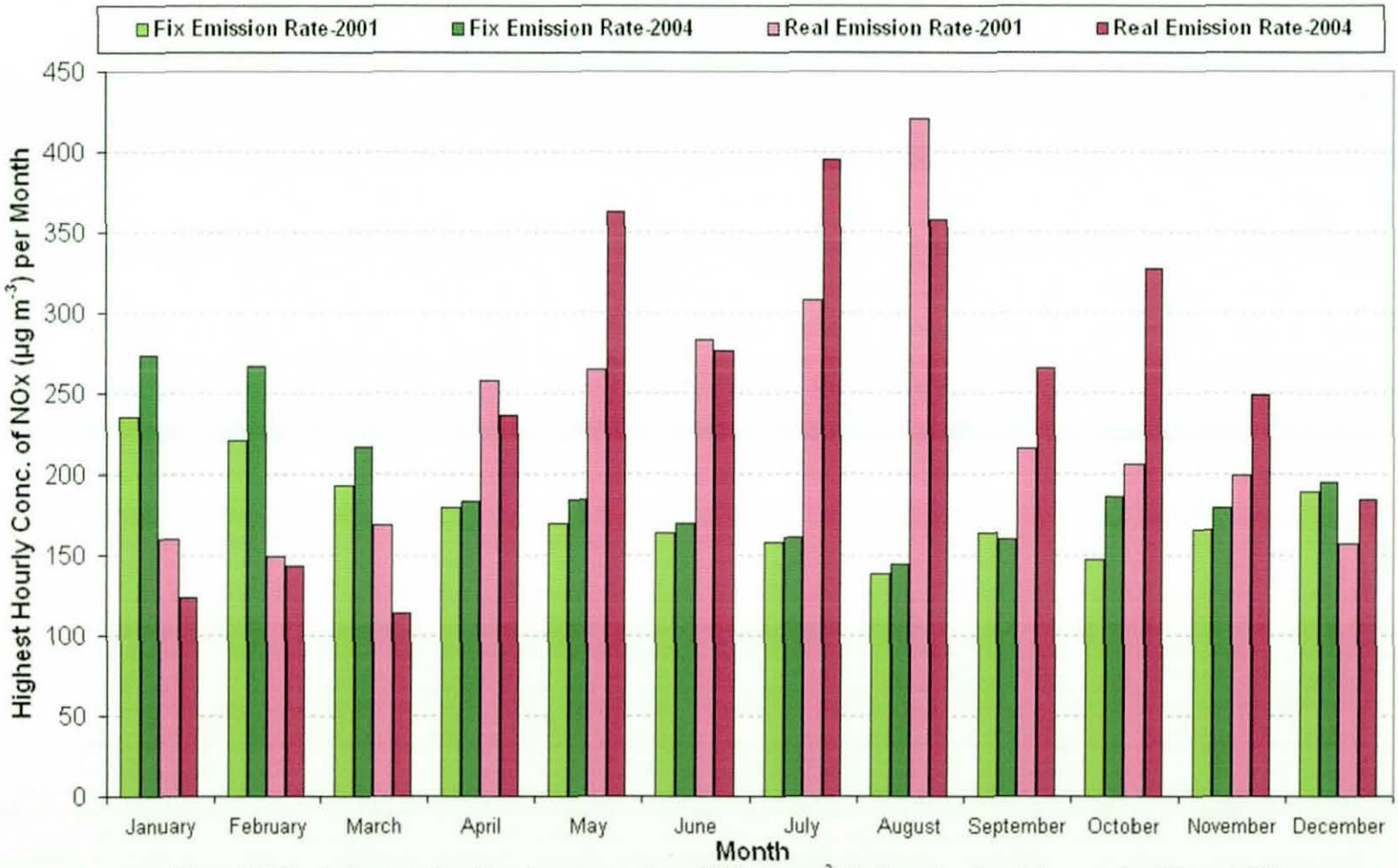

Figure 5.5: The highest predicted hourly concentrations of NOx ($\mu g\ m^{-3}$) for fix and real emissiom raes for 2001 and 2004

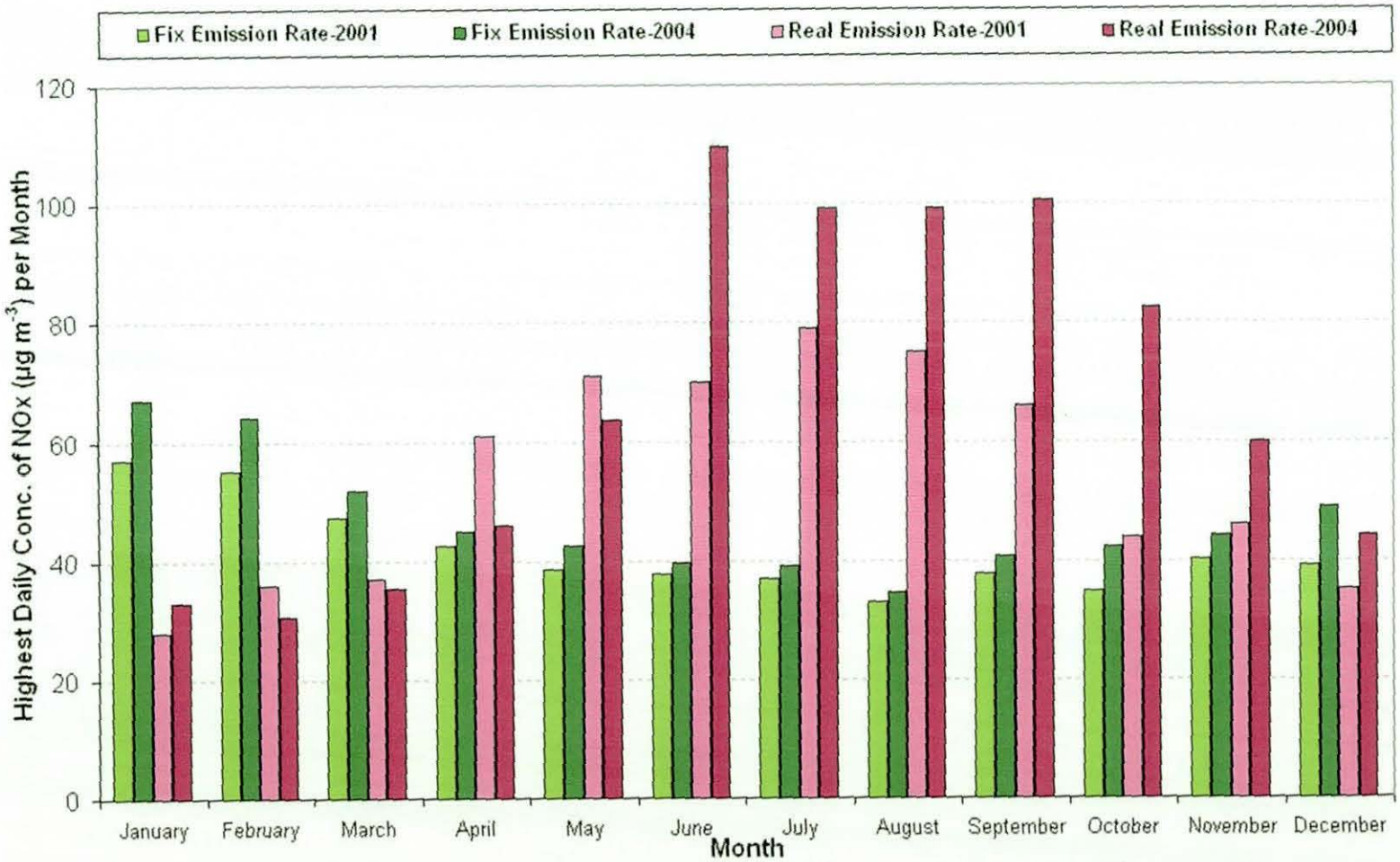

Figure 5.6: The highest predicted daily concentrations of NOx ($\mu g\ m^{-3}$) for fix and real emission rates for 2001 and 2004

5.4: Comparison of Predicted Results from the ISCST4.5 Model using Meteorological Data between 2001 and 2004

A comprehensive model of ground level predicted concentrations of SO_2 and NOx was carried out at various residential areas in Kuwait. Detailed numerical data obtained from this model were then used to study the effects of meteorological conditions and the types of fuel used for power generation in 2001 and 2004.

A comparison of predicted ground level concentrations from both power stations for the years 2001 and 2004 revealed an increase in emission rates of 18.4% for SO_2 and 22.9% for NOx. The prevailing meteorological conditions showed a 2% increase in average temperature. In addition, the average wind speed was 3.7 m s^{-1} for the year 2001 and 4.5 m s^{-1} for the year 2004, with an increase in average wind speed of about 17.8%. These meteorological parameters can have an adverse effect on ground level concentrations of pollutants, as they facilitated dispersion process.

Hourly, daily and annual ground level concentrations for 2001 and 2004 were compared. Hourly predicted ground level concentrations are strongly influenced by prevalent meteorological conditions as they affect the dilution of pollutants, but the effect of high emissions in summer months of the year 2004 was not counterbalanced by diluting effects of meteorological conditions. All of the highest predicted values were in the summer period from July to September for both years.

The highest five hourly predicted ground level concentrations over the total study area were recorded in 2001, with the highest hourly predicted ground level concentration of SO_2 was 4421 μg m^{-3}, observed on the 3rd of August 2001 at 4:00 am, at a distance of 1.7 km from Doha station and a bearing of 96° north. The wind speed and temperature on this date were 1.81 m s^{-1} and 40°C, respectively. The second highest predicted concentration was 3944 μg m^{-3} at a distance of 1.55 km and

a bearing of 81° bearing north from the Doha station, while the third highest value was 3782 μg m^{-3} at a distance of 2 km an a bearing of 83° north from the Doha station. The second and third highest predicted values occurred on the same date and at the same time as the peak concentration. The next highest value was 3729 μg m^{-3}, observed on the 6th of August at 2:00 am at a distance of 1.8 km from the Doha station at a bearing of 97° north, with a wind speed of 2.5 m s^{-1} and a temperature of 35°C. This was followed by a concentration of 3663 μg m^{-3} observed on the 3rd of August at 4:00 am, at a distance of 1.55 km from the Doha station and a bearing of 99° north, with a wind speed of 1.81 m s^{-1} and a temperature of 40°C. When the meteorological conditions of these observations were compared to the top five values observed in 2004, it was apparent that the wind speed and temperature on the 3rd of August 2004 were similar to those on the 6th of August, 2001; the wind speed on August 3, 2004 at 4:00 am was 1.68 m s^{-1} with a temperature of 32°C, while the wind speed on the 6th of August at 2:00 am was 5.14 m s^{-1} with a temperature of 32°C. The wind speed on the 6th of August increased from 2001 to 2004 by 51.4%, while on the 3rd of August, it decreased by 6.6%. Therefore, these predicted results are in agreement with the expected trend, indicating that high temperature and wind speed significantly facilitate the dispersion of pollutants.

Simulation results for 2004 show that the highest predicted hourly ground level concentration was 3436 μg m^{-3} on the 2nd of August at 12:00 pm, recorded 3.5 km from the Doha station at a bearing of 174° north, while the wind speed was 4.15 m s^{-1} and the temperature was 50°C. At the same time, the concentration was recorded to be 3415 μg m^{-3} at a location 3.2 km from the Doha station at a bearing of 67° north. The third highest value of 3396 μg m^{-3} was observed at 12:00 pm on the 13th of August, at a distance of 1.8 km and a bearing of 180° from the Doha station. The corresponding wind speed was recorded as 4.63 m s^{-1}, and the temperature was 49°C. The next highest value observed values was 3302 μg m^{-3} on the 24th of July at 7:00 am, 9.5 km from Doha station at a bearing of 115° north with wind speed of 3.1 m s^{-1}

and a temperature of 45.7°C. The fifth value highest value was 3289 μg m^{-3}, recorded on the 11th of August at 12:00 pm, 2.8 km from the Doha station at a bearing of 180° north, with a wind speed of 4.15 m s^{-1} and a temperature of 47°C.

In comparing the above results with those obtained for 2001, we note that the wind speed at 12:00 pm on the 2nd of August 2001 was 2 m s^{-1} and the temperature was 44°C, while at 12:00 pm on the 13th of August 2001, the wind speed was 2.5 m s^{-1}, and the temperature was 44.2°C. On the 24th of July 2001 at 7:00 am, the wind speed was 1.5 m s^{-1}, and the temperature was 32°C, while on the 11th of August 2001 at 12:00 pm, the wind speed was 2.5 m s^{-1}, and the temperature was 47°C. These data indicate that the percentage increase in the wind speed from 2001 to 2004 was 52% on August 2, 46% on August 13, 52% on July 24, and 40% on August 11. Accordingly, the highest predicted ground level concentrations of pollutants decreased from 4421 μg m^{-3} to 3436 μg m^{-3}, representing a decrease of 22%, which is similar to the increase in the wind speed of 17.8%.

As observed in the hourly results, the distances of the highest predicted concentration values for 2004 were farther from the reference power station than those in 2001. This was due to meteorological conditions such as wind speed and temperature, which were higher in 2004 than in 2001. Again, these results confirm the relationship between the peaks in the concentration of pollutants and the meteorological conditions.

In contrast to the hourly data, the average daily and annual concentrations predicted for the ground level were strongly dependant on emission rates, while the influence of meteorological parameters was not as substantial. This was because the hourly data were averaged. For the predicted daily concentrations of SO_2 at the ground level over the total study area in 2001, the highest recorded concentration was 931 μg m^{-3}, observed on July 9, 2001. The highest daily predicted concentration recorded for

2004 was 1224 μg m^{-3}, observed on June 26. This corresponds to an increase of 23.9%. The second highest value for 2001 was 893 μg m^{-3}, observed on the 12th of August, and 1054 μg m^{-3}, observed on the 18th of July for 2004, representing an increase of 15.3%. The third highest value for 2001 was 893 μg m^{-3}, observed on the 2nd of September, and 1052 μg m^{-3}, observed on the 27th of June (representing an increase of 15.11%). These values were followed by concentrations of 870 μg m^{-3} on the 16th of July in 2001 and 1045 μg m^{-3} on the 24th of June in 2004 (an increase of 16.75%). Finally, the fifth highest values were 851 μg m^{-3} in 2001, observed on the 23rd of May, and 1025 μg m^{-3} in 2004, observed on the 8th of September (an increase of 17.6%). The location of the top five daily predicted values for both 2001 and 2004 was 1.4 km from the Doha power station at a bearing of 157° north. The only exception was that the second highest value observed in 2004 was located 1.65 km from the Doha station at a bearing of 127° north. The increase in the ground level SO_2 concentration for 2004 relative to 2001 is similar to the increase in emission rates of SO_2 for the these two years of approximately 18.4%.

A similar analysis of the five highest predicted annual ground level concentrations of SO_2 shows an increase in the average ground level concentration of 17.6% between 2001 and 2004, which corresponds to an average increase in the emission rates between these two years of 18.4%. This increase is due to the observed 18.4% increase in demand for electric power mentioned earlier. The annual concentration levels of the meteorological conditions were averaged, resulting in the strong dependency of these results on the emission rates.

A similar analysis has been made using the predicted values of nitrogen dioxide (NOx). In the hourly predicted concentrations, the highest predicted concentration in 2001 was 421 μg m^{-3}, observed on the 3rd of August 2001 at 4:00 am at a distance of 1.6 km from the Doha station at a bearing of 86° north. The wind speed and temperature corresponding to this maximum were 1.81 m s^{-1} and 40°C, respectively.

The second highest value observed was 374 μg m^{-3}, at a distance of 1.5 km from the Doha station at a bearing of 81° north, while the third highest value was 368 μg m^{-3}, recorded at a distance of 2 km and a bearing of and 83° north from the Doha station. The fourth highest value was 342 μg m^{-3}, at a distance of 2.6 km the from Doha station and a bearing of 88° north, and the fifth highest value was 341 μg m^{-3}, at a distance of 2 km from the Doha station and a bearing of 97° north. All of these maximum predicted values also occurred on the same day and at the same time as the peak value, but at different locations. When the meteorological conditions corresponding to these top five values in 2004 were compared, the wind speed on the 3rd of August 2004 at 4:00 am was found to be 1.68 m s^{-1}, with a temperature of 32.5°C. The percentage decrease in the wind speed from 2001 to 2004 on the 3rd of August was 7.2%, while the temperature decreased by 18.75%. It is clear from the above results that there was no substantial difference in the wind speed and temperature between 2001 and 2004, so that the emission rates are expected to have the largest effect on the concentration of pollutants.

The predicted results for NOx in 2004 show that the highest predicted hourly ground level concentration was 395 μg m^{-3}, at a distance of 10.4 km and a bearing of 67° north from the Doha power station, while the second highest value was 390 μg m^{-3}, at a distance of 12.6 km and a bearing of 66° north from the Doha power station. The first and second highest values occurred on the 18th of July at 5:00 am and had a corresponding wind speed of 1.68 m s^{-1} and a temperature of 35°C. The third highest value was 389 μg m^{-3} at a distance of 14.6 km from the Doha power station and a bearing of 86° north, while the fourth high value was 388 μg m^{-3} at a distance of 13.6 km from the Doha power station and a bearing of 85° north. The fifth highest value was 384 μg m^{-3} at a location 15.6 km from the Doha power station and a bearing of 94° north. All three of these values occurred on the 18th of July at 6:00 am, and all had a wind speed of 1.8 m s^{-1} and a temperature of 34°C. However, a comparison of the meteorological conditions corresponding to these top five values in 2001 showed

that the wind speed on the 18th of July 2001 at both 5:00 am and 6:00 am was 1.21 m s^{-1}, with a temperature of 34°C. The increases in the wind speed from 2001 to 2004 on the 18th of July at 5:00 am and 6:00 am were 28% and 32.8%, respectively, while the temperature increased by 2.8% at 5:00 am and 0% at 6:00 am. Therefore, these predicted results are in agreement with the theoretically expected trend, indicating that a high wind speed and temperature significantly facilitate the dispersion of pollutants.

As seen from the above results for the five highest values of pollutant concentration, there was no substantial change in the meteorological conditions between the years 2001 and 2004. In these situations, the emission rate would have the largest effect on pollutant concentrations so that the predicted ground level concentrations for 2004 were greater than for 2001, except for the first values, which are almost equal.

In terms of daily and annual ground level concentrations of NOx, the predicted values were strongly dependant on the emission rates, and the influences of meteorological parameters was not as substantial. This was because the hourly data had been averaged. The highest daily predicted concentration of NOx that covered the total study area was 79 μg m^{-3} on the 9th of July for the year 2001 and 109 μg m^{-3} on the 26th of June for 2004. This corresponds to an increase of 27.5%. The second highest value for 2001 was 78 μg m^{-3} on the 3rd of July in 2001 and 100 μg m^{-3} on the 18th of September in 2004 (representing an increase of 22%). The third highest value for 2001 was 75 μg m^{-3}, which was observed on the 21st of August; in 2004, the third highest value was 99 μg m^{-3} on the 15th of July (an increase of 24.3%). The fourth highest value in 2001 was 74 μg m^{-3}, which occurred on the 9th of July, and in 2004, the fourth highest value was 99 μg m^{-3}, on the 22nd of August (an increase of 25.25%). Finally, the fifth maximum value for 2001 was 74 μg m^{-3}, recorded on the 9th of July, and for 2004, it was 97 μg m^{-3}, on the 3rd of September (an increase of 23.7%). The locations of the first and third highest daily predicted values in 2001

occurred at a distance of 1.3 km from the Doha power station at a bearing of 157° north. The second, fourth and fifth highest values were located 0.5 km from the Doha power station at a bearing of 59° north. In 2004, the predicted first, second and fifth values were at distances of 1.4 km from the Doha station and at a bearing of 157° north. The third value was at a distance of 1.7 km from the Doha station and a bearing of 122° north, while the forth value was at a distance of 1.25 km from the Doha power station and a bearing of 179° north. The small increase in the daily ground level NOx concentration of about 22.9% for the year 2004 compared to the year 2001 supports the similar increase in emission rates for the these two years.

A similar analysis of the five highest predicted annual ground level concentrations of NOx showed an increase of 17.4% between 2001 and 2004, which corresponds to an average increase in emissions of 22.98% between these two years. This increase is related to the increased demand of electricity and water desalination. However, in the calculation of daily and annual concentration levels, the meteorological conditions are averaged, resulting in a strong dependency of the results on emission rates.

The SO_2 emission rates have risen by almost 18.4% between 2001 and 2004, which is in agreement with a study conducted by the power ministry, which identifies the yearly increase in emission rates of pollutants as 6% per year. When the ISCST4.5 model was run for both years to determine the daily predicted ground level concentrations for the top values, the overall increase in pollutant concentrations between 2001 and 2004 was identified as 17.6%. Similarly, in the case of NOx, the emission rates rise by 22.98% between 2001 and 2004.

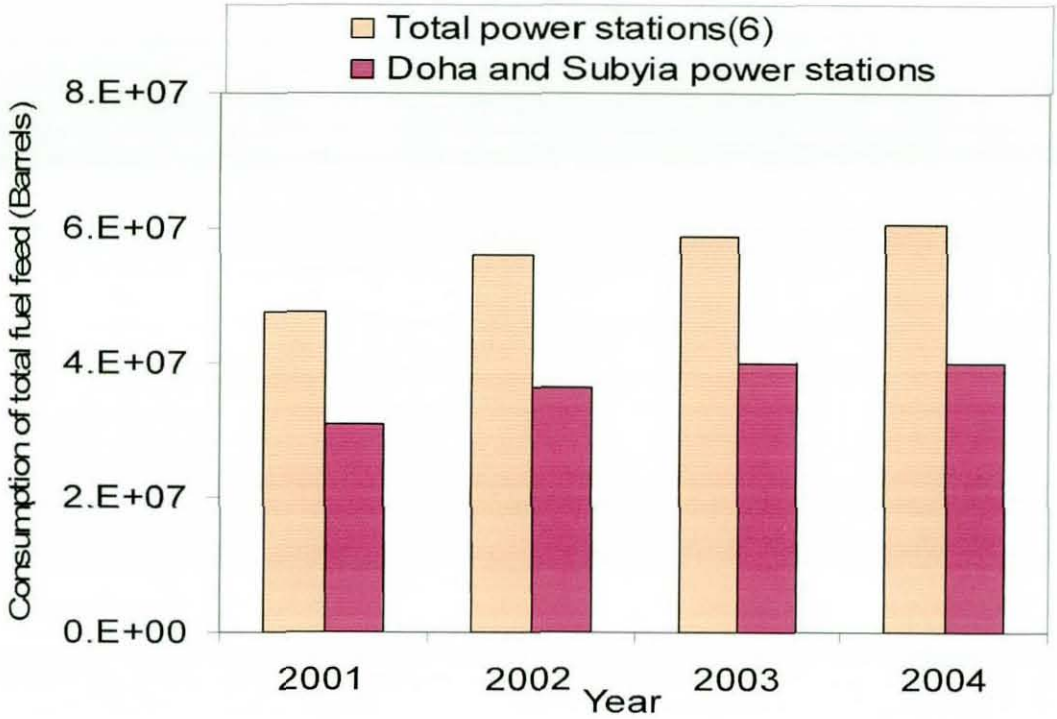

Figure 5.7: Consumption of the total fuel feed (in barrels) for power stations

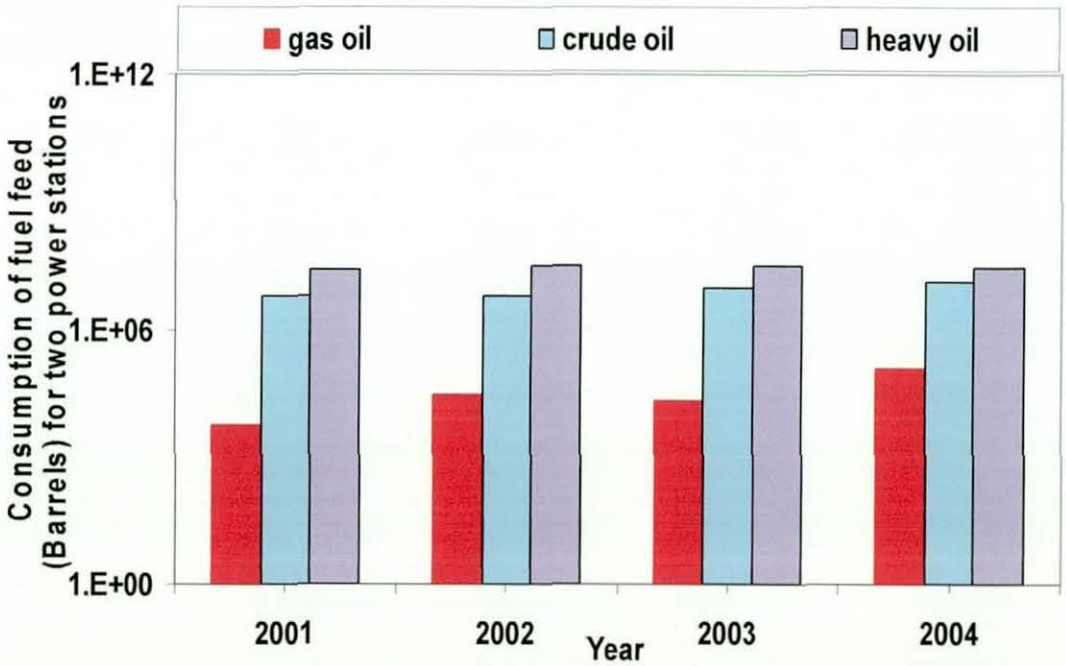

Figure 5.8: Consumption of fuel feed (in barrels) for the Doha and Subyia power stations

Figure (5.7) shows that the total increase in the fuel feed between 2001 and 2004 were 22.8%. However, the reduction in pollutant concentrations in spite of the increase in fuel consumption can be attributed to the growing awareness among the masses and the decision makers, leading to a growing consciousness to reduce emissions using alternate fuels such as natural gas. Since heavy oil contains 4% sulphur, it is used less frequently, and instead decision makers have opted for gas oil and fuels with lower sulphur content.

When the fuel consumption is examined by year, a 82.16% rise in the use of gas oil between 2001 and 2002 is observed (Figure (5.8)), while the consumption of crude oil increased by 1.38%, and that of heavy oil increased by 17.85%. Between 2002, and 2003, however, gas oil consumption decreased by 51%, while crude oil consumption increased by 38.22%, and heavy oil consumption increased by 0.51%. Between 2003, and 2004, the use of gas oil increased by 83.71%, while crude oil consumption increased by 24.74%, and that of heavy oil decreased by 12.51%.

Figure (5.9) shows that there is an increase in the cost of fuel feed by year in the state of Kuwait. Increases in the cost of fuel feed in the power stations were as follows: 22.7% between 2001 and 2002; 12.05% between 2002 and 2003; and 13.02% between 2003 and 2004. The total fuel feed cost for all power stations in the state of Kuwait in 2001 was 314.6 million (KD) and in 2004 was 532 million (KD; 1KD = 0.27$). For the Doha and Subyia power stations, the total fuel feed cost was 198.1 million (KD), and in 2004 the fuel feed was 352.7 million (KD). The increase in the total cost of the fuel feed between 2001 and 2004 was 40.9%, while the increase for the Doha and Subyia stations only was 43.8%.

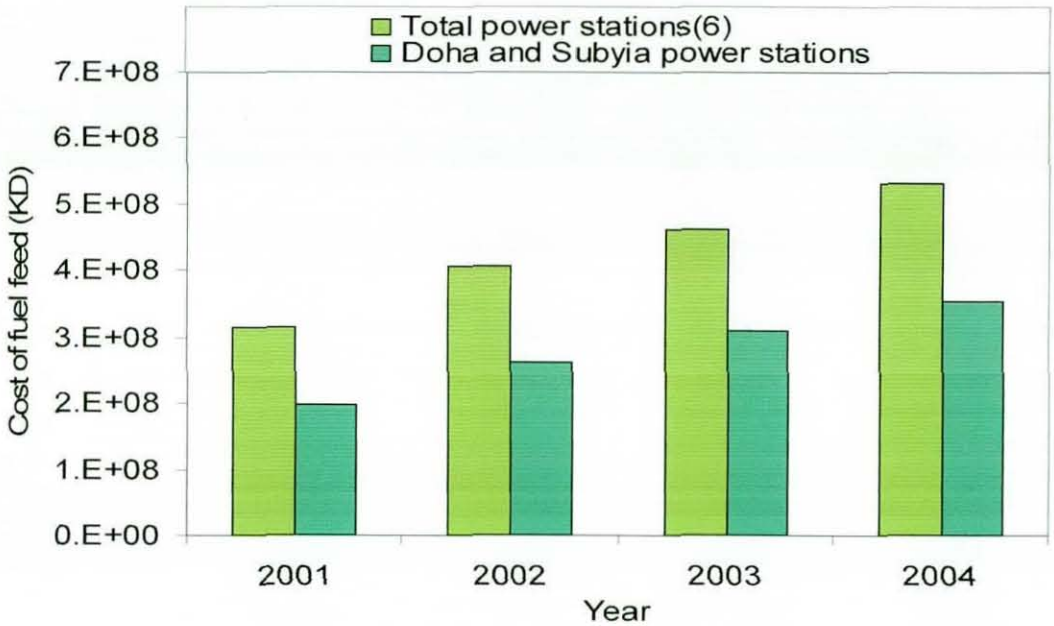

Figure 5.9: The cost of fuel feed (KD) for power stations in Kuwait

5.5: Exceedance Fraction Area of the Standard Limit of (K-EPA)

The fraction of the area that exceeded the standard limits of the Kuwait Environmental Protection Authority (K-EPA) due to the power stations is considered in this section. The exceedance fraction area is the total area that exceeds the standard limits of SO_2 and NOx from the total study area. When we consider the fraction of the daily values with respect to both stations and compare it with the fraction in the Doha station on its own, we see that the difference is comparatively small. This means that the power station at Doha emits a sizeable amount of pollutants on its own, which does not differ much from the combination of the two power stations. This fact is clear in the hourly data, where there is a difference between the two emissions rates, but the difference is very small (Figure 4.15 and 4.16). This can be attributed to the location and wind direction of the power stations, which is of the utmost importance when studying the impacts of the emissions. The Doha station lies in the central portion of Kuwait Bay, and the predominantly northwest wind direction complicates the emissions problem by dispersing the

pollutants over prime residential areas, including Rabia. Subyia, on the other hand, lies to the north of the Bay, and the northwest wind effectively washes out the pollutants over the Persian Gulf, thus reducing the impact on the residential areas.

Figure (5.10) presents the total consumption fuel feed per month for power stations for four years in the state of Kuwait. As shown in this figure, the maximum total consumption of fuel occurred in the year 2004, while the lowest total consumption fuel occurred in the year 2001. In addition, the maximum monthly consumption of fuel feed used in power stations was observed in summer months (July and August) in all four of the years. However, the real emission rates of SO_2 and NOx in Figures (4.13, 4.14, 4.15, and 4.16) have the same trend as Figure (5.10).

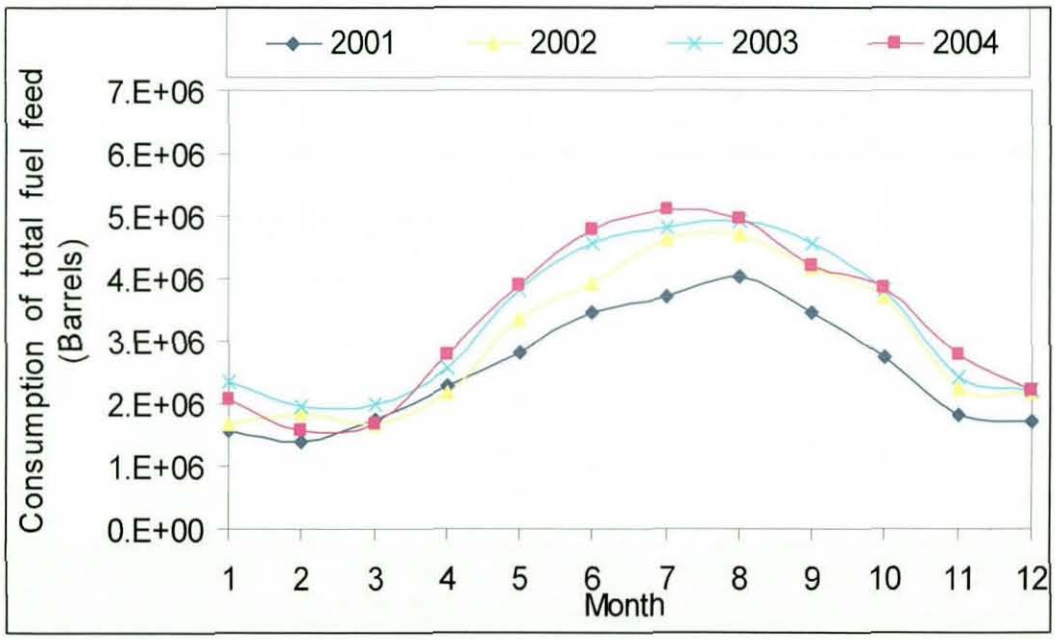

Figure 5.10: Consumption of total fuel feed (in barrels) per month for power stations in Kuwait

In Figure (5.11), we observed that the pollution trend for the hourly ground level predicted concentration of SO_2 became very high in the summer period, particularly in the month of August, when the exceedance fraction area was 88.9% of the total mesh area in 2001 and in July 2004, when the fraction was 97.9% in both power stations. In addition, the lowest polluted fraction area for both power stations was found to be 31.3% in 2001 (observed during the month of December) and 42.3% in February of 2004. In case of daily predicted concentrations, for two power stations the trends in the pollution area were similar to the hourly trends for both stations, with the maximum area polluted comprising approximately 11.5% of the total area in August 2001 and 23.4% in October 2004. The lowest daily polluted areas occurred during February in both years and made up 0.4% and 0.75% of the total area in 2001 and 2004, respectively. The Doha Complex receives the major share of emitted pollutants at approximately 86% of the total emissions, while 14% are received in Subyia.

Interestingly, the exceedance fraction of the two stations is closely followed by the exceedance of the Doha Complex, while the exceedance fraction in the daily concentration was very similar when calculated as a contrast between the two stations and the Doha Complex by itself. The predominance of pollution continues in the summer, with emissions increasing at Subyia as well.

Figure (5.11) shows that the Doha complex responsible for the major share of pollutants emitted to the atmosphere with 86% of the total emissions, while Subyia power station responsible for 14%. However, it is clear from Figure (5.11) that the hourly exceeding limit fraction area from the Doha and Subyia power stations for predicted hourly ground level concentrations of SO_2 was greater in 2004 than in 2001 by 35.8%, and that the daily exceeding limit area was greater by 47.7% in 2004. In addition, it is clear that these emissions are purely related to the activities of that particular season, increasing with the related activities, and subsiding with the

reduction in those activities. Another interesting peculiarity was that the majority of the emissions were recorded during the night, or early morning hours, and more often in the summer (June, July, and August). This can be attributed to the fact that the night and early morning hours have a very low inversion layer, and thus pollutants only have a limited space in which to disperse, resulting in high concentrations. The high operation load of the power stations explains the high pollutant loads in the summers.

For nitrogen oxide (NOx), there was no exceedance fraction area from the two power stations observed in either of the two years. The hourly and daily predicted concentration values of NOx fell within the range of the standard limits of the K-EPA for both years.

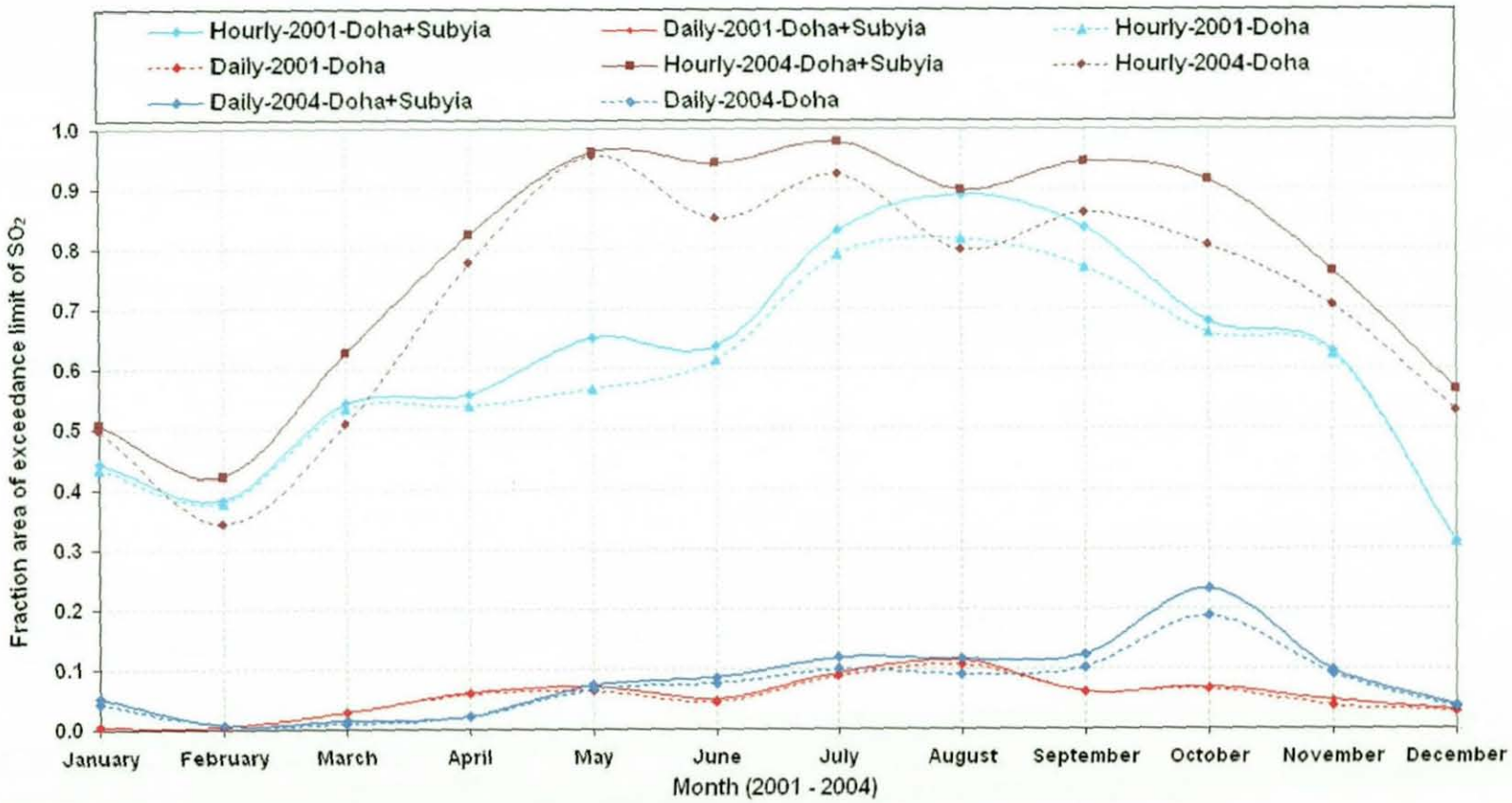

Figure 5.11: Hourly and daily exceedance fraction area limit of SO_2 for 2001 and 2004 from Doha and Subyia stations

5.6: Rose Plots of the Fifty Highest predicted Values of Hourly and Daily Average Concentrations for 2001 and 2004

The concentration rose plots of the highest fifty predicted values were generated in order to study the effects of wind speed and wind direction on the predicted ground level concentrations of pollutants resulting from the ISCST4.5 model considering sixteen sectors. When air pollutants are released from one or many point sources such as stacks, the wind direction determines the paths that the effluents will take. The correlation of air pollution concentrations and wind direction at any location can help to identify the main sources that are responsible for the pollution measured at that site (Wark and Warner, 1981).

The wind direction is considered to be the direction from which the wind blows. Therefore, in our case, a northwest (NW) wind will move pollutants to the southeast (SE) of the source (power stations). This was taken into account in the construction of the concentration rose plots for the fifty maximum values. In addition, it is very important to note that the ISCST4.5 model considers the wind direction to be the direction towards which wind is blowing.

Figures (5.12) and (5.13) present the concentration rose plots of the sulphur dioxide (SO_2) for the fifty highest hourly and daily predicted values for 2001. As seen in these figures, the specified limits set to the K-EPA for hourly and daily emissions over the selection mesh area were violated. For hourly concentrations, Figure (5.12) shows a high hourly mean predicted concentration of SO_2 in the sector extending from E to SES, while a low mean concentration is seen in the opposite sector (extending from WNW to NWN). The highest concentration value observed was 4421 $\mu g\ m^{-3}$ on the 3rd of August 2001, at a distance of 1.7 km from the Doha station and a bearing of 96° north. The second highest value was 3944 $\mu g\ m^{-3}$,

observed 1.55 km from the Doha station source at a bearing of 91° north on the 3rd of August 2001.

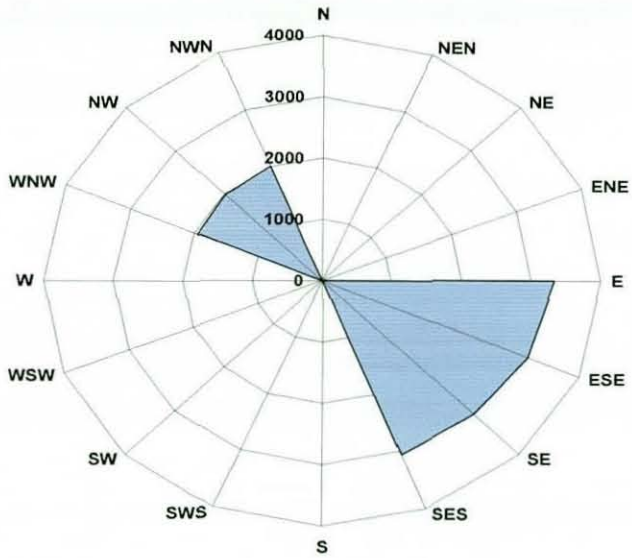

Figure 5.12: The rose plot of the fifty highest values of the hourly average predicted concentrations of SO_2 ($\mu g\ m^{-3}$) around Doha power station for the year 2001

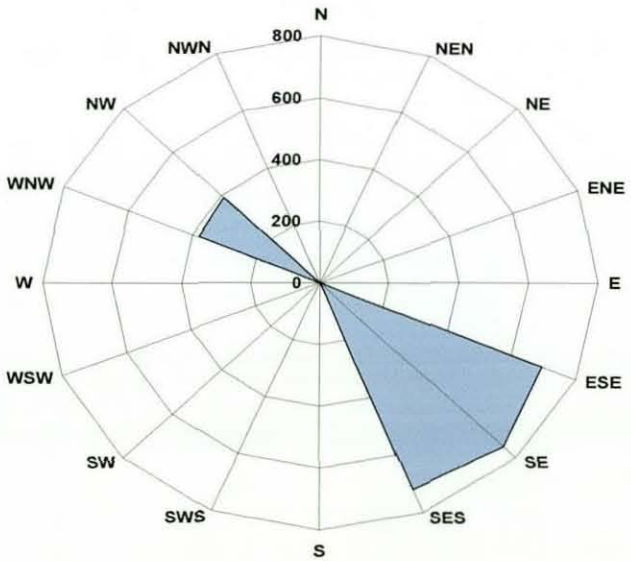

Figure 5.13: The rose plot of the fifty highest values of the daily average predicted concentrations of SO_2 ($\mu g\ m^{-3}$) around Doha power station for the year 2001

These values occurred at 4:00 am in the early morning, with both cases reflecting the influence of meteorological conditions (low temperature, calm winds and a low inversion layer). The hourly concentrations spread in all directions, as shown in the isopleths diagram. However, the hourly concentrations continued to be strongly influenced by the wind direction (Figure 4.26).

At a daily level, the predicted pollutant concentrations were highest in the southeast (SE) of this sector, reflecting the dominant influence of the wind direction. Also, Figure (5.13) shows that the high daily mean concentration of SO_2 was seen in the sector extending from ESE to SES and that the low mean concentration occurred in the opposite sector, which extends from WNW to NW. the highest daily value was 931 $\mu g\ m^{-3}$, observed on the 9th of July 2001, 1.6 km from the Doha station at a bearing of 157° north. The second highest observed value was 794 $\mu g\ m^{-3}$, on the 21st of August 2001, 1.4 km from the Doha station at a bearing of 157° north. The isopleths diagram shows that the highest daily values were in the southeast (SE) direction, which is the direction of the predominant wind over the entire year (Figure 4.27).

Figure (5.14) presents the hourly concentration rose plot for 2004. The high hourly mean concentration of SO_2 was observed in the sector extending from ENE to SES, while the low mean concentration is seen in the opposite sector, which extends from W to NWN. The highest concentration value was 3436 $\mu g\ m^{-3}$, observed on the 2nd of August 2004 at 12:00 pm, at a distance of 3.5 km from the Doha station and at a bearing of 174° north. The second highest value was 3415.9 $\mu g\ m^{-3}$, which was recorded on the 2nd of August 2004 at 12:00 pm, at a distance of 2.9 km from the Doha station source and a bearing of 155° north.

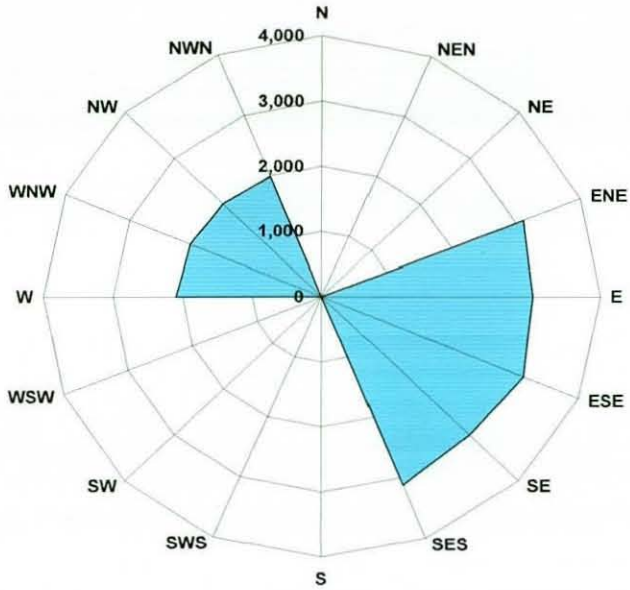

Figure 5.14: The rose plot of the fifty highest values of the hourly average predicted concentrations of SO_2 ($\mu g\ m^{-3}$) around Doha power station for the year 2004

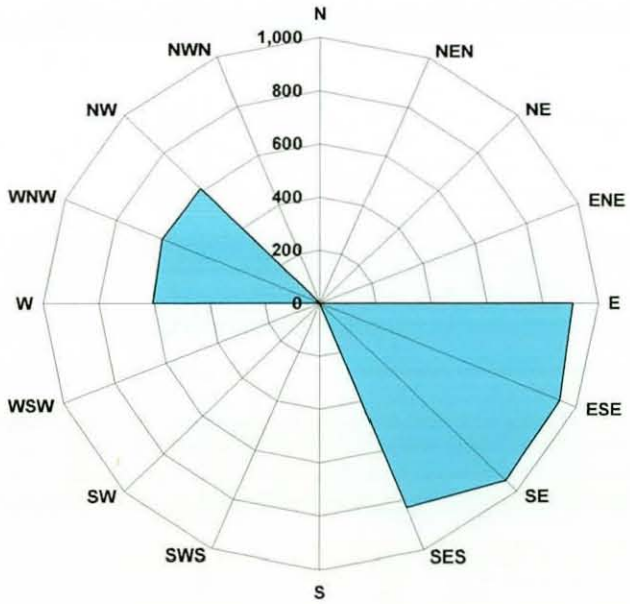

Figure 5.15: The rose plot of the fifty highest values of the daily average predicted concentrations of SO_2 ($\mu g\ m^{-3}$) around Doha power station for the year 2004

However, Figure (5.15) shows that the daily concentration rose of SO_2 for 2004 has a high daily mean concentration of SO_2 in the sector extending from E to SES and low mean concentration in the opposite sector, which extends from W to NW. The maximum concentration was 1224.7 $\mu g\ m^{-3}$, which was recorded on the 26th of June 2004, at a distance of 1.4 km in the SE direction at a bearing of 174° north from the Doha power station. The second highest value was 1054.3 $\mu g\ m^{-3}$, recorded on the 18th of July 2004 and observed at a distance of 2.4 km from the Doha station at a bearing of 167° north.

The daily pollutant concentrations have an average daily value that suppressed the hourly variation in meteorological conditions and showed high values in the south-eastern sector. The predicted values also confirm that high concentrations fade as the plume moves from the source. On an annual basis, the violation of the limit set by the K-EPA is small and is restricted to a nominal area around the Doha power station.

Figure (5.16) presents the rose plot of the fifty highest hourly values of NOx concentrations for 2001. A high hourly mean concentration of NOx was observed in the sector extending from E to SES, and a low mean concentration was observed in the opposite sector (from the WNW to the NWN). The highest hourly value observed was 421 $\mu g\ m^{-3}$, on the 3rd of August 2001 at a distance of 1.6 km from the Doha station and a bearing of 86° north. The second highest value was 375 $\mu g\ m^{-3}$ and was observed on the same day, at a distance of 1.6 km from the Doha station and at a bearing of 81° north at 4:00 am. Both of these cases illustrate the influence of meteorological conditions.

As shown in the Figure (5.17), the pollutant rose plot of nitrogen oxide (NOx) concentrations based on predicted daily values was dominant in the SE direction, with a high daily mean concentration of NOx in the sector extending from ESE to

SES and a low mean concentration is seen in the opposite sector (from WNW to NW). The highest daily value was 79 μg m^{-3}, which was observed on the 9th of July 2001, 1.4 km from Doha plant at a bearing of 157° north. The second highest value was 78 μg m^{-3}, which was observed on the 3rd of July 2001, 0.5 km from the Subyia station at a bearing of 159° north. The daily and hourly values of NOx show variation similar to that of SO_2.

Figures (5.18) and (5.19) show the rose plots of the fifty highest hourly and daily NOx predicted concentrations in 2004. For the hourly concentration, shown in Figure (5.18), a high hourly mean concentration of NOx was found in the sector extending from ENE to SES, while a low mean concentration was seen in the opposite sector (from W to NW). The maximum concentration observed was in month of July and had a value of 395 μg m^{-3}. This maximum was observed on the 18th of the month at 5:00 am, at a distance of 10.4 km from the Doha station and a bearing of 86° north. The second maximum value was 390.4 μg m^{-3}, which was observed on the 18th of July 2004, at a distance of 9.55 km from the Doha station and at a bearing of 91° north.

However, the highest daily mean concentration of NOx for 2004 was observed in the sector extending from E to SES, and a low mean concentration was observed in the opposite sector (from WNW to NWN; Figure 5.19). The maximum predicted daily value was 109.5 μg m^{-3}, which was observed on the 26th of June at a distance of 1.4 km and a bearing of 160° north from the Doha Complex. The second highest value was 100.6 μg m^{-3}, which was observed on the 8th of September 2004, at a distance of 1.6 km from the Subyia station at a bearing of 165° north.

It is obvious from the presented rose plots that the high concentrations predicted were two elliptical loops in the downwind (SE) and upwind (NW) directions. This clearly agrees with the prevalence of a north-westerly wind direction. However, the

Doha power station's plume passes over a larger residential area than that of the Subyia power station. The Subyia power station is built on the north-eastern tip of the Kuwait Bay, resulting in the dispersion of the pollutants over the Bay.

Overall, the fifty maximum hourly predicted concentrations were strongly influenced by the direction of the prevailing winds and by the wind velocity. In 2001, the highest wind velocity was from the northwest (NW) with a frequency of 60%, resulting in maximum concentrations southwest (SE) of the reference point (the Doha stacks). Fifty daily predicted maximum concentrations have also been analyzed according to the prevailing wind direction considering sixteen sectors. The daily mean values have a narrow span reflecting the predominant north-western wind.

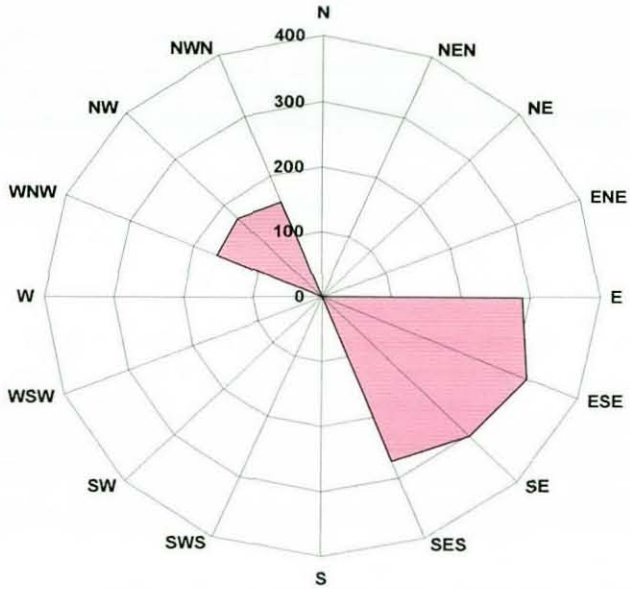

Figure 5.16: The rose plot of the fifty highest values of the hourly average predicted concentrations of NOx ($\mu g\ m^{-3}$) around Doha power station for the year 2001

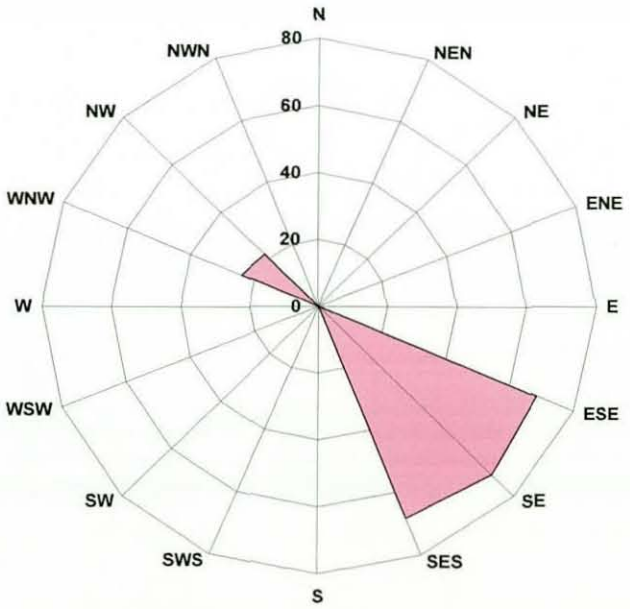

Figure 5.17: The rose plot of the fifty highest values of the daily average predicted concentrations of NOx ($\mu g\ m^{-3}$) around Doha power station for the year 2001

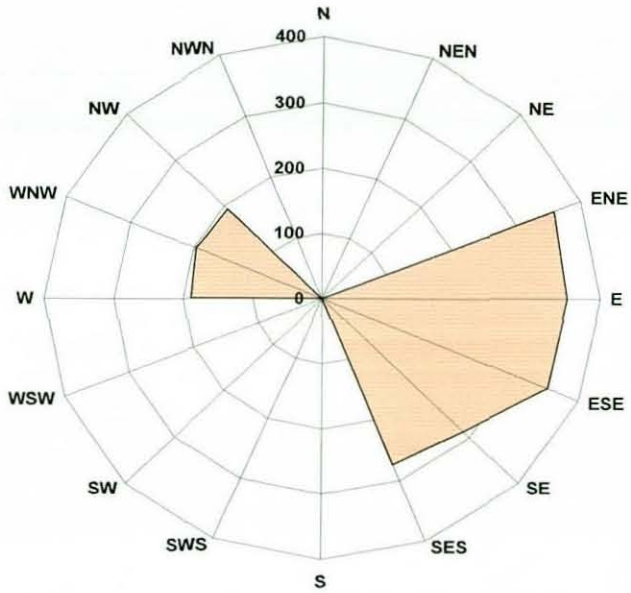

Figure 5.18: The rose plot of the fifty highest values of the hourly average predicted concentrations of NOx (μg m^{-3}) around Doha power station for the year 2004

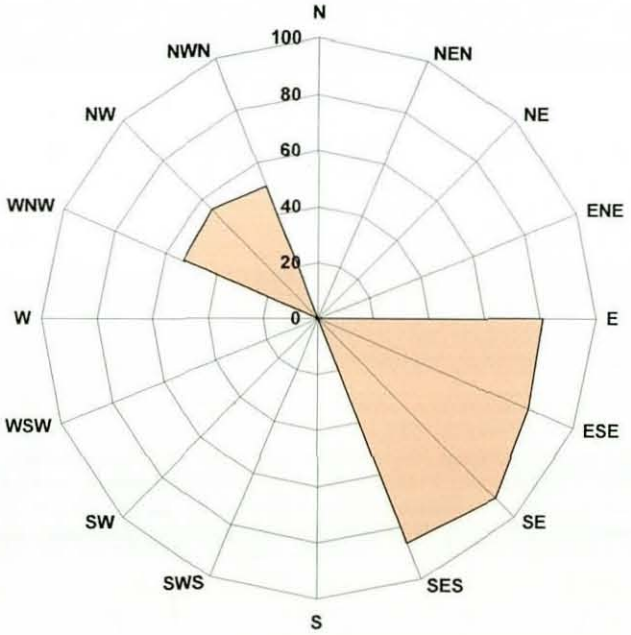

Figure 5.19: The rose plot of the fifty highest values of the daily average predicted concentrations of NOx (μg m^{-3}) around Doha power station for the year 2004

5.7: Conclusions

The power load increased to a maximum in the summer, producing high emissions during this time. Meteorological conditions during this period included high winds and high temperatures, resulting in dust storms that dispersed the high pollutant emissions. These two contradictory parameters resulted in maximum ground level concentrations for particular dominant conditions.

The maximum predicted ground level concentrations for fixed emission rates were found to occur in the early morning hours of the winter months. This was due to the following meteorological conditions in the winter season: low temperature; low wind speed, which resulted in a low inversion layer; and very stable class. While for actual emission rates, the maximum predicted concentrations were observed in the summer months during the early morning. With high temperatures in the summer season, the power stations run at full capacity, especially during the summer months, in order to cover the demand of electricity and water desalination.

The evaluated ground level concentrations for major pollutants are a function of the emission rates and prevailing meteorological conditions. The corresponding meteorological conditions were considered to be the main factor affecting the dispersion process of pollutants under fixed emission rates. In case of real emission rates the emission rates of pollutants from power stations were considered as the main factor in dispersion process. The computed ground level concentration shows that these high emission rates remain regardless of whether the prevalent meteorological parameters (high temperatures, high wind velocities and high inversion layer) are suppressed.

Comparisons of predicted ground level concentrations from both power stations for 2001 and 2004 revealed an increase of 18.4% in emission rates of SO_2 over this time

period, and the prevailing meteorological conditions showed a 2% increase in the average temperature and a 14.6% increase in average wind speed from the year 2001. The rise in the total cost of fuel feed between 2001 and 2004 was 40.9%, while for Doha and Subyia, the increase was 43.8%.

Hourly predicted ground level concentrations were strongly influenced by prevalent meteorological conditions in 2004, which suppressed the effect of the high emissions in that year. All of the highest predicted values occurred between July and September irrespective of the year, reflecting the peak load in the state of Kuwait. Daily and annual average predicted ground level concentrations were strongly dependant on emissions rates, and the influence of meteorological parameters was reduced.

The highest values of SO_2 in the daily average predicted ground level concentrations increased by 17.6% from year 2001 to 2004, and this number was similar to the value for the total increase in emission rates of SO_2 from 2001 to 2004 of approximately 18.4%. For the average annual predicted values, there was an increase of 17.3%, which was identical to the increase in emission rates in the year 2004.

For NOx concentrations, the daily average increased by 24.5%, and the annual average increased by 17.6%. These values are close to the percentage increase in the emission rate of NOx, which increased by 22.98% between the years 2001 and 2004.

The exceedance area from both power stations for the hourly predicted ground level concentrations of SO_2 was greater in 2004 than in 2001 by 35.8%, and the daily exceedance limit area was greater by 47.7%. In the case of NOx for hourly and daily concentrations, the limit area was not exceeded for the years 2001 and 2004.

The fifty maximum hourly predicted concentrations were strongly governed by the prevailing wind direction and wind velocity. In 2001, the highest wind velocity was from the northwest (NW) with a frequency of 60%, resulting in maximum concentrations to the southwest (SE) of the reference point (the Doha stacks). Fifty daily predicted maximum concentrations were also analyzed according to the prevailing wind direction considering sixteen sectors. The daily mean values had a narrow span, reflecting the predominant north-western wind.

Chapter 6

Conclusions and Recommendations for Future Work

6.1: Conclusions

Using the well established ISCT package dispersion of pollutants emitted from the main power stations in Kuwait has been modeled. Influence of meteorological conditions and additional sources of pollution such as cars have also been closely studied. Simulation results for various primary and secondary pollutants have been compared with measured values for 2001 and 2004. These sets of data are shown to be reasonably close in many cases. However, in a number of situations there is noticeable discrepancy between model results and measured values. Overall, the simulation results are shown to be reliable enough to be used for the analysis of the impact of power generation in air quality in urban areas of Kuwait.

The data presented in this thesis show that the monthly measured concentration levels of SO_2 and O_3 in Rabia area in Kuwait were higher in 2001 than in 2004. This is due to factors such as the use of fuels with lower sulphur content in power plants in 2004 and due to prevalent meteorological conditions that has high wind and dusty weather in 2004 as compared to 2001, providing very good dispersion. In the case of NOx, NO_2 and CO, however, the monthly measured concentrations in 2001 were lower than in 2004. This is because of a steady annual rise in the number of vehicles which seems that has overshadowed the emissions from the power plants.

In all cases the pollutant levels were compared with the standard set by Kuwait Environmental Protection Agency to determine the time and positions in which the pollutant levels were higher than allowable limits.

Diurnal patterns were also analyzed for different seasons in 2001 and 2004. The highest measured concentration of SO_2 was predicted to be in the summer season for both years. This is confirmed with the measured data and is due to high demand for

electricity during summer months which requires high fuel consumption and hence high emissions. Results for NO_2 are, the highest measured concentration of NO_2 in 2004 was in summer, whilst in 2001, the highest concentration occurs in the autumn. Significant increase in the number of vehicles between 2001 and 2004 is the main reason for this finding because high levels of NO emitted by cars reduces the production of ozone, which inevitably decreases NO_2 formation.

More detailed analysis of the variation of primary pollutants, such as SO_2, CO and NOx, shows the presence of two maxima during each day. One is in early morning and the second is in the evening. A secondary pollutant, i.e. ozone level, usually passes through a single maximum in afternoons.

In 2001, the highest measured concentration of O_3 is in the summer, and for 2004, the highest concentration recorded was in spring. As O_3, is a product of photochemical oxidation its production is highly dependent on sunlight. In winter and autumn season, days are shorter and colder and photo-oxidation reactions are slower.

The weekdays/weekend effect on O_3 and NO was investigated for 2001 and 2004 during daytime hours from 7:00 am to 9:00 pm during the period from April to September. It was found that on weekends, O_3 levels were high due to lower volumes of traffic, while on weekdays, and O_3 was neutralized by the excessive NO produced by high vehicle density.

This study showed that both in 2001 and 2004 highest measured mean concentrations of SO_2 were in the southeast of the monitoring station in all seasons accompanied with the lowest mean concentration in the opposite sectors (the northwest). This is compatible with the prevailing wind direction which was from northwest about 60% of the time in 2001 and about 46% of the time in 2004 carrying SO_2 emitted from the main power plant in Kuwait (Doha) located northwest of the study area covered in this work. In the case of NOx, the highest measured mean concentrations extended from the ESE sector to the SSW sector in 2001. This

is as expected because the main sources of NOx concentrations were the Doha and Subyia power stations, which are located in the northwest and northeast, respectively plus due to local effects of the traffic movement at this study area. However, in 2004, the highest mean concentrations of NOx extended from the WNW sector to the NNE sector at the Rabia monitoring station. The conclusion is that the main source of NOx in 2004 is the vehicles traffic at the study area.

It should be noted that, in this thesis the main emission source was considered for predicting SO_2 and NOx is the only power generation plant. This indicates that the measured concentration of NOx was attributed to the same emission source and the traffic movements at the study area (Rabia) are the main local emission sources for the emissions of NOx.

Predictions obtained using the ISCST4.5 model show that the highest hourly and daily ground level concentrations of pollutants to be mainly in summer season between June and September, with maximum values observed in August. This is, in general, in agreement with observations and an indication of the influence of peak demand for electricity in summer season. However, most of the highest hourly and daily predicted values for each month occurred in early with the highest values at Doha and a distance of less than 2 km southeast or southwest of the Subyia power station. This is a strong indication of the influence of meteorological conditions on the dispersion of atmospheric pollutants.

To find out the extent of the areas where SO_2 levels exceeds the K-EPA standard, hourly isopleths plots SO_2 concentration were drawn. It was found that, in 2001, in an area of 2378.1 km^2 (approximately 99.1% of the total selected simulation area of 2400 km^2) around the power plants SO_2 levels exceeds the set standard. However, the predicted area where daily average exceeding the K-EPA limits for SO_2 was found to be lower at 395.8 km^2, (approximately 16.5% of the total area under consideration). On an annual basis, the area where the SO_2 limit is exceeded is predicted to be approximately 11.5 km^2, (only 0.5% of the total area under study). Similar analysis for 2004 showed that on hourly basis in 100 % (i.e. 2400 km^2

around the power plants), on daily basis in 40.8% and on annual basis in 0.3% of the study area limits are exceeded.

The predicted NOx from power stations did not exceed the limits set by the K-EPA for permitted hourly, daily or annual values for either year. This means that the main second source of NOx emissions is produced by automobiles.

To evaluate the influence of prevailing meteorological conditions the ISCST4.5 model simulations for 2001 and 2004 obtained using fixed emission rates have been compared for each month independently. Maximum predicted ground level concentrations of primary pollutant occurred in early morning hours in winter months. This is due to the meteorological conditions in the winter which is characterized by low temperatures and low wind velocity resulting in a low inversion layer and stable dispersion. It should however, be noted that fixed emission rate is not realistic and as the electricity consumption increases significantly in summer situation changes. Under variable power demand conditions, five highest predicted hourly, daily and annual ground level concentration values have been compared for 2001 and 2004. Hourly predicted ground level concentrations were strongly influenced by prevalent meteorological conditions, suppressing the effect of the high emissions in 2004. All of the highest predicted values were observed in the period from July to September, irrespective of the year, reflecting peak load conditions of power stations. The overall conclusion is that the average ground level concentrations are strongly dependant on emission rates and are not as strongly influenced by meteorological parameters.

6.2: Recommendations for Future Work

Future work should focus on incorporating other fixed and mobile emission sources of polluting agents in the model simulations to obtain more accurate predictions for air quality in Kuwait. Therefore more effort should be concentrated on collecting field data that are needed to carry out such a task. Obviously, the actual impact and contribution of each individual source can then be evaluated using the methodology used in the present work.

Validation of the model output can also be further improved via extension of the monitoring stations and the range of measurements that they conduct. This needs to be supported by the state of the art technology for accurate monitoring of different pollutants at optimum locations.

Ideally, the comparison of the results produced by ISCTS package with simulations generated by another advance model such as AERMOD and Call-PUFF models should also be carried out. As these models use different methodologies the comparison of their results can provide insight about the validity of their predictions.

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Nomenclature

Symbol	Name of Symbol	Unit
C	Concentration	μg^{-3}
d	Stack diameter	m
F	Fuel consumption	$g\ s^{-1}$
h	Physical stack height	m
H	Effective height or source height	m
L	Coefficient for calculation of σ_y	m
$MW(SO_2)$	Molecular weight of sulphur dioxide	$g\ mol^{-1}$
$MW(S)$	Molecular weight of sulphur	$g\ mol^{-1}$
$Q\ (SO_2)$	SO_2 emission rate	$g\ s^{-1}$
Q	Pollutant emission rate s	$g\ s^{-1}$
R	Correlation coefficient	
SC	Sulphur content weight fraction in fuel	
S	Pasquill stability classes	
t_0	Gas exit temperature	K
t_1	Ambient air temperature	K
U	Mean wind speed	$m\ s^{-1}$
u	Mean wind speed at stack height	$m\ s^{-1}$
v_0	Gas exit velocity	$m\ s^{-1}$
X	Downwind distance from the source	m

Greek letters

Δh	Plume rise height	m
σ_y	Lateral dispersion coefficient	m
σ_z	Vertical dispersion coefficient	m
μ	Micro	
π	Pi	
$\geq$	Greater than or equal	
$\leq$	Small than or equal	
$>$	Greater than	

Acronyms

AQMN	Air Quality Monitoring Network
AAQS	Ambient Air Quality Standard
ISCST3	Industrial Source Complex for Short-Term version 3
ISCST4.5	Industrial Source Complex for Short-Term version 4.5
K-EPA	Kuwait Environmental Public Authority
KIA	Kuwait International Airport
KISR	Kuwait Institute for Scientific Research
MEW	Ministry of Electricity and Water
NWS	National Weather Service
UTM	Universal Transverse Mercator map coordinate system
US-EPA	US-Environmental Protection Agency
SIA	Shuaiba Industrial Area
WHO	World Health Organisation

Appendix (A)
Published Work

During the course of this research, parts of this thesis have been published and other is submitted to journals for publication. In addition, part of this thesis presented in the third conference of the international congress of chemistry and environment in 2007.

A- First published paper:

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Comparative Assessment of Ambient Air Quality in Rabia Area for Years 2001 and 2004 in the State of Kuwait

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Abstract: The hourly air pollutants concentrations were measured continuously by fixed ambient air stations located over the polyclinics in Rabia area in Capital Governorate in the State of Kuwait. The focus of this investigation is to determine the pollution levels of SO_2, NO_2 and O_3 in year 2001 and 2004 to assess the pollution trends. The recorded data are used in identification of the most probable sources of these pollutants. The pollutants levels were compared to evaluate exceedances of Kuwait Environmental Authority Standards. The diurnal patterns were also analyzed for different seasons for two years 2001 and 2004. Weekdays and weekend variation on Ozone pollution has been thoroughly investigated. It is observed that SO_2, NO_2 and O_3 levels were higher in year 2001 as compare to year 2004 due to the application of various mitigation strategies such as relocation of car auction market and transport depot, which were located in the northwestern side of Rabia area with distance of 2 km. The traffic volume all over the country has increased by substantial amount increasing NOx and ozone precursor emissions, which showed the complex balance of NOx and O_3. The O_3 levels of the daytime hours from April to September period has shown high buildup on weekend as compare to weekdays due to the least traffic density on the roads.

Key words: Ambient air pollution, weekdays/weekend effect, seasonal variation, ozone, nitrogen oxides, sulphur dioxide

INTRODUCTION

The air pollution causes persistent smog and health risk to the inhabitants of developing countries such as the state of Kuwait. Since the concept of pollution has existed for a long time, there has been progressing concern about air quality in urban communities. The state of Kuwait is an OPEC member, produces almost two million barrels of oil per day, and has numerous petroleum refineries, petrochemical plants, petroleum dispensing centers, power stations, and oil related industries, and apart from all that, has highly congested roads, with a heavy flux of traffic. The state of Kuwait is located in the Arabian Gulf has a hot dry climate, consists of large uninhabited desert area, with the temperature varying between 40oC and 50oC for at least six months of the year. Therefore, the energy consumption in Kuwait is one of the highest, increasing at an average rate of 7.7%, as compared to developing countries, where this rate is around 2-3 %[1]. Since the state of Kuwait depends mainly on the desalination of seawater to provide its citizens with drinking water, and fulfill the growing demand of electrical power, five major power stations were set up, which work continuously.

The government of Kuwait established the Kuwait Environmental Public Authority (KEPA) in 1995, to safeguard the environment from air pollution due to heavy industrialization. Kuwait EPA established a number of fixed monitoring stations (six stations), to be updated with the air quality in the urban areas, through a monitoring network. These stations continuously measure the levels of pollutants such as SO_2, NO_2, CO, NO, CO_2, H_2S, O_3, and TSP (total suspended particles) in the air, the increasing levels of which effect human health, apart from eroding materials[2].

Bouhamra[3] have reported VOCs concentrations in ambient air after the largest manmade environmental disaster occurred in Kuwait, exploding over six hundred wellhead by the retreating Iraqi army. He reported low concentration but prolonged exposure of these compounds has substantial health risk to Kuwaiti population. Bouhamara et al.,[4] have identified large number of organic compounds in indoor and outdoor air of various Kuwaiti houses using GC/FID with Tenax TA cartridge. The concentrations of various contaminants were reported between 100 and 5000g m-3. In another study, outdoor air quality in Mansouria area is measured for one-month duration, May 1994. Bouhamra and Abdul-Wahab[5] have not reported any violation of residential standards set by Kuwait Environment Public Authority (KEPA).

Air pollutants, especially SO2, NO2, and the major secondary photochemical oxidant, O3 strongly influence plants, and human health, and so the emphasis

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Impact of Emissions from Power Stations on the Ambient Air Quality of Selected Urban Areas in Kuwait

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Abstract: In Kuwait, two main power stations, one comprising of seven-300MW steam generators at Doha and other with eight-300MW steam generators at Subyia cover the major power requirement of Kuwait city. These stations used different types of fuel oil as the prime source of energy that has different sulpher contents (S%). Comprehensive emission inventories for year the 2001 were used to execute Source Complex model for Short-term Dispersion (ISCST4.5) to predict ambient ground level concentrations of sulphur dioxide (SO_2) and nitrogen oxide (NOx) at selected receptors. A yearlong meteorological data were used in conjunction with the dispersion model to compute SO_2 and NOx levels in and around the power stations. For validation of the model, computed results were compared with the measured daily average values at a fixed Kuwait EPA air quality monitoring station located at the roof of polyclinic in Rabia residential area. Contributions of each power station to the highest predicted values were assessed. Significance of the fifty highest hourly, daily and annual ground level concentration values under existing meteorological conditions was analyzed. The results for year 2001 revealed that daily and annual mean predicted SO_2 concentrations had exceedance about 5.7% and 0.16% respectively of the total area under investigation. Based on these results, mitigation strategies would be proposed to abate high pollution levels caused by these power stations.

Key words: Air pollution, ISCST4.5, sulphur dioxide, nitrogen oxide

INTRODUCTION

Rapid industrialization worldwide has triggered off a wave of economic development bringing prosperity and advancement for many nations. However, such activity has not been without degradation of the environment, through the depletion and contamination of existing natural resources and discharge of pollutants into air, water and dumping of solid waste on land. All of these have exerted an enormous load on the environment as a whole damaging the quality of resources available to all existent life forms.

Air Pollution is amongst the most serious global environmental concerns. Apart from incidents and mishaps such as London Fog, Bhopal Gas Tragedy, there are cases that have long-term hazards and need to be addressed urgently. Amongst these are the Ozone Hole problem, Global Warming issue and Acid Rain problem. These concerns however, have led to the formation of specific governing bodies regulating emissions, laws and regulations for controlling these problems.

They have also led to the setting up of treaties such as the Kyoto Protocol, Montreal protocol, Nitrogen oxide protocol and the declaration of representative dates like as June 5-World Environment Day, April 22-Earth Day and September 16-International Day for the Preservation of the Ozone layer.

In the study of air pollution, it is essential to have a complete insight into the nature, behavior and characteristics of a pollutant along with the prevalent meteorological characteristics of the environment into which it is released. This provides the basic data regarding its impact on the environment as well as developing effective measures to check its impairing properties and control the damage that can be caused to nature. Gokhale and Khare[1] have established an empirical relationship between the pollutants concentration in the air and meteorological parameters that has facilitated the construction of design methodologies for the protection of environment. However, in the last decade statistical models have been used more than the traditional deterministic models[2].

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C- Third paper under publication:

Editorial Manager (tm) for Water, Air, & Soil Pollution

Manuscript Draft

Manuscript Number: WATE3207

Title: SO2 and NOx emissions from Kuwait power stations in years 2001 and 2004 and evaluation of the impact of these emissions on air quality using Industrial Sources Complex Short Term (ISCST) model

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Abstract: Comprehensive emission inventories for 2001 and 2004 for Kuwait's main power stations located at Al-Doha and Al-Subyia have been prepared. These inventories are inserted, in conjunction with meteorological data, into the Source Complex model for Short Term Dispersion (ISCST4.5) to predict ambient ground level concentrations of sulphur dioxide (SO2) and nitrogen oxides (NOx) at selected receptors for years 2001 and 2004. The comparison of the results obtained for these two years show the influence of increase in emission rates due to urban and industrial growth. For model validation, computed results are compared with the measured daily average values of SO2 and NOx collected at a fixed Kuwait Environment Protection Agency air quality monitoring station located at the roof of polyclinic in Rabia. Individual contributions of each power station to the highest predicted values are assessed. The five highest hourly, daily and annual ground level concentration values under prevailing meteorological conditions are compared for 2001 and 2004. It is found that the hourly mean concentrations are strongly influenced by the prevailing meteorological conditions. The effect of meteorological conditions has not been that dominant for the daily and annual mean values and the predicted values for 2004 are higher than 2001, simply corresponding to a high emission rates, especially in summer months. Top fifty daily average values of SO2 show a slope of 0.806 for 2001 which means that the model predictions are 20% less than the observed levels. However, the predicted slope of SO2 for 2004 is 0.96 and the model predictions are in very close agreement with the observed data.

Keywords: Thermal, Power Stations, Sulphur Dioxide, Nitrogen Oxides, Emissions, Pollution.

D- Certificate from Conference:

Kuwait Society of Engineers

جمعية المهندسين الكويتية

Kuwait University (KU) – Kuwait Society of Engineers(KSE)
International Congress of Chemistry and Environment ICCE

It is certified that **Bader Nasser Al-Azmi** *has Participated in an oral presentation in The*

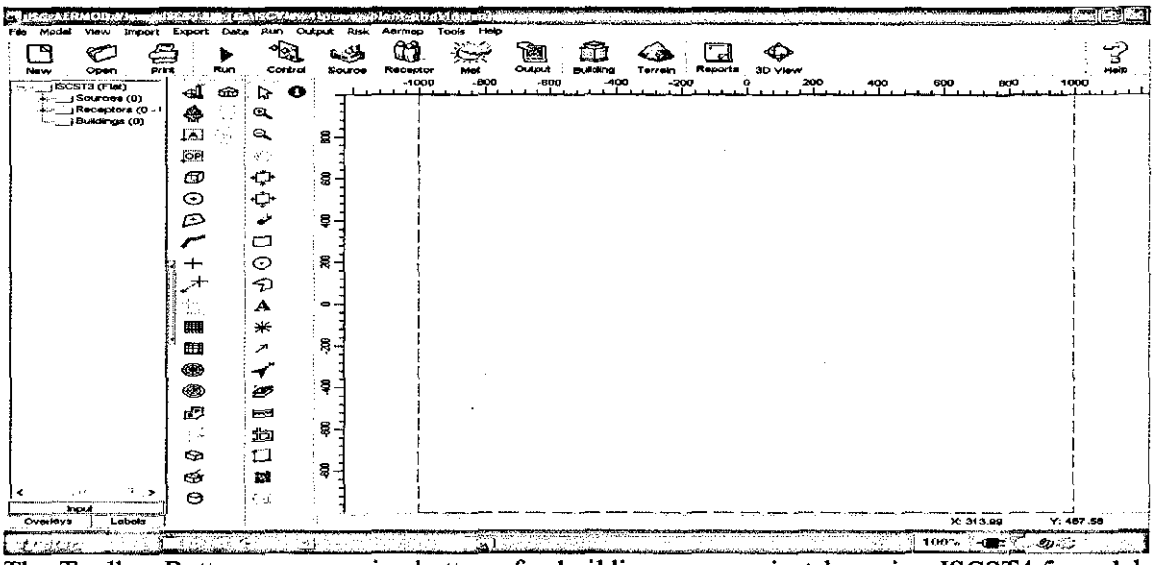
third conference of the international congress of chemistry and environment

held from 18-20 November 2007 in Kuwait.

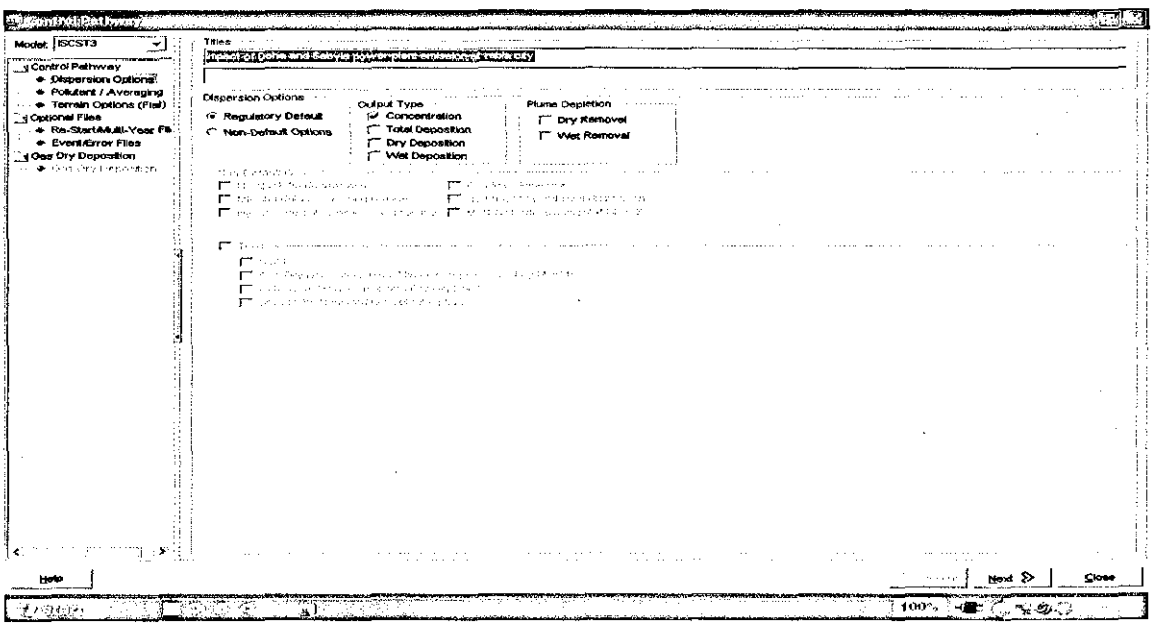
Conference Chairman
Prof. Amir Alhadad
A Alhadad 2007

KSE Chairman
Eng. Talal M. Al-Qahtani

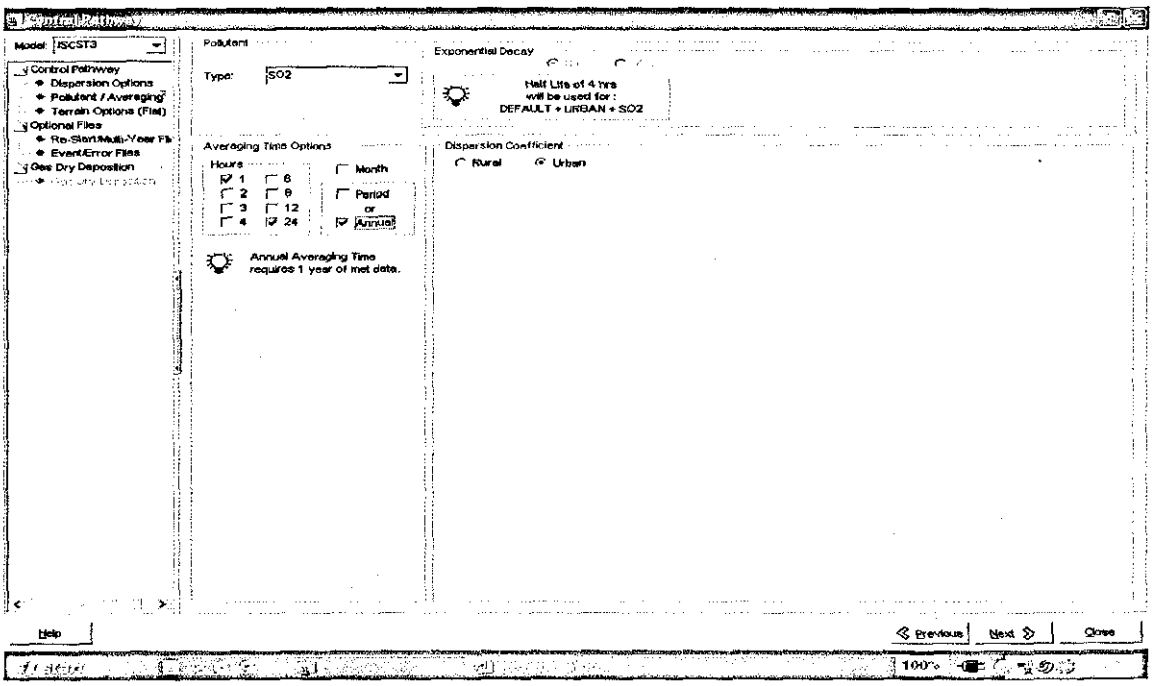
Appendix (B)
Steps of ISCST4.5 Model



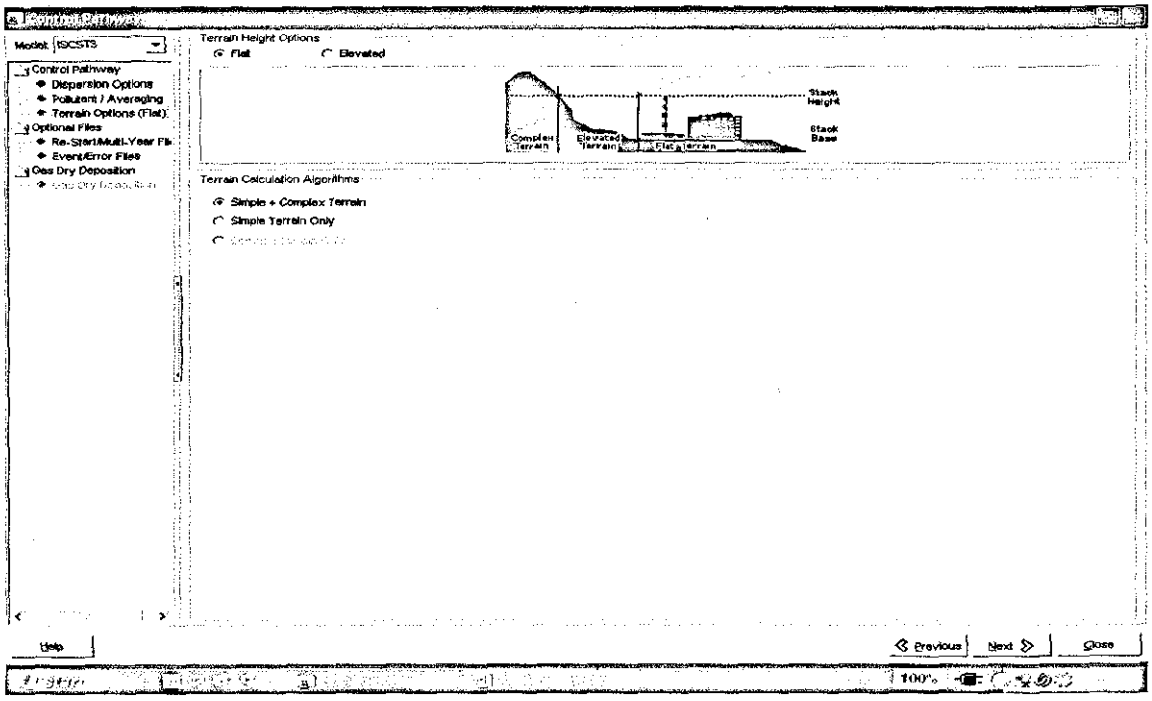
The Toolbar Buttons are a series buttons for building your project by using ISCST4.5 model. However, these buttons provide a fast method of selecting some of the menu commands.



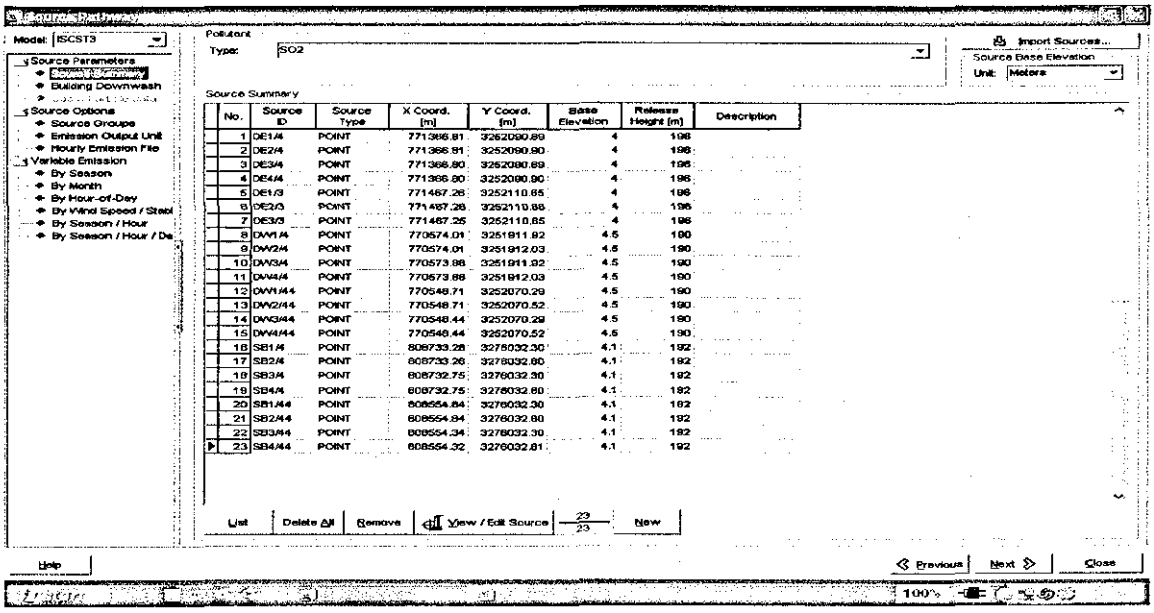
Step (1): The Control Pathway page, allows specifying the overall job control options such as dispersion options, pollutant, output type and averaging times. You have access to the Control Pathway dialog by clicking on the Control menu toolbar button.



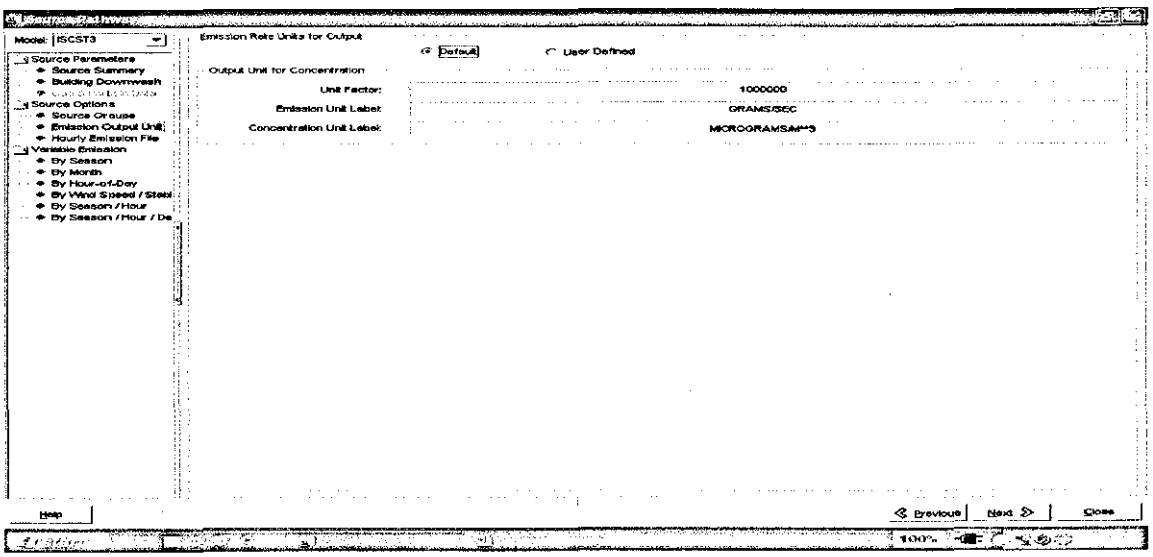
Step (2): The Pollutant averaging page, you can specify the pollutant being modeled, averaging time options and dispersion coefficient.



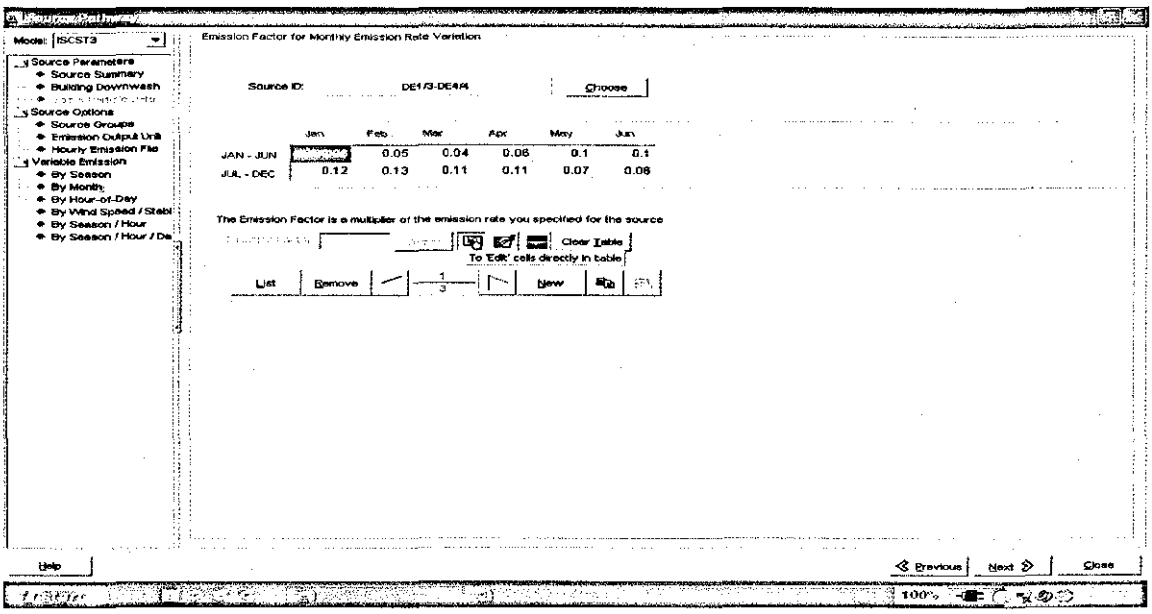
Step (3): The Terrain Options page, you can specify whether you will be modelling the effects of terrain above stack base (simple + complex terrain), in order to be able to input elevated receptor heights and also specify receptor elevations above ground level to model flagpole receptors.



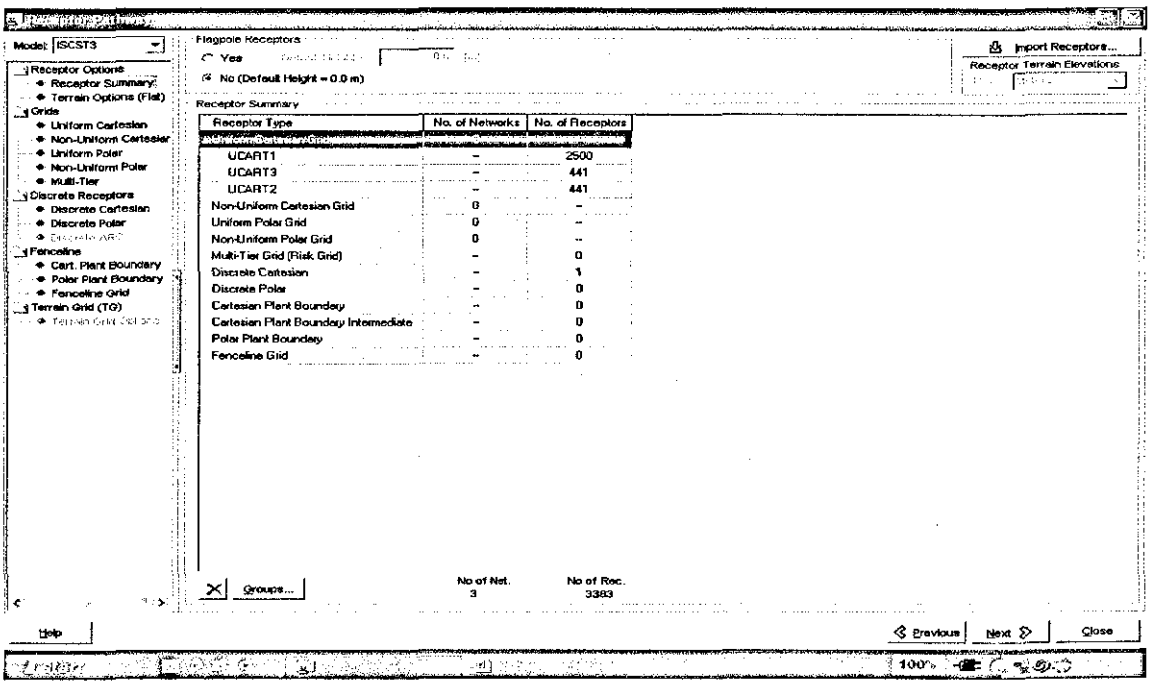
Step (4): The Source Pathway allows you to specify the source input parameters and source group information (Source information's (See Ch.4)) such as source types, building downwash, variable emissions and the coordinates of your sources. Also, in the Source Summary page, you can specify information on the number of sources specified for your current project, pollutant information and source base elevation information.



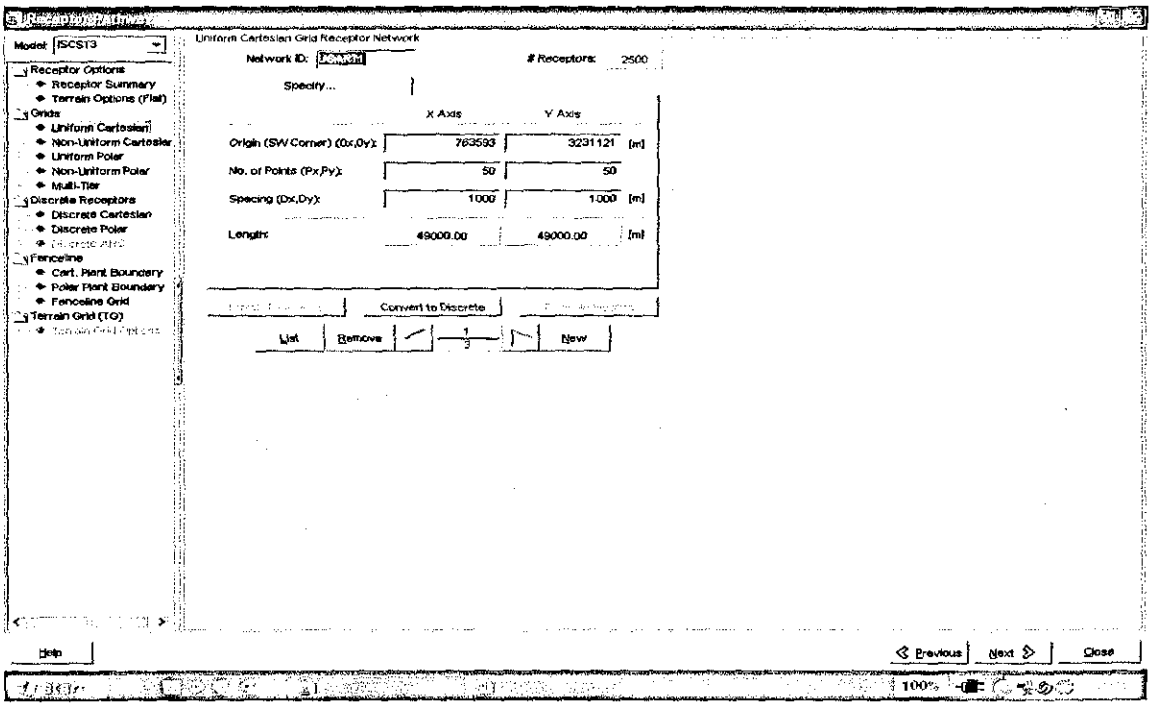
Step (5): The Emission Output Unit window allows you to specify different output units for concentration and deposition calculations. The U.S. EPA models ISCST3, AERMOD, and ISC-PRIME use default output units of micrograms per cubic meter (μg m^{-3}) for concentration calculations and grams per square meter for deposition calculations.



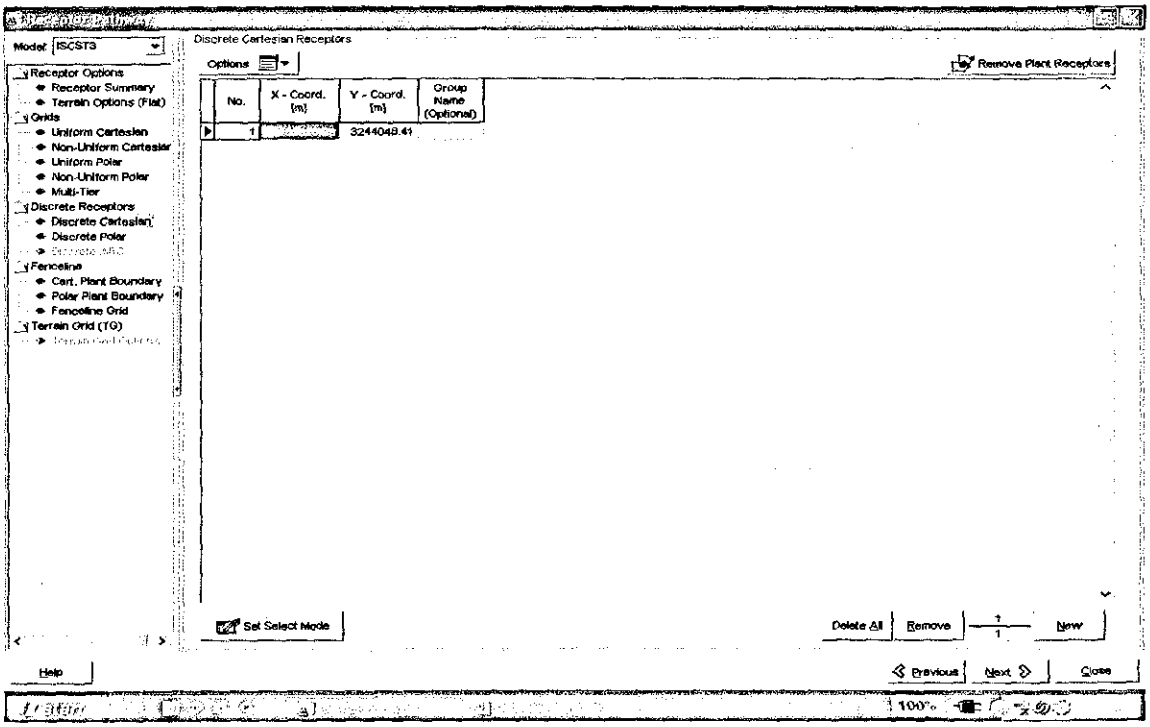
Step (6): In the Variable Emission Rates by any period (In this thesis we select Month period) page, you can specify emission rate factors that vary for specific period (monthly).



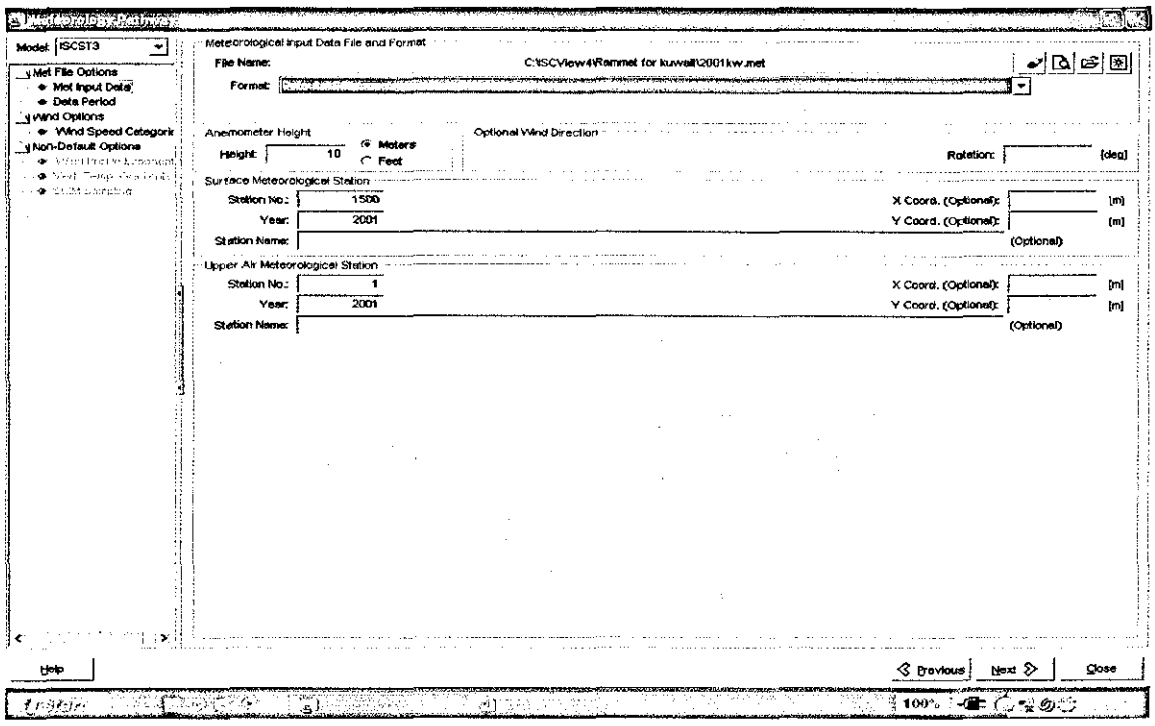
Step (7): The Receptor Pathway allows you to specify the receptor locations for a particular run, define the number and type of receptors in your project, delete selected receptors, define receptor groups, and flagpole options. However, in the Receptor Summary page, you can view a summary of the type of receptors, number of grids, and total number of receptors already specified for the current project.



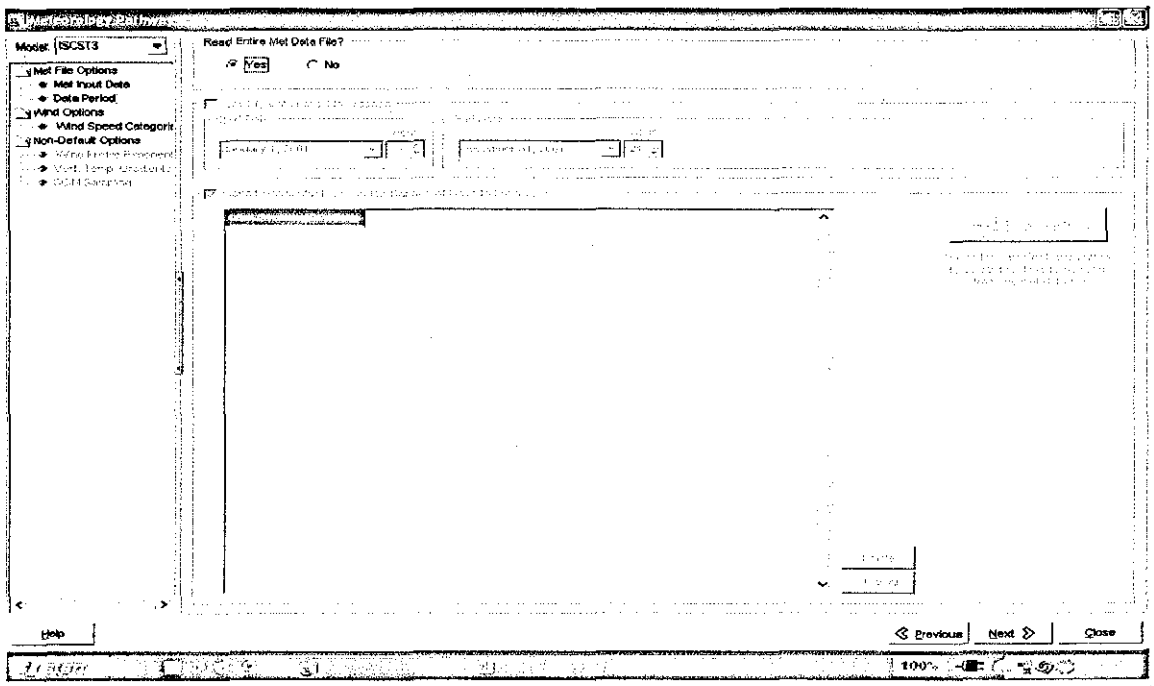
Step (8): In the Uniform Cartesian Grid page, you can define Cartesian grid receptor networks with uniform grid spacing.



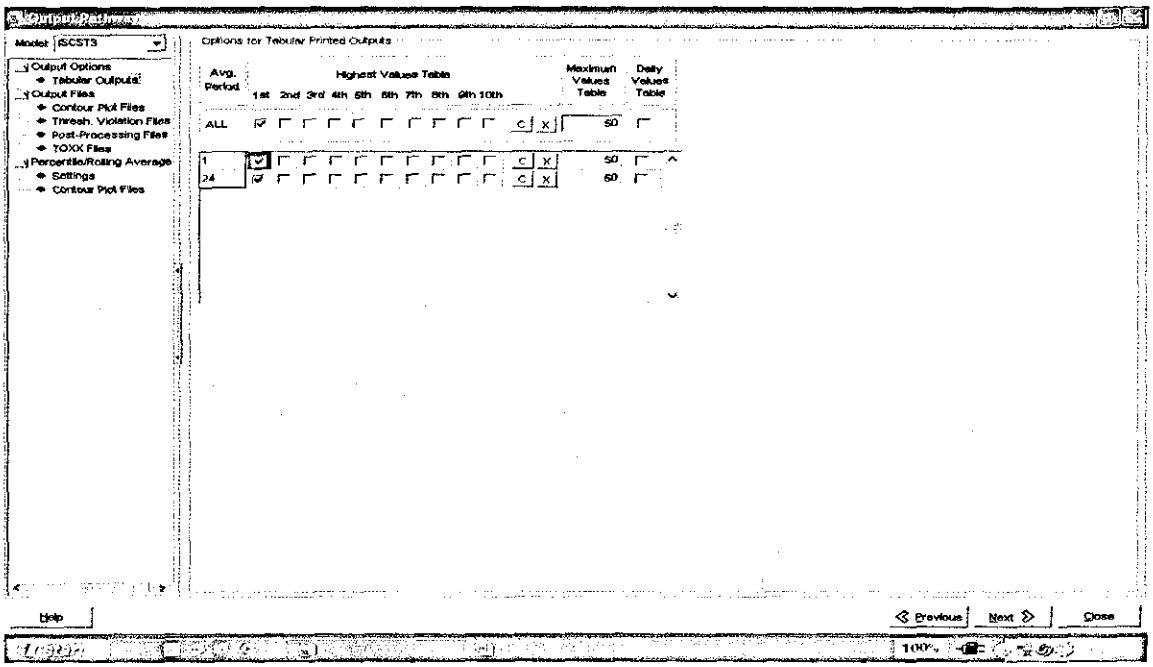
Step (9): The Discrete Cartesian page allows you to define one or more discrete Cartesian receptors.



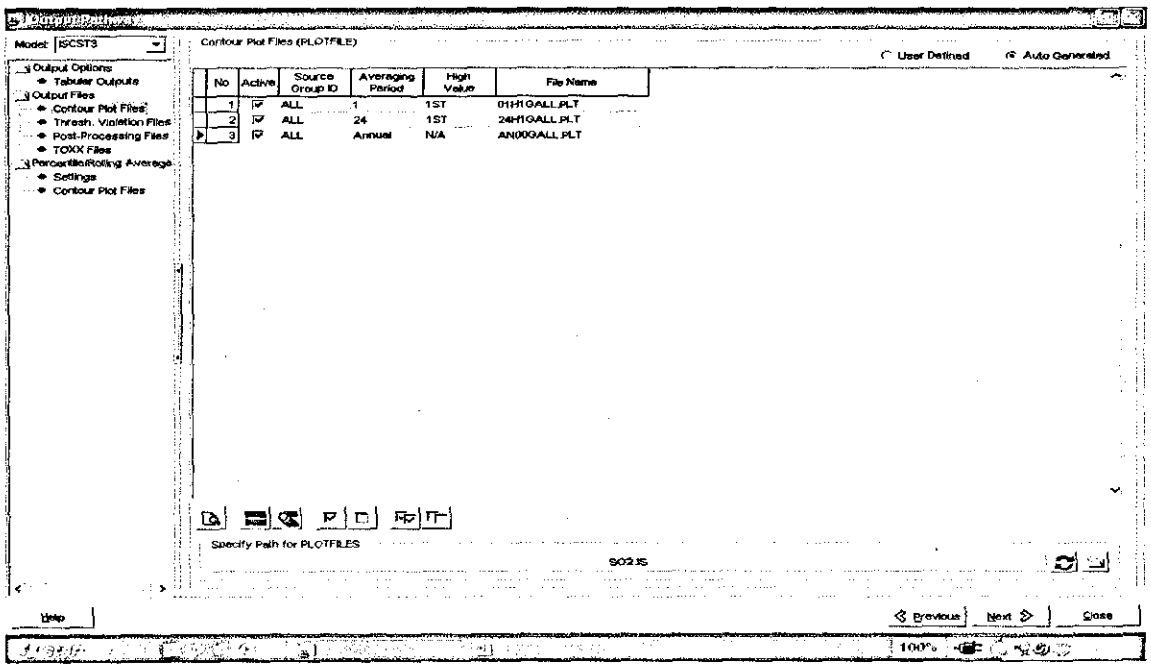
Step (10): The Meteorology Pathway allows you to specify the input meteorological data file and other meteorological variables, including the period to process for the meteorological files.



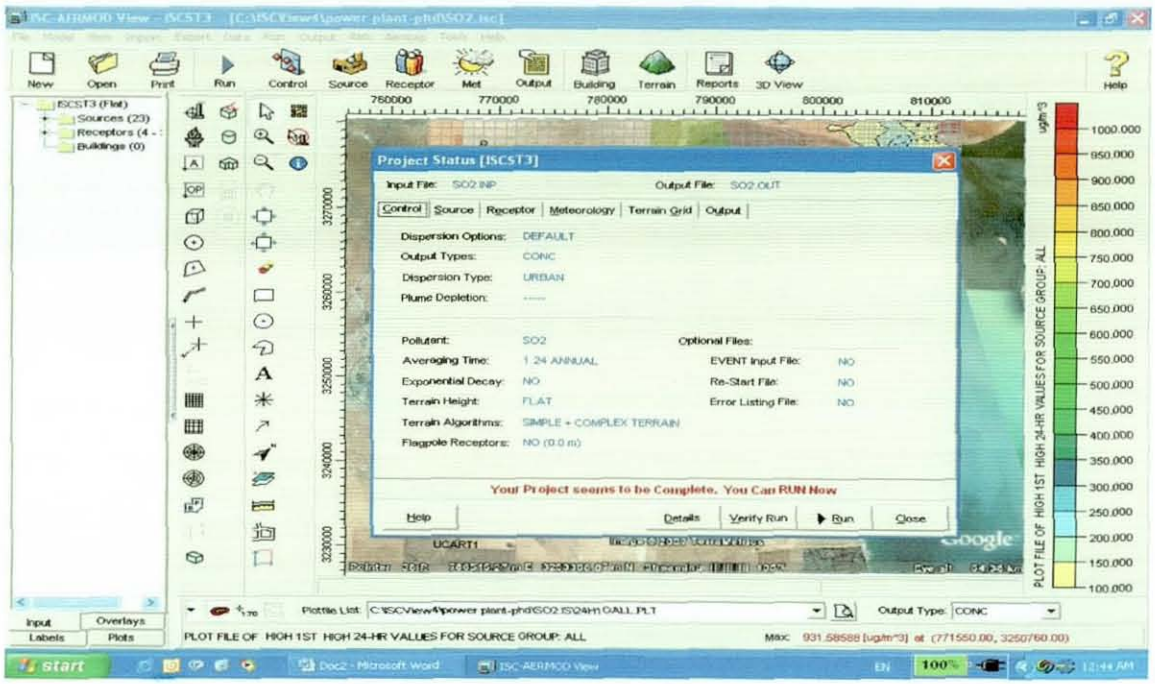
Step (11): The Data Period page allows you to specify particular days or ranges of days to process from the sequential meteorological file input if you do not want to read the entire met data file.



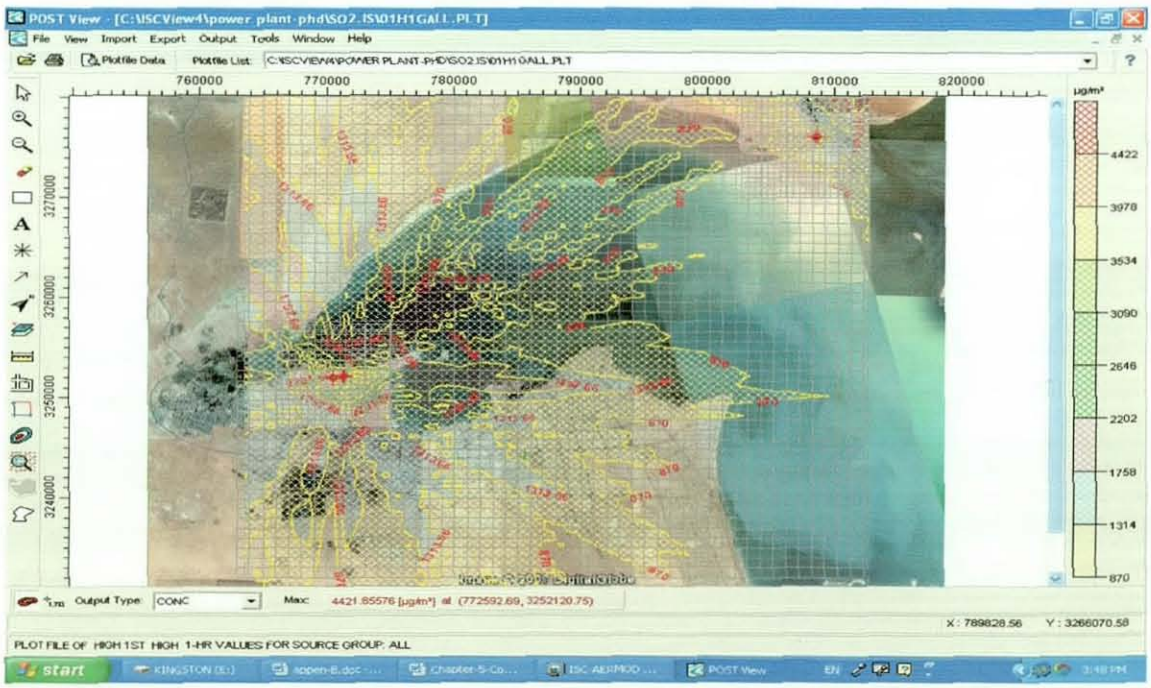
Step (12): The Output Pathway allows you to specify the output options for a particular run such as contour plot files and threshold violation files with 1st, 2nd, until 10th highest values. In the Tabular Outputs page you can define tabular output options for each short-term averaging period selected in the Pollutant averaging window of the Control Pathway.



Step (13): The Contour Plot Files page, allows you to produce files that are suitable for generating contour plots of the concentration and deposition results.



Step (14): The Project Status dialog provides you with a concise way of viewing all the options selected in your project. This dialog can be displayed by clicking on the menu toolbar button or by selecting **Run** and the model will start run.



Step (15): Sample of output as a contour plot for selected mesh area (study area) from ISCST4.5 model.

```
* ISCST3 (02035): impact of Doha and Sebyia power plant emission at rabia city
* MODELING OPTIONS USED:
*  CONC                    URBAN FLAT          DEFAULT
*          PLOT FILE OF  HIGH 1ST  HIGH  1-HR VALUES FOR SOURCE GROUP: ALL
*          FOR A TOTAL OF  3383 RECEPTORS.
*          FORMAT: (3(1X,F13.5),1X,F8.2,3X,A5,2X,A8,2X,A4,6X,A8)
*        X            Y        AVERAGE CONC   ZELEV     AVE     GRP       HIVAL    NET ID
*
  763592.68800 3231120.75000    662.34833      0.00    1-HR    ALL       1ST      UCART1
  764592.68800 3231120.75000    839.32660      0.00    1-HR    ALL       1ST      UCART1
  765592.68800 3231120.75000    906.24280      0.00    1-HR    ALL       1ST      UCART1
  766592.68800 3231120.75000   1136.55469      0.00    1-HR    ALL       1ST      UCART1
  767592.68800 3231120.75000   1160.84924      0.00    1-HR    ALL       1ST      UCART1
  768592.68800 3231120.75000    825.55811      0.00    1-HR    ALL       1ST      UCART1
  769592.68800 3231120.75000    697.58862      0.00    1-HR    ALL       1ST      UCART1
  770592.68800 3231120.75000    652.89624      0.00    1-HR    ALL       1ST      UCART1
  771592.68800 3231120.75000    988.95892      0.00    1-HR    ALL       1ST      UCART1
  772592.68800 3231120.75000   1136.40527      0.00    1-HR    ALL       1ST      UCART1
  773592.68800 3231120.75000   1094.16028      0.00    1-HR    ALL       1ST      UCART1
  774592.68800 3231120.75000    952.30066      0.00    1-HR    ALL       1ST      UCART1
  775592.68800 3231120.75000    946.61169      0.00    1-HR    ALL       1ST      UCART1
  776592.68800 3231120.75000    881.89514      0.00    1-HR    ALL       1ST      UCART1
  777592.68800 3231120.75000    881.10602      0.00    1-HR    ALL       1ST      UCART1
  778592.68800 3231120.75000   1112.91260      0.00    1-HR    ALL       1ST      UCART1
  779592.68800 3231120.75000   1239.65613      0.00    1-HR    ALL       1ST      UCART1
  780592.68800 3231120.75000   1143.45703      0.00    1-HR    ALL       1ST      UCART1
  781592.68800 3231120.75000    973.01117      0.00    1-HR    ALL       1ST      UCART1
  782592.68800 3231120.75000    919.87683      0.00    1-HR    ALL       1ST      UCART1
  783592.68800 3231120.75000    773.50574      0.00    1-HR    ALL       1ST      UCART1
  784592.68800 3231120.75000    904.65942      0.00    1-HR    ALL       1ST      UCART1
  785592.68800 3231120.75000    979.00806      0.00    1-HR    ALL       1ST      UCART1
  786592.68800 3231120.75000    878.98505      0.00    1-HR    ALL       1ST      UCART1
  787592.68800 3231120.75000    768.83136      0.00    1-HR    ALL       1ST      UCART1
  788592.68800 3231120.75000    850.61517      0.00    1-HR    ALL       1ST      UCART1
  789592.68800 3231120.75000    863.82855      0.00    1-HR    ALL       1ST      UCART1
  790592.68800 3231120.75000    749.17535      0.00    1-HR    ALL       1ST      UCART1
  791592.68800 3231120.75000    682.18481      0.00    1-HR    ALL       1ST      UCART1
  792592.68800 3231120.75000    759.75275      0.00    1-HR    ALL       1ST      UCART1
  793592.68800 3231120.75000    621.62024      0.00    1-HR    ALL       1ST      UCART1
  794592.68800 3231120.75000    571.12732      0.00    1-HR    ALL       1ST      UCART1
```

Step (16): Sample of output at each receptors over the selected mesh area.

```
                    *** THE MAXIMUM   SO  24-HR AVERAGE CONCENTRATION   VALUES FOR SOURCE GROUP:  ALL      ***
                    INCLUDING SOURCE(S):    DE1/4   , DE2/4   , DE3/4   , DE4/4   , DE1/3   , DE2/3   , DE3/3
      DW1/4   , DW2/4   , DW3/4   , DW4/4   , DW1/44  , DW2/44  , DW3/44  , DW4/44  , SB1/4   , SB2/4   , SB3/4   , SB4/4
      SB1/44  , SB2/44  , SB3/44  , SB4/44  ,

                         ** CONC OF SO2       IN MICROGRAMS/M**3                    **

RANK        CONC     (YYMMDDHH) AT      RECEPTOR (XR,YR) OF TYPE    RANK        CONC     (YYMMDDHH) AT      RECEPTOR (XR,YR) OF
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  1.     931.58588c(01070924) AT ( 771550.00, 3250760.00)  GC      26.     718.14722 (01070524) AT ( 772063.19, 3250677.50)
  2.     893.68457 (01082124) AT ( 771550.00, 3250760.00)  GC      27.     713.24384 (01051624) AT ( 771550.00, 3250260.00)
  3.     893.44403 (01090224) AT ( 771550.00, 3250760.00)  GC      28.     713.22748c(01071524) AT ( 772063.19, 3250677.50)
  4.     870.86395c(01071624) AT ( 771550.00, 3250760.00)  GC      29.     706.12024c(01070924) AT ( 772063.19, 3250677.50)
  5.     851.49554 (01052324) AT ( 771550.00, 3250760.00)  GC      30.     704.85040 (01041324) AT ( 771550.00, 3250760.00)
  6.     827.27466 (01060824) AT ( 771550.00, 3250260.00)  GC      31.     703.56195c(01071524) AT ( 772050.00, 3250760.00)
  7.     819.10944c(01070924) AT ( 772050.00, 3250260.00)  GC      32.     702.46094c(01071424) AT ( 771550.00, 3250260.00)
  8.     805.89264 (01082224) AT ( 771550.00, 3250760.00)  GC      33.     700.88788 (01072324) AT ( 771550.00, 3250760.00)
  9.     804.34357 (01090224) AT ( 772050.00, 3250260.00)  GC      34.     699.90454 (01060724) AT ( 771550.00, 3250260.00)
 10.     799.83844 (01082124) AT ( 771550.00, 3250260.00)  GC      35.     694.59149c(01071324) AT ( 771550.00, 3250760.00)
 11.     794.80933 (01070324) AT ( 772063.19, 3250677.50)  GC      36.     694.14105 (01082124) AT ( 772050.00, 3249760.00)
 12.     786.26508 (01062324) AT ( 771550.00, 3250760.00)  GC      37.     693.15356c(01042524) AT ( 769050.00, 3252760.00)
 13.     778.25586 (01070324) AT ( 772050.00, 3250760.00)  GC      38.     687.35986 (01061824) AT ( 771550.00, 3250760.00)
 14.     773.36694 (01082124) AT ( 772050.00, 3250260.00)  GC      39.     687.14191 (01090124) AT ( 771550.00, 3250260.00)
 15.     769.88702 (01070324) AT ( 771550.00, 3250760.00)  GC      40.     686.60858 (01052224) AT ( 772050.00, 3249760.00)
 16.     766.24420 (01052224) AT ( 771550.00, 3250260.00)  GC      41.     686.49536 (01070524) AT ( 772050.00, 3250760.00)
 17.     758.82233 (01060724) AT ( 771550.00, 3250760.00)  GC      42.     683.32629c(01070924) AT ( 772550.00, 3249760.00)
 18.     741.83466 (01082424) AT ( 771550.00, 3250760.00)  GC      43.     680.80688 (01082424) AT ( 772063.19, 3250677.50)
 19.     740.79272 (01052324) AT ( 772050.00, 3250260.00)  GC      44.     680.59344 (01052424) AT ( 772050.00, 3250760.00)
 20.     736.75061c(01071624) AT ( 772050.00, 3250260.00)  GC      45.     680.38568 (01070324) AT ( 771550.00, 3251260.00)
 21.     729.46613 (01041724) AT ( 771550.00, 3250760.00)  GC      46.     679.76404 (01082324) AT ( 771550.00, 3250760.00)
 22.     728.52655 (01052224) AT ( 771550.00, 3250760.00)  GC      47.     679.74115 (01082224) AT ( 771550.00, 3250260.00)
 23.     721.56403 (01082024) AT ( 771550.00, 3250260.00)  GC      48.     678.41412 (01070324) AT ( 772050.00, 3250260.00)
 24.     720.92731 (01061024) AT ( 771550.00, 3250760.00)  GC      49.     676.96503 (01090224) AT ( 772550.00, 3249760.00)
 25.     720.32074c(01071524) AT ( 771550.00, 3250760.00)  GC      50.     676.54564 (01070324) AT ( 772550.00, 3250260.00)

*** RECEPTOR TYPES:  GC = GRIDCART
                     GP = GRIDPOLR
                     DC = DISCCART
                     DP = DISCPOLR
```

Step (17): Sample of output of highest 50 values (hourly, daily and annually) over the selected mesh area.

Sample of Input and Output Report of ISCST4.5 Model

```
****************************************
**
** ISCST4.5 Input Produced by:
** ISC-AERMOD View Ver. 4.5
** Lakes Environmental Software Inc.
** Date: 3/13/2008
** File: C:\ISCView4\power plant-phd\SO2.INP
**
****************************************
**
**
****************************************
** ISCST3 Control Pathway
****************************************
**
**
CO STARTING
   TITLEONE impact of Doha and Sabyia power plant emission at rabia
city
   MODELOPT DFAULT CONC  URBAN
   AVERTIME 1 24 PERIOD
   POLLUTID SO2
   TERRHGTS FLAT
   RUNORNOT RUN
CO FINISHED
**
****************************************
** ISCST4.5 Source Pathway
****************************************
```

```
**
**
SO STARTING
** Source Location **
** Source ID - Type - X Coord. - Y Coord. **
   LOCATION DE1/4 POINT 771366.810 3252090.890
   LOCATION DE2/4 POINT 771366.810 3252090.900
   LOCATION DE3/4 POINT 771366.800 3252090.890
   LOCATION DE4/4 POINT 771366.800 3252090.900
   LOCATION DE1/3 POINT 771467.260 3252110.650
   LOCATION DE2/3 POINT 771467.260 3252110.660
   LOCATION DE3/3 POINT 771467.250 3252110.650
   LOCATION DW1/4 POINT 770574.010 3251911.920
   LOCATION DW2/4 POINT 770574.010 3251912.030
   LOCATION DW3/4 POINT 770573.880 3251911.920
   LOCATION DW4/4 POINT 770573.880 3251912.030
   LOCATION DW1/44 POINT 770548.710 3252070.290
   LOCATION DW2/44 POINT 770548.710 3252070.520
   LOCATION DW3/44 POINT 770548.440 3252070.290
   LOCATION DW4/44 POINT 770548.440 3252070.520
   LOCATION SB1/4 POINT 808733.260 3276032.300
   LOCATION SB2/4 POINT 808733.260 3276032.800
   LOCATION SB3/4 POINT 808732.750 3276032.300
   LOCATION SB4/4 POINT 808732.750 3276032.800
   LOCATION SB1/44 POINT 808554.840 3276032.300
   LOCATION SB2/44 POINT 808554.840 3276032.800
   LOCATION SB3/44 POINT 808554.340 3276032.300
   LOCATION SB4/44 POINT 808554.320 3276032.810
** Source Parameters **
   SRCPARAM DE1/4 2965 196.000 408.000 29.40000 3.500
```

```
SRCPARAM DE2/4 2965 196.000 408.000 29.40000 3.500
SRCPARAM DE3/4 2965 196.000 408.000 29.40000 3.500
SRCPARAM DE4/4 2965 196.000 408.000 29.40000 3.500
SRCPARAM DE1/3 2965 196.000 408.000 29.40000 3.500
SRCPARAM DE2/3 2965 196.000 408.000 29.40000 3.500
SRCPARAM DE3/3 2965 196.000 408.000 29.40000 3.500
SRCPARAM DW1/4 7534 190.000 403.000 29.40000 4.300
SRCPARAM DW2/4 7534 190.000 403.000 29.40000 4.300
SRCPARAM DW3/4 7534 190.000 403.000 29.40000 4.300
SRCPARAM DW4/4 7534 190.000 403.000 29.40000 4.300
SRCPARAM DW1/44 7534 190.000 403.000 29.40000 4.300
SRCPARAM DW2/44 7534 190.000 403.000 29.40000 4.300
SRCPARAM DW3/44 7534 190.000 403.000 29.40000 4.300
SRCPARAM DW4/44 7534 190.000 403.000 29.40000 4.300
SRCPARAM SB1/4 4070 192.000 426.000 28.80000 4.300
SRCPARAM SB2/4 4070 192.000 426.000 28.80000 4.300
SRCPARAM SB3/4 4070 192.000 426.000 28.80000 4.300
SRCPARAM SB4/4 4070 192.000 426.000 28.80000 4.300
SRCPARAM SB1/44 4070 192.000 426.000 28.80000 4.300
SRCPARAM SB2/44 4070 192.000 426.000 28.80000 4.300
SRCPARAM SB3/44 4070 192.000 426.000 28.80000 4.300
SRCPARAM SB4/44 4070 192.000 426.000 28.80000 4.300
EMISFACT DE1/3-DE4/4 MONTH 0.06 0.05 0.04 0.06 0.10 0.10
EMISFACT DE1/3-DE4/4 MONTH 0.12 0.13 0.11 0.11 0.07 0.06
EMISFACT DW1/4-DW4/44 MONTH 0.05 0.05 0.07 0.09 0.10 0.10
EMISFACT DW1/4-DW4/44 MONTH 0.11 0.12 0.09 0.09 0.07 0.06
EMISFACT SB1/4-SB4/44 MONTH 0.05 0.04 0.05 0.07 0.10 0.13
EMISFACT SB1/4-SB4/44 MONTH 0.14 0.14 0.11 0.06 0.04 0.06
SRCGROUP ALL
SO FINISHED
```

```
**
****************************************
** ISCST4.5 Receptor Pathway
****************************************
**
**
RE STARTING
   GRIDCART UCART1 STA
                    XYINC 763593.00 50 1000.00 3231121.00 50 1000.00
   GRIDCART UCART1 END
   GRIDCART UCART3 STA
                    XYINC 766050.00 21 500.00 3247260.00 21 500.00
   GRIDCART UCART3 END
   GRIDCART UCART2 STA
                    XYINC 802816.00 21 500.00 3270005.00 21 500.00
   GRIDCART UCART2 END
** DESCRREC "" ""
   DISCCART    785626.03   3244048.41
RE FINISHED
**
****************************************
** ISCST4.5 Meteorology Pathway
****************************************
**
**
ME STARTING
   INPUTFIL C:\ISCView4\RAMMET~1\2001kw.met
   ANEMHGHT 10 METERS
   SURFDATA 1500 2001
   UAIRDATA 1 2001
```

```
ME FINISHED
**
****************************************
** ISCST4.5 Output Pathway
****************************************
**
**
OU STARTING
   RECTABLE ALLAVE 1ST
   RECTABLE 1 1ST
   RECTABLE 24 1ST
   MAXTABLE ALLAVE 50
** Auto-Generated Plotfiles
   PLOTFILE 1 ALL 1ST SO2.IS\01H1GALL.PLT
   PLOTFILE 24 ALL 1ST SO2.IS\24H1GALL.PLT
   PLOTFILE PERIOD ALL SO2.IS\PE00GALL.PLT
OU FINISHED

***********************************
*** SETUP Finishes Successfully ***
***********************************


 *** ISCST4.5 - VERSION 02035 ***    *** impact of Doha and Sabyia
power plant emission at rabia city         ***        03/13/08

                                        ***
***        02:36:35

**MODELOPTs:
PAGE   1

CONC                    URBAN FLAT         DFAULT


                                           ***     MODEL SETUP OPTIONS
SUMMARY        ***
```

```
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -


**Intermediate Terrain Processing is Selected


**Model Is Setup For Calculation of Average CONCentration Values.


  --  SCAVENGING/DEPOSITION LOGIC --
**Model Uses NO DRY DEPLETION.  DDPLETE =  F
**Model Uses NO WET DEPLETION.  WDPLETE =  F
**NO WET SCAVENGING Data Provided.
**NO GAS DRY DEPOSITION Data Provided.
**Model Does NOT Use GRIDDED TERRAIN Data for Depletion Calculations


**Model Uses URBAN Dispersion.


**Model Uses Regulatory DEFAULT Options:
          1. Final Plume Rise.
          2. Stack-tip Downwash.
          3. Buoyancy-induced Dispersion.
          4. Use Calms Processing Routine.
          5. Not Use Missing Data Processing Routine.
          6. Default Wind Profile Exponents.
          7. Default Vertical Potential Temperature Gradients.
          8. "Upper Bound" Values for Supersquat Buildings.
          9. Half-life of 4 hrs for URBAN SO2.


**Model Assumes Receptors on FLAT Terrain.


**Model Assumes No FLAGPOLE Receptor Heights.
```

```
**Model Calculates  2 Short Term Average(s) of:  1-HR  24-HR
    and Calculates PERIOD Averages

**This Run Includes:    23 Source(s);      1 Source Group(s); and
3383 Receptor(s)

**The Model Assumes A Pollutant Type of:  SO2

**Model Set To Continue RUNning After the Setup Testing.

**Output Options Selected:

        Model Outputs Tables of PERIOD Averages by Receptor

        Model Outputs Tables of Highest Short Term Values by Receptor
(RECTABLE Keyword)

        Model Outputs Tables of Overall Maximum Short Term Values
(MAXTABLE Keyword)

        Model Outputs External File(s) of High Values for Plotting
(PLOTFILE Keyword)

**NOTE:  The Following Flags May Appear Following CONC Values:  c for
Calm Hours

                                                                  m for
Missing Hours

                                                                  b for
Both Calm and Missing Hours

**Misc. Inputs:  Anem. Hgt. (m) =    10.00 ;    Decay Coef. =
0.4810E-04 ;    Rot. Angle =     0.0

                 Emission Units = GRAMS/SEC
;  Emission Rate Unit Factor =   0.10000E+07

                 Output Units   = MICROGRAMS/M**3

**Approximate Storage Requirements of Model =     1.4 MB of RAM.

**Input Runstream File:          SO2.INP
```

```
**Output Print File:                SO2.OUT


 *** ISCST4.5 - VERSION 02035 ***     *** impact of Doha and Sabyia
power plant emission at rabia city          ***        03/13/08

                                        ***
***        02:36:35

**MODELOPTs:
PAGE   2

CONC                      URBAN FLAT         DFAULT

                                                   *** POINT SOURCE DATA


             NUMBER EMISSION RATE                        BASE     STACK
STACK    STACK     STACK    BUILDING EMISSION RATE

   SOURCE     PART.  (GRAMS/SEC)     X        Y       ELEV.    HEIGHT
TEMP.   EXIT VEL. DIAMETER   EXISTS   SCALAR VARY

     ID       CATS.                (METERS) (METERS) (METERS) (METERS)
(DEG.K)  (M/SEC)  (METERS)                BY
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - -


  DE1/4         0   0.29650E+04  771366.8 3252091.0     0.0   196.00
408.00    29.40     3.50      NO       MONTH

  DE2/4         0   0.29650E+04  771366.8 3252091.0     0.0   196.00
408.00    29.40     3.50      NO       MONTH

  DE3/4         0   0.29650E+04  771366.8 3252091.0     0.0   196.00
408.00    29.40     3.50      NO       MONTH

  DE4/4         0   0.29650E+04  771366.8 3252091.0     0.0   196.00
408.00    29.40     3.50      NO       MONTH

  DE1/3         0   0.29650E+04  771467.3 3252110.8     0.0   196.00
408.00    29.40     3.50      NO       MONTH

  DE2/3         0   0.29650E+04  771467.3 3252110.8     0.0   196.00
408.00    29.40     3.50      NO       MONTH

  DE3/3         0   0.29650E+04  771467.3 3252110.8     0.0   196.00
408.00    29.40     3.50      NO       MONTH

  DW1/4         0   0.75340E+04  770574.0 3251912.0     0.0   190.00
403.00    29.40     4.30      NO       MONTH

  DW2/4         0   0.75340E+04  770574.0 3251912.0     0.0   190.00
403.00    29.40     4.30      NO       MONTH
```

```
  DW3/4          0   0.75340E+04  770573.9 3251912.0      0.0    190.00
403.00    29.40      4.30       NO        MONTH

  DW4/4          0   0.75340E+04  770573.9 3251912.0      0.0    190.00
403.00    29.40      4.30       NO        MONTH

  DW1/44         0   0.75340E+04  770548.7 3252070.3      0.0    190.00
403.00    29.40      4.30       NO        MONTH

  DW2/44         0   0.75340E+04  770548.7 3252070.5      0.0    190.00
403.00    29.40      4.30       NO        MONTH

  DW3/44         0   0.75340E+04  770548.4 3252070.3      0.0    190.00
403.00    29.40      4.30       NO        MONTH

  DW4/44         0   0.75340E+04  770548.4 3252070.5      0.0    190.00
403.00    29.40      4.30       NO        MONTH

  SB1/4          0   0.40700E+04  808733.3 3276032.3      0.0    192.00
426.00    28.80      4.30       NO        MONTH

  SB2/4          0   0.40700E+04  808733.3 3276032.8      0.0    192.00
426.00    28.80      4.30       NO        MONTH

  SB3/4          0   0.40700E+04  808732.8 3276032.3      0.0    192.00
426.00    28.80      4.30       NO        MONTH

  SB4/4          0   0.40700E+04  808732.8 3276032.8      0.0    192.00
426.00    28.80      4.30       NO        MONTH

  SB1/44         0   0.40700E+04  808554.8 3276032.3      0.0    192.00
426.00    28.80      4.30       NO        MONTH

  SB2/44         0   0.40700E+04  808554.8 3276032.8      0.0    192.00
426.00    28.80      4.30       NO        MONTH

  SB3/44         0   0.40700E+04  808554.3 3276032.3      0.0    192.00
426.00    28.80      4.30       NO        MONTH

  SB4/44         0   0.40700E+04  808554.3 3276032.8      0.0    192.00
426.00    28.80      4.30       NO        MONTH

 *** ISCST3 - VERSION 02035 ***     *** impact of Doha and Sabyia power
plant emission at rabia city          ***        03/13/08

                                        ***
***        02:36:35

**MODELOPTs:
PAGE   3

CONC                     URBAN FLAT         DFAULT


                                          *** SOURCE IDs DEFINING
SOURCE GROUPS ***
```

```
GROUP ID                                                    SOURCE IDs


 ALL        DE1/4    , DE2/4    , DE3/4    , DE4/4    , DE1/3    , DE2/3    ,
DE3/3    , DW1/4    , DW2/4    , DW3/4    , DW4/4    , DW1/44   ,


            DW2/44   , DW3/44   , DW4/44   , SB1/4    , SB2/4    , SB3/4    ,
SB4/4    , SB1/44   , SB2/44   , SB3/44   , SB4/44   ,


 *** ISCST4.5 - VERSION 02035 ***     *** impact of Doha and Sabyia
power plant emission at rabia city          ***        03/13/08

                                        ***
***        02:36:35

**MODELOPTs:
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CONC                     URBAN FLAT         DFAULT


                              *** THE   1ST HIGHEST 24-HR AVERAGE
CONCENTRATION   VALUES FOR SOURCE GROUP:  ALL       ***

                                 INCLUDING SOURCE(S):      DE1/4    ,
DE2/4    , DE3/4    , DE4/4    , DE1/3    , DE2/3    , DE3/3    ,

         DW1/4    , DW2/4    , DW3/4    , DW4/4    , DW1/44   , DW2/44   ,
DW3/44   , DW4/44   , SB1/4    , SB2/4    , SB3/4    , SB4/4    ,

         SB1/44   , SB2/44   , SB3/44   , SB4/44   ,


                                 *** NETWORK ID: UCART2    ;  NETWORK
TYPE: GRIDCART ***


                                      ** CONC OF SO2       IN
MICROGRAMS/M**3                         **


 Y-COORD  |                                                   X-COORD
(METERS)

 (METERS) |       807816.00              808316.00
808816.00              809316.00              809816.00
```

```
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - - -


3280005.0 |     124.02457c(01092424)     106.11313c(01081124)
84.38451c(01080724)     109.48841c(01080724)     133.22636c(01080724)

3279505.0 |     141.37653c(01092424)     110.62547c(01081124)
91.83215c(01080724)     127.65515c(01080724)     150.14551c(01080724)

3279005.0 |     151.70911c(01092424)     116.15651c(01081124)
103.60117c(01080724)     152.55945c(01080724)     161.24159c(01080724)

3278505.0 |     176.42270c(01071924)     133.59769c(01081024)
122.28255c(01080724)     183.52090c(01080724)     160.86099c(01080724)

3278005.0 |     243.02670c(01071924)     152.76012c(01092424)
148.71283c(01080724)     211.56468c(01080724)     154.18819c(01080724)

3277505.0 |     268.92215c(01071924)     181.23933c(01080224)
168.75256c(01080724)     211.01915c(01080724)     151.98117c(01080724)

3277005.0 |     262.80042c(01073124)     244.09694c(01080624)
123.13531c(01080724)     169.53368c(01080724)     111.06025c(01080724)

3276505.0 |     226.77896c(01080524)      42.50222c(01080624)
17.60327c(01091824)      71.37485c(01071824)     177.59282c(01061324)

3276005.0 |     158.18701c(01080124)      18.43631c(01091824)
19.45936c(01091824)      96.76453c(01070424)     244.68474c(01070424)

3275505.0 |      61.26181c(01091524)      44.42733c(01050424)
63.95284c(01070924)     275.86035 (01070324)     352.92923 (01061124)

3275005.0 |     111.43416c(01091524)     202.18456 (01051024)
254.00130c(01090724)     528.92834c(01070924)     523.27051 (01070324)

3274505.0 |     116.05129c(01050424)     232.84724c(01083124)
268.19388c(01090724)     446.13074 (01060824)     526.80212c(01070924)

3274005.0 |     114.39651c(01050424)     226.31888c(01083124)
235.45772 (01053124)     299.85562 (01060524)     484.71347 (01060824)

3273505.0 |     105.71608c(01083124)     190.52776c(01083124)
195.62042 (01053124)     236.11717 (01060524)     351.47913 (01060824)

3273005.0 |     122.13719c(01083124)     154.92659c(01083124)
166.07884c(01090724)     184.92769 (01060524)     210.20996c(01081924)

3272505.0 |     122.95821c(01083124)     135.07181c(01081124)
145.21420c(01090724)     145.01430 (01060524)     167.63823 (01060524)

3272005.0 |     115.26306c(01083124)     121.56574c(01081124)
128.82727c(01090724)     122.83877 (01053124)     144.87941 (01060524)

3271505.0 |     104.09033c(01083124)     109.28439c(01081124)
115.70786c(01090724)     111.67697 (01053124)     134.78400c(01083124)
```

```
3271005.0 |      94.51983c(01081124)      98.43258c(01081124)
105.02481c(01090724)     101.19949 (01053124)     125.59764c(01083124)

3270505.0 |      95.95791c(01081124)      88.92178c(01081124)
96.18874c(01090724)      91.75459 (01053124)     112.96751c(01083124)

3270005.0 |      95.94086c(01081124)      80.57844c(01081124)
88.77355c(01090724)      83.41105 (01053124)      99.51469c(01083124)


 *** ISCST4.5 - VERSION 02035 ***     *** impact of Doha and Sabyia
power plant emission at rabia city          ***         03/13/08

                                        ***
***         02:36:35

**MODELOPTs:
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CONC                     URBAN FLAT          DFAULT


                              *** THE   1ST HIGHEST 24-HR AVERAGE
CONCENTRATION   VALUES FOR SOURCE GROUP:  ALL       ***

                                 INCLUDING SOURCE(S):      DE1/4    ,
DE2/4    , DE3/4    , DE4/4    , DE1/3    , DE2/3    , DE3/3    ,

         DW1/4    , DW2/4    , DW3/4    , DW4/4    , DW1/44   , DW2/44   ,
DW3/44   , DW4/44   , SB1/4    , SB2/4    , SB3/4    , SB4/4    ,

         SB1/44   , SB2/44   , SB3/44   , SB4/44   ,


                                  *** NETWORK ID: UCART2    ;  NETWORK
TYPE: GRIDCART ***

                                      ** CONC OF SO2       IN
MICROGRAMS/M**3                         **

 Y-COORD  |                                                  X-COORD
(METERS)

 (METERS) |       810316.00              810816.00
811316.00              811816.00              812316.00

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -


3280005.0 |    125.23138c(01080724)      86.71064c(01080724)
63.70474c(01080724)      57.91761c(01032224)      46.02917c(01032224)

3279505.0 |    120.20369c(01080724)      80.99305c(01080724)
63.81732c(01080724)      50.71775c(01080724)      40.12918c(01032224)
```

```
3279005.0 |     111.18723c(01080724)      80.09432c(01080724)
61.88711c(01080724)      43.73713c(01080724)      45.31535c(01062824)

3278505.0 |     106.87682c(01080724)      78.95562c(01080724)
52.79440c(01080724)      53.08024c(01062824)      57.50274c(01070824)

3278005.0 |     106.70596c(01080724)      66.24340c(01080724)
63.86359c(01062824)      73.73627c(01070824)      77.12646c(01070824)

3277505.0 |      86.89920c(01080724)      87.21072c(01070824)
96.42510c(01070824)      93.19890c(01070824)      84.10559c(01070824)

3277005.0 |     123.40489c(01070824)     122.05894c(01070824)
107.94554c(01070824)     100.87385c(01061324)      95.90845c(01061324)

3276505.0 |     210.09073c(01061324)     196.99234c(01061324)
173.36514c(01061324)     151.53456c(01061324)     134.40714c(01061324)

3276005.0 |     236.94141c(01070424)     208.46388c(01061324)
194.55516c(01070624)     195.71280c(01070624)     198.10124c(01070624)

3275505.0 |     251.71570c(01070424)     243.45963c(01070424)
211.30925c(01070424)     180.56624c(01070424)     156.69684c(01070624)

3275005.0 |     356.74741 (01061124)     261.07474 (01061124)
186.15602c(01070724)     163.67549c(01070724)     144.17310c(01070724)

3274505.0 |     434.22079 (01070324)     279.61459 (01060224)
227.43715 (01061124)     176.71025 (01061124)     136.27913c(01070724)

3274005.0 |     437.62704 (01090224)     337.38983 (01070324)
221.51857 (01060224)     181.63490 (01061124)     155.71397 (01061124)

3273505.0 |     371.95114c(01071424)     359.59225 (01090224)
266.37106 (01070324)     193.05200c(01062824)     162.08548c(01071024)

3273005.0 |     350.93533 (01060824)     291.41132c(01071424)
296.13333 (01090224)     215.61931 (01070324)     168.07974c(01062824)

3272505.0 |     261.36374 (01060824)     289.28067 (01060824)
246.53908c(01071624)     247.99171 (01090224)     180.34898 (01070524)

3272005.0 |     173.87843 (01060824)     264.15530 (01060824)
234.85823c(01071424)     215.55177c(01071624)     211.38957 (01090224)

3271505.0 |     130.84988c(01081924)     204.13576 (01060824)
235.85143 (01060824)     192.09026c(01071424)     190.78625 (01090224)

3271005.0 |     116.86095c(01083124)     147.40169 (01060824)
209.00029 (01060824)     199.28964c(01072124)     163.45049c(01070924)

3270505.0 |     123.65058c(01083124)     113.44522c(01090724)
166.08234 (01060824)     196.26350 (01060824)     179.99179c(01072124)

3270005.0 |     124.36079c(01083124)     102.08190c(01090724)
126.68336 (01060824)     171.40913 (01060824)     175.23576c(01072124)
```

```
 *** ISCST4.5 - VERSION 02035 ***     *** impact of Doha and Sabyia
power plant emission at rabia city          ***        03/13/08

                                        ***
***        02:36:35

**MODELOPTs:
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CONC                     URBAN FLAT         DFAULT

                              *** THE   1ST HIGHEST 24-HR AVERAGE
CONCENTRATION   VALUES FOR SOURCE GROUP:  ALL       ***

                                 INCLUDING SOURCE(S):      DE1/4    ,
DE2/4    , DE3/4    , DE4/4    , DE1/3    , DE2/3    , DE3/3    ,

         DW1/4    , DW2/4    , DW3/4    , DW4/4    , DW1/44   , DW2/44   ,
DW3/44   , DW4/44   , SB1/4    , SB2/4    , SB3/4    , SB4/4    ,

         SB1/44   , SB2/44   , SB3/44   , SB4/44   ,


                                  *** NETWORK ID: UCART2    ;  NETWORK
TYPE: GRIDCART ***


                                      ** CONC OF SO2       IN
MICROGRAMS/M**3                         **


 Y-COORD  |                                                   X-COORD
(METERS)

 (METERS) |       812816.00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -


3280005.0 |     37.45942c(01032224)

3279505.0 |     45.49342c(01072824)

3279005.0 |     46.49118c(01070824)

3278505.0 |     62.69369c(01070824)

3278005.0 |     74.50728c(01070824)

3277505.0 |     75.29710c(01070824)

3277005.0 |     97.29037c(01070824)

3276505.0 |    121.50710c(01061324)
```

```
3276005.0 |     200.09221c(01070624)

3275505.0 |     157.46588c(01070624)

3275005.0 |     131.53775c(01070424)

3274505.0 |     130.01523c(01070724)

3274005.0 |     129.15025 (01061124)

3273505.0 |     131.79131 (01060324)

3273005.0 |     146.57368c(01071024)

3272505.0 |     145.75615c(01062824)

3272005.0 |     154.83138 (01070524)

3271505.0 |     183.02209 (01090224)

3271005.0 |     172.44336 (01090224)

3270505.0 |     158.53189c(01062224)

3270005.0 |     155.31590c(01072124)


 *** ISCST4.5 - VERSION 02035 ***     *** impact of Doha and Sabyia
power plant emission at rabia city          ***        03/13/08

                                        ***

***        02:36:35

**MODELOPTs:
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CONC                    URBAN FLAT        DFAULT


                              *** THE   1ST HIGHEST 24-HR AVERAGE
CONCENTRATION   VALUES FOR SOURCE GROUP:  ALL      ***

                                 INCLUDING SOURCE(S):      DE1/4    ,
DE2/4    , DE3/4    , DE4/4    , DE1/3    , DE2/3    , DE3/3    ,

         DW1/4    , DW2/4    , DW3/4    , DW4/4    , DW1/44   , DW2/44   ,
DW3/44   , DW4/44   , SB1/4    , SB2/4    , SB3/4    , SB4/4    ,

         SB1/44   , SB2/44   , SB3/44   , SB4/44   ,

                                          *** DISCRETE CARTESIAN
RECEPTOR POINTS ***


                                       ** CONC OF SO2       IN
MICROGRAMS/M**3                          **
```

```
     X-COORD (M)  Y-COORD (M)        CONC      (YYMMDDHH)
X-COORD (M)  Y-COORD (M)        CONC      (YYMMDDHH)

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

       785626.00   3244048.50      101.48782  (01042724)


 *** ISCST4.5 - VERSION 02035 ***    *** impact of Doha and Sabyia
power plant emission at rabia city         ***        03/13/08

                                        ***
***        02:36:35

**MODELOPTs:
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CONC                     URBAN FLAT         DFAULT


                                *** THE MAXIMUM   50   1-HR AVERAGE
CONCENTRATION   VALUES FOR SOURCE GROUP:  ALL      ***

                                      INCLUDING SOURCE(S):    DE1/4    ,
DE2/4    , DE3/4    , DE4/4    , DE1/3    , DE2/3    , DE3/3    ,

         DW1/4    , DW2/4    , DW3/4    , DW4/4    , DW1/44   , DW2/44   ,
DW3/44   , DW4/44   , SB1/4    , SB2/4    , SB3/4    , SB4/4    ,

         SB1/44   , SB2/44   , SB3/44   , SB4/44   ,
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                                        ** CONC OF SO2      IN
MICROGRAMS/M**3                           **


RANK        CONC    (YYMMDDHH) AT      RECEPTOR (XR,YR) OF TYPE    RANK
CONC    (YYMMDDHH) AT      RECEPTOR (XR,YR) OF TYPE

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   1.    4421.21777 (01080304) AT ( 772593.00, 3252121.00)  GC
26.    3136.31445 (01081702) AT ( 771593.00, 3250121.00)  GC

   2.    3944.37402 (01080304) AT ( 772550.00, 3252260.00)  GC
27.    3131.02319 (01080304) AT ( 772050.00, 3252260.00)  GC

   3.    3782.18652 (01080304) AT ( 773050.00, 3252260.00)  GC
28.    3083.54443 (01040803) AT ( 769550.00, 3252260.00)  GC

   4.    3729.97583 (01080602) AT ( 769593.00, 3253121.00)  GC
29.    3080.91748 (01081003) AT ( 770050.00, 3254760.00)  GC

   5.    3663.68335 (01080304) AT ( 772550.00, 3251760.00)  GC
30.    3077.71826 (01082505) AT ( 772050.00, 3250760.00)  GC

   6.    3631.47363 (01080602) AT ( 769050.00, 3253760.00)  GC
31.    3075.54248 (01080103) AT ( 769550.00, 3251760.00)  GC

   7.    3629.14307 (01080602) AT ( 769550.00, 3253260.00)  GC
32.    3053.22485 (01080602) AT ( 768550.00, 3253760.00)  GC

   8.    3565.10791 (01080304) AT ( 773050.00, 3251760.00)  GC
33.    3044.11694 (01073103) AT ( 771050.00, 3253760.00)  GC

   9.    3488.46753 (01080304) AT ( 773593.00, 3252121.00)  GC
34.    3026.71338 (01052501) AT ( 773550.00, 3252260.00)  GC

  10.    3402.50854 (01061302) AT ( 773050.00, 3252260.00)  GC
35.    3021.65796 (01082505) AT ( 771550.00, 3250760.00)  GC

  11.    3364.60352 (01080803) AT ( 770050.00, 3253260.00)  GC
36.    3005.87866 (01082805) AT ( 772593.00, 3252121.00)  GC

  12.    3362.50830 (01080602) AT ( 769050.00, 3253260.00)  GC
37.    3002.91699 (01070203) AT ( 772550.00, 3252760.00)  GC

  13.    3350.38916 (01080602) AT ( 768593.00, 3254121.00)  GC
38.    2995.57544 (01083105) AT ( 771550.00, 3250260.00)  GC

  14.    3333.55762 (01080603) AT ( 770050.00, 3253260.00)  GC
39.    2992.14160 (01080801) AT ( 769050.00, 3254260.00)  GC

  15.    3333.08252 (01080304) AT ( 773550.00, 3252260.00)  GC
40.    2990.82520 (01052505) AT ( 772550.00, 3252760.00)  GC

  16.    3284.11646 (01081003) AT ( 770050.00, 3254260.00)  GC
41.    2985.83447 (01081003) AT ( 770050.00, 3253760.00)  GC
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  17.    3235.24463 (01070203) AT ( 772550.00, 3252260.00)  GC
42.    2969.22217 (01080304) AT ( 774050.00, 3252260.00)  GC

  18.    3233.14917 (01080304) AT ( 772050.00, 3251760.00)  GC
43.    2967.99902 (01061302) AT ( 772593.00, 3252121.00)  GC

  19.    3218.57813 (01080602) AT ( 768550.00, 3254260.00)  GC
44.    2961.47607 (01052501) AT ( 773050.00, 3252260.00)  GC

  20.    3208.48584 (01080304) AT ( 773550.00, 3251760.00)  GC
45.    2953.50757 (01083105) AT ( 771593.00, 3250121.00)  GC

  21.    3169.32397 (01081702) AT ( 771550.00, 3250260.00)  GC
46.    2935.00269 (01070203) AT ( 772050.00, 3252260.00)  GC

  22.    3159.45850 (01061302) AT ( 773550.00, 3252260.00)  GC
47.    2923.67041 (01080905) AT ( 770050.00, 3253760.00)  GC

  23.    3158.71826 (01080202) AT ( 769550.00, 3253760.00)  GC
48.    2921.89917 (01072402) AT ( 776050.00, 3250260.00)  GC

  24.    3158.42236 (01070203) AT ( 773050.00, 3252760.00)  GC
49.    2919.16211 (01071402) AT ( 773050.00, 3251260.00)  GC

  25.    3147.64136 (01061302) AT ( 772550.00, 3252260.00)  GC
50.    2914.80298 (01072402) AT ( 774550.00, 3250760.00)  GC

 *** RECEPTOR TYPES:  GC = GRIDCART

                      GP = GRIDPOLR

                      DC = DISCCART

                      DP = DISCPOLR

                      BD = BOUNDARY


 *** ISCST4.5 - VERSION 02035 ***    *** impact of Doha and Sabyia
power plant emission at rabia city         ***        03/13/08

                                        ***

***        02:36:35

**MODELOPTs:
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CONC                    URBAN FLAT         DFAULT


                                  *** THE MAXIMUM   50  24-HR AVERAGE
CONCENTRATION   VALUES FOR SOURCE GROUP:  ALL      ***

                                     INCLUDING SOURCE(S):    DE1/4    ,
DE2/4    , DE3/4    , DE4/4    , DE1/3    , DE2/3    , DE3/3    ,
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         DW1/4    , DW2/4    , DW3/4    , DW4/4    , DW1/44   , DW2/44   ,
DW3/44   , DW4/44   , SB1/4    , SB2/4    , SB3/4    , SB4/4    ,

         SB1/44   , SB2/44   , SB3/44   , SB4/44   ,


                                          ** CONC OF SO2       IN
MICROGRAMS/M**3                             **


RANK        CONC     (YYMMDDHH) AT      RECEPTOR (XR,YR) OF TYPE    RANK
CONC     (YYMMDDHH) AT      RECEPTOR (XR,YR) OF TYPE

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   1.     931.58588c(01070924) AT ( 771550.00, 3250760.00)  GC
26.     721.56403 (01082024) AT ( 771550.00, 3250260.00)  GC

   2.     893.68457 (01082124) AT ( 771550.00, 3250760.00)  GC
27.     720.92731 (01061024) AT ( 771550.00, 3250760.00)  GC

   3.     893.44403 (01090224) AT ( 771550.00, 3250760.00)  GC
28.     720.32074c(01071524) AT ( 771550.00, 3250760.00)  GC

   4.     870.86395c(01071624) AT ( 771550.00, 3250760.00)  GC
29.     720.15411 (01052224) AT ( 771593.00, 3250121.00)  GC

   5.     851.49554 (01052324) AT ( 771550.00, 3250760.00)  GC
30.     713.24384 (01051624) AT ( 771550.00, 3250260.00)  GC

   6.     827.27466 (01060824) AT ( 771550.00, 3250260.00)  GC
31.     704.85040 (01041324) AT ( 771550.00, 3250760.00)  GC

   7.     822.47235 (01070324) AT ( 771593.00, 3251121.00)  GC
32.     703.56195c(01071524) AT ( 772050.00, 3250760.00)  GC

   8.     819.10944c(01070924) AT ( 772050.00, 3250260.00)  GC
33.     702.46094c(01071424) AT ( 771550.00, 3250260.00)  GC

   9.     805.89264 (01082224) AT ( 771550.00, 3250760.00)  GC
34.     700.88788 (01072324) AT ( 771550.00, 3250760.00)  GC

  10.     804.34357 (01090224) AT ( 772050.00, 3250260.00)  GC
35.     699.90454 (01060724) AT ( 771550.00, 3250260.00)  GC

  11.     799.83844 (01082124) AT ( 771550.00, 3250260.00)  GC
36.     694.59149c(01071324) AT ( 771550.00, 3250760.00)  GC

  12.     791.97113 (01060824) AT ( 771593.00, 3250121.00)  GC
37.     694.14105 (01082124) AT ( 772050.00, 3249760.00)  GC

  13.     786.26508 (01062324) AT ( 771550.00, 3250760.00)  GC
38.     693.67505c(01071524) AT ( 771593.00, 3251121.00)  GC

  14.     778.25586 (01070324) AT ( 772050.00, 3250760.00)  GC
39.     693.15356c(01042524) AT ( 769050.00, 3252760.00)  GC
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  15.     773.36694 (01082124) AT ( 772050.00, 3250260.00)  GC
40.     692.40106 (01082024) AT ( 771593.00, 3250121.00)  GC

  16.     769.88702 (01070324) AT ( 771550.00, 3250760.00)  GC
41.     687.35986 (01061824) AT ( 771550.00, 3250760.00)  GC

  17.     766.24420 (01052224) AT ( 771550.00, 3250260.00)  GC
42.     687.14191 (01090124) AT ( 771550.00, 3250260.00)  GC

  18.     758.82233 (01060724) AT ( 771550.00, 3250760.00)  GC
43.     686.60858 (01052224) AT ( 772050.00, 3249760.00)  GC

  19.     748.61115 (01070524) AT ( 771593.00, 3251121.00)  GC
44.     686.49536 (01070524) AT ( 772050.00, 3250760.00)  GC

  20.     741.83466 (01082424) AT ( 771550.00, 3250760.00)  GC
45.     683.32629c(01070924) AT ( 772550.00, 3249760.00)  GC

  21.     740.79272 (01052324) AT ( 772050.00, 3250260.00)  GC
46.     680.59344 (01052424) AT ( 772050.00, 3250760.00)  GC

  22.     739.06110 (01082124) AT ( 771593.00, 3250121.00)  GC
47.     680.38568 (01070324) AT ( 771550.00, 3251260.00)  GC

  23.     736.75061c(01071624) AT ( 772050.00, 3250260.00)  GC
48.     679.76404 (01082324) AT ( 771550.00, 3250760.00)  GC

  24.     729.46613 (01041724) AT ( 771550.00, 3250760.00)  GC
49.     679.74115 (01082224) AT ( 771550.00, 3250260.00)  GC

  25.     728.52655 (01052224) AT ( 771550.00, 3250760.00)  GC
50.     678.41412 (01070324) AT ( 772050.00, 3250260.00)  GC


 *** RECEPTOR TYPES:  GC = GRIDCART

                      GP = GRIDPOLR

                      DC = DISCCART

                      DP = DISCPOLR

                      BD = BOUNDARY


 *** ISCST4.5 - VERSION 02035 ***    *** impact of Doha and Sabyia
power plant emission at rabia city        ***        03/13/08

                                        ***

***        02:36:35

**MODELOPTs:
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CONC                    URBAN FLAT         DFAULT
```

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                                        *** THE SUMMARY OF MAXIMUM
PERIOD (  8760 HRS) RESULTS ***


                                     ** CONC OF SO2      IN
MICROGRAMS/M**3                        **


NETWORK

GROUP ID                        AVERAGE CONC                RECEPTOR
(XR, YR, ZELEV, ZFLAG)    OF TYPE  GRID-ID

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - -


ALL       1ST HIGHEST VALUE IS     230.77510 AT (  771550.00,
3250760.00,       0.00,       0.00)  GC   UCART3

          2ND HIGHEST VALUE IS     205.33424 AT (  772050.00,
3250260.00,       0.00,       0.00)  GC   UCART3

          3RD HIGHEST VALUE IS     192.56792 AT (  772050.00,
3250760.00,       0.00,       0.00)  GC   UCART3

          4TH HIGHEST VALUE IS     184.81851 AT (  771550.00,
3250260.00,       0.00,       0.00)  GC   UCART3

          5TH HIGHEST VALUE IS     176.31947 AT (  771593.00,
3251121.00,       0.00,       0.00)  GC   UCART1

          6TH HIGHEST VALUE IS     174.10693 AT (  772550.00,
3249760.00,       0.00,       0.00)  GC   UCART3

          7TH HIGHEST VALUE IS     173.57573 AT (  772050.00,
3249760.00,       0.00,       0.00)  GC   UCART3

          8TH HIGHEST VALUE IS     172.84125 AT (  772550.00,
3250260.00,       0.00,       0.00)  GC   UCART3

          9TH HIGHEST VALUE IS     172.00847 AT (  772593.00,
3250121.00,       0.00,       0.00)  GC   UCART1

         10TH HIGHEST VALUE IS     171.95827 AT (  771593.00,
3250121.00,       0.00,       0.00)  GC   UCART1


 *** RECEPTOR TYPES:  GC = GRIDCART
```

```
                    GP = GRIDPOLR

                    DC = DISCCART

                    DP = DISCPOLR

                    BD = BOUNDARY


 *** ISCST4.5 - VERSION 02035 ***    *** impact of Doha and Sabyia
power plant emission at rabia city        ***        03/13/08

                                   ***
***        02:36:35

**MODELOPTs:
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CONC                    URBAN FLAT         DFAULT

                                               *** THE SUMMARY OF
HIGHEST  1-HR RESULTS ***



                                        ** CONC OF SO2      IN
MICROGRAMS/M**3                           **


                                                   DATE
NETWORK

GROUP ID                          AVERAGE CONC     (YYMMDDHH)
RECEPTOR  (XR, YR, ZELEV, ZFLAG)     OF TYPE  GRID-ID

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -


ALL      HIGH  1ST HIGH VALUE IS    4421.21777  ON 01080304: AT (
772593.00,  3252121.00,      0.00,      0.00)  GC   UCART1



 *** RECEPTOR TYPES:  GC = GRIDCART

                      GP = GRIDPOLR

                      DC = DISCCART

                      DP = DISCPOLR

                      BD = BOUNDARY
```

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 *** ISCST4.5 - VERSION 02035 ***    *** impact of Doha and Sabyia
power plant emission at rabia city         ***        03/13/08

                                        ***
***        02:36:35

**MODELOPTs:
PAGE  99

CONC                    URBAN FLAT         DFAULT

                                                 *** THE SUMMARY OF
HIGHEST 24-HR RESULTS ***

                                          ** CONC OF SO2      IN
MICROGRAMS/M**3                             **


                                                        DATE
NETWORK

GROUP ID                           AVERAGE CONC     (YYMMDDHH)
RECEPTOR  (XR, YR, ZELEV, ZFLAG)     OF TYPE  GRID-ID

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - -


ALL      HIGH  1ST HIGH VALUE IS     931.58588c ON 01070924: AT (
771550.00,  3250760.00,      0.00,      0.00)  GC   UCART3



 *** RECEPTOR TYPES:  GC = GRIDCART

                      GP = GRIDPOLR

                      DC = DISCCART

                      DP = DISCPOLR

                      BD = BOUNDARY

   ************************************

   *** ISCST3 Finishes Successfully ***

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