AIR POLLUTION MODELING FOR PETROCHEMICAL INDUSTRIES IN COASTAL AREAS

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By

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ABSTRACT

Air dispersion modeling is the mathematical estimation of pollutants from the emissions sources within a study area. This research focuses on how to rank air toxics from petrochemical industries in Yanbu industrial city in Saudi Arabia and assess their concentration levels at various receptor locations with time. To accomplish this objective, various processing involved in petrochemical industries were reviewed and for selected industries, emission inventory was developed using two sets of emission factor database (USEPA & WHO) and process involved, considering major pollutants simulation runs were made using AERMOD model. To estimate concentration levels at various receptors ambient air quality and meteorological data for three years were collected from petrochemical complex in Yanbu. Upper air and surface meteorological data were processed for use in the dispersion model AERMOD. A critical evaluation on mixing height estimation in urban area from radiosonde is presented; MH method from Sodar is also discussed briefly. A comparative evaluation is presented for the three years data of model in the region considering meteorological data gaps and uncertainties in the emission inventory compilation. Results shows pollution decreases uniformly from 2006 to 2008 and values are reasonable as per standards of Saudi Arabia. Most of the cases pollutants go towards the sea and from Yanbu to Jeddah directions. MH from radiosonde balloon gives non uniform values due to missing data; Comparing of AERMET processing MH and eight diagnostic models show Ayra [1981] correlates better. This study will help in determining long-term impact of pollutants on human health in the vicinity of the industrial complex and also in identifying mitigation measures and pollution control technologies for current operation and future expansion plan.

ACKNOWLEDGMENTS

By the name of Almighty Allah, The most Gracious, The most Merciful whose Peace and blessing is all-time with us.

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LIST OF ABBREVIATIONS

ASOS:	Automated Surface Observing Systems
ABL:	Atmospheric Boundary Layer
CCME:	Canadian Council of Ministers of the Environment
CD144:	Card Deck
COHb:	Carboxyhemoglobin
DOD:	Department of Defense
DQO:	Data quality objectives
EF:	Emission Factors
FAA:	Federal Aviation Administration
G|DP:	Gross Domestic Product
GMT:	Greenwich Mean Time
HC's:	Hydrocarbons
HUSWO:	Hourly United States Weather Observations
ISC:	Industrial Source Complex
KAAIA:	King Abdul Aziz International Airport
MH:	Mixing Height
ML:	Mixing Layer
MYAS:	Madinat Yanbu Al Sinwara
NAAQS:	National Ambient Air Quality Standards
NCDC:	National Climatic Data Center
NWS:	National Weather Service
O_3:	Ozone
PAHs:	Polycyclic Aromatic hydrocarbons
PBL:	Planetary Boundary Layer
PPM:	Parts Per Million
PRIME :	Plume Rise Model Enhancements
QA/QC:	Quality Assurance/Quality Control
QAPP:	Quality assurance project plan
RASS:	Radio Acoustic Sounding System
RCY:	Royal Commission for Yanbu
RCJY:	Royal Commission for Jubail and Yanbu
SAMSON:	Solar and Meteorological Surface Observation Network
SCRAM:	Support Center for Regulatory Air Models
SMOS:	Surface Meteorological Observation System
SODAR:	Sonic Detection And Ranging
TOC:	Total Organic Compounds
TSP:	Total Suspended Particulate
USEPA:	United States Environmental Protection Agency
USGS:	United States Geological Survey

UTM:	Universal Transverse Mercator
VHC:	Volatile Hydrocarbons
VOC:	Volatile Organic Compounds
WHO:	World Health Organization
YANPET:	Yanbu Petrochemical Co.
YPR:	Yanbu Petroleum Refinery

Chapter1

Introduction

1.1. Background of Study area:

In early 1970s, Saudi government launched a long-term national development plan and identified two coastal cities - Jubail on the east coast of the Arabian Gulf and Yanbu on the Red Sea in the west as two new industrial cities. In order to provide infrastructure and public services in these two cities, the Royal Commission for Jubail and Yanbu (RCJY) was established in 1975 as an independent legal entity. Currently, these cities produce more than 10% of the world's petrochemicals, contribute about 12% of the Kingdom's non-oil gross domestic product (GDP), and have created 70% of the Kingdom's non-oil exports. These cities have attracted over 50% of the total foreign investment in the Kingdom of Saudi Arabia. [EESAL, 1982]

A brief description of the primary industries in Yanbu industrial cities is presented in the following sections.

Yanbu Industrial City:

Yanbu Industrial City is located on the Red Sea coast some 350 kms. north west of Jeddah. Yanbu is currently host to 20 utilities for hydrocarbon, petrochemical and metallic industries; besides more than 40 utilities for light industries, Yanbu is also a port city.

By 1988, eight heavy industries were operating in Yanbu, including the Yanbu petroleum refinery (YPR) and the Al-Lajeen aluminum smelting plant, designed to

produce 220,000 tons of aluminums per year. Various heavy industries in Yanbu industrial city are as follows:

1. Arabian Industrial Fibre Co.
2. Safra Co. Ltd.
3. National Petroleum Company (Yanpet)
4. Yanbu National Petrochemical Company (Yansab)
5. Saudi Aramco Mobile Refinery Co.
6. Saudi Arabian Lube Additive Co. (SALACO)
7. Lubrizol Trans Arabian Co. Yanbu Refinery (SAMAREF)
8. Petromin Lubricating Oil Refinery Co.
9. Fuchus Petromin Saudi Arabian Ltd.
10. Crystal Arabian Chlorine Co.

Other than the above heavy industries, there are crude oil and chemical terminals, natural gas liquid facility, power plant and desalination units, wastewater treatment systems.

Safra is the biggest and most modern hydrocarbon plant in the Middle East producing aliphatic and aromatic solvents with huge storage capacities. The production capacity of the plant in Yanbu is continuously expanding to meet increasing demand for the products. Safra Company's facility is being expanded to produce more than 100,000 tons per year of BTX aromatics.

Yanbu National Petrochemical Company (Yansab) has been designed to produce 1.3 million tons per year of ethylene, 900,000 tons per year of polyethylene, 400,000 tons per year of polypropylene, 700,000 tons per year of ethylene glycol, 250,000 tons per year of benzene, xylene and toluene and 100,000 tons per year of butene 1 and butene 2.

National Petrochemical Company (Yanpet) is building a plant to produce approximately 400,000 tons per year of propylene from propane.

Yanbu is also the site of a significant Saudi Aramco project for an export refinery that will enable the oil giant to expand its role as both an upstream and a downstream exporter of hydrocarbons. The 400,000 bpd full-conversion refinery will process Arabian Heavy crude and produce high-quality, ultra-low sulfur refined products that meet current and future US and European product specifications. Already five projects have been commissioned at Yanbu II. In the basic industries category, Saudi Aramco Lubrication Oil Refining Co (Lubref) has set up a plant. The secondary industries category has plants by National Titanium Dioxide Co (Cristal); Hamrani-Fusch Petroleum Company; and Marjan Industrial Waste Treatment Company. Following figures shows the locations of Yanbu Industrial city on map.

Figure 1.1: Location of Yanbu Industrial City (Google map17/08/09)

Environmental Control Department in the Royal Commission for Yanbu (RCY) has set up an air quality program in Yanbu industrial city with four fixed air quality

stations and a mobile unit. The fixed station locations are shown in Figure 1.2 and are as follows:

- Station #1 is located in the buffering zone between the community area and Yanpet
- Station #2 is located near Lubref and the Jeddah-Yanbu highway
- Station #4 is located in the labour camp
- Station #5 is located near the liquefied natural gas (LNG) plant

The pollutants measured at these locations are SO_2, H_2S, CO, NO/NO_2, NMHC, PM_{10}, $PM_{2.5}$, CO, and O_3. These stations also record hourly data on wind speed, wind direction, ambient temperature, and humidity.

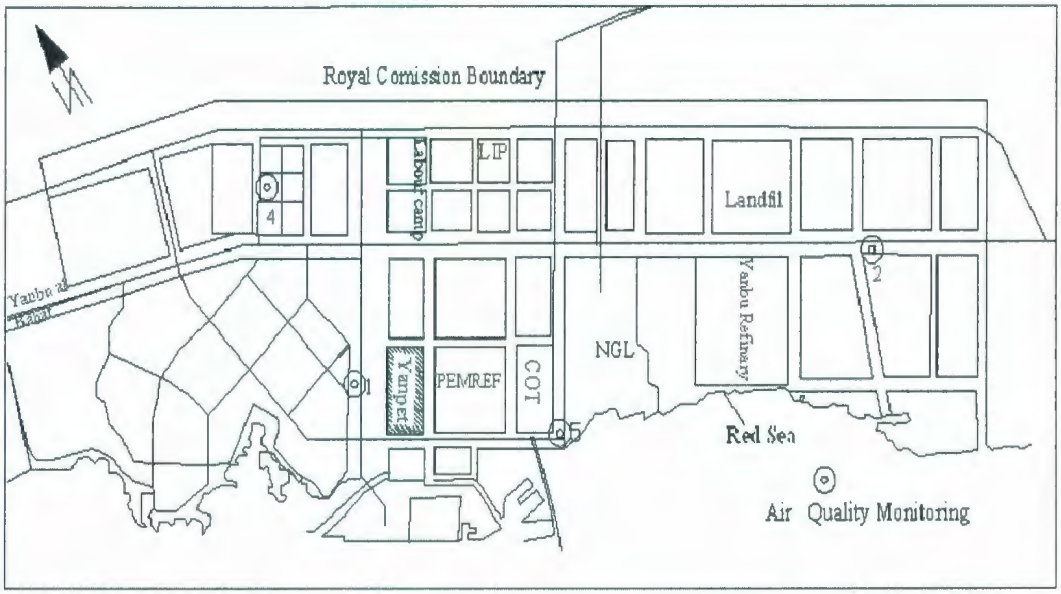


Figure 1.2: Location of Air quality monitoring station at Yanbu Industrial City

Based on the review of the feed stocks and products from the petrochemical industries in Yanbu industrial complexes, it is obvious that benzene, toluene, xylene,

ethylene, propylene, ethylene oxide, vinyl chloride, methanol, ethylene diamine, sulfuric acid, ethylbenzene, hydrogen sulfide, 1-3-butadiene, styrene, ammonia, solvents, industrial chemicals, and catalysts are the potential pollutants to the atmosphere from the plants. The emission rate of these pollution substances will however depend on the processing involved, control technology employed, and operations and maintenance in each industry.

1.2. Objectives of the research:

The main objective of this study to identify air toxics from petrochemical industries in Yanbu and assess their concentration levels at various receptor locations with time, and comparing these values with standards of Saudi Arabia for analysis of violations. This can be accomplished by measurements if adequate data is available or by air dispersion modeling task. Also make a critical evaluation on important parameter such as mixing height (MH) form radiosonde data for the use air dispersion model of urban city.

1.3. Scope of the study:

This study will help in the exposure assessment and health impact assessment from the petrochemical source emissions. This will also help in identifying gaps in the data collection in future studies. It will also guide in identifying mitigation strategies with the current emission and future expansion plan in both by protect human health and minimizing environmental impacts. The scopes of the research are:

(a) Review of ambient air quality and meteorological data being collected.

(b) Review of available emission data.

(c) Study of the chemical processing involved and development of emission inventory of selected primary industries using simplified approach if emission data is not adequate.

(d) Review of dispersion models and selecting the one most suitable considering availability of data and features of the study area.

(e) Meteorological and air quality data processing.

(f) Concentration estimate at various grids and receptor locations under current emission rates and meteorological conditions.

(g) Concentration estimate at various grids and receptor location for future expansion (considering expansion of industrial cities in the next twenty years).

1.4. Structure of the thesis:

Various chapters in this thesis are organized as follows:

Chapter 1 present's background information, research objectives, and study area identification.

Chapter 2 highlights methodology to measure of meteorological parameters, emerging technology for collecting meteorological data, Data formatting for suitable of Regulatory Air Dispersion models, missing data interpolating methodology, review of some air dispersion models with their applications and limitations and inter comparison of the model, overview of some approved met and terrain pre-processors and their inter comparison.

Mixing height methodology is presented in Chapter 3, this chapter also presents a critical review of different mixing height model with AERMOD processed mixing height

an application of urban area. Also compare radiosonde balloon mixing height with AERMOD mixing height.

Chapter 4 describes methodology for emission estimation using two set of emission factor database and case study for two major company of Yanbu city.

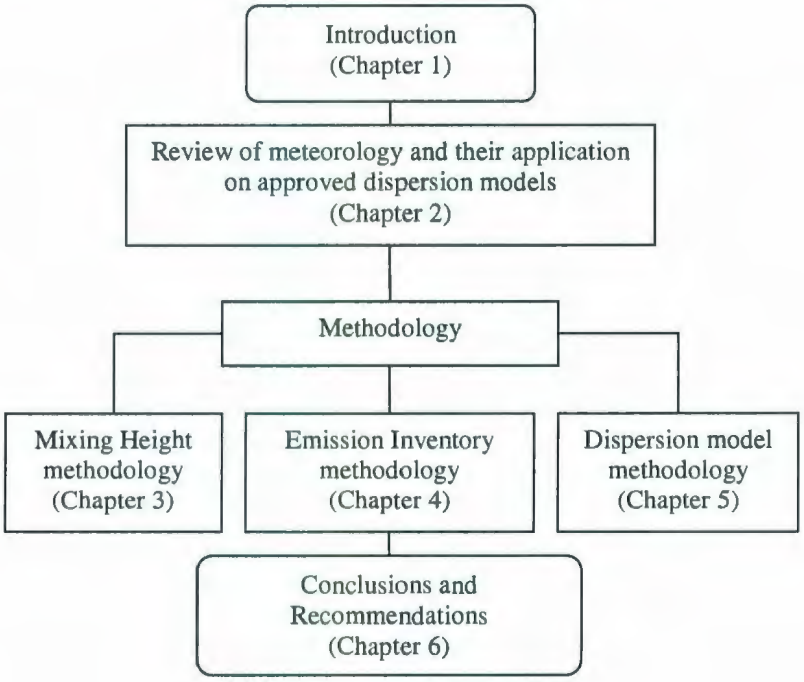


Figure1.3: Structure of the thesis

Methodology to apply AERMOD dispersion model is presented in Chapter 5. It also covers concentration estimates at various receptor points using hourly met data for three years (i.e., 2006, 2007, and 2008).

Chapter 6 summarizes findings of the study and highlights recommendations for future works. Figure 1.3: schematically shows how various chapters are organized in the study. Figure 1.4: showing flow diagram of my study.

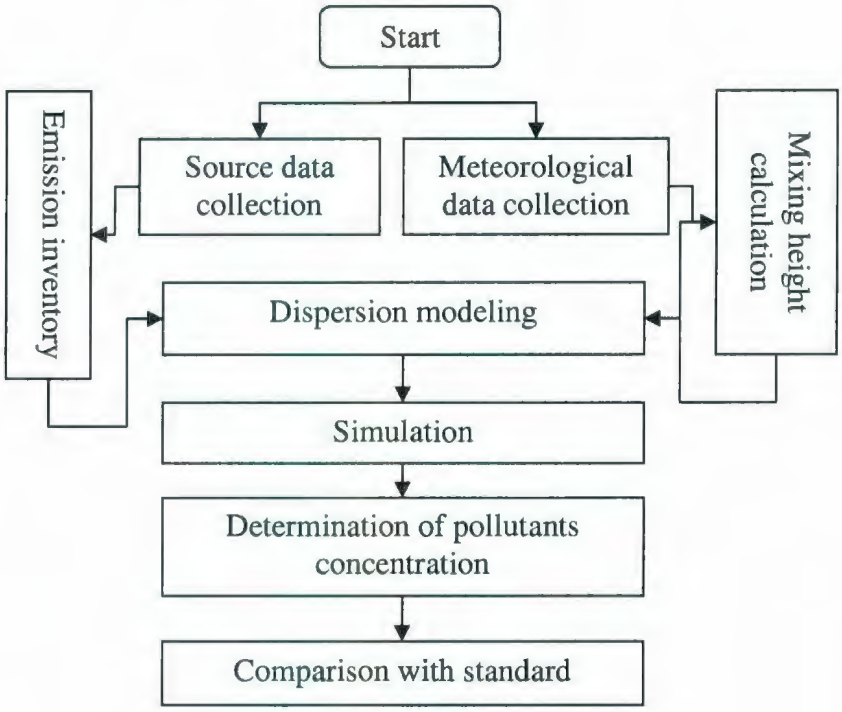


Figure1.4: Flow diagram of my study

Chapter 2

Review of Meteorology & Air Dispersion Modeling

2.1. Introduction:

The word meteorology (coming from Greek meteoros that means "high in the sky" and logia) is the interdisciplinary scientific study of the atmosphere that focuses on weather processes and forecasting. Generally there are two types of meteorological principle exists (1) boundary layer meteorology (2) dynamic meteorology. Boundary layer meteorology is the study of processes in the air layer directly above Earth's surface, known as the atmospheric boundary layer (ABL). For example: the effects of the surface-heating, cooling, and friction-cause turbulent mixing within the air layer. Boundary layer meteorology includes the study of all types of surface-atmosphere boundaries, including oceans, lakes, urban land and non-urban land. On the other hand, dynamic meteorology generally focuses on the physics of the atmosphere. For example: the idea of an air parcel is used to define the smallest element of the atmosphere, while ignoring the discrete molecular and chemical nature of the atmosphere. The fundamental laws of fluid dynamics, thermodynamics, and motion are used to study the atmosphere.

Meteorological data are one of the most important inputs into any air dispersion model. Ground-level concentrations of contaminants are primarily controlled by two meteorological elements: wind direction and speed (for transport), and turbulence and mixing height of the lower boundary layer (for dispersion).

The meteorological data requirements for steady-state Gaussian-plume models (e.g., AERMOD) and advanced dispersion models (e.g., CALPUFF) vary considerably. Steady-state Gaussian-plume models require meteorological data from a single surface station. In

case of the AERMOD, it is assumed that the single station data are applicable to the whole modelling domain up to the top of the boundary layer and that conditions do not vary with height.

Advanced dispersion models including puff, particle and grid models allow meteorological conditions to vary across the modelling domain and up through the atmosphere. This is more complex situation than for steady-state modelling and thus requires more meteorological data. Because meteorological sites do not provide the relevant data at every point in the modelling domain, a meteorological model is used to process and provide the meteorological variables at sites where information is not available. The advanced dispersion model then uses this pre-processed meteorological data for analysis. Because the meteorological data requirements vary greatly between these two model types, the choice of which dispersion model to use can depend on questions regarding the expected meteorological conditions.

There is a range of options for collecting and processing land-based meteorological data, including surface meteorological stations, tethered balloons, radiosonde upper air balloons, remote sensing systems, (sonic detection and ranging SODAR / radio acoustic sounding system RASS, Radar, Lidar) and satellites. Various meteorological processors are also available to process raw data into formats required by air dispersion models. Following are the descriptions of some equipment for collecting surface and upper air data of air dispersion modelling.

2.2. Meteorological data collection systems:

2.2.1. Surface Air Observations:

(a) **Surface Meteorological Observation System (SMOS)/weather station:**

A weather station is a facility with instruments and equipment to make observations of atmospheric conditions in order to provide information to make weather forecasts. The measurements taken include temperature, barometric pressure, humidity, wind speed, wind direction, and precipitation. Wind measurements are taken in open area free of obstructions, while temperature and humidity measurements are kept free from direct solar radiation, or insolation. Manual observations are taken at least once daily, while automated observations are taken at least once an hour [DOE/SC-ARM/TR-031, SMOS handbook, March 2008].

Typical weather stations have the following instruments:

- Thermometer for measuring temperature
- Barometer for measuring barometric pressure/air pressure
- Hygrometer for measuring humidity
- Anemometer for measuring wind speed
- Wind vane for measuring wind direction
- Rain gauge for measuring precipitation

Figure 2.1: SMOS Tower (National science digital library)

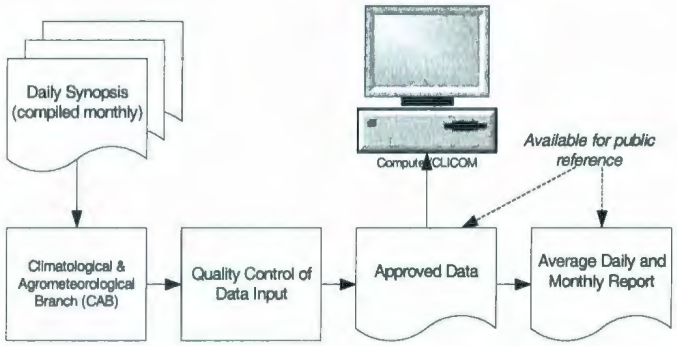


Figure 2.2: Flow of Surface Data Processing

(Francisco B. Amarra, Genandrialine L. Peralta)

(b) **Automated Surface Observing Systems (ASOS)**:

Automated Surface Observing Systems (ASOS) are automated sensor suites that are designed to serve aviation and meteorological observing needs for safe and efficient aviation operations and weather forecasting. Automated airport weather stations have become the backbone of weather observing in the United States and Canada and are becoming increasingly prevalent world-wide due to their efficiency and cost-savings. The ASOS program is a joint effort of the National Weather Service (NWS), the Federal Aviation Administration (FAA), and the Department of Defense (DOD). With the largest and most modern arrangement of weather sensors, the ASOS network has more than doubled the number of full-time surface weather observing locations. ASOS works on a non-stop basis, updating observations every minute. ASOS is installed at more than 900 airports, for example, one of these units is located at Central Park in New York City where they make observations. ASOS detects significant changes, disseminating hourly and special observations via the networks. Additionally, ASOS routinely and automatically provides computer-generated voice observations directly to aircraft in the

vicinity of airports, using FAA ground-to-air radio. These messages are also available via a telephone dial-in port. ASOS observes, formats, archives, and transmits observations automatically.

Figure 2.3: Typical ASOS Unit (Jet Stream - Online School for Weather)

ASOS transmits a special report when conditions exceed pre-selected weather element thresholds, e.g., the visibility decreases to less than 3 miles. ASOS observing parameters and its limitations are shows below:

Automated Surface Observing Systems (ASOS)		
Parameters	Measured by ASOS	Limitations of ASOS
Sky condition	Cloud height and cloud amount	In-cloud and cloud-to-cloud lightning,Clouds that are not directly above the station,Clouds that are more than twelve thousand feet above ground level,Cloud type
Basic present weather information	Type and intensity for rain, snow, and freezing rain	Precipitation that is not in the form of rain or snow, such as hail, ice pellets, and snow grains, Multiple forms of precipitation falling at the same time, Depth of new snowfall, Total snow depth
Pressure	Sea-level pressure and altimeter setting	

Temperature	Ambient temperature and dew point temperature	Volcanic eruptions
Wind	Direction, speed, and character (gusts, squalls)	Blowing dust, Falling ash, Tornadoes
Obstructions to vision	Fog and haze	Shallow or patchy fog, Smoke

Because many of these can pose dangers to aircraft and all of these are of interest to the meteorological community, most of the busier airports also have part-time or full-time human observers that augment, or provide additional information to, the automated airport weather station's observations. Research is on-going to allow the automated stations to detect many of these phenomena.[NOAA, National Weather Service]

2.2.2. Upper Air Observation:

(a) **Radiosonde upper air balloons:**

A radiosonde is a unit for use in weather ballons that measures various atmospheric parameters and transmits them to a fixed receiver. Radiosondes may operate at a radio frequency of 403 MHz or 1680 MHz and both types may be adjusted slightly higher or lower as required.A rubber or latex balloon filled with either helium or hydrogen lifts the device up through the atmosphere. The maximum altitude to which the balloon ascends is determined by the diameter and thickness of the balloon. Balloon sizes can range from 150 grams to 3000 grams. As the balloon ascends through the atmosphere, the pressure decreases, causing the balloon to expand. An 800 gram balloon will burst at about 21 kilometres (69,000 ft) [Dian J. Gaffen. Radiosonde Observations, 2008]. The weight of a radiosonde is typically 250 grams. It should also be noted that the average

radiosonde is lost and never recovered, however for the more expensive instrument packages balloon bourne unmanned gliders (or UAV's) are used to ensure recovery.

Worldwide there are more than 800 radiosonde launch sites. Most countries share data with the rest of the world through international agreements. Nearly all routine radiosonde launches occur at 0000 UTC and 1200 UTC to provide an instantaneous snapshot of the atmosphere. This is especially important for numerical modeling. Raw upper air data is routinely ingested by numerical models. Forecasters often view the data in a graphical format, plotted on thermodynamic diagrams such as Skew-T log-P diagrams, Tephigrams, and or Stuve diagrams, all useful for the interpretation of the atmosphere's vertical thermodynamics profile of temperature and moisture as well as kinematics of vertical wind profile.

Radiosonde Components:

The complete radiosonde system, or rawinsonde, consists of a balloon-borne radiosonde instrument package, a radio receiver, a tracking unit, and a recorder.

Figure 2.4: Upper Air Balloon (www.crh.noaa.gov/grb/, 17/04/09)

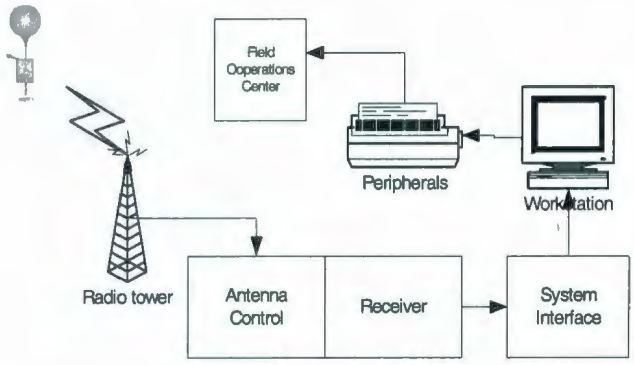


Figure 2.5: Upper Air Data Flow Diagram

(Francisco B. Amarra, Genandrialine L. Peralta)

Ground unit:

The following equipment is located at the upper air observing station to track the radiosonde, receive the telemetry data, and process these data into a useable form.

- Radio Receiver:
- Antenna
- Frequency Meter (Output to other devices)
- Pulse Controller
- Recorder
- Modern radiosondes measure or calculate the following variables:
- Pressure
- Altitude
- Geographical position (Latitude/Longitude)
- Temperature
- Relative humidity
- Wind speed and direction

- Ozone concentration

Radiosonde chart analysis:

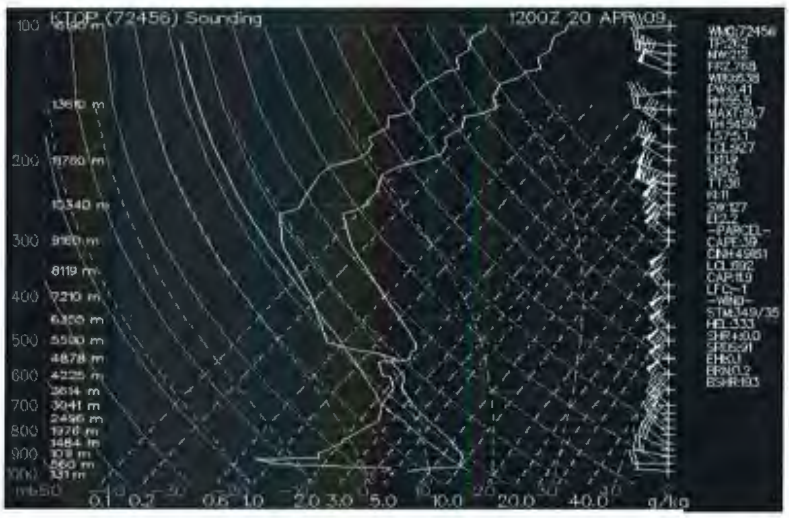


Figure 2.6: Skew T diagram (www.weather.unisys.com)

A Skew T plot is a standard plot used by meteorologists to analyze data from a balloon sounding. This is a plot of temperature with height as denoted by pressure. The pressure lines are plotted horizontally in blue and are also on an inverse log scale. The concept of Skew T means that the temperature is not plotted vertically but angles off to the right at a 450 angle. The temperature lines of the Skew T are in blue. The green lines are called dry adiabats. The light blue dashed lines are saturation adiabats. The yellow dashed lines are lines of constant mixing ratio. The sounding is plotted as two white lines. The right line is the temperature profile. The left line is the dew point profile. The winds are plotted as wind barbs with height (see below) on the right edge of the plot. The picture below shows the diagram.

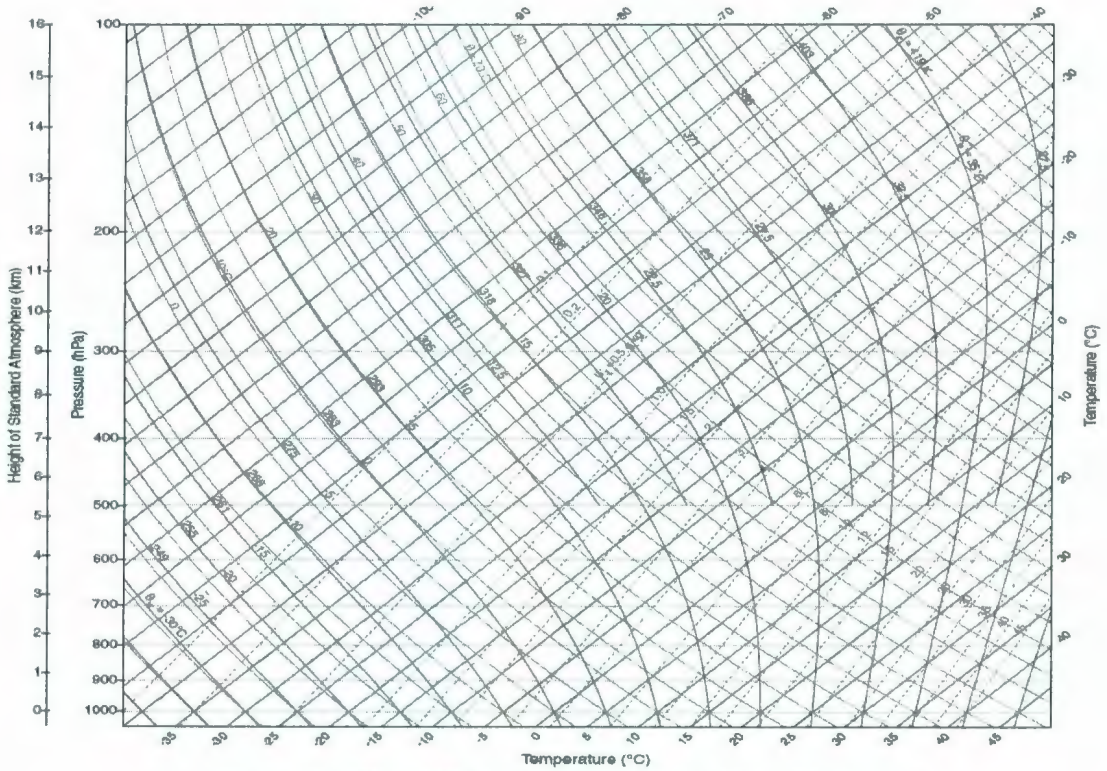


Figure 2.7: Skew T diagram (www.weather.unisys.com)

(b) **SODAR (Sonic Detection And Ranging)**:

SODAR is a meteorological instrument that measures the scattering of sound waves by atmospheric turbulence. Sodar systems are like radar (radio detection and ranging) systems except that sound waves rather than radio waves are used for detection. Other names used for Sodar systems include sounder, echo sounder and acoustic radar. Sodar systems are used to measure wind speed at various heights above the ground and the thermodynamic structure of the lower layer of the atmosphere. Commercial sodars operated for the purpose of collecting upper-air wind measurements consist of antennas that transmit and receive acoustic signals. A mono-static system uses the same antenna for transmitting and receiving, while a bi-static system uses separate antennas. The difference between the two antenna systems determines whether

atmospheric scattering is by temperature fluctuations (in mono-static systems) or by both temperature and wind velocity fluctuations (in bi-static systems).Most Sodar systems operate by issuing an acoustic pulse and then listen for the return signal for a short period of time. Generally, both the intensity and the Doppler (frequency) shift of the return signal are analyzed to determine the wind speed, wind direction and turbulent character of the atmosphere. A profile of the atmosphere as a function of height can be obtained by analyzing the return signal at a series of times following the transmission of each pulse. The return signal recorded at any particular delay time provides atmospheric data for a height that can be calculated based on the speed of sound.

Sodar systems typically have maximum ranges varying from a few hundred meters up to several hundred meters or higher. Maximum range is typically achieved at locations that have low ambient noise and moderate to high relative humidity. At desert locations, sodar systems tend to have reduced altitude performance because sound attenuates more rapidly in dry air.

(c) **Wind profiler:**

A wind profiler is a type of weather observing equipment that uses radar or sound waves (SODAR) to detect the wind speed and direction at various elevations above the ground. Readings are made at each kilometer above sea level, up to the extent of the troposphere (i.e., between 8 and 17 km above mean sea level). Above this level there is inadequate water vapor present to produce a radar "bounce." The data synthesized from wind direction and speed is very useful to meteorological forecasting and timely reporting for flight planning.

(d) **Radio Acoustic Sounding System (RASS) :**

A radio acoustic sounding system (RASS) is a system for measuring the atmospheric lapse rate using backscattering of radio waves from an acoustic wave front to measure the speed of sound at various heights above the ground. From the speed of sound, the temperature of the air in the planetary boundary layer can be computed [Raghavan, Soundararajan, 2003]. Since the speed of sound is related to temperature, temperature profiles can be obtained. The maximum altitude range of RASS systems is typically 750 meters, although observations have been reported up to 1.2 km in moist air [Kaimal, J., 1994]. Immediately adjacent to the profiler are four special speakers that are part of the Radio Acoustic Sounding System (RASS) in addition to the profiler.

2.2.3. Systems used for measure of some primary meteorological variables:

(a) **Wind Speed:**

Although wind is a vector quantity and may be considered as a primary variable in itself, it is more common to consider wind speed (the magnitude of the vector) and wind direction (the orientation of the vector) separately as scalar variables. Wind speed determines the amount of initial dilution experienced by a plume and appears in the denominator of the Gaussian dispersion equation. Wind speed is also used to determine the amount of plume rise and in downwash calculations. Wind speed may also be used, in conjunction with other variables, in the derivation of atmospheric stability categories. The most commonly used anemometers for air quality modelling and analysis purposes are:

1. Cup Anemometers

2. Vane-oriented and Fixed-mount Propeller Anemometers
3. Wind Speed Transducers

(b) **Wind Direction:**

Wind direction is generally defined as the orientation of the wind vector in the horizontal. Wind direction for meteorological purposes is defined as the direction from which the wind is blowing and is measured in degrees clockwise from true north. Wind direction determines the transport direction for a plume in Gaussian models. The standard deviation of the wind direction or elevation angle fluctuations, sigma theta and sigma phi, respectively, may also be used, in conjunction with wind speed, to derive the atmospheric stability category. The most common instrument for measuring wind direction is:

1. Wind Vanes
2. U-V and UVW Systems
3. Wind Direction Transducers
4. Standard Deviation and Turbulence Data

(c) **Temperature and Temperature Difference:**

The ambient temperature is used in determining the amount of rise experienced by a buoyant plume. The vertical temperature difference is used in calculating plume rise under stable atmospheric conditions and is also used in determining Monin-Obukhov length, a stability parameter. Both the temperature and temperature difference are measured by the following instrument:

1. Temperature Sensors (resistance temperature detector (RTD)
2. Thermocouples

(d) **Atmospheric Water Vapour:**

The quantity of water vapour in the atmosphere may be expressed in terms of several different units of measurement. These are: (l) vapour pressure; (2) saturation deficit; (3) relative humidity; (4) dew point temperature; (5) specific humidity; (6) mixing ratio; and (7) absolute humidity. All except relative humidity provide a complete specification of the amount of water vapour in the air. Determination of relative humidity requires that ambient temperature and pressure also be known [Middleton, W. E. K. and A. F. Spilhaus, 1953]., while no existing EPA regulatory models incorporate water vapour measurements, it may be an important variable in determining impacts from moist sources, such as cooling towers. It is also a useful measurement in validating other variables. Most on-site meteorological monitoring programs for air quality modelling applications incorporate dew point measurements. Many sensors that provide relative humidity measurements, typically in conjunction with a temperature measurement, are commercially available. Types of instrumentation are:

1. Psychrometers
2. Hygrometers

(e) **Precipitation:**

Precipitation, like water vapour, is not used by existing EPA regulatory models but provides useful information for the data review and validation process. It would also be important in considering the effects of wet deposition. The two main classes of precipitation measuring devices suitable for on-site meteorological programs are the:

1. Tipping bucket rain gauge and
2. Weighing rain gauge.

Both types of gauges measure total liquid precipitation.

(f) **Pressure:**

Atmospheric or barometric pressure can provide information to the meteorologist responsible for reviewing on-site data that may be useful in evaluating data trends and is also used in conjunction with air quality measurements. There are two basic types of instruments available for measuring atmospheric pressure:

1. Mercury barometer and
2. Aneroid barometer.

(g) **Radiation:**

Solar radiation and net radiation are related to the stability of the atmosphere. Cloud cover and ceiling height data, taken routinely at National Weather Service stations, provide an indirect estimation of radiation effects and are used in conjunction with wind speed to derive an atmospheric stability category. The instruments that are used most frequently to measure solar radiation are:

1. Pyranometer
2. Net radiometer
3. Pyrheliometer

(h) **Mixing Height:**

The depth of the mixed layer, or mixing height, is an important variable in EPA regulatory models. The mixing height determines the vertical extent of the dispersion process for releases below the mixing height, while releases above the mixing height are assumed to have no ground-level impacts. Morning and afternoon mixing heights are estimated for selected National Weather Service stations from the vertical temperature profiles observed at 1200 Greenwich Mean Time (GMT) and surface temperature measurements [Holzworth, G. C.,1972]. Hourly mixing heights are estimated from the

twice-daily mixing height values, sunrise and sunset times, and hourly stability categories by the meteorological pre-processor for EPA regulatory models [USEPA, 1977]. The Doppler SODAR provides another method for determining mixing height data that may be applicable on a case by case basis.

2.3. Meteorological data preparing for regulatory air dispersion model:

2.3.1. Meteorological data formats for surface air observations:

The SURFACE pathway defines all the necessary information for processing National Weather Service hourly surface weather observations data that complies with an established format. These data provide information on temperature, winds, and cloud cover (particularly important) that can be used in estimating dispersion parameters. Pre-processors can read and process a variety of formats. Hourly NWS surface observations are stored in a variety of compact formats. Data stored in one of these formats is referred to as archived data. For processing archive data on a PC, the file format must be specified as one of the following: Card Deck (CD144), Support Center for Regulatory Air Models (SCRAM), Solar and Meteorological Surface Observation Network (SAMSON), Hourly United States Weather Observations (HUSWO) or TD-3280.

2.3.2. Meteorological data formats for upper air observations:

The UPPERAIR pathway defines all the necessary information for processing National Weather Service rawinsonde (sounding) data. These data provide information on the vertical structure of the atmosphere. The height, pressure, dry bulb temperature, relative humidity (which is used to obtain dew point temperature), and winds are

reported. The data come from about 50 stations around the United States, and most countries in the world have an upper air observation program. The data are generally collected twice-daily, at 0000 Greenwich Mean Time (GMT) and 1200 GMT (these times are also referred to as 00Z and 12Z, respectively). Available formats for upper air mixing height are SCRAM and NCDC (TD-9689).

2.3.3. Rules for the Format of On-Site Data:

There is no standard archive format or content for on-site data, however, the U.S. EPA defines the following rules for the format of on-site data:

- The data for one observation period can be one or more data records, and the records for the period must be continuous;
- There can be up to 12 equally-spaced observation periods per hour, i.e., as frequent as every 5 minutes;
- The same set of variables must appear for all observation periods but not all the same variables must appear on every record in the observation period;
- The date and time information for each observation must be contained in the first record of the group; these may occur in any order within the first record, and must be integer format; on-site meteorological variables can appear on the first record;
- Single-level variables (e.g., heat flux and observed mixing heights) must be read before any multi-level variables (e.g., wind and temperature);
- The file must be ASCII and it must be in a form that can be read using Fortran FORMAT statements.

- Blanks in the format specification must be avoided because AERMET recognizes blanks as field delimiters on keywords.

2.4. Meteorological Pre-processors for Regulatory Air Dispersion Models:

A preprocessor is a program that processes its input data to produce output that is used as input to another program. The output is said to be a preprocessed form of the input data, which is often used by some subsequent programs like compilers.The pre-processor that organizes and processes meteorological data and estimates the necessary boundary layer parameters for dispersion calculations is known as meteorological pre-processors. Example: PCRAMMET, AERMET (met data pre-processors for AERMOD), AERMAP (terrain data pre-processors for AERMOD), CALMET (met data pre-processors for CALPUFF) etc. Brief of AERMOD pre-processors and CALPUFF pre-processors are discussed following sections.

2.4.1. Meteorological pre-processors for AERMOD model:

AERMET:

The AERMET program is a meteorological pre-processor that organizes and processes available meteorological data into a format suitable for use by the AERMOD air dispersion model. The AERMET program prepares hourly surface data and upper air data for use in the U.S. EPA AERMOD short-term air quality dispersion model. AERMET was designed to allow for future enhancements to process other types of data and to compute boundary layer parameters with different algorithms. There are three stages to processing the data. The first stage extracts meteorological data and assesses

data quality through a series of quality assessment checks. The second stage merges all data available for 24-hour periods and writes these data together in a single intermediate file. The third and final stage reads the merged meteorological data and estimates the necessary boundary layer parameters for dispersion calculations by AERMOD. The following flow chart shows details of AERMET data processing steps:

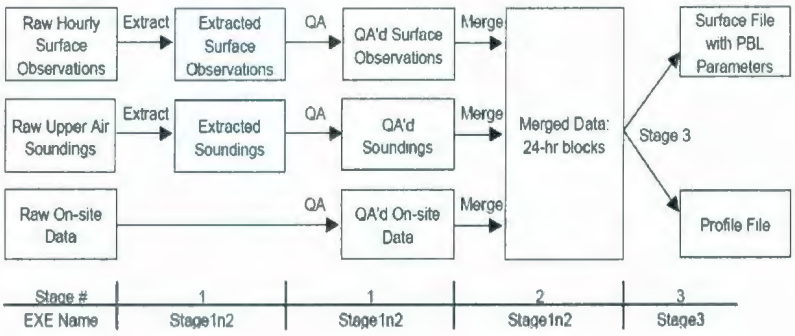


Figure 2.10: Steps of AERMET pre-processors (US EPA, 2002)

AERMET creates two files for AERMOD:

Surface File: a file of hourly boundary layer parameter estimates.

Profile File: is a file of multiple-level observations of wind speed, wind direction, temperature, and standard deviation of the fluctuating components of the wind.

AERMAP:

AERMAP has been developed to process the terrain data in conjunction with a layout of receptor and sources to be used in AERMOD control files. AERMOD does not process its own terrain. AERMAP has been designed to process the standardized data to produce terrain elevations for each receptor and source and a receptor hill height values

for use with complex terrain [USEPA, 1998]. AERAMP outputs the results in a format that can easily be cut and pasted into an AERMOD control file. With the assumption that terrain will affect air quality concentrations at individual receptors, AERMAP first determines the elevation at each receptor and source and then searches for the terrain height and location that has the greatest influence on dispersion for an individual receptor. This height is the referred to as the height scale. There are two basic types of input data that are needed to run AERMAP, the first is an input run stream file that directs the actions of AERMAP through a set of options, and defines the receptor and source locations. The second type of input data needed to run AERMAP is Digital Elevation Model (DEM) data. DEM data are computer files of evenly spaced terrain elevation points called nodes. Each DEM file covers a standardized section based on latitude and longitude coordinates. These data files are obtainable through several commercial internet sites and the United States Geological Survey (USGS).

2.4.2. Meteorological pre-processors for CALPUFF model:

PCRAMMET:

PCRAMMET is a meteorological pre-processor used for preparing National Weather Service (NWS) data for the use of U.S. EPA short term air quality dispersion models such as: ISCST3, CRSTER, RAM, MPTER, BLP, SHORTZ, and COMPLEX1. PCRAMMET is also used to prepare meteorological data for the CALTRANS model, CAL3QHCR and by the CALPUFF puff dispersion model [USEPA, June1999]. The operations performed by PCRAMMET include:

1. Calculating hourly values for atmospheric stability from meteorological surface observations;
2. Interpolating the twice daily mixing heights to hourly values;

3. Calculating the parameters for dry and wet deposition processes;
4. Outputting data in the standard (PCRAMMET unformatted) or ASCII format required by regulatory air quality dispersion models.

The input data requirements for PCRAMMET depend on the dispersion model and the model options for which the data is being prepared. The minimum input data requirements for PCRAMMET are:

1. The twice-daily mixing heights,
2. The hourly surface observations of wind speed, wind direction, dry bulb temperature, opaque cloud cover, and ceiling height.
3. Station pressure measurements are required for dry deposition estimates.
4. Precipitation type and precipitation amount measurements for those periods where precipitation was observed are required for wet deposition estimates.

PCRAMMET View supports a number of different file formats. The following is a schematic representation of the inputs necessary to run PCRAMMET.

CPRAMMET:

CPRAMMET is a modification to PCRAMMET that augments its treatment of relative humidity and solar radiation when preparing an 'ISC' met data file of the type accepted by CALPUFF. A mixing height file and a surface meteorological data file in CD144, SAMSON, or HUSWO format and produce an 'extended' ISC data file that may be used in CALPUFF. Other requires inputs are same to PCRAMMET.

CALMET:

CALMET is a pre-processor to CALPUFF. In recent years CALMET has been increasingly used in USA and Australasia and is used here to illustrate the features of a diagnostic meteorological model. The CALMET meteorological model [Scire et al., 2000] is a diagnostic meteorological model developed as a component of the CALPUFF modelling system for use in air quality applications. CALMET in its basic form is designed to produce hourly fields of three-dimensional winds and various micro-meteorological variables based on the input of routinely available surface and upper air meteorological observations only. CALMET consists of a diagnostic wind field module and micro-meteorological modules for over-water and over-land boundary layers.

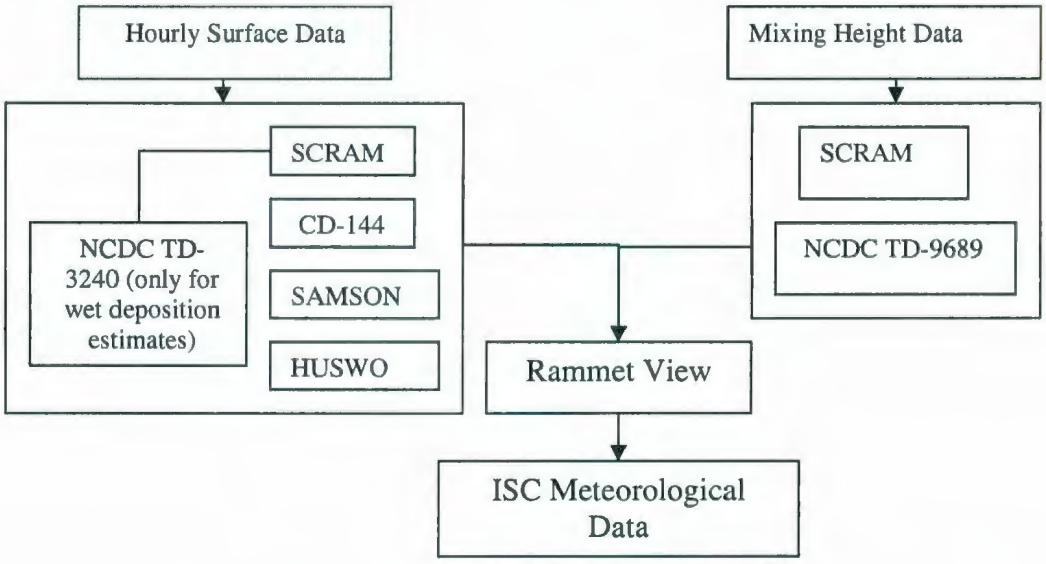


Figure 2.11: File format supporting by PCRAMMET

The diagnostic wind field module uses a two-step approach to the computation of the wind fields [Douglas and Kessler, 1998]. In the first step, the initial-guess wind field is adjusted for terrain effects to produce a step 1 wind field. The second step consists of

an objective analysis procedure to introduce observational data into the step 1 wind field to produce a final wind field, the step 2 wind field. The input data requirements for CALMET include:

Surface meteorological data: Hourly observations of: wind speed, wind direction, temperature, cloud cover, ceiling height, surface pressure, and relative- humidity.

Hourly precipitation data: Precipitation rates and precipitation type code (part of surface data file).

Upper air data: Twice-daily observed vertical profiles of: wind speed, wind direction, temperature, pressure, and elevation.

Hourly gridded wind fields (optional)

- MM4, MM5 output
- ETA, RUC2 output
- RAMS output

Over water observations (optional): Air-sea temperature difference, air temperature, relative humidity, over water mixing height, wind speed, wind direction, and overeater temperature gradients above and below mixing height.

Geophysical data: Gridded fields of: terrain elevations, land use categories, surface roughness length (optional), albedo (optional), bowen ratio (optional), soil heat flux (optional), anthropogenic heat flux (optional), and leaf area index (optional).

Advantages of CALMET:

- Observations can be incorporated into the model to produce realistic meteorological fields.

- CALMET can reproduce fine-scale effects (down to a couple of hundred metres' resolution) and still maintain efficient model run times on a personal computer.
- Output from the prognostic meteorological models such as MM5 and TAPM can be incorporated into the CALMET run, providing information in data-sparse regions. This combined approach is the preferred way of operating CALMET.

Disadvantages of CALMET:

- The CALMET/CALPUFF system is technically more advanced than a plume model and is perceived as being difficult to regulate and complex to use.
- There are potentially extra costs required for running CALMET.

2.4.3. Comparison between PCRAMMET, AERMET & CALMET pre-processors:

Table 2.1: Comparison between PCRAMMET, AERMET & CALMET

Features	PCRAMMET	AERMET	CALMET
Surface input data	Wind speed, wind direction, dry bulb temperature, opaque cloud cover, and ceiling height.	Wind speed, wind direction, dry bulb temperature, opaque cloud cover, and ceiling height.	Wind speed and direction, temperature, cloud cover, cloud ceiling, and relative humidity
Upper air data	Upper level data from daily morning soundings	Morning soundings of wind, temperature and dew point	Twice-daily observed vertical profiles of wind speed, wind direction, temperature, pressure, elevation.
Dry deposition input data	Station pressure	Station pressure	Station pressure
Wet deposition input data	Hourly precipitation data	Hourly precipitation data	Precipitation rates, precipitation type code
Calculated parameters	Pasquill-Gifford stability classes, twice daily mixing height, parameters for dry and wet deposition estimates.	Calculates hourly turbulence parameters, surface heat flux, friction velocity, mixing height, Monin-Obukhov length and other boundary layer parameters	Gridded 3-dimensional fields of the three components of wind and temperature, and 2-dimensional fields of stability class, friction velocity, mixing height, Monin-Obukhov length, convective velocity scale, and precipitation rate (Scire et al., 2000).
Operation performed on Dispersion model	ISCST3, CRSTER, RAM, MPTER, BLP, SHORTZ, and COMPLEX1. CALTRANS CAL3QHCR,CALPUFF(screening model)	AERMOD	CALPUFF
Availability of Mesoscale models	No	No	Yes, MM5, RAMS and MC2
Meteorological conditions	Uniform	Uniform	Non-uniform, spatially varying

2.5. Procedures for Missing Data values interpolation:

The meteorological data required for short-term air quality dispersion modeling consist of hourly surface observations and morning and afternoon mixing heights. The meteorological pre-processor program requires surface data and mixing height data in proper format. In order for the program to function properly, these data must be 100% complete. Data acquired from the National Climatic Data Center (NCDC) occasionally have periods of missing data. If the lengths of these periods are not excessive, reasonable values may be substituted without seriously degrading the modeling results.

As with on-site data, a data set that is less than 90% complete should not be used for air quality modeling purposes. Substitutions for missing data should only be made to complete the data set for modeling applications and should not be used to achieve the 90% criterion.

The procedure for providing substitute values for missing data has two parts. The first part is an objective procedure that applies to single isolated hours with missing surface data and single isolated days of missing mixing height data. Substitutions for those data are accomplished using procedures described below.

The second part is a subjective procedure that applies to longer sequences of missing data. Substitutions for those data require judgment and should be accomplished by an air quality meteorologist based on scientific knowledge and professional experience. The procedures, described in detail below, are generally consistent with procedures used historically by EPA.

2.5.1. Procedures for substituting Surface Data:

(a) The Objective Procedure:

Hourly surface weather observations of opaque cloud cover, ceiling height, temperature, wind direction, and wind speed are required.

Substitutions for missing surface data are made as follows:

1. **Opaque cloud cover**: If opaque cloud cover is missing, then total cloud cover is used. If total cloud cover is also missing, then a "0" is used for opaque cloud cover if the ceiling is greater than 7000 feet (high level clouds are generally not opaque) and a "7" if the ceiling is less than or equal to 7000 feet. If the opaque cloud cover, total cloud cover, and ceiling are all missing, values of ceiling and opaque (or total) cloud cover from the preceding hour are used, provided that values from both the preceding and the succeeding hours are present (i.e., only a single hour is missing). If two or more consecutive hours of cloud cover (both opaque and total) are missing, then the subjective procedure outlined below should be used.
2. **Ceiling height**: If ceiling height is missing, and either the opaque cloud cover or the total cloud cover is less than or equal to 5, then "---" (the code for unlimited ceiling) is used. Otherwise, if the ceiling height is missing, but values for both the preceding and succeeding hours are present, then the value from the preceding hour is used. If two or more consecutive hours of ceiling height are missing, then the subjective procedure outlined below is used.

3. **Temperature:** If temperature is missing, then a value interpolated between the preceding hour and the succeeding valid hour is substituted. If two or more consecutive hours of temperatures are missing, then the subjective procedure outlined below is followed.
4. **Wind speed and direction**: If a single hour of wind direction and speed is missing then the average direction and average speed from the four hours surrounding that hour is substituted. Except for the first two and last two hours of the year, this average is derived from the two hours before and two hours after the hour of the missing value. In the interest of simplicity, the average wind direction is obtained from the mean unit vector wind. If two or more consecutive hours of either wind direction or wind speed are missing, then the subjective procedure outlined below should be used.

(b) The Subjective Procedure:

When the objective procedure does not provide a substitute value for some parameters, the data are reviewed by an air quality meteorologist. A substitute value is identified, based on the following procedure, using sound scientific knowledge and professional experience.

1. **Ceiling height and Cloud cover:** If a ceiling height value is missing, then the five ceiling height values before and after that hour is reviewed to obtain appropriate values to substitute. For an opaque cloud cover of 5 or less, the value for ceiling height must be "---" to indicate unlimited ceiling (by definition, the ceiling is unlimited when the cloud cover is 5/10 or less). If the opaque value is 6

or greater, the values before and after that hour are reviewed to derive appropriate ceiling values.

2. **Temperature:** If temperature is missing, then the temperature values on either side of the data void are reviewed. Often an interpolation can be made for up to a few hours. However, these values may need to be adjusted to be consistent with the other meteorological factors. Adequately simulate daily maxima or minima for other days of similar meteorological conditions.
3. **Wind direction:** If a wind direction value is missing, the data values a few hours (perhaps five or so) on either side of the data void are reviewed. It is important to maintain not only consistency of wind direction but also some consistency of wind variability. Otherwise, a few hours with the wind from the same direction will result, which can produce unreasonably high estimates of 8-hour and 24-hour average concentrations.
4. **Wind speed:** If wind speed is missing, the five values both before and after the data void are reviewed. Any obvious patterns of wind speed should be continued and adjusted, if needed, to make the substitute data realistic from an air quality modeling viewpoint.

2.5.2. Procedures for substituting mixing height data:

Both a morning mixing height and an afternoon mixing height are required for each day of the year. Objective substitutions for missing mixing heights are made as follows:

(a) The Objective Procedure:

1. Afternoon mixing height: If a single afternoon mixing height is missing, the value interpolated between the preceding and successive afternoon mixing heights are used.
2. Morning mixing height: If a single morning mixing height is missing, the value interpolated between the preceding and succeeding morning mixing heights is used.

If two or more consecutive afternoon mixing heights or two or more consecutive morning mixing heights is missing, then the subjective procedure outlined below is used.

(b) The subjective procedure:

The following procedure is recommended for substituting values for missing morning or afternoon mixing height values, when the objective procedure described above is not appropriate. The procedure with mixing height data, as with surface data, requires careful meteorological judgment and professional experience in order to derive appropriate substitute values.

As a general rule, a sequence of missing mixing heights of five days or more are not filled in. Also, any missing sequence of four days that does not have adequate continuity (at least five full days on either side of the data void) is also not filled in. Such files cannot be used as input to the RAMMET (or PCRAMMET) pre-processor, since doing so produces values of zero for the mixing height, resulting in unrealistic modeling results.

2.6. Quality Assurance and Quality Control of Data:

Quality Assurance/Quality Control (QA/QC) procedures are required to ensure that the data collected meet standards of reliability and accuracy. Quality Control (QC) is defined as those operational procedures that will be routinely followed during the normal operation of the monitoring system to ensure that a measurement process is working properly. These procedures include periodic calibration of the instruments, site inspections, data screening, data validation, and preventive maintenance. The QC procedures should produce quantitative documentation to support claims of accuracy. Quality Assurance (QA) is defined as those procedures that will be performed on a more occasional basis to provide assurance that the measurement process is producing data that meets the data quality objectives (DQO). These procedures include routine evaluation of how the QC procedures are implemented (system audits) and assessments of instrument performance (performance audits).

The QA/QC procedures should be documented in a Quality Assurance Project Plan (QAPP) and should include a "sign-off" by the appropriate project or organizational authority [Lockhart, 1985]. The QAPP should include the following:

1. Project description - how meteorology is to be used
2. Project organization - how data validity is supported
3. QA objective - how QA will document validity claims
4. Calibration method and frequency - for meteorology
5. Data flow - from samples to archived valid values
6. Validation and reporting methods - for meteorology

7. Audits - performance and system
8. Preventive maintenance
9. Procedures to implement QA objectives - details
10. Management support - corrective action and reports

It is important that the person providing the QA be independent of the organization responsible for the collection of the data and the maintenance of the measurement systems. Some recommendations of QAQC are discussed below:

1. Quality Assurance/Quality Control (QAQC) procedures should provide quantitative documentation to support claims of accuracy and should be conducted by persons independent of the organization responsible for the collection of the data and the maintenance of the measurement systems.
2. Procurement documents for meteorological monitoring systems should include the specifications for instrument systems and should identify the test method by which conformance with the specification will be determined. Persons responsible installing meteorological systems should review documentation provided on conformance-testing and should conduct independent acceptance tests to verify claims of accuracy.
3. Routine system calibrations and system audits should be performed at the initiation of a monitoring program (within 30 days of start-up) and at least every six months thereafter. More frequent calibrations and audits may be needed in the early stages of the program if problems are encountered or if valid data retrieval rates are unacceptably low. Documentation of all calibrations should include a description of the system "as found", details of any adjustments to the instrument,

and a description of the system "as left"; this documentation is necessary for any claims of data validity.

4. Regular and frequent routine operational checks of the monitoring system are essential to ensuring high data retrieval rates. These should include visual inspections of the instruments for signs of damage or wear, inspections of recording devices to ensure correct operation, and periodic preventive maintenance. The latter should include periodic checks of wind speed and wind direction bearing assemblies, cleaning of aspirated shield screens in temperature systems, removal and recharging (at least quarterly) of lithium chloride dew cells, cleaning of the mirror in cooled mirror dew cells, clearing the precipitation gauge funnel of obstructing debris, and frequent (preferably daily) cleaning of the optical surface of a pyranometer or net radiometer. This review should be performed weekly and preferably on a daily basis.

2.7. Review of Air Dispersion Models:

Air dispersion modeling is the mathematical simulation of how air pollutants disperse in the ambient atmosphere. It is performed with computer programs that solve the mathematical equations and algorithms that simulate the pollutant dispersion. The dispersion models are used to estimate or to predict the downwind concentration of air pollutants emitted from sources such as industrial plants and vehicular traffic. Such models are important to governmental agencies tasked with protecting and managing the ambient air quality. Several factors impact the fate and transport of contaminants in the atmosphere including meteorological conditions, site configuration, emission release characteristics, and surrounding terrain, among others. There are some examples of air

dispersion models include: Box model, Gaussain model, Lagrangian model, Eulerian model, and Dense gas model. Following are brief descriptions of these model:

Box model :

The box model is the simplest of the model types. It assumes that a given volume of atmospheric air in a geographical region is in the shape of a box. It also assumes that the air pollutants inside the box are homogeneously distributed and uses that assumption to estimate the average pollutant concentrations anywhere within the airshed. Uses of this model are very limited in its ability to accurately predict dispersion of air pollutants over an airshed because the assumption of homogeneous pollutant distribution is much too simple.

Gausian model :

The Gaussian model is the oldest [Bosanquet, C.H. and Pearson, J.L. 1936] and the most commonly used model type. It assumes that the air pollutant dispersion has a Gausian distribution, meaning that the pollutant distribution has a normal probability distribution. Gaussian models are most often used for predicting the dispersion of continuous, buoyant air pollution plumes originating from ground-level or elevated sources. Gaussian models may also be used for predicting the dispersion of non-continuous air pollution plumes (called puff models). The primary algorithm used in Gaussian modeling is the Generalized Dispersion Equation for a Continuous point-source plume.[Beychok, Milton R. 2005]

Lagrangian model:

A Lagrangian dispersion model mathematically follows pollution plume parcels (also called particles) as the parcels move in the atmosphere, and they model the motion of the parcels as a random walk process. The Lagrangian model then calculates the air pollution dispersion by computing the statistics of the trajectories of a large number of the pollution plume parcels.

Eulerian model :

An Eulerian dispersions model is similar to a Lagrangian model in that it also tracks the movement of a large number of pollution plume parcels as they move from their initial location. The most important difference between the two models is that the Eulerian model uses a fixed three-dimensional cartesian grid [Zannetti, P., 1990] as a frame of reference rather than a moving frame of reference.

Dense gas model :

Dense gas models are models that simulate the dispersion of dense gas pollution plumes (i.e., pollution plumes that are heavier than air).

Applications of Air Quality Modeling:

Air quality models are unique tools for:

- Establishing emission control legislation; i.e., determining the maximum allowable emission rates that will meet fixed air quality standards.
- Evaluating proposed emission control techniques and strategies.
- Selecting locations of future sources of pollutants, in order to minimize their environmental impacts.

- Planning the control of air pollution episodes.
- Assessing responsibility for existing air pollution levels; evaluating present source-receptor relationships.

2.7.1. Overview of AERMOD Dispersion Model:

AERMOD is the air dispersion model that incorporates concepts such as planetary boundary layer theory and advanced methods for handling complex terrain. AERMOD was introduced in 1996 as the eventual replacement to the ISCST3 model for regulatory permitting. The AERMOD atmospheric dispersion modeling system is an integrated system that includes three modules [Prater, E.T. and Midgley, C., A , Brode, R.W, Vol. 17, No. 3]:

- A steady-state dispersion model designed for short-range (up to 50 kilometers) dispersion of air pollution emissions from stationary industrial sources.
- A meteorological data preprocessor (AERMET) that accepts surface meteorological data, upper air soundings, and, optionally, data from on-site instrument towers. It then calculates atmospheric parameters needed by the dispersion model, such as atmospheric turbulence characteristics, mixing heights, friction velocity, Monin-Obukov length, and surface heat flux.
- A terrain preprocessor (AERMAP) the main purpose of a terrain preprocessor is to provide a physical relationship between terrain features and the behavior of air pollution plumes. It generates location and height data for each receptor location. It also provides information that allows the dispersion model to simulate the effects of air flowing over hills or splitting to flow around hills.

AERMOD also includes PRIME (Plume Rise Model Enhancements) which is an algorithm for modeling the effects of downwash created by the pollution plume flowing over nearby buildings [Lloyd L. Schulman, 1980]

AERMOD contains basically the same options as the ISCST3/ISCPRIME model with a few exceptions, which are described below:

1. AERMOD requires two types of meteorological data files: a file containing surface scalar parameters and a file containing vertical profiles. These two files are produced by the US EPA AERMET meteorological pre-processor program.
2. For applications involving elevated terrain the user must input a hill height scale along with the receptor elevation. The US EPA AERMAP terrain pre-processing program can be used to generate hill height scales as well as terrain elevations for all receptor locations.
3. The urban option in AERMOD results in altering dispersion parameters due to the urban heat island effect. The urban population is an input to this option.
4. AERMOD has additional options for inputting area sources.
5. AERMOD does not have an option for varying emission rates by stability class.

2.7.2. Overview of CALPUFF Dispersion Model:

CALPUFF is a multi-layer, multi-species, non-steady-state puff dispersion model that simulates the effects of time and space varying meteorological conditions on pollution transport, transformation and removal. CALPUFF can be applied on scales of tens to hundreds of kilometres. It includes algorithms for sub-grid scale effects (such as terrain impingement), as well as, longer range effects (such as pollutant removal due to

wet scavenging and dry deposition, chemical transformation, and visibility effects of particulate matter concentrations).

CALPUFF [Scire, J.S., D.G. Strimaitis, and R.J. Yamartino, 2000] is a puff model that is capable of fully accounting for hour-by-hour and spatial variations in wind and stability. CALPUFF contains additional algorithms that allow it to emulate AERMOD (or ISCST3) at short distances where puff models are generally less reliable. Further, CALPUFF has been evaluated and found to be reasonably accurate at distances up to 300 km. Thus, CALPUFF can be recommended for use for all distances up to 300 km. CALPUFF is particularly useful in modelling situations that involve long-range transport (up to 300 km, light wind and calm conditions, wind reversals such as land-sea (or lake) breezes and mountain-valley breezes, and complex wind situations found in very rugged terrain). CALPUFF is a more complex model with increased meteorological data requirements.

The CALPUFF modeling system has three main components:

1. CALMET (a diagnostic 3-D meteorological model),
2. CALPUFF (the transport and dispersion model), and
3. CALPOST (a post-processing package).

This system is a comprehensive modeling tool that includes meteorological and geophysical data processors, a meteorological model, a puff-based dispersion model, and a post-processing module.

Application of CALPUFF:

- Toxic pollutant deposition
- Near-field impacts from
  - point
  - line
  - area
  - volume sources
- Forest fire impacts
- Visibility assessments
- Long range transport studies.

2.7.3. Comparative study of AERMOD and CALPUFF models:

Table 2.2: Relative study of AERMOD vs. CALPUFF Model

Feature	AERMOD	CALPUFF
Time and cost	Less	More
The detail of source and site data	Same	Same
Meteorological and terrain data	Require less input data	Require more input data and time
Configuring model and processing time	Take less time	Take more time because of the large number of variables
Causality effects	Models cannot account for causality effects	Models can account for causality effects
Scale of impact	Near field impact within 50 Km	Applied on scales of Tens meters to hundreds of kilometres
Wind feature	Uniform steady state wind analysis is consider	Complex non-uniform wind field is consider
Model application	Rural and urban areas, flat and complex terrain, surface and elevated releases.	Same as AERMOD also applicable on mountain areas and coastal and over-water interaction.
Meteorological pre-processors	AERMET	CALMET(diagnostic 3-dimensional meteorological model)
shoreline fumigation	Not consider	Consider
Light wind and calm Conditions	Not consider	Consider

Chapter 3

Mixing Height Methodology for a Critical Evaluation of Urban Mixing Height Estimation

3.1. Introduction:

The planetary boundary layer (PBL), also known as the atmospheric boundary layer (ABL) is in the lowest part of the atmosphere and its behaviour is directly influenced by Earth's surface and responds to surface forcing such as frictional drag, evapotranspiration, heat transfer, pollutant emission, and topography [Cooper and Eichinger,1994]. Above the PBL is the free atmosphere where the effects of friction from Earth's surface are negligible and the motion of air can be treated as an ideal fluid [Glickman, 2000]. Within the PBL, several identifiable layers can exist that depend on the state of the atmosphere and local conditions. These layers are displayed in Figure 3.1: and include the surface layer, mixing layer (ML), entrainment zone, stable layer, residual layer, and capping inversion.

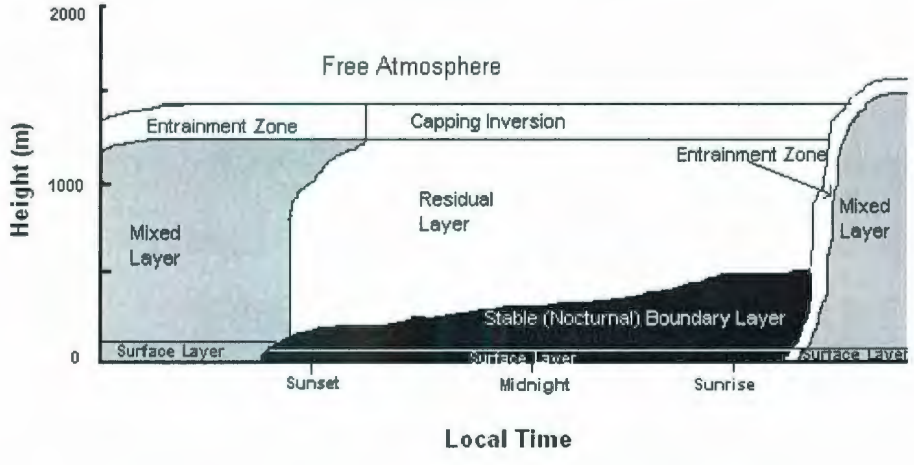


Figure 3.1: The diurnal evolution of the PBL (Stull, 1988)

The surface layer is the layer of a the atmosphere in contact with the earth's surface and is where the generation of mechanical turbulence by strong winds or wind shear is greater than the generation of buoyant turbulence associated with large thermal gradient [Glickman, 2000]. The atmospheric surface layer is the lowest part of the ABL (typically the bottom 10%). During daytime convective conditions, an ML (is the middle of 35% to 70% of PBL) is above the surface layer and is characterized by turbulence created from forced or free convection that actively mixes such quantities as aerosols, potential temperature, and wind speed [Stull, 1988]. On warm sunny days, the surface forcing are dominated by the solar heating of Earth's surface and convective thermals are the main cause of development of the well-mixed PBL, which is often called the convective boundary layer [Marsik et al., 1995]. At the top of the ML there exists a stable layer called the entrainment zone that is not well-mixed and within which turbulence intensity decreases upwards [Seibert et al., 2000]. This layer is an interface between the ML and the free atmosphere and is often called an inversion layer because there is a temperature increase with height. Above the entrainment zone, in the free atmosphere, the temperature usually decreases with height and the atmosphere becomes less stable.

Knowledge of the structure and characteristics of the PBL is important to fully understand profiles of momentum, heat, and moisture in the lower atmosphere and to characterize the transport and diffusion of pollutants. Within the PBL, the ML is of particular importance because the ML depth determines the volume in which daytime pollution is primarily concentrated. The ML height is defined by the American Meteorological Society as the location of a capping temperature inversion or statically stable layer of air and often associated with, or measured by, a sharp increase of potential temperature with height, a sharp decrease of water-vapour mixing ratio, a sharp decrease

in turbulence intensity, a sharp decrease in pollution concentration, a change of wind speed to geostrophic, a minimum of turbulent heat flux, and a maximum of signal intensity from remote sensors [Glickman, 2000].

The ABL height should be higher in urban areas than in the rural case. As pollutants can be dispersed vertically, we also speak of the mixing layer. The mixing depth represents the height reached by pollutants after release from sources at ground-level. Most dispersion models require an estimate of the mixing height (MH) or ABL height so that any effective limit on vertical spread can be modelled.

The ML height depends on many factors including variations in surface albedo, surface moisture, synoptic conditions, local circulation patterns, cloud cover, horizontal advection, land use, and the urban heat island effect [Seibert et al. 2000; Marsik et al.; 1995; Dayan et al., 1988]. Therefore, the ML height at a particular time and place is influenced by geographical location and environmental conditions.

Methods for determining the ML heights depend upon the types of observations available. Different instruments used for inferring the ML height have different strengths and are often only appropriate under certain conditions. Even under optimal conditions, ML height estimates differ because each instrument requires the use of a different variable or method as to which feature best defines the depth of ML for that instrument. Thus, no single instrument is adequate by itself to fully determine the ML height of an area of interest.

There have been several techniques used to determine the ML height. Techniques have included the use of Rawinsonde, Radiosonde, Wind profiler, Lidar, Sodar, and measurements of aerosol concentrations and other in-situ data.

Mixing height is one of the most important parameters requested by different atmospheric pollution models as an input data for forecasting the air quality. When pollutants are emitted into the atmospheric boundary layer (ABL), they disperse horizontally and vertically because of the action of convection and mechanical turbulences until it becomes completely mixed. In spite of the fact that there is still no unique definition and no general accepted method for calculating the mixing height, however, the depth of the mixed layer is defined as the mixing height, which determines the volume available for the dispersion of pollutants. The greater the depth of the mixed layer the larger the available volume to dilute pollutant emissions. This chapter focuses the ML heights inferred from radiosonde of Jeddah city using potential temperature increase method and comparing that MH from eight diagnostic models from surface air observations. By statistical analysis of the eight diagnostic models with AERMET processing MH suggests which do best with my study area. MH from Sodar using backscatter method of same city is also presented. Figure 3.2: show mixing height methodology flow diagram.

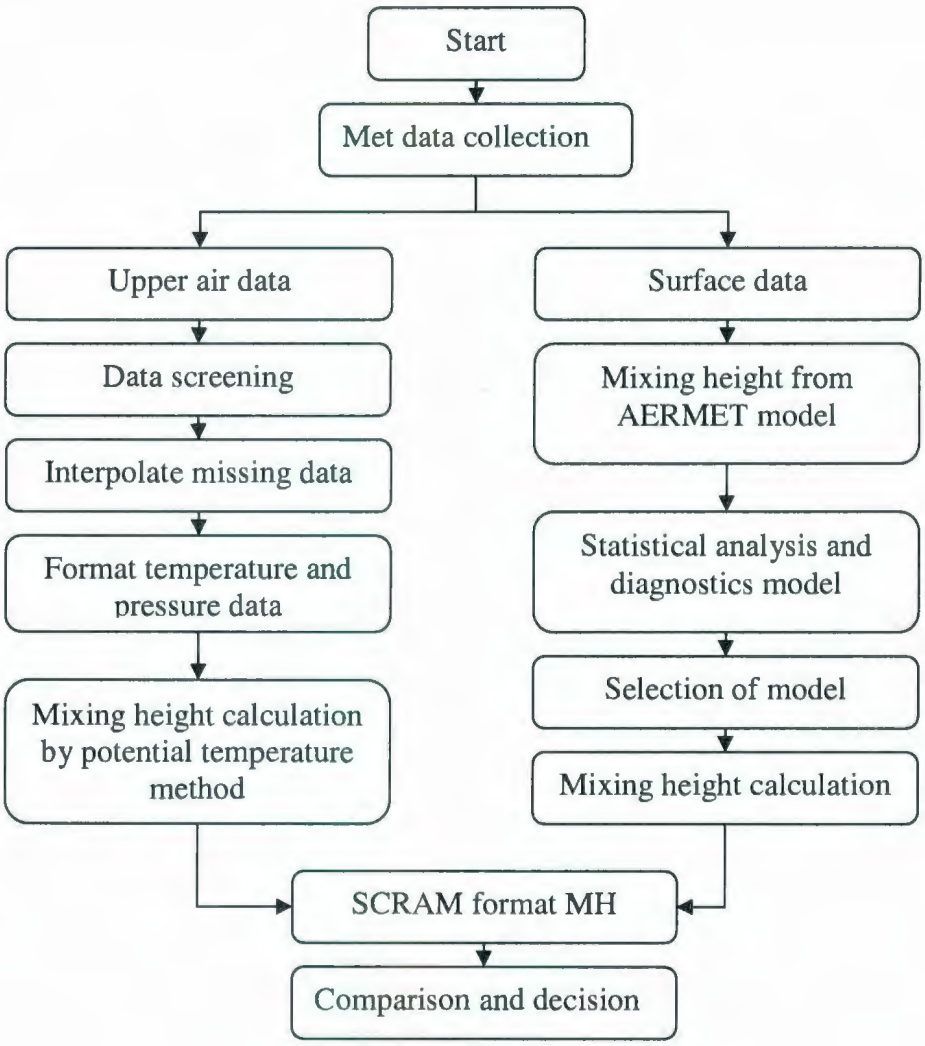


Figure 3.2: Flow diagram of MH methodology

3.2. Methods for estimating the urban MH:

In this section, only a brief overview of methods to estimate MH will be given. The background information of this instrumentation has summarized in earlier section.

3.2.1. Experimental methods:

In general terms, the MH can be estimated experimentally from measured vertical profiles by several means or criteria, e.g.:

• The level where turbulence or the heat flux diminishes to, say, ~5%, of its surface value;

• A level of discontinuity in the wind/temperature/dew point profiles (from radiosonde data);

• The level of strong back-returns from thermal discontinuities (inversions) or of strong decay of back-returns from thermal fluctuations (top of turbulent layer), from Sodar and Wind profilers/ RASS (Radio Acoustic Sounding System);

• The level of strong decay of aerosol back-scatter signal from lidar probing or ceilometer's;

• The level of decay in turbulent motions as measured by pulse Doppler Lidar.

3.2.2. MH from radiosonde data:

Radiosonde systems obtain profiles of temperature, pressure, and relative humidity as they ascend through the atmosphere and send these measurements to a ground receiver. ML height estimates can be determined using radiosonde data by analyzing the vertical stability of the atmosphere. A well-mixed layer has nearly constant potential temperature values with height. If the ML was not well-mixed, the ML height was taken as the point where the potential temperature is at least 2 degrees greater than the average potential temperature of the ML. There have been more detailed methods that use potential temperature to determine the ML height around the city of Atlanta, Georgia, [Marsik et al., 1995]. For the θ increase method, the ML height was the point where the potential temperature was at least 2 degrees greater than the potential temperature in the ML [Heffter 1980, Marsik et al., 1995]. The potential temperature was evaluated at 10mb levels.

Determining the ML from mixing ratio data is often used in combination with the potential temperature [Beyrich and Gorsdorf, 1995]; [Cooper and Eichinger, 1994]; [Stull, 1988] or separately when the potential temperature data is ambiguous [Senff et al., 2002].In a well-mixed layer, moisture is a conserved quantity and mixing ratio values are nearly constant with height. The location of the significant decrease in the mixing ratio found at the inversion base can be used to identify the ML height [Senff et al., 2002]; [Cooper and Eichinger, 1994]; [Stull, 1988].

The ML height can also be identified using the atmospheric temperature profiles. Techniques that use temperature are similar to techniques that use potential temperature in that a temperature profile that has a dry adiabatic lapse rate is equivalent to a well mixed potential temperature profile. Likewise, a temperature profile that does not have a dry adiabatic lapse rate is equivalent to a potential temperature profile that is not well mixed. Therefore, the ML height can be determined as the point where the temperature becomes less than dry adiabatic or there is a significant temperature increase with height [Baxter, 1991]; [Kalthoff et al., 1998]; [Coulter, 1979].

ML height using radiosonde data is commonly estimated using computer models and compared with ML heights estimated by other methods. The bulk Richardson number methods calculate the ML height and depend on the level used for the near-surface temperature and wind, the parameterization of shear production of turbulence in the surface layer, and the consideration of an excess surface temperature under convective conditions [Seibert et al., 2000]; [Grimsdell and Angevine, 1998] used a bulk Richardson method to compare computed ML heights from radiosonde data to measured wind profiler ML heights. The bulk Richardson method overestimated the ML heights, due to

the nature of the Richardson number calculation where the input values did not accurately represent the measurement spacing and the strength of turbulence.

The "parcel method" consists of using the most recent radiosonde data and following the dry adiabatic from the surface with the measured or expected maximum temperature up to its intersection with the temperature profile [Seibert et al., 2000]. This method determines the ML height as the equilibrium level of a hypothetical rising parcel of air. Refinements to this method differ in how the temperature of the air parcel is measured and the thermodynamic variable used to define the equilibrium level [Seibert et al., 2000].

The method by [Holzworth, 1964] and refinements to this method have been used in several studies [Van Pul et al, 1994; Holzworth, 1967; Miller, 1967; Garrett, 1981]. Generally, the Holzworth method was used to forecast ML heights at times when radiosonde soundings were not available (usually in the afternoon), and was based on the concept that heating of the surface during the daytime results in vertical mixing that allows the development of a dry adiabatic lapse rate. In the simple form, this method consists of extending a dry adiabatic from the maximum surface temperature to its intersection with the most recent temperature profile (usually in the morning) and neglecting temperature advection. Refinements to the Holzworth method depend on the location and nature of the study.

Theory of potential temperature (θ) increase method:

The **potential temperature** (θ) of a parcel of fluid at pressure P is the temperature that the parcel would acquire if adiabatically brought to a standard reference

pressure P_0, usually 1000 millibars. The potential temperature is denoted θ and, for air, is often given by

$$\theta = T\left(\frac{P_0}{P}\right)^{\frac{R}{cp}}$$

For an altitude change dz, the atmospheric pressure change is:

$$dp = -\rho g dz \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where g the acceleration of gravity, considered constant is, ρ is the specific mass of air, which is considered as an ideal gas:

$$\rho = \frac{m}{V} = \frac{p\mu}{RT}$$

Put this expression in (1):

$$\frac{dp}{p} = -\frac{\mu g}{RT} dz$$

If the air temperature is uniform and equals T_0

$$\frac{dp}{p} = -\frac{\mu g}{RT_0} dz$$

After integration, we have:

$$p(z) = p(0)\mathbf{e}^{-\frac{\mu g}{RT_0}z} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

And if

$$T(z) = T(0) - \Lambda z \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Then

$$\frac{dp}{p} = -\frac{\mu g}{R\left[T(0) - \Lambda z\right]} dz \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Furthermore Knowing that:

$$\int \frac{dz}{T(0)-\Lambda z} = -\frac{1}{\Lambda}\int \frac{d\left[T(0)-\Lambda z\right]}{T(0)-\Lambda z} = -\frac{1}{\Lambda}\ln\left(T(0)-\Lambda z\right) \quad \text{..... (5)}$$

By integrating both members of (4), we obtain:

$$\ln\frac{p(z)}{p(0)} = \frac{\mu g}{R\Lambda}\ln\frac{T(0)-\Lambda z}{T(0)} = \frac{\mu g}{R\Lambda}\ln\left(1-\frac{\Lambda z}{T(0)}\right)$$

$$p(z) = p(0)\left(1-\frac{\Lambda z}{T(0)}\right)^{\frac{\mu g}{R\Lambda}} \quad \text{..... (6)}$$

The free convection occurs if:

$$\frac{\rho(z)}{\rho(0)} > 1$$

The ratio of specific masses can be expressed as follows:

$$\frac{\rho(z)}{\rho(0)} = \frac{p(z)}{p(0)}\frac{T(0)}{T(z)} = \left(1-\frac{\Lambda z}{T(0)}\right)^{\frac{\mu g}{R\Lambda}-1}$$

The last term is larger than unity if its exponent is negative:

$$\frac{\mu g}{R\Lambda} - 1 < 0$$

Then:

$$\Lambda > \frac{\mu g}{R} = \frac{0.029\times 10}{8.31} = 0.035\ \frac{\mathrm{K}}{\mathrm{m}}$$

In vertical motion, the pressure of the parcel always equals that of the surrounding air, and the latter depends on the altitude. The parcel temperature T_{parcel} depends on the pressure.

We can write:

$$\frac{dT_{\text{parcel}}}{dz} = \frac{dT_{\text{parcel}}}{dp}\frac{dp}{dz}$$

p is simultaneously the pressure of air in the parcel and that of the surrounding air.

Expression for $\frac{dT_{\text{parcel}}}{dp}$

By using the equation for adiabatic processes, $pV^{\gamma} = \text{const}$ and equation of state, we can deduce the equation giving the change of pressure and temperature in a quasi-equilibrium adiabatic process of an air parcel:

$$T_{\text{parcel}} p^{\frac{1-\gamma}{\gamma}} = \text{const} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Where, $\gamma = \frac{c_p}{c_V}$ is the ratio of isobaric and isochoric thermal capacities of air.

By logarithmic differentiation of the two members of equation (7), we have:

$$\frac{dT_{\text{parcel}}}{T_{\text{parcel}}} + \frac{1-\gamma}{\gamma}\frac{dp}{p} = 0$$

or

$$\frac{dT_{\text{parcel}}}{dp} = \frac{T_{\text{parcel}}}{p}\frac{\gamma-1}{\gamma} \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Note: we can use the first law of thermodynamic to calculate the heat received by the parcel in an elementary process: $dQ = \frac{m}{\mu} c_V dT_{\text{parcel}} + pdV$. This heat equals zero in an adiabatic process. Furthermore, using the equation of state for air in the parcel $pV = \frac{m}{\mu} RT_{\text{parcel}}$, we can derive equation (7)

Expression for $\frac{dp}{dz}$

From equation (1) we can deduce:

$$\frac{dp}{dz} = -\rho g = -\frac{pg\mu}{RT}$$

Where T is the temperature of the surrounding air. On the basis of these two expressions, we derive the expression for dT_{parcel} / dz :

$$\frac{dT_{\text{parcel}}}{dz} = -\frac{\gamma - 1}{\gamma} \frac{\mu g}{R} \frac{T_{\text{parcel}}}{T} = -G \quad \text{..... (9)}$$

In general, G is not a constant

If at any altitude $T = T_{\text{parcel}}$, then instead of G in equation (9), we have:

$$\Gamma = \frac{\gamma - 1}{\gamma} \frac{\mu g}{R} = \text{const} \quad \text{..... (10)}$$

or

$$\Gamma = \frac{g}{c_p}$$

Numerical value is:

$$\Gamma = \frac{1.4-1}{1.4}\frac{0.029\times 10}{8.31} = 0.00997\ \frac{\text{K}}{\text{m}} \approx 10^{-2}\,\frac{\text{K}}{\text{m}}$$

Thus, the expression for the temperature at the altitude z in this special atmosphere (called adiabatic atmosphere) is:

$$T(z) = T(0) - \Gamma z \quad \text{... (11)}$$

Again, the water vapour is a triatomic gas, its thermal capacities are $C_p = 4R$ and $C_V = 3R$, their ratio $\gamma = \frac{c_p}{c_V}$. If in the air parcel there is also unsaturated water vapour, then the content of the parcel is a mixture of air with molar ratio $\frac{p_0 - p_{\text{water}}}{p_0}$ and water vapour with molar ratio $\frac{p_{\text{water}}}{p_0}$. Its thermal capacities are the following:

$$c_p = \frac{(p_0 - p_{\text{water}})\frac{7}{2}R + p_{\text{water}}4R}{p_0} = \frac{7}{2}R + \frac{1}{2}\frac{p_{\text{water}}}{p_0}R$$

$$c_V = \frac{5}{2}R + \frac{1}{2}\frac{p_{\text{water}}}{p_0}R$$

Water vapour in the parcel is unsaturated, therefore $p_{\text{water}} < 2.64$ kPa. We put

$$\varepsilon = \frac{1}{2}\frac{p_{\text{water}}}{p_0} < \frac{2.6}{200} = 0.013 << 1$$

$$\gamma = \frac{c_p}{c_V} < \frac{7}{5} - \frac{4}{25}\varepsilon = \frac{7}{5} - 0.002$$

By using the equation (11) of the adiabatic lapse rate Γ we can find the limit of its relative decrease:

$$\frac{|\Delta\Gamma|}{\Gamma} < \frac{4}{1000}$$

Substitute T in equation (8) by its expression given in equation (3), we have:

$$\frac{dT_{\text{parcel}}}{T_{\text{parcel}}} = -\frac{\gamma-1}{\gamma}\frac{\mu g}{R}\frac{dz}{T(0)-\Lambda z}$$

Integration gives:

$$\ln\frac{T_{\text{parcel}}(z)}{T_{\text{parcel}}(0)} = -\frac{\gamma-1}{\gamma}\frac{\mu g}{R}\left(-\frac{1}{\Lambda}\right)\ln\frac{T(0)-\Lambda z}{T(0)}$$

Finally, we obtain:

$$T_{\text{parcel}}(z) = T_{\text{parcel}}(0)\left(\frac{T(0)-\Lambda z}{T(0)}\right)^{\frac{\Gamma}{\Lambda}} \text{ ---------- (12)}$$

Atmospheric stability

In order to know the stability of atmosphere, we can study the stability of the equilibrium of an air parcel in this atmosphere. At the altitude z_0, where $T_{\text{parcel}}(z_0) = T(z_0)$, the air parcels is in equilibrium. Indeed, in this case the specific mass ρ of air in the parcel equals ρ'- that of the surrounding air in the atmosphere. Therefore, the buoyant force of the surrounding air on the parcel equals the weight of the parcel. The resultant of these two forces is zero. Remember that the temperature of the air parcel $T_{\text{parcel}}(z)$ is given by equation (7), in which we can assume approximately $G = \Gamma$ at any altitude z near $z = z_0$.Now, consider the stability of the air parcel equilibrium:

Suppose that the air parcel is lifted into a higher position, at the altitude $z_0 + d$ (with d>0), $T_{\text{parcel}}(z_0 + d) = T_{\text{parcel}}(z_0) - \Gamma d$ and $T(z_0 + d) = T(z_0) - \Lambda d$.

- In the case that the atmosphere has temperature lapse rate $\Lambda > \Gamma$, we have $T_{\text{parcel}}(z_0 + d) > T(z_0 + d)$, then $\rho < \rho'$. The buoyant force is then larger than the air parcel weight; their resultant is oriented upward and tends to push the parcel away from the equilibrium position.

Conversely, if the air parcel is lowered to the altitude $z_0 - d$ (d>0), and $T_{\text{parcel}}(z_0 - d) < T(z_0 - d)$ then $\rho > \rho'$.

The buoyant force is then smaller than the air parcel weight; their resultant is oriented downward and tends to push the parcel away from the equilibrium position (see Figure a).

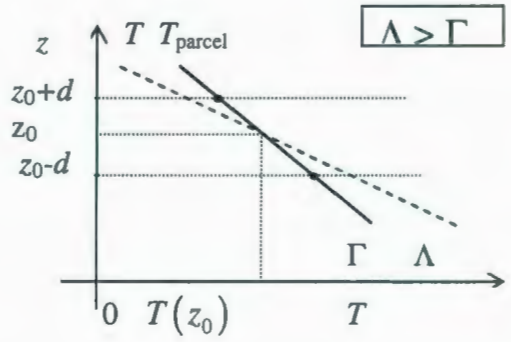
So, the equilibrium of the parcel is unstable, and we found that: An atmosphere with a temperature lapse rate $\Lambda > \Gamma$ is unstable.

- In an atmosphere with temperature lapse rate $\Lambda < \Gamma$, if the air parcel is lifted to a higher position, at altitude $z_0 + d$ (with d>0), $T_{\text{parcel}}(z_0 + d) < T(z_0 + d)$, then $\rho > \rho'$.

The buoyant force is then smaller than the air parcel weight; their resultant is oriented downward and tends to push the parcel back to the equilibrium position.

Conversely, if the air parcel is lowered to altitude $z_0 - d$ (d >0), $T_{\text{parcel}}(z_0 - d) > T(z_0 - d)$ and then $\rho < \rho'$. The buoyant force is then larger than the air parcel weight; their resultant is oriented upward and tends to push the parcel also back to the equilibrium position (see Figure b).

So, the equilibrium of the parcel is stable, and we found that: An atmosphere with a temperature lapse rate $\Lambda < \Gamma$ is stable.

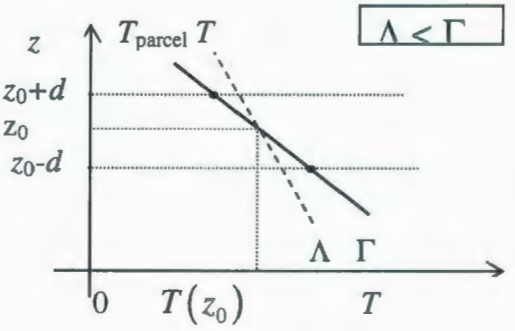


$T_{parcel} > T \Rightarrow \rho_{parcel} < \rho$ up↑

$T_{parcel} < T \Rightarrow \rho_{parcel} > \rho$ down↓

unstable

Figure a



$T_{parcel} < T \Rightarrow \rho_{parcel} > \rho$ up↑

$T_{parcel} > T \Rightarrow \rho_{parcel} < \rho$ down↓

stable

Figure b

Figure 3.3: Stability determinations from lapse rate

• In an atmosphere with lapse rate $\Lambda = \Gamma$, if the parcel is brought from equilibrium position and put in any other position, it will stay there, the equilibrium is indifferent. An atmosphere with a temperature lapse rate $\Lambda = \Gamma$ is neutral.

In a stable atmosphere, with $\Lambda < \Gamma$, a parcel, which on ground has temperature $T_{\text{parcel}}(0)$ $> T(0)$ and pressure $p(0)$ equal to that of the atmosphere, can rise and reach a maximal altitude h, where $T_{\text{parcel}}(h) = T(h)$.

In vertical motion from the ground to the altitude h, the air parcel realizes an adiabatic quasi-static process, in which its temperature changes from $T_{\text{parcel}}(0)$ to $T_{\text{parcel}}(h) = T(h)$, Using (12), we can write:

$$\left(1-\frac{\Lambda h}{T(0)}\right)^{-\frac{\Gamma}{\Lambda}} = \frac{T_{\text{parcel}}(0)}{T(h)} = \frac{T_{\text{parcel}}(0)}{T(0)\left(1-\frac{\Lambda h}{T(0)}\right)}$$

$$\left(1-\frac{\Lambda h}{T(0)}\right)^{1-\frac{\Gamma}{\Lambda}} = T_{\text{parcel}}(0)\times T^{-1}(0)$$

$$1-\frac{\Lambda h}{T(0)} = T_{\text{parcel}}^{\frac{\Lambda}{\Lambda-\Gamma}}(0)\times T^{-\frac{\Lambda}{\Lambda-\Gamma}}(0)$$

$$h = \frac{1}{\Lambda}T(0)\left[1-T_{\text{parcel}}^{\frac{\Lambda}{\Lambda-\Gamma}}(0)\times T^{-\frac{\Lambda}{\Lambda-\Gamma}}(0)\right]$$

$$= \frac{1}{\Lambda}\left[T(0)-T_{\text{parcel}}^{\frac{\Lambda}{\Lambda-\Gamma}}(0)T^{\frac{\Gamma}{\Gamma-\Lambda}}(0)\right]$$

So that the maximal altitude h has the following expression:

$$h = \frac{1}{\Lambda}\left[T(0)-\left(\frac{(T(0))^{\Gamma}}{(T_{\text{parcel}}(0))^{\Lambda}}\right)^{\frac{1}{\Gamma-\Lambda}}\right]$$

Stable mixing height calculation [Karppinen et al, 1998] uses only the potential temperature gradient to estimate the stable mixing height *h*:

$$h = \frac{4.5}{g_1 + 0.005};\ g_1 = \left(\frac{\theta_2 - \theta_1}{z_2 - z_1}\right);\ g_1 > 0.01\ ^0\text{K/m}$$

Where $\theta 1$ and $\theta 2$ are the potential temperatures measured at levels z1 and z2.

3.2.3. MH from evaluation of diagnostic model:

Several diagnostic models for the determination of the height of the nocturnal boundary layer have been evaluated. They are based on friction velocity u^* and wind speed near the ground, u_{10}. The models are summarised in Table 3.1. In the present study the computation of mixing heights, according to the above-mentioned models, has been carried out using surface wind speed measurements and computed values of friction velocity, Monin-Obukhov length supplied by AERMET pre-processor. A number of indirect algorithms for the estimate of *h* in nocturnal, stable conditions, when the mixing is dominated by mechanical turbulence, are reviewed and compared with mixing heights derived from AERMET. Among the others Ayra (1981), that makes use of friction velocity and coriolicis factor given the best results, and correlate very positively with AERMET than others methods. Table 3.1 mixing height algorithms:

Table 3.1: Mixing Height Algorithm

1.	$h_1 = 0.142\left(\frac{u_*}{f}\right)$	Arya (1981)
2.	$h_2 = 10L$	Kitaigorodskii and Joffre, 1988
3.	$h_3 = 0.4\left(\frac{u_*L}{f}\right)^{0.5}$	Nieuwstadt (1984)
4.	$h_4 = 0.43\left(\frac{u_*L}{f}\right)^{0.5} + 29.3$	Ayra (1981) after Zilitinkevic (1972)
5.	$h_5 = 125(u_{10})$	Benkley and Schulman (1979)
6.	$h_6 = 2300(u_*)^{1.5}$	Venkatram (1980)
7.	$h_7 = 28(u_{10})^{1.5}$	Nieuwstadt (1984)
8.	$h_8 = 1980(u^*)^{1.5}$	Venkatram (1980)

3.2.4. ML Height from Sodar/Lidar/Radar/Ceilometers:

The different types of vertical profilers (Sodars, Lidars, Radars, Ceilometers, etc.) have the potential to provide better and more continuous information on the vertical structure of the ABL and to estimate the MH better than radiosondes. Interpretation can be difficult when the lower atmosphere exhibits multiple layers. Their main weaknesses arise from the limitation on their use in urban areas (e.g. due to noise) and the need of expert personnel so that usually they are not in continuous operational use. However, they are sometimes used for some other purposes (e.g. for nuclear emergency preparedness systems or other monitoring purposes) and thus could be used for MH estimation in urban or semi-urban areas.

3.2.5. Doppler radar Sodar:

Doppler radar sodar is a type of Sodar, with the Radio Acoustic Sounding System (RASS) added to Doppler, the instrument can measure virtual temperature up to 1200m. Doppler Sodar systems basically consist of one sole antenna (phased array type) and an electronic case. In the electronic case are the computer, transceiver, and power amplifier. Also included are interconnecting cables and a small mount for the antenna. The system allows for full control of the antenna beams: four of the electronically steered beams are tilted (30° or 15°) or from vertical and turned 90° from each other to provide the horizontal component of wind velocity. The last beam is pointed vertically and provides that component of the wind. The system software controls the sequence and rate of operation for each beam. These are non system parameters which can be changed through keyboard input. Different antennas are available for different ranges.

3.2.6. Sodar Methodology:

(a) For Sodar the MH can be deduced from the vertical profile of the echo intensity or from a spectral analysis of the vertical velocity. Methods based on the former have been summarised by [Beyrich, 1997]. In stable conditions, the MH is identified as a local minimum level of the structure parameter for temperature C_T^2, just above its first maximum from the surface [Klapisz & Weill, 1985]: MHstable = z (C_T^2=min). Under convective conditions, since the maximum measurement level reached by the sodar was always below the MH, a similarity method based on profiles of the vertical standard deviation σ_w was applied, as suggested by [Seibert *et al.*, 1978]. In such conditions, the σ_w maximum level is taken as the third of the MH, i.e.: MHconv = c·z (σ_w =max.), with an

"empirical" factor c ≈ 3. For neutral conditions the MH was not estimated from Sodar measurements. Where structure parameter for temperature $C_T^2 = D_T(r) * r^{\frac{-2}{3}}$

Where $D_T(r) = \left\langle [T(x+r) - T(x)]^2 \right\rangle$ is the temperature structure function in which the average of temperature measured at point x and x+r.

(b) The Acoustic Received Echo backscatter method:

In general, the temperature inversion layers are associated with strong backscattered acoustic signal. In particular the maximum echo value is received from the inversion layer, the base of which acts as the roof of the mixing layer. Thus, the height at which the base of the inversion layer is observed is the MH [D.N. Asimakopoulos, C.G. Helmis, and J. Michopoulos, 2003]. So, MH can be determined by a visual inspection of the average backscatter profile. It should be noted here that, similar echo profiles could be obtained from other physical mechanisms such as from a shallow mixing layer which is set by a temperature inversion or by a thick nocturnal temperature inversion under the presence of a low level jet or other cases. During these cases special care should be taken to select the top of the first inversion or else the MH depth.

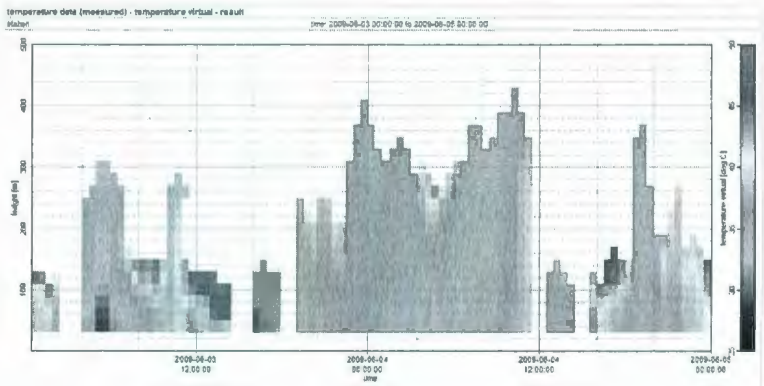


Figure 3.4: Temperature backscatter from Sodar

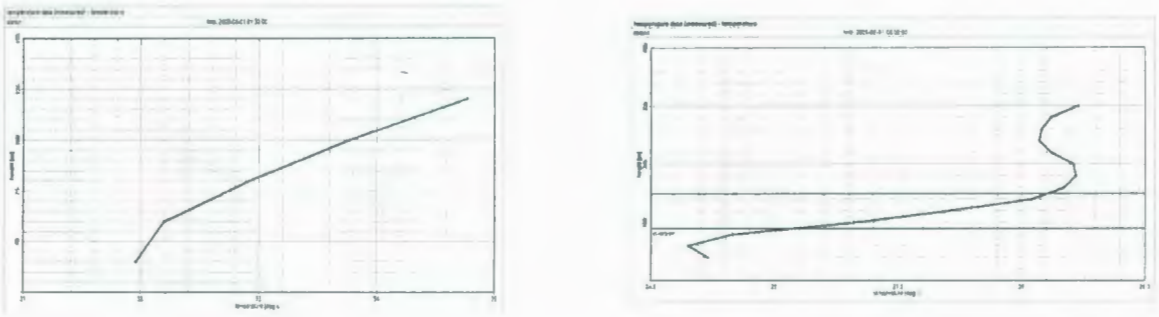


Figure 3.5: Temperature profiles from Sodar

3.3. Results and Discussions

3.3.1: Results from radiosonde:

The meteorological data used in this study were taken for the period of January to July and November 2006 in the area of King Abdul Aziz International Airport Jeddah in the city of Saudi Arabia. This site is located at 21.42 N and 39.11 E with a height of 17 m above the sea level. It is still a representative of an urban environment due to the large extension of the urbanized area of Riyadh city. The available data are profiles of wind speed and direction and temperature profiles. Besides, the KAAIA stations supplied synoptic surface meteorological data (air temperature, wind speed, wind direction, cloud cover, etc.). Most values of wind speed, observed during the selected period, are lower than 4 ms^{-1}, with the exception of 30% of cases where wind speed ranged from 4.5 to 11 ms-1 and the sky was generally clear. As shown in Table 3.2 and Figure 3.6, mixing height values were calculated for the above mentioned period of January to July and November 2006 as per availability of data. These include the average values of mixing height at 12:00 and 00:00 (UTC). Table 3.3 and Figure 3.7 show calculated morning and afternoon mixing height from AERMET using surface data of Jeddah city in 2006. As

shown in the Table of Radisonde data, there are not very marked differences between the AM and PM mixing height values in summer days. On the other hand, during the winter months (January), the mixing heights are also quite uniform but show smaller differences but at November the differences are high. These discrepancies are due to lack of data. The quality of upper air data is not good. If we analyze Table 3.3 and Figure 3.7 of AERMET process mixing height from surface data, there are very marked differences in summer days, but the winter period has some uniform differences. These observations are related to the sever weather condition, the drastic changes of the surface roughness, and the high level of solar radiation that prevail in Jeddah city. Table 3.4 shows the percentage differences of AERMET process mixing height and Balloon upper air mixing height. From this analysis the difference is not uniform and rate is high, due to bad quality of upper air observations. If missing value is less then the difference will be reduced. From the analysis of diagnostic model for January shows that equation of h_l Ayra (1981) correlates close to AERMET prepossesses for 2006 surface data of Jeddah city. The correlation factor and related graph are shown in Figure 3.8, Figure 3.9.

Table 3.2: Monthly Mixing Height for Jeddah City, Jan. to Dec. 2006
(from Radiosonde)

		JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	NOVEM
PM	MAX	1415	1365	1208	1255	1144	1291	1386	1412
	MIN	10	11	88	82	57	159	192	563
	AVE	701	745	797	881	724	657	799	990
AM	MAX	1493	1240	1154	1093	1166	1137	1115	1288
	MIN	85	69	62	56	52	159	373	50
	AVE	851	760	749	650	688	590	789	755

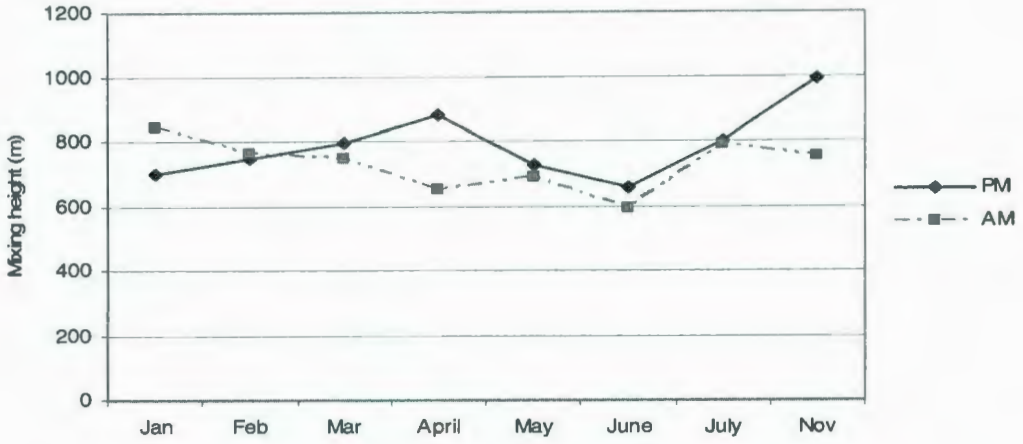


Figure 3.6: Monthly average mixing height from radiosonde

Table 3.3: Monthly Mixing Height for Jeddah City, Jan. to Dec. 2006

(from AERMET)

		JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	NOVEM
PM	MAX	4476	4055	3607	3529	3696	4097	3960	3102
	MIN	1548	1439	1656	1880	1061	2345	2492	1685
	AVE	2560	2145	2286	2588	2821	3285	3217	2452
AM	MAX	2573	2613	2683	3275	3057	3018	3850	2353
	MIN	103	431	290	835	394	796	1050	630
	AVE	1242	1226	1244	1645	1734	1813	1794	1286

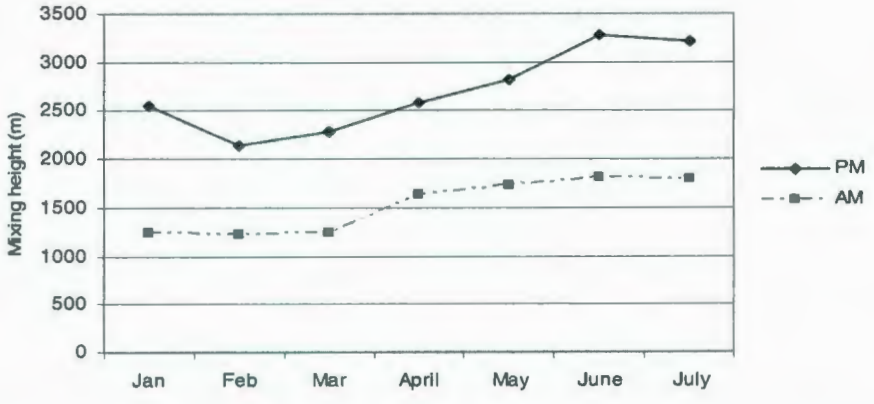


Figure 3.7: Monthly average mixing height from AERMET pre-processors

Table 3.4: Percentage variations of upper air MH & surface air MH of Jeddah City, From Jan. to Dec. 2006

MONTHLY AVERAGE PERCENTAGE DIFFERENCE OF BALLON UPPER AIR DATA & AERMET PROCESS SURFACE DATA MIXING HEIGHT									
		JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	NOVEM
PM	AVE	71%	66%	64%	65%	73%	80%	76%	60%
AM	AVE	4%	20%	33%	60%	52%	67%	55%	35%

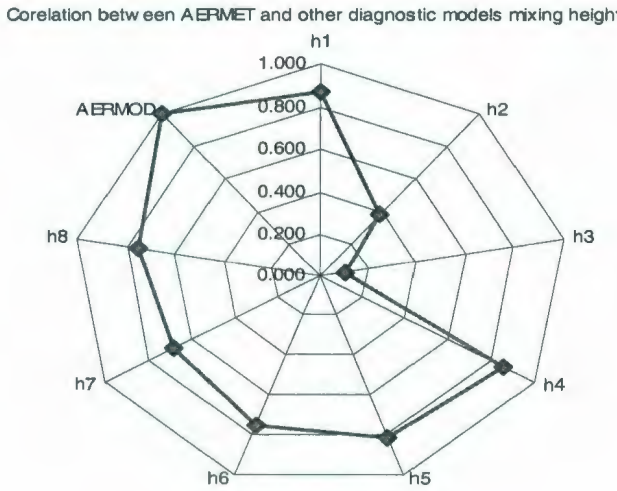


Figure 3.8: Correlation of diagnostic models with AERMET mixing height January 2006

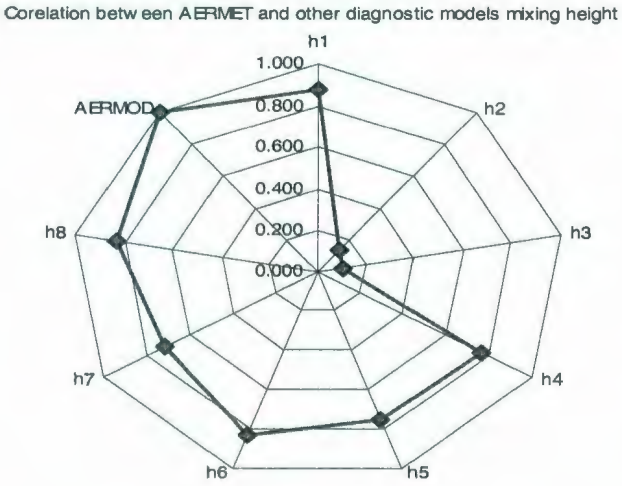


Figure 3.9: Correlation of diagnostic models with AERMET mixing height February 2006

3.4. Conclusions:

The aim of this study was to present case studies on mixing height calculations, and make a decision if upper air observation is not available mixing height from surface observations is reliable for use in modeling purposes. This approach is adopted using the meteorological conditions observed at the standard height at the surface and upper air stations near to KAAIA. The assumption is that these meteorological measurements are representative of the urban area. Our conclusion is that the average Mixing Height from upper air in Jeddah city is ranged from 590 m to 851 m for the early morning period and from 657 m to 990 m in the afternoon time. On the other hand the average Mixing Height from AERMET processed surface observation in Jeddah city within the same year 2006 ranges from 1226 m to 1813 m for the early morning period and from 2145 m to 3285m in the afternoon time. From this analysis AERMET mixing height is within good agreement. The database from upper air balloon has lot of missing data and that might be the reasons of high deviations. Besides, the diagnostic model Ayra (1981) correlated better with AERMET for this case study. So, if upper air observations are not available this diagnostic model will give good results with using surface observations. For future studies, mixing height derived here should be compared with values derived by using different techniques, e.g. remote sounding systems (Lidars, Sodars, RASS, Wind profiling radars), taking into account the impact of terrain irregularities, changes in the surface roughness, and surface heat fluxes.

Chapter 4

Emission Inventory for Selected Petrochemical Industries in Yanbu City

4.1. Introduction:

Emissions and releases to the environment are the starting point of every environmental pollution problem. Information on emissions therefore is an absolute requirement in understanding environmental problems and in monitoring progress towards solving these. Emission inventories provide this type of information. An emission inventory is an accounting of the amount of pollutants discharged into the atmosphere. It usually contains the total emissions for one or more specirfic greenhouse gases or air pollutants, originating from all source categories in a certain geographical area and within a specified time span, usually a specific year.An emission inventory is generally characterized by the following aspects:

1. The types of activities that cause emissions, (why)
2. The chemical or physical identity of the pollutants included, (what)
3. The geographic area covered, (where) and
4. The time period over which emissions are estimated. (when)

Emission inventories are developed for a variety of purposes:

Policy uses: by policy makers to

1. Track progress towards emission reduction targets,

2. Develop strategies and policies or;

Scientific use: Inventories of natural and anthropogenic emissions are used by scientists as inputs to air quality models.

The following sections describe the background of study area Yanbu city, methodology of preparing emission enventory, results and discussions of the case study of selected region.

4.2. Air Quality Standards:

From the point of view of pollution, control is based on process and control improvement, but before control is introduced some measurement must be observed to define its limit, therefore it is necessary to have an air quality standard to serve the limit for all pollutant emissions rate. Establishing the specific standard is important since it will serve as the basis for control of sources, without knowing the standard control cannot be introduced. In general, there are two types of air quality standards. The first class of standards NAAQS (such as the U.S. National Ambient Air Quality Standards) set maximum atmospheric concentrations for specific pollutants. Environmental agencies enact regulations which are intended to result in attainment of these target levels. The second class (such as the North American Air Quality Index) take the form of a scale with various thresholds, which is used to communicate to the public the relative risk of outdoor activity. The scale may or may not distinguish between different pollutants. Primary standards are designed to protect human health, with an adequate margin of safety, including sensitive populations such as children, the elderly, and individuals suffering from respiratory disease. Secondary standards are designed to protect public welfare from

any known or anticipated adverse effects of a pollutant (e.g. building facades, visibility, crops, and domestic animals).There are different types of standards used and made by different countries to control their pollutant emissions such as CCME (Canadian Council of Ministers of the Environment), DEFRA (UK's Department for Environment, Food and Rural Affairs), Kingdom of Saudi Arabia Standard, etc. United states and Kingdom of Saudi Arabia Standard are listed in tables 4.1. and 4.2 respectively.

Table 4.1: National Ambient Air Quality Standards for United States

Pollutant	Type	Standard	Averaging Time[a]	Regulatory Citation
SO_2	Primary	0.14 ppm (365 µg/m³)	24-hour	40 CFR 50.4(b)
SO_2	Primary	0.030 ppm (80 µg/m³)	annual	40 CFR 50.4(a)
SO_2	Secondary	0.5 ppm (1,300 µg/m³)	3-hour	40 CFR 50.5(a)
PM_{10}	Primary and Secondary	150 µg/m³	24-hour	40 CFR 50.6(a)
$PM_{2.5}$	Primary and Secondary	35 µg/m³	24-hour	40 CFR 50.7(a)
$PM_{2.5}$	Primary and Secondary	15 µg/m³	annual	40 CFR 50.7(a)
CO	Primary	35 ppm (40 mg/m³)	1-hour	40 CFR 50.8(a)(2)
CO	Primary	9 ppm (10 mg/m³)	8-hour	40 CFR 50.8(a)(1)
O_3	Primary and Secondary	0.12 ppm	1-hour[b]	40 CFR 50.9(a)
O_3	Primary and Secondary	0.075 ppm	8-hour	40 CFR 50.10(a)
NO_2	Primary and Secondary	0.053 ppm (100 µg/m³)	annual	40 CFR 50.11(a) and (b)
Pb	Primary and Secondary	0.15 µg/m³	Rolling 3 months	40 CFR 50.12

Note a: Each standard has its own criteria for how many times it may be exceeded, in some cases using a three year average.

Note b: As of June 15, 2005, the 1-hour ozone standard no longer applies to areas designated with respect to the 8-hour ozone standard (which includes most of the United States, except for portions of 10 states).

Source: USEPA

Table 4.2: Saudi Arabia Ambient Air Quality Standard

Pollutant	One-Hour average	Period of measurement (24-Hour) average	Annual average
SO_2	0.28 ppm (730 µg/m³)	0.14 ppm (365 µg/m³)	0.03 ppm (80 µg/m³)
Nitrogen oxides NO_x	0.35 ppm (660 µg/m³)		0.053 ppm (100 µg/m³)
Inhalable particulate PM_{15}		340 µg/m³)	80 µg/m³
Photochemical oxidants Ozone	0.15 ppm (290 µg/m³)		
Hydrogen sulfide	0.14 ppm (200 µg/m³)	0.03 ppm (40 µg/m³)	
Carbon monoxide CO	35 ppm (40 µg/m³)	8-hour average 9 ppm (10 mg/m³)	
Fluorides	Monthly average 0.001 ppm (1.0 µg/m³)		

Source : Final Report AR-15-26

4.3. Methodology for Emission Estimation:

This section provides an overview of commonly used air contaminant emission estimation methods and the applicability. The most commonly utilized emission estimation methods are:

1. Emission factors (EF)

2. Engineering calculations

3. Fuel analysis (mass balance)

4. Continuous emission monitor data

5. Source test data

Emission Factors:

Emission factors are the most common method for air contaminant emission estimation. The majority of EF has been developed from source test data for many different industries and activities. Careful evaluation of the source of the EF and the conditions for its use are required for proper application. Air Pollutant emission factors are representative values that attempt to relate the quantity of a pollutant released to the ambient air with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per megagram of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages. The equation for the estimation of emissions before emission reduction controls are applied is:

$$E = A \times EF$$

and for emissions after reduction controls are applied:

$$E = A \times EF \times (1\text{-}ER/100)$$

Where:

E = emissions, in units of pollutant per unit of time

A = activity rate, in units of weight, volume, distance or duration per unit of time

EF = emission factor, in units of pollutant per unit of weight, volume, distance or duration)

ER = overall emission reduction efficiency, in %

Emission factors are used bythe atmospheric dispersion modelers and others to determine the amount of air pollutants being emitted from sources within industrial facilities.

Engineering Calculations:

Engineering calculations are assumptions and/or judgements used to estimate quantities of chemicals released or emitted. The quantities are estimated by using physical and chemical properties and relationships (e.g., ideal gas law, Ragout's law) or by modifying an emission factor to reflect the chemical properties of the chemical in question. Engineering calculations rely on the input of process parameters, so a thorough knowledge of the process is required. Engineering calculations can also include computer models. There are several computer models available for estimating emissions from industrial sources, water and wastewater treatment facilities that take into account the physical and chemical properties of the effluent streams. Many of the VOC emission factors are based on a combination of empirical data, engineering judgement, and engineering calculations.

Mass Balance:

Mass balance is also often utilized for air contaminant emission estimates. A mass balance involves determining the amount of a chemical entering and leaving an operation. A thorough understanding of the process and all of the process input and output streams is required. The majority of SOx emission factors for fuel combustion are based on mass balance. The sulfur content of the fuel or waste is utilized to estimate the SO_2 emissions. The quality of these emission estimates are improved by collecting and analyzing samples of all fuels or wastes of interest over an extended period of time. A sampling plan that

takes into account temporal changes in and homogeneity of fuel or waste composition should be developed.

Monitoring Data:

If measurement methods and data quality have been assured, using monitoring data or source test measurements is usually the best method for developing emission estimates for a specific source. At a facility, monitoring data may be available from monitoring performed to meet environment regulation monitoring requirements or may have been collected through an occupational health and safety assessment. If a limited amount of direct measurement data is available or if the monitoring data are not representative, additional emission estimation techniques should be explored. Monitoring data is the most widely accepted method if the monitoring systems meet accepted quality assurance/quality control (QA/QC) requirements.

Source Test Measurements:

The vast majority of PM emission factors are developed from source test measurements and the measurement of $PM/PM_{2.5}$ is an evolving science. It is important to understand some of the complications with $PM/PM_{2.5}$ source sampling as background for understanding the uncertainties in $PM/PM_{2.5}$ emission factors. Source characterization approaches for particulate matter fall into two general categories: source-level sampling and ambient-level sampling. The general sampling and analytical principles for characterizing particulate mass, size, and composition are similar for the two types of measurements, but the specific approaches differ due to the differences in effluent ducting, gas temperature, pollutant concentrations and background composition. In the context of regulatory enforcement, source-level sampling from ducted emissions is currently the accepted approach for total suspended particulate and PM_{10} measurements

for stationary sources, while ambient level sampling using dilution is the accepted approach for mobile source particulate emission measurements.

4.4. Source Characterization:

To compile an emission inventory first step is source characterization. All sources of the pollutants must be identified and quantified. Sources of air pollution refer to the various locations, activities or factors which are responsible for the releasing of pollutants in the atmosphere. These sources can be classified into two major categories which are:

Anthropogenic sources (human activity) mostly related to burning different kinds of fuel.

- Stationary Sources: include smoke stacks of power plants, manufacturing facilities (factories) and waste incinerators, as well as furnaces and other types of fuel-burning heating devices ;
- Mobile Sources: include motor vehicles, marine vessels, aircraft etc .
- Chemicals, dust and controlled burn practices in agriculture and forestry management. Controlled or prescribed burning is a technique sometimes used in forest management, farming, prairie restoration or greenhouse gas abatement.
- Fumes from paint, hair spray, varnish aerosol sprays and other solvents .
- Waste deposition in landfills, which generate methane. Methane is not toxic; however, it is highly flammable and may form explosive mixtures with air.
- Military, such as nuclear weapons, toxic gases, germ warfare and rocketry.

Natural sources:

- Dust from natural sources, usually large areas of land with little or no vegetation.
- Methane, emitted by the digestion of food by animals, for example cattle.
- Radon gas from radioactive decay within the Earth's crust.
- Smoke and carbon monoxide from wildfires.
- Volcanic activity, which produce sulfur, chlorine, and ash particulates.

The types of air pollutant emission sources are commonly characterized as either point, line, area or volume sources:

- **Point source:** A point source is a single, identifiable source of air pollutant emissions (for example, the emissions from a combustion furnace flue gas stack). Point sources are also characterized as being either elevated or at ground-level. A point source has no geometric dimensions.

- **Line sources:** is a one-dimensional source of air pollutant emissions (for example, the emissions from the vehicular traffic on a roadway).

- **Area source:** An area source is a two-dimensional source of diffuse air pollutant emissions (for example, the emissions from a forest fire, a landfill or the evaporated vapors from a large spill of volatile liquid).

- **Volume source:** A volume source is a three-dimensional source of diffuse air pollutant emissions. Essentially, it is an area source with a third (height) dimension (for example, the fugitive gaseous emissions from piping flanges,

valves and other equipment at various heights within industrial facilities such as oil refineries and petrochemical plants).

Sources may be characterized as either urban or rural because urban areas constitute a so-called heat island and the heat rising from an urban area causes the atmosphere above an urban area to be more turbulent than the atmosphere above a rural area.

Sources may be characterized by their elevation relative to the ground as either **surface** or **ground-level**, **near surface** or **elevated** sources.

Sources may also be characterized by their time duration:

- **puff** or **intermittent**: short term sources (for example, many accidental emission releases are short term puffs)
- **continuous**: a long term source (for example, most flue gas stack emissions are continuous)

4.4.1. Source Data Collection of Study Area:

Yanbu city is one of the modern industrial cities in Saudi arabia. Areas of Yanbu are divided as: (1) Heavey indutry, (2) Light industry, (3) Port facilities, (4) Community area, (5) Community support area, (6) Open space, buffer zones, recreation areas.

The aim of source data collection is to provide enough information for the calculation of quantity of emissions from stationary sources within Yanbu city. These

data have collected from various literature review of this city and visiting their companies website.

Stationary Sources: stationary sources in Yanbu are located both in heavy industry and light industry areas. Collected data include following information for stationary sources:

1. Location, type and size,
2. Processes and operations,
3. Fuel type and fuel combustion,
4. Stack characteristics,
5. Exit gas characteristics, and
6. Air pollution control characteristics.

Existing industries in heavy and light industry areas are listed in Tables 4.3. and 4.4 respectively. Locations of these industries are shown in Figure 4.2.

Table 4.3: Existing industries at heavy industry area

Industry Name	Location No
Purified Terephthalic Acid (PTA)	5
Arabian Industrial Fibers Co. (Ibn Rushd)	8
Safra Co. Ltd	9
Saudi Yanbu Petrochemical Co. (Yanpet)	11
Saudi Aramco Mobil Refinery Co. Ltd (SAMREF)	12
Crude Terminal	13
Power and Desalination Plant (MYASPP)	14
Sanitary Sewage Wastewater Treatment	15 &16
Saudi Arabian Lube additives Co. Ltd (SALACO)	18
Arabian chemical Terminals (ACT)	19
Lubrizol Trans Arabian Co. Ltd	20
Natural Gas Liquid (NGL) Plant	22
Yanbu Refinery	23
Petromin Lubricating Oil Refinery Co. (LUBEREF II)	24

Fuchs Petroleum Saudi Arabia Ltd	26
Alhamrani Fuchs Grease Plant	27
Crystal	28
Arabian Chlorine Co. Ltd. (ACC)	29
National Gas and Industrialization Co. (GASCO)	42

Table 4.4: Existing industries at light industry area

Industry Name	Location No
General Agencies and Contracting (GAC)	1
Woodwool Cement Plant	2
AYTB Company	5
Abdullah Hasem Industrial Gases & Equipment Co. Ltd. (AHG)	10
Jotun Saudia Co.	13
Abudawood Industrial Co. Ltd.	14
Shairco Fiberglass	15
Best Foods Saudi Arabia	17
ABB-TEMECO	26
Iscosa Industries and Maintenance Ltd.	27
Zahid Tractor	29
Tawfik Printing Press	30
Al Zamil Refrigiration	32

Highlighted two major indutries in the above tables have been considered for the case study. Because objective of the study to rank of air concentrations within different grid and develop a methodology of emission calculations.Selected two industry has contribute major pollutions. Emissions from these industries have been calculated using two different sets of emission factors and compared.

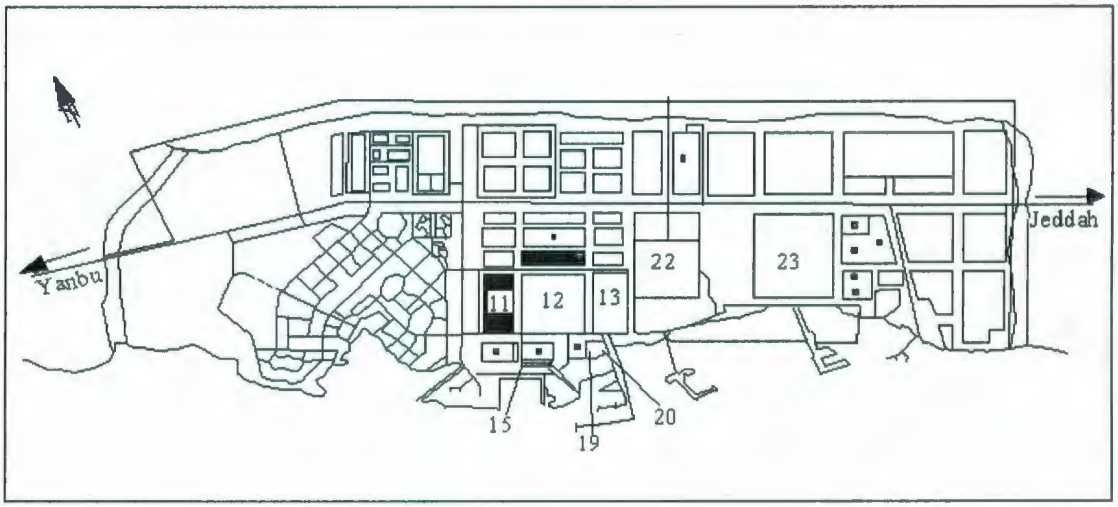


Figure 4.1: Locations of Heavy and Light Industries at MYAS

4.4.2. Case Study:

a. Source characterization:

1. Safra Co. Ltd:

Location: Heavy industry area, No.9

Type: Production of Hydrocarbon solvents

Size:Quantity of products of safra is:

Table 4.5: Quantity of products of Safra Co. Ltd

Products	Unit (Metric tonne/year)
Desulfurized kerosene	63000
Kerosene fractionates	63000
Dearomatized kerosene	25920
Dearomatized white spirit	43200
Toluene	8230
Xylene	15010
Benzene	15980
C-9 solvent	9200

Process or Operations: Following processes are involved in Safra:

Kerosene Desulfurized : Desulfurized kerosene is produced from kerosene.

Kerosene fractionation: Light white spirit, medium white spirit and white spirit are produced from kerosene.

Hydro Dearomatiztion: Dearomatiztion kerosene and dearomatized white spirit are produced.

Reformate fractionation: Toluene, xylene, benzene, and C-9 solvent are produced.

Fuel and Fuel combustion: Kerosene and fuel gases are burned in heater furnaces. Number of heaters are two, operating 345 days/year.

Waste gases are burned in incinerator.

Quantity of fuel burned:

Kerosene: 6300 MT/year with heat content of 11000 kcal/kg. sulfur content is 1.2% by volume.

Fuel gas: 800 MT/year with heat content of 12760 kcal/kg. sulfur content is 1.05% by volume.

Waste gas: 16600 MT/year, contains 1.5% H_2S.

Stack Characteristics:

Heater stacks: 18.4 m. height, 1.37m. diameter at the top.

7.2 m. height, 0.57m. diameter at the top.

Incinerator stack: 33.4 m. height, 0.76m. diameter at the top.

Exit Gas Characteristics: Exit gas temperatures are 750^0C and 800^0C from heaters and 300^0C from incinerator.

Air pollution control equipment Characteristics: Not available

2. Saudi Yanbu Petrochemical Co. (Yanpet):

Location: Heavy industry area, No.11

Type: Petroleum complex to produce ethylene, ethylene glycol and polythylene.

Size:Quantity of products of YANPET are:

Table 4.6: Quantity of products of YANPET Co. Ltd

Products	Unit (MT/year)
Polymer grade ethylene	688000
Propylene	22000
Polyethylene resin	530000
Ethylene glycols	335000

Process or Operations: Following unit are involved in Yanpet:

Ethylene unit : Polymer grade ethylene and Propylene are produced from chemical grade ethane.

Polyethylene unit : Polyethylene resin is produced from polymer grade ethylene .

Glycol unit : Glycols (monoethylene glycol, diethylene glycol and triethylene glycol) are produced from polymer grade ethylene.

Process flow diagram of YANPET is shown in Figure 4.2.

Fuel and Fuel combustion: Fuel gas is burned in the boilers for steam generation. Mix fuel (ethane, methane, and hydrogen) is burned in ethane crackers for heat generation. Waste liquid hydrocarbon and waste gases are burned in incinerators.

Four boilers are operating 24 hours a day for 365 days ayear and prodduce 450 tons of steam per hour.

Similary the number of ethane crackers are 12, normally 11 are in operation.Each has a capacity of $31x10^6$ kcal/hr. and operates 24 hours/day, 365 days/year .

There are three incinerators operating 24 hours aday, for 365 days a year and each has a capacity of $21.5x10^6$ kcal/hr.

Quantity of fuel burned:

Fuel gas : 185,600 MT/year with heat content of 47,400 kJ/kg. sulfur content is less than 0.02% by weight.

Mix fuel : 190,000 MT/year with heat content of 71,000 kJl/kg. sulfur content is less than 0.01% by weight.

Wasteliquid HC and waste gases: 46,000 MT/year, with heat content of 45,000 kJ/kg. sulfur content is not known.

Stack Characteristics:

Boilers stacks (4) : 50 m. height, 2.5m. diameter at the top.

Eathane crackers stacks (6) : 50 m. height, 2.5m. diameter at the top.

Waste liquid/gas incinerators stacks (3) :30 m. height, 2.5m. diameter at the top.

Exit Gas Characteristics:

Source	Temperature ^{0}C	Velocity m/s	NOx, ppm	SO_2, ppm
Boiler stack	180	10	100	5
Eathane cracker stack	200	10	NA	NA
Waste incinerator stack	850	8	NA	NA

Source:Yanpet Co., Ltd.[EESAL (1984) under contract GSTE-4021]

Air pollution control equipment characteristics: Not available

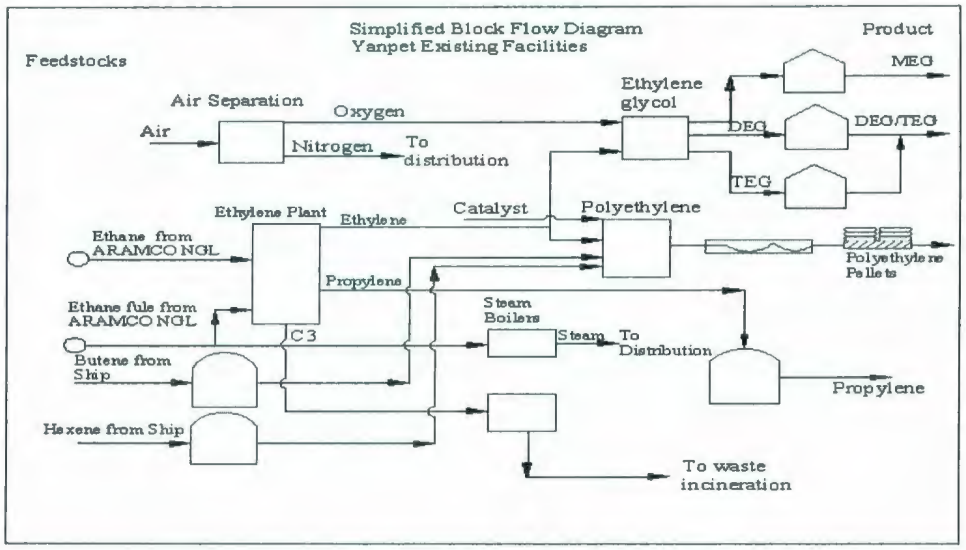


Figure 4.2: Process Flow diagram of YANPET

b. Methodology of pollutants emissions estimation:

Emissions of sulfur dioxide, nitrogen oxides, carbon monoxide, hydrocarbon and particulates are determined from stationary sources. Emissions of specific pollutants related to nature of manufacturing industrial processes are also determined. Very limited measured field test data was available. Therefore, emission factors were mainly used in conjunction with a limited source information obtained through source data collection phase. Engineering knowledge and judgement were also used to review the sources to arrive at a realistic estimate.

Emission factors according to the sources were reviewed from literature. Table of emission factors from USEPA [AP 42,Volume I,1995], and emission factors from WHO [World Health Organization,1982] are listed in Appendix A.

Procedure for estimating emissions from Stationary sources:

1. Emissionns from fuel combustion in stationary sources were estimated by using information (type, quantity, specific gravity, sulfur content) on burned fuel and emission factor values of each pollutant.

   $E = Q \times EF$

   Where, *E*= emission kg/year

   Q= quantity of fuel burned, ton/year

   EF= emission factor, kg/ton

2. Emissions from processes in stationary sources were estimated by yearly quantity of product produced in the process and emission factor value of that process.

   $E = Q_p \times EF_p$

   Where, *E*= emission kg/year

   Q_p= quantity of product ton/year

   EF_p= emission factor of product, kg/ton

4.4.3. Results and Discussions:

The yearly emissions of the above two selected companies are calculated from two sets of EF data sets and these values were compared. Figures 4.3 and 4.4 show the total yearly emissions from Safra compay. The typical pollutants from Safra is SOx, NOx, carbon monoxides, hydrocarbon, total organic compounds (TOC), volatile organic compounds (VOC) and particulates. From WHO [World Health Organization,1982] data 65% of SOx, 10% of NOx, 3% of particles, 20% of SO_2, 1% of CO and 1% of HC are emitted from Safra. According to USEPA [AP 42, Fifth edition,1995] these values are quite different. The respective percentage of SO_2 is 64%, NOx 4%, particles 9%, VOC 7%, TOC 13% and methane 3%. Figure 4.7 shows the comparative study of these

pollutants emission rate. Yanpet industry yearly emission rates are shown in Figures 4.5 and 4.6 respectively.The typical pollutants from Yanpet is SOx, NOx, carbon monoxides, hydrocarbon, total organic compounds (TOC), volatile organic compounds (VOC), methane and particulates. Figure 4.8 shows relative values of these pollutants according to WHO and USEPA EF data sets. Table 4.7 represent final emission inventory according to WHO [1982] EF and USEPA[AP 42, 1995] EF of that company with source classification code of MYAS city. From these study USEPA data sets is more effective and organized these dataset also have compounds of hydrocarbon. For both companies the emissions calculated using US EPA approach are higher values than values obtained using WHO factors. Yearly emissions of benzene are less from USEPA dataset.

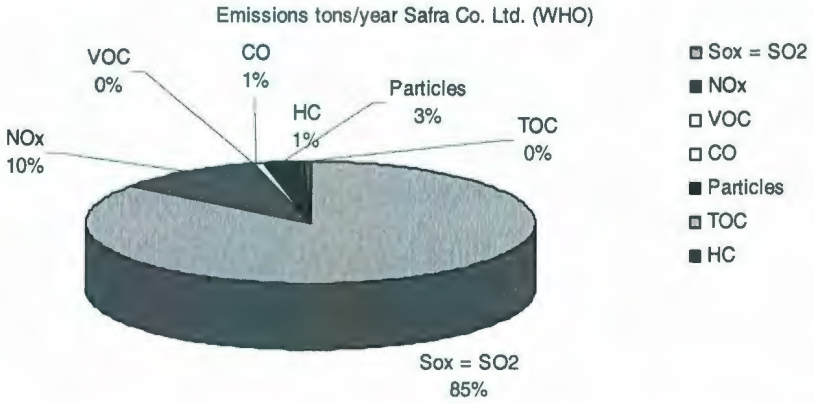


Figure 4.3: Emissions Safra Co. Ltd. (WHO 1982, EF)

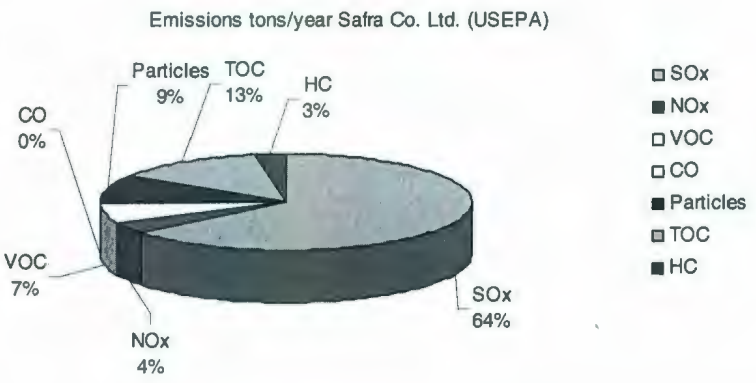


Figure 4.4: Emissions Safra Co. Ltd. (USEPA AP 42, EF)

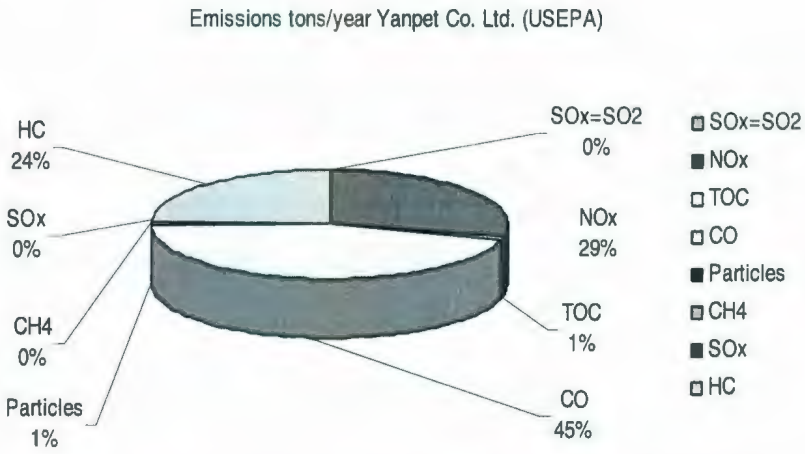


Figure 4.5: Emissions Yanpet Co. Ltd. (WHO, 1982 EF)

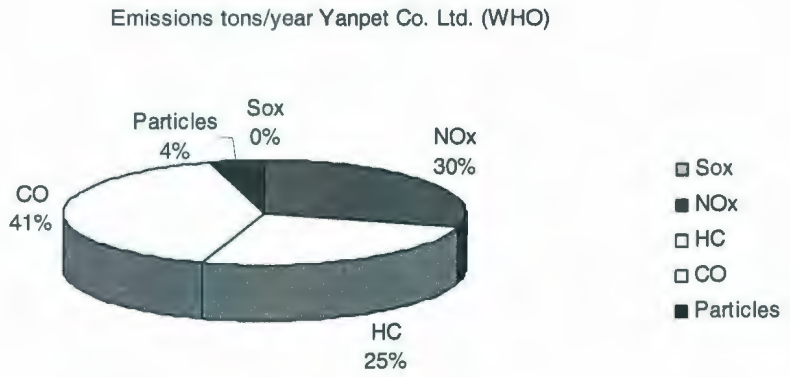


Figure 4.6: Emissions Yanpet Co. Ltd. (USEPA AP 42 EF)

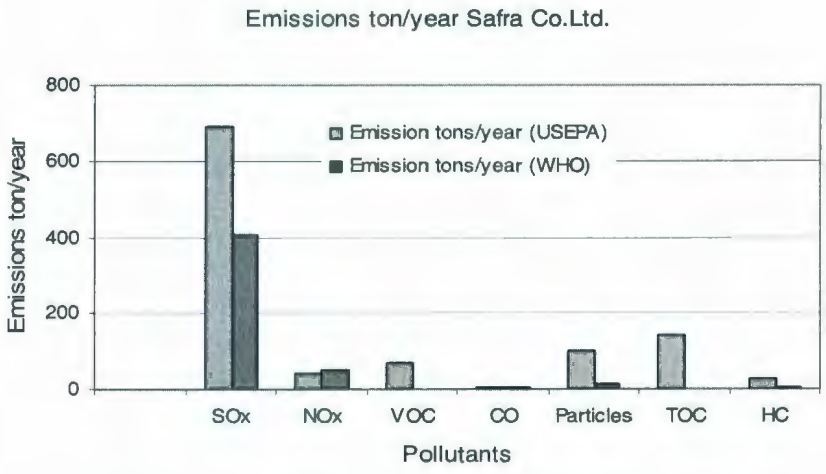


Figure 4.7: Comparative emission Rate of Safra Co. Ltd.

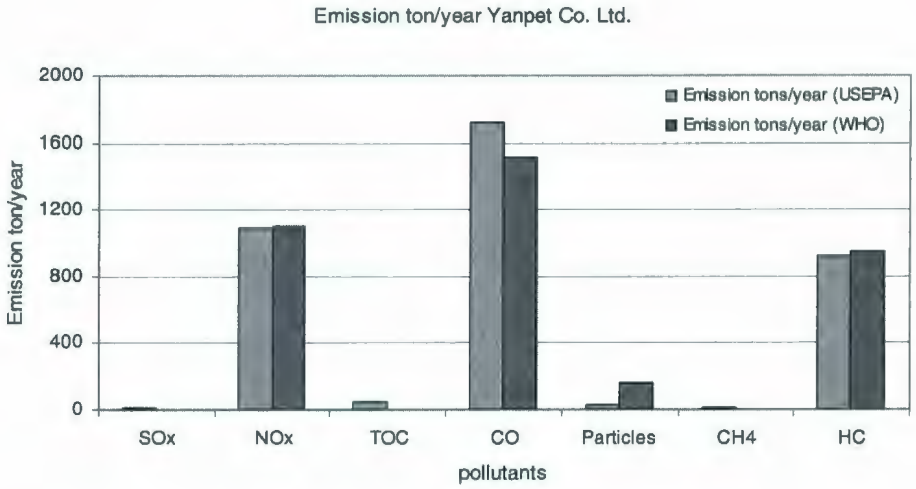


Figure 4.8: Comparative emission Rate of Yanpet Co. Ltd

Table 4.7: Emissions tons/year

Sector	SCC	EF data set	Source	Fuel Type	SOx	NOx	CO	HC	PM	TOC	CH_4	SO_2
Petrochemical Industry												
Saudi Yanbu Petrochemical Co. Yanpet	3513	WHO (1982)	Boiler	Fuel gas	0.074	482.56	64.96	11.69	70.53			
			Incinerator	Waste liquid HC & waste gas	0.009	119.60	1380	920	17.48			
			Ethane crackers	Mix fuel	0.038	494	66.50	11.97	72.20			
		USEPA (AP 42, 1995)	Boiler	Fuel gas		289.54	167.04		15.59	22.27	4.45	0.045
			Incinerator	Waste liquid HC & waste gas	5.52	506	1380	920				
			Ethane crackers	Mix fuel		296.40	171		15.96	22.80	4.56	0.023
Safra Co. Ltd.	3511	WHO (1982)	Heater	Fuel gas, kerosene	314.58	49.33	3.99	2.63	13.72			
			Incinerator	Waste gas								93.49
		USEPA (AP 42, 1995)	Heater	Fuel gas, kerosene	70.40	43.28	3.78		98.79	140.8	29.44	283.35
			Incinerator	Waste gas								407.26

4.4. Conclusions and Recommendations:

Air pollution becomes major concern of modern world. This chapter describe preparation of emission inventory of Yanbu industrial city. Two major industries Safra and Yanpet yearly emission were calculated using two different types of EF data sets and comparing these values. The typical pollutants from from these are SOx, NOx, carbon monoxides, hydrocarbon, total organic compounds (TOC), volatile organic compounds (VOC) and particulates. For both companies the emissions calculated using USEPA(AP 42, 1995) dataset gives higher values than values obtained using WHO (1982) datasets. Reason can be USEPA data sets is more effective and organized these dataset also have compounds of hydrocarbon. Time of preparation and availability of data can also be a reason.

Chapter 5

Air Dispersion model methodology

5.1. Introduction:

Air dispersion modeling is the mathematical simulation of how air pollutants disperse in the ambient atmosphere. It is performed with computer programs that solve the mathematical equations and algorithms which simulate the pollutant dispersion. The dispersion models are used to estimate or to predict the downwind concentration of air pollutants emitted from sources such as industrial plants and vehicular traffic. Such models are important to governmental agencies tasked with protecting and managing the ambient air quality. Several factors impact the fate and transport of contaminants in the atmosphere including meteorological conditions, site configuration, emission release characteristics, and surrounding terrain, among others.

Historically, the most frequently used dispersion model have been based on the Gaussian (or normal) distribution where the air contaminant concentration profile through the plume has the shape of the normal bell curve in both the vertical and lateral direction. The concentration is the greatest at the plume centerline and decreases with distance away from the centerline. The rate at which the plume spreads as it travels downwind is a function of atmospheric turbulence. Gaussian models have long been used for dispersion calculations and are routinely used to support the permitting of air pollutant emission sources. As with any model, the accuracy of the model results is dependent upon the quality of the input data. Overview of various air dispersion models with their advantages and limitations have discussed in chapter 2, section 2.7.

5.2. Model chooses within study area:

One of the key elements of an effective dispersion modelling study is to choose an appropriate tool to match the scale of impact and complexity of a particular discharge. When choosing the most appropriate model the principal issues to consider are:

- The complexity of dispersion (e.g. terrain and meteorology effects)
- The potential scale and significance of potential effects, including the sensitivity of the receiving environment (e.g. human health versus amenity effects).

In medium-complex atmospheric and topographical conditions with relatively simple effects, Gaussian-plume models can produce reliable results. In more complex atmospheric and topographical conditions, advanced puff or particle models and meteorological modelling may be required to maintain a similar degree of accuracy. In choosing the most appropriate model it is very important to understand the model's limitations and apply it only to the situations that match its capabilities.

The choice of an appropriate dispersion model is dependent on the intended application. If study areas are located within 20 kilometres of the coast and so the majority of air pollution concentrations over urban areas are affected by highly variable coastal airflows. The situation is further complicated by complex topography. In such environments simple Gaussian-plume models may not provide the best results. This is likely to be especially true if pollutants cause effects at distances greater than about 10 kilometres from their source and under fumigation conditions. In these situations an advanced dispersion model may be more suited to the situation and provide better results. In situations of complex terrain or near coastal boundaries, significant changes in meteorological conditions can occur over short distances. Advanced models can simulate the effects of coastal areas and

terrain effects on pollutant transport and dispersion in a much more realistic way than a Gaussian-plume model, which assumes spatial uniformity in the meteorology. Though Yanbu is a coastal city but not within is 20 kilometres of the coast, it is 350 kilometres from coast that why we can use AERMOD dispersion model for our study. Further for sound decision compare the results with CULPUFF were better but due to data gap we can not incorporate that.

5.3. Input data information of ISC-AERMOD View for Yanbu Industrial City:

The ISC-AERMOD View interface require input data in five main categories: control pathway, source/emission parameters, land use/terrain information, receptor types, and meteorological conditions Specific requirements vary by source type and the model to be used.

Control Pathway (CO):

Control pathway used to specify dispersion option as regulatory or non regulatory default option, urban or rural settings, pollutant types, dispersion coefficient, averaging time etc. For this study input option set by followings:

- Dispersion option; (regulatory , non default option)
- Averaging time; (1 hr, 8 hr, 24 hr ,dispersion co-efficient for urban setting)
- For urban setting; (population: 188430 & surface roughness 1.0)
- Pollutant; (type, exponential option)

Meteorological Input Data:

Meteorological data is used by the model to help simulate plume transport and dispersion. Requirements of meteorological data (on hourly basis) are: date, time, cloud cover, temperature, net radiation, wind speed and direction. Atmospheric boundary layer parameters are mixing height and wind profile. Data quantifying the wind direction and speed, ambient temperature, mixing height and atmospheric stability are used as input to the model. Meteorological data recorded hourly by nearby representative weather stations are often used as input to refined models. Use of actual meteorological data recorded at representative locations can be used to predict both short and long-term concentrations. Three sets of pre-processed meteorological data as per required format (see chapter 2 section 2.3.1~2.3.2) were used. Year 2006, 2007 and 2008 met data have been collected with anemometer height 10m have been considered for this study.

Source / emission data:

Source/emission parameters define how the emissions are released into the atmosphere. For example, for pollutants that are vented from stacks, emission information needed by models include the temperature and velocity of the gases exiting the stack, height and diameter of the stack, and emission rates of the pollutants to be addressed. Models also require dimensions of adjacent building structures if estimating pollutant concentrations due to downwash (entrainment of pollutants into building wakes and cavities). This thesis considered two industries Safra Co. Ltd., Yanpet Co. Ltd. And their associated five elevated point sources (boiler, incinerator, ethane crackers etc.). The details input of source data has discussed at chapter 4 section 4.4.2. The emission rate required by model shown in Table 4.7 and Table 4.8, where emissions are tonnes/year.

Land Use Data:

Land use information and terrain elevations are also important input parameters in the dispersion modeling analysis. The rate at which a plume disperses and eventually reaches ground level is affected by the degree of urbanization of the surrounding area. Generally, greater plume dispersion is found in urban environments due to enhanced mechanical and thermal turbulence. Land use within the vicinity of the facility is used to determine whether the area should be viewed as urban or rural. Additionally, terrain information is input to the model. This data is used to establish the base elevation of on site structures including buildings and the stack. It is also used to establish the elevation of receptors where pollutant concentration is to be predicted. This model considered as flat terrain.

Receptor Data:

The ISC dispersion model computer programs allow the user to select either a Cartesian (X, Y) or a polar (r, θ) receptor grid system. In the Cartesian system, the X-axis is positive to the east of a user-specified origin, and the Y-axis is positive to the north of this origin. In the polar system, r is the radial distance measured from the user-specified origin, and the angle θ (azimuth bearing) is measured clockwise from north. If pollutant emissions are dominated by a single source or by a group of sources in close proximity, a polar coordinate system with its origin at the location of the dominant source or sources is the preferred receptor grid system. However, if the industrial source complex comprises multiple sources that are not located at the same point, a Cartesian coordinate system is usually more convenient. Additionally, if the UTM coordinate system is used to define source locations and/or to extract the elevations of receptor

points from USGS topographic maps, the UTM system can also be used in the ISC model calculations.

In the polar coordinate system, receptor points are usually spaced at 10 degree intervals on concentric rings. Thus, there are 36 receptors on each ring. The radial distances from the origin to the receptor rings are user selected and are generally set equal to the distances to the expected maximum ground-level concentrations for the major pollutant sources under the most frequent stability and wind-speed combinations.

In the Cartesian coordinate system, the X and Y coordinates of the receptors are specified by the user. The spacing of grid points is not required to be uniform so that the density of grid points can be greatest in the area of the expected maximum ground-level concentrations.

Uniform Cartesian gird receptor network of 441 receptors cover all the area of conceptual maps. No. of points 21x21 have used in this study. Following figures shows the grid system and point sources of the model of yanbu city.

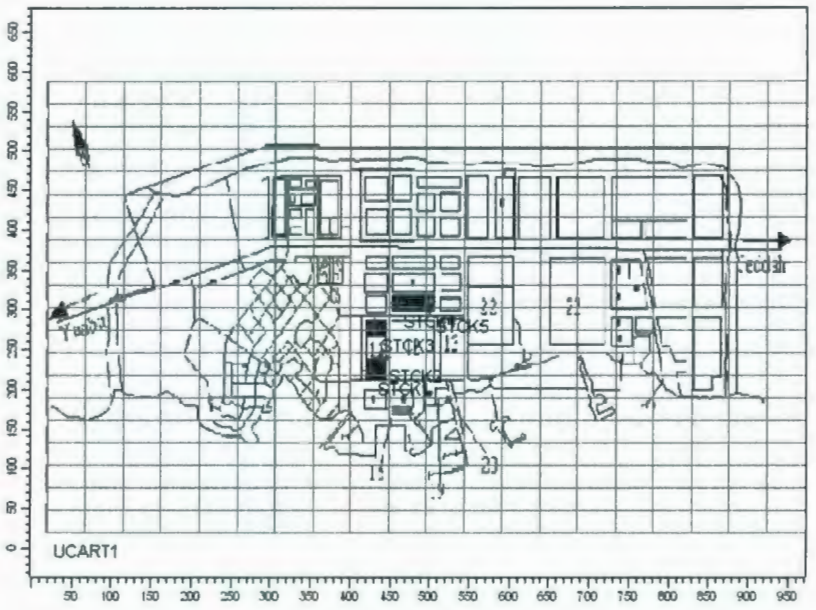


Figure 5.1: model developed for Yanbu city showing Grid

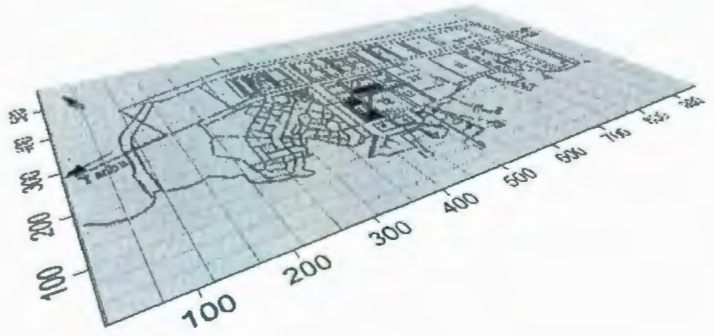


Figure 5.2: model developed for Yanbu city showing 3D of point sources

Model results included at appendix C1~C6. And concentrations compared with Table 4.2 Saudi Arabia Ambient Air Quality Standard of chapter 4.

5.4: Methodology:

The ISC Short Term model accepts hourly meteorological data records to define the conditions for plume rise, transport, diffusion, and deposition. The model estimates the concentration or deposition value for each source and receptor combination for each hour of input meteorology, and calculates user-selected short-term averages [USEPA, 1995]. The AERMOD model uses a steady-state Gaussian plume equation to model emissions from point sources, such as stacks and isolated vents.

CALPUFF is a Lagrangian puff model. The model is programmed to simulate continuous puffs of pollutants being emitted from a source into the ambient wind flow. As the wind flow changes from hour to hour, the path each puff takes changes to the new wind flow direction. Puff diffusion is Gaussian and concentrations are based on the contributions of each puff as it passes over or near a receptor point. A sufficiently large number of puffs is necessary to adequately reproduce the plume solution at near-field receptors. CALPUFF was originally designed for mesoscale applications and treated emissions as integrated puffs.

This section describes the Gaussian point source model, including the basic Gaussian equation, the plume rise formulas, and the formulas used for determining dispersion parameters.

5.4.1. Gaussian plume equation for a continuous elevated source:

For steady state Gaussian plume equation considers each source and each hour, the origin of the source's coordinate system is placed at the ground surface at the base of the stack. The x axis is positive in the downwind direction, the y axis is crosswind (normal)

to the x axis and the z axis extends vertically. The fixed receptor locations are converted to each source's coordinate system for each hourly concentration calculation. The hourly concentrations calculated for each source at each receptor are summed to obtain the total concentration produced at each receptor by the combined source emissions. For a steady-state Gaussian plume, the hourly concentration at downwind distance x (meters) and crosswind distance y (meters) is given by [Boubel , et.al., 1994]:

$$C(x,y) = \frac{QKVD}{2\pi u_s \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \text{---------- (1)}$$

Where,

Q = pollutant emission rate (mass per unit time)

K = a scaling coefficient to convert calculated concentrations to desired units (default value of (1×10^6) for Q in g/s and concentration in μg/m3)

V = vertical term

D = decay term

σ_y, σ_z = standard deviation of lateral and vertical concentration distribution (m)

u_s = mean wind speed (m/s) at release height.

Equation 1 includes a vertical term V, a decay term D, and dispersion coefficients (σ_y and σ_z). The dispersion coefficients and the vertical term are discussed below. It should be noted that the vertical term includes the effects of source elevation, plume rise, limited mixing in the vertical, and the gravitational settling and dry deposition of larger particulate (with diameters greater than about 0.1 microns).

The decay term, which is a simple method of accounting for pollutant removal by physical or chemical processes, is of the form

$$D = \exp[-\Psi * x / u_s] \quad \text{---------- (2)}$$

Where

Ψ = the decay coefficient (s^{-1}) (a value of zero means decay is not considered)

x = downwind distance (m)

For example, if T1/2 is the pollutant half life in seconds, the Ψ is obtain from the relationship

$$\psi = \frac{0.693}{T_{1/2}} \quad \text{---------- (3)}$$

The effects on ambient concentrations of gravitational settling and dry deposition can be neglected for gaseous pollutants and small particulates (less than about 0.1microns in diameter). The Vertical Term without deposition is given by

$$V = \frac{1}{2}\exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] + \sum_{\substack{j=1,\infty \\ j=1,4}}\left(\exp\left[-\frac{1}{2}\left(\frac{H_j}{\sigma_z}\right)^2\right]\right) \quad \text{---------- (4)}$$

Where: $H_1 = 2iH_m - H - H_R$

$H_2 = 2iH_m + H - H_R$

$H_3 = 2iH_m - H + H_R$

$H_4 = 2iH_m + H + H_R$

H = Effective stack height.

H_m = Mixing height.

H_R = Receptor height

H= effective stack height = sum of actual stack height, hs, and buoyant rise, δh

H_m = mixing height (m)

It should be noted that, if the effective stack height, H, exceeds the mixing height, H_m, the plume is assumed to remain elevated and ground-level concentration is set equal to zero. The vertical term defined by Equation 4 changes the form of the vertical concentration distribution from Gaussian to rectangular at longer downwind distances. Consequently, in order to reduce computational time without a loss of accuracy, Equation 4 is changed to

$$V = \frac{\sqrt{2 * \sigma_z}}{z_i} \text{ ---------- (5)}$$

at downwind distances where the σ_z/zi ratio is greater than or equal to 1.6.

The empirical dispersion coefficients, σ_y and σ_z, used in the model are those suggested by Pasquill-Gifford curves, and reported by [Turner,1970]. Values of σ_y and σ_z are represented as a function of downwind distance from the emission source and the stability of the atmosphere. The equations used to calculate σ_y and σ_z for rural mode are of the form

$$\sigma_y = 465.11628 \text{ x } \tan(T) \text{ ---------- (6)}$$

$$T = 0.017453293 (c - d \ln x) \text{ ---------- (7)}$$

Where, x is the downwind distance in kilometres and the coefficients c and d are functions of stability class. The equation used to calculate σ_z is of the form

$$\sigma_z = ax^b \text{ ---------- (8)}$$

Where, the downwind distance x is in kilometres and the coefficients (a, b) are functions of stability class and downwind distance.

Tables 5.1 and 5.2 shows the equations used to determine σ_y and σ_z for the urban option. These expressions were determined by Briggs as reported by [Gifford, 1976] and represent a best fit to urban vertical diffusion data reported by [McElroy and Pooler, 1968].

Table 5.1: Parameters Used to Calculate Pasquill-Gifford σ_y [Boubel , et.al., 1994]

$\sigma y = 465.11628\ (x) \tan (T)$

$T = 0.017453293\ [c - d \ln(x)]$

Pasquill Stability Category	c	d
A	24.1670	2.5334
B	18.3330	1.8096
C	12.500	1.0857
D	8.3330	0.72382
E	6.2500	0.54287
F	4.1667	0.36191

Where σ_y is in meters and x is in kilometers.

Table 5.2: Briggs Formulas Used to Calculate Mcelroy-Pooler σ_y [Boubel , et.al., 1994]:

BRIGGS FORMULAS USED TO CALCULATE Mcelroy-Pooler σ_y	
Pasquill Stability Category	σy(meters)*
A	0.32 x (1.0 + 0.0004 x)-1/2
B	0.32 x (1.0 + 0.0004 x)-1/2
C	0.22 x (1.0 + 0.0004 x)-1/2
D	0.16 x (1.0 + 0.0004 x)-1/2
E	0.11 x (1.0 + 0.0004 x)-1/2
F	0.11 x (1.0 + 0.0004 x)-1/2

* Where x is in meters

Table 5.3: Briggs Formulas Used to Calculate Mcelroy-Pooler σ_z [Boubel , et.al., 1994]:

BRIGGS FORMULAS USED TO CALCULATE Mcelroy-Pooler σ_z	
Pasquill Stability Category	σ_z (meters)*
A	0.24 x (1.0 + 0.001 x)1/2
B	0.24 x (1.0 + 0.001 x)1/2
C	0.20 x
D	0.14 x (1.0 + 0.0003 x)-1/2
E	0.08 x (1.0 + 0.0015 x)-1/2
F	0.08 x (1.0 + 0.0015 x)-1/2

* Where x is in meters.

Atmospheric stability is determined indirectly from the amount of incoming solar radiation at the surface (insolation), and the wind speed. Pasquill suggested a six-category classification scheme from A for extremely unstable to F for moderately stable, based on the range of these two parameters as listed table 5-4 and description of these parameters shown by table 5-5.

Table 5.4: Pasquill chart to determine atmospheric stability class [Boubel , et.al., 1994]:

Surface wind speed (at 10m), m/s	Day			Night	
	Incoming solar radiation			Thinly overcast or 4/8 low cloud	3/8 cloud
	Strong	Moderate	Slight		
2	A	A-B	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Table 5.5: Description of Stability classes [Boubel , et.al., 1994]:

Stability class	Class description
A	Extremely unstable
B	Unstable
C	Slightly unstable
D	Neutral
E	Slightly stable
F	Stable to extremely stable

* By wind-speed and stability categories (applied to fugitive sources of wind-blown dust).

5.4.2. Wind Speed Profile:

The wind power law is used to adjust the observed wind speed, u_{ref}, from a reference measurement height, z_{ref}, to the stack or release height, h_s. The stack height wind speed, u_s, is used in the Gaussian plume equation (Equation 1), and in the plume rise formulas described in Section 1.1.4. The power law equation is of the form:

$$u_s = u_{ref}\left(\frac{h_s}{z_{ref}}\right)^p \text{ ---------- (9)}$$

Where, p is the wind profile exponent. Values of p may be provided as a function of stability category and wind speed class.

5.4.3. Plume Rise formula:

According to the vertical term equation (4) the effective stack height H= hs+ δh, where hs is stack height and δh is plume rise. For the simplicity of Briggs equation, AERMOD model use the equation (10) for estimate plume rise.

$$dh = \frac{114CF^{\frac{1}{3}}}{U} \text{ ---------- (10)}$$

Where dh in meters, U is wind speed at stack height z=hs. And the buoyancy flux F.

$$F = \frac{gv_s D_s^{\,2}(T_s - T_a)}{4T_a} \text{ ---------- (11)}$$

Where

Vs =gas exit velocity and greater than 1.5U (m/s)

Ds = inside diameter of stack (m).

g =9.8 m/s2

Ts &T a= gas temperature at stack exit and ambient temperature (K)

$$C = 1.58 - 41.4\frac{d\theta}{dz} \text{ ---------- (12)}$$

Where, dθ/dz is potential temperature difference (k/m).

5.5. Data analysis and discussions:

Emissions are analyzed according to source category, pollutant, and specific geographical area. The damage by air pollution causes in the human organism and in some cases more severe damage to animals, to plant life, accelerates the deterioration of materials and even to our climate. Sulfur dioxide, which generally comes from combustion of high-sulfur fossil fuels, contributes a lot of air pollution problem each

year. Maximum 1 hr sulphur dioxide in year 2008 is 324$\mu g/m^3$ where standard is 730 $\mu g/m^3$. Other major pollutants like NOx is 538$\mu g/m^3$ standard is 660 $\mu g/m^3$, CO is 740 $\mu g/m^3$, standard is 40000 mg/m^3, and Particulate 80$\mu g/m^3$ where standard is 150 $\mu g/m^3$. Standards of Saudi Arabia were considered. From the Table 5.6 and Figure 5.3 we can say SOx concentration is average 2.82 times and 1.82 times more on compare to year 2008 with respect to year 2006 and 2007. The reason is meteorological conditions and concern of the risk of air pollution. The 24 hour average concentration of SO_2 is reasonable for the selected two company but if we consider all industries the scenario will be changed, for that care should be taken and need to establish proper control device. If we analyse NOx Table 5.7 and Figure 5.4 yearly concentration varies mostly in same average times like SOx. But if we compare maximum 1 hr. concentration with standard it is reasonable but for two companies it is high value, so proper NOx control equipment is recommended for the Yanbu city. And yearly CO and total suspended particles vary with same average rate in 2008 than 2006 & 2007 that is 2.50 and 1.55 times respectively. Also their maximum average concentration is less than standards, and that is reasonable for two companies. According to EPA [AP 42] there are total organic compounds (TOC) and volatile organic compounds come from Safra and Yanpet company ltd. There yearly average varies 2.80 for 2006 and 1.80 for year 2007 as compared year 2008. Tables 5.10, 5.11 and Figures 5.7 & 5.8 show relative concentration and concentration graph of TOC & VOCs.

Table 5.6: Maximum hourly Average SOx Concentration from AERMOD

Year	Max.1 hr. average $\mu g/m^3$	Max.8 hr. average $\mu g/m^3$	Max.24 hr. average $\mu g/m^3$
2006	333	221	115
2007	332	218	127
2008	324	199	110
Standard $\mu g/m^3$	730		365

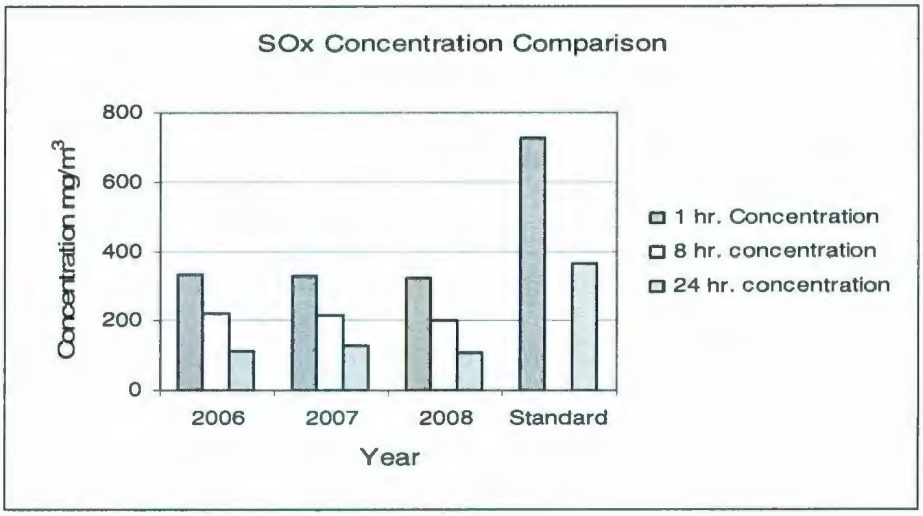


Figure 5.3: Maximum hourly SOx concentration compared with standard of Saudi Arabia

Table 5.7: Maximum hourly Average NO_x Concentration from AERMOD

Year	Max.1 hr. average $\mu g/m^3$	Max.8 hr. average $\mu g/m^3$	Max.24 hr. average $\mu g/m^3$
2006	521	333	216
2007	541	348	225
2008	538	328	201
Standard $\mu g/m^3$	660		

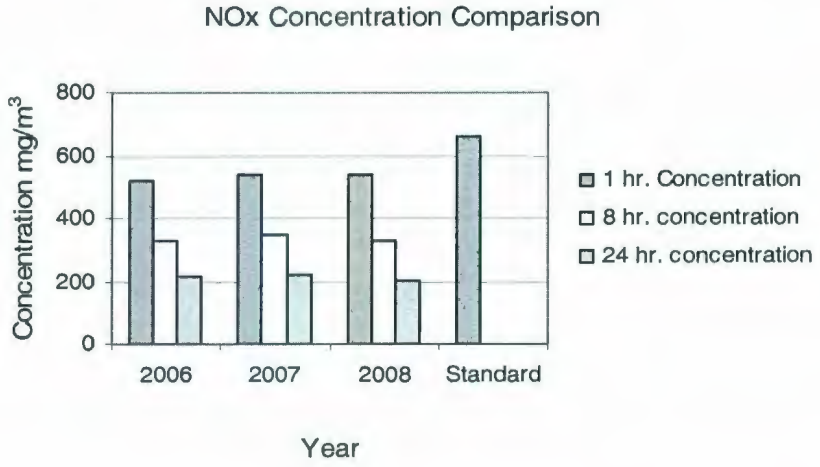


Figure 5.4: Maximum hourly NOx concentration compared with standard of Saudi Arabia

Table 5.8: Maximum hourly Average CO Concentration from AERMOD

Year	Max.1 hr. average $\mu g/m^3$	Max.8 hr. average $\mu g/m^3$	Max.24 hr. average $\mu g/m^3$
2006	769	450	253
2007	720	434	263
2008	740	389	332
Standard mg/m^3	40,000	10,000	

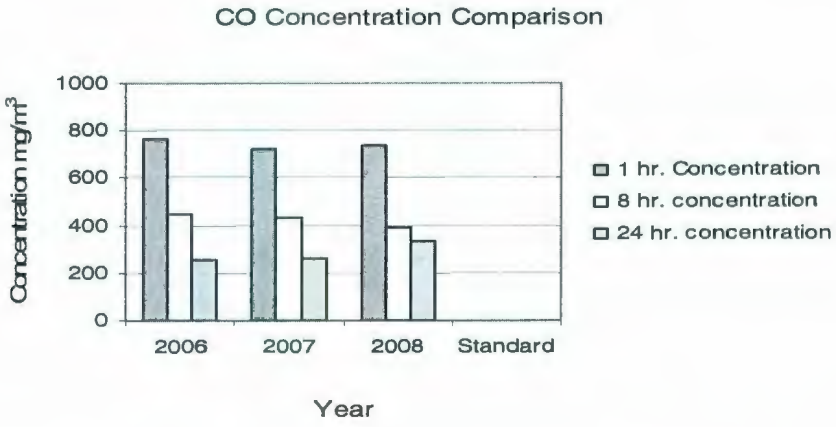


Figure 5.5: Maximum hourly CO concentration compared with standard of Saudi Arabia

Table 5.9: Maximum hourly Average TSP Concentration from AERMOD

Year	Max.1 hr. average $\mu g/m^3$	Max.8 hr. average $\mu g/m^3$	Max.24 hr. average $\mu g/m^3$
2006	78	50	32
2007	81	52	34
2008	80	49	30
Standard $\mu g/m^3$	150		340

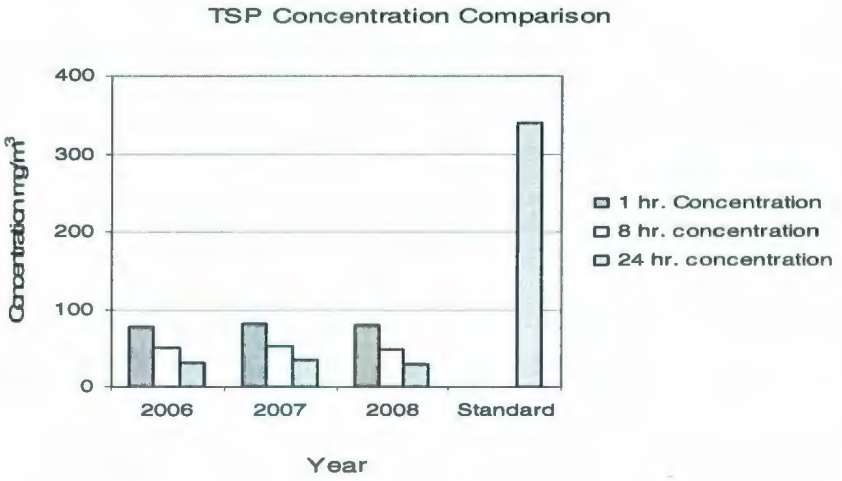


Figure 5.6: Maximum hourly TSP concentration compared with standard of Saudi Arabia

Table 5.10: Maximum hourly Average TOC Concentration from AERMOD

Year	Max.1 hr. average $\mu g/m^3$	Max.8 hr. average $\mu g/m^3$	Max.24 hr. average $\mu g/m^3$
2006	74	49	25
2007	73	48	28
2008	72	44	24
Standard $\mu g/m^3$			

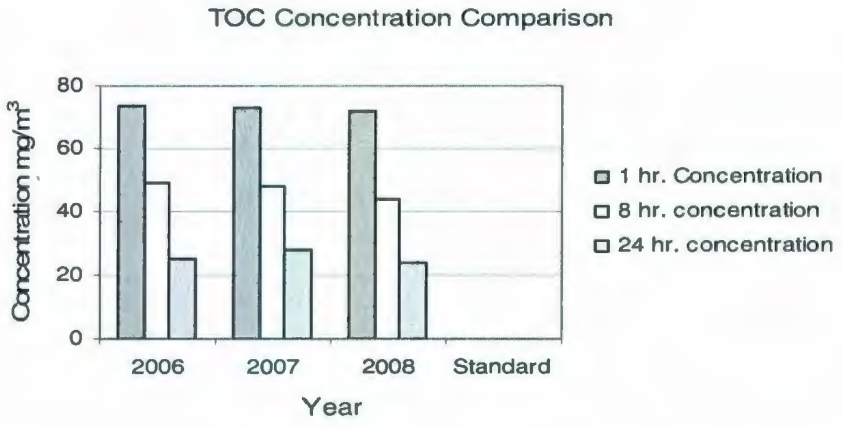


Figure 5.7: Maximum hourly TOC concentration compared with standard of Saudi Arabia

Table 5.11: Maximum hourly Average VOC Concentration from AERMOD

Year	Max.1 hr. average $\mu g/m^3$	Max.8 hr. average $\mu g/m^3$	Max.24 hr. average $\mu g/m^3$
2006	37	24	13
2007	37	24	14
2008	36	22	12
Standard $\mu g/m^3$			

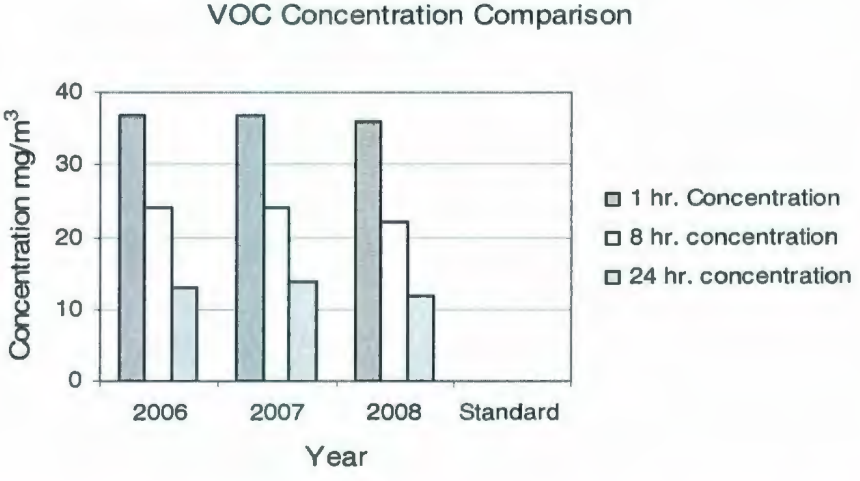


Figure 5.8:Maximum hourly VOC concentration compared with standard of Saudi Arabia

5.6. Proposed Pollution Control Program:

Atmospheric stability is determined indirectly from the amount of incoming solar radiation at the surface (insolation), and the wind speed. Pasquill suggested a six-category classification scheme from A for extremely unstable to F for moderately stable, based on the range of these two parameters as listed Table 5-5.

Types of pollutants emitted from the industrial area are: SO2, NOx, CO, HC, VOC, Particles. SO_2, NOx, CO emissions are originated from fuel (diesel-oil) combustion. Hydrocarbons (HC's) and particulate emissions are originated from both process and fuel (diesel-oil) combustion. Air quality standards are legal limits of air pollutant levels (concentrations) in the ambient air during a specific time period in a specific geographical area. Air quality standards characterize allowable levels of each pollutant in the ambient air and define the amount of exposure permitted to the population and/or to ecological systems. It means that the quality of air will be managed to meet the ambient air quality standards. Enforcement of ambient air quality standard is difficult. Enforcement action is on a reduction of the air pollution emissions. Air pollution source standards (emission standards) limit the amount of pollutants emitted from stationary sources to the atmosphere. Emission standards generally fall into one of four categories; numerical rate, fuel specification, equipment design, and prohibitive. Emissions standards either limit the emission of a specific pollutant, regardless of the process or equivalent or limit the emission of a specific pollutant from a specific process or type of equipment. Emission limits may be stated in absolute terms or in relative terms.

Regulation may require the same emission limit for all sources, regardless with size or capacity of the source or may vary the allowable emission with the size or capacity

of the source. Stationary sources of Yanbu emit pollutants into the atmosphere. Quantities of these pollutants are expressed as gm/s. Most of the time wind was transporting the pollutants away from the city center. But some meteorological conditions which may occur in the future, pollutants may cause the accumulation of pollutants over city center. In such case, the control program is necessary. Pollution control program will base on emission standards because of excellent simplicity and enforceability. Each emission source will be controlled by responsible organization in Yanbu in order to meet emission standards. Each emission source will provide emissions rate data to responsible organization for their emissions every month or every six month depending on size of the source. If emission rate exceeds the standards, the source will forced to reduce the emission to standard level. Proposed Control devices are:

Particulate Control:

- Mechanical collectors (dust cyclones, multicyclones)
- Electrostatic precipitators: An electrostatic precipitator (ESP), or electrostatic air cleaner is a particulate collection device that removes particles from a flowing gas (such as air) using the force of an induced electrostatic charge. Electrostatic precipitators are highly efficient filtration devices that minimally impede the flow of gases through the device, and can easily remove fine particulate matter such as dust and smoke from the air stream.
- Baghouses: Designed to handle heavy dust loads, a dust collector consists of a blower, dust filter, a filter-cleaning system, and a dust receptacle or dust

removal system (distinguished from air cleaners which utilize disposable filters to remove the dust).

- Particulate scrubbers: Wet scrubber is a form of pollution control technology. The term describes a variety of devices that use pollutants from a furnace flue gas or from other gas streams.

Acid Gas/SO2 Control:

- Wet scrubbers
- Dry scrubbers
- Flue gas desulfurization

NOx Control:

- Low Nox burners
- Selective catalytic reduction (SCR)
- Selective non-catalytic reduction (SNCR)
- Exhaust gas recirculation

CO Control:

- Baffle spray scrubber
- Cyclonic spray scrubber
- Ejector venturi scrubber.
- Spray tower
- Wet scrubber

Chapter 6

Conclusions and Recommendations

6.1. Conclusions:

This thesis presents an evaluation of various air emission concentrations of petrochemical industry with time. A regulatory air dispersion model AERMOD was used to run and simulate the concentrations. Two major petrochemical industries and three years of processed meteorological data in Yanbu city Saudi Arabia was considered. To estimate emissions, emission inventory were prepared for the two industries using EF methodology and two sets of EF data sets (USEPA, WHO), and processes involved within these industries were also considered. This thesis also developed a methodology for MH estimation from upper air balloon data. For that 2006 Jeddah city radiosonde data were considered. MH was retrieved from AERMET processing surface data in the same year and compared their values with radiosonde data. Eight diagnostic models were used in the same year and compared these models with AERMET processing MH for the months of January and February by correlation method. An example of MH from SODAR data of Jeddah city is also presented. Keeping the objectives in perspectives, the following are the conclusions from this study:

1. Types of pollutants emitted from the industrial area are: SO_2, NOx, CO, HC, VOC, Particles.
2. Based on the evaluation results, the total concentrations is average 2.5 times more in 2006 and 1.5 times more in 2007 compared to year 2008.
3. All pollutants are within limits as compared with standards of Saudi Arabia.

4. Most of the times Pollutants are disperse near the industries or towards the red sea and Yanbu to Jeddah directions.
5. There are no emission control devices in the two industry, using proper control device like scrubbers, low NOx burners, catalytic converter, adsorption systems such as activated carbon will help in reducing emission afrom these industries.
6. Based on emission inventory, results shows USEPA dataset gives quite high value than WHO dataset and also gives more compounds than WHO.
7. MH from radisonde data are not shows marked differences in summer days. During the winter months (January), the mixing heights are also quite uniform but show smaller differences but at November the differences are high. Lot of missing data is the reason of these discrepancies.
8. AERMET processing mixing height from surface data, shows very marked differences in summer days, but the winter period has some uniform differences.
9. From this analysis the percentage differences of AERMET processing mixing height and balloon upper air mixing height is not uniform and rate is high, due to bad quality of upper air observations data.
10. From the analysis of diagnostic model shows that equation of MH (h_1), Ayra (1981) correlates close to AERMET pre-processors mixing height.

6.2. Recommendations for future work:

This study will help in determining long-term impact of pollutants on human health in the vicinity of the industrial complex and also in identifying mitigation measures and pollution control technologies for current operation and future expansion plan. There are some recommendations from this thesis that include:

1. Using puff dispersion model for coastal city is more appropriate, if data is available use CALPUFF model and compare the two models AERMOD and CALPUFF results for sound decisions.
2. Mixing height derived here should be compared with values derived by using different techniques, e.g. remote sounding systems (Lidars, Sodars, RASS, wind profiling radars) etc.
3. Should be taking into account the impact of terrain irregularities, changes in the surface roughness, and surface heat fluxes.
4. After implementation of proper control device estimate the concentrations and compare the values.
5. Develop a risk estimation methodology for accurate estimation of risk associated by the pollutants.
6. Review latest technologies for meteorological data collections and their impletation in regulatory air dispersion models.

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APPENDIX-A

Emission factor data table

Emission Factors for Particulate Matter (PM), Particulate Matter Less Than 10 Micrometers (PM_{10}), and Lead (Pb) From Waste Oil Combustors[a]

	PM[b]		PM-10[c]		Pb[d]	
Source Category (SCC)	Emission Factor ($lb/10^3$ gal)	EMISSION FACTOR RATING	Emission Factor ($lb/10^3$ gal)	EMISSION FACTOR RATING	Emission Factor ($lb/10^3$ gal)	EMISSION FACTOR RATING
Small boilers (1-03-013-02)	64A[d]	C	51A	C	55L[f]	D
Space hearers Vaporizing burner (1-05-001-14, 1-05-002-14)	2.8 A	D	ND	NA	0.41L	D
Atomizing btimer (1-05-001-13, 1-05-002-13)	66A	D	57A	E	50L	D

Emission Factors for Nitrogen Oxides (NOx), Sulfur Oxides (SOx), and Carbon Monoxide (CO) From Waste Oil Combustors[a]

Source Category (SCC)	NO_x[b]		SO_x[b]		CO[c]	
	Emission Factor ($lb/10^3$ gal)	EMISSION FACTOR RATING	Emission Factor ($lb/10^3$ gal)	EMISSION FACTOR RATING	Emission Factor ($lb/10^3$ gal)	EMISSION FACTOR RATING
Small boilers (1-03-013-02)	19	C	147S[d]	C	5	D
Space heaters Vaporizine burner (1-05-001-14, 1-05-002-14)	11	D	100S[d]	D	1.7	D
Atomizine burner (1-05-001-13, 1-05-002-13)	16	D	107S[d]	D	2.1	D

Emission Factors for Total Organic Compounds (TOC), Hydrogen Chloride (HCl), And Carbon Dioxide (CO_2) From Waste Oil Combustors[a]

Source Category (SCC)	TOC[b]		HCl[b]		CO_2[c]	
	Emission Factor ($lb/10^3$ gal)	EMISSION FACTOR. RATING	Emission Factor ($lb/10^3$ gal)	EMISSION FACTOR RATING	Emission Factor ($lb/10^3$ gal)	EMISSION FACTOR RATING
Small boilers (1-03-013-02)	1.0	D	66Cl[d]	C	22,000	C
Space heaters Vaporizine burner (1-05-001-14, 1-05-002-14)	1.0	D	ND	NA	22,000	D
Aromizimr burner (1-05-001-13, 1-05-002-13)	1.0	D	ND	NA	22,000	D

Emission Factors for Nitrogen Oxides (NOx) and Carbon Monoxide (CO) From Natural Gas Combustion[a]

	NOx[b]		CO	
Combustor Type (MMBtu/hr Heat Input) [SCC]	Emission Factor ($lb/10^6 scf$)	Emission Factor Rating	Emission Factor ($lb/10^6$ scf)	Emission Factor Rating
Laree Wall-Fired Boilers(>100) [1-01-006-01,1-02-006-01, 1-03-006-01]				
Uncontrolled (Pre-NSPS)[e]	280	A	84	B
Uncontrolled (Post-NSPS)[e]	190	A	84	B
Controlled - Low NO_x burner?	140	A	84	B
Controlled - Flue gas recirculation	100	D	84	B
Small Boilers (<100) [1-01-006-02, 1-02-006-02, 1-03-006-02, 1-03-006-03]				
Uncontrolled	100	B	84	B
Controlled - Low NO_x burners	50	D	84	B
Controlled – Low NOx burners/Flue gas recirculation	32	C	34	B
Tangential-Fired Boilers (all sizes) [1-01-006-04]				
Uncontrolled	170	A	24	C
Controlled - Flue gas recirculation	76	D	98	D
Residential Furnaces (<0.3) [No SCC]				
Uncontrolled	94	B	40	B

Emission Factors for Criteria Pollutants and Greenhouse Gases from Natural Gas Combustion[a]

Pollutant	Emission Factor (lb/L0* set)	Emission Factor Rating
CO_2[b]	120,000	A
Lead	0.0005	D
N_2O(Uncontrolled)	2.2	E
N_2O(controlled – low-NOx burner)	0.64	E
PM (Total)[c]	7.6	D
PM (Condensable)[c]	5.7	D
PM (Filterable)[c]	1.9	B
SO_2[d]	0.6	A
TOC	11	B
Methane	2.3	B
voc	5.5	C

Criteria Pollutant Emission Factors for Fuel Oil Combustion[a]

	SO_2[b]		SO_3[c]		NOx[d]		CO[e]		Filterable	PM[f]
Firing Configuration (SCC)[a]	Emission Factor (lb/10^3 gal)	Emission Factor Rating	Emission Factor (lb/10^3 gal)	Emission Factor Rating	Emission Factor (lb/10^3 gal)	Emission Factor Rating	Emission Factor (lb/10^3 gal)	Emission Factor Rating	Emission Factor (lb/10^3 gal)	Emission Factor Rating
Boilers> 100 million Btu/hr										
No.6 oil fired, normal firing (1-01-004-01), (1-02-004-01), (1-03-004-01)	157S	A	5.7S	C	47	A	5	A	9.19(S)+3.22	A
No.6 oil fired, normal firing, low NOx burner (1-01-004-01), (1-02-004-01)	157S	A	5.7S	C	40	B	5	A	9.19(S)+3.22	A
No.6 oil fired, tangential firing. (1-01-004-04)	157S	A	5.7S	C	32	A	5	A	9.19(S)+3.22	A
No. 6 oil fired, tangential firing, low NOx burner.(1-01-004-04)	157S	A	5.7S	C	26	E	5	A	9.19(S)+3.22	A
No.5 oil fired, normal firing (1-01-004-05), (1-02-005-04)	157S	A	5.7S	C	47	B	5	A	10	B
No. 5 oil fired, tangential firing (1-01-004-06)	157S	A	5.7S	c	32	B	5	A	10	B

No. 4 oil fired, normal firing (1-01-005-04) (1-02-005-04)	150S	A	5.7S	c	47	B	5	A	7	B
No. 4 oil fired, tangential firing (1-01-005-05)	150S	A	5.7S	c	32	B	5	A	7	B
No. 2 oil fired (1-01-005-01). (1-02-005-01), (1-03-005-01)	157S	A	5.7S	c	24	D	5	A	2	A
No.2 oil fired LNB/FGR (1-01-005-01),(1-02-005-01), (1-03-005-01)	157S	A	5.7S	A	10	D	5	A	2	A
Boilers< 100 million Btu/hr										
No. 6 oil fired (1-02-004-02/03) (1-03-004-02/03)	157S	A	2S	A	55	A	5	A	10	B
No. 5 oil fired (1-03-004-04)	157S	A	2S	A	55	A	5	A	9.19(S)+3.22	A
No.4 oil fired (1-03-005-04)	150S	A	2S	A	20	A	5	A	7	B
Distillate oil fired (1-02-005-02/03) (1-03-005-02/03)	142S	A	2S	A	20	A	5	A	2	A
Residential Furnace (A2104004/ A2104011)	142S	A	2S	A	18	A	5	A	0.4[g]	B

Emission Factors for Total Organic Compounds (TOC), Methane, and Nonmethane TOC (NMTOC) From Uncontrolled Fuel Oil Combustion[a] Emission Factor Rating: A

Firing Configuration (SCC)	TOC[b] Emission Factor (lb/10^3 gal)	Methane[b] Emission Factor (lb/10^3 gal)	NMTOC[b] emission factor (lb/10^3 gal)
Utility boilers			
No. 6 oil fired, normal firing (1-01-004-01)	1.04	0.28	0.76
No. 6 oil fired, tangential firing (1-01-004-04)	1.04	0.28	0.76
No. 5 oil fired, normal firing (1-01-004-05)	1.04	0.28	0.76
No. 5 oil fired, tangential firing (1-01 -004-06)	1.04	0.28	0.76
No. 4 oil fired, normal firing (1-01-005-04)	1.04	0.28	0.76
No. 4 oil fired, tangential firing (1-01-005-05)	1.04	0.28	0.76
Industrial boilers			
No. 6 oil fired (1-02-004-01/02/03)	1.2S	1.CC	0.2S
No. 5 oil fired (1-02-004-04)	1.2S	1.CC	0.2S
Distillate oil fired (1-02-005-01/02/03)	0.252	0.052	0.2
No. 4 oil fired (1-02-00 5-04)	0.252	0.052	0.2
Commercial/institutional/residential combustors			
No. 6 oil fired (1-03-004-01/02/03)	1.605	0.475	1.13
No. 5 oil fired(1-03-004-04)	1.605	0.475	1.13
Distillate oil fired (1-03-005-01/02/03)	0.556	0.216	0.54
No. 4 oil fired (1-03-005-04)	0.556	0.216	0.34
Residential furnace (A21040O4/A2104011)	2.493	1.78	0.713

Cumulative Particle Size Distribution and Size-Specific Emission Factors for Uncontrolled Industrial Boilers Firing Distillate Oil[a] Emission Factor Rating: E

Particle Size[b] (um)	Cumulative Mass % =< Stated Size	Cumulative Emission Factor (lb/10^3 gal)
15	68	1.33
10	50	1.00
6	30	0.58
2.5	12	0.25

1.25	9	0.17
1.00	8	0.17
0.625	2	0.04
TOTAL	100	2.00

Cumulative Particle Size Distribution and Size-Specific Emission Factors Uncontrolled Commercial Boilers Burning Residual or Distillate Oil[a], Emission Factor Rating: D

	Cumulative Mass	% Stated Size	Cumulative Emission Factor[1] ($lb/10^3 gal$)	
Particle Size[b] (um)	Residual Oil	Distillate Oil	Residual Oil	Distillate Oil
15	78	60	6.50A	1.17
10	62	55	5.17A	1.08
6	44	49	3.67A	1.00
2.5	23	42	1.92 A	0.83
1.25	16	38	1.33 A	0.75
1.00	14	37	1.17A	0.75
0.625	13	35	1.08A	0.67
TOTAL	100	100	8.34 A	2.00

Emission Factors for Stationary Combustion Sources (WHO, 1982)

Emission factor, (kg/ton fuel burned)						
Source	Fuel Burned	Particulate	Sulfur Dioxide	Nitrogen Oxides	Hydro-carbon	CO
Power Plant	Lignite	*3.5a()*	15(s)	7	0.5	0.5
	Anthracite	8.5(a)	19(2)	9	0.015	0.5
	Bituminous Coal	8.0(a)	19(s)	*9*	0.15	0.5
	Fuel oil	1.04	19.9(s)	13.2	0.13	0.66
	Natural gas	0.29	19.9(s)	11.5	0.019	0.32
	Natural gas	0.24*	16.6(s)*	9.6*	0.016*	0.27*

Industrial and commercial furnace	Lignite	3.5(a)	15(s)	3	0.5	1
	Anthracite	1(a)	19(s)	5	0.1	1
	Bituminous Coal	6.5(a)	19(s)	7.5	0.5	1
	Fuel oil, residual	2,87	19(s)	7.5	0.37	0.52
	Oil, distillate	2,13	20.1(s)	7.5	0.41	0.59
	Liquefied Petroleum Gas	0.21** 0.38	0.0l**(s) 0.02(s)	1.43** 2.6	0.016** 0.063	0.19** 0.35
	Natural gas	0.34	20(s)	3.6	0 058	0.32
	Natural gas	0.29*	6.6(a)	3*	0.048*	0.27*
A *S* * **	*is the percentage ash content of combustible by weight, is the percentage sulfur content of combustible by weight, emission factors are expressed as kg/10^3 m^3 fuel burned, emission factors are expressed as m^3 fuel burned.*					

Emissions Factors for industrial Processes (WHO. 1982)

Industry and process	Emission factors, (kg/ton product)				
	particulate	Sulfur dioxide	Nitrogen oxide	HC	Other
Manufacture of Industrial Chemical Basic inorganic chemicals					
Hydrochloric acid					
W.O- emission controls					HC1-3
With controls					HCJ-2
Sulfuric acid		20			
Nitric acid					
W.O, emission controls			26.2		
With controls			2.5		
Phosphoric acid					Fluorides
(wet process)					20.1
Phosphoric acid					
(Thermal process)	5.1				
Ammonia factory				45	NH_3-101

Chlor-alkali (mercury cell) W.O. emission controls					Cl_2-306
With water absorber					Cl_2-8.5
Sodium hydroxide (diaphragm cell)					
W.O, emission controls					Cl_2 -60
With water absorber					Cl_2-11
Soap & Detergents:					
Detergent manufacturing					
W.O. Emission Controls 45					
With dry cyclone	4				

Industry And	Emission factors, (kg/ton product)				
Process	Particulate	Sulfur dioxide	Nitrogen oxides	HC	Other
Fertilizer manufacturing					
Normal super Phosphate	4.5				Fluorides 0.075
Triple super-phosphate					Fluorides 0.015
Diammonium	41				Fluorides 0.02
Phosphate					
Nitrate fertilizer (NH_3+HNO_3)	5		2		NH_3-1.5
Urea	10	0.7	2		NH_3-5
Synthetic resin, plastic & fibers: Rayon fibers					CS2-27.5 H_2-S-3
Vulcanizable elastomers					
Butadiene				20	
All others				5	
Vinyl resin	17			3.5	
Paint manufacturing	1			15	
Surface coating				560	
Varnish manufacturing				40	

	Particulate/1000 m^3 gas burned	0.00057
	NCV10O0 bbl oil burned	2,900
	NO/lOOOm^3 gas burned	0.00065
	CO/1000 bbl oil burned	negligible
	CO/1000 m^3 gas burned	negligible
	HCHO/1000 bbl oil burned	25
	HCHO/1000 m^7 gas burned	0.000088
B. Fluid catalytic	Hydrocarbon/1000 bb 1 of fresh feed	220
Units	Particulate/ton catalyst circulation	1.8
	NO2/1000 bbl of fresh feed	63
	CO/1000 bbl of fresh feed	13,700
	HCHO/1000 bbl of fresh feed	19
	NH3/1000 bbl of fresh feed	54
C Moving bed	Hydrocarbon/1000 bbl of fresh feed	87
Catalytic	Particulate/ton catalyst circulation	4
Cracking units	NO_2/1000 bbl of fresh feed	5
	CO/1000 bbl of fresh feed	3,800
	HCHO/1000 bbl of fresh feed	12
	NH_3/ bbl of fresh feed	5
D. Compressor	*HO 1000 m^y* of fuel gas burned	0.034
Internal	NO/1000 m^3 of fuel gas burned	0.024
combustion	CO/1000 m^3 of fuel gas burned	negligible
engines	HCHO/1000 m^3 of fuel gas burned	3.1
	NH3/1000 m^3 of fuel gas burned	5.7

Source of Sulfur Dioxide Emission in a Petroleum Refinery(R.L. Byers, *et al*, 1977)

Operation	Emission Source	Emission Factor
Atmospheric Distillation	Direct fired furnace	400.5 Kg/1000 scm
Vacuum distillation	Direct fired furnace and fractionation vacuum system	400.5 Kg/1000 scm
Hydrodesulfurization Naptha	Process heater and catalyst regeneration	5632 g/1000 litres fuel
Catalytic reforming	Process heater and catalyst regeneration	5632 g/1000 litre fuel

Catalytic cracking	Preheat furnace	400.5 kg/1000 scm
	Catalyst regeneration	238 kg/1000 bbl. Feed
	CO waste heat boiler	238 kg/1000 bbl. Feed
Isomerization	Process heater and catalyst regeneration	5632 g/1000 litre fuel
Alkylation	Isostripper heater	400.5 Kg/1000 scm
Hydrogen plant	Heater	400.5 Kg/1000 scm

Factors for Particulate Emission from Refinery operations (Sitting, M., 1977)

Source	Units of Factor	Value
Boilers and heaters	Kg/1,000m^3 of fuel gas burned kg/bbl of fuel oil burned	0.32 0.36
Fluid catalytic units		
With electrostatic Precipitators	Percent of catalyst circulated	0.0009
Without electrostatic Precipitators	Percent of catalyst circulated	0.005
Moving bed units, high Efficiency centrifugal Separators	Percent of catalyst circulated	0.002

Emission Factors for Petroleum (Hesketh, H.E., 1974)

Source	Emissions	Emission Factor Kg/MT product
Petroleum (Crude Oil) Catalytic Cracking Units	Particulate	0.25
	SO_x	1
	CO	25
	Organic vapours	0.5
	NOx	0.25
	NH3	0.1
	H_2S	0.0005

Emission Factors for Hydrocarbon in Petroleum Refinery (Sax, N. L, 1974)

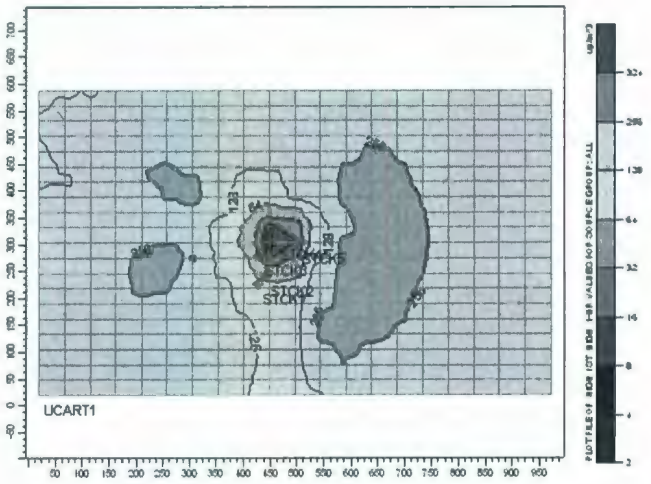
	Processes	Unit for Emission	Emission Factor
1.	Miscellaneous process equipment Slowdown system a. With control b. Without control	HC/1000 bbl refinery capacity	 5 300
2.	Process drains a. With control b. Without control	HC/1000 bbl waste water	 8 210
3.	Vacuum jets a. With control b. Without control	HC/1000 bbl vacuum distillation capacity	negligible 130
4.	Cooling towers	HC/1000 litre cooling water capacity	22.7
5.	Vessel relief valves	HC/1000 bbl refinery capacity	11
6.	Pipelines valve and flanges	HC/1000 bbl refinery capacity	28
7.	Pump seals	HC/1000 bbl refinery capacity	17
8.	Compressor	HC/1000 bbl refinery capacity	5
9.	Others (air blowing, blend changing and sampling)	HC/1000 bbl refinery capacity	10

APPENDIX-B

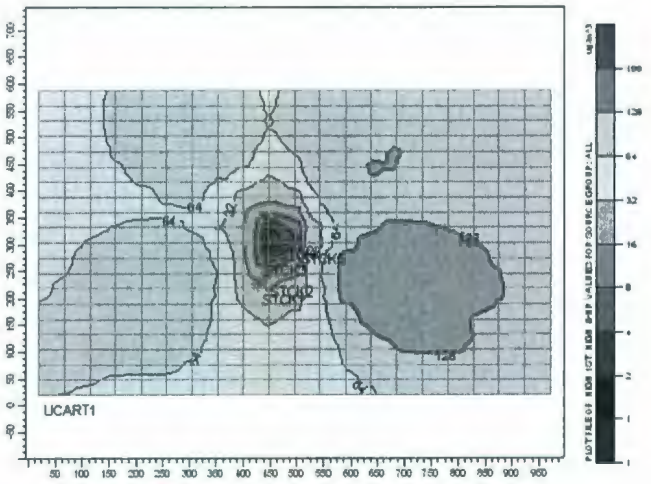
Pollution Concentration from AERMOD Model

APPENDIX-B1

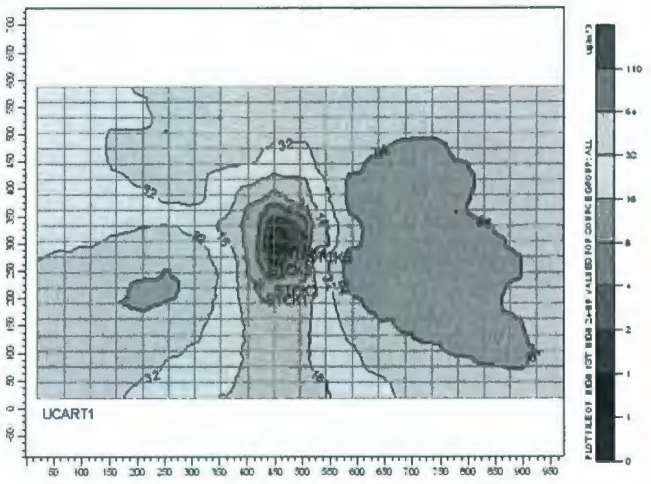
SO_X CONCENTRATION



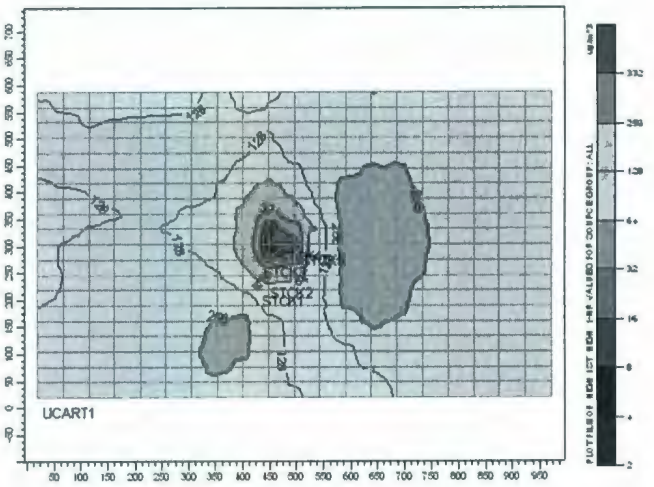
1hr. average SOx concentration 2008



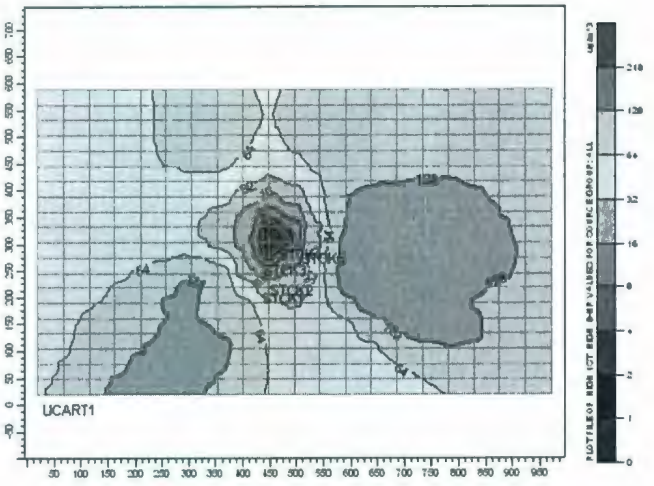
8 hr. average SOx concentration 2008



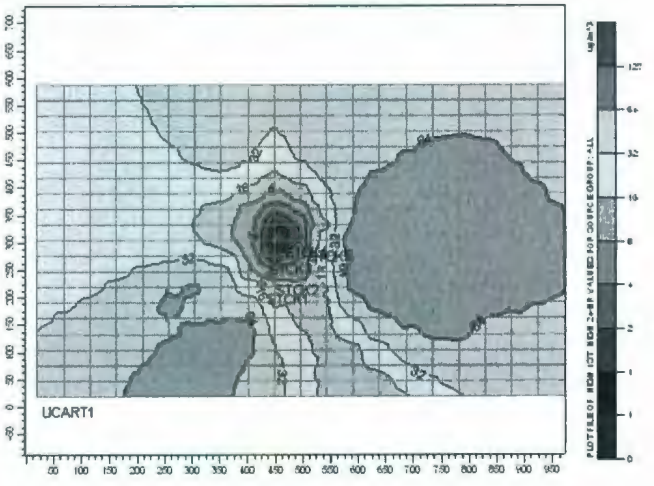
24 hr. average SOx concentration 2008



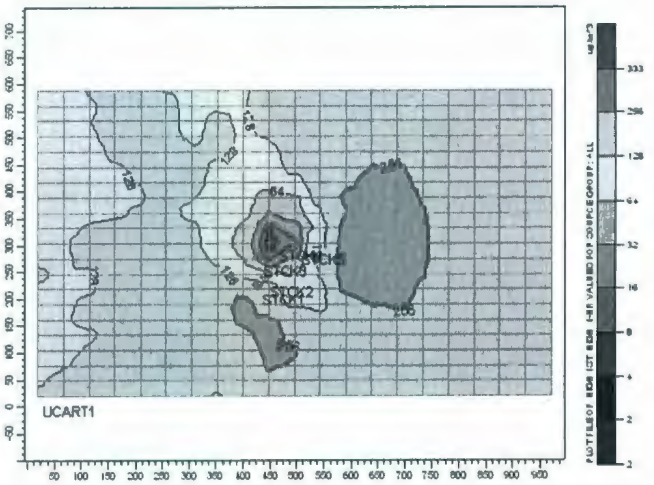
1hr. average SOx concentration 2007



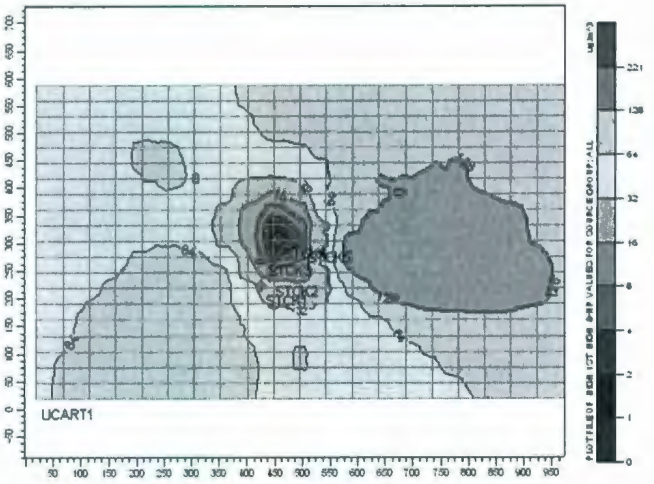
8 hr. average SOx concentration 2007



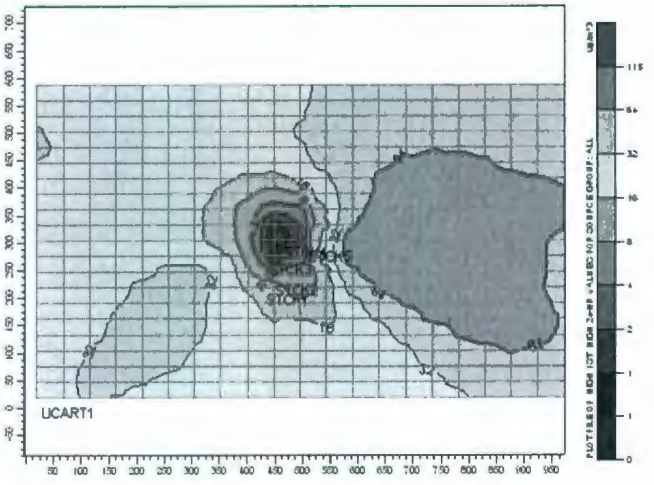
24 hr. average SOx concentration 2007



1hr. average SOx concentration 2006



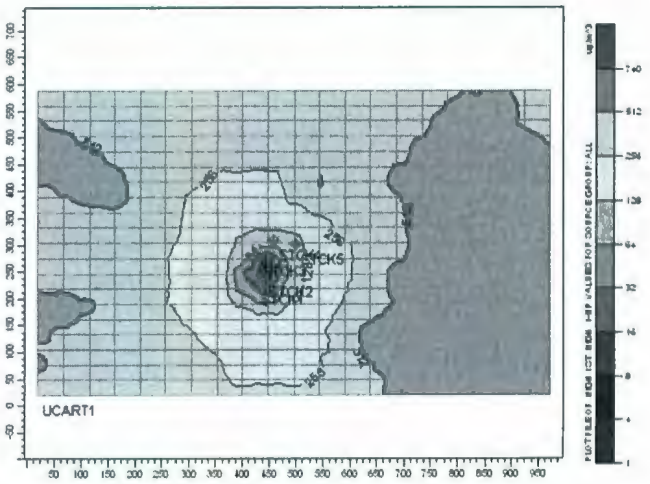
8 hr. average SOx concentration 2006



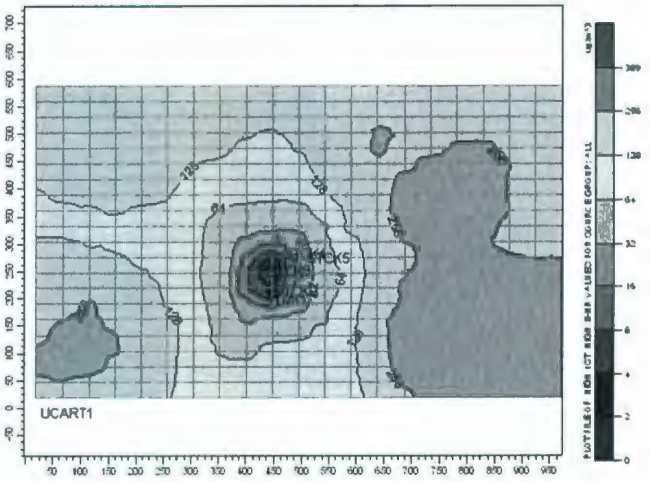
24 hr. average SOx concentration 2006

APPENDIX-B2

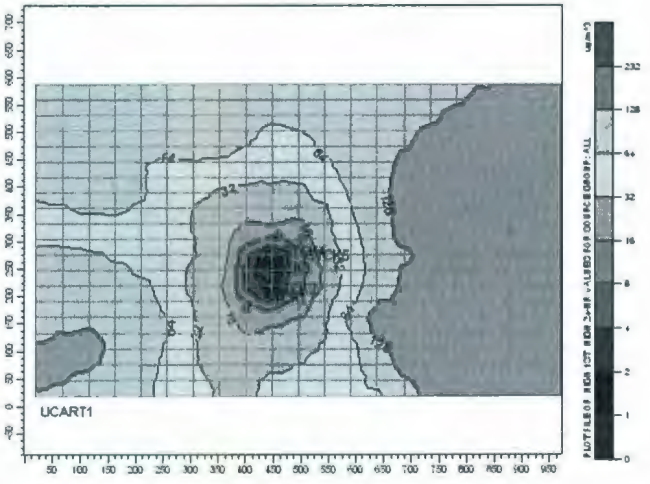
CO CONCENTRATION



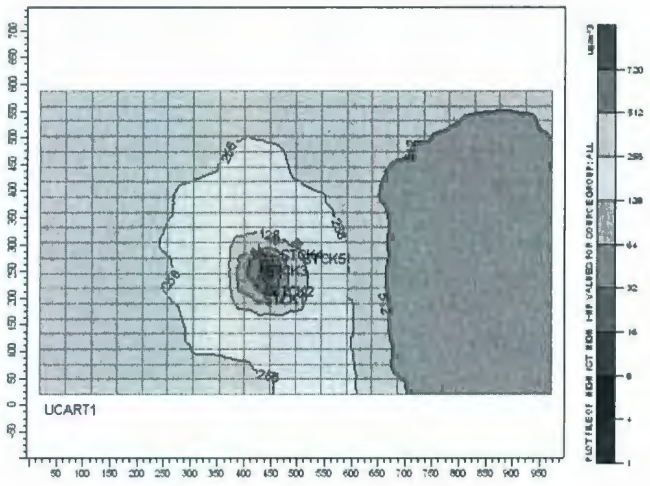
1 hr. average CO concentration 2008



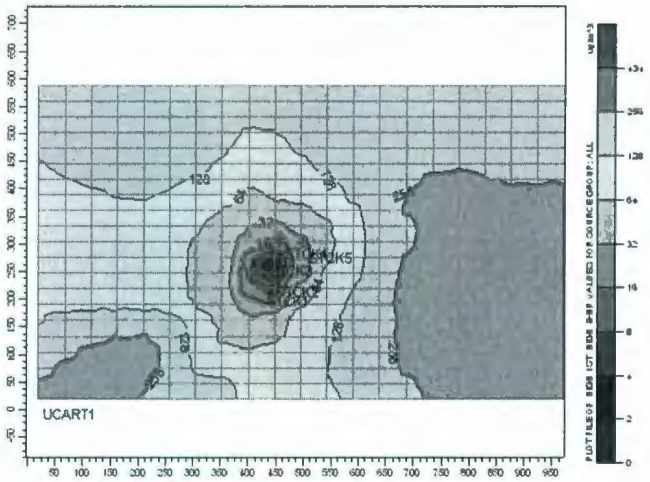
8 hr. average CO concentration 2008



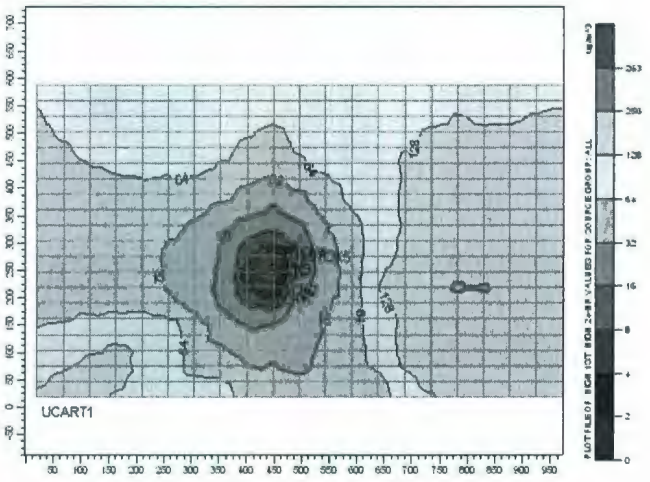
24 hr. average CO concentration 2008



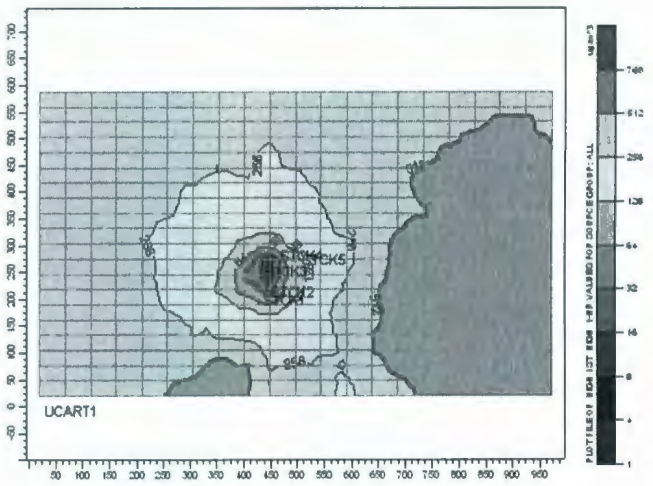
1 hr. average CO concentration 2007



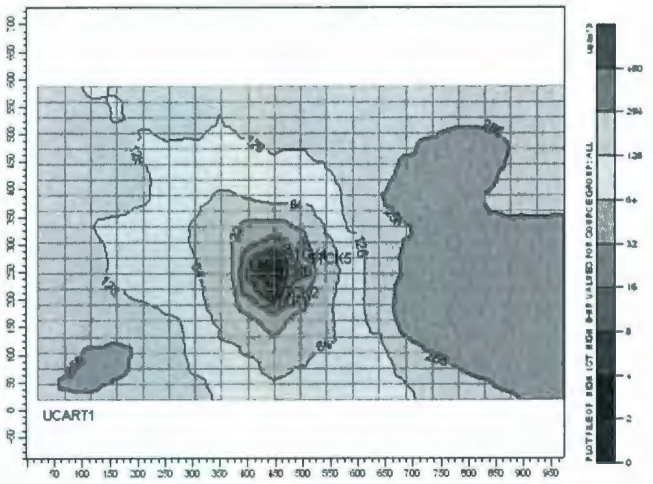
8 hr. average CO concentration 2007



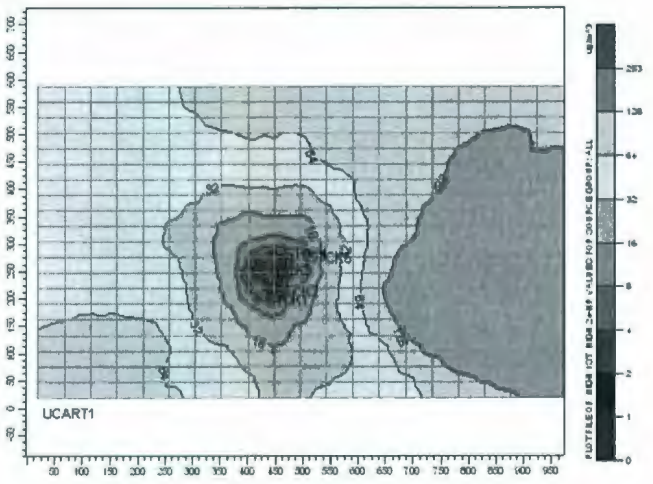
24 hr. average CO concentration 2007



1 hr. average CO concentration 2006



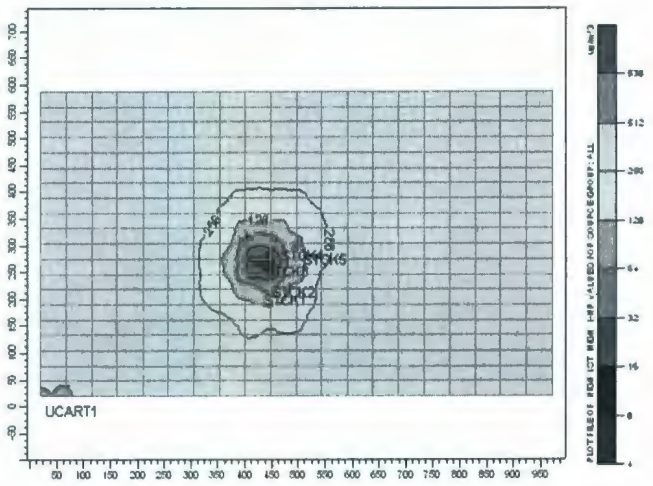
8 hr. average CO concentration 2006



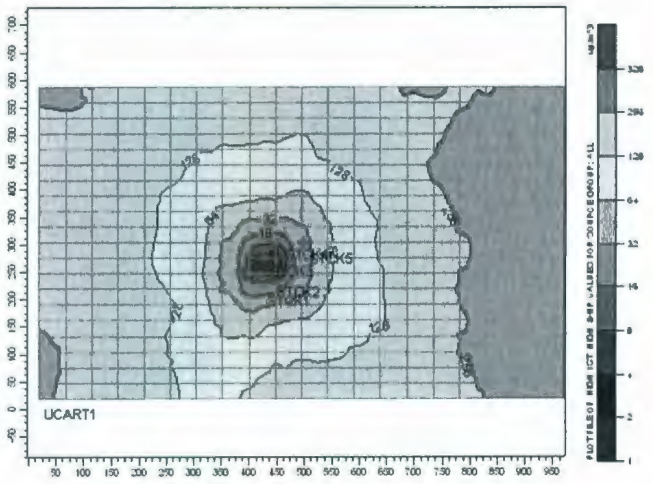
24 hr. average CO concentration 2006

APPENDIX-B3

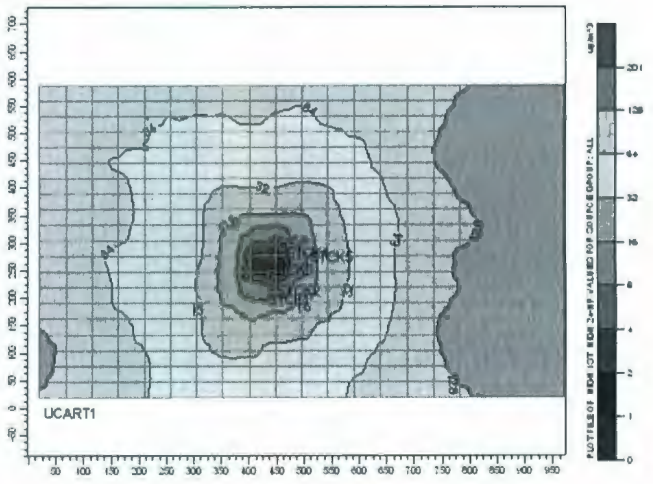
NOx CONCENTRATION



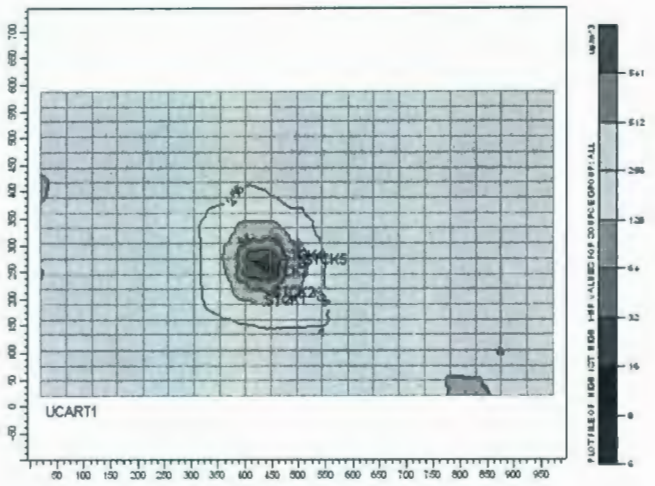
1 hr. average NOx concentration 2008



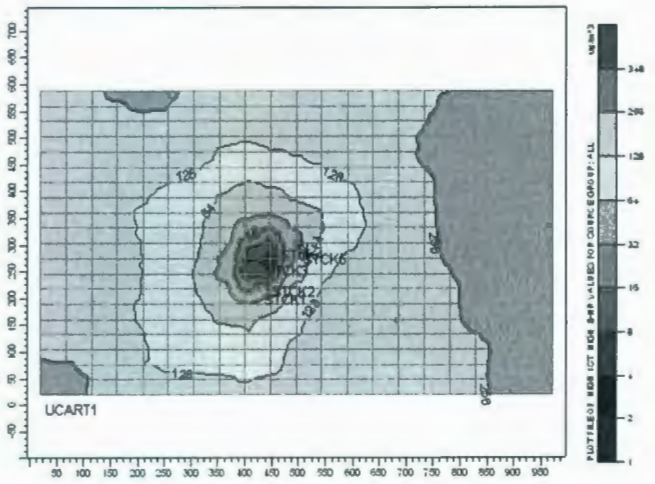
8 hr. average NOx concentration 2008



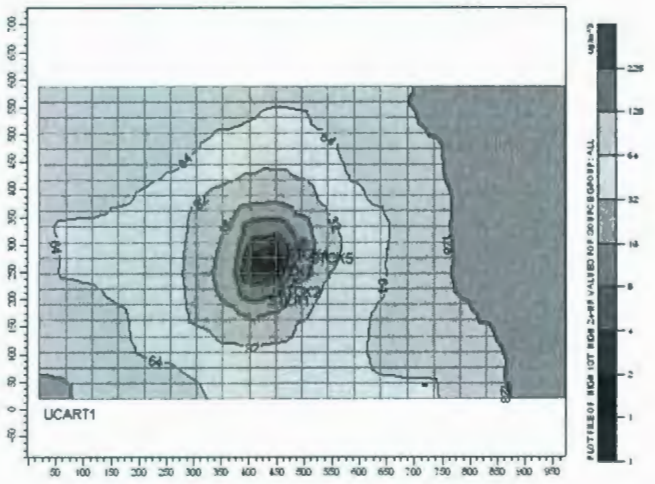
24 hr. average NOx concentration 2008



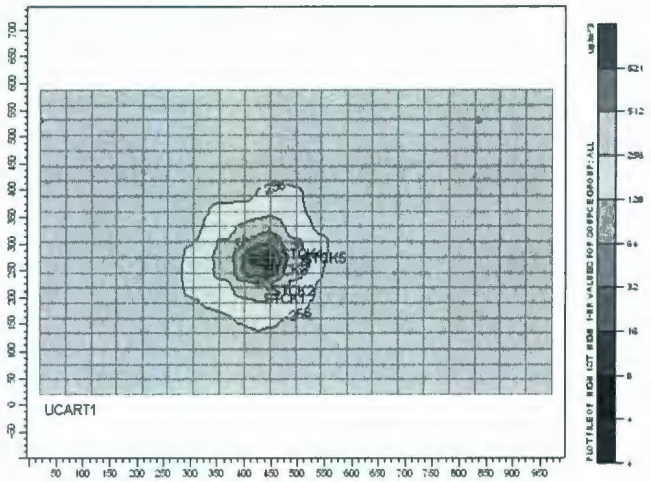
1 hr. average NOx concentration 2007



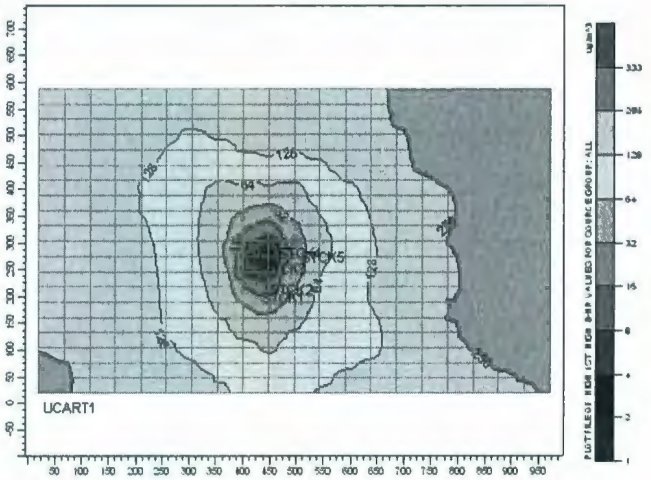
8 hr. average NOx concentration 2007



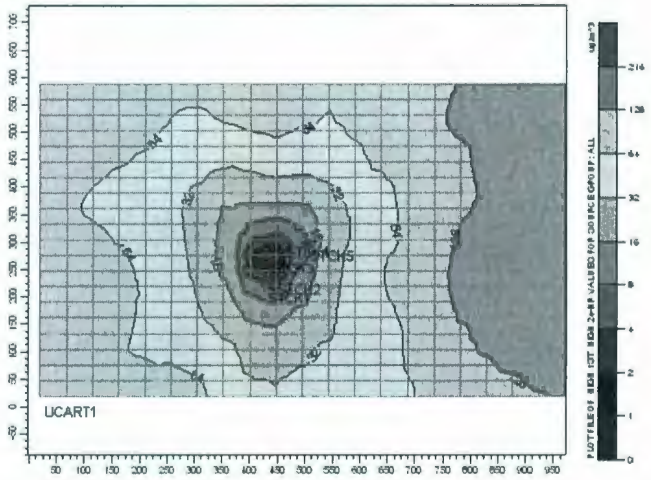
24 hr. average NOx concentration 2008



1 hr. average NOx concentration 2006



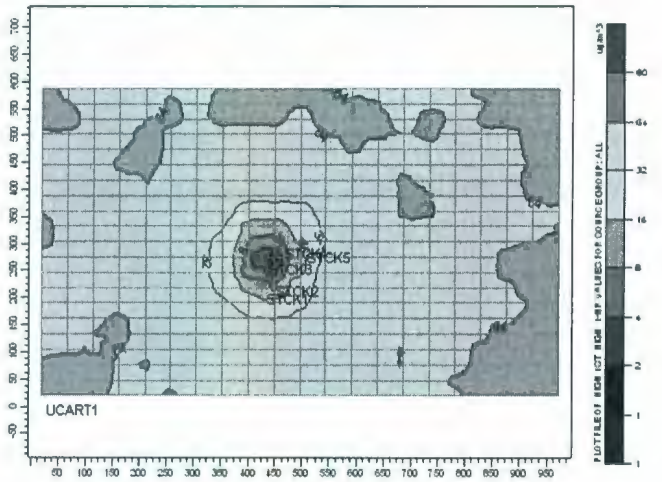
8 hr. average NOx concentration 2006



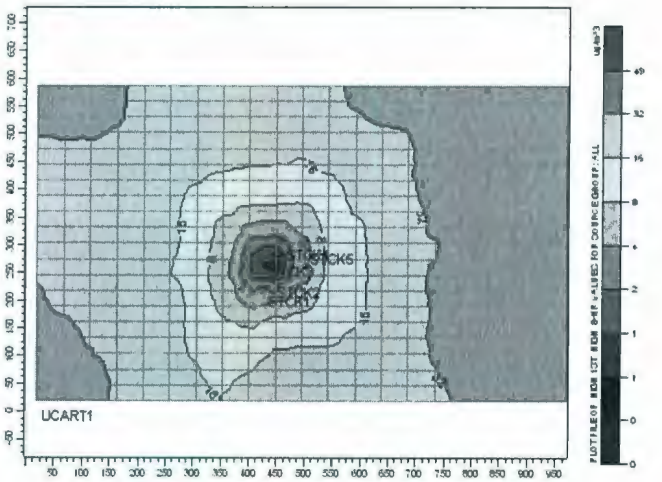
24 hr. average NOx concentration 2006

APPENDIX-B4

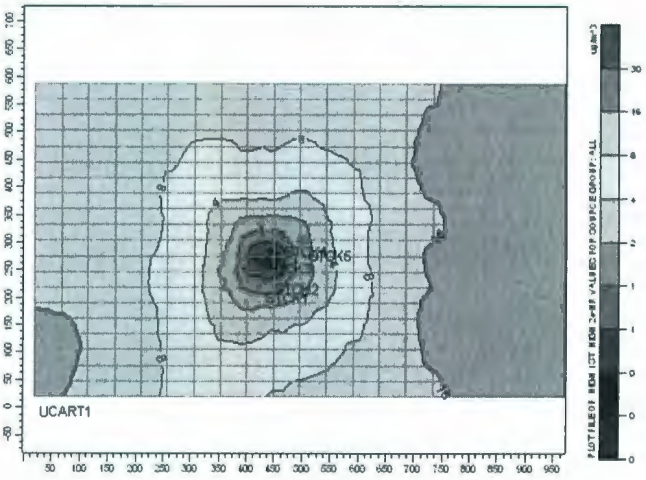
TSP CONCENTRATION



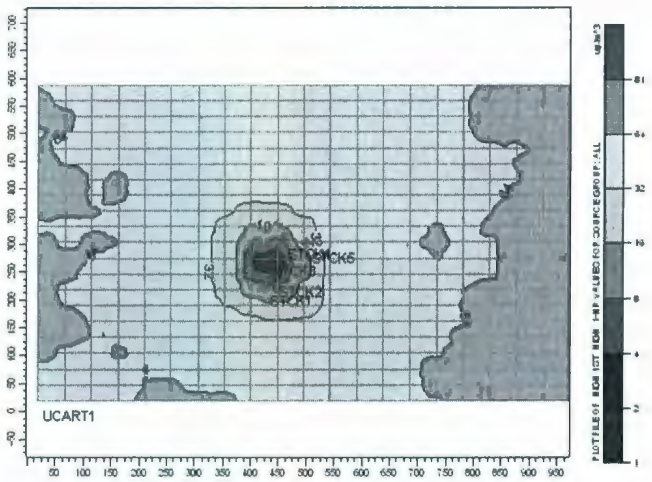
1 hr. average PM concentration 2008



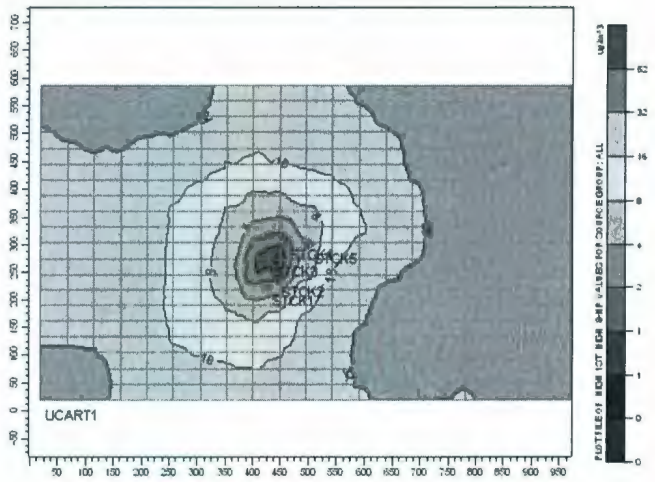
8 hr. average PM concentration 2008



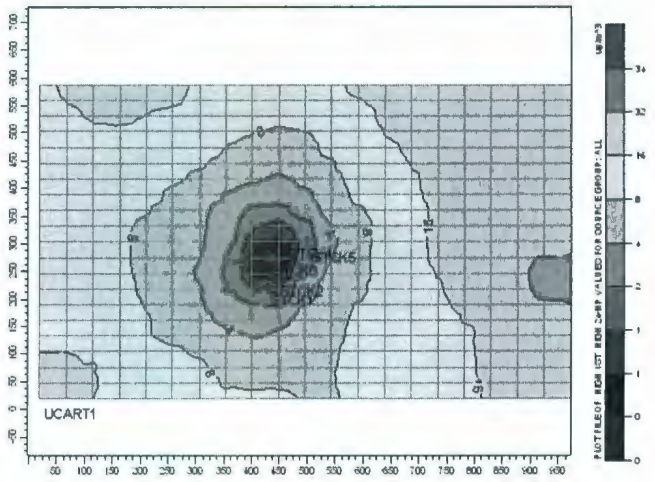
24 hr. average PM concentration 2008



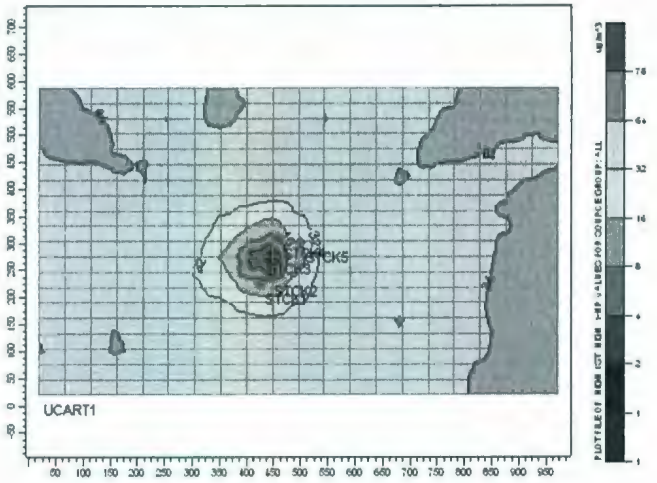
1 hr. average PM concentration 2007



8 hr. average PM concentration 2007



24 hr. average PM concentration 2007



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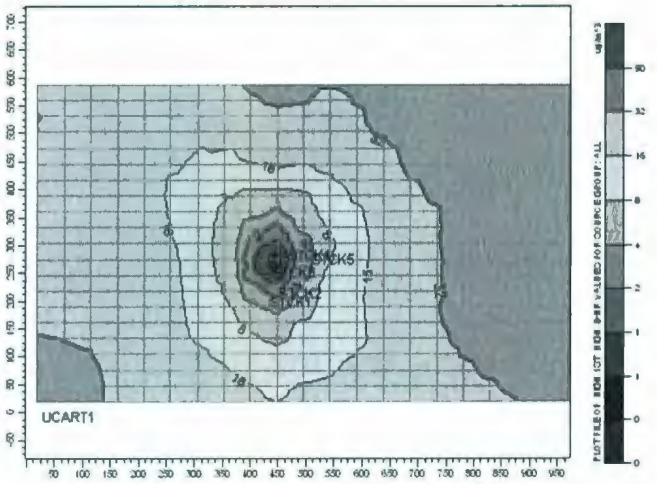

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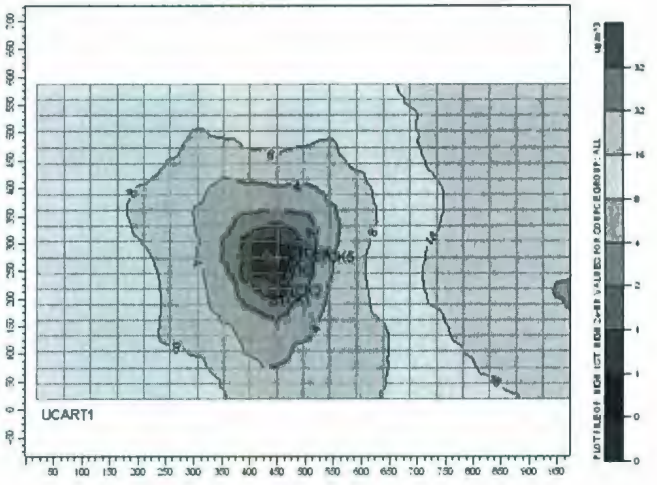
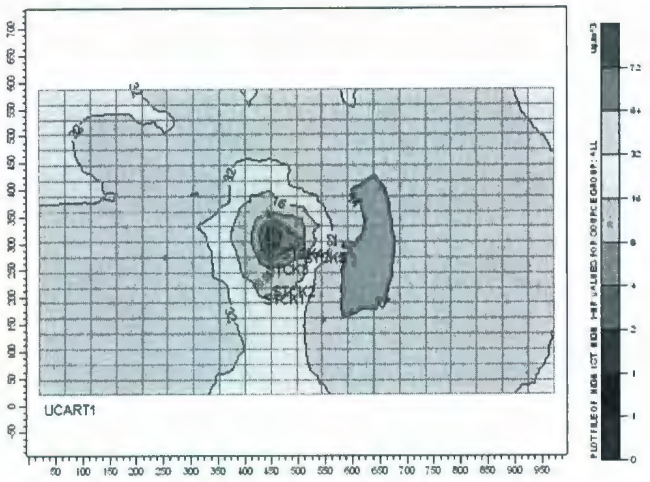


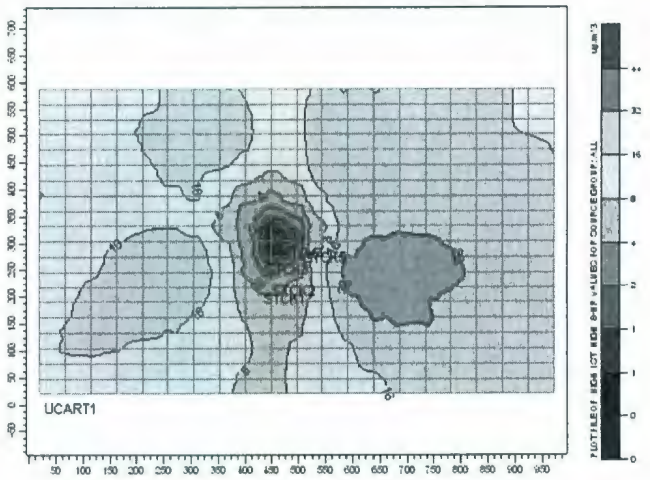
24 hr. average PM concentration 2006

APPENDIX-B5

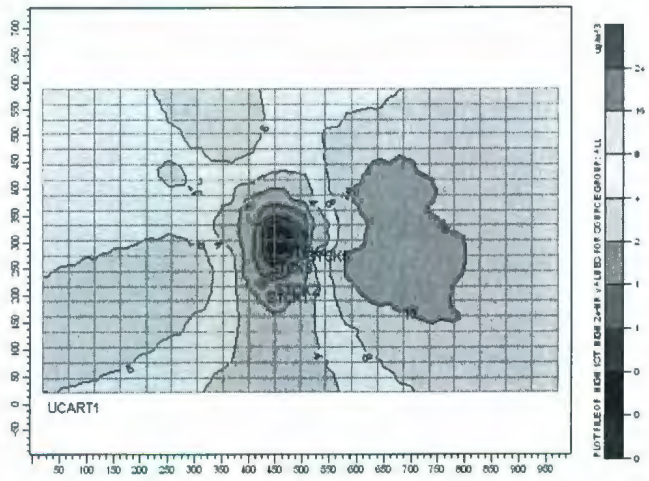
TOC CONCENTRATION



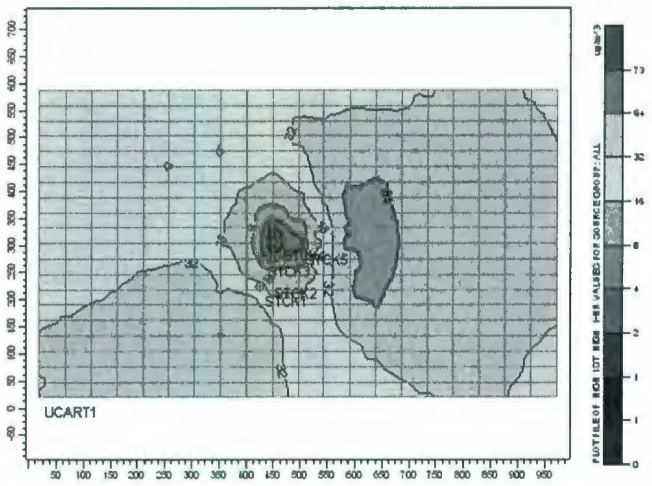
1 hr. average TOC concentration 2008



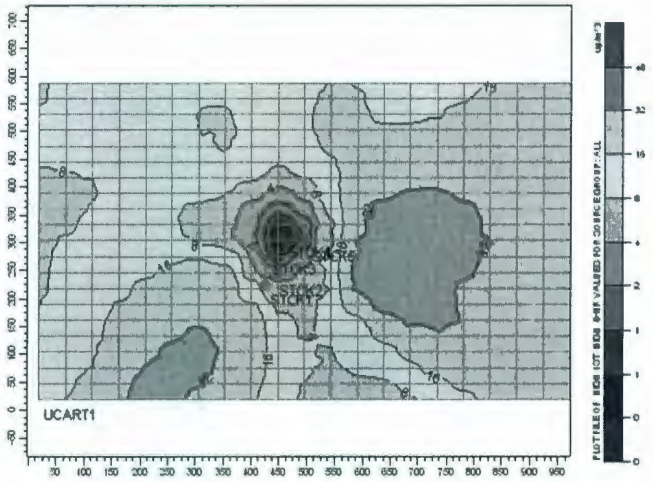
8 hr. average TOC concentration 2008



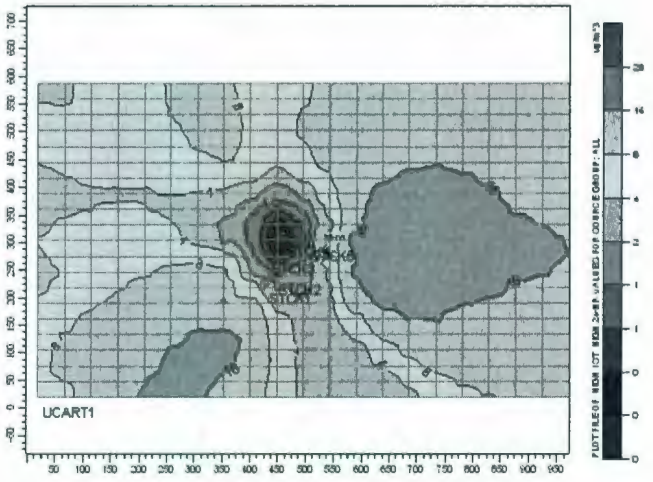
24 hr. average TOC concentration 2008



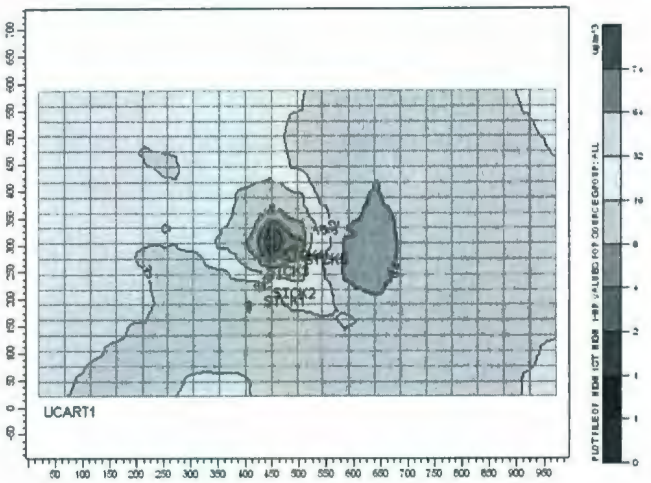
1 hr. average TOC concentration 2007



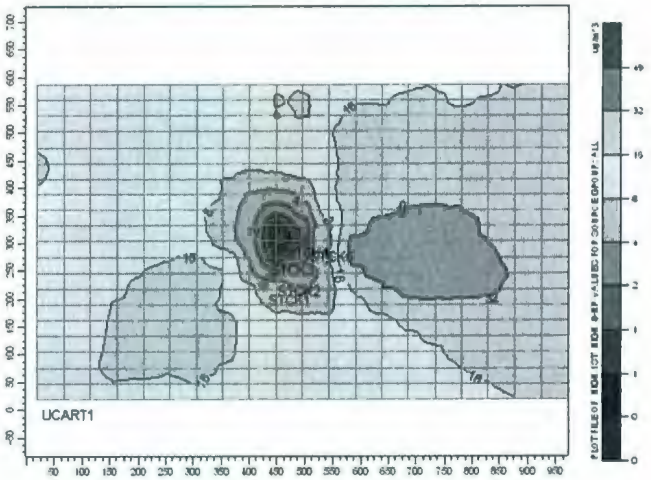
8 hr. average TOC concentration 2007



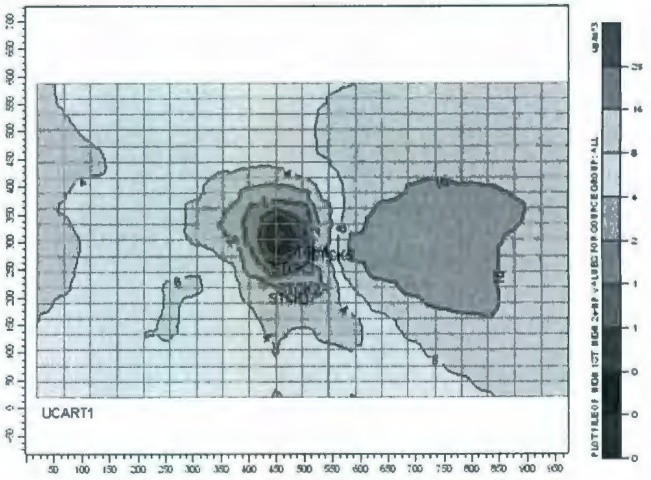
24 hr. average TOC concentration 2007



1 hr. average TOC concentration 2006



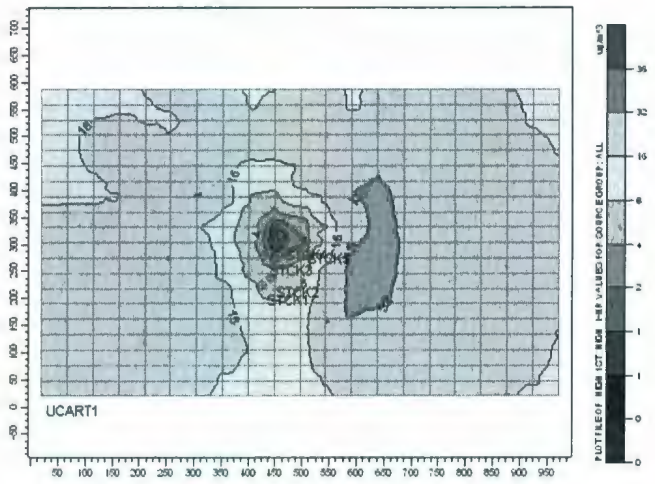
8 hr. average TOC concentration 2006



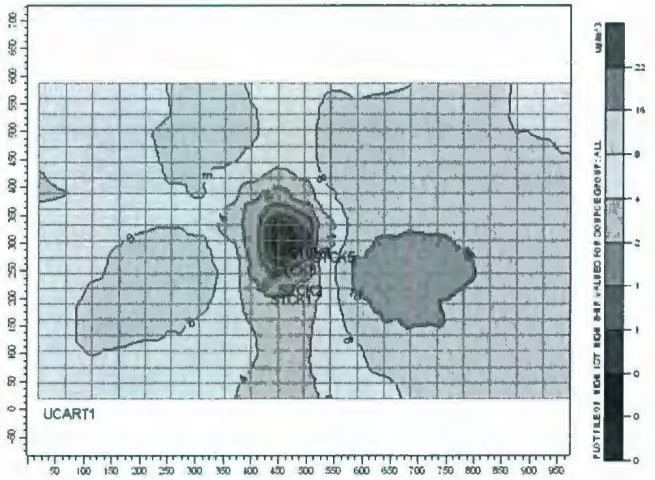
24 hr. average TOC concentration 2006

APPENDIX-B6

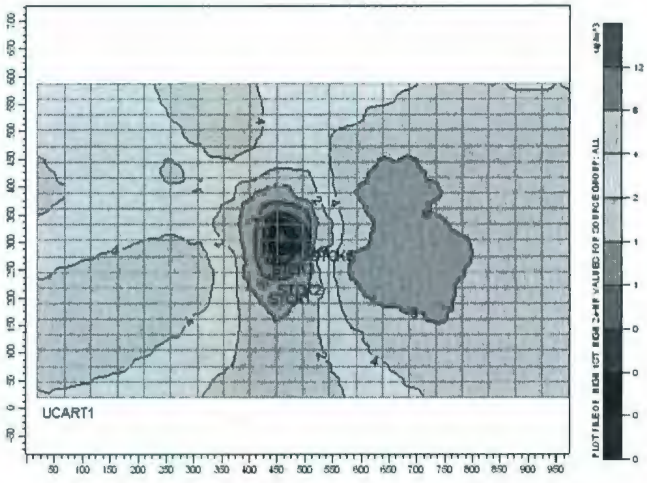
VOC CONCENTRATION



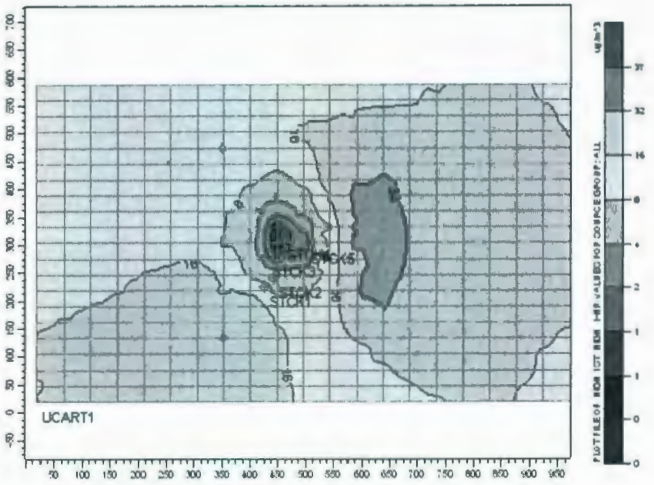
1 hr. average VOC concentration 2008



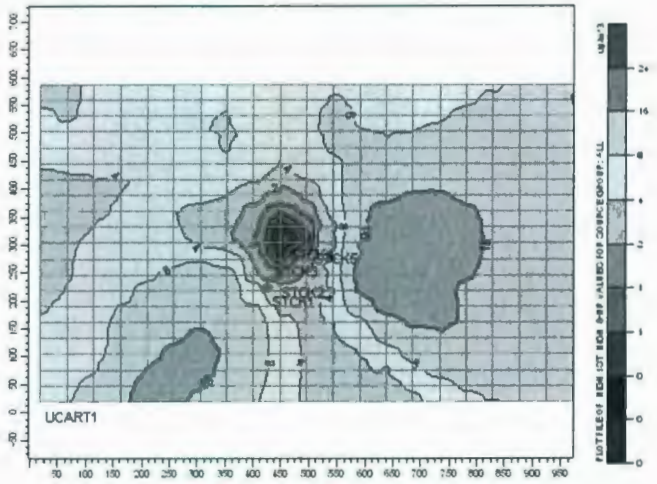
8 hr. average VOC concentration 2008



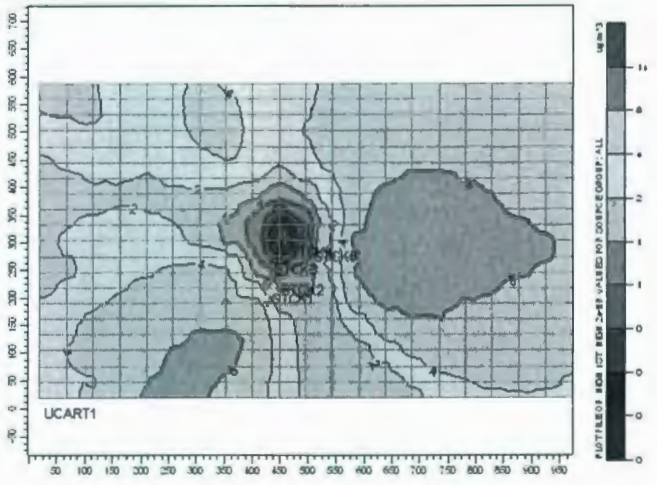
24 hr. average VOC concentration 2008



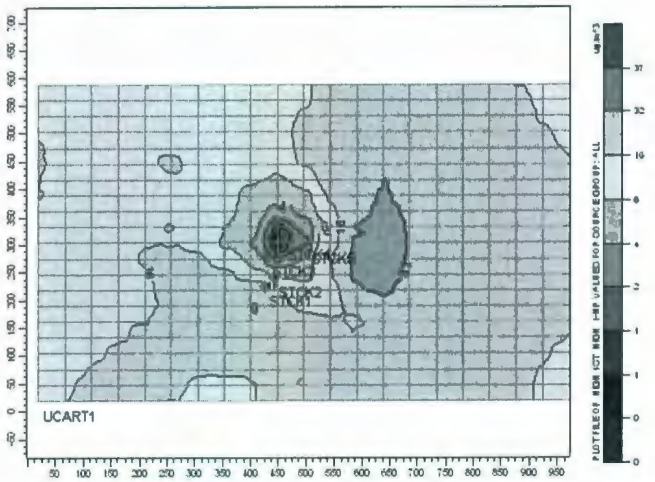
1 hr. averageVOC concentration 2007



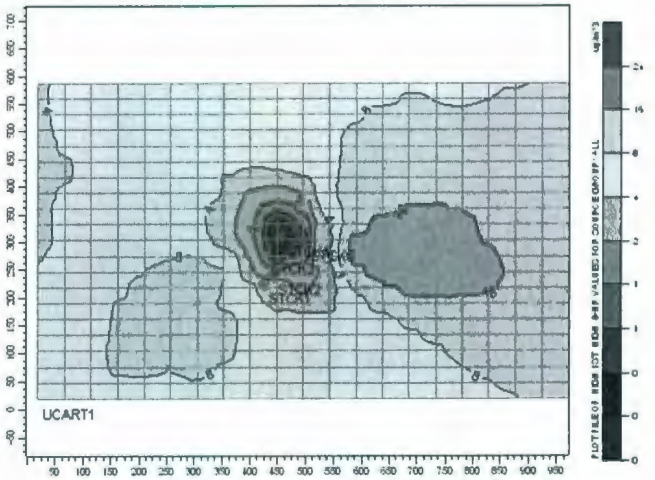
8 hr. average VOC concentration 2007



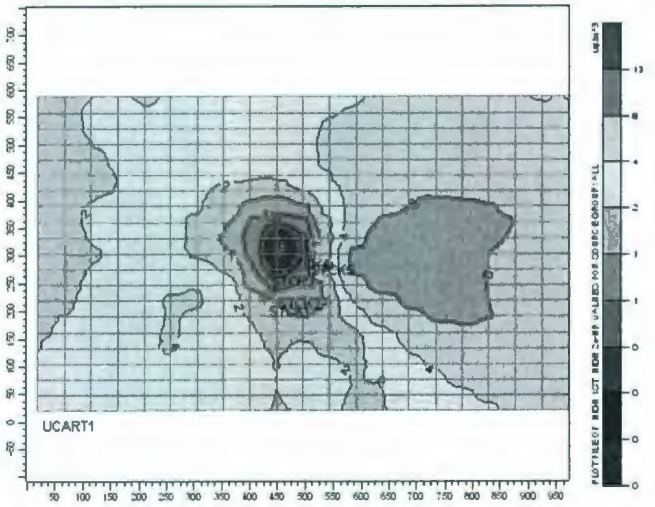
24 hr. average VOC concentration 2007



1 hr. average VOC concentration 2006



8 hr. average VOC concentration 2006



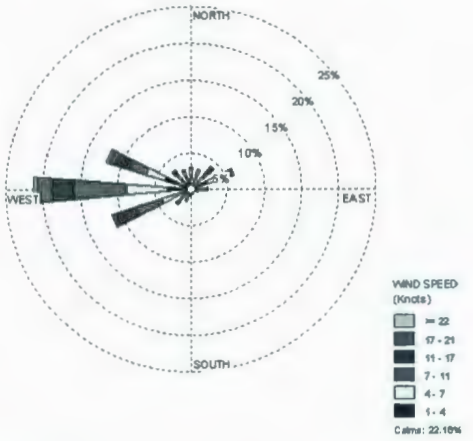
24 hr. average VOC concentration 2006

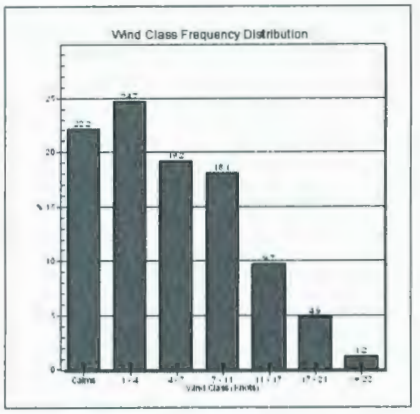
APPENDIX-C

WIND ROSE DIAGRAM

APPENDIX-C1

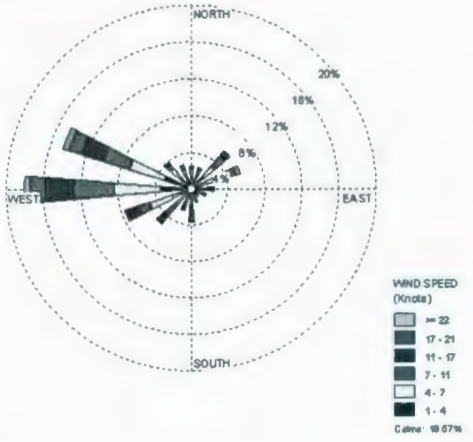
MONTHLY WIND ROSE-2008

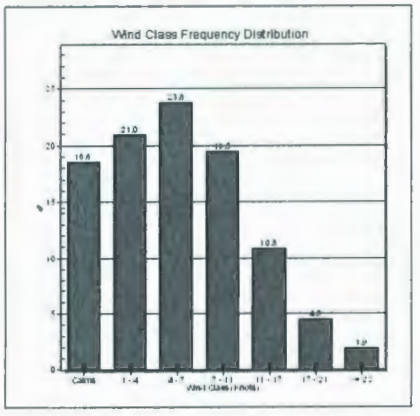




Wind Rose January-08

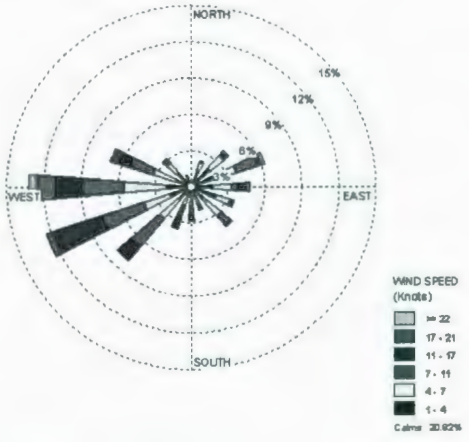
Wind Class Frequency Distribution January-08

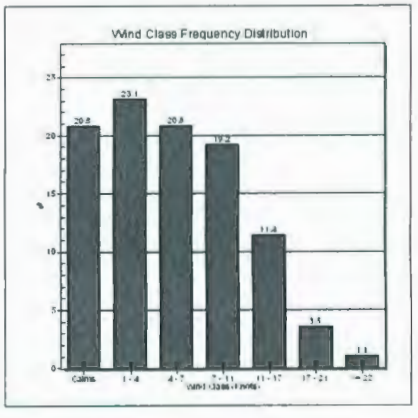




Wind Rose February-08

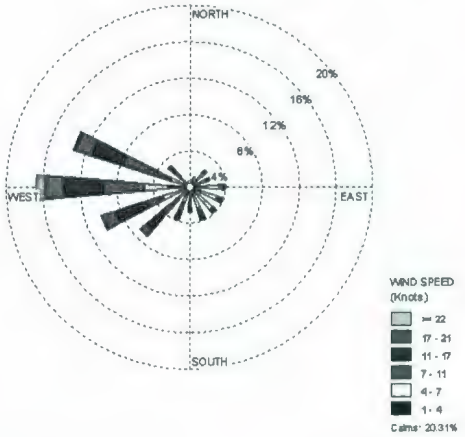
Wind Class Frequency Distribution February-08

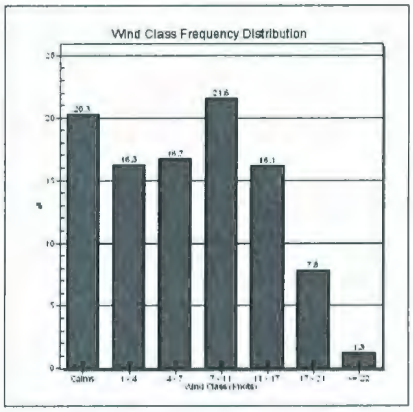




Wind Rose March -08

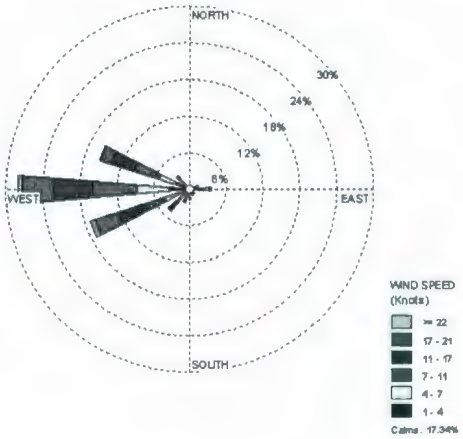
Wind Class Frequency Distribution March-08

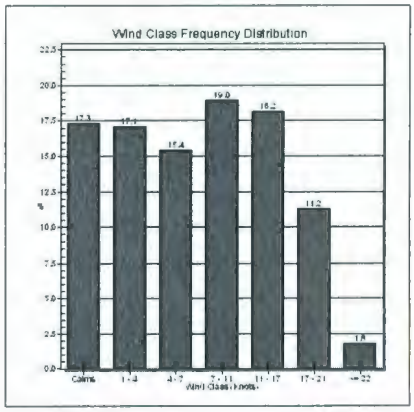




Wind Rose April -08

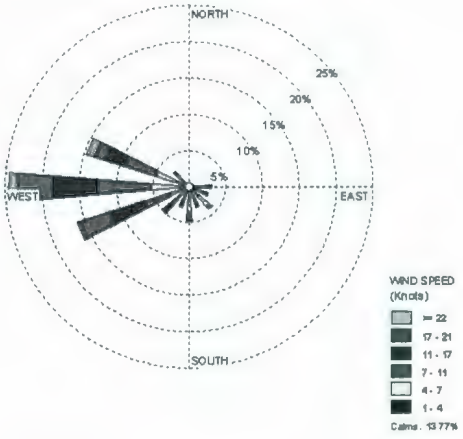
Wind Class Frequency Distribution April -08

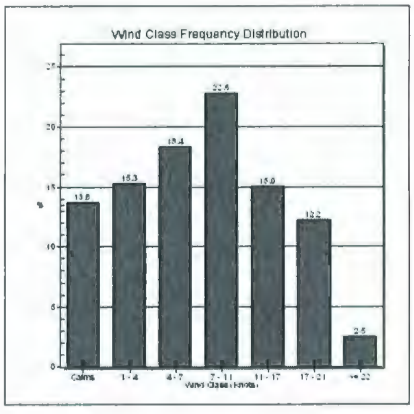




Wind Rose May-08

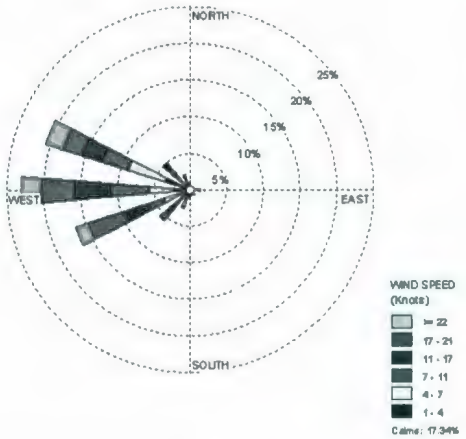
Wind Class Frequency Distribution May-08

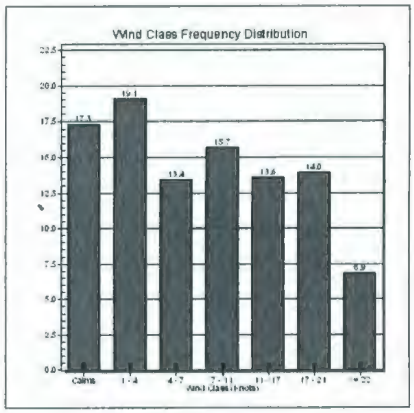




Wind Rose June-08

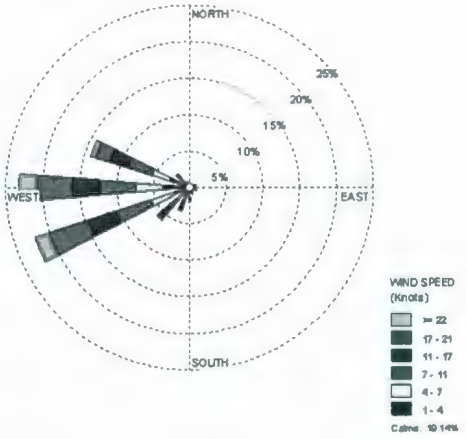
Wind Class Frequency Distribution June-08

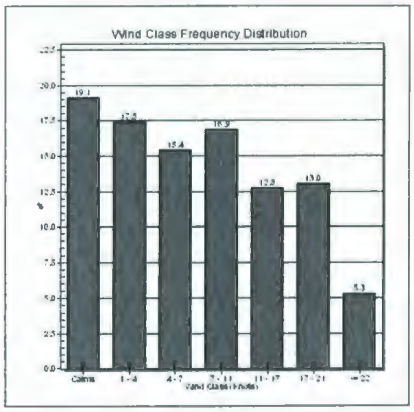




Wind Rose July-08

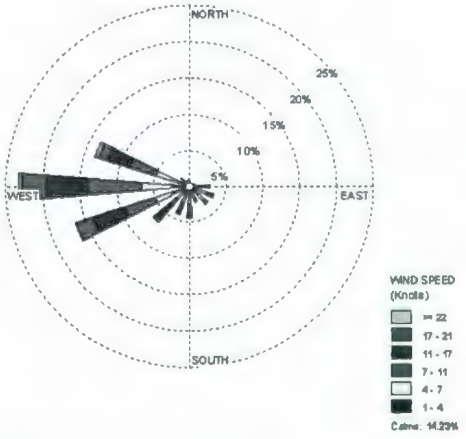
Wind Class Frequency Distribution July-08

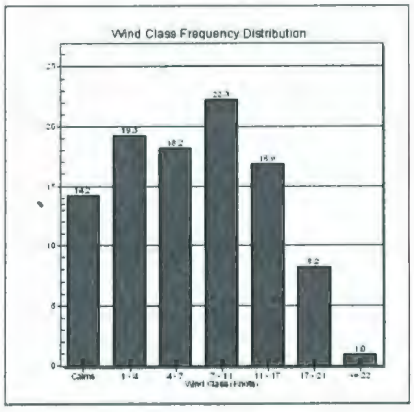




Wind Rose August -08

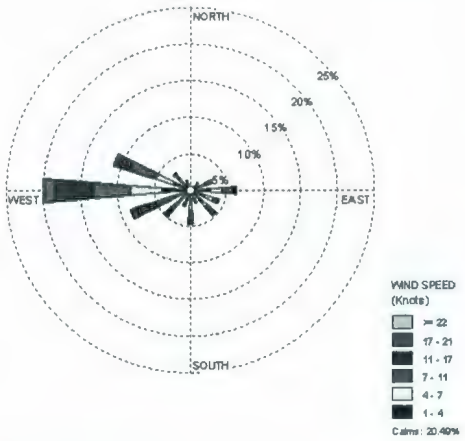
Wind Class Frequency Distribution August -08

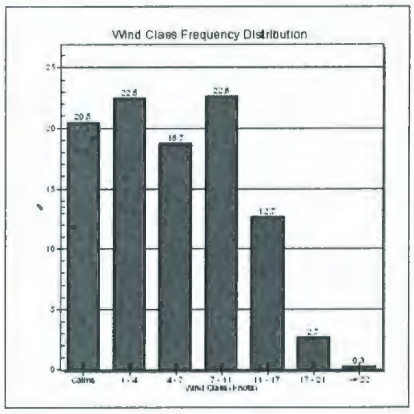




Wind Rose September -08

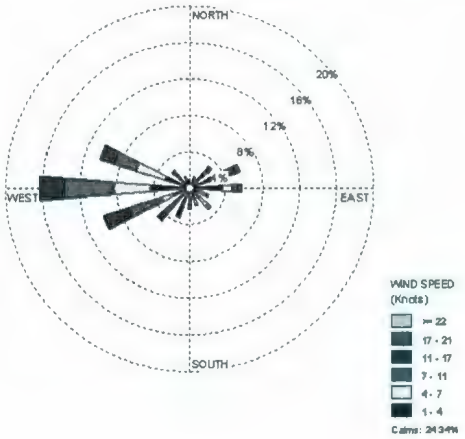
Wind Class Frequency Distribution September- 08

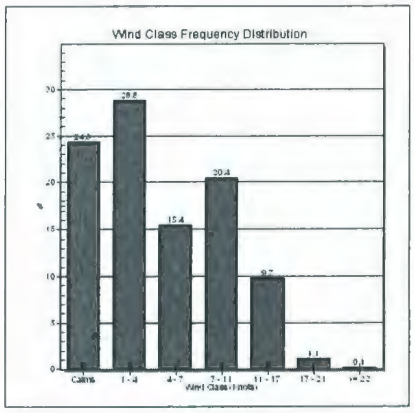




Wind Rose October-08

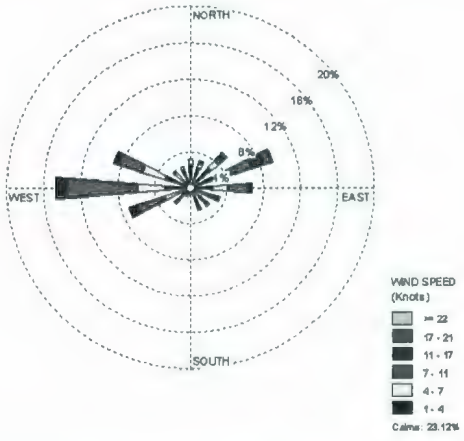
Wind Class Frequency Distribution October-08

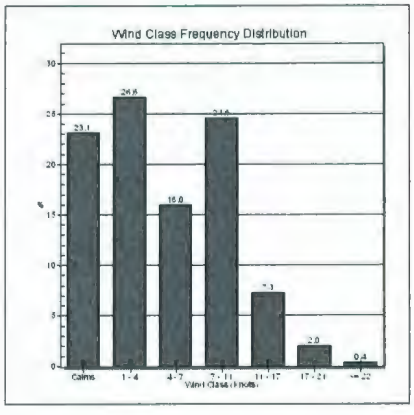




Wind Rose November -08

Wind Class Frequency Distribution November -08



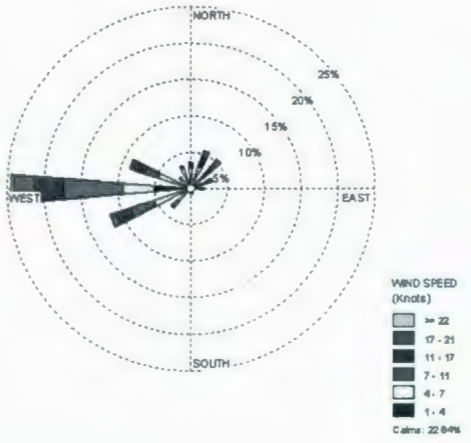


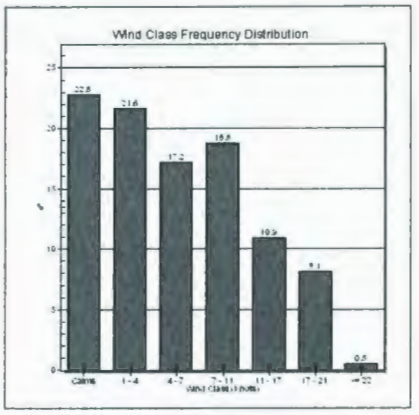
Wind Rose December -08

Wind Class Frequency Distribution December-08

APPENDIX-C2

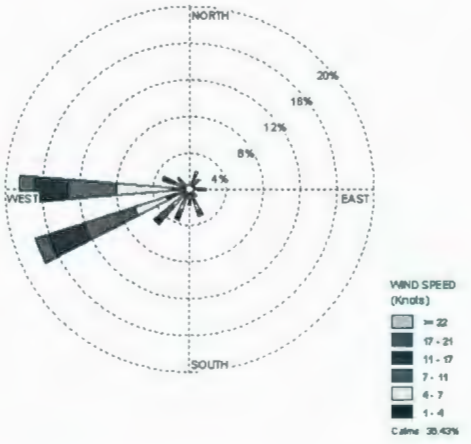
MONTHLY WIND ROSE-2007

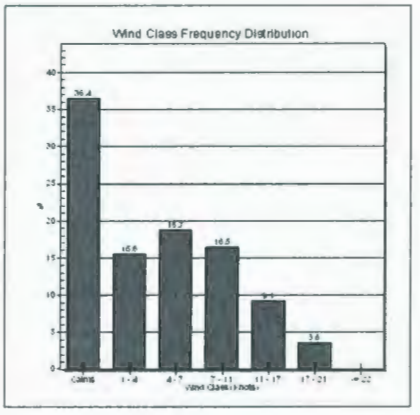




Wind Rose January-07

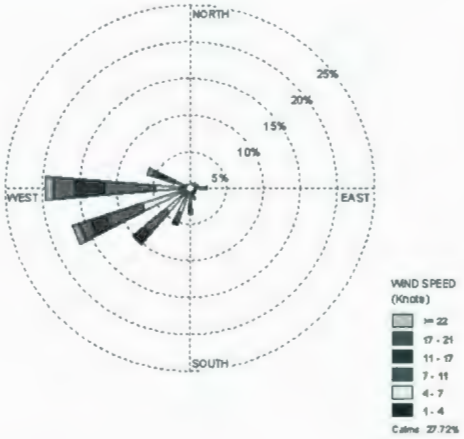
Wind Class Frequency Distribution January-07

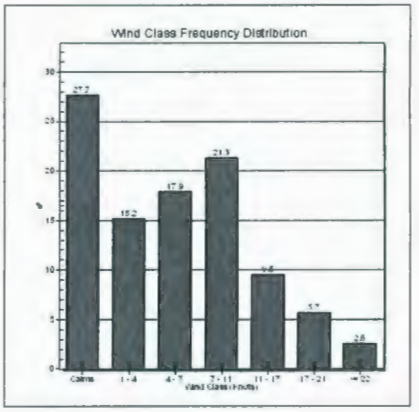




Wind Rose February-07

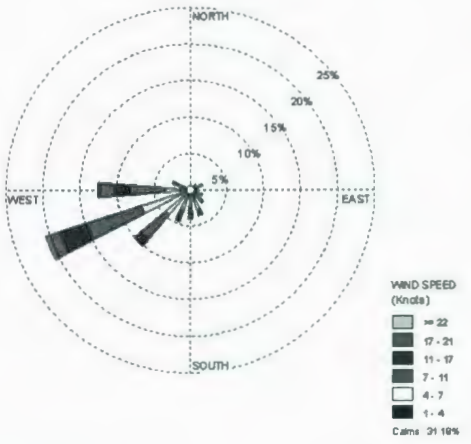
Wind Class Frequency Distribution February-07

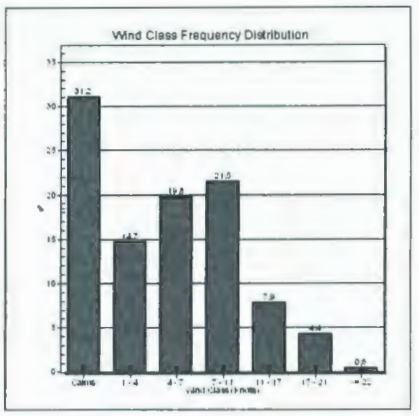




Wind Rose March -07

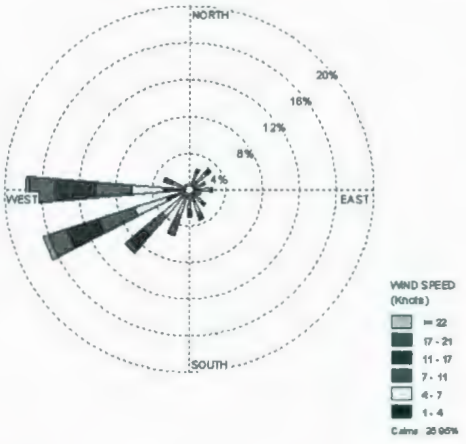
Wind Class Frequency Distribution March-07

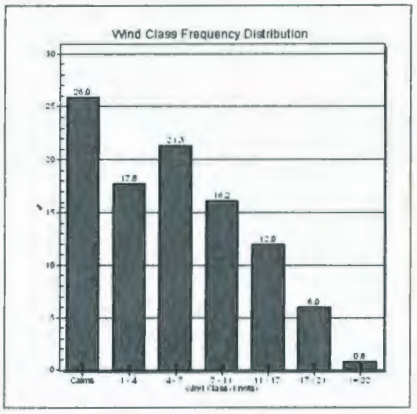




Wind Rose April -07

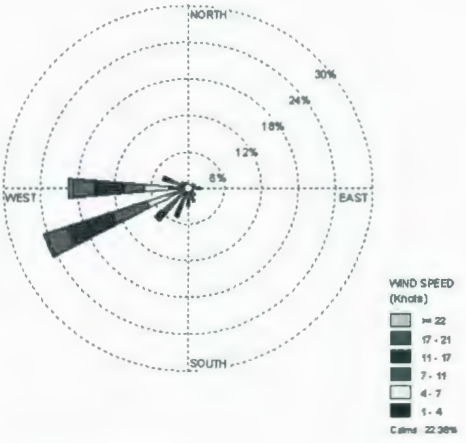
Wind Class Frequency Distribution April -07

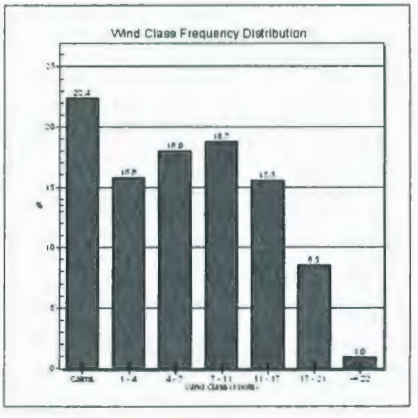




Wind Rose May-07

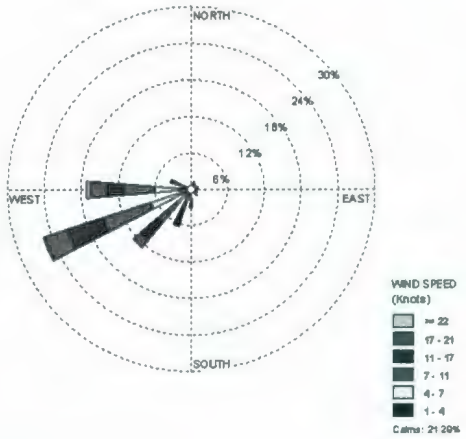
Wind Class Frequency Distribution May-07

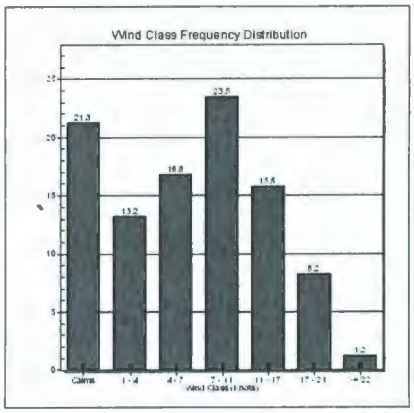




Wind Rose June-07

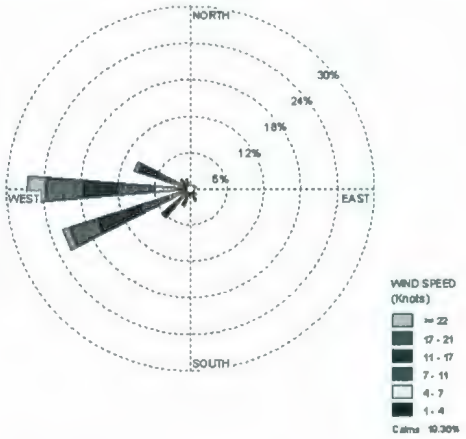
Wind Class Frequency Distribution June-07

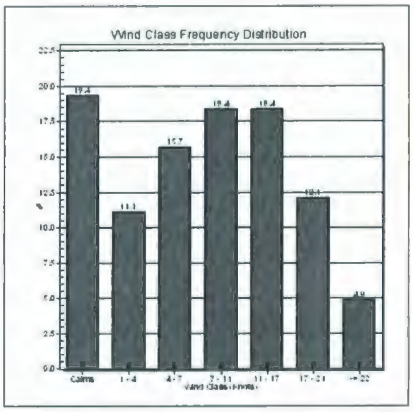




Wind Rose July-07

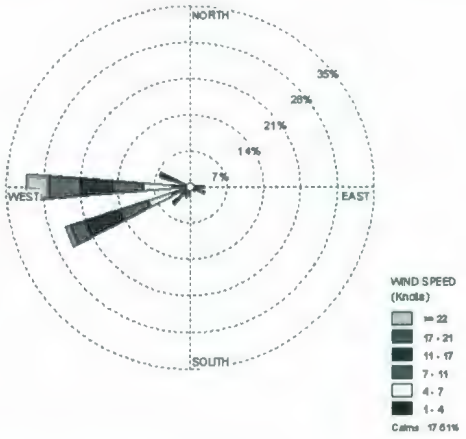
Wind Class Frequency Distribution July-07

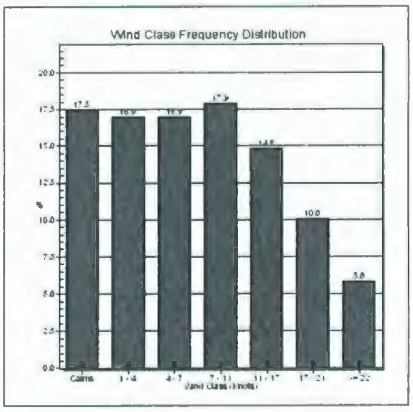




Wind Rose August -07

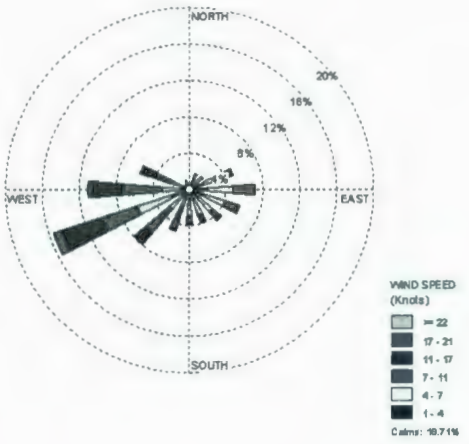
Wind Class Frequency Distribution August -07

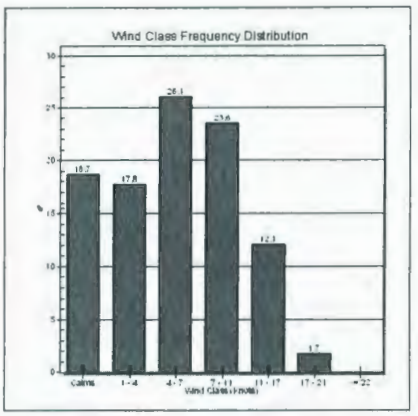




Wind Rose September -07

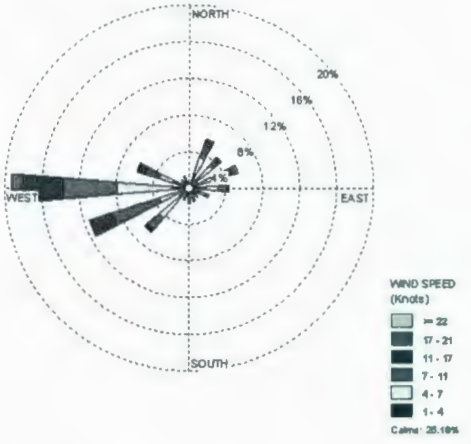
Wind Class Frequency Distribution September- 07

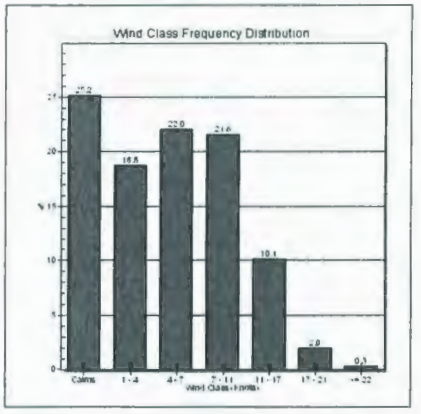




Wind Rose October-07

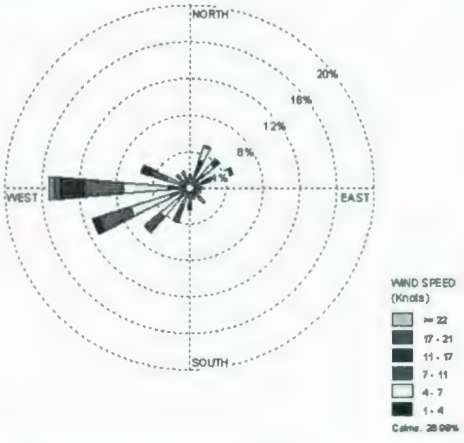
Wind Class Frequency Distribution October-07

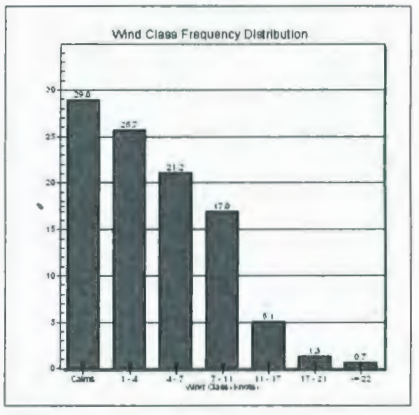




Wind Rose November -07

Wind Class Frequency Distribution November -07



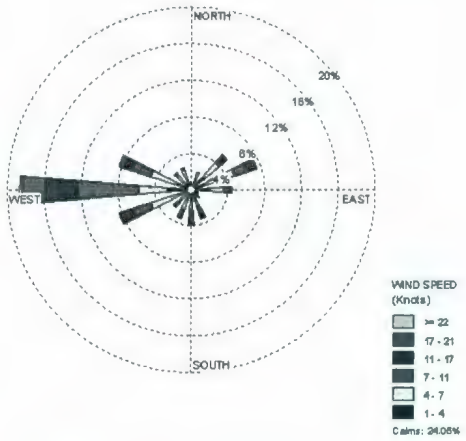


Wind Rose December -07

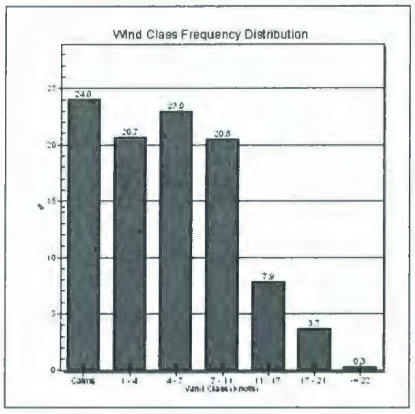
Wind Class Frequency Distribution December-07

APPENDIX-C3

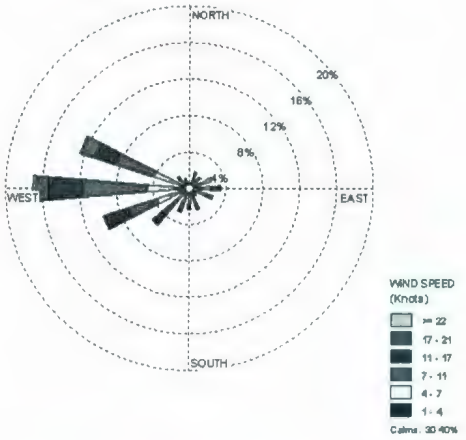
MONTHLY WIND ROSE-2006



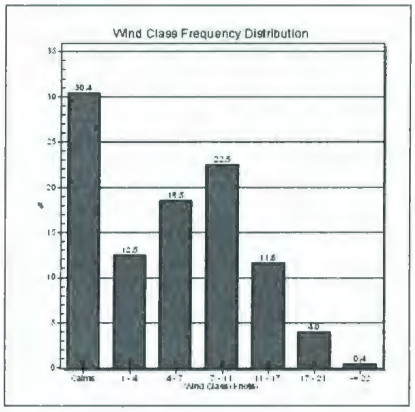
Wind Rose January-06



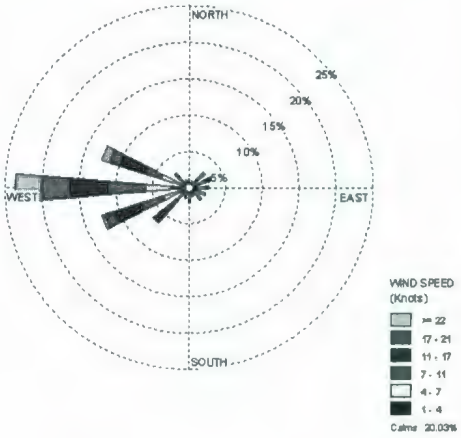
Wind Class Frequency Distribution January-06



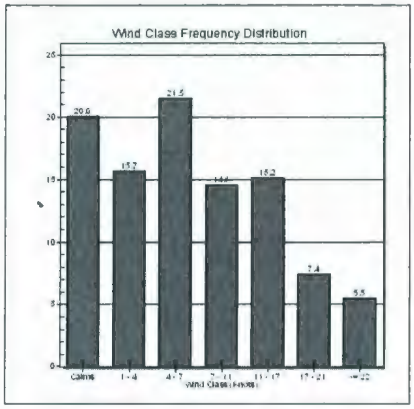
Wind Rose February-06



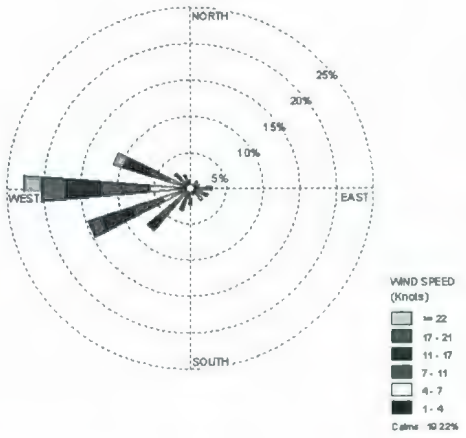
Wind Class Frequency Distribution February-06



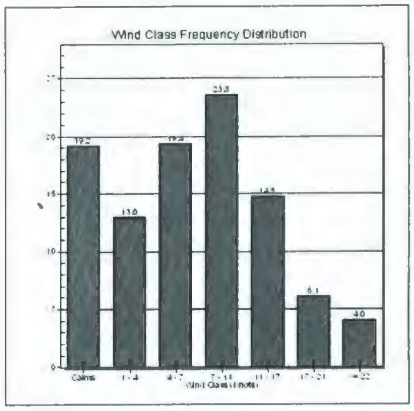
Wind Rose March -06



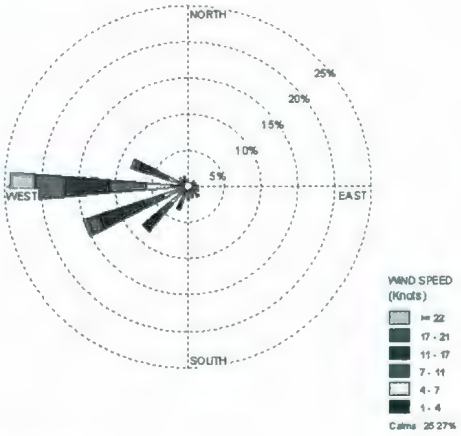
Wind Class Frequency Distribution March-06



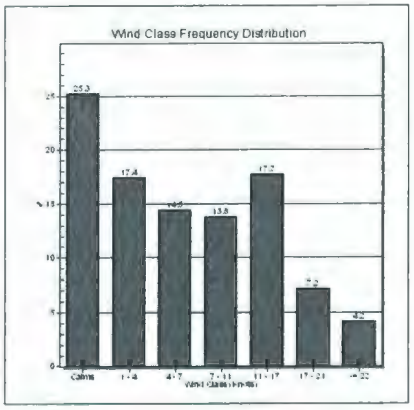
Wind Rose April -06



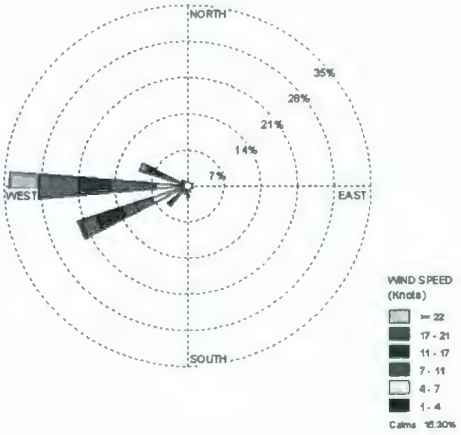
Wind Class Frequency Distribution April -06



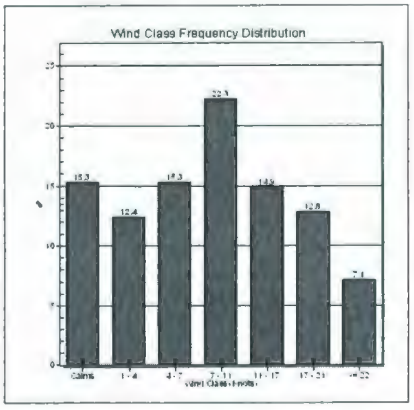
Wind Rose May-06



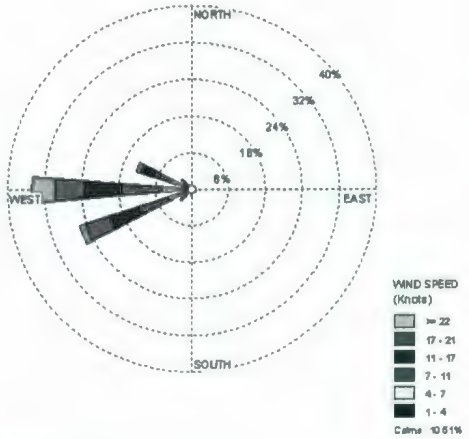
Wind Class Frequency Distribution May-06



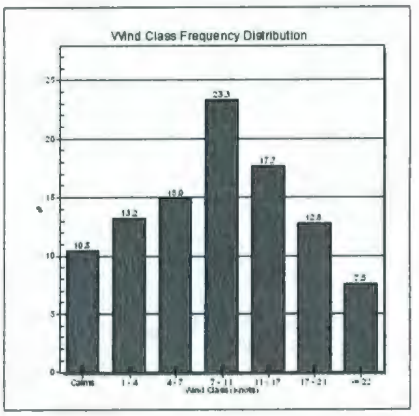
Wind Rose June-06



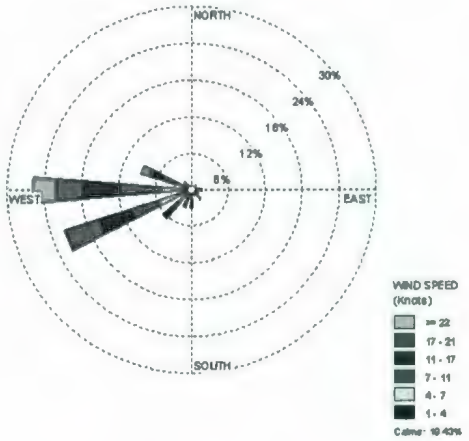
Wind Class Frequency Distribution June-06



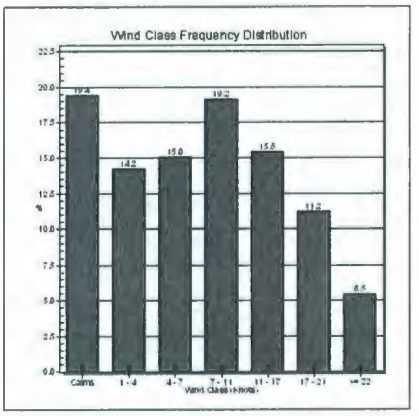
Wind Rose July-06



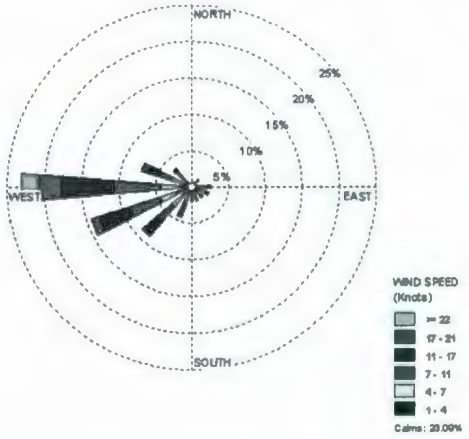
Wind Class Frequency Distribution July-06



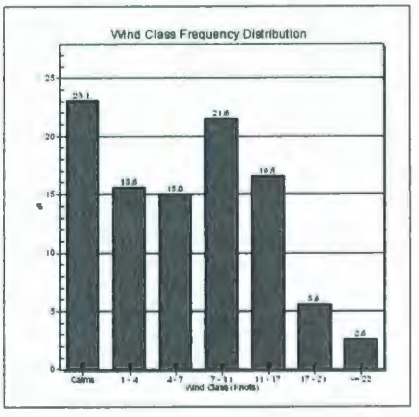
Wind Rose August -06



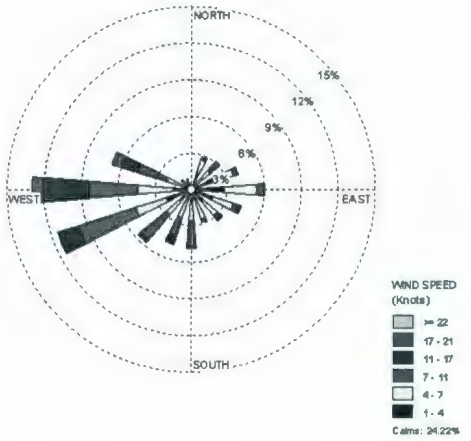
Wind Class Frequency Distribution August -06

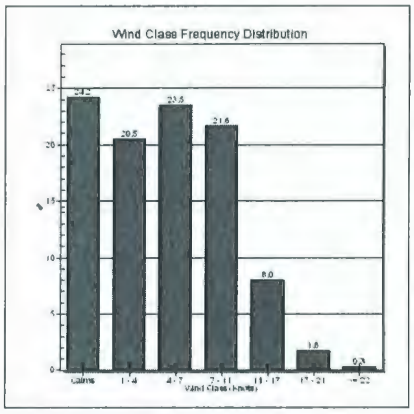


Wind Rose September -06



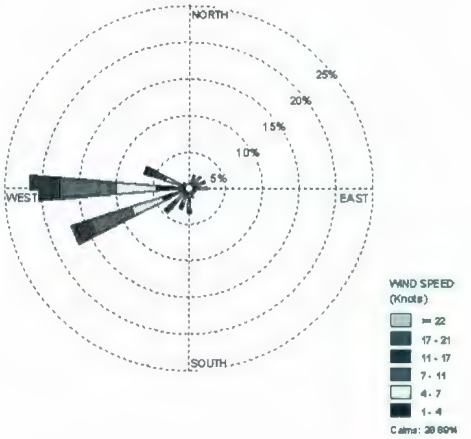
Wind Class Frequency Distribution September- 06

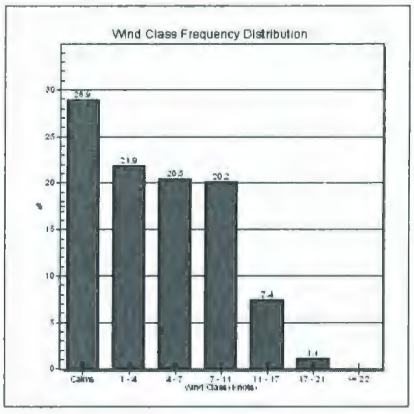




Wind Rose October-06

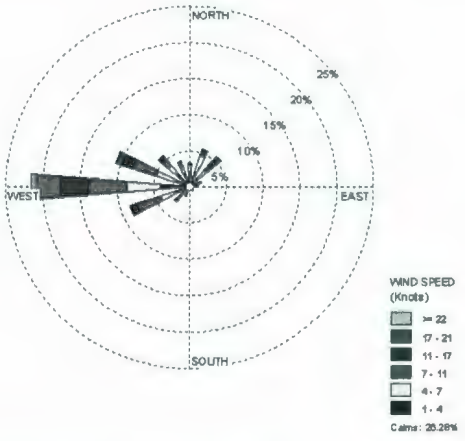
Wind Class Frequency Distribution October-06

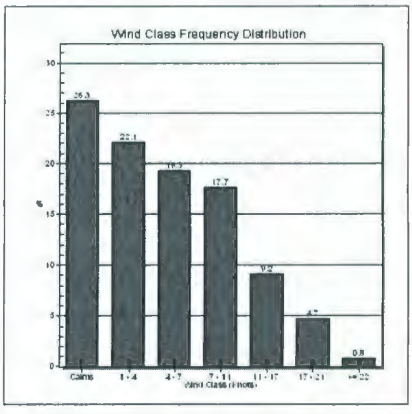




Wind Rose November -06

Wind Class Frequency Distribution November -06



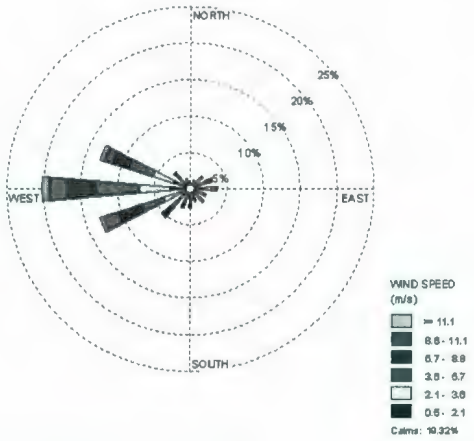


Wind Rose December -06

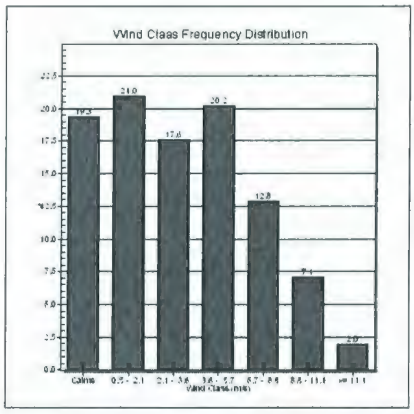
Wind Class Frequency Distribution December-06

APPENDIX-C4

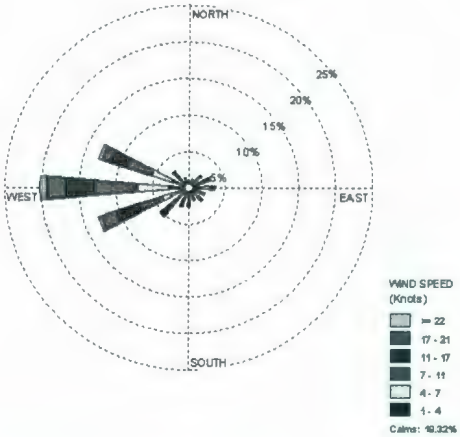
YEARLY WIND ROSE-2008



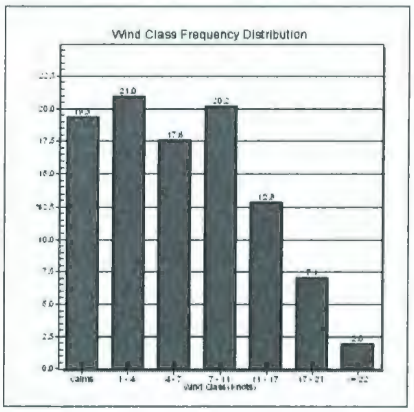
Surface Wind Rose-2008



Surface Wind Class Frequency Distribution -2008



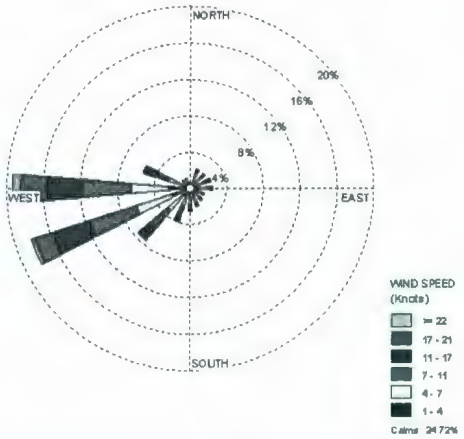
Profile Wind Rose-2008



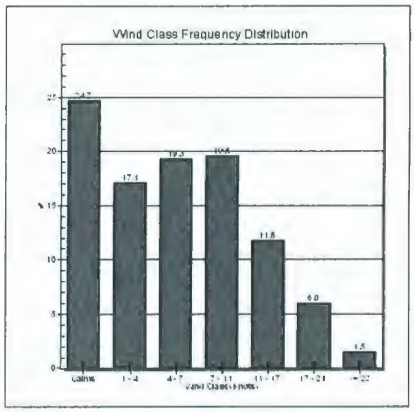
Profile Wind Class Frequency Distribution -2008

APPENDIX-C5

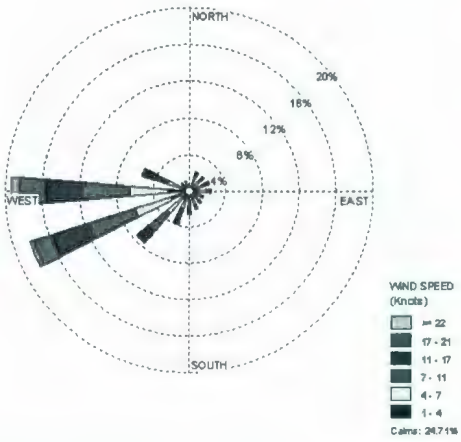
YEARLY WIND ROSE-2007



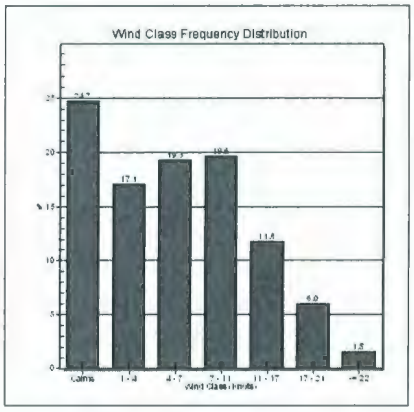
Surface Wind Rose-2007



Surface Wind Class Frequency Distribution -2007



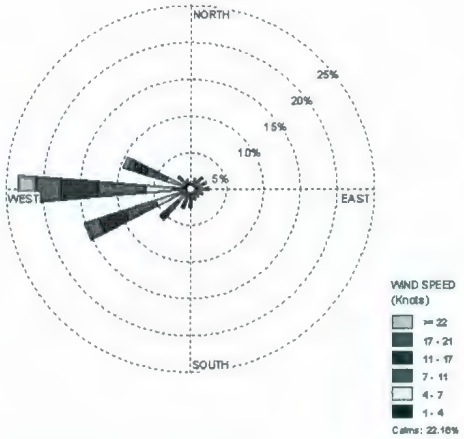
Profile Wind Rose-2007



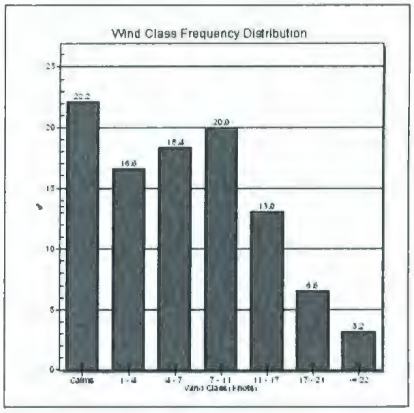
Profile Wind Class Frequency Distribution -2007

APPENDIX-C6

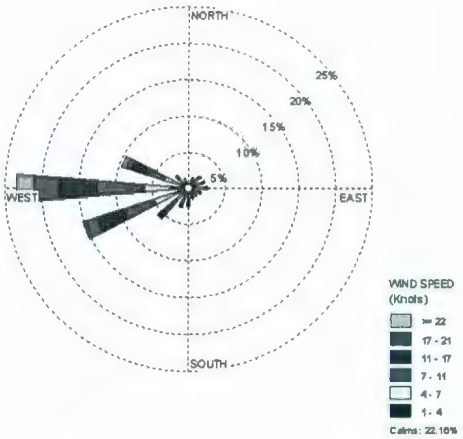
YEARLY WIND ROSE-2006



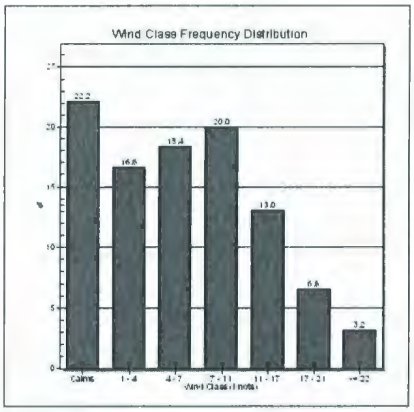
Surface Wind Rose-2006



Surface Wind Class Frequency Distribution -2006



Profile Wind Rose-2006



Profile Wind Class Frequency Distribution -2006