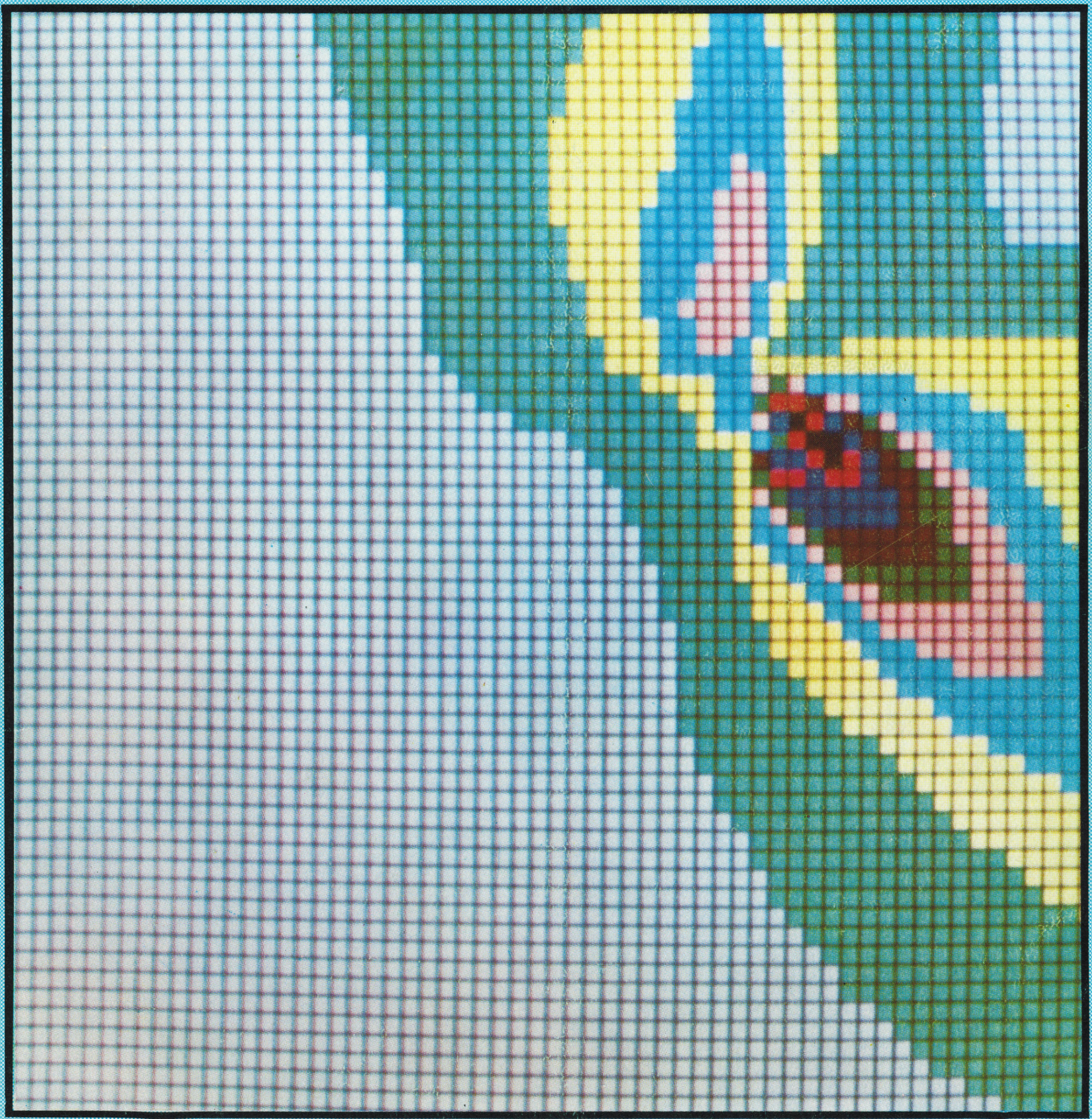
Paolo Zannetti

FINAL REPORT

Air pollution dispersion and prediction model for Shuaiba Industrial Area

EES-45

Volume II – Technical Report



SUBMITTED TO: SHUAIBA AREA AUTHORITY

KUWAIT INSTITUTE FOR SCIENTIFIC RESEARCH
P. O. BOX 24885 SAFAT
KUWAIT

JULY 1983

The cover picture provides a graphic representation of the ground level NO_x concentration field in the Shuaiba region as simulated by a numerical diffusion computation; darker colors indicate higher concentrations. This picture was produced using the HAZIENDA image processing system at the Kuwait Scientific Center of IBM. We thank Mr. Jesus Rueda of IBM for the preparation and the production of this picture.

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KISR 1090 A

FINAL REPORT

AIR POLLUTION DISPERSION AND PREDICTION MODEL FOR SHUAIBA INDUSTRIAL AREA

VOLUME II – TECHNICAL REPORT

EES-45

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ENVIRONMENTAL AND EARTH SCIENCES DIVISION

SUBMITTED TO
SHUAIBA AREA AUTHORITY

"RESTRICTED"

KUWAIT INSTITUTE FOR SCIENTIFIC RESEARCH
P. O. BOX 24885 SAFAT
KUWAIT

AUGUST 1983

ABSTRACT FORM

Title: Air Pollution Dispersion and Prediction Model for Shuaiba Industrial Area

Project No. (if applicable) EES-45

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ABSTRACT (Summary of not more than 300 words, in English and Arabic)

This report contains Volume II of a five-volume final report to the SAA for the project "Air Pollution Dispersion and Prediction Model for Shuaiba Industrial Area" (EES-45). Volume II is the key technical document of this study.

This report presents a detailed task-by-task description of the project structure, activities and achievements. Particular emphasis is given to the possible utilization of project results and to the future air quality needs in the region. Recommendations to SAA discussing the scope of work for continuing this project are also enclosed.

KEY WORDS

Air Pollution, Computer Modeling

Signature

July 31/1983

Date

ABSTRACT FORM

Title: نموذج انتشار التلوث الجوى والتنبوء به لمنطقة الشعيبة الصناعية

Project No. ____________
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Type of Publication (circle one) : Proposal Interim Report [✓ Final Report] Periodical Article Conference Paper Manual/Brochure Patent Application

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ABSTRACT (Summary of not more than 300 words, in English and Arabic)

يتضمن هذا التقرير المجلد الثاني من التقرير الختامي الوارد في خمسة مجلدات والمقدم للادارة العامة لمنطقة الشعيبة حول مشروع "صياغة نموذج انتشار التلوث الجوى والتنبوء به لمنطقة الشعيبة الصناعية EES 45) • ويعتبر المجلد الثاني أهم وثيقة فنية لهذه الدراسة•

ويقدم هذا التقرير وصفا مفصلا يناقش كل مهمة من المهام المرتبطة بتكوين المشروع ونشاطاته وانجازاته • وقد تم التركيز بصورة خاصة على امكانية الاستفادة من نتائج المشروع والاحتياجات المستقبلية لنوعية الهواء في المنطقة• ويتضمن التقرير كذلك التوصيات المقدمة للادارة العامة لمنطقة الشعيبة والتي تناقش الهدف من الاستمرار في هذا المشروع •

KEY WORDS

Signature

July 31/1983
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Preface

The Kuwait atmosphere was polluted for a long time before the recent staggering urban and industrial development of the country. Dust episodes, in fact, have always characterized Kuwait air quality, especially during summer time.

Dust episodes, being natural phenomena, present completely different characteristics from urban and industrial anthropogenic pollution, in which a huge quantity of reactive and non-reactive pollutants (gases and particulates), having serious potentially adverse effects, are discharged into the atmosphere. It is a frequently expressed opinion, however, that, since Kuwait air quality is already bad because of natural dust, little or nothing needs to be done about urban and industrial air pollution. Scientific facts show exactly the opposite.

It was clearly found that major industrial air pollutants present synergistic effects in which their reactivity or hazard is increased by the presence of atmospheric aerosols (i.e., particulates). Therefore, natural dust pollution in Kuwait is a further reason for requiring less urban and industrial pollution.

An example will clarify this concept. SO_2, the major industrial pollutant, does not have major adverse respiratory effects on humans since it is absored by the moist lining of the upper respiratory system. But when aerosols are present, SO_2 can be absorbed into the surface of such particles and be carried deep into the lung, where it can be deposited on the pulmonary membrane. Thus, SO_2 becomes an irritant of the bronchioles and alveoli.

The importance of this subject fully justifies SAA and KISR efforts in research and development to assess (using the most advanced technology) the air pollution phenomena and their ecological consequences.

Acknowledgments

The authors express their gratitude to the Shuaiba Area Authority, the major sponsor of this study, and to the Environmental and Earth Sciences Division of KISR, which provided support and encouragement. We also thank the Directorate General of Civil Aviation (Meteorological Department, Climatological Division) for providing the meteorological data collected at the Kuwait International Airport.

SAA personnel have actively contributed to this project. We particularly acknowledge the contribution of Mr. Fakhry Dorgham, who coordinated the activity of the SAA staff in the project, and Mr. Hussain Al-Adhad, who supervised important data collection activities.

The assistance and support of many people have been extremely important during this 18-month project. The authors wish to mention in particular the contribution of Mr. Mahmoud Izzo Safar, who provided his expertise in meteorology, Mr. Mohammed Ibrahim Abuseil, who supervised the computerized data collection, Ms. Maha Kortom and Ms. Mariam Al-Attiah, who provided programming help, and Messrs. Daniel Wooster, Sami Mohammed, Wajeeh Kittaneh and Hussain Al-Adhad, who reviewed and improved the collection of emission data. Ms. Mildred D'Souza deserves special mention for her careful secretarial assistance.

The valuable contribution of a few consultants in some specialized fields was an asset to the project. Dr. Richard Boubel, Environmental Consultant, and Mr. Eugene Wellman, President of BWR Consultants, provided help in source sampling and emission evaluations, and Dr. Ivar Tombach Vice-President of AeroVironment, reviewed the hardware used in the project.

The quality of the report has been improved by the comments and review of Dr. Hassan El-Baroudi, Head of the Environmental Sciences Department, and Dr. Fikry Khalaf, Division Director of the Environmental and Earth Sciences Division. Dr. Philip Sticksel, expert from Battelle Memorial Institute of Columbus, Ohio, developed the first detailed work plan for the project and later provided expert review of the final report. Dr. Sticksel's contribution is gratefully acknowledged. We extend our appreciation to Mrs. Patricia Kurtz of KISR for her careful final editorial review of the manuscript.

The initial KISR efforts for the development of the project objectives and scope for SAA were led by Mr. Dhari Al-Ajmi, an air pollution staff member in the Environmental Sciences Department at that time. His efforts led to the authorization of this work by SAA. Before this authorization, Mr. Dhari Al-Ajmi started his graduate studies in the U.K toward a Doctorate Degree in the area of air pollution. We acknowledge his early efforts in developing this investigation.

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List of Abbreviations

APS	Air Pollution Study
CDM	Climatological Dispersion Model
CMS	Conversational Monitoring System
CO_2	Carbon Dioxide
CO	Carbon Monoxide
EPA	Environmental Protection Agency (U.S.)
GMT	Greenwich Meridian Time
ISCLT	Industrial Source Complex-Long Term
ISCST	Industrial Source Complex-Short Term
KAI	Kuwait Asbestos Industry
KCC	Kuwait Cement Company
KISR	Kuwait Institute for Scientific Research
KMIC	Kuwait Melamine Industrial Company
KNPC	Kuwait National Petroleum Company
KOC	Kuwait Oil Company
KWI	Kuwait International Airport
LPF	Lime Product Factory
MC-LAGPAR	Monte-Carlo Lagrangian Particle
NH_3	Ammonia
NTIS	National Technical Information Service (U.S.)
NO_x	Nitrogen Oxides (NO and NO_2)
NWS	National Weather Service (U.S.)
PG	Pasquill-Gifford
PIC	Petrochemical Industrial Company
SAA	Shuaiba Area Authority
SAS	Statistical Analysis System
SIA	Shuaiba Industrial Area
SNPS	Shuaiba North Power Station
SSPS	Shuaiba South Power Station
SO_2	Sulfur Dioxide
TSP	Total Suspended Particulates
UNAMAP	User's Network for Applied Models in Air Pollution
UTM	Universal Transverse Mercator

1. Introduction and Overview

1.1 Background and Objectives

In the last fifteen years, two fields in the world of science and technology have shown remarkable growth:

- the computer field, with its impressive improvements in both hardware and software capabilities; and
- the field of environmental studies.

These two areas have many things in common, because computer methods are indispensable tools in most environmental analyses. Whereas the computer "revolution" speeds up technological development, however, environmental studies often warn against too rapid growth and the possible environmental degradation associated with it. In particular, public and private organizations throughout the world have expressed a growing concern about the environmental effects of the discharge of pollutants into bodies of water and the atmosphere. Atmospheric pollution has often received special attention, because of its immediate respiratory effects and the high number of people potentially exposed to this form of contamination.

The Shuaiba Area Authority (SAA), in its continuous effort to protect the local environment through scientific research and investigation, asked the Kuwait Institute for Scientific Research (KISR) to formulate and develop a joint SAA-KISR Air Pollution Study (APS) aiming at the following major objectives for the Shuaiba Industrial Area (SIA):

"1. To establish an air pollution dispersion and prediction model for the Shuaiba Industrial Area.
2. To determine the most important parameters affecting the emission, of pollutants, their modes of dispersion.
3. To establish grid systems (or any other equivalent methodology) for the interpretation of the required results.
4. To assess the effectiveness of distances and heights of the major emitting facilities within the Shuaiba Industrial Area and its vicinity.

5. To conduct experimental studies on the modes of tranport of pollutants, their interactions, fall out patterns and dispersion.
6. To specify the needed effective heights of emission sources (with special reference to new and planned sources).
7. To predict and estimate short term and long term pollution episodes, taking into account the nature of pollutants present in the area.
8. To simulate different conditions and compute their corresponding dispersion modes.
9. To evaluate, verify, and compare model inputs and outputs.
10. To evaluate the performance, sensitivity and objectives of the models' outputs.
11. To evaluate and critically assess all model outputs in relation to measured established parameters.
12. To recommend appropriate uses for the model in planning industrial site allocation."

KISR's answer to this challenging air pollution program was the preparation of an official proposal to SAA (see Zannetti, 1982b, for its final version). In that proposal, KISR recommended the division of the air pollution program into three phases (see Fig. 1-1) and formulated a detailed work plan for the implementation of the first phase, having the following objectives:

"1. To collect and analyse existing air quality and meteorological data available at the SAA/EPC (Environmental Protection Center).
2. To set up and develop additional air quality and meteorological equipment for better understanding of pollutant transport and dispersion in the Shuaiba and Mina Abdullah industrial areas.
3. To have in operaton several single source and multiple source dispersion models that could be used to predict short term concentrations from point sources in the Shuaiba and Mina Abdullah industrial areas.
4. To test the applicability of these models on selected locations from individual selected point sources.
5. To check and modify, if required, the accuracy of dispersion equations for suitability to conditions in Kuwait."

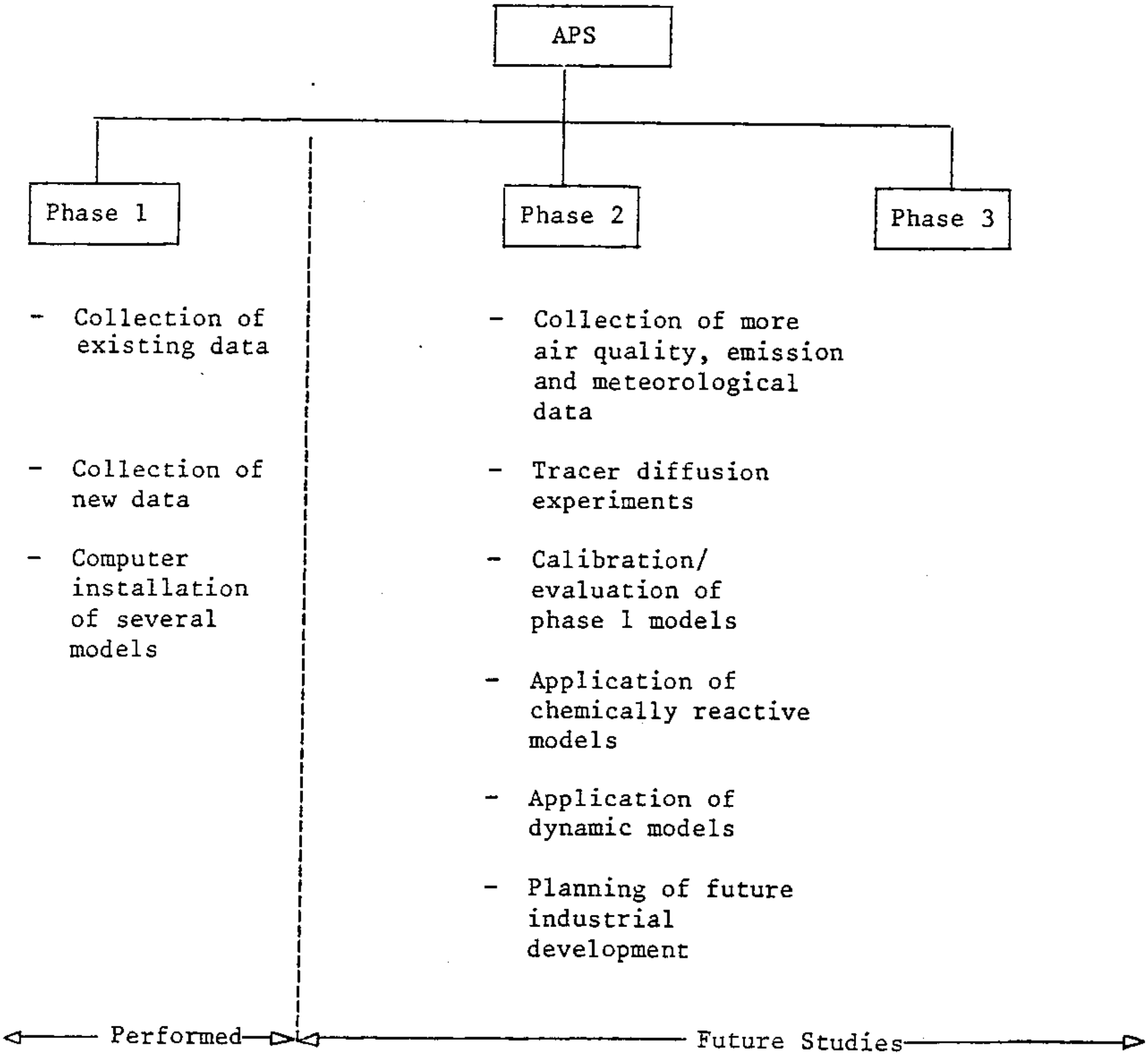

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Fig. 1-1. Basic structure of the Air Pollution Study (APS).

SAA approved the proposal and, consequently, this Phase 1 study (KISR coded EES-45) was performed during December 1981-May 1983. This report presents the results of this study and KISR's recommendations for the continuation of this important scientific activity, whose final output will provide SAA decision makers with accurate and reliable numerical tools for cost-effective planning of future development in the SIA.

1.2 The Shuaiba Industrial Area (SIA)

The SIA, which in this report includes the industrial areas of Shuaiba, Al-Ahmadi and Mina Abdullah, is one of the largest industrial regions in the Arabian Gulf area (see Fig. 1-2). This important production center is characterized by multiple industrial activities (see the pictures at the end of this section) whose intense growth in the last few years has created concern for the possible ecological degradation that could be associated with such intense development.

The main industrial facilities in the area are:

- Kuwait National Petroleum Company (KNPC):
    - Shuaiba refinery
    - Mina Abdulla refinery

  in which naphtha, kerosene, diesel and gas oil are produced
- Kuwait Cement Company (KCC) for cement production
- Kuwait Melamine Industries Company (KMIC) for the production of pure melamine
- Petrochemical Industries Company (PIC):
    - plant A, for urea and ammonia production
    - plant B, for urea and ammonia production
- Power stations for the production of electric power and desalinated water:
    - Shuaiba North Power Station (SNPS)
    - Shuaiba South Power Station (SSPS)

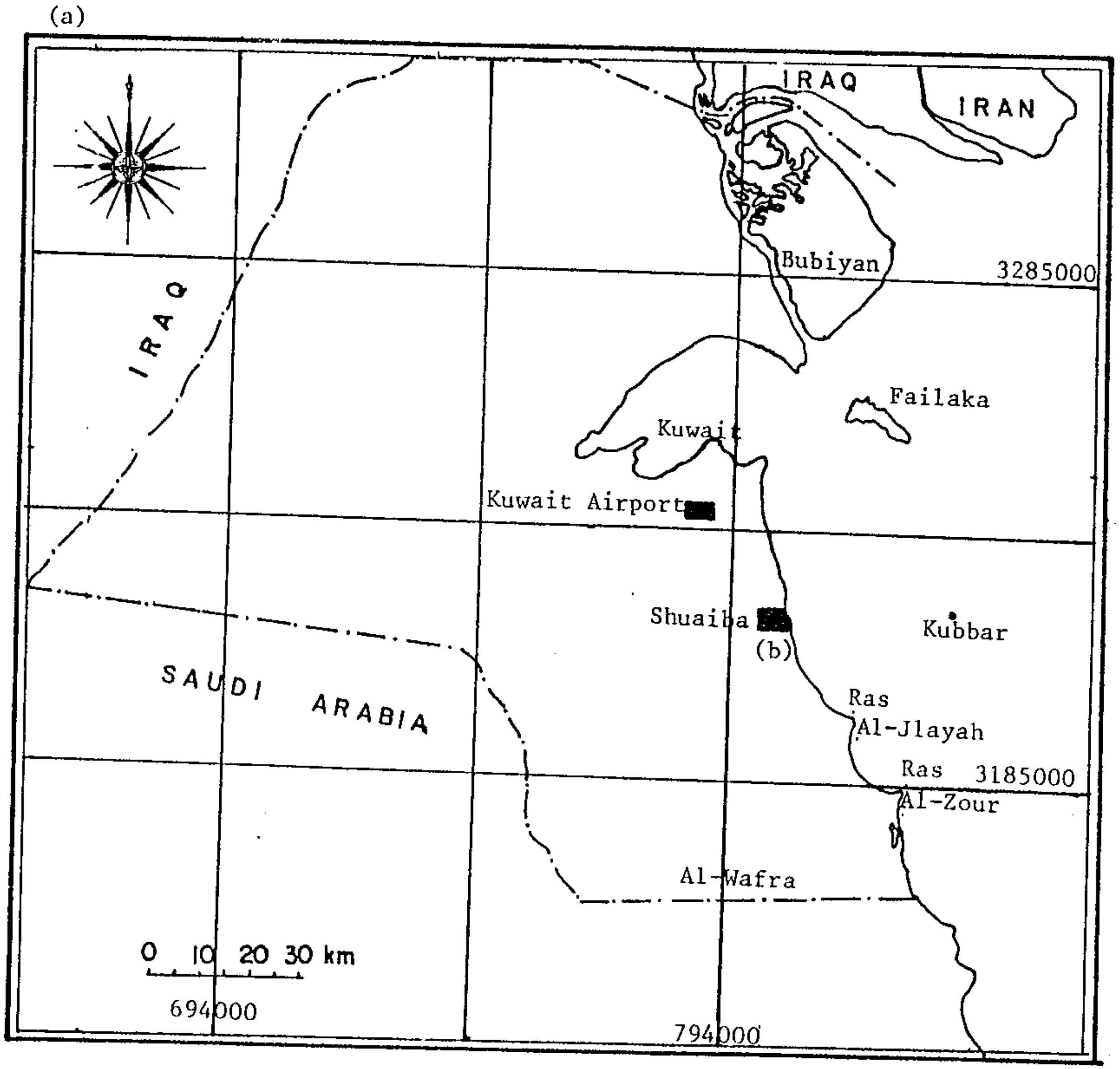

Fig. 1-2. The Kuwait region (a) and the Shuaiba Industrial Area (b).

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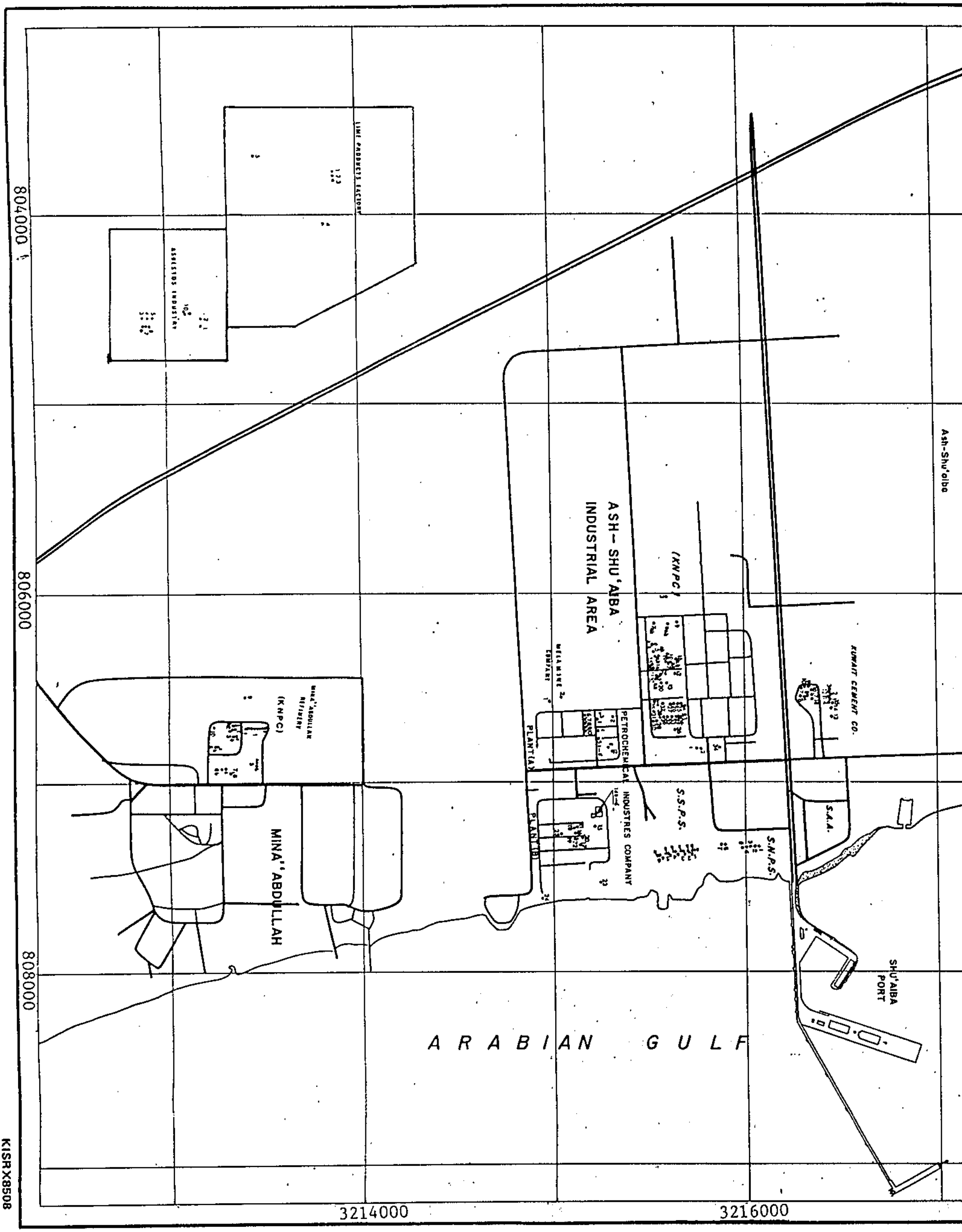
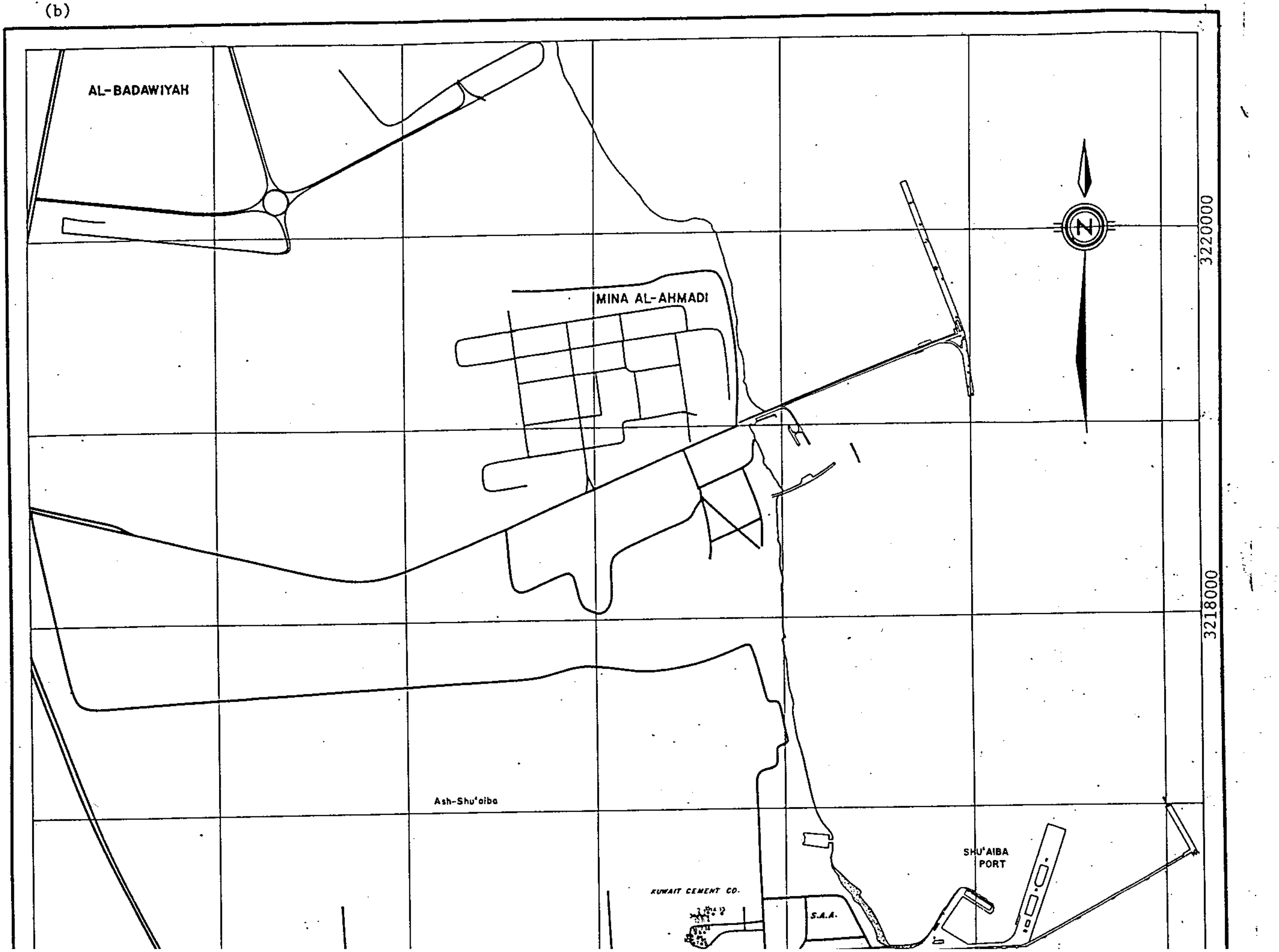

LIME PRODUCTS FACTORY
ASBESTOS INDUSTRY
MINA' ABDULLAH REFINERY
(KNPC)
MINA' ABDULLAH
ASH-SHU'AIBA INDUSTRIAL AREA
(KNPC)
MELAMINE COMPANY
PETROCHEMICAL INDUSTRIES COMPANY
PLANT (A)
PLANT (B)
S.S.P.S.
S.N.P.S.
S.A.A.
KUWAIT CEMENT CO.
Ash-Shu'aiba
SHU'AIBA PORT
ARABIAN GULF
804000
806000
808000
3214000
3216000

(b)


AL-BADAWIYAH
MINA AL-AHMADI
N
3220000
3218000
Ash-Shu'aiba
SHU'AIBA PORT
KUWAIT CEMENT CO.
S.A.A.

- Lime Products Factory (LPF) for the production of lime bricks
- Kuwait Asbestos Industry (KAI) for the production of pipes
- Kuwait Oil Company (KOC) in Al-Ahmadi:
    - refinery
    - gas liquid plant

A more detailed description of SAA industrial activities and production statistics can be found in a recent SAA technical brochure (SAA, 1982).

Atmospheric discharges from the industrial stacks of the SIA are mainly composed of the following pollutants (in order of importance):

1) sulfur dioxide (SO_2), the most significant pollutant in the SIA;
2) particulate matter, particularly, urea dust and cement dust;
3) ammonia (NH_3);
4) hydrogen sulfide (H_2S), mercaptans, hydrocarbons (HC);
5) nitrogen oxides (NO_x).

A more detailed description of the characteristics of the main industrial processes and emissions in the SIA is available in two separate reports already provided to SAA during the course of the project (KISR 977A, Appendix A; and KISR 1017A, Appendix A). The abstracts of these reports have been included in Sections 7 and 8 of Volume III of this final report.

1.3 Air Quality Problems in Shuaiba

The SIA, like most industrial areas throughout the world, clearly shows the existence of complex local air quality problems. Even though lethal episodes have never been recorded in the area, occurrences of adverse effects (e.g., odors) causing complaints from local workers and residents in the surrounding urban areas are not unusual.

In addition to the possible health-related adverse effects (still to be proved, however), some economic damages from air pollution effects have been clearly identified; for example:

- the corrosion of the silver points of the connection tubes in the SSPS, most probably caused by the effects of the sulfur compounds; and,

- the precipitation of cement dust, which is causing serious technical problems to the air insulators of both SSPS and SNPS.

The study of the adverse effects of SIA emissions is in its infancy. Nevertheless, we have enough evidence to state that problems exist and that more statistical correlations (especially for health-related problems) need to be done to fully assess this point.

1.4 Need for This Study

An abundance of studies can be found presenting a somewhat pessimistic analysis of the short-term adverse effects induced by the industrial pollutants in the atmosphere. Reliable studies warn about the possible catastrophic effects of the global increase of carbon dioxide (CO_2) emissions on the energy balance of the earth, whose temperature could rise a few degrees in the next few decades as a consequence of such emissions (Manabe and Wetherald, 1980). Other studies show a clear correlation between atmospheric pollution and adverse effects on human health, based on the evidence of the morbidity/mortality effects of pollutants such as sulfur dioxide (SO_2), carbon monoxide (CO), and suspended particulates (see the interesting review of this problem by Theodore, 1981).

As a consequence of these studies especially, the publicity given them by the media), people's concern has grown. Moreover, important air quality laws and regulations for the protection of the atmospheric environment have been passed by practically all industrialized countries (see, for example, the important historical review by Stern, 1982, of the air pollution legislation in the United States). Substantial funding has been provided by private and public organizations for air pollution research and development in recognition of the important role a clean environment plays in the society of today.

It was imperative for Kuwait to follow this trend and different organizations were (and are) involved in environmental studies and applications. SAA, in particular, early recognized the need for environmental planning of the industrial development and clearly identified air quality as a key problem in the SIA. Furthermore, it was recognized that air pollution modeling techniques are the key numerical tool for any industrial development planning under the constraint of acceptable air quality levels (standards).

1.5 Why Air Quality Modeling?

The entire history of scientific research can be seen as a continuous formulation of new theories and laws expressed by equations of different degrees of complexity. All these formulations, however, are approximations of the complexity of the real world. They provide only a simulation of the reality and are valid only under specific simplifying assumptions. In other words, these formulations can be seen as analytical models, in which a set of equations emulate some properties of nature.

It was only with the development of digital computers in the last twenty years, however, that simulation modeling techniques became extremely successful. In fact, many problems (e.g., in physics) are described by a set of equations (e.g., partial differential equations), whose analytical solution is practically impossible to find. Computer methods, through a proper spatial and temporal discretization, allow the computation of a numerical solution to these problems. This technique has been extremely useful for the simulation of two and three dimensional time-dependent problems in which computer techniques can provide an excellent tool in simulating, under proper conditions, the behavior of the real world. Such techniques have been called numerical models or numerical simulations of reality.

A third category of models should be mentioned just for completeness: These are smaller scale representations of the actual physical process and sometimes have been very successful in simulating the dynamics of complex physical systems. (In air pollution, for example, wind tunnel, water tank and smog chamber studies have been extremely useful in evaluating turbulent diffusion theories or inferring new hypotheses.)

Whatever the model used (analytical, numerical, or physical), the intent is always the same: the simulation of the real world. The importance of this simulation, however, is not only in improving a pure process of knowledge; a successful model also represents the only tool for evaluating the consequences of changes in existing conditions. A well-calibrated model can provide simulations under a variety of scenarios in which the effect of different strategies can be predicted and fully evaluated.

As an example, let us describe some possible applications of a "good" air pollution model, i.e., a model capable of simulating the atmospheric dispersion process, thus relating the ambient pollutant concentrations to:

1) pollutant emission rates (e.g., from industrial sources); and,
2) meteorological parameters (e.g., wind, temperature).

Such a model, after proper calibration and a performance test, can be used, among other things, for

- Evaluating the different relative contribution of each pollution source, thus assessing the major responsibles for existing pollution levels.
- Evaluating the emission reductions required to meet some established air quality standards.
- Assessing the environmental impact of different possible future emission patterns in the area (e.g., installation of new factories, relocation of existing facilities, installation of emission control devices, etc.).
- Providing least-cost emission reduction strategies, in which, if a certain improvement in the air quality is required, the most cost-effective modifications to the existing emissions are evaluated (this, however, requires not only a good diffusion model, but also numerical optimization routines and the evaluation of the cost of each emission reduction).

From these considerations, it can easily be seen that modeling in general, and air quality modeling in particular, represents an indispensable tool for planners and decision makers. Naturally, field measurements (e.g., concentration data from air quality networks) are important for evaluating the present degree of contamination and for assessing priorities of intervention strategies. Only the application of advanced and reliable modeling techniques , however, provides an effective evaluation of what needs to be done or what we can expect from different control policies.

Air pollution modeling techniques are summarized in Fig. 1-3. Air pollution numerical models represent the most important category, because of their extensive application throughout the world. Such numerical models can be:

1. Deterministic, in which a clear relation between a cause (emissions) and an effect (concentrations) is simulated.
2. Statistical, in which either field measurements (e.g., ambient concentrations) are statistically analyzed to infer semi-empirical relationships)e.g., between concentration values and meteorological parameters) or diffusion is simulated by stochastic methodologies.
3. Mixed, in which both deterministic and statistical techniques are used.

Deterministic models have been the most commonly used type, especially in regulatory applications in the United States where such models were proposed and accepted (Clean Air Act Amendments of 1970 and, especially, 1977) as a routine tool in multi-million dollar decisions evaluating emission standard requirements. Therefore, the economic implications of model results are extremely important, especially in the U.S., and a great deal of effort has been spent in evaluating the reliability of such numerical techniques and their limitations. In fact, most scientists agree that air pollution legislation in the U.S. has pushed the application of some modeling techniques (e.g., the Gaussian model) much beyond their limits of applicability. This error should not be repeated by emerging countries, like Kuwait, which can benefit from such previous experiences.

A proper application of a deterministic air pollution model is described in Fig. 1-4, which points out the following important factors:

1. A technical analysis is required to properly select the air pollution model to be used. The air quality problem must be analyzed (e.g., reactive or non-reactive pollutants), the averaging time must be selected (e.g., hourly or yearly concentrations), the computational domain must be considered (e.g., flat or complex terrain), and the characteristics of the model must be assessed (e.g., which diffusion theory).

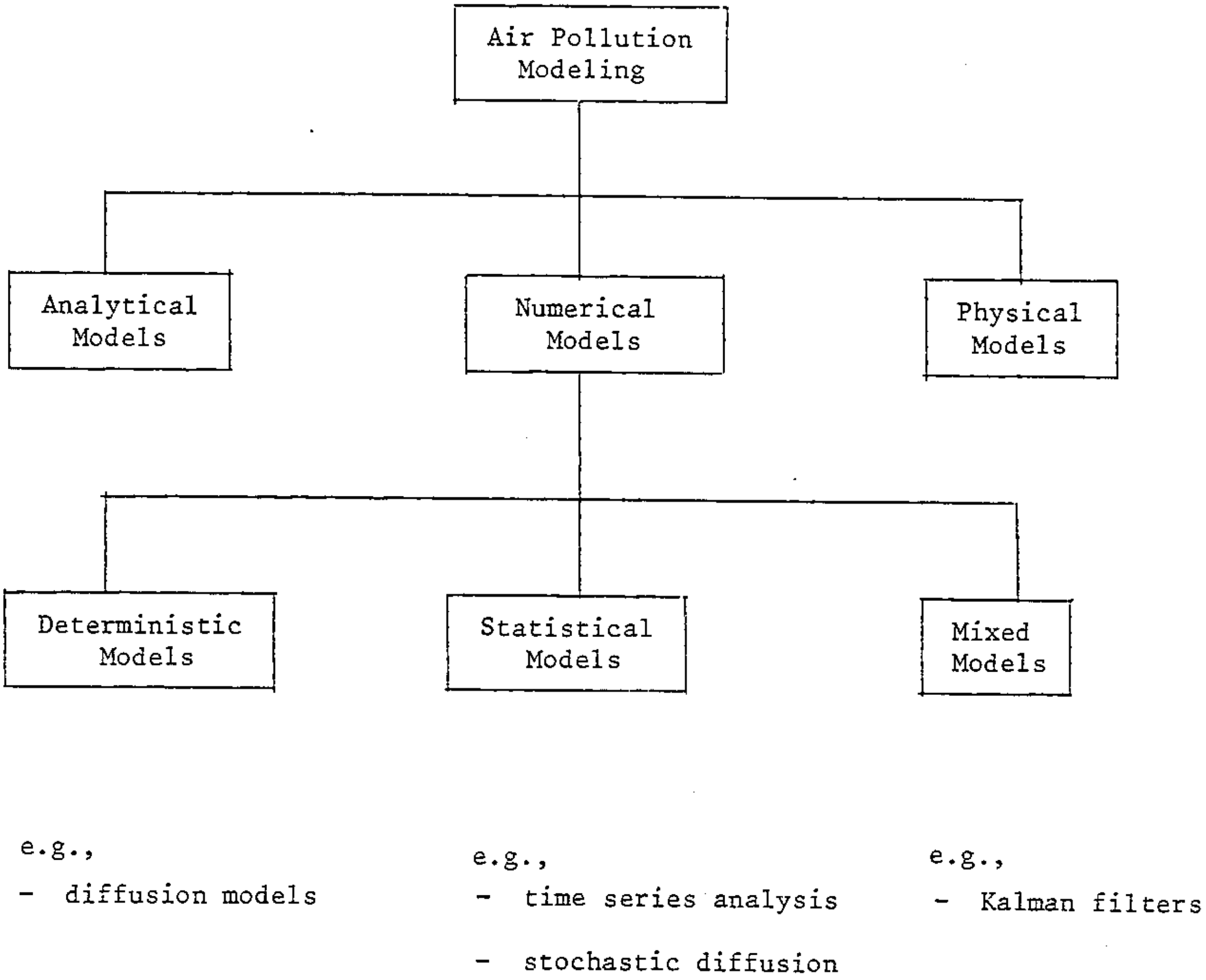


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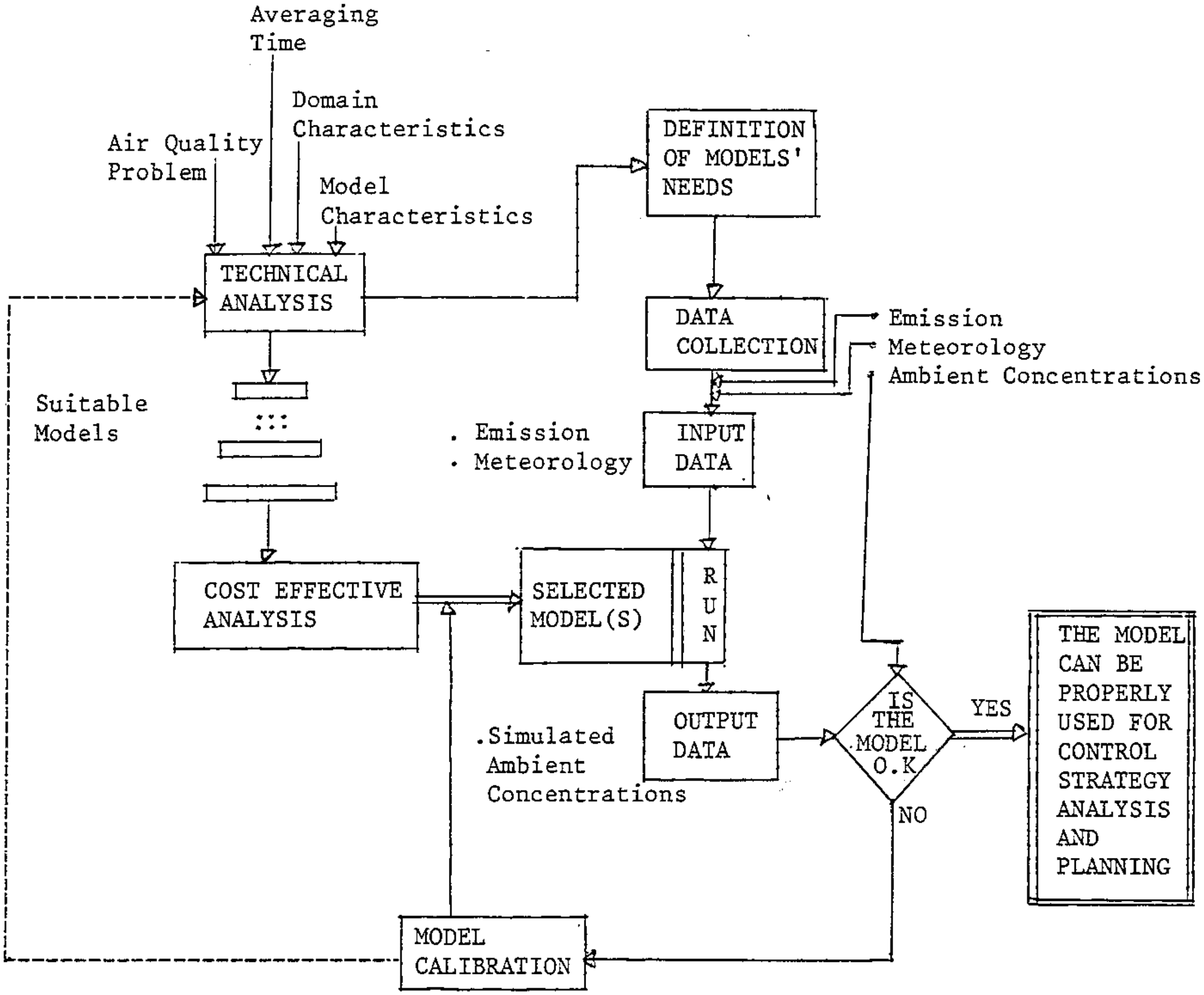
Fig. 1-3. Air pollution modeling techniques.



KISRX 8593

Fig. 1-4. Optimal application of air quality modeling techniques.

2. Appropriate data should be collected to run the models and to evaluate their performances, based on the technical analysis.
3. The model(s) finally selected must be cost-effective.
4. Emission and meteorological parameters are needed to run the model, and ambient concentration measurements are essential for good model calibration and performance evaluation.
5. The model(s) can be used for control strategy analysis and planning only after a successful performance evaluation.

In many cases, these requirements cannot be met. A classical example occurs when models are used to evaluate the air quality impact of a new factory situated in a deserted area, which will start its operations in five years. In such a case in the U.S., models are the major tool for providing the industry with an emission permit; but, since the emission will not occur for another five years, no air quality data can be collected, and the models must be applied without the proper calibration evaluation described in Fig. 1-4. It is not surprising that, often, such multi-million dollar decisions, based only on air pollution modeling results, are strongly challenged by the industrial sector.

In conclusion, the brief analysis in this section shows that, during planning and decision making, there is no substitute for air pollution modeling, which represents, especially for emerging countries, an indispensable tool. Scientists warn, however, about the possible negative economic consequences of some inappropriate applications of such methodologies for regulatory purposes.

1.6 A Guide to This Report

As introduced in Section 1.1, a three-phase Air Pollution Study (APS) has been defined. The first phase of this study (Project EES-45, December 1981-May 1983) has been completed, and a five-volume final report was submitted to SAA, the main sponsor of this study. The present report is Volume II of this five-volume final report, and is the key technical document of the study.

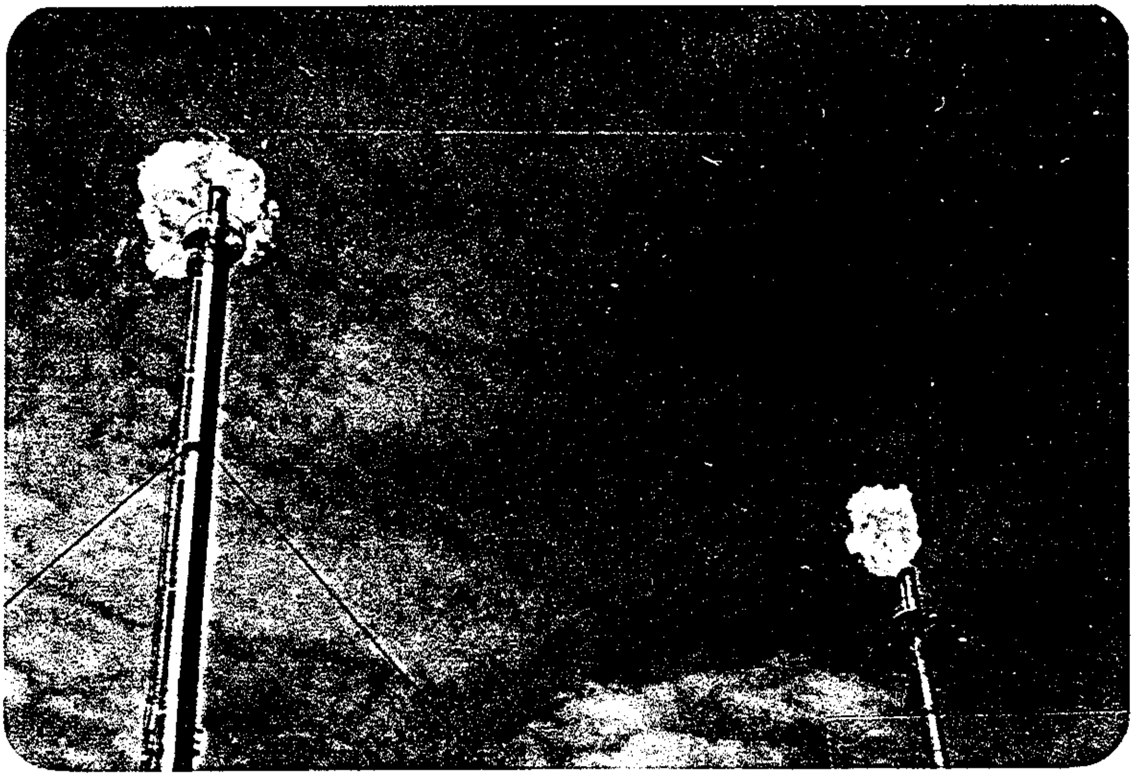
The other volumes contain:

Volume I : Executive Summary Report
Volume III : Special Studies and Appendices
Volume IV : Software User's Manuals
Volume V : Data and Program Listing (a full computer printout of these files is being provided separately to SAA and is also available on computer magnetic tape).

This volume has been organized in the following way: After the introduction (Section 1), the project structure (four tasks) and objectives are described in Section 2, then Sections 3 to 6 describe the activities performed during each of the four tasks, and project results are described in Section 7.

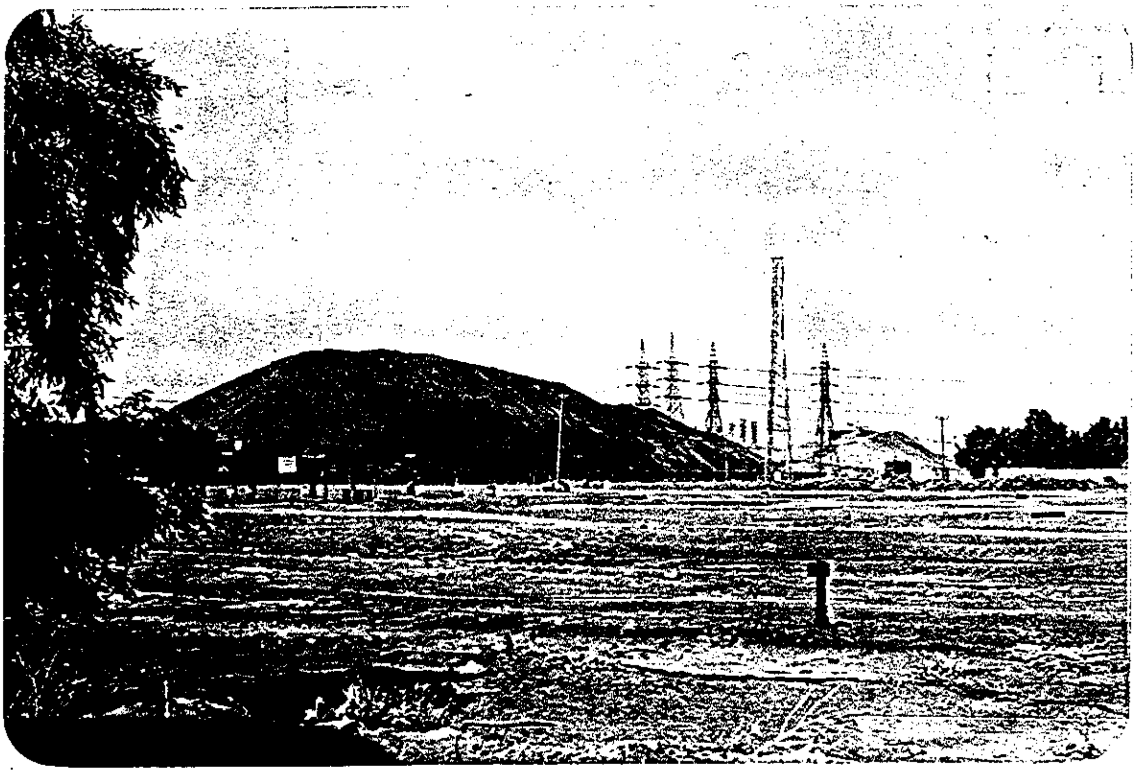
The remainder of the report deals with the future of the APS. Possible uses of project results are discussed in Section 8, and future needs for a successful continuation of this activity are discussed in Section 9. Finally, Section 10 presents a detailed work plan for Phase II of the APS for SAA consideration and evaluation.

To facilitate the reading of this final report, a list of abbreviations has been enclosed at the beginning of Volume II.



KISRX 8594

Flares at KNPC in Shuaiba.

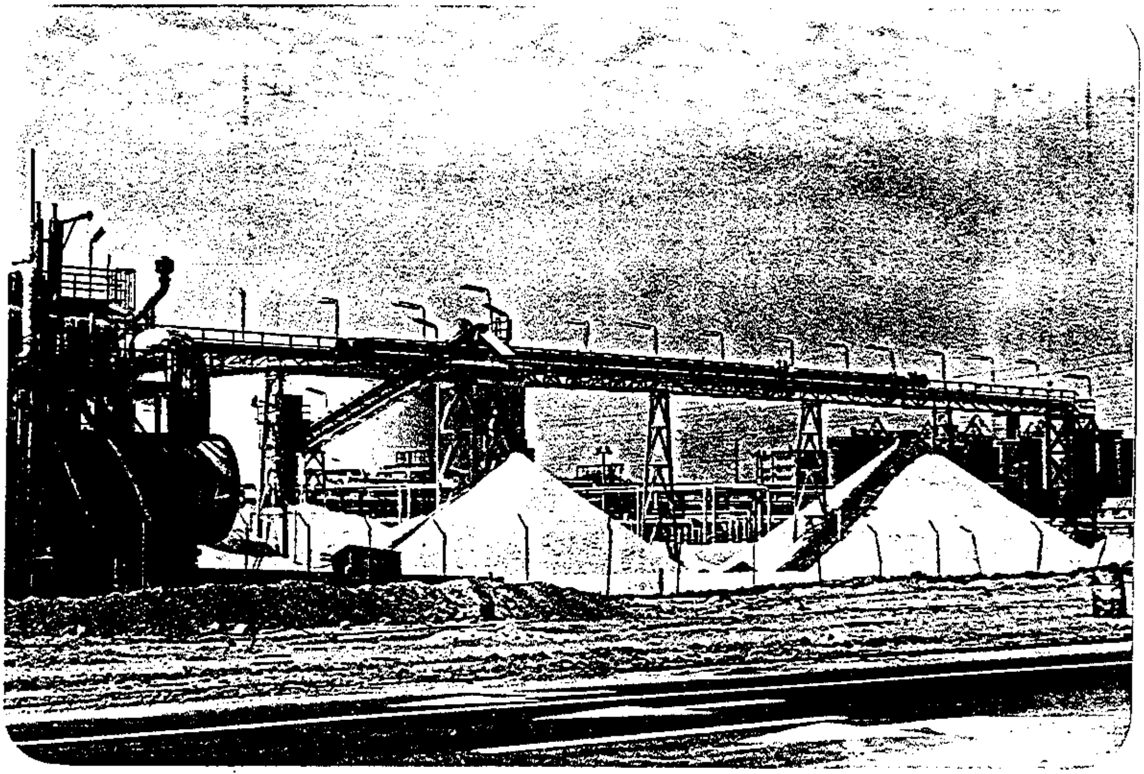


KISRX 8595

Cement piles in Shuaiba.

KISRX 8596

Intermittent plume at the SNPS.



Sulfur piles at KNPC. KISRX 8597

2. Structure and Objectives of the Project

This section describes the structure of the EES-45 project, its organization and its expected objectives. In spite of some modifications performed during the 18-month study, the basic project structure and objectives, as described in the original KISR proposal (Zannetti, 1982b) have remained unchanged. General comments on the activity expected from each task are briefly presented in this section, and a full description of the four tasks' actual performance is presented in Sections 3 through 6.

2.1 Task and Subtask Organization

Section 1 shows, among other things, why air quality modeling is so important in environmental studies. The application of a model, however, is the last step in a long procedure that involves the collection and analysis of a suitable amount of data. As shown in Fig. 1-4, pollutant emission data and meteorological data are indispensable for any model run, and air quality ambient concentration measurements are required for model calibration and evaluation. According to these considerations, the project was originally divided into three tasks, with a fourth task being added during the study. These tasks are:

- Task 1: Collection and Preliminary Analysis of Existing Data
- Task 2: Performance of Additional Measurements
- Task 3: Establishment of Non-reactive Dispersion and Prediction Models
- Task 4: Special Data Analysis and Definition of a Prototype Data Base

As can be seen from this structure, much emphasis was put on data collection and data analysis, especially meteorological analysis. It was recognized that a thorough meteorological understanding is an essential prerequisite for any air pollution study. Moreover, it is clear that the results of air pollution models (as well as the results of all computer codes) depend on the quality and quantity of the input data, and that an insufficient or inaccurate data collection makes modeling applications just a numerical exercise.

The project was divided into the tasks and subtasks (Fig. 2-1) discussed in the rest of this section.

2.2 Task 1 Activity--Collection and Preliminary Analysis of Existing Data

Task 1 activity was intended to cover primarily three types of computerized collection:

1) Meteorological data in Kuwait;
2) Air quality ambient concentrations in the SIA; and,
3) Emission data from the stacks in the SIA.

2.2.1 Meteorological Data

Most applications of air pollution models require hourly averages of major meteorological parameters such as wind speed, wind direction, temperature, etc. Temperature vertical structure is also an extremely important parameter in air pollution studies since temperature profiles strongly affect the dispersion characteristics of a plume (Fig. 2-2), where the behavior of different plumes is related to typical vertical profiles of the temperature in the atmosphere.

2.2.2 Air Quality Data

Ambient pollutant concentrations can be collected for different purposes. For example, odor problems and real time control of accidental releases require instantaneous measurements during such short-term episodes, yet many epidemiological studies require long-term averages and, therefore, a continuous prolonged monitoring activity. Data can be collected on paper or stored in computers for subsequent statistical analysis, computation of trends, etc. In general, much greater monitoring activity is needed when concentration data are collected for validating and calibrating diffusion models.

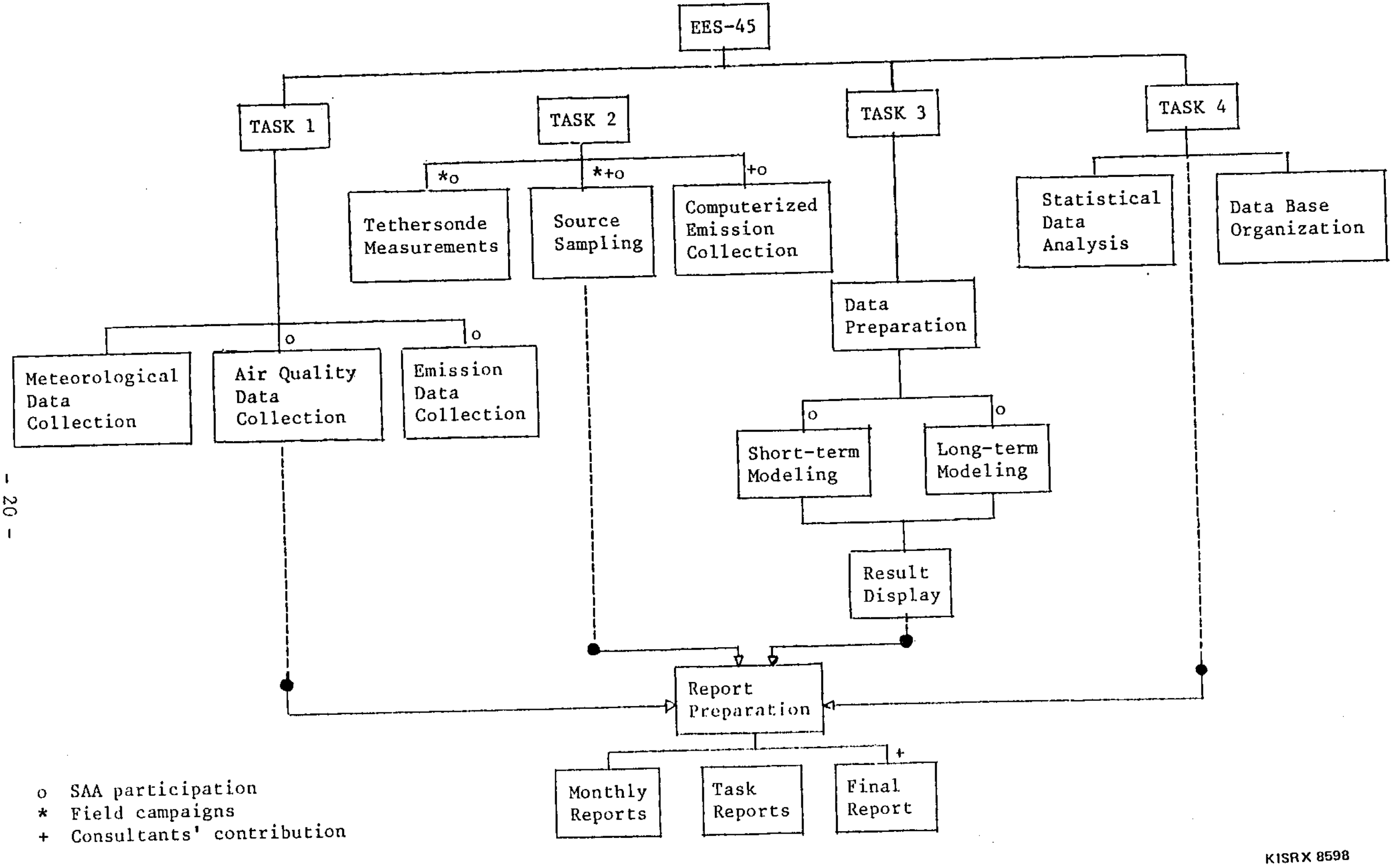


Fig. 2-1. EES-45 project structure.

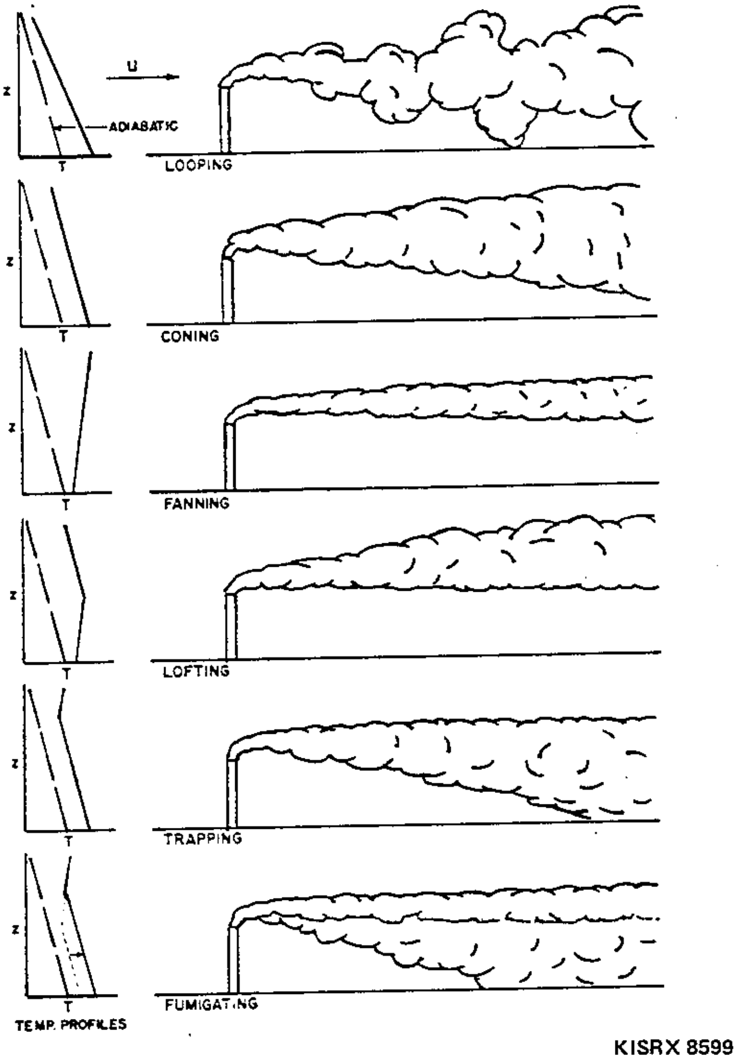


Fig. 2-2. Plume types for various thermal stabilities. The first three plumes occur with uniformly varying temperature with elevation: unstable, adiabatic (neutral), and stable. The last three plumes are caused by discontinuities in stability of atmospheric layers (from Stern, 1976, p. 406).

2.2.3 Emission Data

Whereas ambient concentrations are the effect, emissions are the cause. Therefore, any air pollution study aiming at practical objectives requires valid information about the major pollutant sources and their emission characteristics. In industrial emissions, two types of parameters need to be specified:

1) source parameters (location, stack height, stack exit diameter); and
2) emission parameters (volume flow, composition, temperature).

Source parameters are fixed and easy to collect, but emission parameters are highly variable and represent one of the major reasons for uncertainty in air pollution modeling applications. In most cases, only typical emission parameters are available, representing the most common emission activity conditions (normal industrial production). Peaks in work load, malfunctioning, maintenance operations and other factors, however, are responsible for large variations in these parameters, up to the point that, if a specific short-term period (e.g., a week) needs to be analyzed, a specific emission inventory should be performed for that week (even on an hourly basis) to provide the model with suitable data. If long-term analyses are performed (e.g., for computing yearly averages), typical constant emission values can generally be used.

2.3 Task 2 Activity--Performance of Additional Measurements

Air pollution studies in Kuwait are in their infancy and, therefore, Task 1 could not be expected to provide sufficient information. Task 2 was thus designed to perform additional measurements, store them in the computer, and provide a more suitable input to the air pollution models. Three main activities were deemed appropriate to provide important additional information for this study:

1. Tethersonde measurements, in which the vertical structure of the atmosphere is monitored by instrumentation attached to a balloon.
2. Stack testing, in which direct measurements of stack emission parameters are performed.
3. Computerized emission inventory, in which all emission data are collected, organized and checked.

2.3.1 Tethersonde Measurements

As shown in Fig. 2-2, plume behavior is strongly affected by the vertical atmospheric structure, especially the temperature profile. Although remote sensing instruments (e.g., acoustic sounders) provide useful information on atmospheric turbulent status, only meteorological towers or instrumentation attached to a balloon could provide detailed information on temperature variation with height.

There are two major types of balloon measurements:

1. Radiosonde balloons that cannot be recovered but can reach an altitude of 30 km.
2. Tethersonde balloons, which can fly up to 1 km attached to a tetherline and therefore can be recovered.

For air pollution applications, in which the atmospheric boundary layer (first 500-1000 m) represents the diffusion domain, the tethersonde instrumentation is generally the most appropriate, and, therefore, was selected for this study.

2.3.2 Stack Testing

Experts in industrial processes can easily provide an approximate evaluation of the emission parameters for most industrial activities. Production rates and amount of fuels often allow pretty good estimates, especially for combustion processes, which generally represent the greatest emissions in an industrial area (for SO_2, in particular). Nevertheless, a need exists for direct field measurements of stack emission parameters when:

1. The emission parameters cannot be evaluated because of the complexities of the industrial process.
2. Emission parameters need to be confirmed by some control authority.
3. Emission parameters need to be checked for assuring a proper model input.

All these conditions exist in the SIA so stack testing of industrial emissions was included in the study.

2.3.3 Computerized Emission Collection

Emission data represent very dynamic information, because of the continuous changes that can be expected in a heavily industrial area. Only a properly computerized collection (e.g., Runca et al., 1978) can handle the requirements of this task.

2.4 Task 3 Activity--Establishment of Non-Reactive Dispersion and Prediction Models

Computer modeling is the major activity of this project and a full description of modeling theories and techniques is presented in Section 5. Non-reactive modeling, in which pollutants are assumed to be inert gases, is the logical initial step in air pollution studies. Chemical reactions, however, should be included after transport and diffusion phenomena are fully understood. The possibility of future application of chemically reactive models in the SIA is discussed in Section 10.

As illustrated in Fig. 2-1, after the important data preparation step (in which meteorological and emission data are summarized and arranged in a specified format), two types of computer models can be applied: (1) short-term models, e.g., for the simulation of hourly concentrations; or (2) long-term models, e.g., for the simulation of annual average concentrations.

As previously anticipated, short-term modeling is difficult and, if not properly performed, can provide questionable results. Emission data are rarely accurate enough to represent hour-by-hour cases, and meteorological estimates (especially wind direction) are not accurate enough to evaluate the exact trajectory of the plumes. But when long-term averages are simulated, it often happens that, through a compensation of the different modeling errors, reasonable simulations (sometimes excellent, as, for example, in Runca et al., 1976) of ambient ground level concentrations are obtained.

Still, acceptable short-term simulations are essential for evaluating worst-case scenarios (episodes). The more accurate long-term simulations, however, represent the best tool for industrial planning because of their reliability in evaluating the total (e.g., annual average) impact of possible different emission scenarios.

A proper and effective display of the simulated concentrations represents the common final point of both short-term and long-term air pollution modeling simulation techniques.

2.5 Task 4 Activity--Special Data Analysis and Definition of a Prototype Data Base

The importance of this task (an additional one with respect to the original final proposal by Zannetti, 1982b) was recognized during the course of the study when it became clear that more data analysis was required (especially of the meteorological data). At the same time, the need for defining an organized data base structure was identified, thus requiring a study to define such a prototype for the project data.

2.6 Expected Project Accomplishments

Through the performance of these tasks, the following main objectives were expected to be achieved:

1. The computerized collection and analysis of suitable data for both this study and possible future air pollution investigations.
2. The installation and evaluation of several selected computer diffusion models for possible future utilization by SAA.

Another important activity in the project not explicity mentioned before was the training of SAA staff in air pollution related topics. This aspect of the project and its achievements are fully discussed in Section 7.

3. Task 1--Collection of Available Data

Task 1 activity started with a full investigation of data availability in Kuwait, which was followed by a systematic computerized collection of the available data deemed relevant to the study. The following pages describe the collection of the three types of data needed for this study: meteorological, ambient air quality, and industrial emission.

3.1 Meteorological Data

Many field investigations were performed during the initial phase of the project to evaluate the availability of meteorological data in Kuwait. In this phase, the project team visited and checked meteorological instrumentation at several monitoring sites (SAA, Port, Mena Abdullah, Tower D, etc.). After a careful investigation, it was concluded that only the data collected at the Kuwait International Airport (KWI, see location in Fig. 1-2) showed the continuous reliability required for meaningful climatological analyses and long-term air pollution modeling applications.

KWI instrumentation and data collection practices are fully discussed in a report (KISR 784, Enclosure 1) already provided to SAA as part of this project. (The abstract of this report is in Section 2 of Volume III.) Some concern was initially expressed on the representativeness of KWI data for the Shuaiba region, which is located 25 km southeast of the airport along the coastline. Further analyses, however, showed that most meteorological phenomena present a consistent horizontally homogeneous pattern in the region, and, therefore, KWI data represent Shuaiba meteorology well (see the special study on vertical profile comparison in Section 15 of Volume III of this report). Two types of data were collected at the KWI: hourly measurements of meteorological variables, and daily radiosonde flight information.

3.1.1 Hourly Measurements

The following meteorological observations at KWI were recorded on an hourly basis on the KISR computer:

- total cloudiness
- wind direction
- wind speed
- visibility
- present weather
- past weather
- pressure
- dry bulb temperature
- wet bulb temperature
- vapor pressure
- relative humidity
- amount, form and height of low clouds
- form of medium clouds
- form of high clouds
- dew point

Since air pollution modeling techniques require hourly information on pollutant transport, hourly average wind data were collected instead of simple wind readings at the last ten minutes of each hour. In this way, the collected wind data better represent the effective total transport phenomena in the area.

3.1.2 Radiosonde Measurements

In addition to the hourly measurements, KWI radiosonde measurements provide vertical profiles of pressure, temperature, humidity, and wind direction and speed twice a day at 1100 and 2300 h GMT (Greenwich Meridian Time, i.e., 0200 and 1400 h local time). The analysis of these vertical measurements allowed the daily evaluation of temperature inversion and mixing height parameters, as discussed below.

3.1.3 Temperature Inversions

Generally, temperature decreases with height (temperature lapse rate Λ), where

$$\Lambda = -\frac{\partial T}{\partial z} \tag{3.1}$$

T is the temperature ($^{\circ}C$) of the air and z is the altitude (m). In adiabatic conditions for dry air, it is

$$\Lambda = \Gamma = 9.8 \; 10^{-3} \;\; {}^{\circ}C/m \tag{3.2}$$

where Γ is the dry adiabatic lapse rate, i.e., about one degree of temperature decrease every 100 m.

The different behavior of the plumes in Fig. 2-2 can be explained as a function of the relation between the actual temperature lapse rate Λ (solid line) and Γ (dashed line). Three basic cases are found:

1) $\Lambda > \Gamma$, unstable conditions (looping), typically occurring during daytime with light winds
2) $\Lambda = \Gamma$, neutral conditions (coning), generally the most frequent
3) $\Lambda < \Gamma$, stable conditions (fanning), typically occurring during nighttime with light winds

In this definition, atmospheric stability, neutrality or instability must be seen as a simple categorization of the turbulent status of the atmosphere. In other words, unstable conditions are characterized by a higher intensity of wind fluctuations generating greater turbulent diffusion rates, whereas stable conditions give the opposite effect. It may happen that, at certain elevations, $\Lambda < 0$, a condition in which the temperature is increasing with the altitude. An atmospheric layer in which $\Lambda < 0$ is called an inversion layer and is characterized by very stable conditions.

Two types of inversion layers are found:

1. Ground-based inversions, typically occurring during nighttime with clear sky and low winds, in which the temperature is increasing from the ground level up to, say, 300 m.

2. Elevated inversions, typically occurring during daytime when an atmospheric layer (e.g., from 800 to 900 m of altitude) shows a sharp temperature increase with height.

Multiple inversions can be found, as illustrated in Fig. 3-1, thus creating extremely complex conditions for plume diffusion simulations.

3.1.4 Mixing Heights

The atmospheric mixing height is defined as the height above the ground to which released pollutants are vertically diffused by atmospheric turbulence processes. It represents a key parameter in air pollution modeling computations since, at least for ground-level emissions, a lower mixing height means less vertical diffusion, i.e., less dilution and higher ground level concentrations. Most of the worst situations in the history of air pollution episodes have been characterized by stagnant conditions with low mixing heights.

In some meteorological conditions, the mixing height can be clearly identified, such as in the "trapping" case of Fig. 2-2 in which neutral conditions above the ground are topped by an elevated inversion layer. In this case, a plume emitted below the inversion layer is trapped between the ground and the bottom of the inversion layer, and the mixing height is, evidently, the height of the bottom of the elevated inversion. Other situations, however, are not so clearly definable and approximations need to be made.

Acoustic sounding instruments are the most appropriate equipment available today for a continuous evaluation of the atmospheric mixing height. Unfortunately, such instrumentation is only rarely available in air pollution studies and, consequently, techniques were developed, especially in the U.S., to evaluate mixing heights from standard airport data (U.S. National Weather Service data). The method developed by Holzworth (1972) was particularly successful and has been adopted for this study. This technique allows the daily evaluation of the urban morning (minimum) mixing height and the afternoon (maximum) mixing height, using the radiosonde temperature profile collected in the early morning, and the maximum surface temperature in the afternoon.

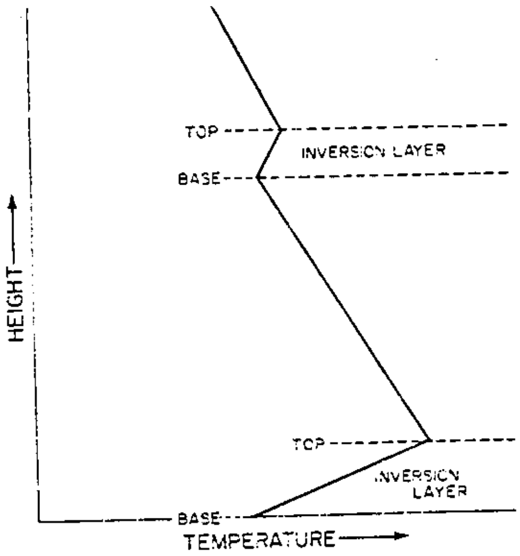


Fig. 3-1. Surface inversion and inversion aloft (from Stern, 1976, p. 340)

This technique has been officially accepted by the U.S. Environmental Protection Agency (EPA) for regulatory air pollution applications. From minimum and maximum mixing height values, the hourly variation of such important parameters can be inferred using interpolation techniques (see Section 4.1.1).

3.1.5 Daily Information Collected from Radiosonde Sounding

For each KWI radiosonde sounding (0200 and 1400 h local time) the following information was collected in KISR's computer:

- surface inversion (if present):
  - temperature
  - wind direction
  - wind speed

    at the surface

  - height
  - temperature
  - wind direction
  - wind speed

    at the top of the surface inversion

- elevated inversion (if present):
  - height
  - temperature
  - wind direction
  - wind speed

    at the bottom of the elevated inversion

  - height
  - temperature
  - wind direction
  - wind speed

    at the top of the elevated inversion

- mixing height (by the Holzworth method)
- meteorology at 300 m:
  - wind direction
  - wind speed
  - temperature

- meteorology at 600 m:
  - wind direction
  - wind speed
  - temperature

All the hourly and daily data were collected for a six-year period (1977-1982), input into the KISR computer, checked and validated. Specific detailed information on the collected meteorological data files can be found in a report already submitted to SAA as part of this project (KISR 866, Appendix E, the abstract of which is in Section 6 of Volume III of this final report). Moreover, Volume V of this final report lists all the data files collected in the project.

3.2 Ambient Air Quality Data

After a careful analysis, it was found that available air quality measurements in Shuaiba did not provide sufficient and complete information for air quality modeling applications. Therefore, a plan was made for collecting more air quality data in Task 2 (see Section 4.2).

3.3 Industrial Emission Data

Available information on industrial processes and emission rates was found in the report prepared by Cremer and Warner (1975). Analyzing this report with SIA representatives, however, showed that considerable changes had been made in the SIA and that emission parameters needed to be re-evaluated for this project. Therefore, contacts were made with representatives of all SIA industrial groups to collect a preliminary detailed inventory of each stack's parameters and emission values.

A preliminary unpublished report on this topic was prepared as a Task 1 activity, describing all the collected emission information. This report was subsequently reviewed and expanded to incorporate some new information collected in Task 2 (see Section 4.3).

3.4 Conclusion

Task 1 activity was completed in September 1982. Its major accomplishments were:

- The important and impressive set of meteorological data collected at the KWI.
- The preliminary investigation for a more updated evaluation of industrial emissions.

Many future studies in air pollution and other disciplines will strongly benefit from the availability of the extensive synoptic Kuwait meteorological information collected in computerized form.

4. Task 2--The Collection of New Data

As expected, Task 1 pointed out that more and better data should be collected, so special data collection activities were planned and executed for meteorological data, ambient air quality concentrations, and emission data.

4.1 Meteorology

Two meteorological activities were performed:

1. The computation of hourly atmospheric stability and mixing height.
2. The collection of tethersonde data.

4.1.1 Hourly Stability and Mixing Height

Atmospheric stability is a key meteorological parameter in air pollution applications since it strongly affects plume shape and behavior. The simplest and most frequently used way to represent atmospheric stability is the Pasquill method (Slade, 1968; Turner, 1970), officially recommended by the U.S. EPA in regulatory modeling applications in the United States. According to this method, atmospheric stability is divided into the following Pasquill stability classes:

- A, extremely unstable
- B, moderately unstable
- C, slightly unstable
- D, neutral
- E, slightly stable
- F, moderately stable

The additional class

- G, very stable

is sometimes added to this scheme.

Semi-empirical methodologies have been defined for evaluating the hourly stability class from standard meteorological measurements. Many different meteorological measurements can be used to estimate stability (e.g., the temperature vertical gradient $\Delta T/\Delta z$ or the standard deviation of the horizontal wind direction σ_θ). The most common method, however, is the Pasquill-Gifford (PG) method (Slade, 1968; Turner, 1970), in which wind speed, solar radiation and cloudiness provide a tabular evaluation of the atmospheric stability (as in Table 4-1). Using such a scheme, the atmospheric stability class (which is not directly measured by specific instrumentation) can be evaluated on an hourly basis.

Similarly, the mixing height should be evaluated at each hour for diffusion modeling applications. This evaluation can be done by interpolation techniques, using minimum and maximum recorded mixing height values (see Section 3.1.4).

A computer program (the CRSTER pre-processor) was developed in the United States for performing, among other things, the computation of hourly mixing height and stability from standard U.S. NWS (National Weather Service) meteorological measurements. The CRSTER pre-processor stability computation is similar to the simple scheme of Table 4-1; the mixing height interpolation is made using current, previous and following day values, and two different techniques are used for urban and rural computations (see the scheme illustrated in Fig. 4-1). This computer program was analyzed and modified to accept KWI data as an input, thus providing appropriate results for Kuwait.

The stability values obtained by the CRSTER pre-processor were further analyzed to fully evaluate the important relationship between atmospheric stability and wind direction (stability roses). The results of this analysis are briefly discussed in Section 7.1 and fully presented in a technical report already provided to SAA as part of this project (KISR 844, Appendix B, abstract enclosed in Section 4 of Volume III of this final report).

4.1.2 Tethersonde Measurements

Surface meteorological data are always insufficient to represent the complex diffusion features of elevated industrial plumes. After a preliminary analysis, it was concluded that more meteorological elevated measurements (vertical profiles) were essential to this study, and that the tethersonde balloon instrumentation was the most reliable piece of hardware for project needs.

Table 4-1. The basic Pasquill-Gifford algorithm for the evaluation of atmospheric stability.

Wind Velocity (ms^{-1})	Day (incoming solar radiation)			Night (cloudiness)	
	Strong	Moderate	Slight	Thin overcast or $\geq 4/8$ Cloudiness	$\leq 3/8$ Cloudiness
<2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	D
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

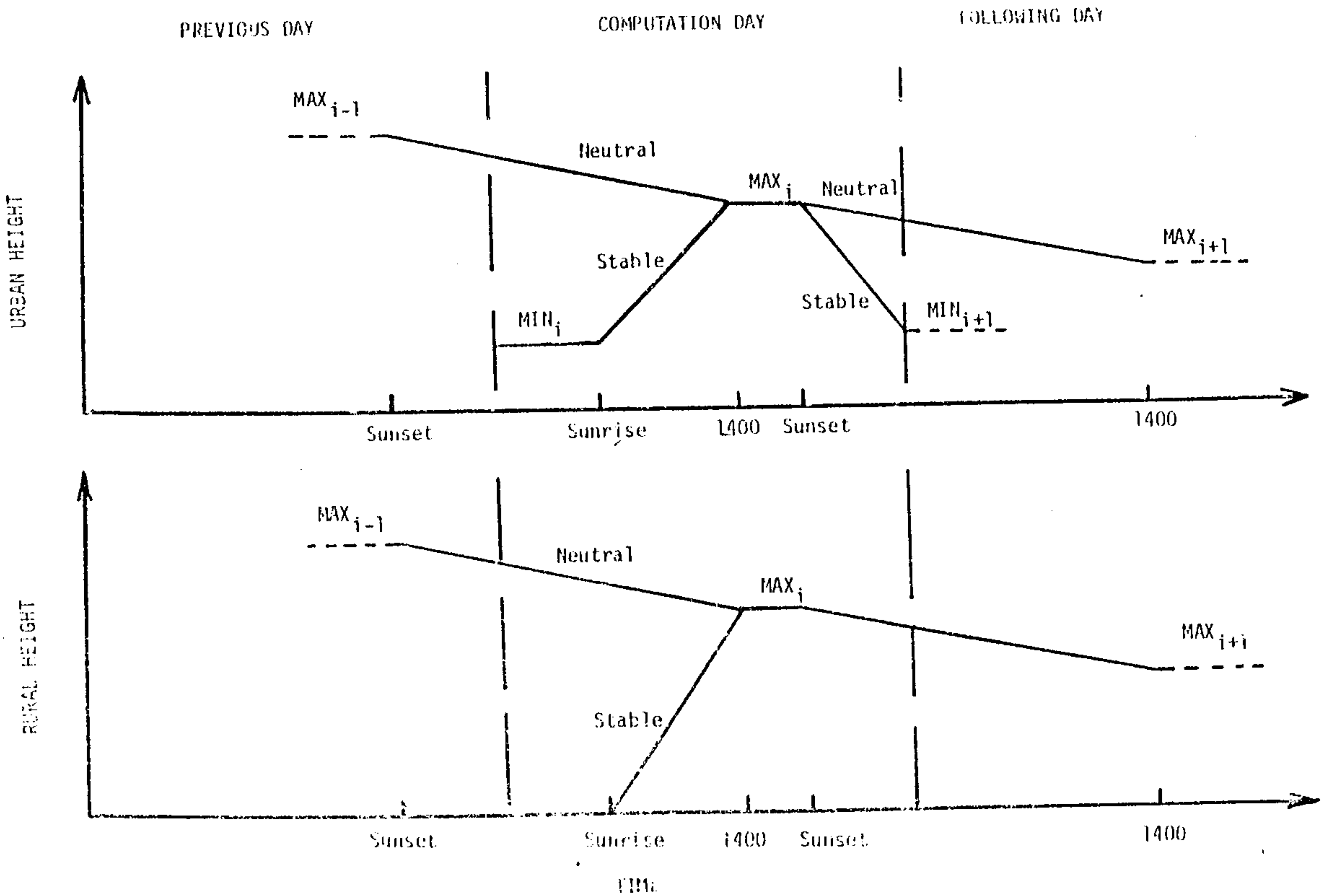


Fig. 4-1. Determination of hourly mixing heights by the CRSTER pre-processor (from U.S. EPA, 1977, pp. 2-15).

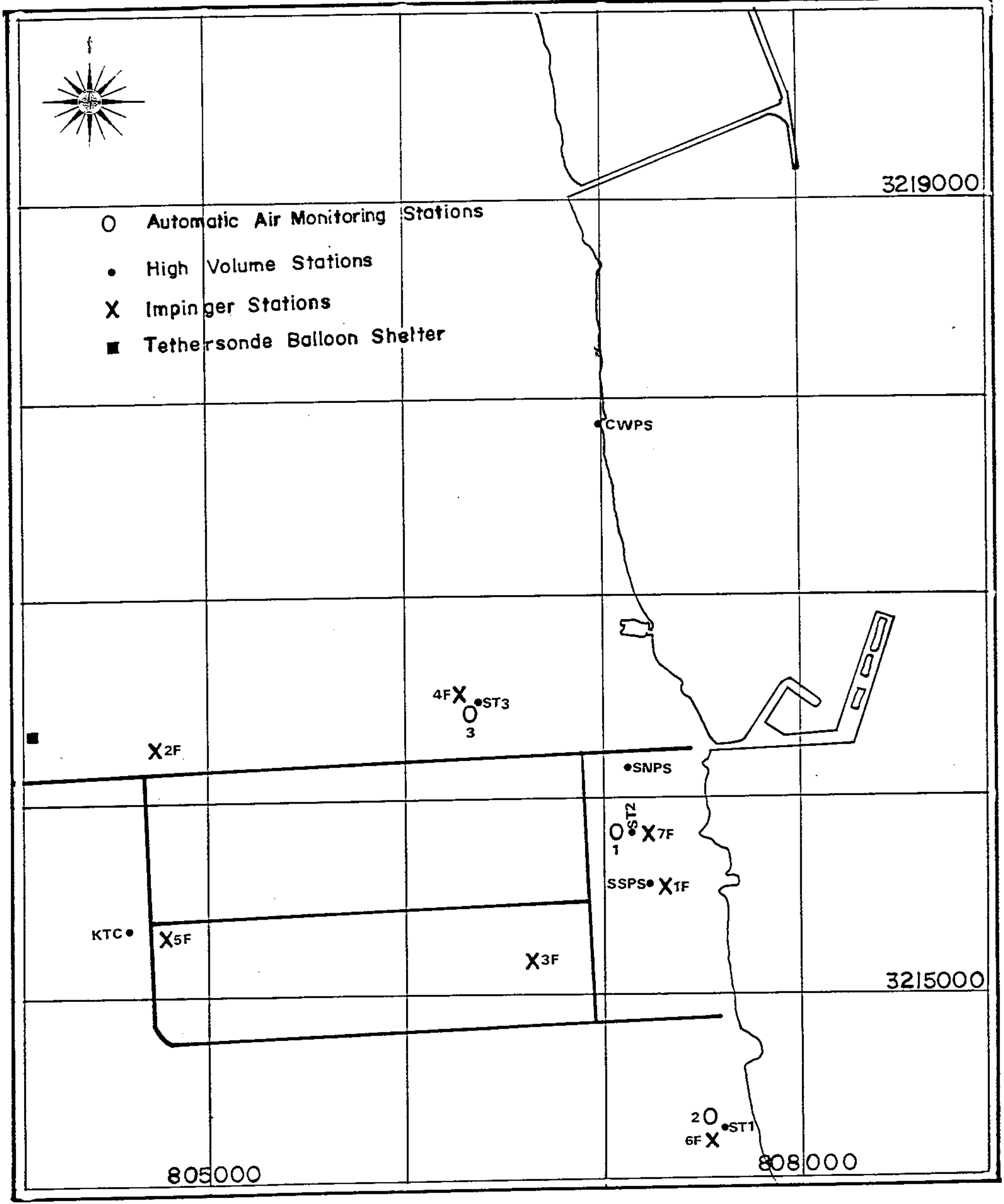
A member of the project team was sent to the U.S. to visit the tethersonde manufacturer (Atmospheric Instrumentation Research, Inc.) to examine the instruments and to receive proper training in using the equipment. The instrumentation was purchased, tested and installed in a special shelter in the SIA (see location in Fig. 4-2).

The tethersonde balloon instrument (see Fig. 4-3) consists of four major parts:

1. The plastic balloon, which, after being filled with 2.4 m^3 of helium, can carry the meteorological instrumentation (airborne package) aloft. Due to its aerodynamic shape, the balloon stabilizes in line with the wind, thus allowing a magnetic sensor to measure wind direction.
2. The airborne package, which is carried aloft by the balloon. It measures:
    - pressure
    - temperature
    - wet-bulb temperature
    - wind speed
    - wind direction
3. The electrical winch, to launch and pull back the balloon.
4. The ground station, which receives the telemetry signal from the sensor package aloft, processes the signal, and yields both analog and digital outputs, which are recorded, printed and displayed. Up to 42 variables may be processed by the ground station.

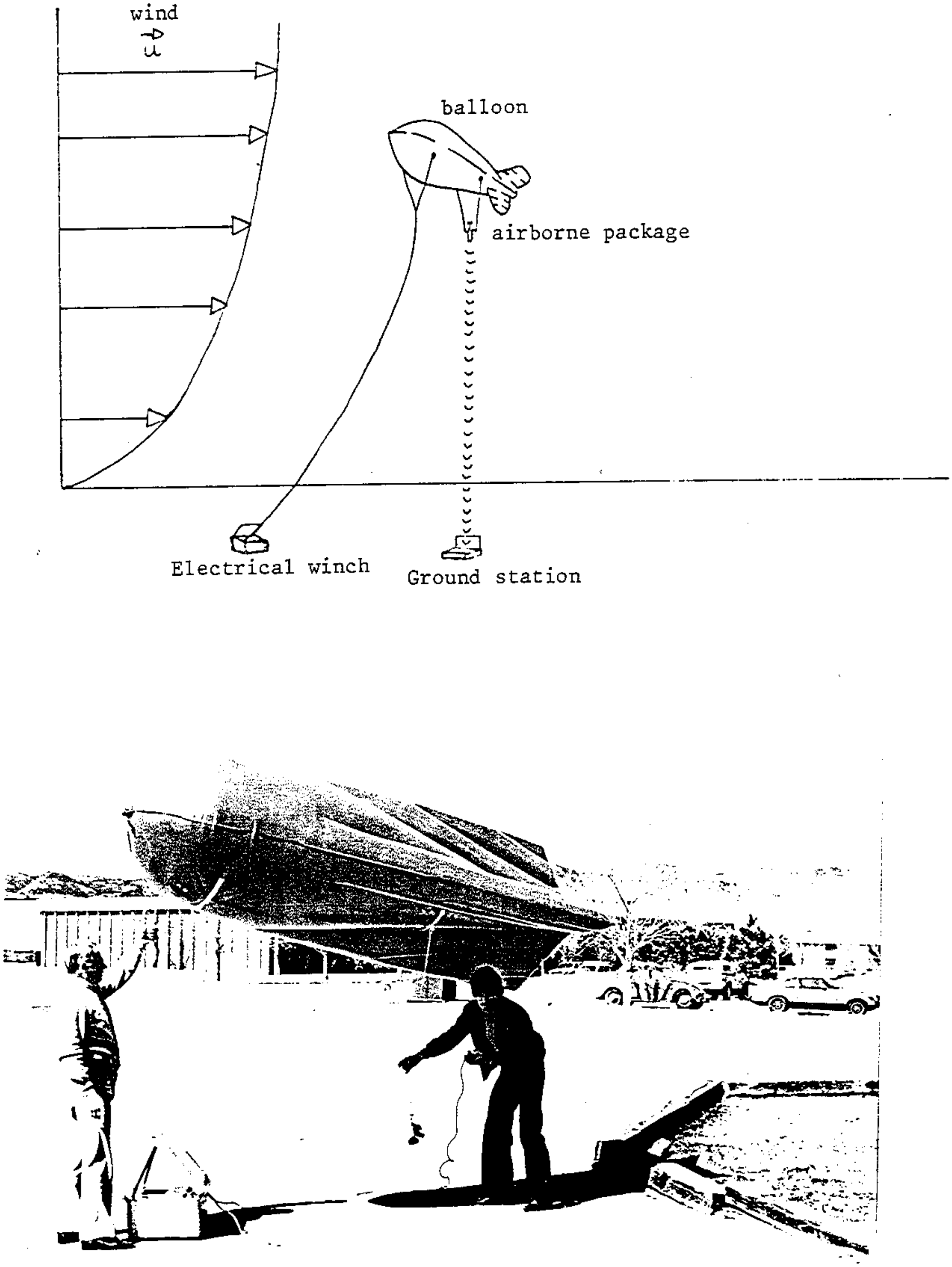
The tethersonde system was intensively used in Shuaiba in the three-month period December 1982 through February 1983, when an average of three experiments per week at different times of the day were performed by SAA and KISR staff. A full report on this special study can be found in Section 14 of Volume III of this final report.

The major result of this intense tethersonde field activity (see also Section 7.1) has been the discovery of good agreement between the tethersonde data in the SIA and the radiosonde measurements at the KWI. This agreement allows the use of KWI data for air pollution modeling simulations in the SIA. Another important result was the expansion of



KISRX 8600

Fig. 4-2. Location of the tethersonde shelter and the air quality monitoring points in the Shuaiba Industrial Area (standard SAA/EPC abbreviations have been used to label the monitoring points, e.g., CWPS, 4F, ST3, etc.).



KISRX 8601

Fig. 4-3. Tethersonde balloon instrumentation (a) and tethersonde balloon (b).

the SAA personnel capabilities in using such advanced equipment and interpreting its measurement data.

4.2 Ambient Air Quality

At the beginning of the project, it was thought that new automatic SAA air quality stations would be installed in the SIA during the early part of the project. These stations would have provided the required information for calibrating and evaluating project modeling techniques. Unfortunately, the installation was delayed, so its utilization for modeling purposes should therefore be made in the next phase (1983-85) of this SAA-KISR air pollution study.

To compensate for this lack of data, the Environmental Protection Center (EPC) of the SAA decided to increase the number of fixed monitoring stations providing daily averages of sulfur dioxide (SO_2), ammonia (NH_3) and total suspended particulate (TSP). During September-December 1982, seven high-volume samplers (for daily monitoring of TSP) and seven impingers (for daily monitoring of SO_2 and NH_3) were operated by the EPC in the SIA (see locations in Fig. 4-2). These data were collected and entered into the KISR computer for further analysis.

We do not believe that the air quality data collected in Tasks 1 and 2 are sufficient for a full modeling calibration/evaluation. Therefore, this important activity has been proposed as part of the continuation of this study (see Sections 9 and 10).

4.3 Industrial Emissions

The review activity in Task 1 confirmed the paucity of information on emission parameters in the SIA. Emission parameter evaluation is a delicate and important step, requiring experience and specific competence. Therefore, it was deemed important to ensure, through the help of an external consultant, a good emission inventory of the SIA stacks. After a careful review of possible candidates, Dr. Richard Boubel, an internationally-known expert on air pollution, was selected for this study.

Dr. Boubel, Consulting Environmental Engineer, assisted by Mr. Eugene Wellman, President of BWR Associates, Environmental Consultants, Inc., came to Kuwait and performed the following major tasks:

1) reviewed the KISR-SAA emission inventory;
2) planned source sampling experiments in the SIA;.
3) trained local SAA personnel in source sampling;
4) performed actual source sampling in the SIA with trained source testers;
5) made preliminary evaluation of fugitive emission factors;
6) made preliminary suggestion of cost-effective future emission control.

A full description of Dr. Boubel's activity and accomplishments has been previously submitted to SAA as part of this project (KISR 1017A, Appendix A; abstract enclosed in Section 8 of volume III of this final report). This report also contains two important proposals for suitable source sampling activity in the SIA. For complete information on this subject, a description of source sampling methods and techniques has also been submitted to SAA as part of this project (KISR 866, Appendix B, abstract enclosed in Section 5 of Volume III of this final report).

The major results of Dr. Boubel's consultancy work were:

1. SAA-KISR personnel trained in source sampling of industrial stacks, the best technique to evaluate, through direct in-stack sampling, the emission parameters of a certain source (see in Fig. 4-4, a schematic description of the particulate sampling instrumentation used in this project). Unfortunately, most stacks in the SIA are not presently equipped for such activity and only a few stacks were actually sampled.
2. A detailed evaluation of emission parameters in the SIA through the analysis of industrial processes, type and amount of fuels, production rates, etc. New values were obtained that properly update previous evaluation studies (Cremer and Warner, 1975).

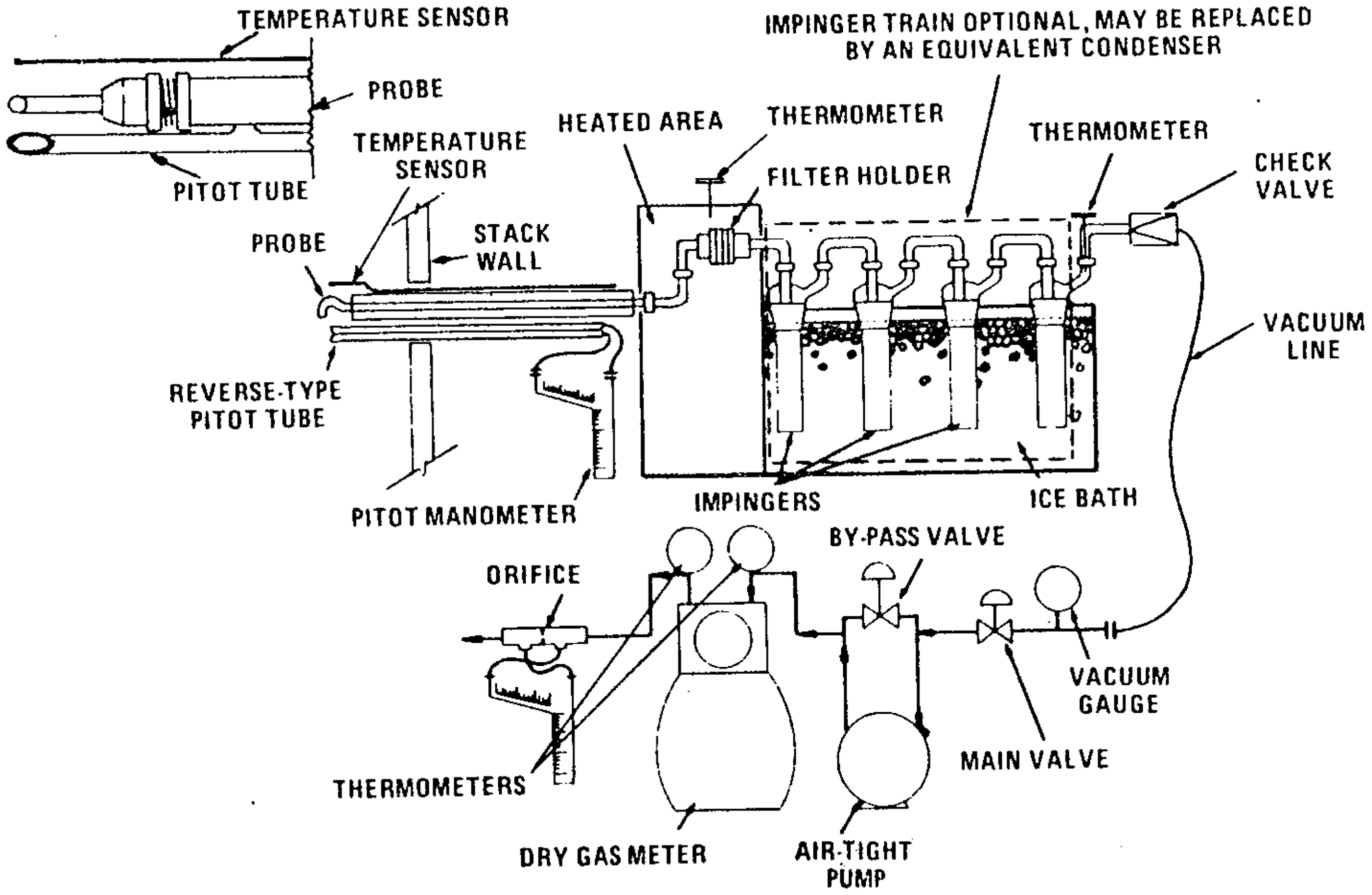


Fig. 4-4. Particulate sampling instrumentation
(from U.S. Government, 1981, p. 340).

At the same time as Dr. Boubel's review and evaluation activity, a KISR-SAA group performed a detailed stack-by-stack analysis for computerized collection of source and emission parameters. This activity consisted mainly of organizing the data provided by the industries without attempting a critical review (or modification) of the received information. A report describing this computerized data collection was provided to SAA as part of this project (KISR 977A, Appendix A, abstract enclosed in Section 7 of Volume III of this final report).

The last step of this procedure was the comparison of these two sets of information (Dr. Boubel's data and industry's data) and their synthesis to prepare the proper emission input for the model runs (see Section 5.4). We do not believe that such final emission parameters evaluated for diffusion model simulations are absolutely correct; as Dr. Boubel pointed out in his report, much more source sampling activity is still required in the SIA. Nevertheless, our computerized emission collection is a major step forward and provides a very reasonable and updated evaluation of most industrial emissions in the SIA. We believe that, with a limited review effort and some source sampling activity, the SIA industries will be able to obtain an excellent evaluation of their emission data in the near future.

4.4 Conclusion

Task 2 was completed in February 1983. Its major accomplishments were:

1. The collection of new important information (tethersonde data and emission data).
2. The intensive training of SAA personnel on tethersonde measurement and source sampling techniques.
3. The checking and revision, where necessary, of previously-gathered source and emission parameters.

At the end of this task, all the data required as a suitable input (emission, meteorology) to air pollution dispersion models were satisfactorily obtained in a fully computerized form.

5. Task 3--Modeling Simulations

This activity represents the core of this study, since a reliable computer simulation of diffusion processes in the SIA is its ultimate goal of the three-phase APS project.

This section, after an introductory description of modeling theories, techniques and selected approaches presents the simulation results obtained in the SIA, using the data collected in the previous tasks.

5.1 Theories Behind Atmospheric Diffusion Processes

The molecular diffusivity of the air is extremely low and plays almost no role in actual atmospheric diffusion. Turbulent processes are the major factor in pollutant dispersion, especially vertical dispersion. Unfortunately, turbulent diffusion phenomena are characterized by semi-random fluctuations and a full, acceptable mathematical theory for their representation has not yet been found. Approximate theories and numerical representations, however, are available and these often allow more than acceptable simulations of the real world.

In air pollution applications such theories are mainly:

1) Gaussian Assumptions
   - steady-state
   - dynamic
2) Grid Models
   - Eulerian
     - first-order closure
     - higher-order closure
   - Lagrangian
3) Statistical Models
4) Similarity Theories

The Gaussian assumption is the most common application in air pollution modeling in the U.S., and has been accepted by the U.S. EPA as an official regulatory tool. This technique has been chosen as the most appropriate one for our study and is fully discussed in Section 5.1.1.

Grid models are more complex and can handle, at least in theory, complicated non-stationary non-homogeneous meteorological conditions. Especially when chemical reactions are involved, they represent a very important tool, and their utilization will probably be necessary in future modeling studies in the SIA (see Section 9.4).

Statistical models are extremely relevant in air pollution studies, since they seem to be the only technique able to provide a reasonable representation of the stochastic (semi-random) effects of atmospheric turbulent diffusion. Lagrangian modeling techniques, in particular, are probably today the most important numerical representation of non-reactive diffusion processes (see Section 5.1.2).

Similarity theories allow the simulation of atmospheric diffusion solely from principles of similarity theory and dimensional analysis. They will not be further discussed in this report.

5.1.1 Gaussian Models

The basic Gaussian assumption is shown in Fig. 5-1, in which both vertical and horizontal cross sections of the plume have a Gaussian concentration distribution. In mathematical notation (Zannetti, 1981a),

$$\chi = \frac{Q}{2\Pi\sigma_y\sigma_z\left|\underset{\sim}{u}\right|} \exp\left[-\tfrac{1}{2}\left(\frac{c}{\sigma_y}\right)^2\right] \exp\left[-\tfrac{1}{2}\left(\frac{h_s + \Delta h - z_r}{\sigma_z}\right)^2\right] \qquad (5.1)$$

where $\chi = \chi\,(\underset{\sim}{s},\underset{\sim}{r})$ is the concentration in $\underset{\sim}{r} = (x_r, y_r, z_r)$ due to the emission in $\underset{\sim}{s} = (x_s, y_s, h_s)$; Q is the emission rate; $\sigma_y = \sigma_y(j_h, d)$ and $\sigma_z = \sigma_z(j_z, d)$ are the plume standard deviations (horizontal and vertical) expressed as a function of horizontal and vertical turbulence states, j_h and j_z, and downwind distance $d = \left|(\underset{\sim}{r} - \underset{\sim}{s})\cdot\underset{\sim}{u}\right| / \left|\underset{\sim}{u}\right|$; (u_x, u_y, u_z) is the wind velocity vector; c is the crosswind distance $c = (\left|\underset{\sim}{r} - \underset{\sim}{s}\right|^2 - d^2)^{\frac{1}{2}}$; and $h_e = h_s + \Delta h$ is the effective emission height due to the release height h_s and the plume rise Δh. Eq. (5.1) is applied for $d \geq 0$; if $d < 0$, then the concentration χ is zero.

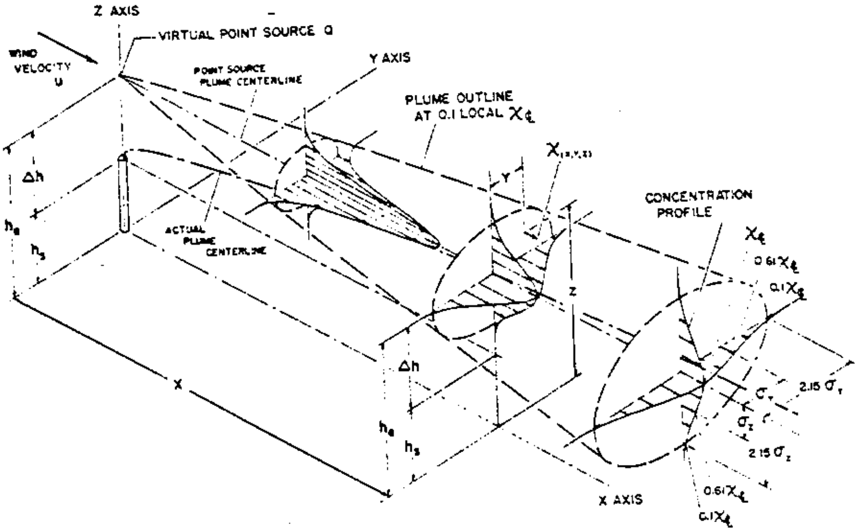


Fig. 5-1 - Three-dimensional representation of a Gaussian plume (from Stern, 1976, p. 441).

As can easily be seen, Eq. (5.1) refers to a stationary state (χ does not depend on time), uses meteorological conditions (wind and turbulence states) that must be considered homogeneous and stationary in the modeled area, and cannot work in calm conditions where $|\underset{\sim}{u}| = 0$. The simplicity of the Gaussian approach, however, its relatively easy use with clearly measurable meteorological parameters and, especially, the elevation of this methodology to the quantitative decision-controlling level (U.S. EPA, 1978) have simulated research aimed at removing the limitations of the Gaussian theory to treat the complex situations of the real world.

To overcome these limitations, some modelers have recently attempted to extend the applicability of Eq. (5.1). In particular, the segmented plume approach (Chan and Tombach, 1978; Chan, 1979) and the puff approach (Lamb, 1969; Roberts et al., 1970) have been successfully applied to pseudo-steady-state conditions. Both these methods break up the plume into a series of independent elements (segments or puffs) that evolve in time as a function of temporally and spatially varying meteorological conditions. Plume segments are still described by Eq. (5.1), and the contribution of one puff at $\underset{\sim}{p}(t)$ to a receptor at r during the interval $|t-\Delta t(t)/2, \Delta t + \Delta t(t)/2|$, for the general case of Δt time dependent, will be

$$\chi = \frac{Q(t_0)\ \Delta t(t_0)}{(2\Pi)^{3/2}\ \sigma_x(t)\sigma_y(t)\sigma_z(t)} \quad \exp\left[-\tfrac{1}{2} \left| \left[\underset{\sim}{p}(t) - \underset{\sim}{r}\right] \div \underset{\sim}{\sigma}(t) \right|^2 \right] \qquad (5.2)$$

where $\underset{\sim}{\sigma}(t) = \left[\sigma_x(t),\ \sigma_y(t),\ \sigma_z(t)\right]$ and the vector notation $\underset{\sim}{\gamma} = \underset{\sim}{\alpha} \div \underset{\sim}{\beta}$ means that its components are $(\gamma)_i = (\underset{\sim}{\alpha})_i/(\underset{\sim}{\beta})_i$, for i = x, y and z.

In Eq. (5.2) note that Q and the sigmas are puff- and time-dependent, and no reflection or decay term has been considered. The concentration at r during the interval $\left[t - \Delta t/2,\ t + \Delta t/2\right]$ will be calculated by the summing of contributions $\chi = \chi\left[\underset{\sim}{p}(t),\ \underset{\sim}{r}\right]$ of Eq. (5.2) from all existing puffs.

Substantial improvements in the Gaussian puff modeling theory have recently been obtained by Ludwig et al. (1977), Sheih (1978) and Zannetti (1981a).

In spite of these extensions of the Gaussian assumption, the more simple Gaussian steady-state formula, Eq. (5.1), remains the key technique for most regulatory air pollution models. When used in its climatological version (Runca et al., 1976) for computing seasonal and annual averages, Eq. (5.1) often provides very good simulation results, especially considering the uncertainties of the input values and the extreme numerical simplification of the complex physical phenomenon being modeled.

Such success can be statistically explained as follows: model formulation and parameterization (e.g., stability classification, sigma functions, plume rise, etc.) produce values with large error bounds but little bias. Therefore, although computations at specific single hours may give poor results, a long-term averaging process leads to a definite error compensation, giving acceptable climatological simulations.

Another explanation derives from the fact that Gaussian models give non-zero concentration results only at those receptors downwind of the emitting source, whereas actual measurements are affected by background values and situations such as a meandering plume. The result is that the model always underpredicts in those hours when the wind is not blowing directly from the source to the receptor. Such underprediction can be compensated for by an overprediction when the wind is blowing in the particular sector of interest. This was exactly the case found by Zannetti (1977) in this analysis of the successful climatological results of Runca et al. (1976); that is, success was due to this overestimation-underestimation effect. In particular, the concentration overestimation of the "successful" Gaussian model during selected conditions of stationary wind blowing from the source to the receptor was of a factor of 2 to 5.

5.1.2 Lagrangian Particle Modeling

Simulation modeling is a problem of numerical discretization of a physical system. Such discretization, performed through computer experiments, is particularly important in those cases in which physical theories need to be investigated or verified but laboratory experiments are unable to reproduce the complexities of the real world (e.g., stellar evolution).

During the last few decades, under the influence of huge developments in computer computational capabilities, discretization methods have become a major subject of investigation and development. Four major computational techniques have been developed and applied:

- finite difference methods;
- finite element methods;
- boundary element methods;
- particle methods.

The last technique (Hockney and Eastwood, 1981) is probably the most advanced numerical algorithm available and, more importantly, the most promising tool for numerical simulations with future generations of computer systems.

Using particle models, the temporal evolution of a physical system is described by the dynamics of a finite number of interacting particles. Therefore, such models are typically Lagrangian ones, whereas, for example, finite difference methods are purely Eulerian representations of physical systems.

Three main types of particle models can be defined:

- Particle-particle (PP) models, where all interaction forces between particles are computed at each time step.
- Particle-mesh (PM) models, where forces are computed using a field equation (on a grid) for the potential field.
- PP-PM (or P^3M) models, a hybrid approach where interparticle forces are split into a short-range component (computed using the PP method) and a slowly varying one (represented in the mesh system by the PM method).

Particle models can be purely deterministic or (partially) based on statistical methods. In the first case, the simulation of particle time evolution is unique. In the second case, Monte-Carlo techniques are used to produce semi-random "perturbations" and, therefore, model output represents just one realization in an infinite set of possible solutions.

Length and time scales (as in all discretization systems) play an important role in particle models. In particular, the relation between the actual physical particles (or elements) and the computer model simulation particles is an important factor for the interpretation of the simulation results. In general, three possible cases can be found:

- A one-to-one correspondence between actual and simulated particles, as, for example, in molecular dynamics simulation.
- A description of fluid elements (position, vorticity) as particles, such as in vortex fluid simulations, where the correspondence to physical particles (molecules) is totally lost.
- The use of "superparticles", i.e., simulation particles representing a cloud of physical particles having similar characteristics.

Particle models have been mostly used for simulating (and understanding) the spiral structure of the galaxies, for plasma dynamics simulation and for obtaining realistic representations of turbulence in fluids. Air Pollution dispersion by particle methods is still in its infancy, even though interesting studies have been published in the last few years (Watson and Barr, 1976; Hanna, 1979; Lamb et al., 1979a and 1979b; Lange, 1978; Patterson et al., 1981).

Even though a fully satisfactory theoretical treatment of turbulent diffusion has not yet been achieved, Lagrangian particle numerical methods seem particularly suitable to simulate the diffusion of a substance released into a turbulent flow. In the atmospheric boundary layer, for example, emitted gaseous material can be described by a suitable number of particles moving, at each time step, according to pseudo-velocities. These pseudo-velocities simulate the effects of the three basic dispersion components:

(1) the transport caused by the mean fluid velocity (average wind),

(2) the (seemingly) random turbulent fluctuations of wind components

(both horizontal and vertical), and (3) the molecular diffusion (if not negligible). Only several thousands particles can be handled by present computers. Therefore, the pseudo-velocities cannot simulate a single molecule's motion, they just define an algorithm for the computation of the particle density distribution on a particle ensemble basis.

Pseudo-velocity computation is the most important (and difficult) task in particle modeling. Because of their Lagrangian nature, particle displacements should be computed using suitable Lagrangian measurements of the flow. Unfortunately, Lagrangian properties are difficult to measure and must be inferred from Eulerian measurements. Different methods have been proposed for relating Eulerian and Lagrangian statistics, but none has been found totally satisfactory. Among many studies in this field, an acceptable statistical estimator, at least for ocean currents, has been presented by Davis (1982), and Hanna (1981a) has evaluated and tested semi-empirical relations for the atmospheric boundary layer.

Pseudo-velocity vectors $\underset{\sim}{u}_e$ for each particle have been frequently approximated by

$$\underset{\sim}{u}_e = \bar{\underset{\sim}{u}}_e + \underset{\sim}{u}'_e \qquad (5.3)$$

where $\bar{\underset{\sim}{u}}_e$ is the best estimate of the average (Eulerian wind field at the particle location) and $\underset{\sim}{u}'_e$ is a "diffusivity" velocity. Since, in Eq. (5.3), $\bar{\underset{\sim}{u}}_e$ is supposed to be known, computing $\underset{\sim}{u}'_e$ is the key problem of Lagrangian particle modeling. Two fundamental approaches can be followed: deterministic and statistical.

5.1.2.1 The Deterministic Computation of $\underset{\sim}{u}'_e$.

A typical example of the deterministic approach is given by the particle-in-cell method of Lange (1978), where, after some manipulation of the K-theory diffusion equation, we obtain a space-dependent

$$\underset{\sim}{u}'_e = \left(-\frac{K}{C}\right) \nabla C \qquad (5.4)$$

where K is the usual eddy diffusion coefficient and C the concentration, computed as the number of particles in the each cell. This method requires partitioning the computational domain into cells and is able to duplicate K-theory dispersion with the important feature of removing the numerical advection errors associated with finite-difference solutions.

Using this method, the motion of a single particle will be affected by the time-varying concentration field, i.e., by the positions of the other particles (PM model).

5.1.2.2 *The Statistical Computation of $\mathbf{u}'_e$.* The statistical approach (Monte Carlo-type models) certainly seems to be more flexible and appealing. According to the statistical approach, $\mathbf{u}'_e$ is a semi-random component computed by manipulating computer-generated random numbers. To perform this computation, it has been generally assumed that Eulerian measurements of the wind vector can provide statistical information on $\mathbf{u}'_e$. These two parameters are not the same, however, and further investigation is required to fully assess this point.

As a first approximation, we can accept this assumption and use, for the diffusivity velocity $\mathbf{u}'_e$, a statistical generation scheme based on our understanding (and Eulerian measurements) of the wind vector. In particular, Hanna (1979a) has shown that it is a plausible assumption to describe both Eulerian and Lagrangian wind vector fluctuations by a simple Markov process (autocorrelation process of the first order).

If we extend this assumption to $\mathbf{u}'_e$, we have (scalar computation)

$$\mathbf{u}'_e(t_2) = \mathbf{R}_e(t_2-t_1)\ \mathbf{u}'_e(t_1) + \mathbf{u}''_e(t_2) \tag{5.5}$$

where $\mathbf{R}_e(t_2-t_1)$ contains the autocorrelation with lag $\Delta t = t_2 - t_1$ of the $\mathbf{u}'_e$ components, and $\mathbf{u}''_e$ is a purely random (Gaussian white noise) component.

Equation (5.5) is the key formula for statistically computing $\mathbf{u}'_e$, which will simply be a recursive sum of two terms--the first function of the "previous" $\mathbf{u}'_e$ of the same particle, and the second purely randomly generated. Since Eq. (5.5) will be computed independently for each particle, two eventually coincident particles at t_1 will have, in general, different displacements, even if their past history is the same. Using this approach, the motion of a particle is not affected by the position of the other particles and, therefore, this numerical algorithm is extremely fast since no particle interacting forces need to be computed.

To apply Eq. (5.5), we need the initial $\underset{\sim}{u}'_e(t_0)$ for each particle at its generation time t_0 (often assumed to be a zero vector) and the computation of $\underset{\sim}{R}_e$ and $\underset{\sim}{u}''_e$, which can be approximately made using Eulerian measurements and semi-empirical assumptions (Zannetti, 1982a).

In addition to the general reservation about the extension of Eulerian statistics to Lagrangian parameters, major problems have been found regarding:

1. The treatment of the negative cross-correlation between along wind and vertical wind fluctuations.
2. The conditions for zero correlation between the two horizontal components of wind fluctuations.
3. The skewed distribution of the vertical wind fluctuation.
4. The treatment of vertical variation of turbulent fluctuation intensities, i.e., $\sigma = \sigma(z)$.

Solutions to these problems have been proposed however, especially by Zannetti (1981b; 1982a), Hanna (1981b, and 1981c), and Diehl et al. (1982).

5.2 Available Computer Codes for Air Pollution Modeling

Although the development of *ad hoc* diffusion models for the SIA is the ultimate future goal of our SAA-KISR research activity, in this first phase of the project we focussed our attention on the application of available, reliable and tested computer codes.

Many air pollution diffusion packages have been developed, especially in the United States, where computer diffusion codes are used as an official regulatory tool for emission permit authorization.

In 1973 (Benarie, 1980), the EPA instituted the User's Network for Applied Models of Air Pollution (UNAMAP), which consists of a library of computer programs stored at EPA's Computer Center at Research Triangle Park, North Carolina. This programs are available to EPA regional offices via a teleprocessing network and are extended to non-EPA users via the

INFONET network of Computer Sciences Corporation, under contract by the General Services Administration.

UNAMAP is also available by placing an order with the National Technical Information Service (NTIS) for a magnetic tape containing the programs and the text input; for reference, the accession number PB-240-273/LL should be used.

In addition to the UNAMAP programs (mainly Gaussian packages), that are in the public domain, special diffusion programs were developed by private companies. Among them are:

MESOPUFF,	a Gaussian puff model developed by Environmental Research and Technology, Inc.
MATHEW/ADPIC,	a particle model developed by the Lawrence Livermore Laboratory.
BPM,	a trajectory puff plume model developed by Systems Applications, Inc.
IMPACT,	a K-theory grid model developed by Systems Applications, Inc.
MESOGRID,	a K-theory grid model developed by Environmental Research and Technology, Inc.
PDM,	a plume/puff dispersion model developed by Systems Applications, Inc.
AVACTA II,	a segmented plume model developed by AeroVironment, Inc. (available to KISR).
ARAP,	a second order closure model developed by Aeronautical Research Associates of Princeton, Inc.

Many other packages dealing with air pollution chemistry and photochemistry are available that need not be mentioned here, since the objective of this initial study is the simulation of non-reactive pollutants in the SIA.

5.3 Selected Approaches

The following models were selected for this study:

1) ISCST
2) ISCLT
3) PTMAX
4) PTMTP
5) CDM
6) MC-LAGPAR

They are briefly described below. User's instructions on the practical utilization of these selected programs have been enclosed in Volume IV of this final report.

5.3.1 ISCST

This UNAMAP model (Industrial Source Complex--Short Term, ISCST) is a steady-state Gaussian plume model that can be used to assess pollutant concentrations from sources associated with an industrial source complex. This model can account for settling and dry deposition of particulates; downwash; area, line and volume sources; plume rise as a function of downwind distance; separation of point sources, and limited terrain adjustment. Average concentration or total deposition may be calculated in 1-, 2-, 3-, 4-, 6-, 8-, 12- and 24-hour time periods. An 'N'-day average concentration (or total deposition) or an average concentration (or total deposition) over the total number of hours may also be computed.

This package (Bowers et al., 1979) is probably the best and most complete EPA-approved Gaussian model for short-term simulations. A full technical description of this model has been enclosed in Section 10 of Volume III of this final report.

5.3.2 ISCLT

This UNAMAP model (Industrial Source Complex--Long Term, ISCLT) is a steady-state Gaussian plume model that can be used to assess pollutant concentrations from sources associated with an industrial source complex. This model can account for settling and dry deposition of particulates; downwash; area, line and volume sources; plume rise as a function of downwind distance; separation of point sources; and limited terrain adjustment.

ISCLT is designed to calculate the average (climatological) seasonal and annual ground level concentration or total deposition from multiple continuous point, volume and area sources. Provision is made for special discrete X, Y receptor points that may correspond to sampler sites, points of maxima or special points of interest. Sources can be positioned anywhere relative to the grid system.

This package (Bowers et al., 1979) is probably the best and most complete EPA-approved Gaussian model for long-term simulations. A full description of this model has been enclosed in Section 10 of Volume III of this final report.

5.3.3 PTMAX

This UNAMAP package (Turner and Busse, 1973) performs an analysis of the maximum short-term concentrations from a single point source as a function of stability and wind speed. The final plume height is used for each computation. PTMAX uses Briggs plume rise methods and Pasquill-Gifford (PG) dispersion methods to estimate hourly concentrations for stable pollutants.

This simple code can run in small computers and has therefore been selected for computations in the SAA-EPC computer facilities.

5.3.4 PTMTP

This UNAMAP package (Turner and Busse, 1973) estimates the concentration in a number of arbitrarily located receptor points at or above ground level. Plume rise is determined for each source. Downwind and crosswind distances are determined for each source-receptor pair. Concentrations at a receptor from various sources are assumed additive. Hourly meteorological data are used: both hourly concentrations and averages over any averaging time from one to 24 hours can be obtained. PTMTP uses Briggs plume rise methods and Pasquill-Gifford dispersion methods to estimate hourly concentrations for stable pollutants.

This code (Turner and Busse, 1973), is similar but much more simple than ISCST and therefore selected for running in the EPA-EPC small computer.

5.3.5 CDM

This UNAMAP package (Climatological Dispersion Model, CDM) determines long-term climatological (seasonal or annual) quasi-stable pollutant concentrations at any ground level receptor using average emission rates from point and area sources and a joint frequency distribution of wind direction, wind speed, and stability for the same period.

This code (Busse and Zimmerman, 1973) is similar but much more simple than ISCLT and was therefore selected for running in the SAA-EPC small computer.

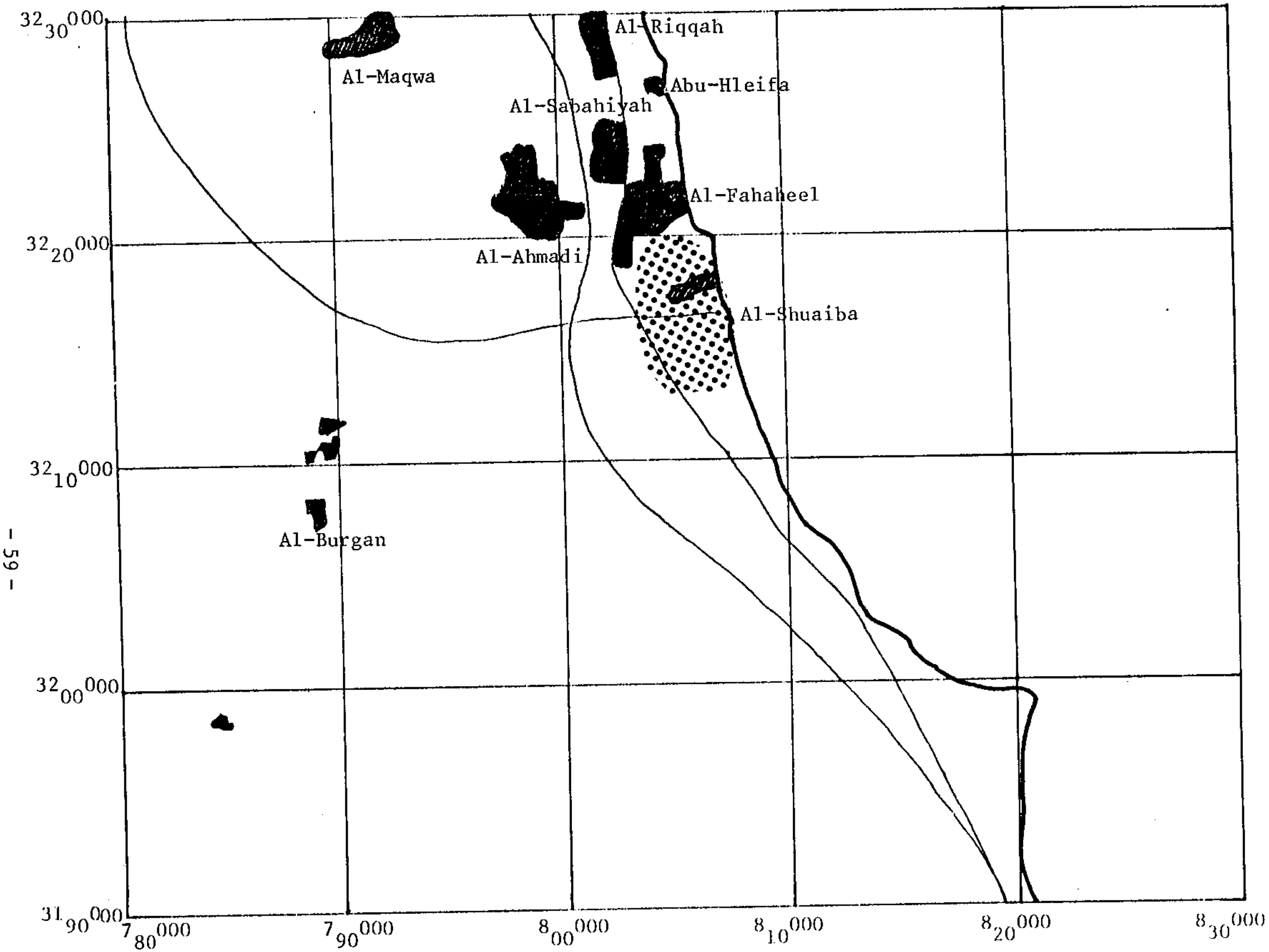
5.3.6 MC-LAGPAR

As discussed in Section 5.1.2, Lagrangian particle modeling techniques are the most advanced numerical tool for non-reactive air pollution dispersion modeling. Since a prototype computer code (written in APL) had been developed by Zannetti and Al-Madani (1983), it was decided to elaborate this prototype into a full APL computer code for future simulations of special complex diffusion cases in the SIA. The structure of this Monte-Carlo Lagrangian particle (MC-LAGPAR) code is described in Section 11 of Volume III of this final report.

5.4 Actual Long-term Simulations by ISCLT

Section 4.3 presented all the efforts made to collect a proper computerized emission inventory of SIA stacks. A final analysis of this emission information allowed a summarization of stack and emission parameters for modeling purposes. In this final phase, industrial stacks characterized by small emission rates were dropped and some contradictions in previously collected data were eliminated. At the end of this procedure, the data were properly prepared for modeling input and, in this format, have been enclosed in Section 7 of Volume III of this final report. These data represent our best present knowledge of SIA pollutant emissions of SO_2 (78 sources), NO_x (76 sources), NH_3 (5 sources), cement dust (18 sources), and urea dust (8 sources).

The ISCLT model was used to simulate the multi-source climatological long-term ground-level impact of these above five pollutants in 30 x 30 km area surrounding the SIA. Concentrations were calculated on 3721 (61 x 61) ground-level receptors, with a resolution of 500 m. KWI meteorological data, properly elaborated by our modified version of the CRSTER pre-processor (see Section 4.1.1) were used to provide the required meteorological frequency tables for the ISCLT runs. Fig. 5-2 shows the outline of the area around the SIA in which diffusion computations have been made.



KISRX 8602

Fig. 5-2. Area surrounding the SIA. Dark regions represent populated areas, and the dotted region covers the SIA. UTM coordinates are also displayed.

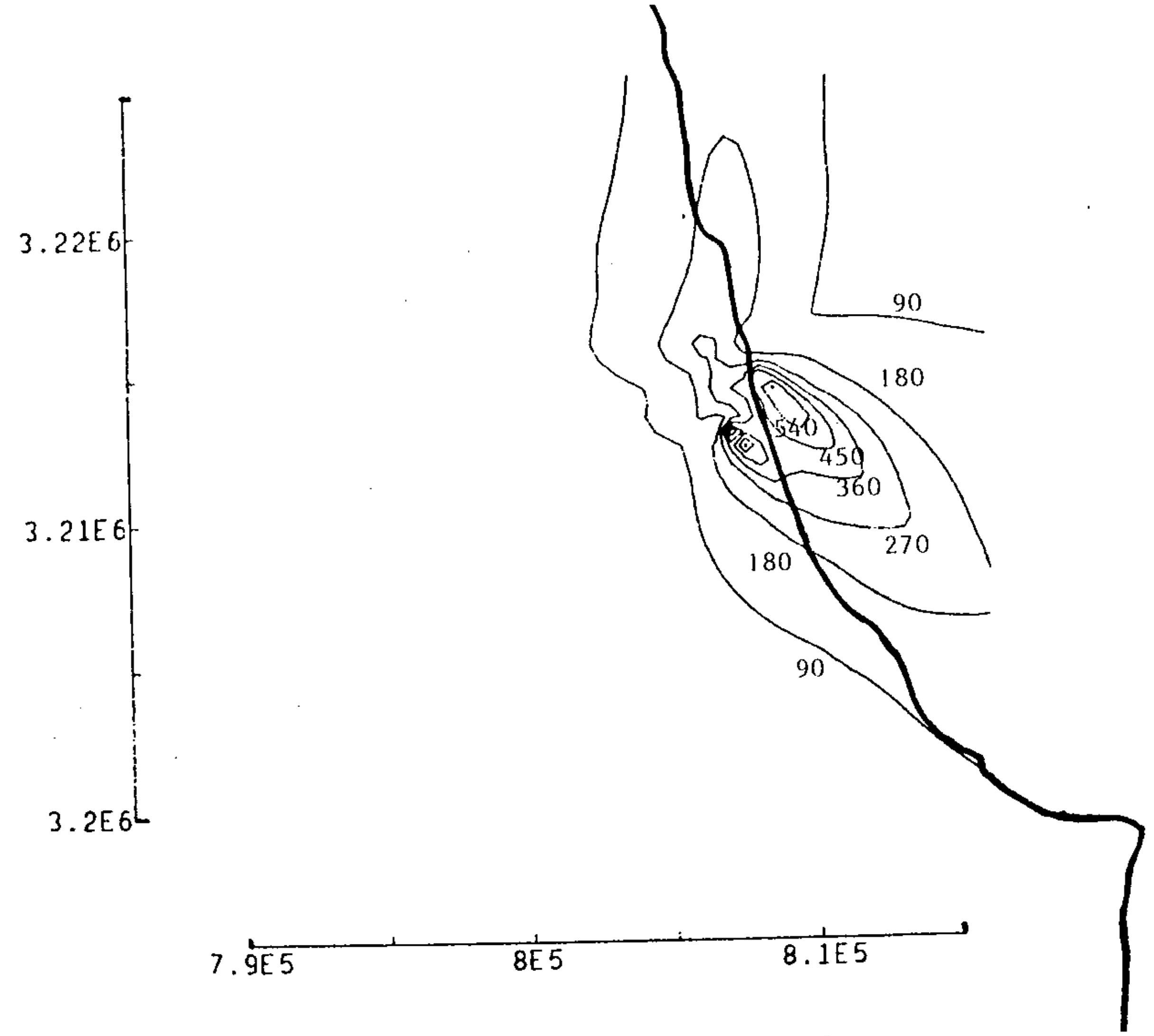


Fig. 5-3. Summer isopleths of SO_2 ($\mu g/m^3$).

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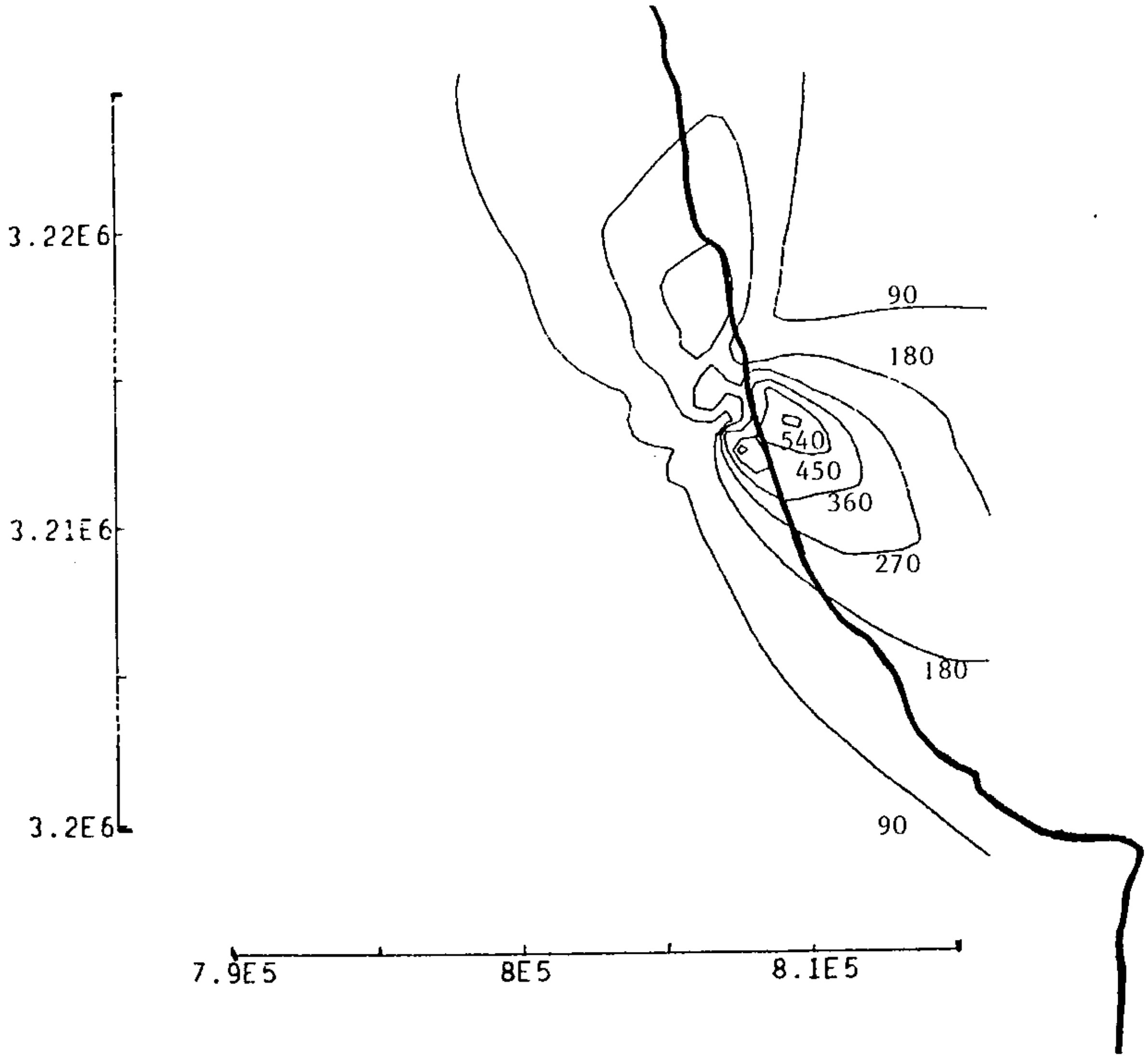

Fig. 5-4. Winter isopleths of SO_2 ($\mu g/m^3$).

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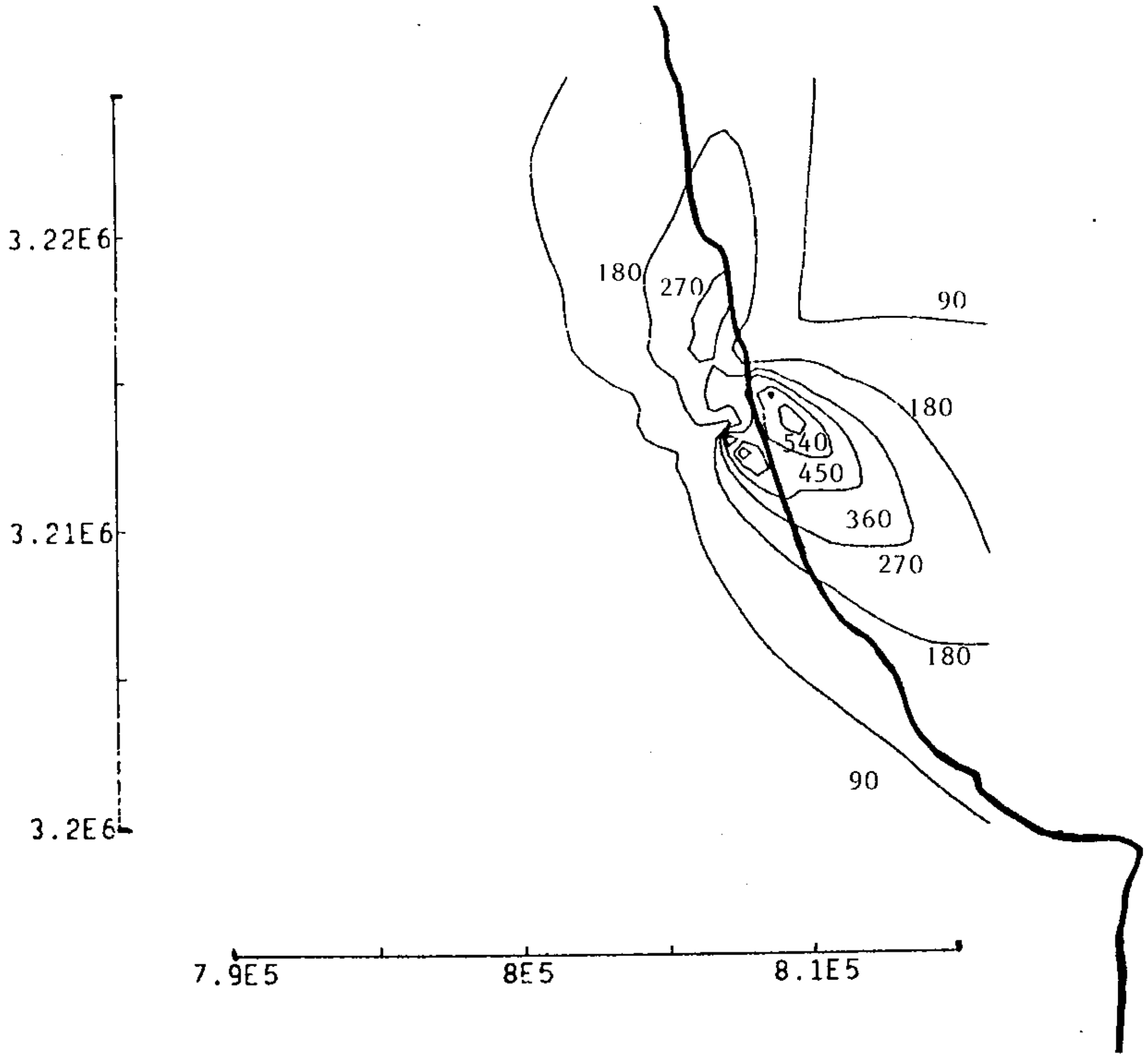

Fig. 5-5. Annual isopleths of SO$_2$ ($\mu g/m^3$).

KISRX 8605

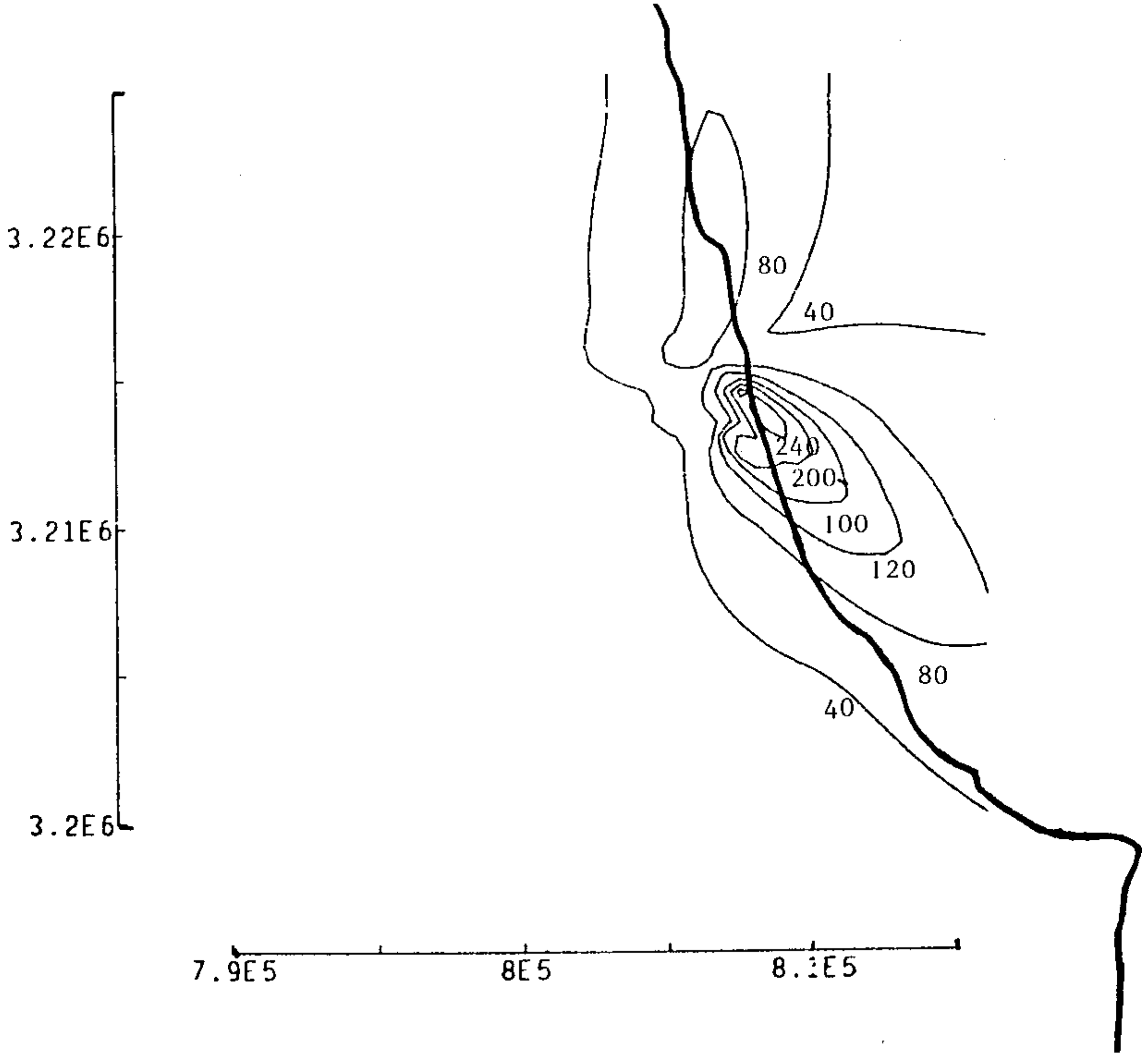

Fig. 5-6. Summer isopleths of NO_x ($\mu g/m^3$).

KISRX 8606

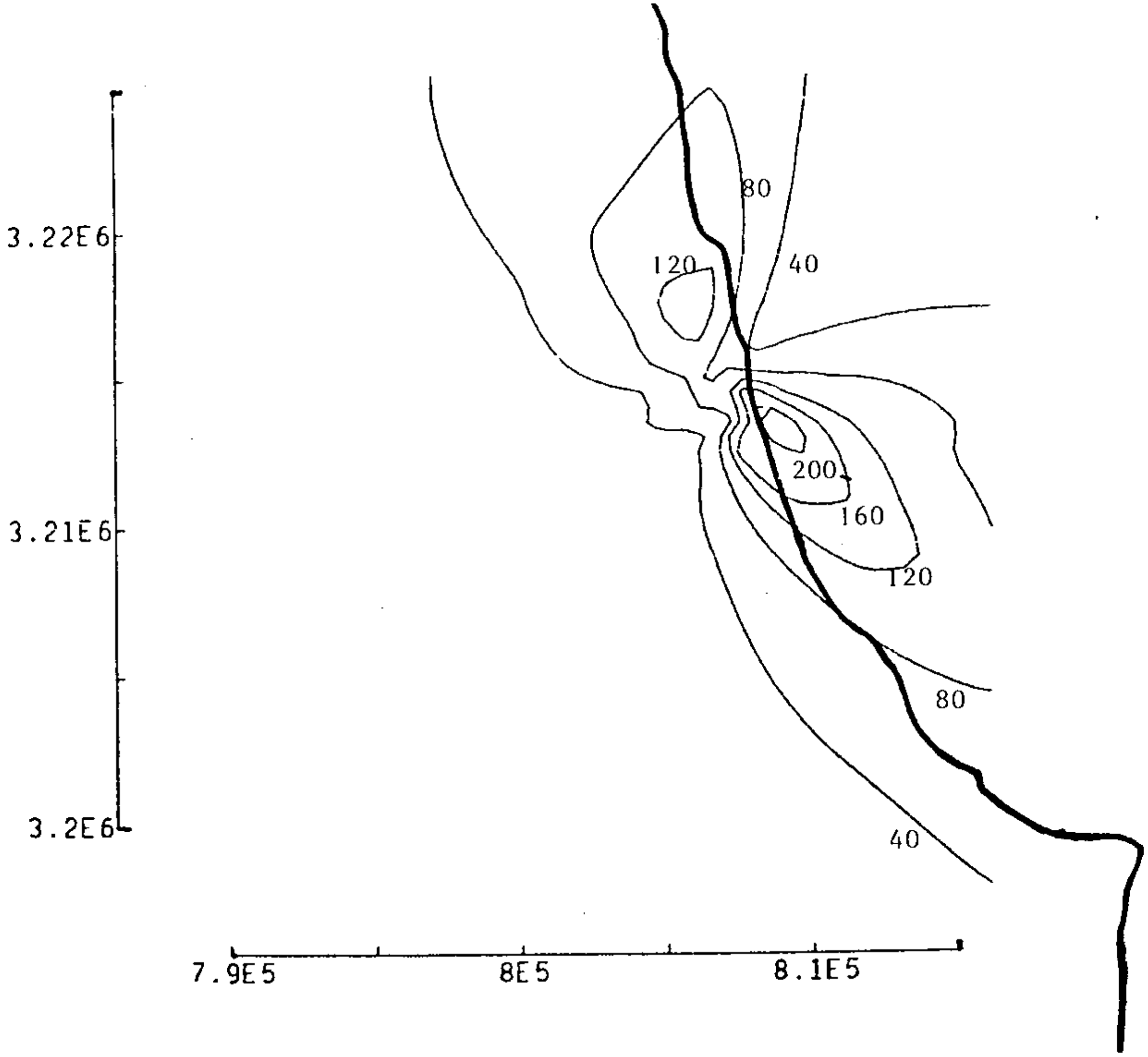

Fig. 5-7. Winter isopleths of NO_x ($\mu g/m^3$).

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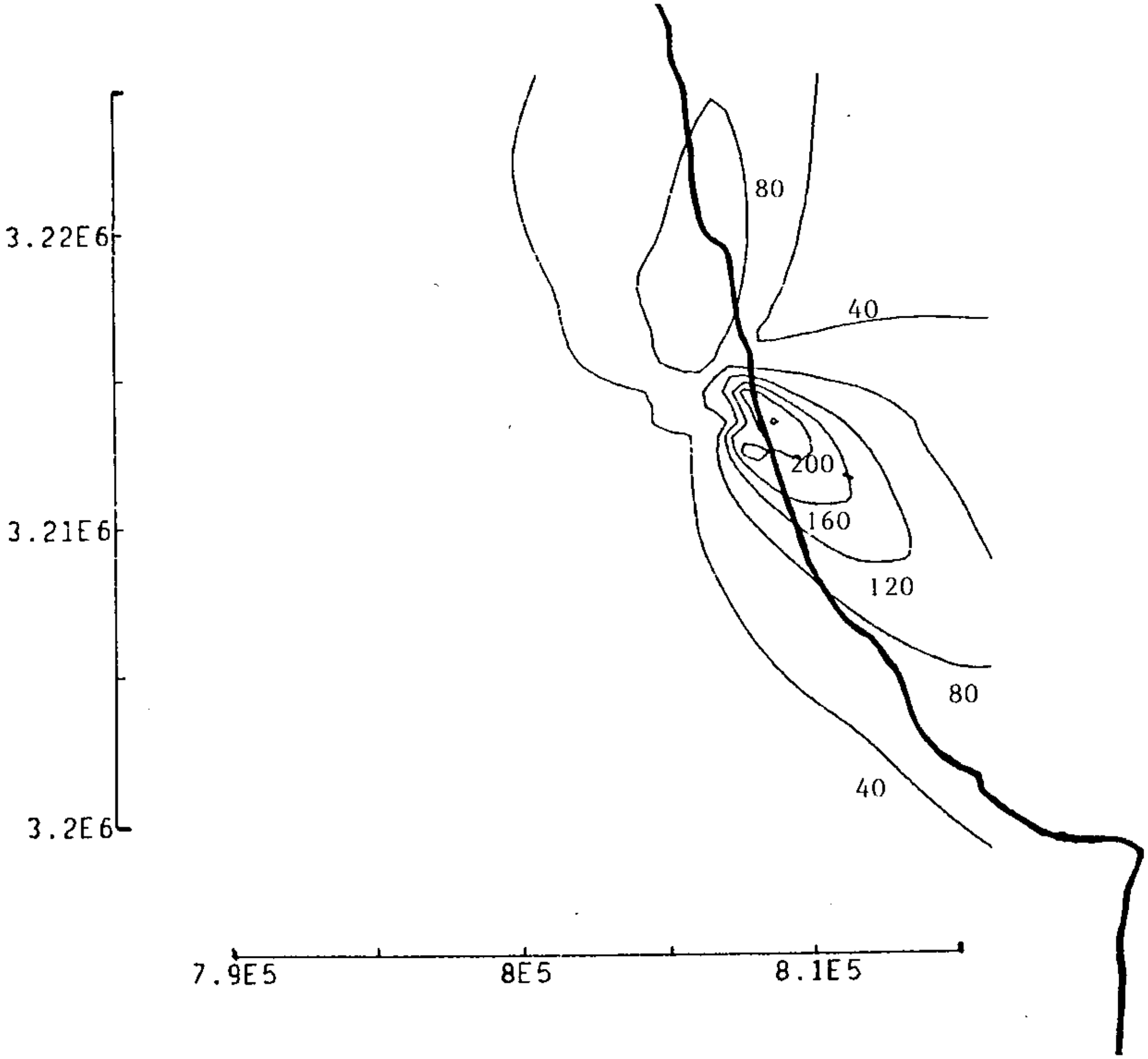

Fig. 5-8. Annual isopleths of NO_x ($\mu g/m^3$).

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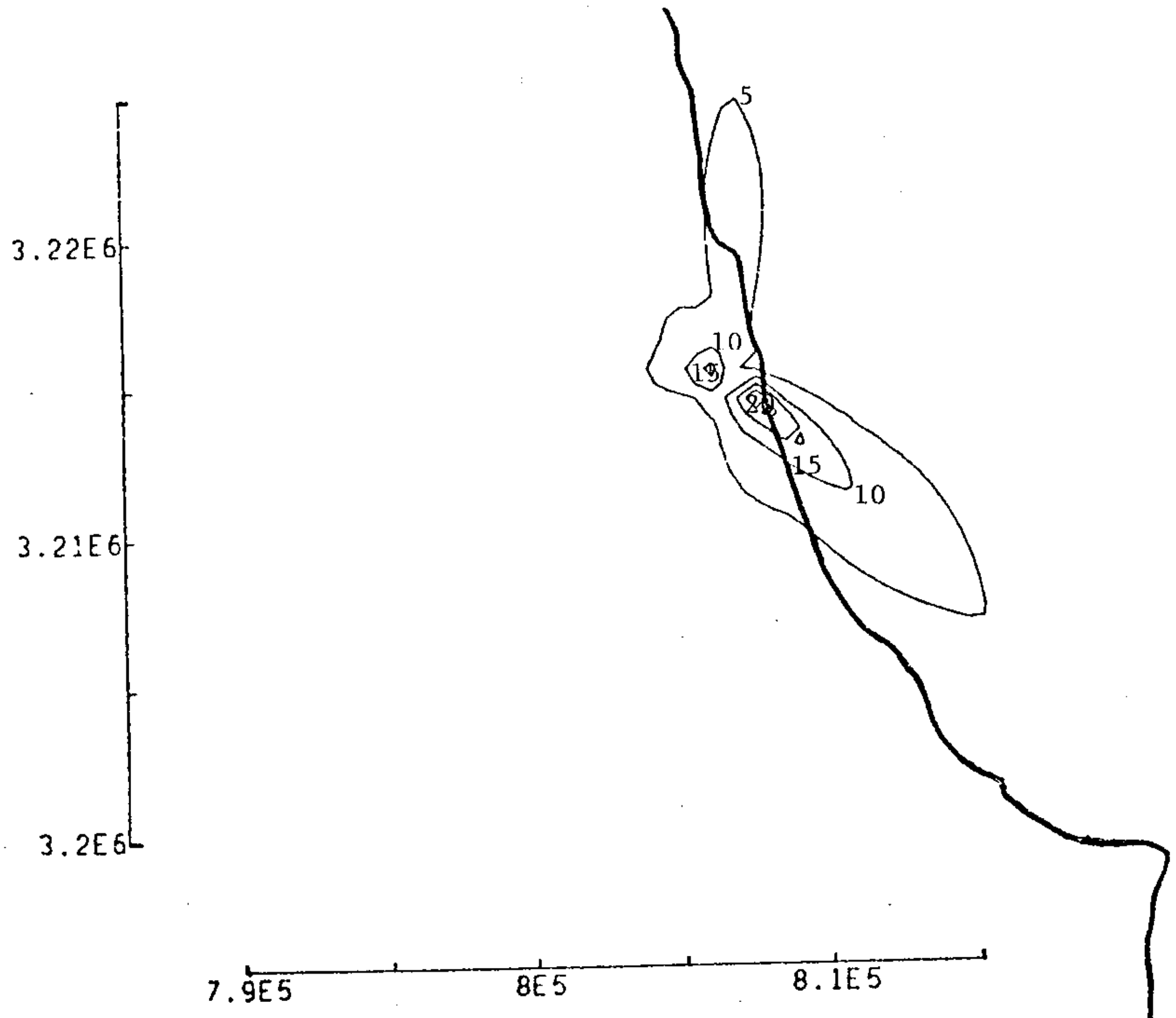


Fig. 5-9. Summer isopleths of NH_3 ($\mu g/m^3$).

KISRX 8609

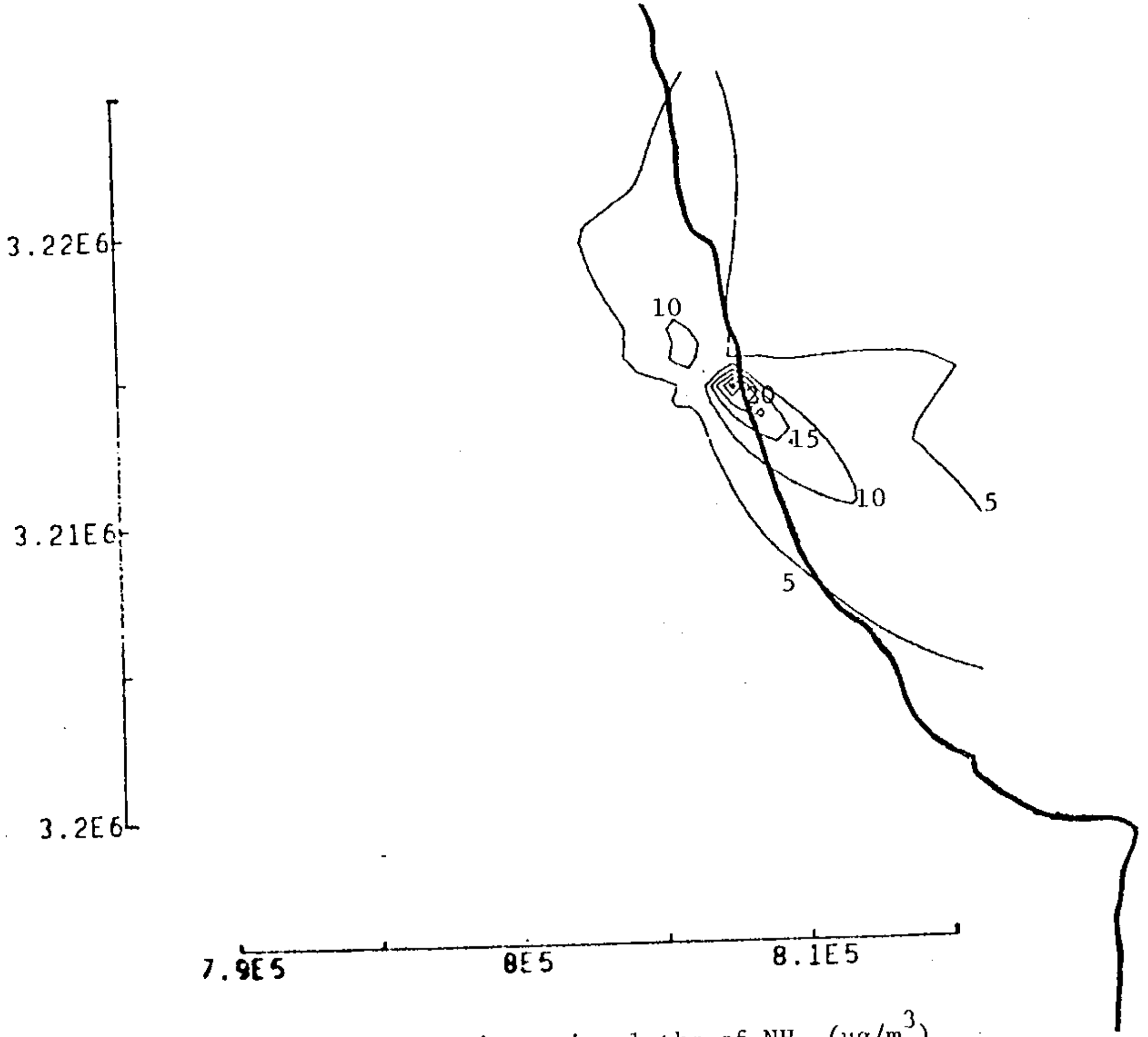


Fig. 5-10. Winter isopleths of NH_3 ($\mu g/m^3$).

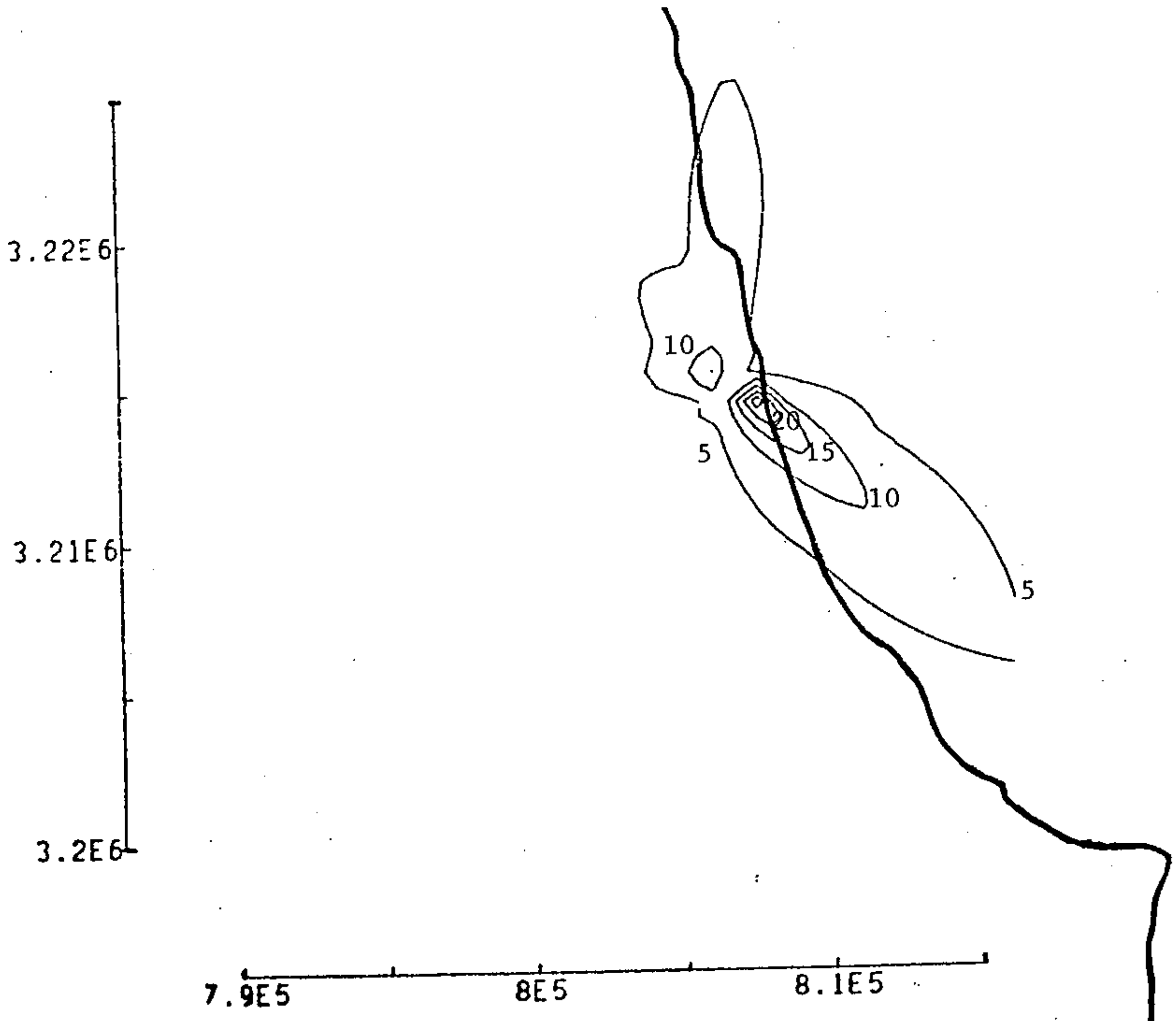


Fig. 5-11. Annual isopleths of NH_3 ($\mu g/m^3$).

KISRX 8611

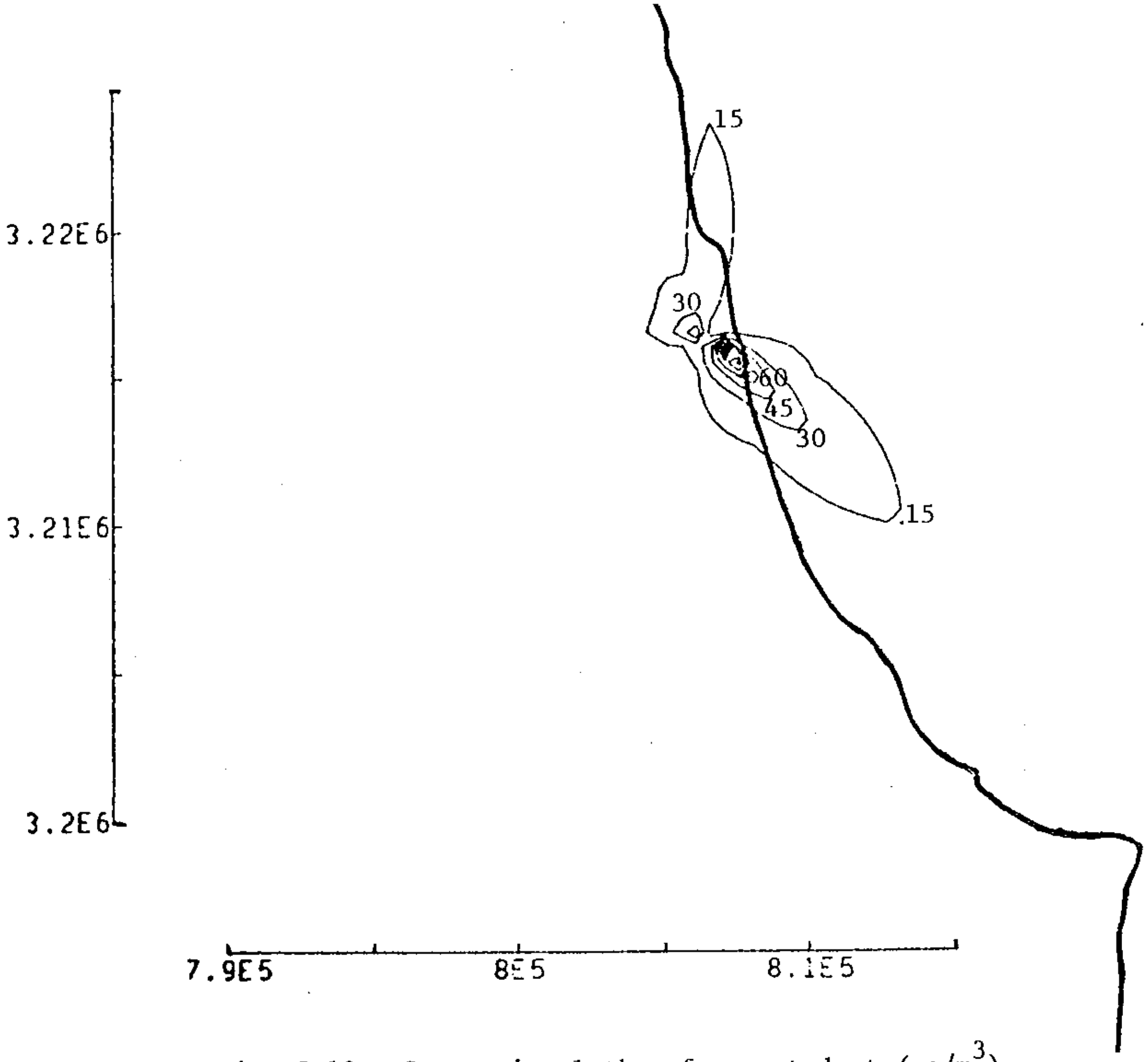


Fig. 5-12. Summer isopleths of cement dust ($\mu g/m^3$).

KISRX 8612

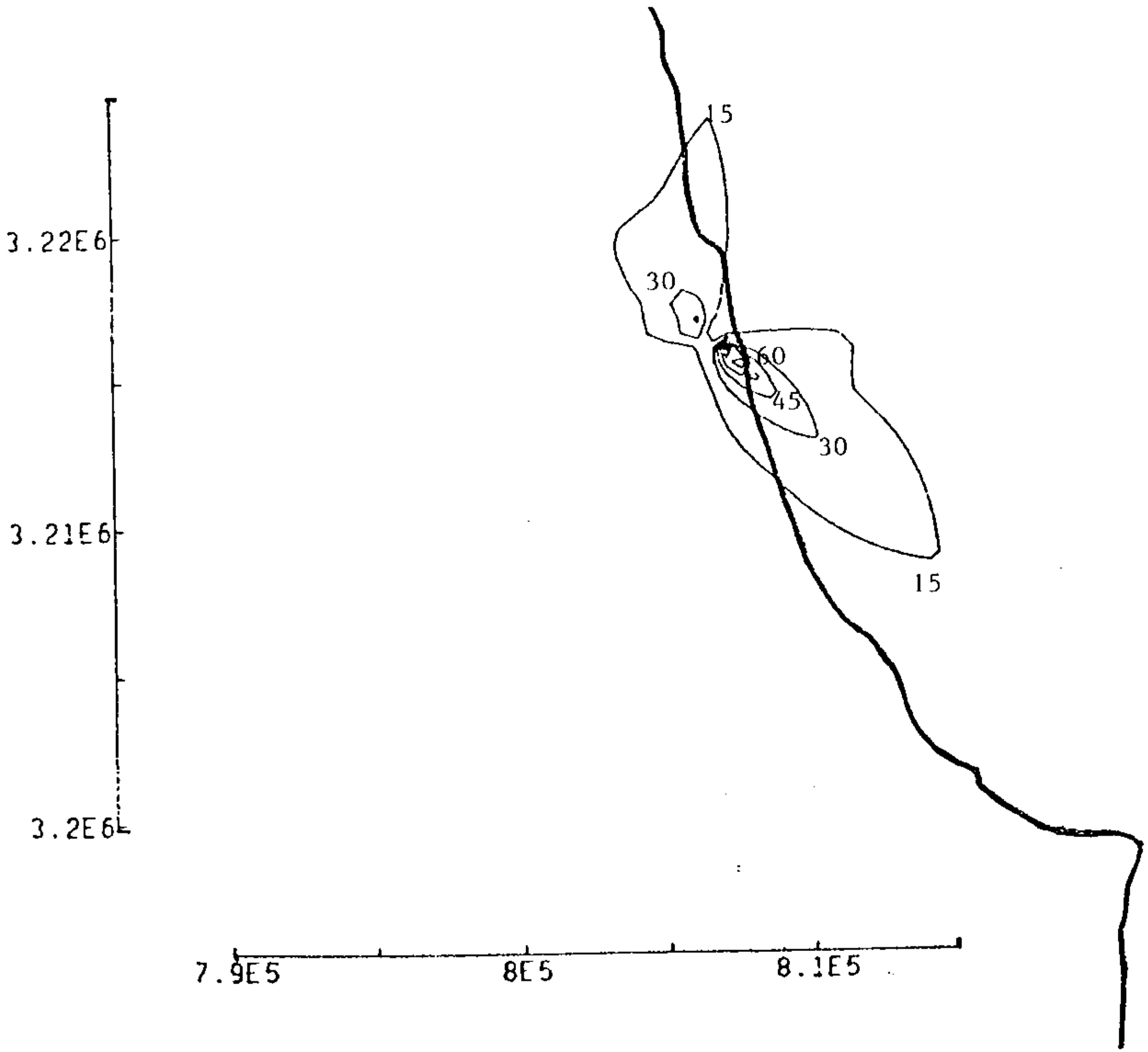


Fig. 5-13. Winter isopleths of cement dust ($\mu g/m^3$).

KISRX 8613

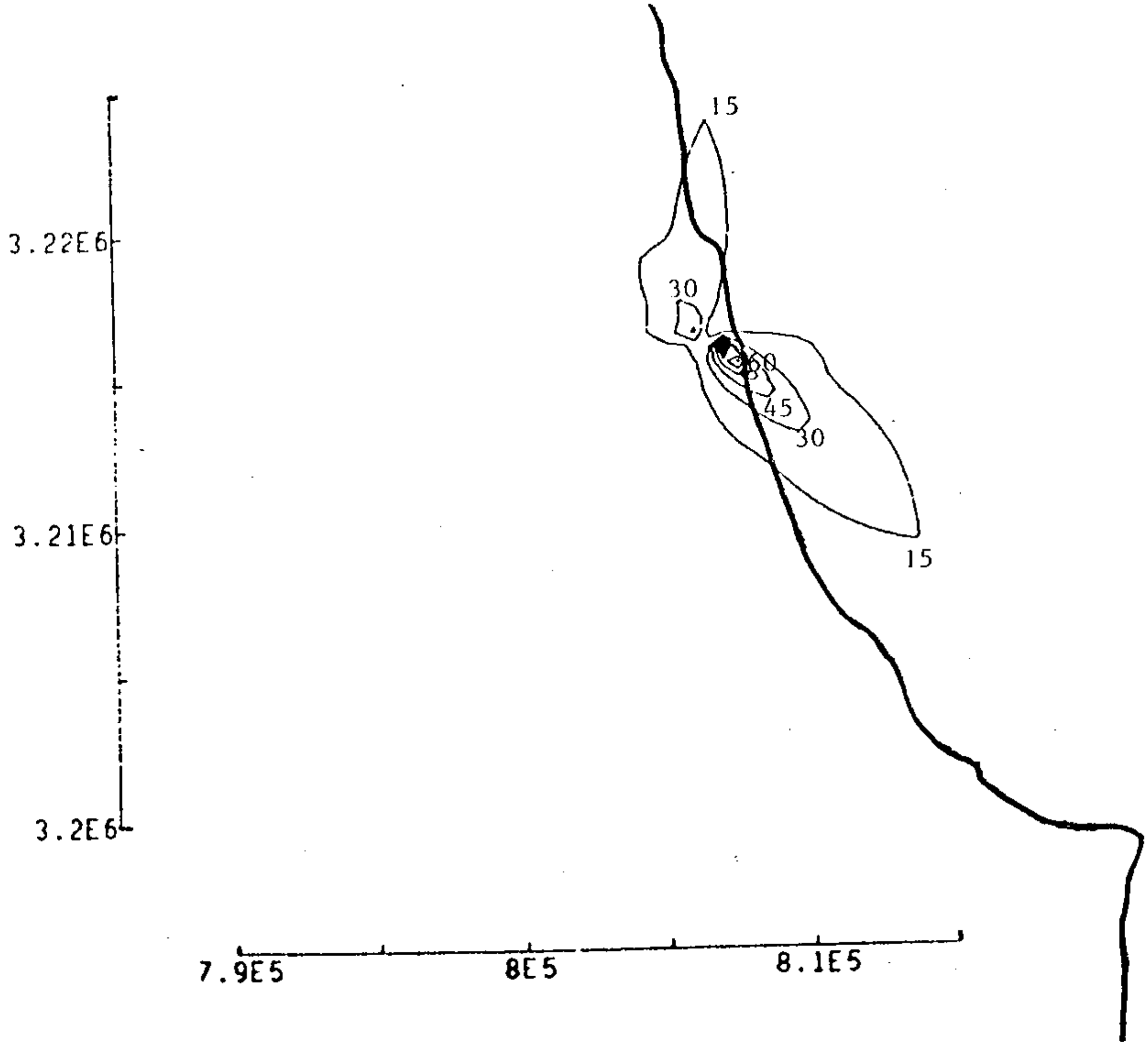


Fig. 5-14. Annual isopleths of cement dust ($\mu g/m^3$).

KISRX 8614

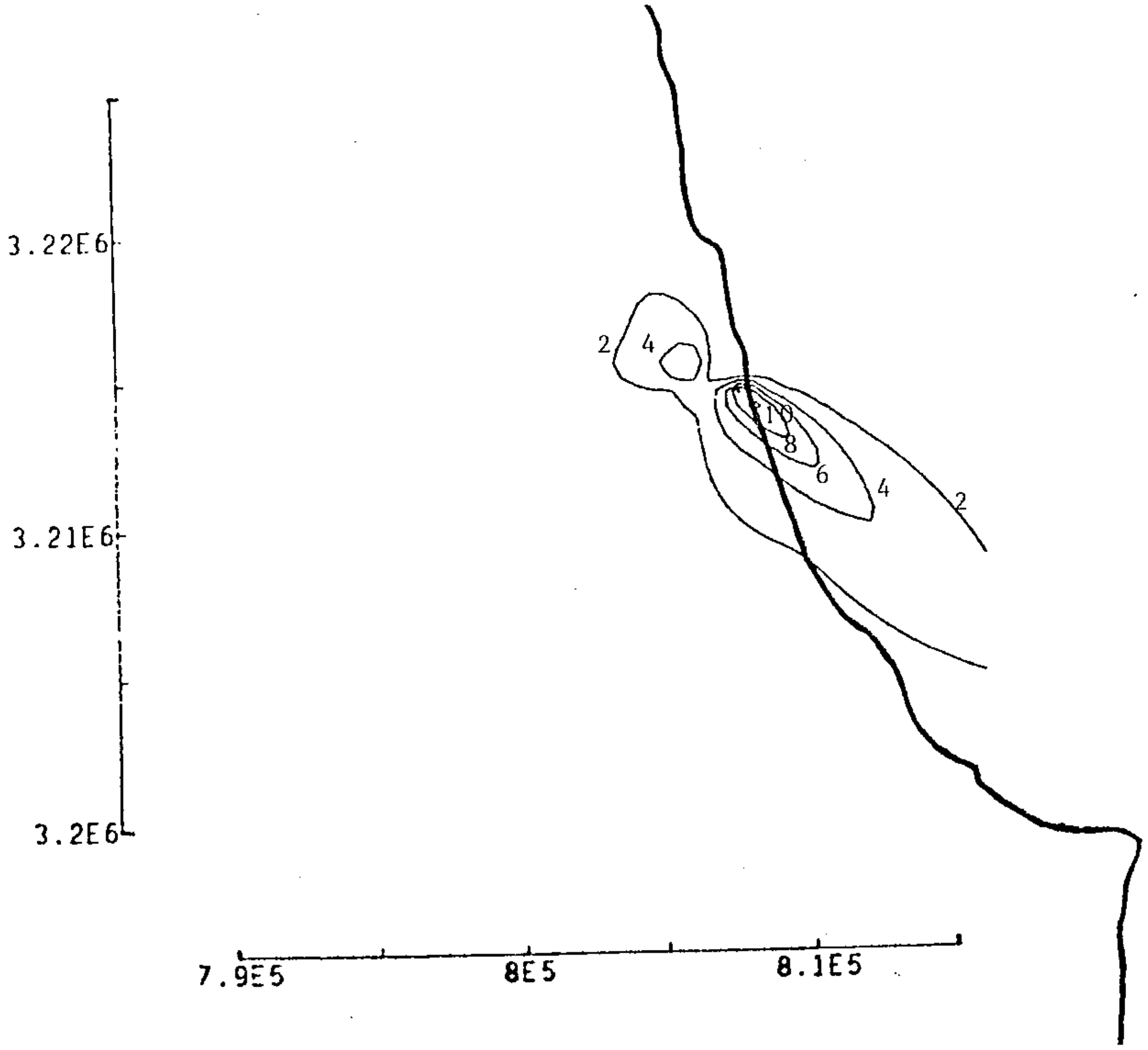


Fig. 5-15. Summer isopleths of urea dust ($\mu g/m^3$).

KISRX 8615

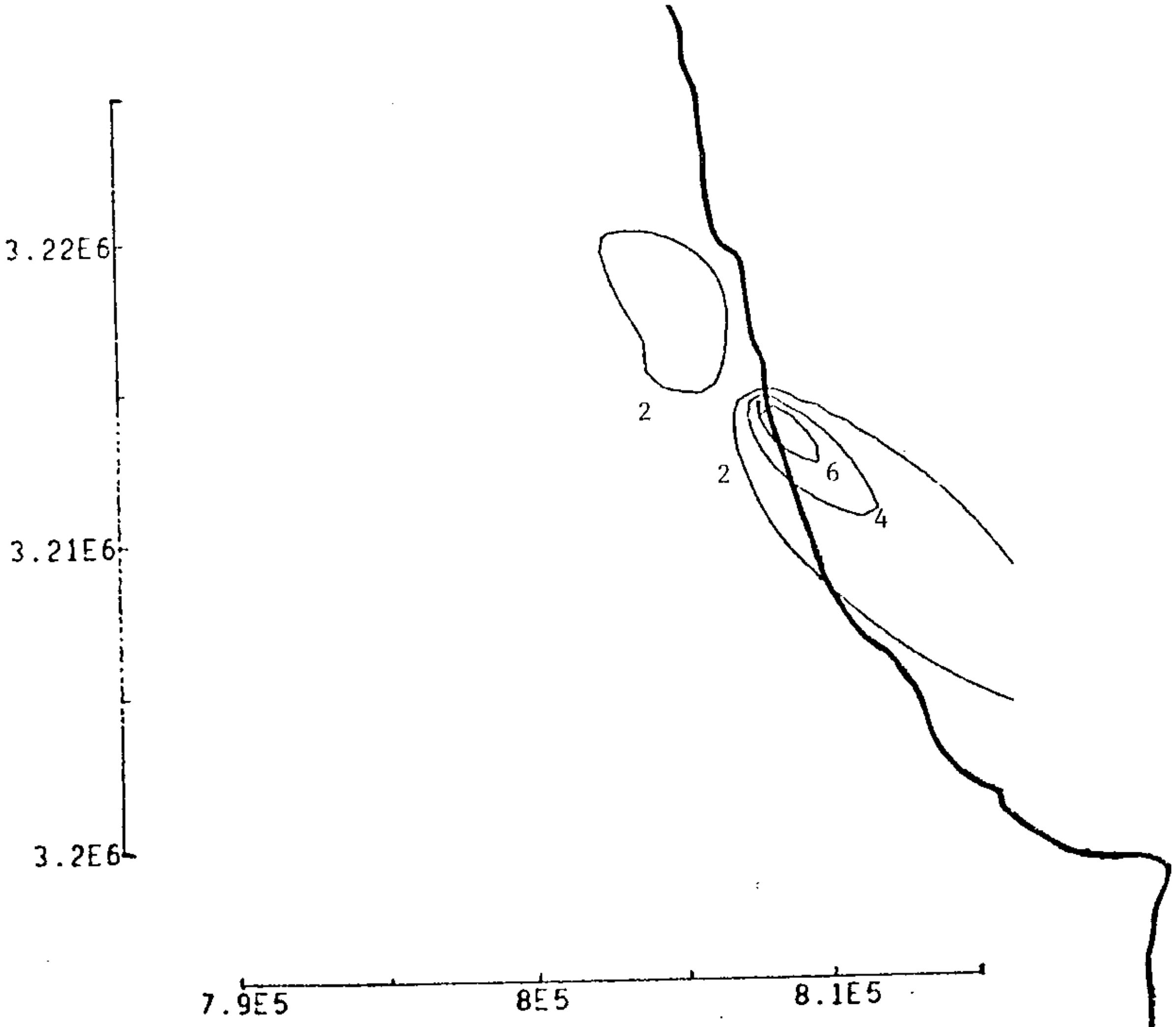


Fig. 5-16. Winter isopleths of urea dust ($\mu g/m^3$).

KISRX 8616

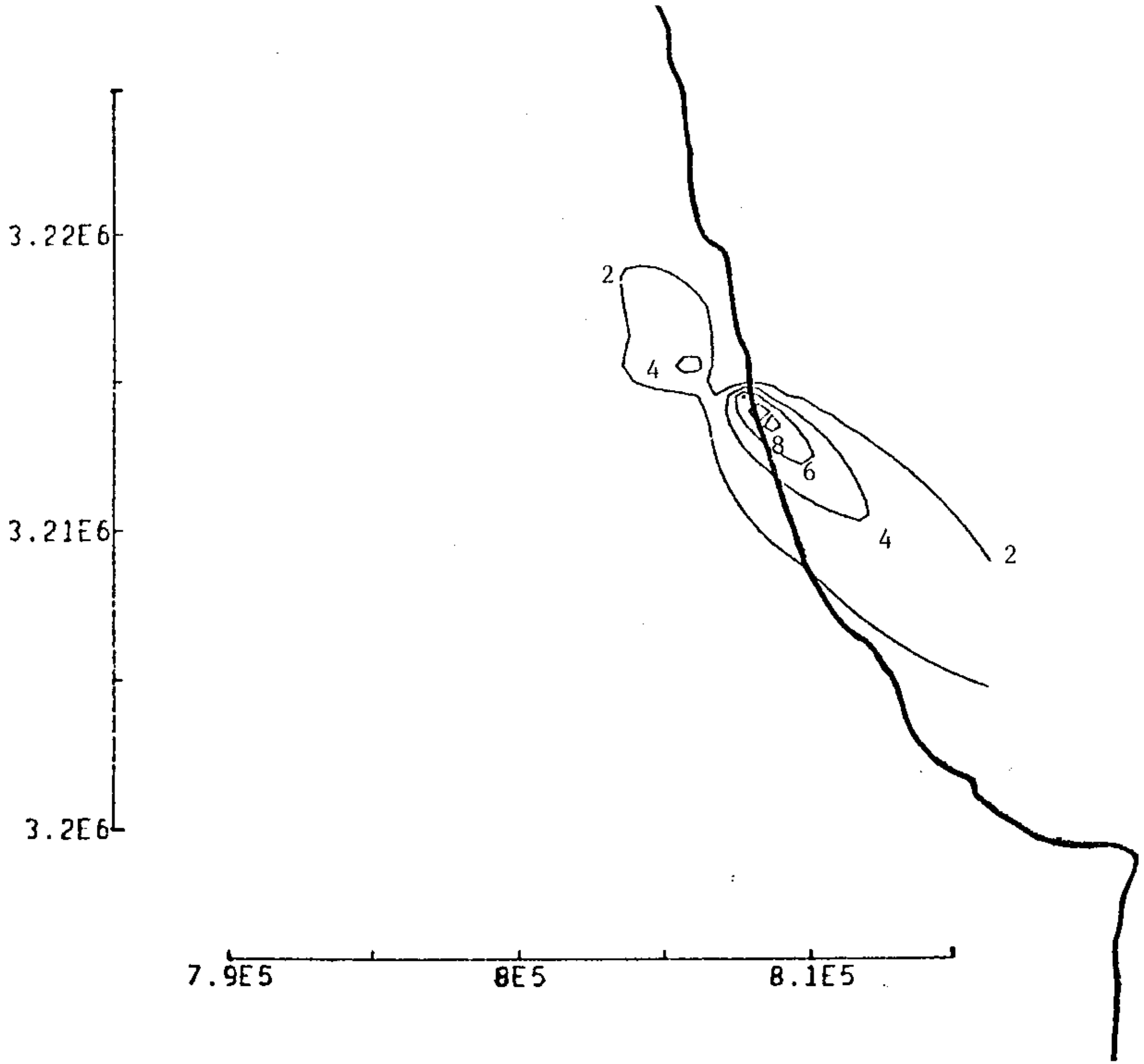


Fig. 5-17. Annual isopleths of urea dust ($\mu g/m^3$).

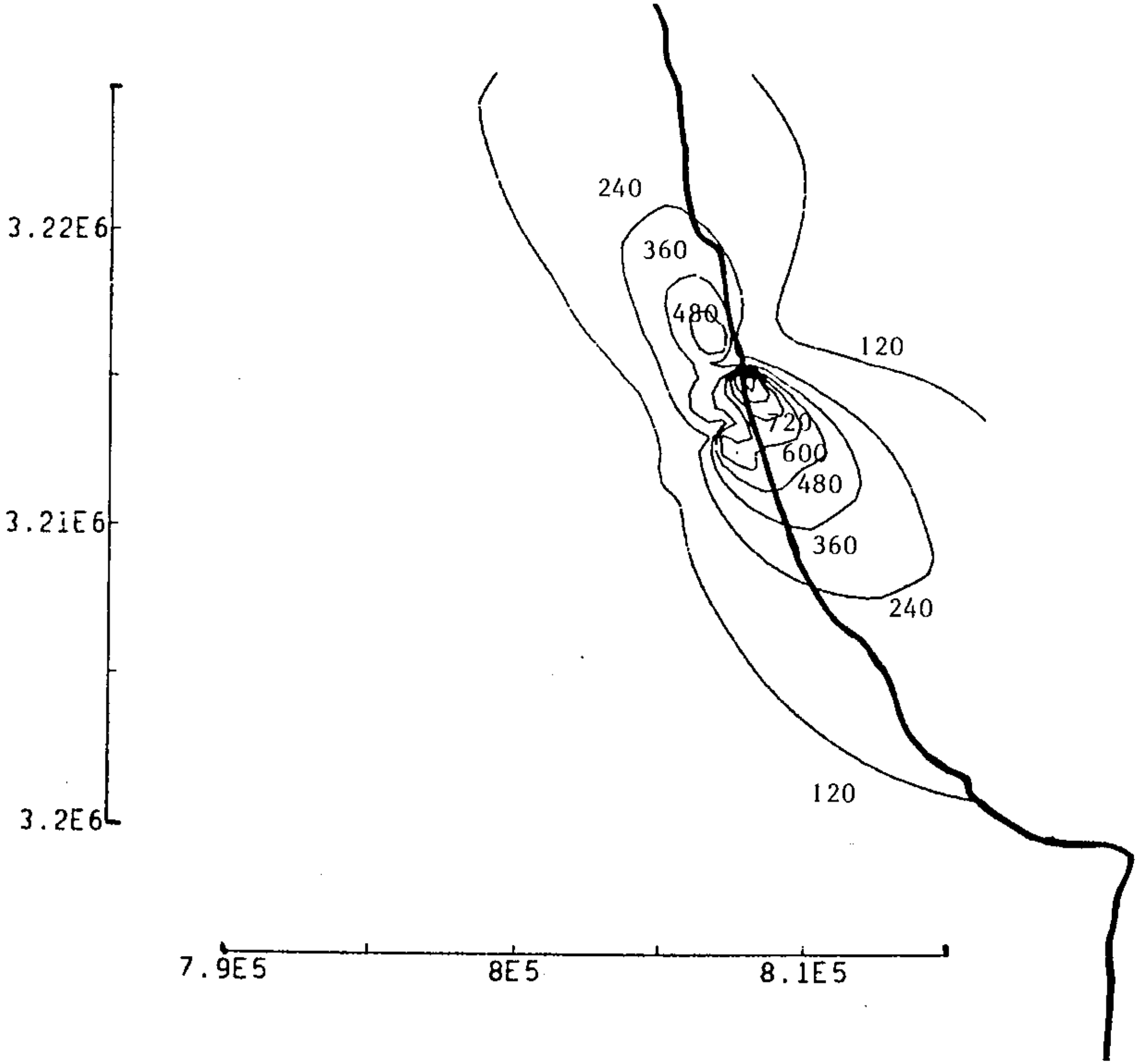


Fig. 5-18. Isopleth of SO_2 during September-December 1982 (μg/m^3).

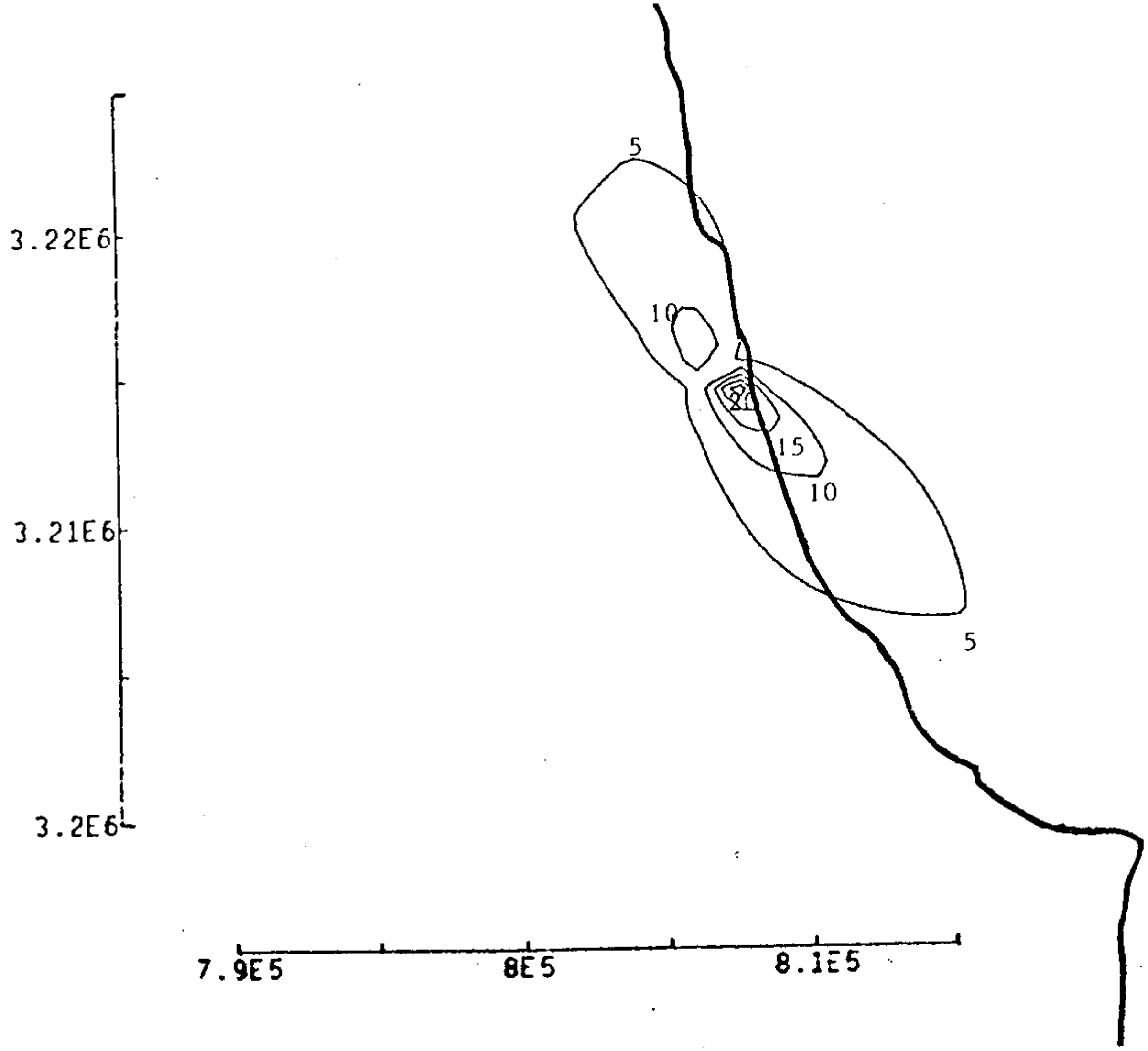


Fig. 5-19. Isopleths of NH_3 during September-December 1982 ($\mu g/m^3$).

Figs. 5-3 through 5-17 present, on the same scale as Fig. 5-2, the ground level output concentration isopleths, where, in all such figures, the UTM (Universal Transverse Mercator) coordinate system has been adopted.

Three isopleths are provided for each of the pollutants (SO_2, NO_x, NH_3, cement and urea):

1. Summer isopleths, in which five years (1978-1982) of summer meteorological data (April to October) have been used.
2. Winter isopleths, in which five years (1978-82) of winter meteorological data (January, February, March, November, December) have been used.
3. Annual isopleths, in which all the five year (1978-82) meteorological data have been used.

Finally, Figs. 5-18 and 5-19 show the isopleths of SO_2 and NH_3, respectively, during the four-month period September-December 1982, when some intensive air quality measurements were collected (see Section 4.2) and can therefore be compared to the modeling simulation outputs.

To complement the information presented in Figs. 5-3 to 5-19, a table is enclosed for each figure, (Tables 5-1 to 5-17) containing the ten locations (in UTM coordinates) at which the highest concentrations were found.

5.5 Short-Term Simulations

Even though long-term climatological simulations are the most important in industrial development planning, reliable short-term (e.g., hourly) simulations are often required for evaluating high-concentration episodes and accidental release situations.

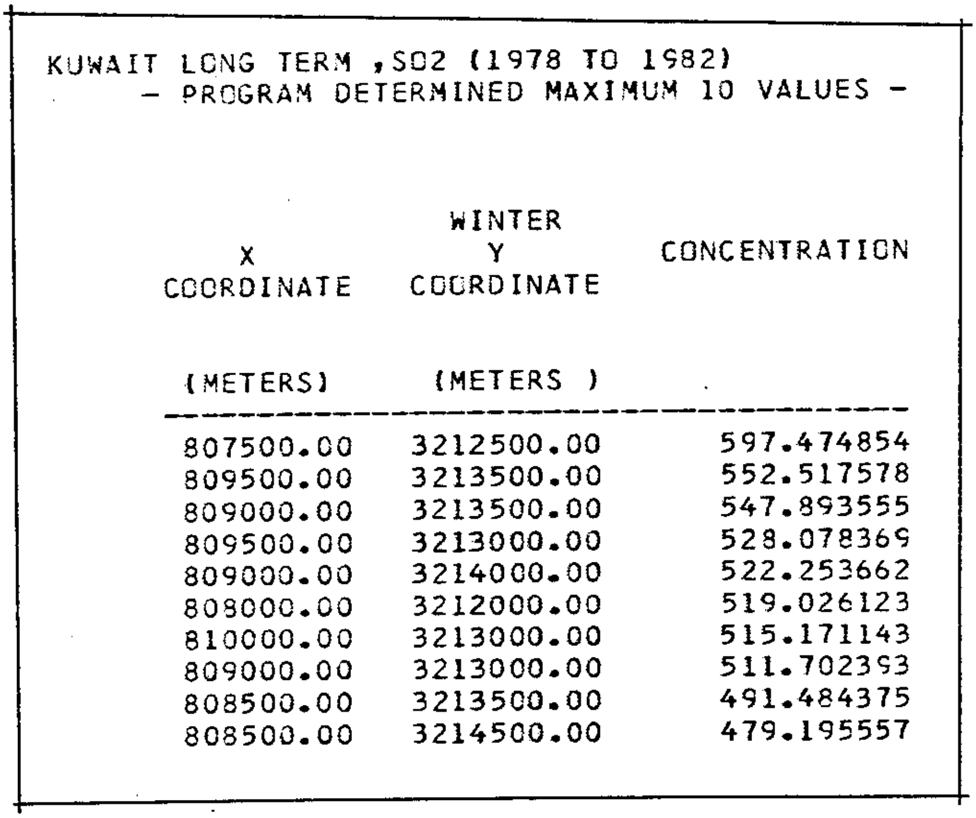
Two short-term models have been used in this project:

- The ISCST model, which has been applied to simulate actual diffusion conditions in the SIA during selected days with high potential of maximum pollution impact.
- The MC-LAGPAR model, which was specifically developed in this project for advanced simulations of complex diffusion cases and was just applied to simulate hypothetical (but extremely meaningful) conditions.

Table 5-1. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated SO_2 concentrations in Fig. 5-3.

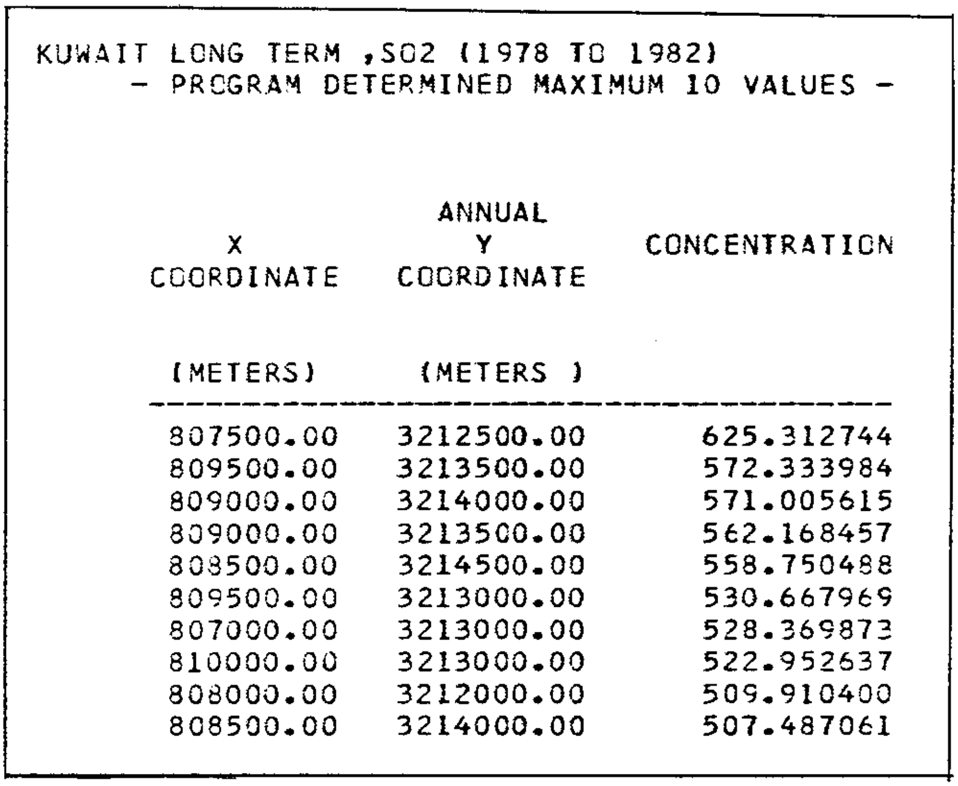
```
KUWAIT LONG TERM ,SO2 (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                      SUMMER
       X                Y          CONCENTRATION
   COORDINATE      COORDINATE


    (METERS)        (METERS )
   ---------------------------------------
    807500.00      3212500.00        653.150635
    808500.00      3214500.00        638.305420
    807000.00      3213000.00        631.965332
    809000.00      3214000.00        619.757568
    809500.00      3213500.00        592.150391
    809000.00      3213500.00        576.443359
    808500.00      3214000.00        552.179932
    809500.00      3213000.00        533.257812
    810000.00      3213000.00        530.734375
    808000.00      3215000.00        522.152832
```

Table 5-2. Location (UTM) and concentration (μg/m^3) of the ten highest simulated SO_2 concentrations in Fig. 5-4.



```
KUWAIT LONG TERM ,SO2 (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                     WINTER
      X                Y           CONCENTRATION
  COORDINATE      COORDINATE


   (METERS)        (METERS )
  ------------------------------------------------
   807500.00      3212500.00           597.474854
   809500.00      3213500.00           552.517578
   809000.00      3213500.00           547.893555
   809500.00      3213000.00           528.078369
   809000.00      3214000.00           522.253662
   808000.00      3212000.00           519.026123
   810000.00      3213000.00           515.171143
   809000.00      3213000.00           511.702393
   808500.00      3213500.00           491.484375
   808500.00      3214500.00           479.195557
```

Table 5-3. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated SO_2 concentrations in Fig. 5-5.

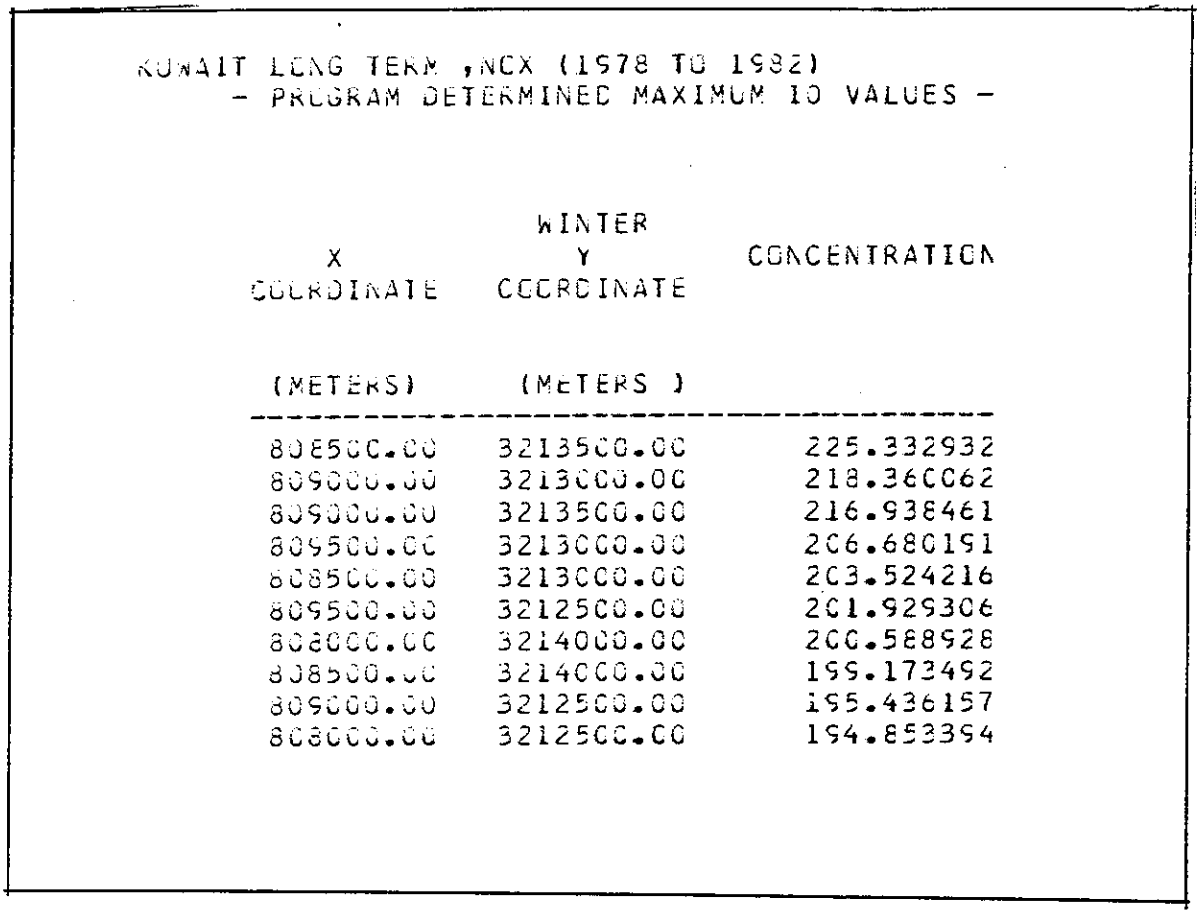


```
KUWAIT LONG TERM ,SO2 (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -



                     ANNUAL
         X             Y          CONCENTRATION
     COORDINATE    COORDINATE


      (METERS)      (METERS )
     ----------------------------------------
      807500.00    3212500.00        625.312744
      809500.00    3213500.00        572.333984
      809000.00    3214000.00        571.005615
      809000.00    3213500.00        562.168457
      808500.00    3214500.00        558.750488
      809500.00    3213000.00        530.667969
      807000.00    3213000.00        528.369873
      810000.00    3213000.00        522.952637
      808000.00    3212000.00        509.910400
      808500.00    3214000.00        507.487061
```

Table 5-4. Location (UTN) and concentration ($\mu g/m^3$) of the ten highest simulated NO_x concentration in Fig. 5-6.

```
KUWAIT LONG TERM ,NOX (1978 TO 1982)
      - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                         SUMMER
        X                  Y             CONCENTRATION
    COORDINATE        COORDINATE


     (METERS)          (METERS )
    ------------------------------------------------
     808500.00        3213500.00          265.419189
     808000.00        3214000.00          262.671143
     807500.00        3214500.00          258.689697
     809000.00        3213500.00          245.085556
     808500.00        3214000.00          244.974991
     809000.00        3213000.00          243.907089
     807500.00        3212500.00          240.330460
     808000.00        3214500.00          231.796707
     808000.00        3213500.00          227.572906
     808500.00        3213000.00          226.545914
```

Table 5-5. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated NO_x concentrations in Fig. 5-7.



```
KUWAIT LONG TERM ,NOX (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                         WINTER
       X                   Y            CONCENTRATION
   COORDINATE         COORDINATE


   (METERS)            (METERS )
   ------------------------------------------------
    808500.00         3213500.00          225.332932
    809000.00         3213000.00          218.360062
    809000.00         3213500.00          216.938461
    809500.00         3213000.00          206.680191
    808500.00         3213000.00          203.524216
    809500.00         3212500.00          201.929306
    808000.00         3214000.00          200.588928
    808500.00         3214000.00          199.173492
    809000.00         3212500.00          195.436157
    808000.00         3212500.00          194.853394
```

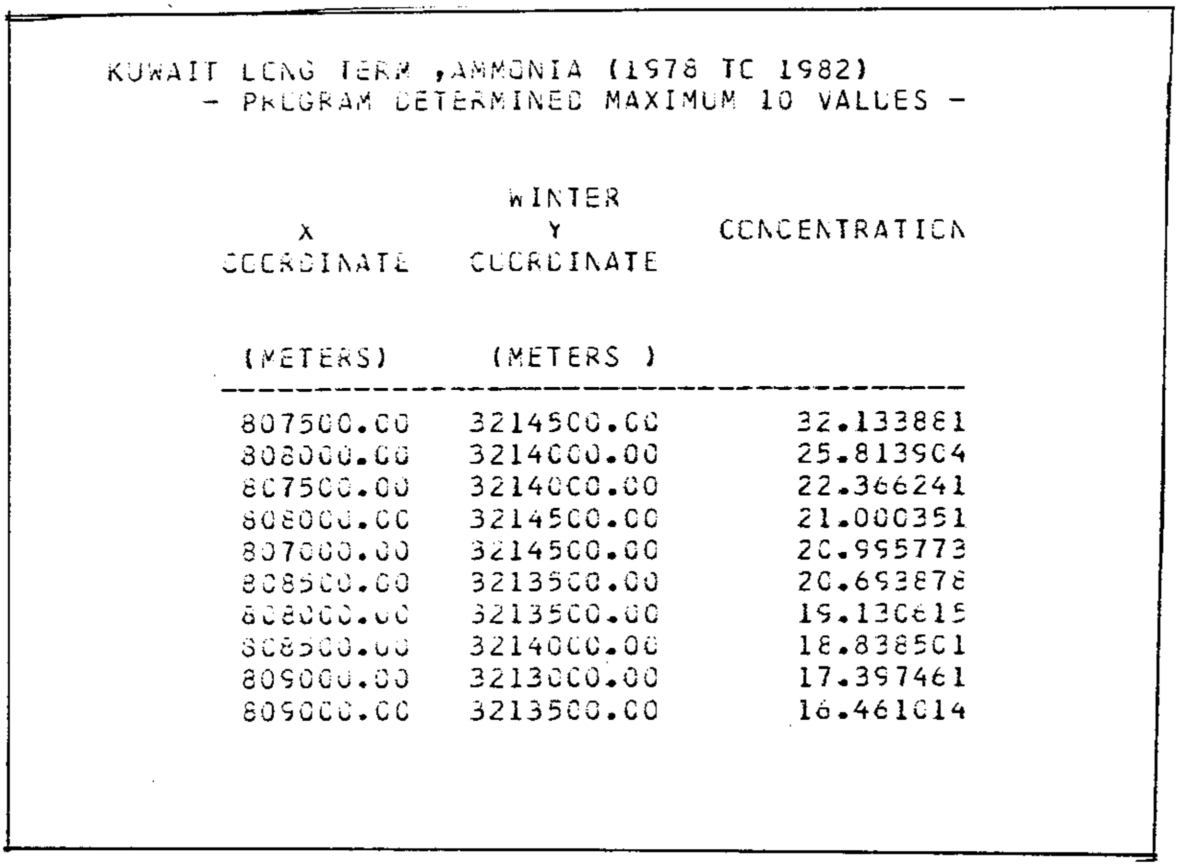
Table 5-6 Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated NO_x concentrations in Fig. 5-8.

```
KUWAIT LONG TERM ,NOX (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                          ANNUAL
          X                 Y             CONCENTRATION
     COORDINATE        COORDINATE


       (METERS)         (METERS )
     ---------------------------------------------------
       808500.00        3213500.00           245.375977
       808000.00        3214000.00           231.630005
       809000.00        3213000.00           231.133545
       809000.00        3213500.00           231.011963
       808500.00        3214000.00           222.074219
       807500.00        3212500.00           216.764648
       807500.00        3214500.00           215.977417
       809500.00        3213000.00           215.475464
       808500.00        3213000.00           215.035034
       809500.00        3212500.00           209.818481
```

Table 5-7. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated NH_3 concentrations in Fig. 5-9.

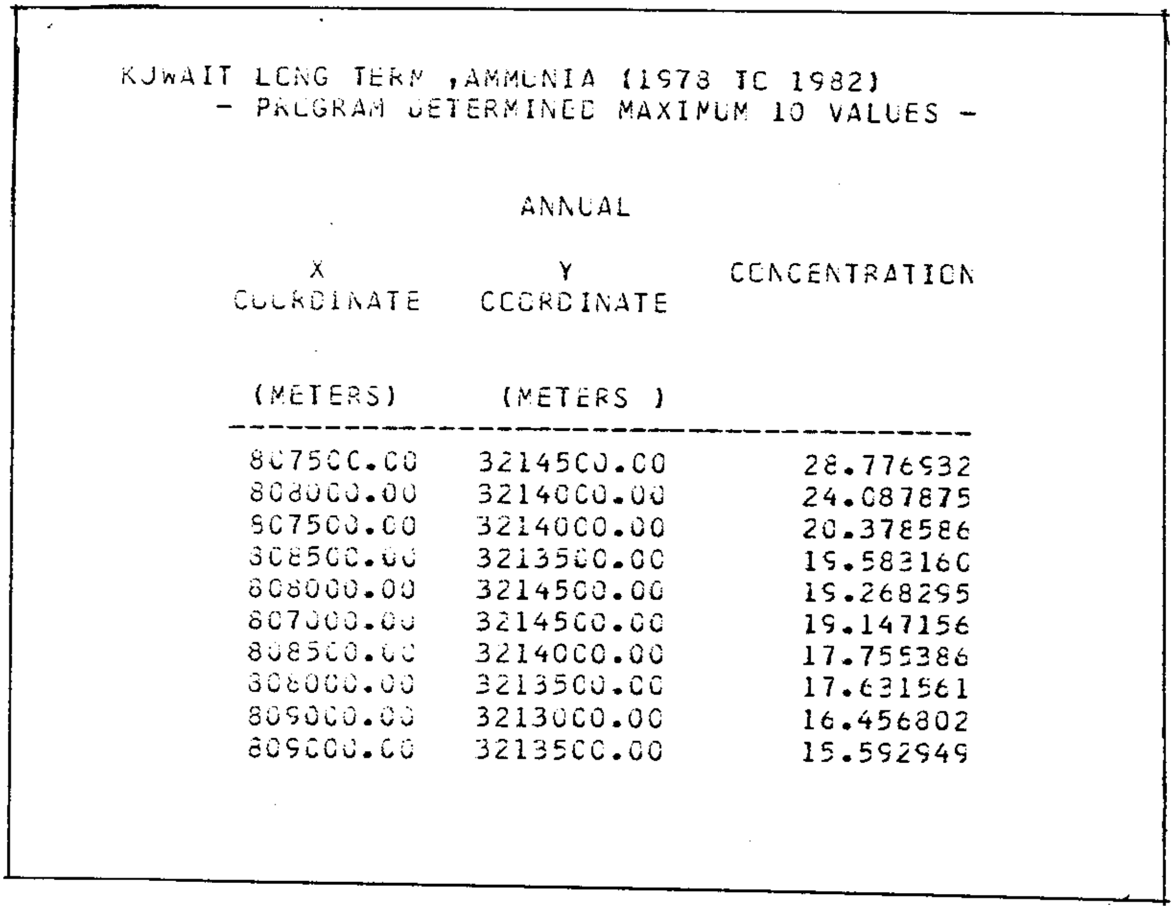
```
KUWAIT LONG TERM ,AMMONIA (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -

                          SUMMER
         X                  Y             CONCENTRATION
    COORDINATE         COORDINATE


    (METERS)           (METERS )
    --------------------------------------------------
      807500.00        3214500.00              25.419983
      808000.00        3214000.00              22.361862
      808500.00        3213500.00              18.472458
      807500.00        3214000.00              18.390945
      808000.00        3214500.00              17.536240
      807000.00        3214500.00              17.298553
      806000.00        3215500.00              17.149979
      808500.00        3214000.00              16.672287
      808000.00        3213500.00              16.132507
      809000.00        3213000.00              15.516162
```

Table 5-8. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated NH_3 concentrations in Fig. 5-10.



```
KUWAIT LONG TERM ,AMMONIA (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                       WINTER
       X                 Y            CONCENTRATION
   COORDINATE       COORDINATE


    (METERS)         (METERS )
   ----------------------------------------------
    807500.00       3214500.00             32.133881
    808000.00       3214000.00             25.813904
    807500.00       3214000.00             22.366241
    808000.00       3214500.00             21.000351
    807000.00       3214500.00             20.995773
    808500.00       3213500.00             20.693878
    808000.00       3213500.00             19.130619
    808500.00       3214000.00             18.838501
    809000.00       3213000.00             17.397461
    809000.00       3213500.00             16.461014
```

Table 5-9. Location (UTM) and concentration (μg/m^3) of the ten highest simulates NH_3 concentrations in Fig. 5-11.

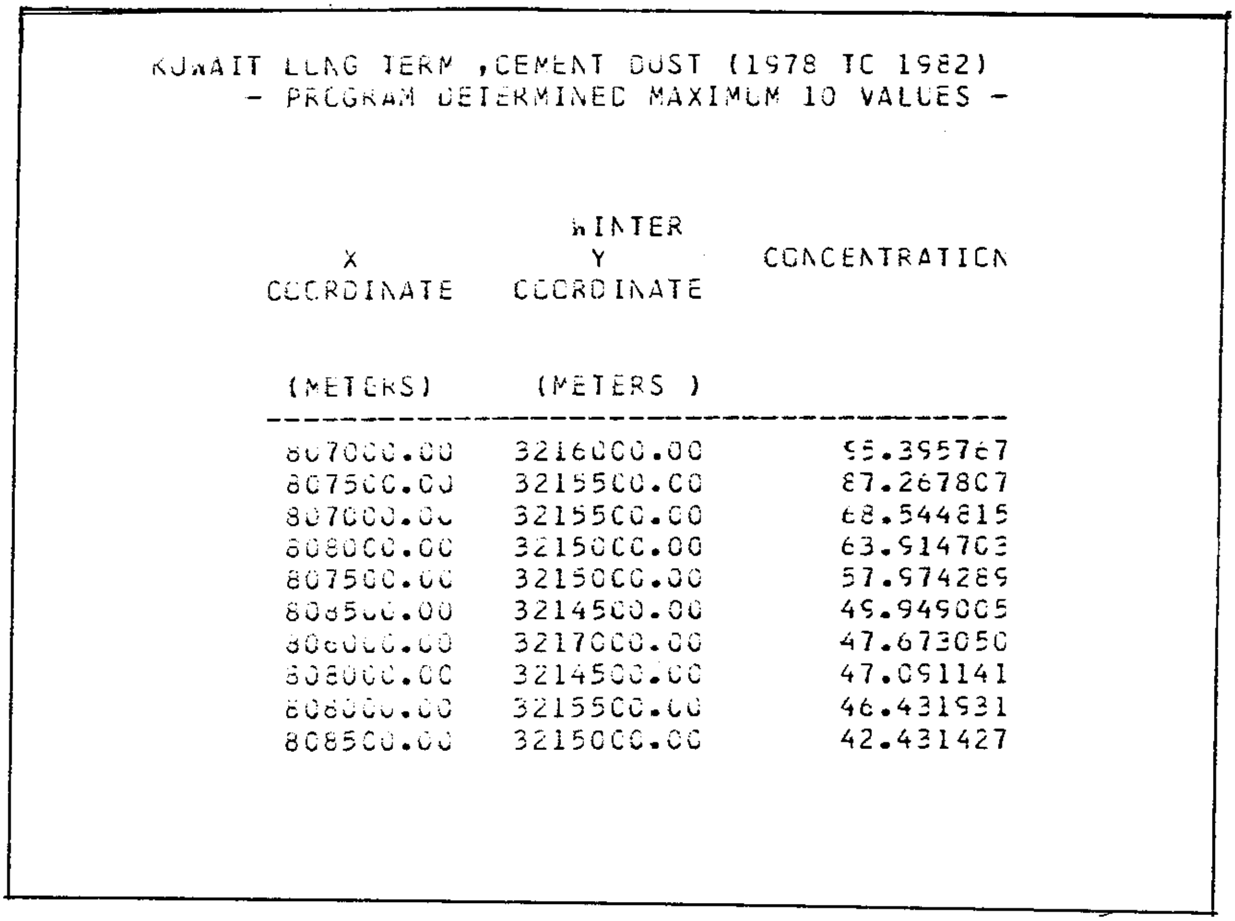


```
KUWAIT LONG TERM ,AMMONIA (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -

                        ANNUAL

       X                 Y            CONCENTRATION
   COORDINATE       COORDINATE


    (METERS)         (METERS )
  -----------------------------------------------
   807500.00        3214500.00          28.776932
   808000.00        3214000.00          24.087875
   807500.00        3214000.00          20.378586
   808500.00        3213500.00          19.583160
   808000.00        3214500.00          19.268295
   807000.00        3214500.00          19.147156
   808500.00        3214000.00          17.755386
   808000.00        3213500.00          17.631561
   809000.00        3213000.00          16.456802
   809000.00        3213500.00          15.592949
```

Table 5-10. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated cement dust concentrations in Fig. 5-12.

```
KUWAIT LONG TERM ,CEMENT DUST (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                          SUMMER
          X                  Y            CONCENTRATION
      COORDINATE       COORDINATE


       (METERS)         (METERS )
      ------------------------------------------------
       807000.00       3216000.00          120.094864
       807500.00       3215500.00           97.354263
       807000.00       3215500.00           69.692947
       808000.00       3215000.00           68.542038
       807500.00       3215000.00           59.604996
       808000.00       3216500.00           56.976868
       808500.00       3214500.00           51.734116
       808000.00       3215500.00           49.432999
       808000.00       3214500.00           47.747360
       808500.00       3215000.00           43.858200
```

Table 5-11. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated cement dust concentrations in Fig. 5-13.



```
KUWAIT LONG TERM ,CEMENT DUST (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                        WINTER
      X                   Y              CONCENTRATION
  COORDINATE         COORDINATE

   (METERS)           (METERS )
------------------------------------------------------
   807000.00         3216000.00              95.395767
   807500.00         3215500.00              87.267807
   807000.00         3215500.00              68.544815
   808000.00         3215000.00              63.914703
   807500.00         3215000.00              57.974289
   808500.00         3214500.00              49.949005
   808000.00         3217000.00              47.673050
   808000.00         3214500.00              47.091141
   808000.00         3215500.00              46.431931
   808500.00         3215000.00              42.431427
```

Table 5-12. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated cement dust concentrations in Fig. 5-14.

```
   KUWAIT LONG TERM ,CEMENT DUST (1978 TO 1982)
        - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                          ANNUAL
          X                 Y            CONCENTRATION
      COORDINATE       COORDINATE


       (METERS)         (METERS )
     ----------------------------------------------------
       807000.00       3216000.00          107.745316
       807500.00       3215500.00           92.311035
       807000.00       3215500.00           69.118881
       808000.00       3215000.00           66.228363
       807500.00       3215000.00           58.789642
       808500.00       3214500.00           50.841553
       808000.00       3215500.00           47.932465
       808000.00       3214500.00           47.419250
       806000.00       3216500.00           47.113617
       808500.00       3215000.00           43.144806
```

Table 5-13. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated urea dust concentrations in Fig. 5-15.

```
KUWAIT LONG TERM ,UREA DUST (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                    SUMMER
     X                Y          CONCENTRATION
 COORDINATE      COORDINATE


  (METERS)        (METERS )
 ---------------------------------------------
  808000.00      3214000.00          10.927484
  807500.00      3214500.00          10.207679
  808500.00      3213500.00           9.716839
  808500.00      3214000.00           8.865669
  809000.00      3213000.00           8.354614
  807500.00      3214000.00           8.255304
  809000.00      3213500.00           8.205586
  808000.00      3213500.00           8.112053
  808000.00      3214500.00           7.829480
  808500.00      3213000.00           7.436338
```

Table 5-14. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated urea dust concentration in Fig. 5-16.

```
KUWAIT LONG TERM ,UREA DUST (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                       WINTER
      X                  Y              CONCENTRATION
  COORDINATE        COORDINATE


   (METERS)          (METERS )
  -----------------------------------------------------
   808000.00       3214000.00                8.078875
   808500.00       3213500.00                7.741640
   809000.00       3213000.00                6.908208
   808500.00       3214000.00                6.732294
   808000.00       3213500.00                6.660541
   809000.00       3213500.00                6.598498
   808500.00       3213000.00                6.297234
   807500.00       3214500.00                6.150337
   809500.00       3212500.00                6.074990
   809500.00       3213000.00                6.025017
```

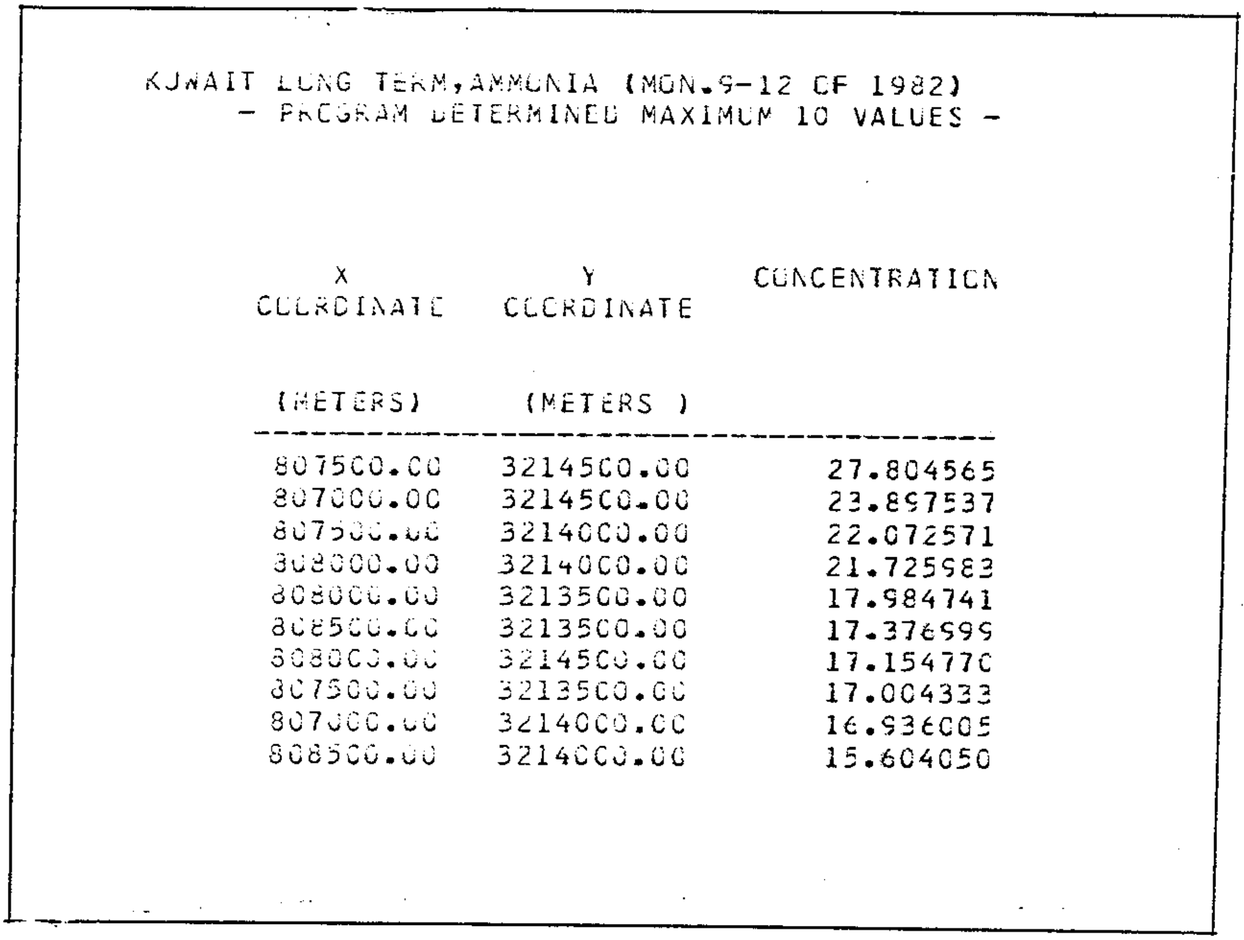
Table 5-15. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated urea dust concentrations in Fig. 5-17.

```
KUWAIT LONG TERM ,UREA DUST (1978 TO 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -


                           ANNUAL
               X             Y           CONCENTRATION
          COORDINATE    COORDINATE


           (METERS)      (METERS )
          ----------------------------------------------
           808000.00    3214000.00              9.503174
           808500.00    3213500.00              8.729233
           807500.00    3214500.00              8.179001
           808500.00    3214000.00              7.798982
           809000.00    3213000.00              7.631411
           809000.00    3213500.00              7.402042
           808000.00    3213500.00              7.386296
           807500.00    3214000.00              7.112783
           808500.00    3213000.00              6.866786
           809500.00    3213000.00              6.639651
```

Table 5-16. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated SO_2 concentrations in Fig. 5-18.

```
KUWAIT LONG TERM ,SO2 (SEP._DEC. 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -



        X              Y          CONCENTRATION
    COORDINATE    COORDINATE


     (METERS)      (METERS )
    ---------------------------------------------
     808000.00     3215000.00       1048.23657
     807500.00     3215000.00        943.421631
     808000.00     3214500.00        943.355713
     808500.00     3214500.00        892.924805
     807500.00     3214500.00        795.273437
     808500.00     3214000.00        789.000488
     808000.00     3214000.00        766.245361
     809000.00     3214000.00        743.136963
     807500.00     3212500.00        722.001953
     808500.00     3213500.00        704.123291
```

Table 5-17. Location (UTM) and concentration ($\mu g/m^3$) of the ten highest simulated NH_3 concentrations in Fig. 5-19.



```
KUWAIT LONG TERM,AMMONIA (MON.9-12 OF 1982)
     - PROGRAM DETERMINED MAXIMUM 10 VALUES -



           X             Y          CONCENTRATION
       COORDINATE    COORDINATE


        (METERS)      (METERS )
       ---------------------------------------
        807500.00    3214500.00          27.804565
        807000.00    3214500.00          23.897537
        807500.00    3214000.00          22.072571
        808000.00    3214000.00          21.725983
        808000.00    3213500.00          17.984741
        808500.00    3213500.00          17.376599
        808000.00    3214500.00          17.154770
        807500.00    3213500.00          17.004333
        807000.00    3214000.00          16.936005
        808500.00    3214000.00          15.604050
```

5.5.1 Actual Simulations by ISCST

Using the PTMAX model described in Section 5.3.3 it was possible to identify, for a typical emission source in the SIA, the worst meteorological conditions for pollution diffusion in the region. Meteorological scenarios were identified, during stable, neutral and unstable conditions. The historical meteorological data collected at the KWI were then carefully analyzed to find real situations similar to the three worst-case meteorological scenario conditions.

The following three days were representative of the possible worst case impacts:

- February 23, 1981, for stable conditions
- January 17, 1981, for neutral conditions
- August 27, 1981, for unstable conditions

The actual meteorological data of these three days were prepared in a proper format for the ISCST run. The emission data previously used for the ISCLT runs (Section 5.4) were utilized for these three ISCST 24-hour simulations in which ground level concentrations were simulated at each hour on 3721 (61 x 61) receptors.

The results of these three runs are summarized in Tables 5-18 to 5-32, where for each of the five pollutants (SO_2, NO_x, NH_3, cement dust, urea dust) and each of the three days, the 50 locations showing the highest hourly concentration impacts are listed (UTM coordinate system).

The simulations are useful for evaluating possible episode impacts in the SIA. Nevertheless, episodes are generally characterized not only by adverse meteorological conditions, but also by abnormally high emission values. Care should, therefore, be exercised in evaluating the results of these simulations in which average emission parameters were used.

5.5.2 Examples of MC-LAGPAR Simulations

As discussed before, MC-LAGPAR was developed more for the future than the present, since very advanced and sophisticated techniques like this one are expected to be strongly needed in the future developments of this SAA-KISR collaboration. In this section, only a few theoretical simulations of puff releases will be presented to show the unique flexibility and simulation power of the technique.

Fig. 5-20 shows three vertical sections characterizing the sequential evolution of a single puff, simulated by 2000 particles. Such particles are instantaneously released at the same location, i.e., the black dot in (0,500), and are displayed after 180, 360 and 540 seconds, respectively. The wind speed (along x) has a linear vertical increase from 1 m/s at the ground to 3 m/s at 500 m, remaining constant above that altitude. An elevated inversion layer is simulated between 600 and 700 m by assuming the following values for σ_w (the standard deviation of the vertical wind fluctuations):

- linear increase from 0.5 m/s at the ground to 1.5 m/s at 600 m
- 0.15 m/s inside the elevated inversion (600-700 m)
- 0.5 m/s above the inversion layer

One can easily see the ability of the model to simulate a complex fumigation case in which part of the puff is fumigated to the ground, much is trapped inside the inversion layer, and only a few particles are able to perforate the inversion.

Fig. 5-21 shows three vertical sections of a puff (2000 particles) instantaneously released from the black dot (0,0) at ground level. In this case the puff is displayed after 270, 540 and 810 seconds, respectively. Both wind speed (along x) and the standard deviations of wind fluctuations are assumed to increase with the height z, proportional to the power law $(z/500)^{0.2}$.

Again, Fig. 5-21 shows the outstanding simulation capabilities of the technique and its potential handling of shear flow conditions, which are practically impossible to be simulated by any other modeling approach.

5.6 Conclusion

The long-term and short-term simulations presented in this Section, together with the initial review of air pollution modeling techniques, represent the core result of this study.

This is just the first step in the development of air pollution models for Kuwait. Nevertheless, the results already obtained provide valuable information for SAA decision makers.

Table 5-18. Concentration (μg/m^3), hour, and location (UTM) of the 50 highest simulated concentrations of SO_2 on February 23, 1981.

*** KUWAIT ISCST,SO2 (DAY 54 1981) ***

* 50 MAXIMUM 1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER) *

* FROM ALL SOURCES *

RANK	CON.	HOUR	DAY	X OR RANGE (METERS)	Y(METERS) OR DIRECTION (DEGREES)	RANK	CON.	HOUR	DAY	X OR RANGE (METERS)	Y(METERS) OR DIRECTION (DEGREES)
1	6499.93359	19	54	805000.0	3205500.0	26	4761.85937	19	54	806000.0	3209500.0
2	6484.83203	19	54	805000.0	3205000.0	27	4676.04687	19	54	803500.0	3200500.0
3	6446.18750	19	54	804500.0	3203000.0	28	4605.79297	19	54	805500.0	3206000.0
4	6331.97656	19	54	804500.0	3203500.0	29	4532.48437	19	54	806000.0	3210000.0
5	6303.15625	19	54	804500.0	3202500.0	30	4360.44141	19	54	804500.0	3205000.0
6	6162.83594	19	54	804000.0	3201000.0	31	4348.57031	19	54	804500.0	3200500.0
7	6158.02734	19	54	805500.0	3207500.0	32	4251.43359	19	54	804000.0	3203000.0
8	6148.00391	19	54	804000.0	3200500.0	33	4245.76172	19	54	805000.0	3203000.0
9	6145.50391	19	54	805000.0	3204500.0	34	4238.51172	19	54	806000.0	3209000.0
10	6105.84766	19	54	805000.0	3206000.0	35	4205.78516	19	54	805000.0	3207000.0
11	5978.31641	19	54	804000.0	3201500.0	36	4048.46387	19	54	803500.0	3201000.0
12	5960.26953	19	54	804500.0	3202000.0	37	4010.51074	8	54	814000.0	3207000.0
13	5937.62500	19	54	805500.0	3207000.0	38	4000.70630	8	54	814500.0	3206500.0
14	5927.41406	19	54	804500.0	3204000.0	39	3908.76001	8	54	815500.0	3205000.0
15	5800.59375	19	54	805500.0	3208000.0	40	3902.58936	8	54	816000.0	3204500.0
16	5593.86719	19	54	805000.0	3204000.0	41	3874.81519	8	54	815000.0	3206000.0
17	5563.27344	19	54	804000.0	3202000.0	42	3870.62671	8	54	813500.0	3207500.0
18	5482.15234	19	54	804500.0	3201500.0	43	3835.54443	21	54	805500.0	3200500.0
19	5355.50000	19	54	805500.0	3206500.0	44	3835.54443	20	54	805500.0	3200500.0
20	5294.68750	19	54	805000.0	3206500.0	45	3825.73340	19	54	805500.0	3205500.0
21	5246.34766	19	54	804500.0	3204500.0	46	3810.47534	8	54	816500.0	3204000.0
22	4992.62891	19	54	804000.0	3202500.0	47	3808.30542	8	54	815000.0	3205500.0
23	4933.95312	19	54	805000.0	3203500.0	48	3802.57568	8	54	813000.0	3208500.0
24	4928.64062	19	54	804500.0	3201000.0	49	3765.43188	8	54	812500.0	3209000.0
25	4864.00391	19	54	805500.0	3208500.0	50	3694.78003	8	54	817500.0	3202500.0

Table 5-19. Concentration ($\mu g/m^3$), hour, and location (UTM) of the 50 highest simulated concentrations of SO_2 on January 17, 1981.

*** KUWAIT ISCST,SO2 (DAY 17 1981) ***

* 50 MAXIMUM 1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER) *

* FROM ALL SOURCES *

RANK	CON.	HOUR	DAY	X OR RANGE (METERS)	Y(METERS) OR DIRECTION (DEGREES)	RANK	CON.	HOUR	DAY	X OR RANGE (METERS)	Y(METERS) OR DIRECTION (DEGREES)
1	3010.61597	8	17	804000.0	3217000.0	26	2544.28906	20	17	806000.0	3217000.0
2	2938.34277	11	17	805500.0	3216000.0	27	2540.40771	6	17	801500.0	3215000.0
3	2888.37354	9	17	805000.0	3217000.0	28	2524.37524	24	17	806000.0	3219000.0
4	2880.81636	10	17	805500.0	3216500.0	29	2522.33008	5	17	802500.0	3218000.0
5	2812.46205	24	17	806500.0	3218000.0	30	2521.71021	5	17	804500.0	3217000.0
6	2761.11450	10	17	804500.0	3217000.0	31	2494.74341	6	17	802000.0	3215000.0
7	2756.23096	4	17	807000.0	3218000.0	32	2487.36841	6	17	801000.0	3215000.0
8	2659.02949	15	17	806000.0	3218000.0	33	2486.47900	2	17	805000.0	3218000.0
9	2655.55990	8	17	805000.0	3216500.0	34	2482.38696	15	17	805500.0	3219000.0
10	2654.06423	5	17	803500.0	3217500.0	35	2477.93140	22	17	805500.0	3217500.0
11	2640.96218	8	17	803000.0	3217500.0	36	2465.44702	2	17	806000.0	3217000.0
12	2624.62891	9	17	804000.0	3217500.0	37	2463.62964	5	17	803000.0	3218000.0
13	2619.23315	12	17	806500.0	3217500.0	38	2452.64771	1	17	805500.0	3217500.0
14	2610.39449	22	17	805000.0	3218000.0	39	2445.77563	22	17	804000.0	3219000.0
15	2591.47021	23	17	806000.0	3217500.0	40	2444.20654	20	17	805500.0	3217500.0
16	2582.55352	17	17	806000.0	3217000.0	41	2431.38916	17	17	805000.0	3218000.0
17	2582.55352	14	17	806000.0	3217000.0	42	2431.38916	14	17	805000.0	3218000.0
18	2576.58594	21	17	806000.0	3217000.0	43	2428.80762	21	17	805000.0	3218000.0
19	2572.42529	22	17	804500.0	3218500.0	44	2424.33472	1	17	806000.0	3217000.0
20	2566.70801	11	17	805000.0	3216000.0	45	2419.49146	16	17	805500.0	3218500.0
21	2553.63306	23	17	805500.0	3218000.0	46	2413.15967	8	17	802500.0	3217500.0
22	2552.57593	17	17	805500.0	3217500.0	47	2385.21802	5	17	802000.0	3218500.0
23	2552.57593	14	17	805500.0	3217500.0	48	2371.88086	4	17	807000.0	3217500.0
24	2548.81860	21	17	805500.0	3217500.0	49	2370.61060	6	17	800500.0	3215000.0
25	2548.14404	2	17	805500.0	3217500.0	50	2363.41675	16	17	806000.0	3217500.0

Table 5-20. Concentration ($\mu g/m^3$), hour, and location (UTM) of the 50 highest simulated concentrations of SO_2 on August 27, 1981.

```
             ***                    KUWAIT ISCST,SO2 (DAY 239 1981)              ***

        * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)      *

                                    * FROM ALL SOURCES *

                                 X      Y(METERS)                                      X      Y(METERS)
                                OR         OR                                         OR         OR
                              RANGE     DIRECTION                                   RANGE     DIRECTION
RANK      CON.      HOUR DAY (METERS)   (DEGREES)     RANK      CON.      HOUR DAY (METERS)   (DEGREES)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

  1    6317.49219     9  239  806500.0  3212500.0      26    4839.65625     7  239  816500.0  3217000.0
  2    5388.82031    20  239  813500.0  3226500.0      27    4836.70703    20  239  815500.0  3230500.0
  3    5374.62500    20  239  814500.0  3228000.0      28    4783.31250    20  239  814500.0  3227500.0
  4    5367.37500    20  239  815000.0  3229000.0      29    4755.43750     7  239  817500.0  3217000.0
  5    5343.30859    20  239  814000.0  3227500.0      30    4701.21094    20  239  813000.0  3225000.0
  6    5312.74609    20  239  813000.0  3225500.0      31    4680.06250     7  239  818500.0  3217560.0
  7    5283.00781    20  239  815500.0  3230000.0      32    4666.40625    20  239  814000.0  3228000.0
  8    5280.55078    20  239  814000.0  3227000.0      33    4662.63672     7  239  816000.0  3217000.0
  9    5226.83203    20  239  814500.0  3228500.0      34    4650.41797    20  239  812000.0  3223500.0
 10    5165.33984    20  239  816000.0  3230500.0      35    4627.58984    20  239  816000.0  3230000.0
 11    5131.23047    20  239  815500.0  3229500.0      36    4576.51562    20  239  811500.0  3223000.0
 12    5114.92187     7  239  820000.0  3217500.0      37    4550.21094     7  239  818000.0  3217000.0
 13    5066.48828    20  239  812500.0  3224500.0      38    4525.85156    14  239  805500.0  3216000.0
 14    5061.48828     7  239  819500.0  3217500.0      39    4496.43359    16  239  805000.0  3216500.0
 15    5061.00547    20  239  813500.0  3226000.0      40    4488.72266    14  239  806000.0  3216000.0
 16    5056.06547     7  239  820500.0  3217500.0      41    4447.85156    20  239  814500.0  3229000.0
 17    5048.80469    20  239  815000.0  3229500.0      42    4445.44141    20  239  814000.0  3226500.0
 18    5017.93359    20  239  812500.0  3225000.0      43    4395.80859    20  239  815500.0  3229000.0
 19    5008.98828    20  239  815000.0  3228500.0      44    4395.74609    13  239  806000.0  3215500.0
 20    4980.98437    20  239  813000.0  3226000.0      45    4391.72266    11  239  807000.0  3215000.0
 21    4940.30859     7  239  819000.0  3217500.0      46    4337.52344    15  239  805500.0  3215500.0
 22    4924.48437     7  239  821000.0  3217500.0      47    4316.46484     7  239  815500.0  3217000.0
 23    4902.64844    20  239  812000.0  3224000.0      48    4297.48828     7  239  818000.0  3217500.0
 24    4862.55219     7  239  817000.0  3217000.0      49    4285.16406     7  239  818500.0  3217000.0
 25    4852.51953    20  239  813500.0  3227000.0      50    4245.47656     7  239  821000.0  3218000.0
```

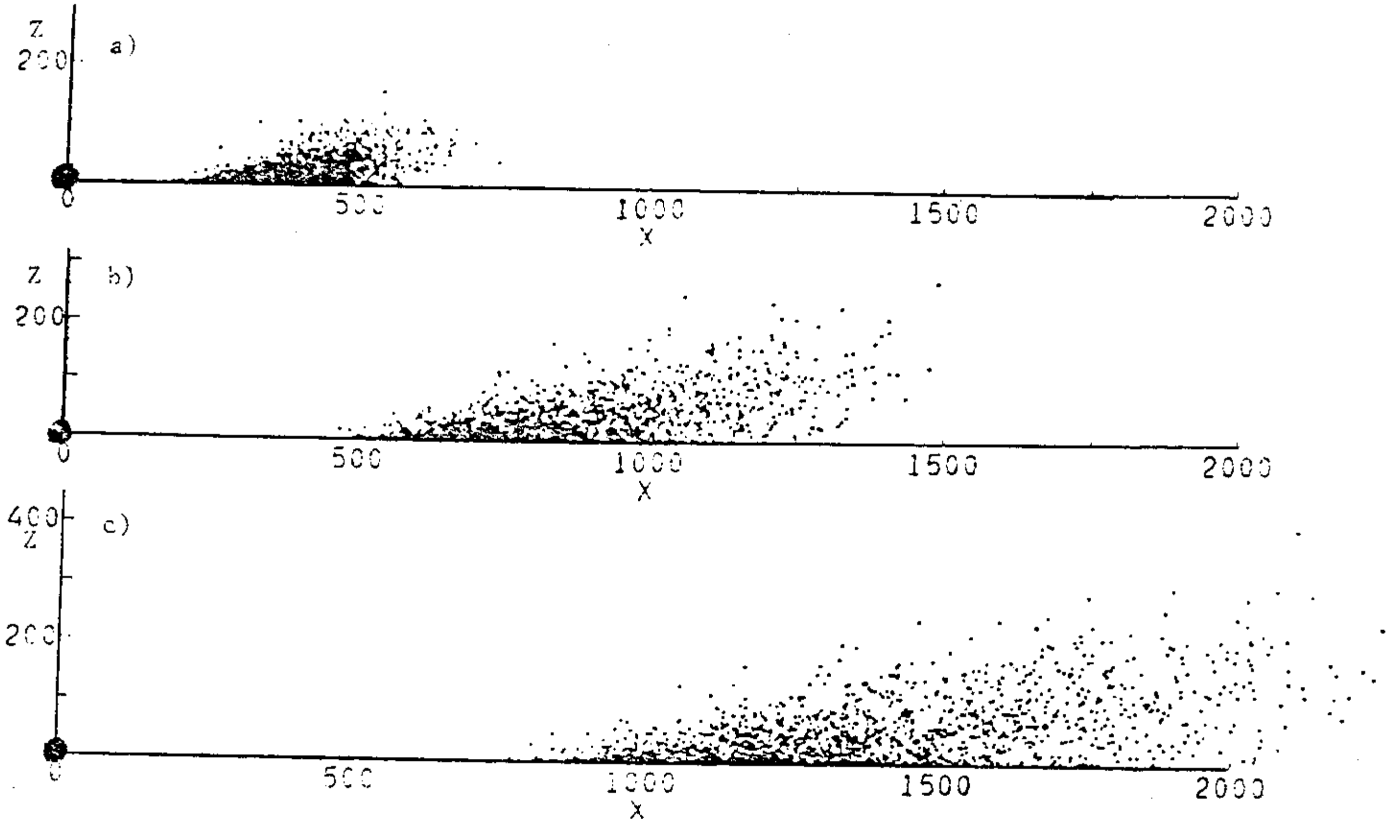


Fig. 5-21. Puff ground level release in shear flow conditions.

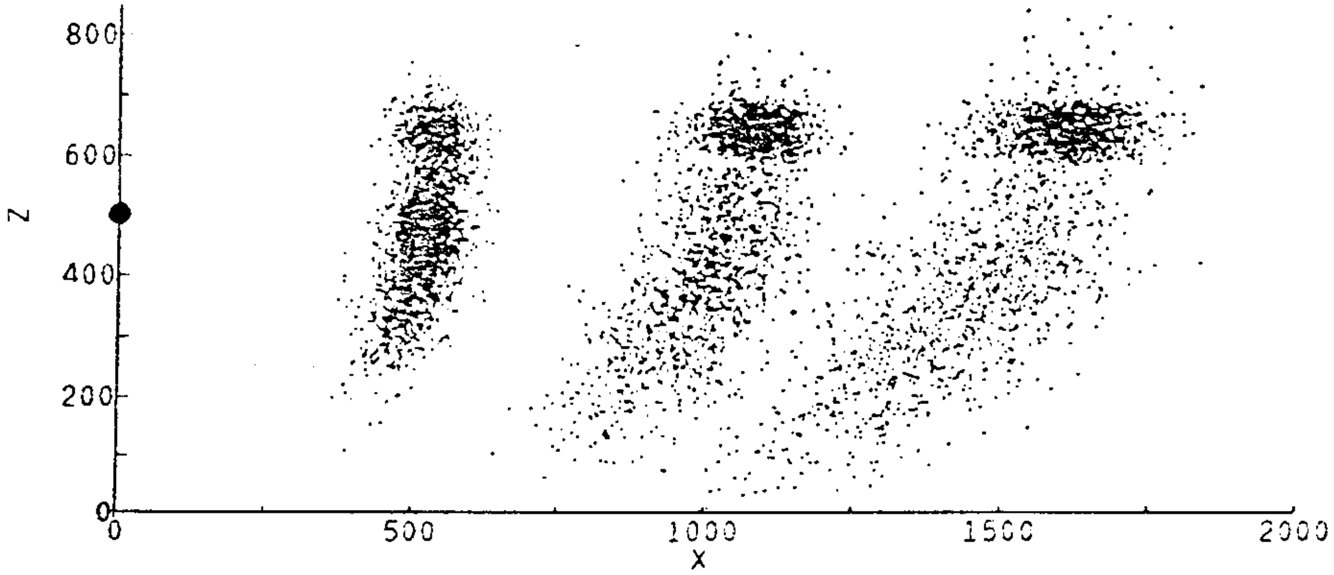


Fig. 5-20. Puff partial fumigation due to an elevated inversion layer.

Table 5-21. Concentration ($\mu g/m^3$), hour, and location (UTM) of the 50 highest simulated concentrations of NO_x on February 23, 1981.

```
             ***                 KUWAIT ISCST,NCX (DAY 54 1981)                  ***

          * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)     *

                                      * FROM ALL SOURCES *

                                  X        Y(METERS)                                          X        Y(METERS)
                                  OR          OR                                              OR          OR
                                RANGE     DIRECTION                                         RANGE     DIRECTION
 RANK      CON.      HOUR DAY  (METERS)   (DEGREES)      RANK      CON.      HOUR DAY  (METERS)   (DEGREES)
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   1    2384.20728    19   54   804000.0  3202000.0       26    1801.48755    19   54   804500.0  3202000.0
   2    2362.08521    19   54   804000.0  3201500.0       27    1787.69629    19   54   804000.0  3204000.0
   3    2349.05591    19   54   804500.0  3204000.0       28    1787.41943    21   54   805500.0  3201000.0
   4    2335.24561    19   54   804000.0  3202500.0       29    1787.41943    20   54   805500.0  3201000.0
   5    2306.97339    19   54   804500.0  3203500.0       30    1785.23315    19   54   805500.0  3208000.0
   6    2302.56079    19   54   804500.0  3204500.0       31    1778.45068    19   54   803500.0  3202000.0
   7    2283.63354    19   54   803500.0  3200500.0       32    1759.22510    19   54   805000.0  3204500.0
   8    2277.08643    19   54   804000.0  3201000.0       33    1750.59814    23   54   808000.0  3201000.0
   9    2214.06885    19   54   804000.0  3203000.0       34    1745.33545    19   54   805500.0  3207500.0
  10    2187.44800    19   54   804500.0  3203000.0       35    1722.28198    21   54   805500.0  3201500.0
  11    2178.24219    19   54   805000.0  3206000.0       36    1722.28198    20   54   805500.0  3201500.0
  12    2170.01758    19   54   804500.0  3205000.0       37    1716.99268    19   54   805000.0  3207500.0
  13    2167.59595    19   54   803500.0  3201000.0       38    1710.10352    19   54   804500.0  3206000.0
  14    2142.20361    19   54   804000.0  3200500.0       39    1661.40356    22   54   806500.0  3200500.0
  15    2127.19287    19   54   805000.0  3205500.0       40    1656.56714    19   54   805500.0  3208500.0
  16    2110.63208    19   54   805000.0  3206500.0       41    1633.90454    23   54   808000.0  3201500.0
  17    2027.30078    19   54   804000.0  3203500.0       42    1631.14795    21   54   805500.0  3202000.0
  18    2011.41406    19   54   804500.0  3202500.0       43    1631.14795    20   54   805500.0  3202000.0
  19    1996.24707    19   54   803500.0  3201500.0       44    1627.40063    22   54   806500.0  3201000.0
  20    1975.45947    19   54   805000.0  3205000.0       45    1588.25464    22   54   806500.0  3201500.0
  21    1966.50317    19   54   804500.0  3205500.0       46    1580.40015     8   54   814500.0  3205500.0
  22    1942.40967    19   54   805000.0  3207000.0       47    1578.16016    19   54   804500.0  3201500.0
  23    1835.21460    23   54   808000.0  3200500.0       48    1573.34912     8   54   814000.0  3206000.0
  24    1825.39380    21   54   805500.0  3200500.0       49    1570.99390    19   54   805500.0  3207000.0
  25    1825.39380    20   54   805500.0  3200500.0       50    1566.03198    23   54   807500.0  3204500.0
```

Table 5-22. Concentration ($\mu g/m^3$), hour, and location (UTM) of the 50 highest simulated concentrations of NO_x on January 17, 1981.

```
         ***                 KUWAIT ISCST,NOX (DAY 17  1981)                 ***

       * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)      *

                                    * FROM ALL SOURCES *

                                    X      Y(METERS)                                          X      Y(METERS)
                                   OR         OR                                             OR         OR
                                 RANGE    DIRECTION                                        RANGE    DIRECTION
 RANK        CON.      HOUR DAY (METERS)  (DEGREES)        RANK        CON.      HOUR DAY (METERS)  (DEGREES)
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   1      1083.13940     4   17  806000.0  3218500.0        26      894.46899    16   17  805500.0  3217000.0
   2      1043.02881     4   17  806000.0  3219000.0        27      893.46021     7   17  801000.0  3215500.0
   3      1004.52222     4   17  806000.0  3218000.0        28      884.83862     8   17  804000.0  3216500.0
   4       997.71143     4   17  806500.0  3214500.0        29      883.64868    23   17  804500.0  3218000.0
   5       945.60229     4   17  806000.0  3219500.0        30      882.90869    10   17  803500.0  3217000.0
   6       935.34521     9   17  804000.0  3217000.0        31      882.12842    12   17  805500.0  3217500.0
   7       934.32690    22   17  804500.0  3217500.0        32      881.96216    10   17  804500.0  3216500.0
   8       928.58008    24   17  805500.0  3218000.0        33      880.61133     7   17  803000.0  3215500.0
   9       926.55933     8   17  803000.0  3217000.0        34      878.35083    15   17  805000.0  3218000.0
  10       924.40039    16   17  806000.0  3214500.0        35      876.74780     1   17  804500.0  3217500.0
  11       922.62085     7   17  802000.0  3215500.0        36      872.21704    22   17  803500.0  3218500.0
  12       916.60498    23   17  805000.0  3217500.0        37      872.11035    24   17  806000.0  3217000.0
  13       916.39526     2   17  804500.0  3217500.0        38      870.10669     9   17  803000.0  3217500.0
  14       916.20752    17   17  805000.0  3217000.0        39      869.17554    11   17  804500.0  3216000.0
  15       916.20752    14   17  805000.0  3217000.0        40      868.47827     8   17  802000.0  3217500.0
  16       915.59058     2   17  805000.0  3217000.0        41      868.42334    13   17  806000.0  3214000.0
  17       915.46289    21   17  805000.0  3217000.0        42      866.32471     7   17  800500.0  3215500.0
  18       914.41187    22   17  804000.0  3218000.0        43      865.55420     5   17  802500.0  3217500.0
  19       914.24878     7   17  802500.0  3215500.0        44      864.57690     2   17  804000.0  3218000.0
  20       913.67065     7   17  801500.0  3215500.0        45      863.80469    20   17  804500.0  3217500.0
  21       910.48486    11   17  804000.0  3216000.0        46      862.99976    16   17  804500.0  3218500.0
  22       903.31738    17   17  804500.0  3217500.0        47      862.74829    20   17  805000.0  3217000.0
  23       903.31738    14   17  804500.0  3217500.0        48      860.86816    12   17  806000.0  3216500.0
  24       903.05176    22   17  805000.0  3217000.0        49      855.08447    15   17  804500.0  3219000.0
  25       902.72510    21   17  804500.0  3217500.0        50      853.51099     4   17  805500.0  3221000.0
```

Table 5-23. Concentration ($\mu g/m^3$), hour, and location (UTM) of the 50 highest simulated concentrations of NO_x on August 27, 1981.

```
          * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)      *

                                    * FROM ALL SOURCES *

                                 X        Y(METERS)                                           X        Y(METERS)
                                 OR          OR                                               OR          OR
                                RANGE     DIRECTION                                          RANGE     DIRECTION
RANK      CON.      HOUR DAY  (METERS)    (DEGREES)      RANK      CON.      HOUR DAY  (METERS)    (DEGREES)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

  1     1963.11230   20  239   815000.0   3229500.0       26     1761.02759    7  239   817000.0   3217000.0
  2     1959.85693   20  239   815500.0   3230500.0       27     1754.98730   20  239   816000.0   3230500.0
  3     1947.60620   20  239   814000.0   3228000.0       28     1753.06543   20  239   812500.0   3225000.0
  4     1939.63354   20  239   814500.0   3228500.0       29     1748.10718   20  239   812000.0   3224500.0
  5     1939.36475   20  239   814500.0   3229000.0       30     1745.73437   20  239   814500.0   3229500.0
  6     1923.77856   20  239   813500.0   3227000.0       31     1689.28491    7  239   819500.0   3217000.0
  7     1906.62085   20  239   815000.0   3230000.0       32     1683.63599   20  239   815500.0   3229500.0
  8     1901.50391    7  239   821000.0   3217500.0       33     1678.75586   20  239   815000.0   3230500.0
  9     1893.06396   20  239   815500.0   3230000.0       34     1676.31494   20  239   813000.0   3225500.0
 10     1888.52539    7  239   820500.0   3217500.0       35     1664.58838   20  239   814000.0   3227000.0
 11     1884.96313   20  239   814000.0   3227500.0       36     1652.25073    7  239   816500.0   3217000.0
 12     1860.61816   20  239   813000.0   3226000.0       37     1650.59375    7  239   819000.0   3217500.0
 13     1849.14331   20  239   813000.0   3226500.0       38     1641.68604   20  239   812000.0   3225000.0
 14     1844.05273    7  239   820000.0   3217500.0       39     1633.15503   20  239   812500.0   3226000.0
 15     1842.17432   20  239   815000.0   3229000.0       40     1608.29810   20  239   811500.0   3223500.0
 16     1838.64697   20  239   813500.0   3227500.0       41     1606.85864   20  239   811500.0   3224000.0
 17     1837.08789    7  239   818000.0   3217000.0       42     1600.12598    7  239   820000.0   3217000.0
 18     1822.54248   20  239   812500.0   3225500.0       43     1598.94507   20  239   812000.0   3224000.0
 19     1821.22754    7  239   817500.0   3217000.0       44     1597.34985   20  239   813000.0   3227000.0
 20     1815.39868    7  239   818500.0   3217000.0       45     1593.24097   20  239   815000.0   3228500.0
 21     1801.29102   20  239   814000.0   3228500.0       46     1545.38379   20  239   813500.0   3226000.0
 22     1796.71826   20  239   813500.0   3226500.0       47     1543.96948   20  239   813500.0   3228000.0
 23     1765.38721   20  239   814500.0   3228000.0       48     1533.18530    7  239   815500.0   3216500.0
 24     1765.11768    7  239   819500.0   3217500.0       49     1530.48291   20  239   812500.0   3224500.0
 25     1763.53735    7  239   819000.0   3217000.0       50     1529.81030    7  239   815000.0   3216500.0
```

Table 5-24. Concentration ($\mu g/m^3$), hour, and location (UMT) of the 50 highest simulated concentrations of NH_3 on February 23, 1981.

```
          ***                  KUWAIT ISCST,AMMONIA (DAY 54 1981)      ***

            * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)      *

                                     * FROM ALL SOURCES *

                                   X       Y(METERS)                                        X       Y(METERS)
                                  OR          OR                                           OR          OR
                                RANGE     DIRECTION                                      RANGE     DIRECTION
 RANK       CON.     HOUR DAY  (METERS)   (DEGREES)        RANK       CON.     HOUR DAY  (METERS)   (DEGREES)
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   1     1012.98926   54   54   807000.0  3214000.0         26     399.77832    9   54   807500.0  3214000.0
   2      778.05566   54   54   807000.0  3213500.0         27     395.08618   18   54   808000.0  3208500.0
   3      714.64062   18   54   807000.0  3213500.0         28     394.57080   19   54   805500.0  3209000.0
   4      604.45483   16   54   807000.0  3214000.0         29     392.80200   18   54   808000.0  3210000.0
   5      597.34692   18   54   807500.0  3211500.0         30     391.56299   19   54   805500.0  3209500.0
   6      571.37891   18   54   807500.0  3211000.0         31     389.58521    9   54   808500.0  3212500.0
   7      557.68970   13   54   807000.0  3215000.0         32     388.03613    9   54   809500.0  3211500.0
   8      542.46289    9   54   808000.0  3213500.0         33     367.47266   54   54   807500.0  3212500.0
   9      536.77686   18   54   807000.0  3213000.0         34     367.01660   19   54   805500.0  3208500.0
  10      531.43994   18   54   807500.0  3212000.0         35     359.99683   19   54   805000.0  3207000.0
  11      493.57495   18   54   807500.0  3210500.0         36     359.41675   11   54   807000.0  3215000.0
  12      488.68115   54   54   807000.0  3213000.0         37     358.95424   18   54   808000.0  3208000.0
  13      488.25404   12   54   807000.0  3215000.0         38     356.46509   19   54   806000.0  3211500.0
  14      461.73682   16   54   807000.0  3214500.0         39     354.85449   54   54   807500.0  3213000.0
  15      459.35229   18   54   807000.0  3214000.0         40     354.43604   19   54   805000.0  3206500.0
  16      459.06641   15   54   807000.0  3214500.0         41     350.81543   54   54   807500.0  3213500.0
  54      437.58252   15   54   807000.0  3214000.0         42     344.93066   54   54   807500.0  3212000.0
  18      431.14014    9   54   809000.0  3212000.0         43     344.47119   18   54   807000.0  3212500.0
  19      423.32837    9   54   808500.0  3213000.0         44     341.64038   18   54   807500.0  3213500.0
  20      419.07642   18   54   808000.0  3209500.0         45     341.26318   18   54   807500.0  3213000.0
  21      454.92358   18   54   808000.0  3209000.0         46     341.12183    9   54   809000.0  3212500.0
  22      412.53809   16   54   807000.0  3213500.0         47     340.99902   18   54   808000.0  3210500.0
  23      403.96573   13   54   807500.0  3214500.0         48     339.71509   11   54   807500.0  3214500.0
  24      402.44507   18   54   807500.0  3210000.0         49     339.67285   19   54   805000.0  3207500.0
  25      400.74609   18   54   807500.0  3212500.0         50     338.26367   19   54   805500.0  3210000.0
```

Table 5-25. Concentration ($\mu g/m^3$), hour, and location (UTM) of the 50 highest simulated concentrations of NH_3 on January 17, 1981.

```
           ***                    KUWAIT ISCST,AMMONIA (DAY 17  1981)    ***

         * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)     *

                                     * FROM ALL SOURCES *

                                    X       Y(METERS)                                         X       Y(METERS)
                                   OR          OR                                            OR          OR
                                 RANGE     DIRECTION                                       RANGE     DIRECTION
 RANK       CON.      HOUR DAY  (METERS)   (DEGREES)      RANK       CON.      HOUR DAY  (METERS)   (DEGREES)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   1     345.18555     6   17   805000.0   3215000.0       26     123.22975     8   17   804000.0   3216500.0
   2     302.46411     6   17   804500.0   3215000.0       27     118.70483     9   17   804500.0   3216500.0
   3     245.14406     6   17   805500.0   3215000.0       28     118.05876    22   17   804500.0   3217500.0
   4     232.29237     6   17   804000.0   3215000.0       29     117.13994     6   17   803000.0   3214500.0
   5     196.82726     5   17   804500.0   3216500.0       30     115.19125    24   17   806000.0   3217000.0
   6     177.96925     8   17   805000.0   3216000.0       31     114.75371    22   17   806000.0   3216000.0
   7     173.54614     6   17   803500.0   3215000.0       32     113.56374     2   17   805500.0   3216500.0
   8     162.79686     5   17   803500.0   3217000.0       33     112.33485    16   17   805500.0   3217000.0
   9     157.66469     5   17   805000.0   3216000.0       34     110.45998     8   17   804500.0   3216000.0
  10     156.86012     5   17   805500.0   3216000.0       35     109.38890     6   17   800000.0   3214500.0
  11     153.48827     5   17   804000.0   3216500.0       36     108.15929    11   17   805000.0   3215500.0
  12     151.17700     6   17   802000.0   3214500.0       37     107.44101    10   17   805000.0   3216000.0
  13     149.26833    22   17   805500.0   3216500.0       38     107.19322    15   17   805500.0   3217500.0
  14     147.53685     6   17   801500.0   3214500.0       39     106.70526     4   17   806500.0   3217000.0
  15     142.63545     6   17   802500.0   3214500.0       40     106.14415    11   17   805500.0   3215500.0
  16     137.01453     6   17   801000.0   3214500.0       41     103.80376     5   17   801500.0   3218000.0
  17     136.80066    22   17   805000.0   3217000.0       42     103.77197    17   17   805500.0   3216500.0
  18     132.85768     4   17   806500.0   3216500.0       43     103.77197    14   17   805500.0   3216500.0
  19     132.37885    15   17   806000.0   3216500.0       44     103.76086    21   17   805500.0   3216500.0
  20     130.56331     6   17   803000.0   3215000.0       45     103.70242     5   17   802000.0   3217500.0
  21     129.21217     5   17   802500.0   3217500.0       46     103.52115     2   17   805000.0   3217000.0
  22     126.99704     5   17   803000.0   3217000.0       47     102.94676    23   17   805000.0   3217500.0
  23     126.08307     9   17   805500.0   3216000.0       48     101.09576    22   17   804000.0   3218000.0
  24     125.76413     8   17   803500.0   3216500.0       49     100.36522     8   17   802500.0   3217000.0
  25     123.50565     6   17   800500.0   3214500.0       50      99.91702     6   17   802500.0   3215000.0
```

Table 5-26. Concentration (μg/m^3), hour, and location (UTM) of the 50 highest simulated concentrations of NH_3 on August 27, 1981.

```
            ***                 KUWAIT ISCST,AMMONIA (DAY 239 1981)          ***

          * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)     *

                                  * FROM ALL SOURCES *

                                    X      Y(METERS)                                               X      Y(METERS)
                                   OR         OR                                                  OR         OR
                                 RANGE    DIRECTION                                             RANGE    DIRECTION
RANK       CON.      HOUR DAY  (METERS)  (DEGREES)           RANK       CON.      HOUR DAY  (METERS)  (DEGREES)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

  1      832.97095    17  239  806500.0  3216000.0            26      407.18750    20  239  809500.0  3220000.0
  2      624.35742    16  239  806000.0  3215500.0            27      404.60864    19  239  807000.0  3219000.0
  3      622.27954     7  239  812000.0  3216000.0            28      395.45435     7  239  814000.0  3216000.0
  4      612.60156     9  239  806500.0  3214500.0            29      389.26758    20  239  810500.0  3221500.0
  5      605.78589     7  239  812500.0  3216000.0            30      387.62646    20  239  809000.0  3219000.0
  6      578.94458    11  239  806500.0  3215000.0            31      381.30835     9  239  806500.0  3214000.0
  7      567.24048     7  239  811500.0  3216000.0            32      378.11353    20  239  810000.0  3220500.0
  8      547.26660     7  239  813000.0  3216000.0            33      375.25073    20  239  810000.0  3221000.0
  9      537.22119     8  239  806000.0  3213000.0            34      374.57275     7  239  817000.0  3216500.0
 10      514.48828    19  239  807000.0  3218000.0            35      370.22827    20  239  811000.0  3222500.0
 11      502.18604    19  239  807000.0  3217500.0            36      367.89746     7  239  814000.0  3216500.0
 12      491.46899     7  239  809000.0  3215500.0            37      355.82642     4  239  817000.0  3217000.0
 13      483.57861     8  239  806000.0  3213500.0            38      355.53223    15  239  805500.0  3215000.0
 14      471.90161     7  239  813500.0  3216000.0            39      354.37939     8  239  805000.0  3210500.0
 15      466.66577    19  239  807000.0  3218500.0            40      353.42847    19  239  807000.0  3217000.0
 16      458.47510     8  239  805500.0  3212000.0            41      351.32153     5  239  817000.0  3218500.0
 17      454.23486     7  239  815500.0  3216500.0            42      347.65039     6  239  817500.0  3219500.0
 18      451.24707     7  239  815000.0  3216500.0            43      347.22461     5  239  815500.0  3218000.0
 19      445.39941     7  239  809500.0  3215500.0            44      346.67676     5  239  818500.0  3219000.0
 20      438.34253     7  239  816000.0  3216500.0            45      346.61719     2  239  817000.0  3218500.0
 21      426.64111     7  239  811000.0  3216000.0            46      345.69629    19  239  807000.0  3219500.0
 22      425.01953     8  239  805500.0  3211500.0            47      345.25732     4  239  816500.0  3217000.0
 23      423.46973     7  239  814500.0  3216500.0            48      345.24609     3  239  817000.0  3218000.0
 24      409.94165     7  239  816500.0  3216500.0            49      344.58838     6  239  815000.0  3218500.0
 25      408.92358    17  239  806500.0  3216500.0            50      343.80493    13  239  806000.0  3215000.0
```

Table 5-27. Concentration ($\mu g/m^3$), hour, and location (UTM) of the 50 highest simulated concentrations of cement dust on February 23, 1981.

```
               ***                 KUWAIT ISCST,CEMENT DUST(DAY 54  1981)           ***

            * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)      *

                                          * FROM ALL SOURCES *

                                     X      Y(METERS)                                                 X      Y(METERS)
                                    OR         OR                                                    OR         OR
                                  RANGE    DIRECTION                                               RANGE    DIRECTION
 RANK      CON.      HOUR DAY   (METERS)   (DEGREES)          RANK      CON.      HOUR DAY   (METERS)   (DEGREES)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   1     1977.96606   13   54   807000.0   3216000.0           26     1184.33398   22   54   806500.0   3208500.0
   2     1733.34912   12   54   807000.0   3216000.0           27     1181.42236   21   54   806000.0   3209500.0
   3     1709.96167   11   54   807000.0   3216000.0           28     1181.42236   20   54   806000.0   3209500.0
   4     1484.58887    9   54   807500.0   3215000.0           29     1181.39844    3   54   811500.0   3210500.0
   5     1391.25146   18   54   807000.0   3214000.0           30     1178.21875    5   54   810000.0   3212000.0
   6     1376.54956   19   54   805500.0   3211500.0           31     1175.65552    1   54   813000.0   3211000.0
   7     1318.27710   18   54   807000.0   3213500.0           32     1174.23584   23   54   807000.0   3211000.0
   8     1296.65259   17   54   807000.0   3214500.0           33     1173.93921    2   54   812500.0   3210500.0
   9     1295.24170   19   54   806000.0   3214000.0           34     1170.18994   22   54   806500.0   3208000.0
  10     1275.57764    9   54   808000.0   3214500.0           35     1169.16382   22   54   806500.0   3210500.0
  11     1273.42407   19   54   806000.0   3213500.0           36     1168.86084    1   54   812500.0   3211500.0
  12     1270.49341   19   54   805500.0   3212000.0           37     1163.42065    4   54   811500.0   3211000.0
  13     1228.92065   16   54   806500.0   3215500.0           38     1160.22754    5   54   812000.0   3209500.0
  14     1227.02271   21   54   806000.0   3210000.0           39     1160.10425    2   54   810500.0   3212500.0
  15     1227.02271   20   54   806000.0   3210000.0           40     1158.38379    5   54   811500.0   3210000.0
  16     1207.43506    2   54   811500.0   3211500.0           41     1154.97876    4   54   810500.0   3212000.0
  17     1201.26025   21   54   806000.0   3210500.0           42     1153.56445   17   54   807000.0   3214000.0
  18     1201.26025   20   54   806000.0   3210500.0           43     1153.49268   22   54   806500.0   3207500.0
  19     1199.73169   22   54   806500.0   3209500.0           44     1148.51709    2   54   813000.0   3210000.0
  20     1195.16504    2   54   811000.0   3212000.0           45     1145.59863    3   54   812000.0   3210000.0
  21     1194.96924   22   54   806500.0   3209000.0           46     1142.31128    8   54   808500.0   3214000.0
  22     1194.59424    2   54   812000.0   3211000.0           47     1134.97876   22   54   806500.0   3207000.0
  23     1191.84009    4   54   811000.0   3211500.0           48     1134.58984   22   54   806500.0   3211000.0
  24     1190.05933   19   54   805500.0   3211000.0           49     1130.09277   23   54   807000.0   3210500.0
  25     1189.87427   22   54   806500.0   3210000.0           50     1129.43140   23   54   807000.0   3211500.0
```

Table 5-28. Concentration (μg/m^3), hour, and location (UTM) of the 50 highest simulated concentrations of cement dust on January 17, 1981.

```
          ***                 KUWAIT ISCST,CEMENT DUST(DAY 17  1981)          ***

             * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)      *

                                         * FROM ALL SOURCES *

                                      X      Y(METERS)                                                  X      Y(METERS)
                                     OR         OR                                                     OR         OR
                                   RANGE    DIRECTION                                                RANGE    DIRECTION
 RANK        CON.       HOUR DAY  (METERS)  (DEGREES)          RANK        CON.       HOUR DAY  (METERS)  (DEGREES)
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   1      1194.46729     5   17   805500.0  3217000.0           26       572.63745    12   17   806000.0  3217500.0
   2       993.13428    22   17   806000.0  3217000.0           27       567.62061    22   17   805000.0  3218000.0
   3       845.64209     2   17   806000.0  3217000.0           28       557.10937     6   17   803000.0  3216000.0
   4       834.91479     7   17   805500.0  3216500.0           29       543.34253     7   17   804000.0  3216500.0
   5       823.62769    22   17   805500.0  3217500.0           30       533.12476     1   17   805500.0  3217500.0
   6       803.06079    17   17   806000.0  3217000.0           31       520.95752    10   17   805500.0  3217000.0
   7       803.06079    14   17   806000.0  3217000.0           32       517.82153    16   17   805500.0  3218000.0
   8       802.44629    21   17   806000.0  3217000.0           33       493.30396     3   17   805500.0  3217500.0
   9       799.59521     7   17   805000.0  3216500.0           34       482.21484     5   17   803500.0  3218000.0
  10       785.23535     9   17   805500.0  3217000.0           35       476.50781    24   17   806000.0  3218000.0
  11       753.69019     5   17   804500.0  3217500.0           36       476.21924    19   17   805500.0  3217500.0
  12       712.15283     8   17   805000.0  3217000.0           37       474.67578    20   17   805500.0  3217500.0
  13       704.82617     3   17   806000.0  3217000.0           38       460.75391     6   17   802500.0  3216000.0
  14       703.15845     1   17   806000.0  3217000.0           39       458.71851     8   17   804000.0  3217500.0
  15       689.79297    19   17   806000.0  3217000.0           40       448.33154     7   17   803500.0  3216500.0
  16       684.80200    15   17   806000.0  3217500.0           41       443.01440    18   17   805500.0  3217500.0
  17       664.74072     7   17   804500.0  3216500.0           42       439.15698     2   17   805000.0  3218000.0
  18       652.55591    18   17   806000.0  3217000.0           43       432.62427     4   17   806500.0  3217000.0
  19       650.30884     2   17   805500.0  3217500.0           44       432.04736    11   17   806000.0  3216500.0
  20       647.62646    20   17   806000.0  3217000.0           45       409.83789    22   17   804500.0  3218500.0
  21       630.10620     6   17   803500.0  3216000.0           46       403.55322    17   17   805000.0  3218000.0
  22       608.41260     6   17   804000.0  3216000.0           47       403.55322    14   17   805000.0  3218000.0
  23       601.77832    17   17   805500.0  3217500.0           48       403.47754    21   17   805000.0  3218000.0
  24       601.77832    14   17   805500.0  3217500.0           49       399.05933     6   17   804500.0  3216000.0
  25       601.59131    21   17   805500.0  3217500.0           50       381.26221    23   17   805000.0  3218500.0
```

Table 5-29. Concentration ($\mu g/m^3$), hour, and location (UTM) of the 50 highest simulated concentrations of cement dust on August 27, 1981.

```
           ***                    KUWAIT ISCST,CEMENT DUST(DAY 239 1981)           ***

        * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)      *

                                      * FROM ALL SOURCES *

                                  X        Y(METERS)                                            X        Y(METERS)
                                  OR          OR                                                OR          OR
                                RANGE     DIRECTION                                           RANGE     DIRECTION
 RANK        CON.      HOUR DAY  (METERS)  (DEGREES)           RANK        CON.      HOUR DAY  (METERS)  (DEGREES)
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   1      2287.60352    12  239   806500.0  3216000.0           26      1270.26660    24  239   810000.0  3222500.0
   2      2280.55420    18  239   806500.0  3217500.0           27      1250.40771     7  239   811500.0  3217000.0
   3      1787.60278     8  239   806000.0  3215000.0           28      1246.68359     5  239   811500.0  3218000.0
   4      1644.23291    18  239   806500.0  3217000.0           29      1245.43042     2  239   814500.0  3219000.0
   5      1621.64600     7  239   810500.0  3217000.0           30      1228.81909    14  239   806000.0  3216500.0
   6      1586.21924    18  239   806500.0  3218000.0           31      1224.49805     4  239   813000.0  3217500.0
   7      1493.76782    20  239   808000.0  3219000.0           32      1222.83447     4  239   815500.0  3218000.0
   8      1491.93457     7  239   811000.0  3217000.0           33      1218.21411     6  239   811500.0  3218500.0
   9      1460.01978    17  239   806500.0  3217000.0           34      1210.85522     3  239   814500.0  3218500.0
  10      1458.44629     7  239   810000.0  3217000.0           35      1210.56592     3  239   814000.0  3218500.0
  11      1350.86963     8  239   805500.0  3213500.0           36      1210.06665    23  239   810000.0  3225000.0
  12      1350.26001    20  239   808500.0  3220000.0           37      1209.96875     6  239   815500.0  3220000.0
  13      1329.45947     6  239   813000.0  3219000.0           38      1204.86084     2  239   811500.0  3218000.0
  14      1320.29834     5  239   813000.0  3218500.0           39      1198.93970     5  239   816000.0  3219500.0
  15      1310.66992    20  239   809000.0  3220500.0           40      1184.98364     4  239   815000.0  3218000.0
  16      1299.93848    23  239   809000.0  3222500.0           41      1182.56860    21  239   811000.0  3224000.0
  17      1290.98804     4  239   812500.0  3217500.0           42      1182.09253    21  239   811500.0  3225000.0
  18      1284.03979     2  239   813000.0  3218500.0           43      1180.39697    24  239   811000.0  3224000.0
  19      1282.34766    21  239   809500.0  3221500.0           44      1180.09741    24  239   811500.0  3225000.0
  20      1279.13794    24  239   809500.0  3221500.0           45      1175.24805     6  239   810500.0  3218000.0
  21      1277.03394    20  239   809500.0  3221500.0           46      1174.19556     2  239   816000.0  3219500.0
  22      1276.42065     3  239   812500.0  3218000.0           47      1172.10547     3  239   816000.0  3219000.0
  23      1275.41724     5  239   814500.0  3219000.0           48      1171.97852    23  239   809500.0  3223500.0
  24      1273.80200     6  239   814000.0  3219500.0           49      1156.39966     6  239   816500.0  3220500.0
  25      1273.07520    21  239   810000.0  3222500.0           50      1151.57080    23  239   809500.0  3224000.0
```

Table 5-30. Concentration ($\mu g/m^3$), hour and location (UTM) of the 50 highest simulated concentrations of urea dust on February 23, 1981.

```
            ***               KUWAIT ISCST,UREA DUST(DAY 54  1981)                ***

        * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)       *

                                   * FROM ALL SOURCES *

                                  X       Y(METERS)                                            X       Y(METERS)
                                  OR         OR                                                OR         OR
                                RANGE     DIRECTION                                          RANGE     DIRECTION
 RANK      CON.      HOUR DAY  (METERS)   (DEGREES)          RANK      CON.      HOUR DAY  (METERS)   (DEGREES)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   1     187.87518    13   54   808000.0  3214500.0           26     117.37494    19   54   804500.0  3204500.0
   2     170.59026    12   54   808000.0  3214500.0           27     116.78040    15   54   807000.0  3213500.0
   3     162.32204    16   54   807000.0  3213500.0           28     116.52863    19   54   804000.0  3201500.0
   4     156.34000    15   54   807000.0  3214000.0           29     115.52940    19   54   804000.0  3202000.0
   5     151.71111    17   54   807500.0  3212000.0           30     114.90599    16   54   807500.0  3212500.0
   6     146.26825    16   54   807000.0  3214000.0           31     114.30766    19   54   805000.0  3205500.0
   7     145.41022    17   54   807500.0  3212500.0           32     113.94492    19   54   804500.0  3203000.0
   8     142.62169    14   54   807000.0  3214000.0           33     113.87384    19   54   804000.0  3201000.0
   9     139.67578    17   54   807500.0  3211500.0           34     112.44904    15   54   807500.0  3214000.0
  10     138.82416    11   54   807500.0  3214500.0           35     111.94322    15   54   807500.0  3213000.0
  11     135.32306    10   54   808000.0  3214000.0           36     110.84840    17   54   808000.0  3210500.0
  12     131.89342    13   54   807500.0  3214500.0           37     110.59737    17   54   807500.0  3213000.0
  13     131.80786    16   54   807000.0  3213000.0           38     110.35503    19   54   804000.0  3202500.0
  14     130.19904    10   54   808500.0  3213500.0           39     108.78471    19   54   805000.0  3207000.0
  15     128.65016    13   54   808500.0  3214000.0           40     108.38791    17   54   808000.0  3211000.0
  16     128.19470    15   54   807500.0  3213500.0           41     108.31586    19   54   804000.0  3200500.0
  17     127.25200    16   54   807500.0  3213000.0           42     107.84149    19   54   804500.0  3205000.0
  18     122.27760    11   54   808000.0  3214000.0           43     107.42342    12   54   808500.0  3214000.0
  19     121.15082    19   54   804500.0  3204000.0           44     106.71849    14   54   807000.0  3213500.0
  20     120.53026    17   54   807500.0  3211000.0           45     106.37099    17   54   808000.0  3210000.0
  21     119.87444    12   54   807500.0  3214500.0           46     105.59146    11   54   808000.0  3214500.0
  22     119.80482    16   54   807500.0  3213500.0           47     105.21280    19   54   804500.0  3202500.0
  23     119.66864    19   54   804500.0  3203500.0           48     104.99355    19   54   805000.0  3205000.0
  24     118.89009    19   54   805000.0  3206000.0           49     103.28345    10   54   808500.0  3213000.0
  25     117.40781    19   54   805000.0  3206500.0           50     101.59380    19   54   803500.0  3200500.0
```

Table 5-31. Concentration ($\mu g/m^3$), hour, and location (UTM) of the highest simulated concentrations of urea dust on January 17, 1981.

```
          ***                  KUWAIT ISCST,UREA DUST(DAY 17  1981)                ***

        * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)       *

                                   * FROM ALL SOURCES *

                                   X        Y(METERS)                                          X        Y(METERS)
                                   OR          OR                                              OR          OR
                                  RANGE     DIRECTION                                         RANGE     DIRECTION
RANK        CON.      HOUR DAY   (METERS)   (DEGREES)         RANK        CON.      HOUR DAY  (METERS)   (DEGREES)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

  1       110.15506    6   17   804500.0   3215000.0           26       62.07166    22   17   804500.0   3217500.0
  2       100.55356    6   17   805000.0   3215000.0           27       61.94847     9   17   804500.0   3216500.0
  3        98.00775    6   17   804000.0   3215000.0           28       61.72183     9   17   804000.0   3217000.0
  4        93.34109    5   17   804500.0   3216500.0           29       61.25491     6   17   803000.0   3214500.0
  5        89.71260    5   17   803500.0   3217000.0           30       60.93878     6   17   799500.0   3214500.0
  6        85.93196    8   17   805000.0   3216000.0           31       60.06306     5   17   803000.0   3217500.0
  7        85.82317    6   17   801500.0   3214500.0           32       59.48141     9   17   805500.0   3216000.0
  8        85.32463    6   17   802000.0   3214500.0           33       58.91643     8   17   803000.0   3217000.0
  9        81.83170    6   17   801000.0   3214500.0           34       57.37881     5   17   802000.0   3218000.0
 10        81.11319    6   17   803500.0   3215000.0           35       57.29642     5   17   802000.0   3217500.0
 11        78.45262    8   17   804000.0   3216500.0           36       57.26608    22   17   804000.0   3218000.0
 12        77.73981    6   17   802500.0   3214500.0           37       55.80766     5   17   800500.0   3218500.0
 13        77.39662    5   17   802500.0   3217500.0           38       55.14627    15   17   805500.0   3217500.0
 14        75.49115    6   17   800500.0   3214500.0           39       54.88576    10   17   804000.0   3216500.0
 15        70.44037    8   17   803500.0   3216500.0           40       54.79271     1   17   805000.0   3217000.0
 16        68.24133    6   17   800000.0   3214500.0           41       54.79092     5   17   804000.0   3217000.0
 17        65.87326    6   17   803000.0   3215000.0           42       54.74303    15   17   806000.0   3216500.0
 18        65.59666    5   17   801500.0   3218000.0           43       54.40134    10   17   805000.0   3216000.0
 19        65.20923   22   17   805000.0   3217000.0           44       54.04050     6   17   799000.0   3214500.0
 20        64.42416    8   17   802500.0   3217000.0           45       53.62109    23   17   805000.0   3217500.0
 21        64.24207    5   17   804000.0   3216500.0           46       53.50793     6   17   802500.0   3215000.0
 22        63.13911   22   17   805500.0   3216500.0           47       53.34697     9   17   803000.0   3217500.0
 23        63.08354    5   17   803000.0   3217000.0           48       53.24187     1   17   804500.0   3217500.0
 24        62.59149   11   17   805500.0   3215500.0           49       53.16521     2   17   805500.0   3216500.0
 25        62.39160   11   17   805000.0   3215500.0           50       52.95404    16   17   805500.0   3217000.0
```

Table 5-32. Concentration ($\mu g/m^3$), hour, and location (UTM) of the 50 highest simulated concentrations of urea dust on August 27, 1981.

```
              ***                 KUWAIT ISCST,UREA DUST(DAY 239 1981)                      ***

            * 50 MAXIMUM  1-HOUR AVERAGE CONCENTRATION (MICROGRAMS/CUBIC METER)        *

                                      * FROM ALL SOURCES *

                                    X       Y(METERS)                                             X       Y(METERS)
                                   OR          OR                                                OR          OR
                                  RANGE    DIRECTION                                            RANGE    DIRECTION
 RANK       CON.      HOUR DAY  (METERS)   (DEGREES)       RANK       CON.      HOUR DAY  (METERS)   (DEGREES)
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

   1      216.74927    15  239   805500.0   3215000.0        26      151.64235    18  239   807000.0   3217000.0
   2      216.39362    13  239   806000.0   3215000.0        27      150.88266     7  239   820000.0   3217000.0
   3      195.50746    16  239   806000.0   3215500.0        28      149.19319     8  239   805000.0   3210000.0
   4      194.09225    17  239   806500.0   3216500.0        29      148.93858     7  239   818000.0   3217000.0
   5      188.16876    14  239   805500.0   3215500.0        30      148.66631     7  239   812000.0   3216000.0
   6      187.65077    17  239   806500.0   3216000.0        31      147.21407     7  239   814500.0   3216500.0
   7      177.57535    16  239   805000.0   3216000.0        32      146.44574     7  239   817500.0   3216500.0
   8      176.81258    10  239   806500.0   3214500.0        33      146.35439     8  239   805500.0   3211500.0
   9      176.57486    15  239   806000.0   3215000.0        34      145.21335    12  239   807000.0   3214500.0
  10      174.11554     7  239   816000.0   3216500.0        35      144.29320     7  239   813500.0   3216000.0
  11      173.53333     7  239   815500.0   3216500.0        36      144.08875     7  239   820500.0   3217000.0
  12      171.34869    14  239   806000.0   3215500.0        37      139.91121     8  239   805500.0   3211000.0
  13      168.68343    18  239   807000.0   3217500.0        38      139.39227    18  239   807000.0   3218500.0
  14      168.59076     7  239   816500.0   3216500.0        39      138.57831    15  239   805000.0   3215000.0
  15      165.22971     9  239   806500.0   3214000.0        40      138.41084    20  239   812000.0   3224000.0
  16      164.96236     7  239   815000.0   3216500.0        41      137.70927     7  239   817500.0   3217000.0
  17      161.77943    17  239   806500.0   3217000.0        42      136.12100     8  239   805000.0   3209500.0
  18      159.17648     7  239   812500.0   3216000.0        43      135.86394     7  239   821000.0   3217000.0
  19      158.83148     7  239   817000.0   3216500.0        44      135.64844    20  239   812500.0   3225000.0
  20      157.94728    18  239   807000.0   3218000.0        45      134.79211     8  239   804500.0   3208500.0
  21      157.29175     7  239   819000.0   3217000.0        46      134.71654     8  239   805000.0   3210500.0
  22      155.98581     7  239   813000.0   3216000.0        47      134.33099     9  239   806500.0   3213000.0
  23      155.54520     7  239   819500.0   3217000.0        48      134.27858    20  239   811500.0   3223000.0
  24      155.32274     7  239   818500.0   3217000.0        49      133.00632     7  239   818000.0   3216500.0
  25      151.69005     9  239   806500.0   3213500.0        50      132.52939    20  239   811000.0   3222500.0
```

Three models, in particular, have been applied: ISCLT, ISCST, and MC-LAGPAR. The first two are of the Gaussian type and provide simulations that are a sequence of hourly steady-state (Gaussian formula in Eq. 5.1) conditions. The third is a fully dynamic model in which evolutionary phenomena can be taken into account to the highest degree of resolution.

6. Task 4--Special Data Analysis and Definition of a Prototype Data Base

During the course of the project two additional needs were clearly identified:

1. The requirement for more data analysis to fully understand and evaluate the physical information contained in the collected data.
2. The requirement for a preliminary data organization structure (data base) to facilitate future data retrieval and advanced manipulation.

The activity in this task provided a proper development of these two areas, as discussed below.

6.1 Statistical Data Analysis

A very sophisticated statistical package (SAS, Statistical Analysis System) was selected as the major software tool to perform a basic analysis of the collected meteorological, air quality and emission data.

Figs. 6-1 to 6-20 show the plotted results of these analyses in which, for each continuous meteorological parameter (wind speed, temperature, pressure, relative humidity), five yearly plots (from 1978 to 1982) are displayed showing the main statistical features of each variable. Moreover, the complete results of the SAS analysis of temperature, pressure and relative humidity have been appended in Section 12 of Volume III of this final report.

Two important meteorological variables, wind direction and atmospheric stability (see Section 4.1) are discontinuous variables and, therefore, cannot be analyzed like the previous continuous ones were. For these two variables, bar charts have been produced by SAS and are presented in Figs. 6-21 to 6-30 (one figure for each variable for each year from 1978 to 1982).

6.2 Definition of a Prototype Data Base

The huge amount of data collected in the project created the need for developing advanced data base techniques. To this end, a preliminary study was conducted to identify the most appropriate methods for manipulating air pollution or, more generally, environmental data.

After this preliminary identification work, which provided the basic ideas on a proper data base structure for the collected data, a computer prototype was developed, tested and implemented in KISR. This prototype data base provides a preliminary but important software tool for the proper, organized, advanced handling of the collected data.

This data base development constitutes a special study inside the project, which is fully presented in Section 13 of Volume III of this final report.

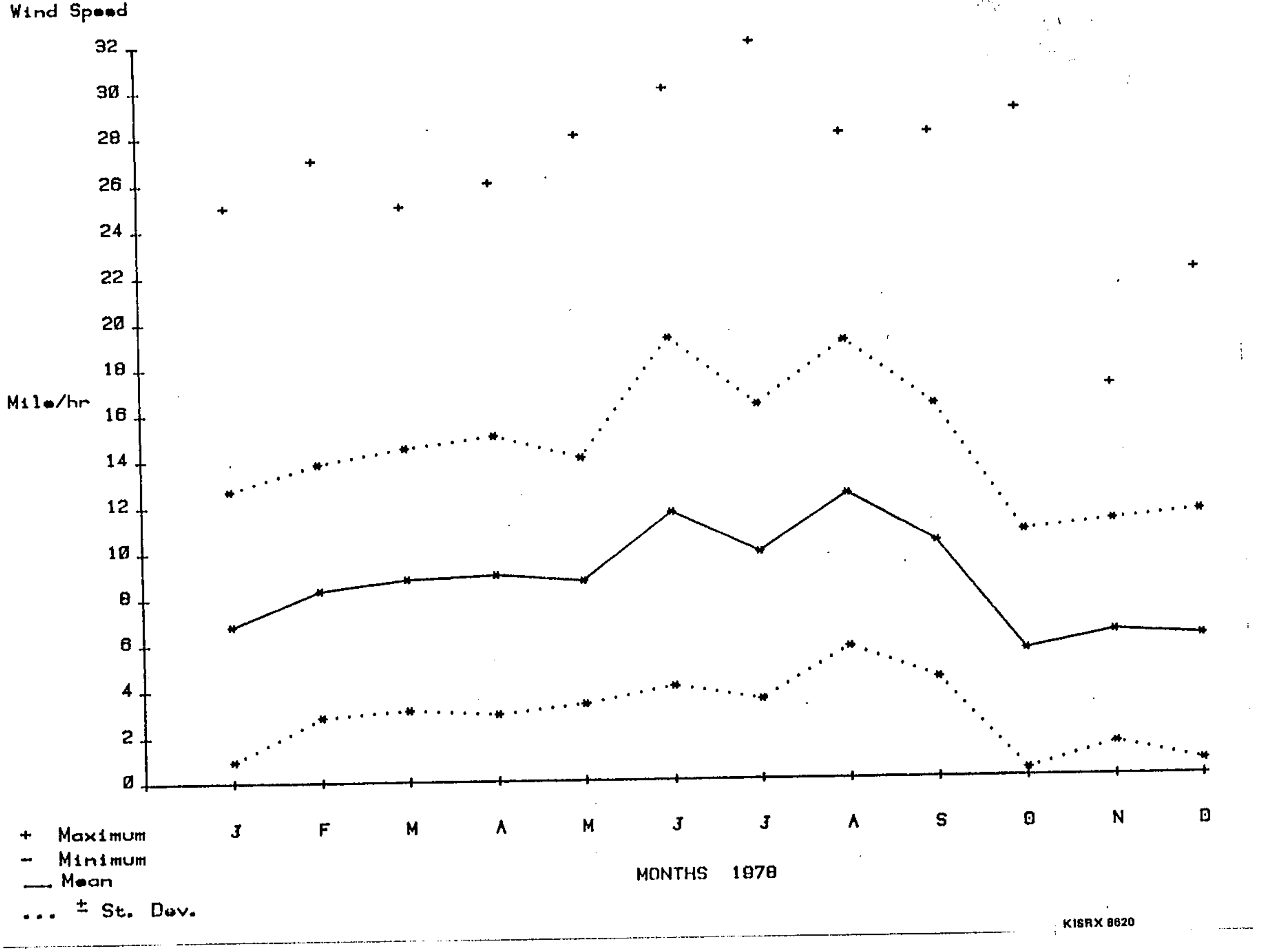


Fig. 6-1. Wind speed in 1978.

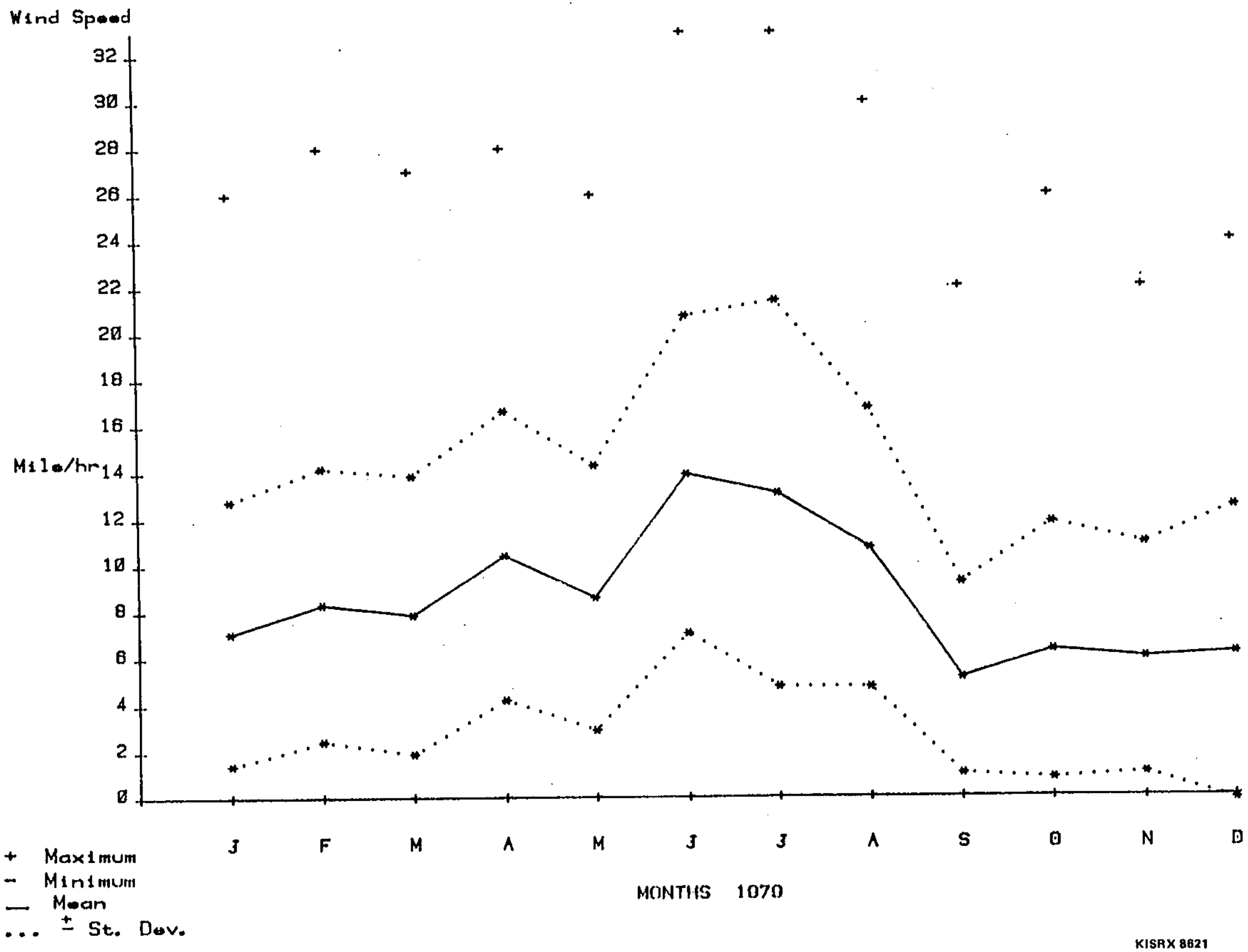


Fig. 6-2. Wind speed in 1979.

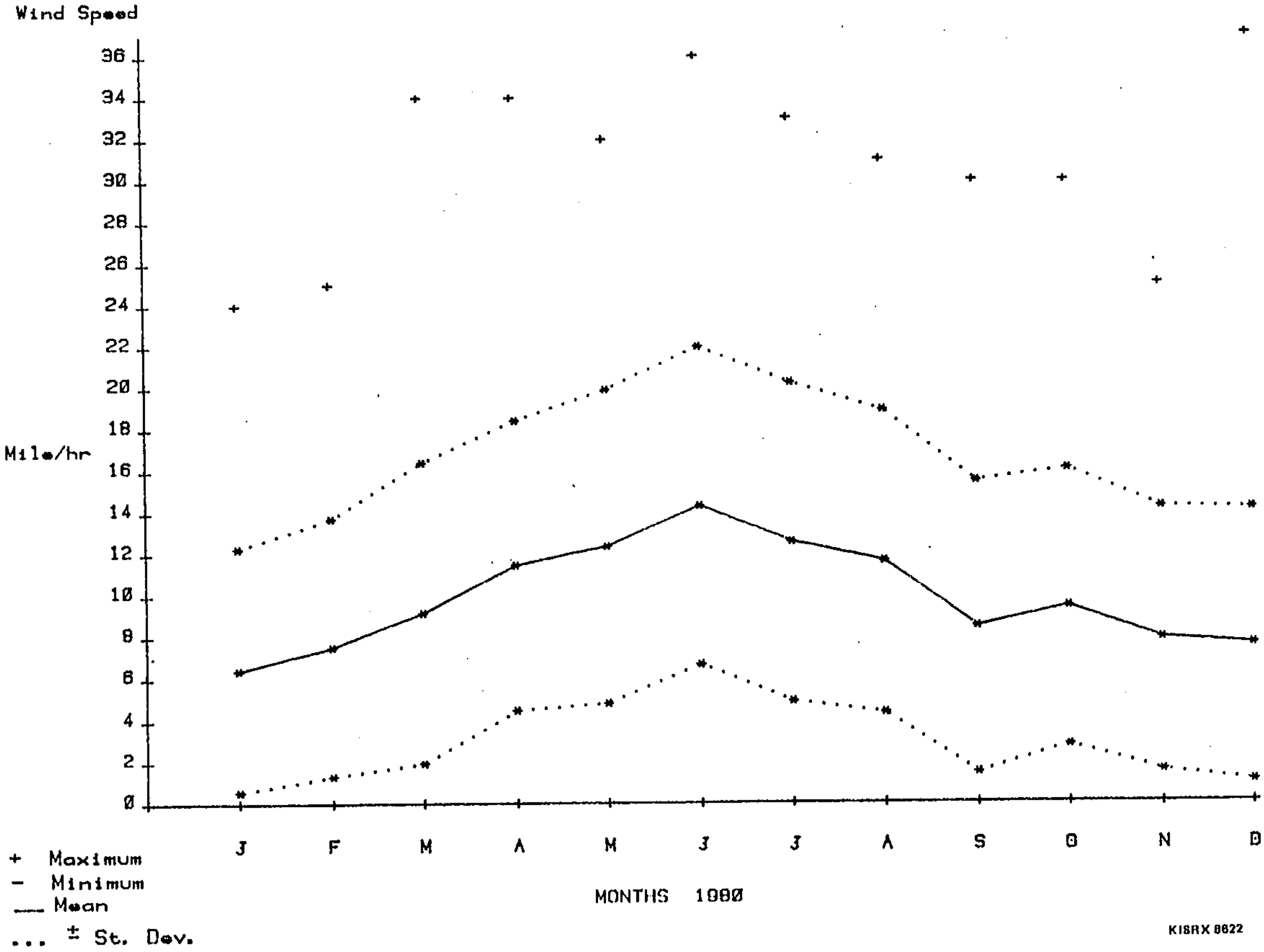


Fig. 6-3. Wind speed in 1980.

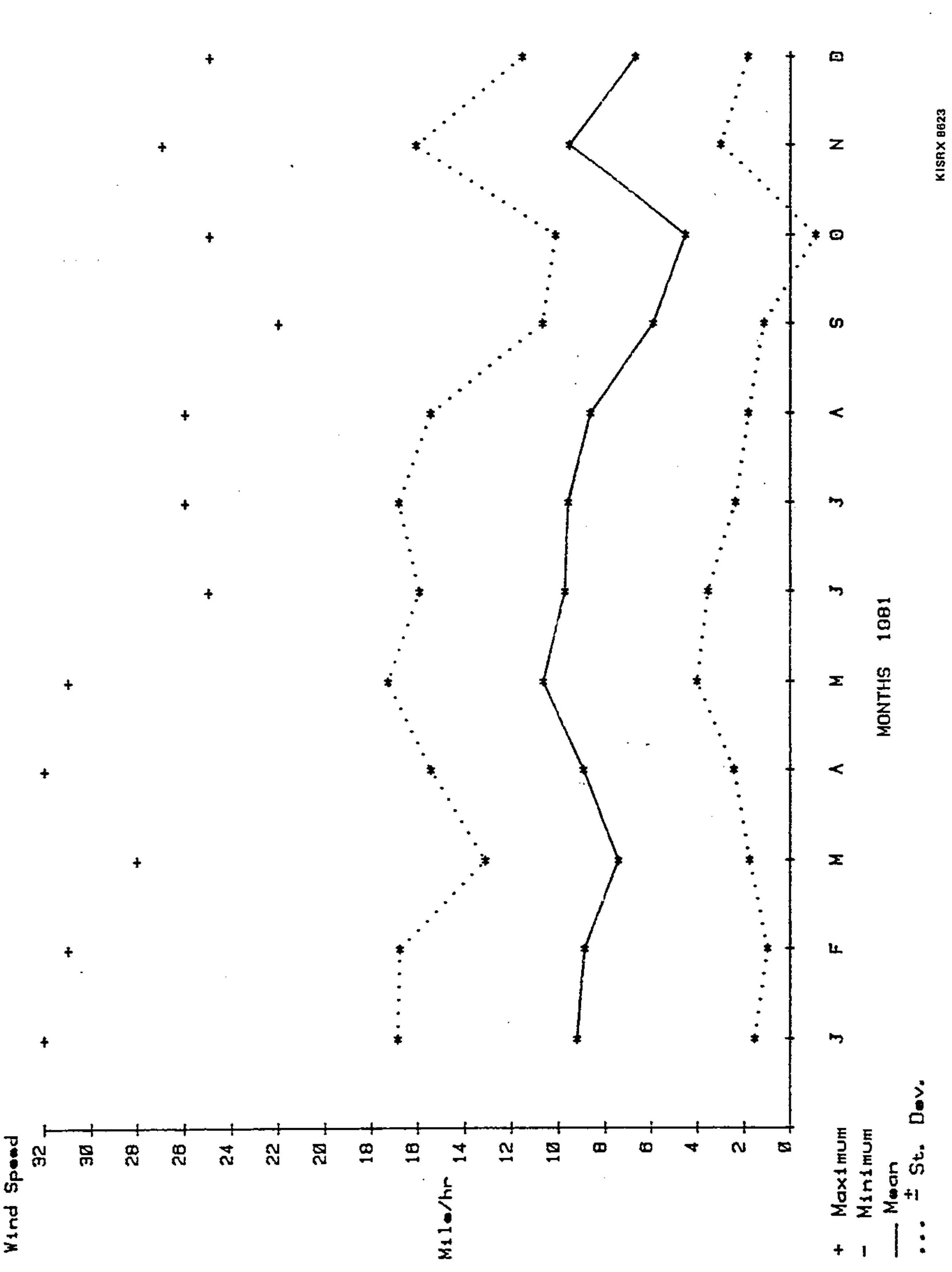


Fig. 6-4. Wind speed in 1981.

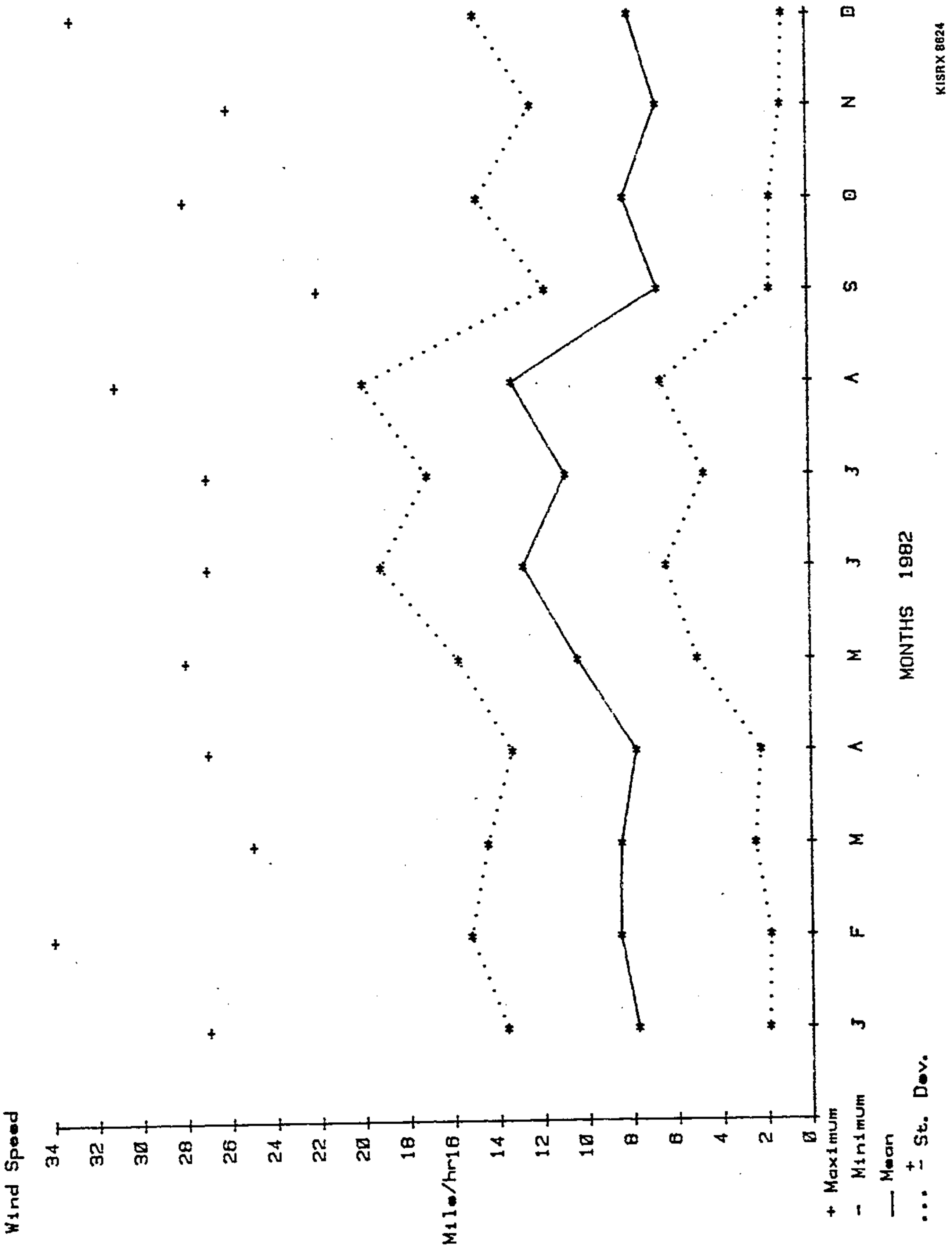


Fig. 6-5. Wind speed in 1982.

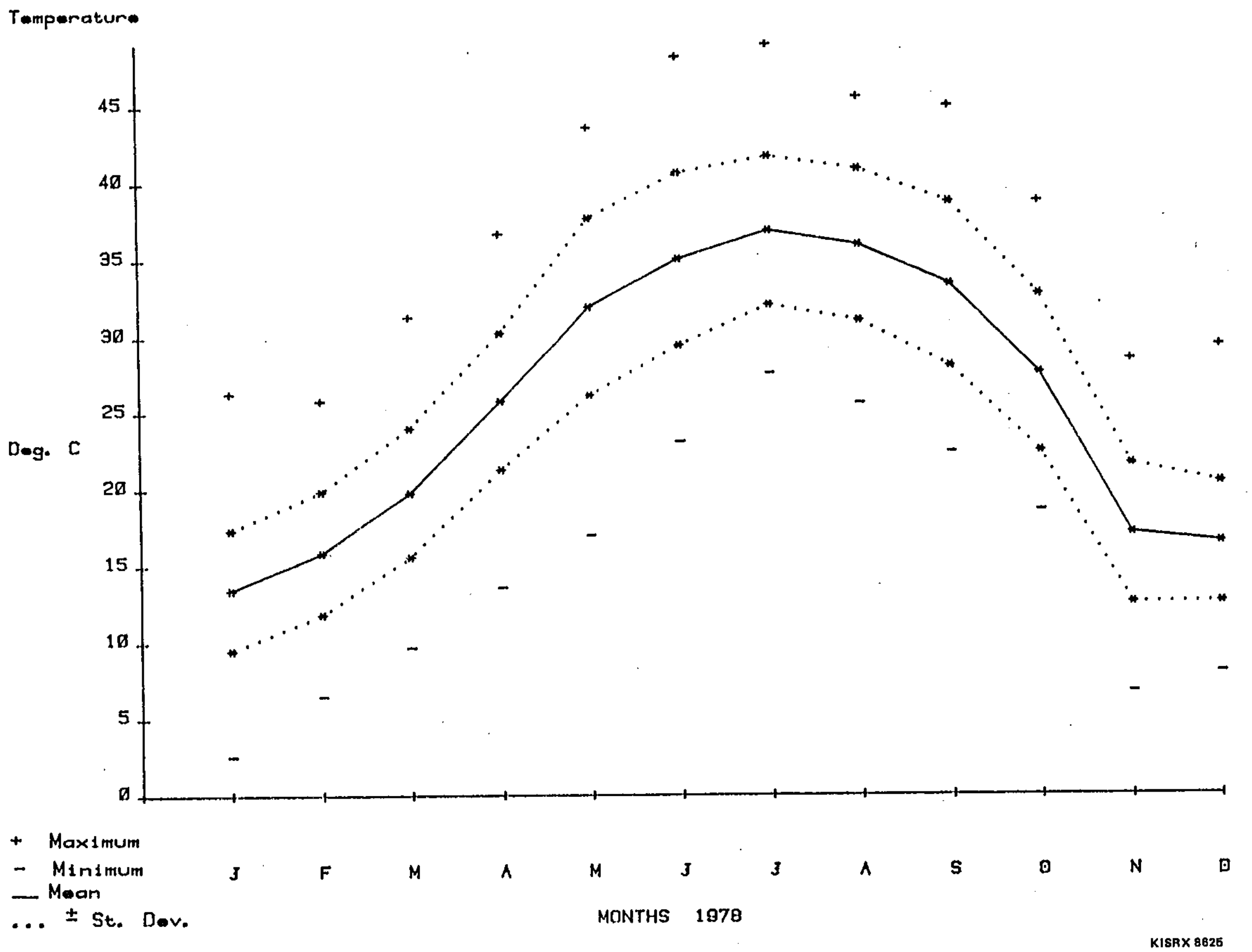


Fig. 6-6. Temperature in 1978.

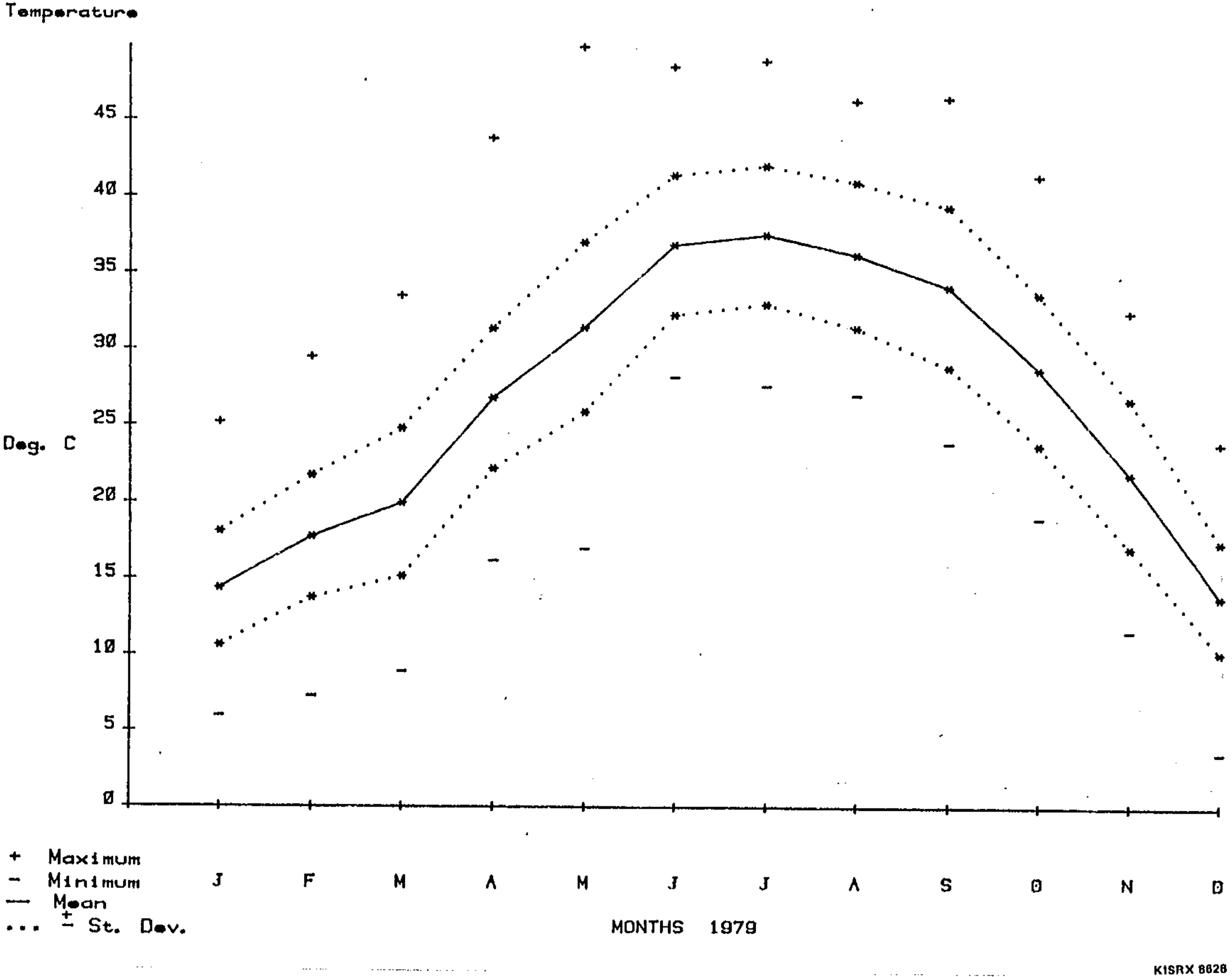
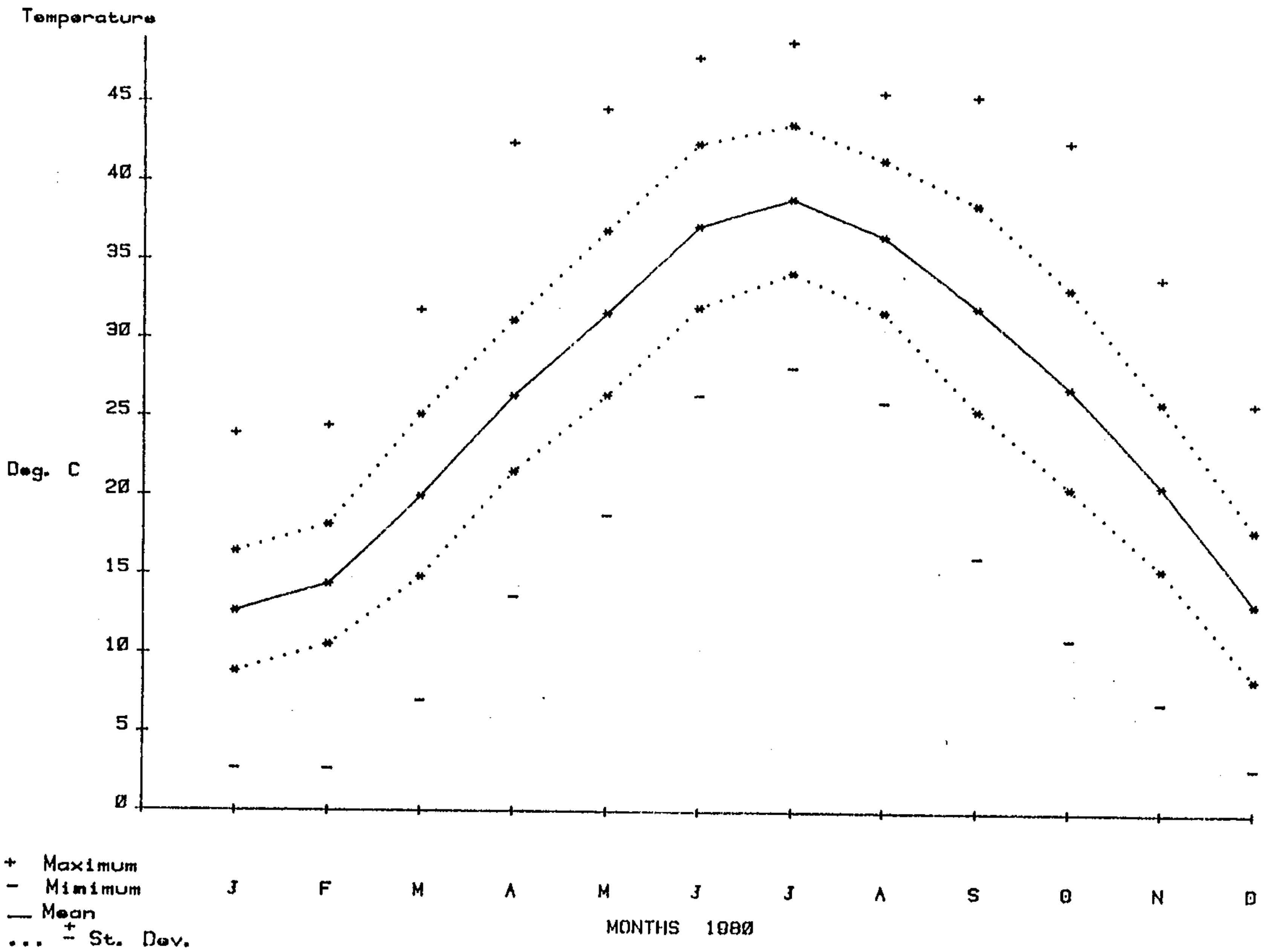


Fig. 6-7. Temperature in 1979.



KISRX 8827

Fig. 6-8. Temperature in 1980.

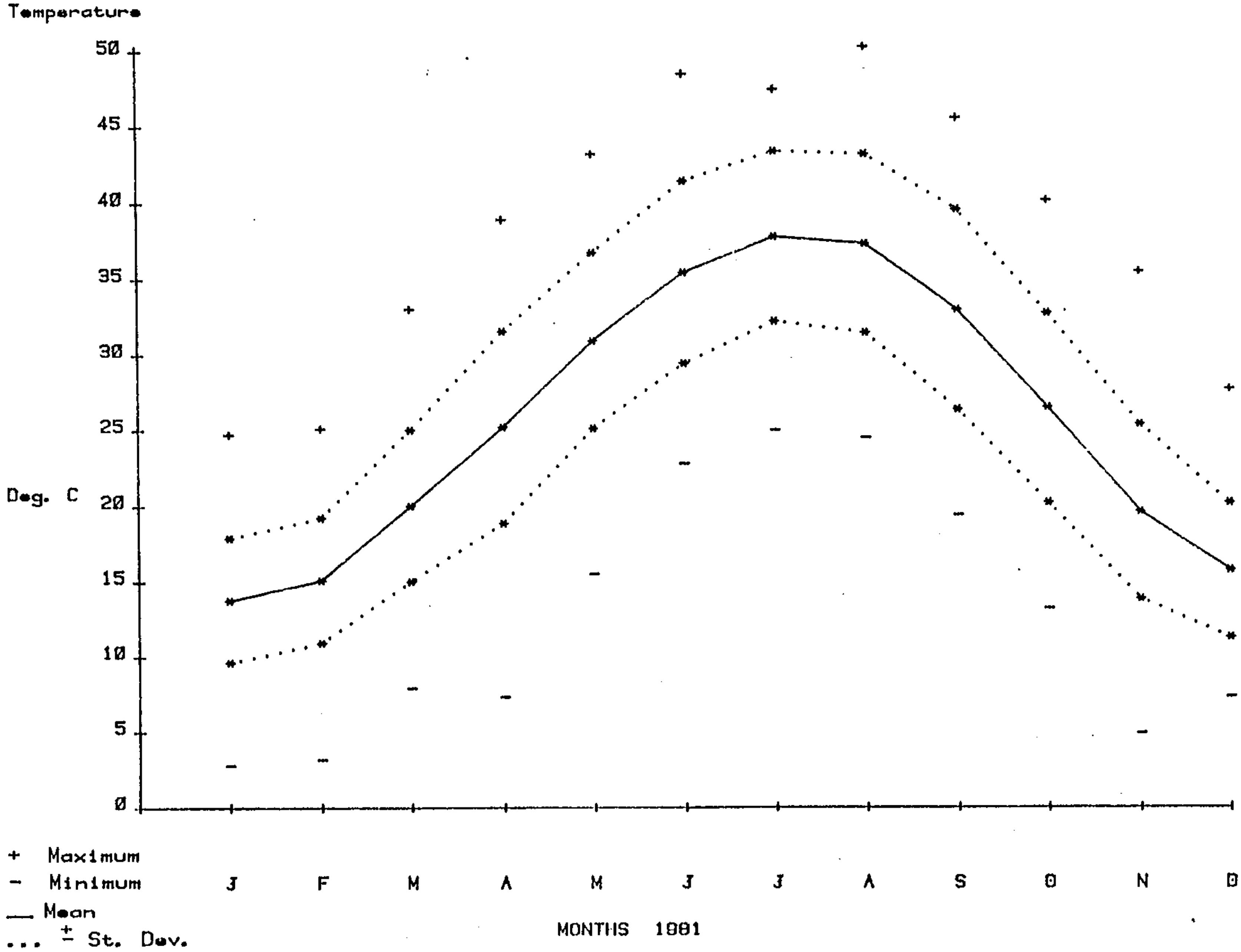


Fig. 6-9. Temperature in 1981.

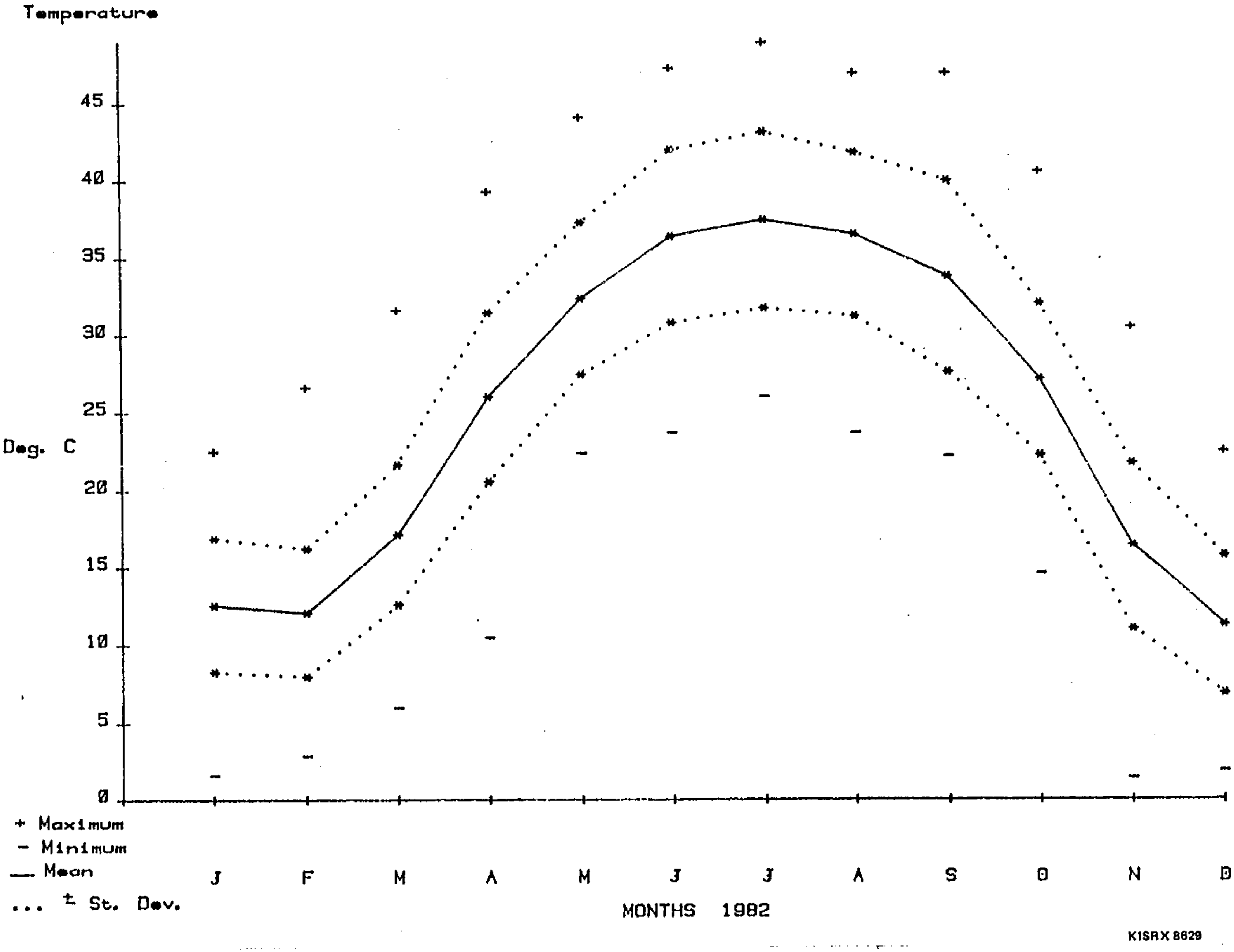


Fig. 6-10. Temperature in 1982.

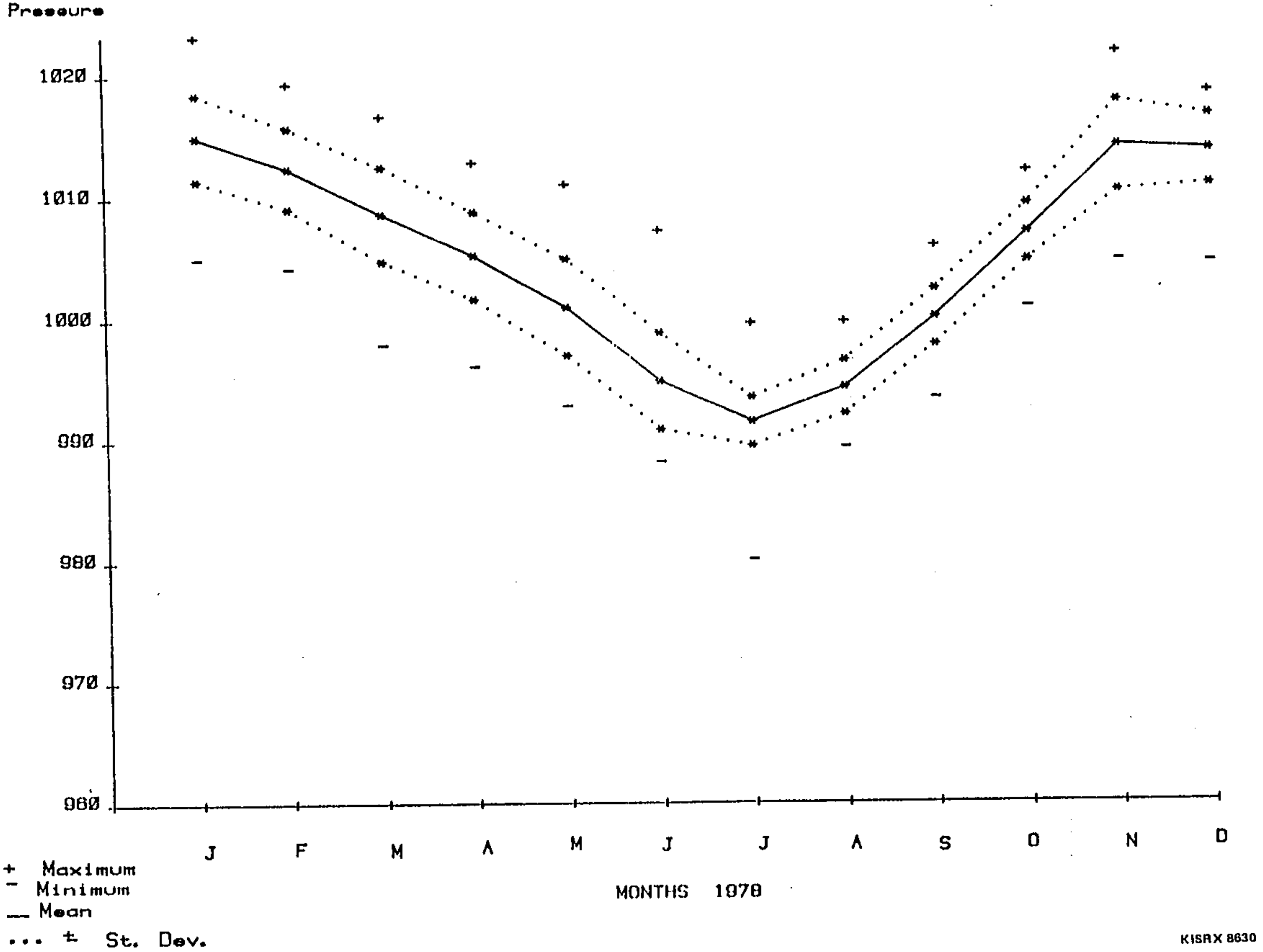


Fig. 6-11. Pressure in 1978 (in millibars, mb).

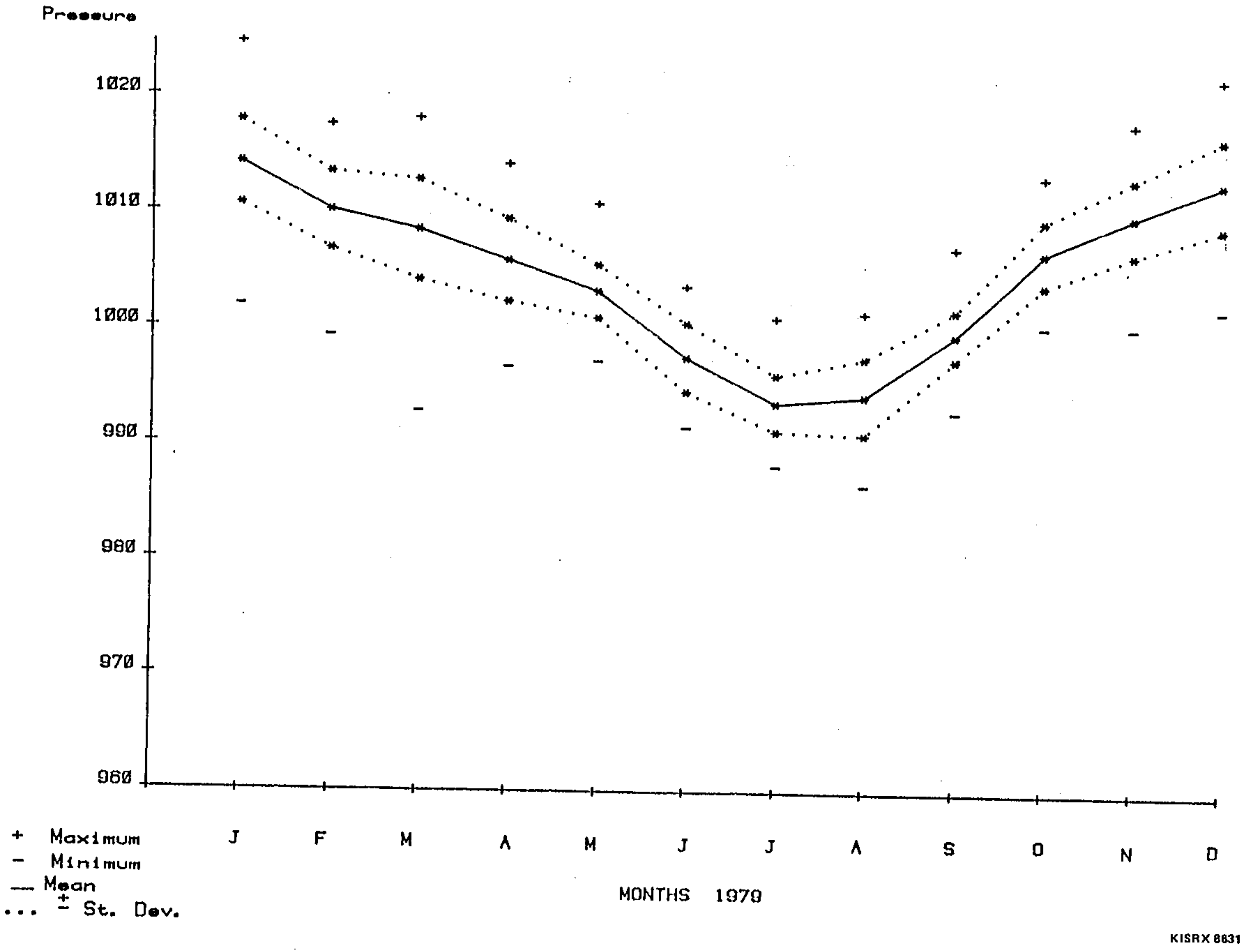
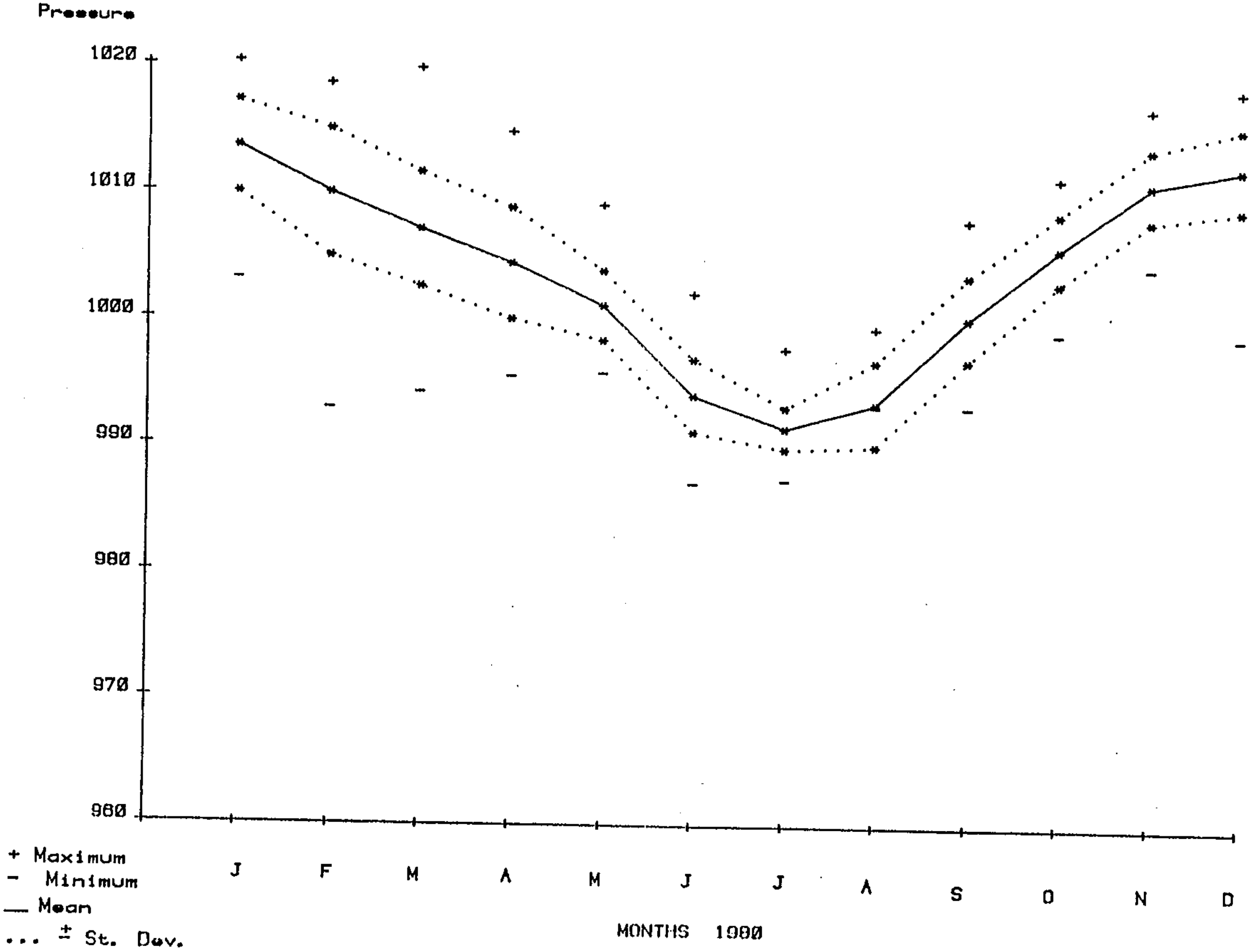


Fig. 6-12. Pressure in 1979 (in millibars, mb).



KISRX 8632

Fig. 6-13. Pressure in 1980 (in millibars, mb).

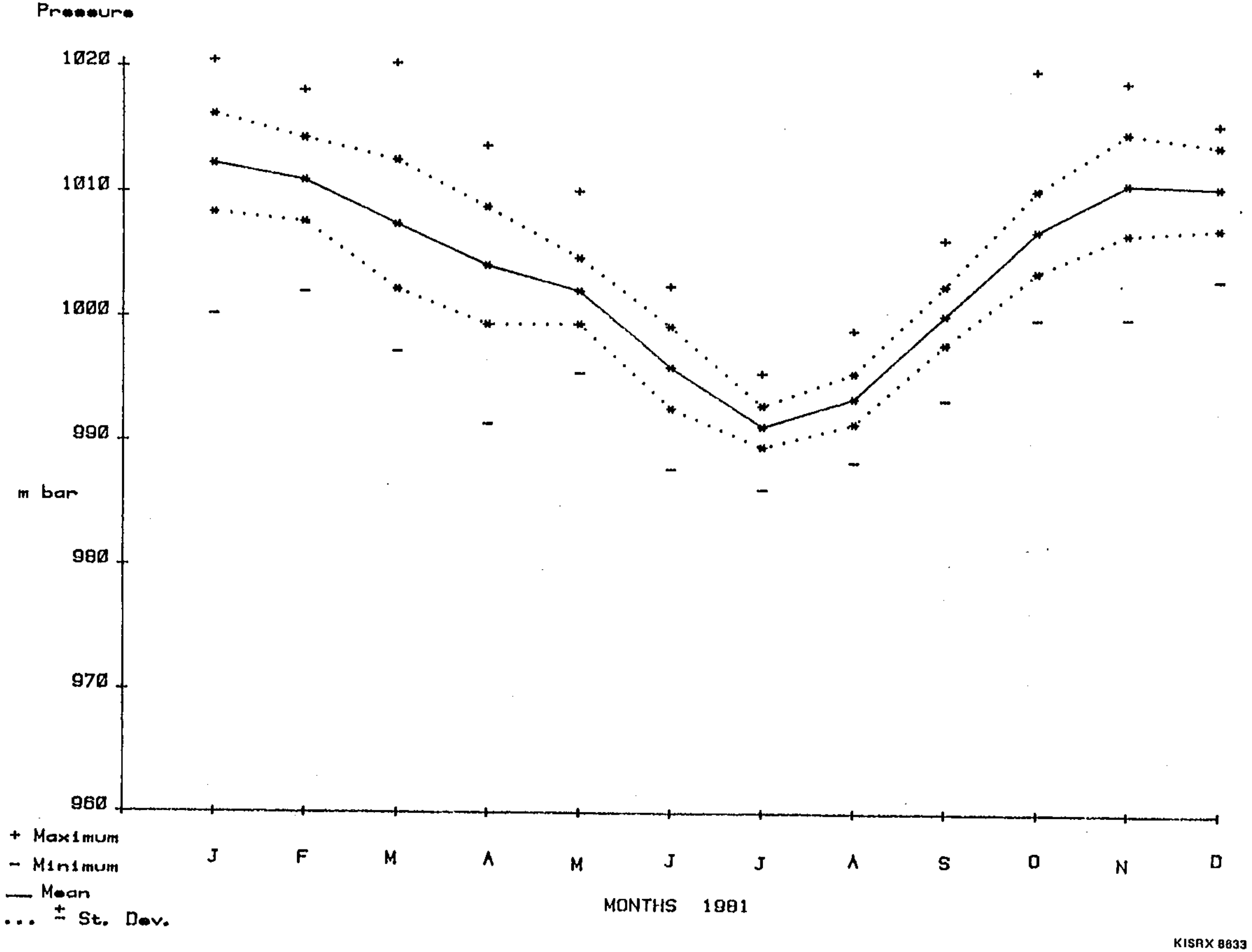


Fig. 6-14. Pressure in 1981 (in millibars, mb).

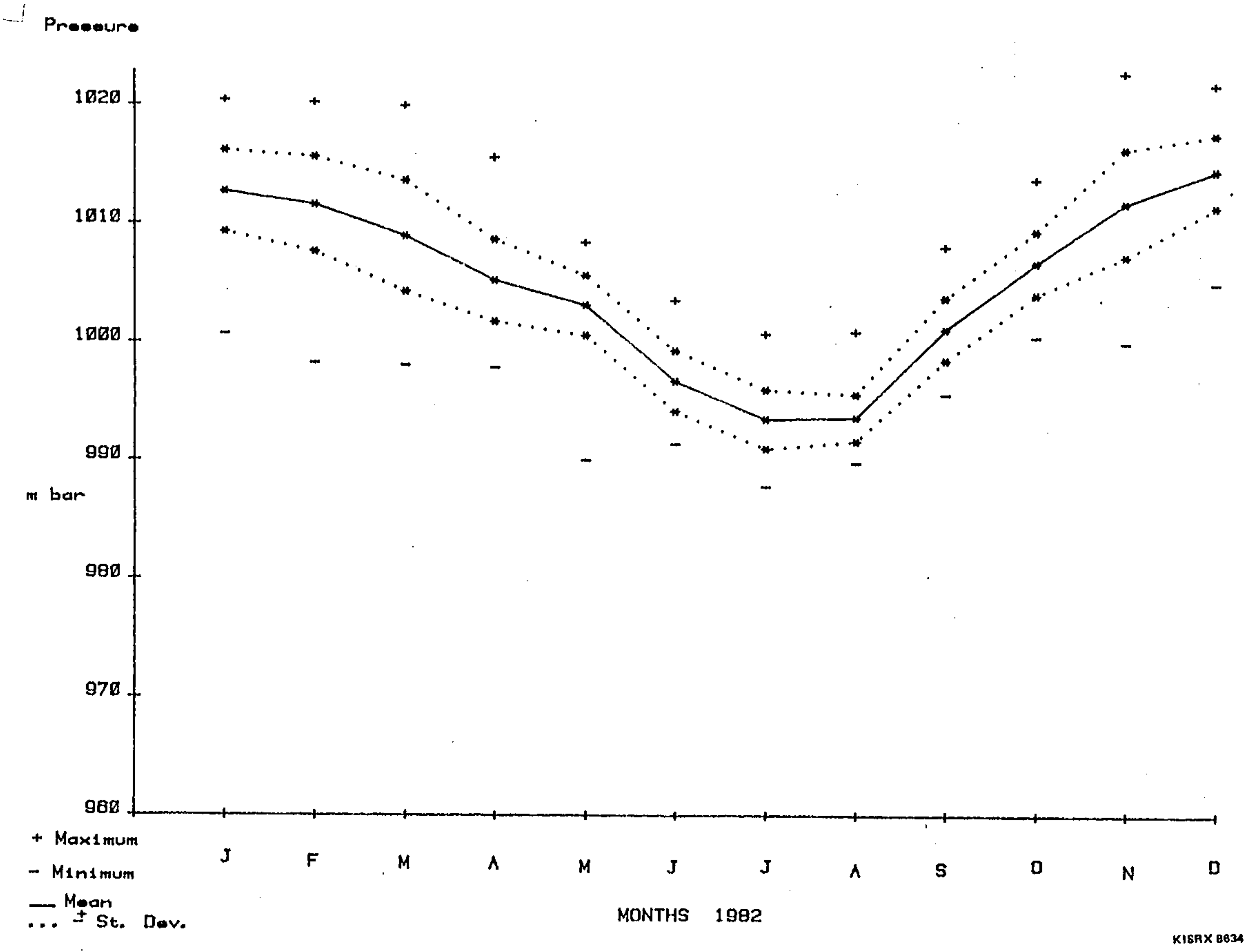


Fig. 6-15. Pressure in 1982 (in millibars, mb).

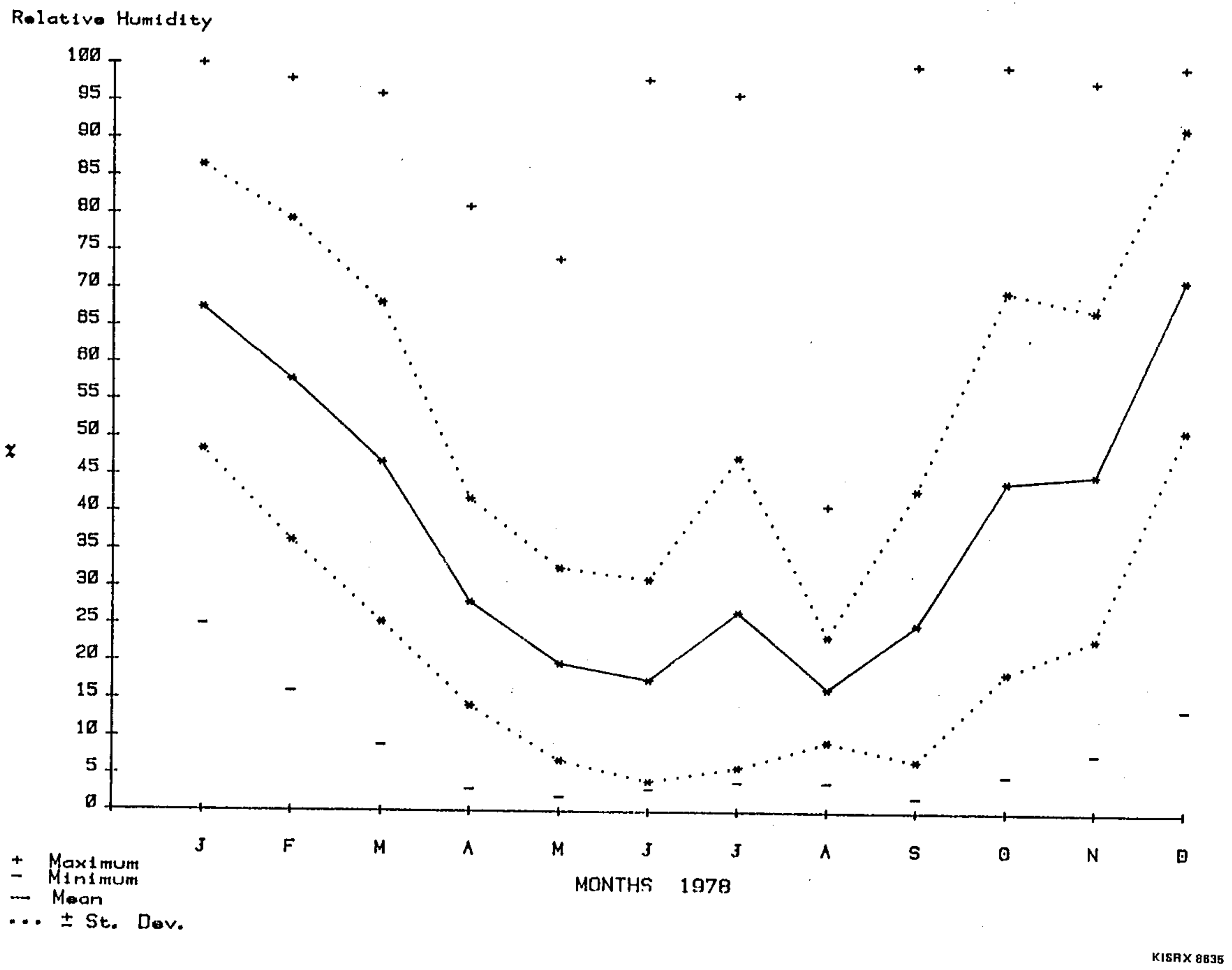


Fig. 6-16. Relative humidity in 1978.

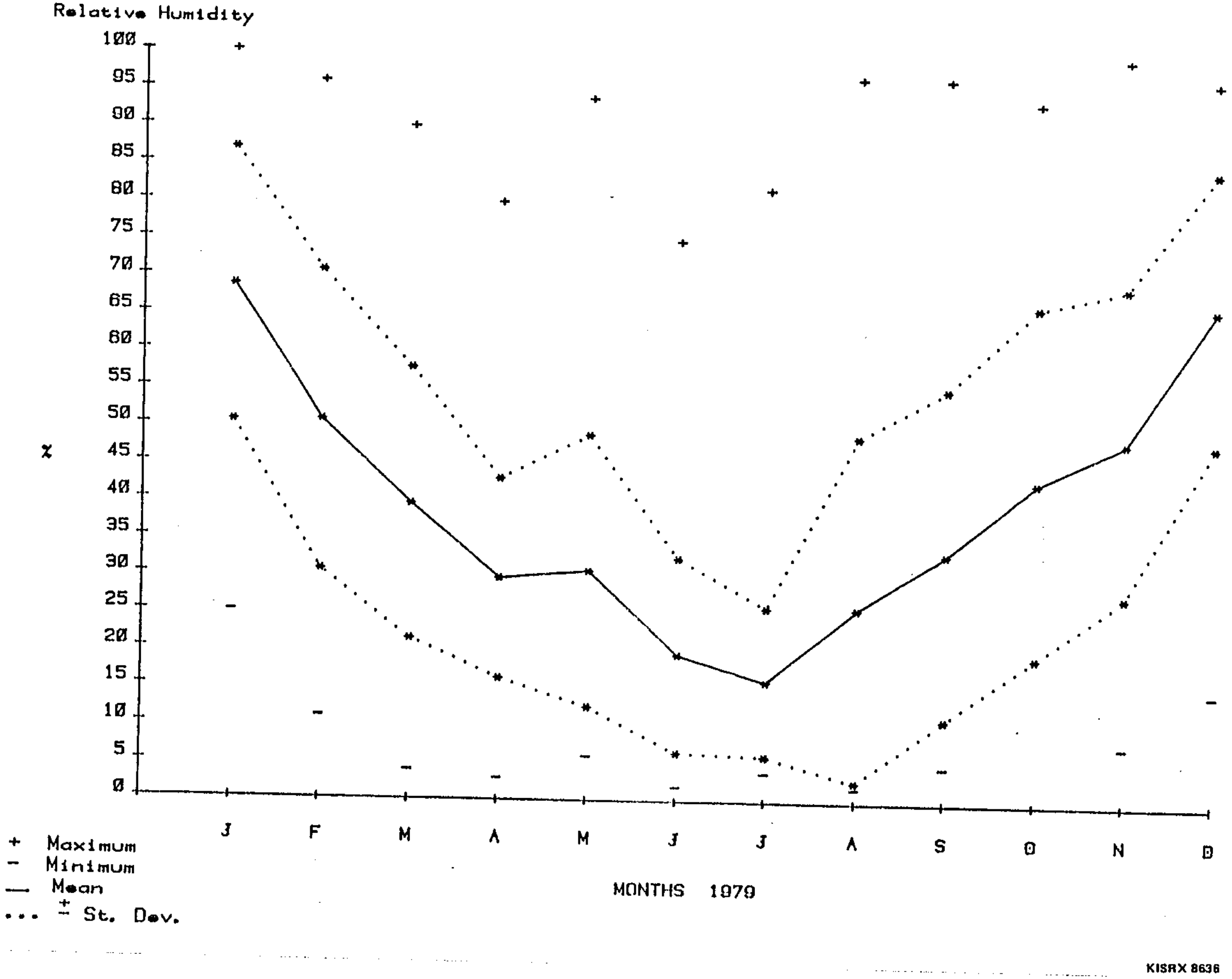
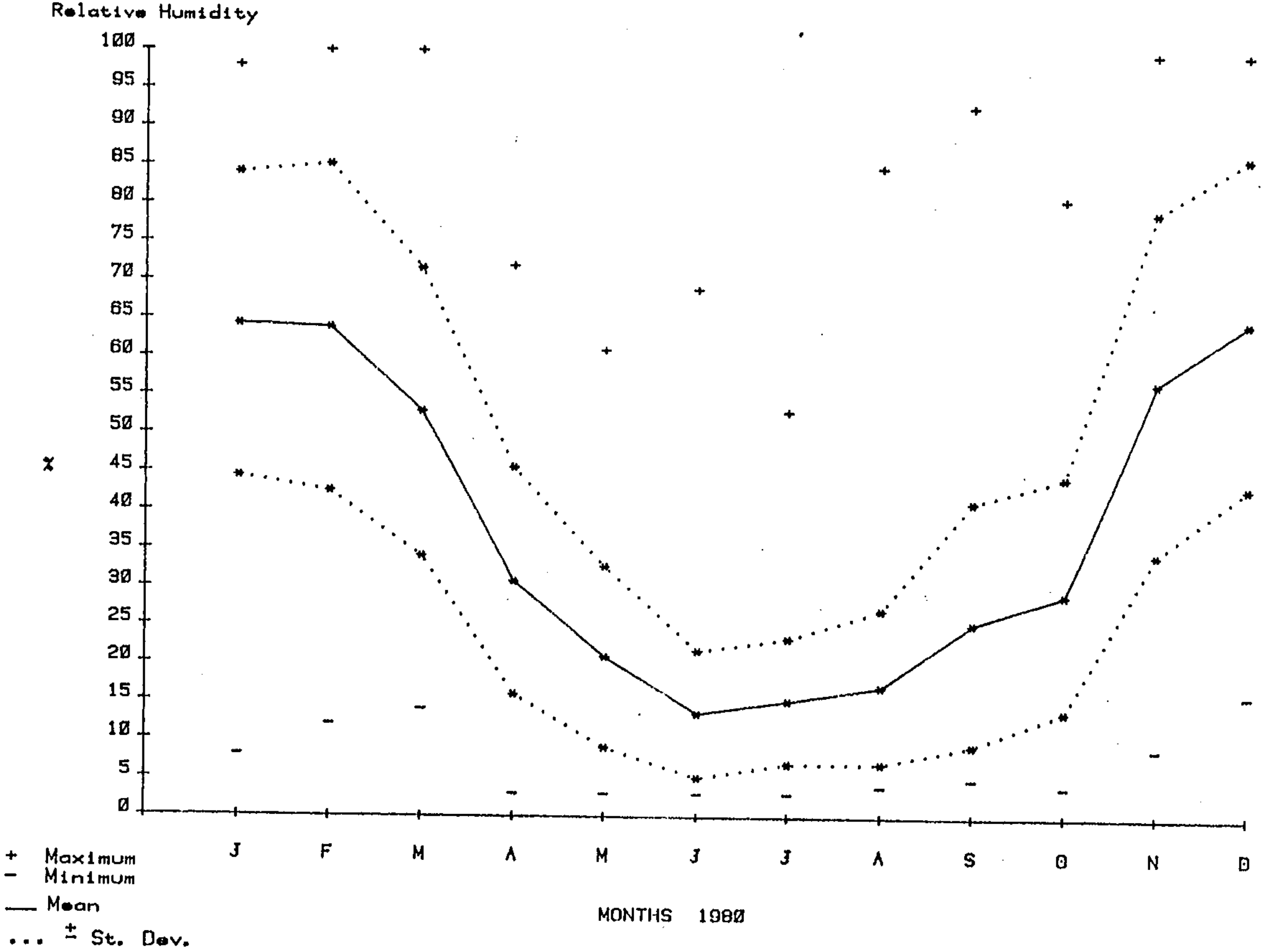


Fig. 6-17. Relative humidity in 1979.



KISRX 8637

Fig. 6-18. Relative humidity in 1980.

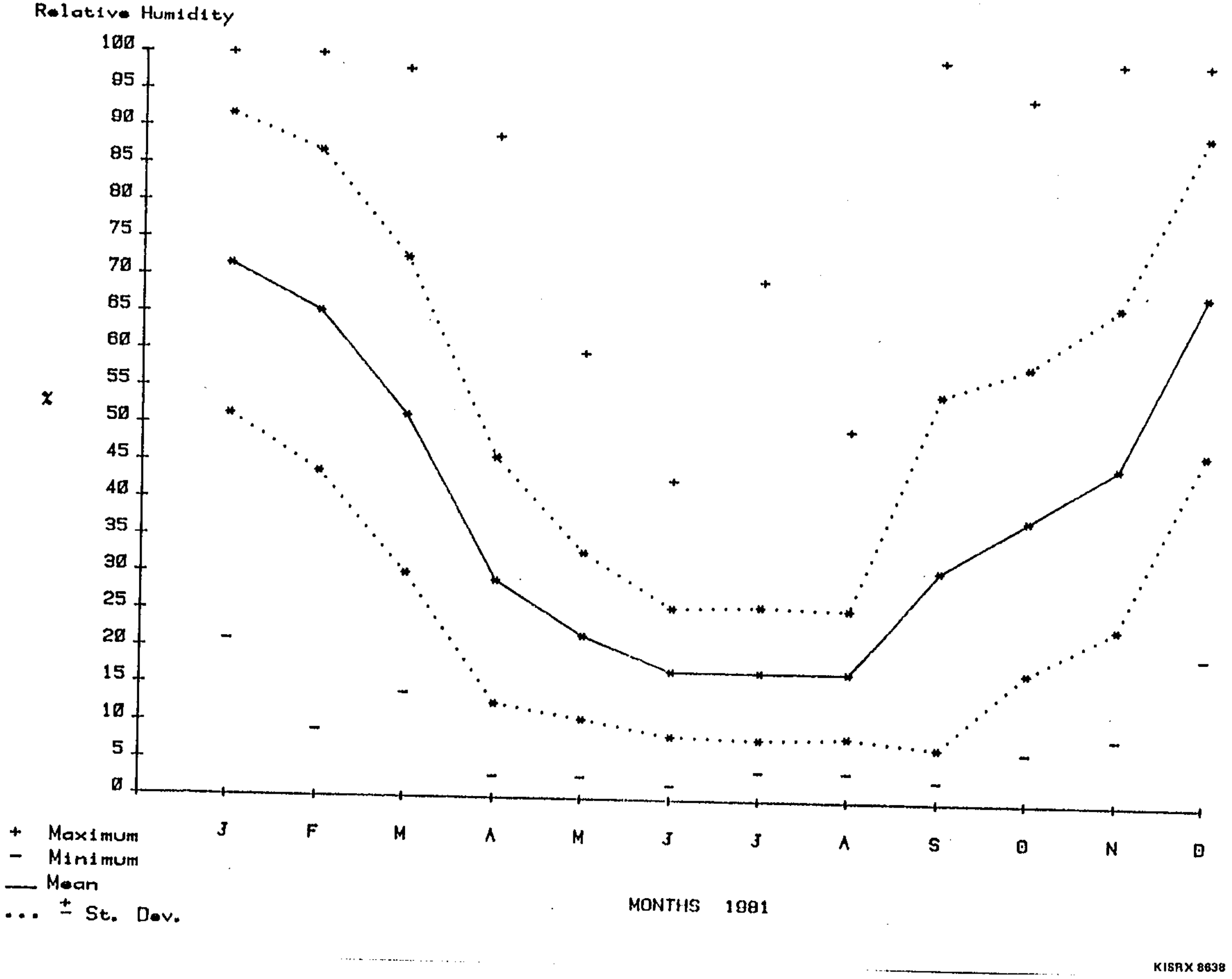


Fig. 6-19. Relative humidity in 1981.

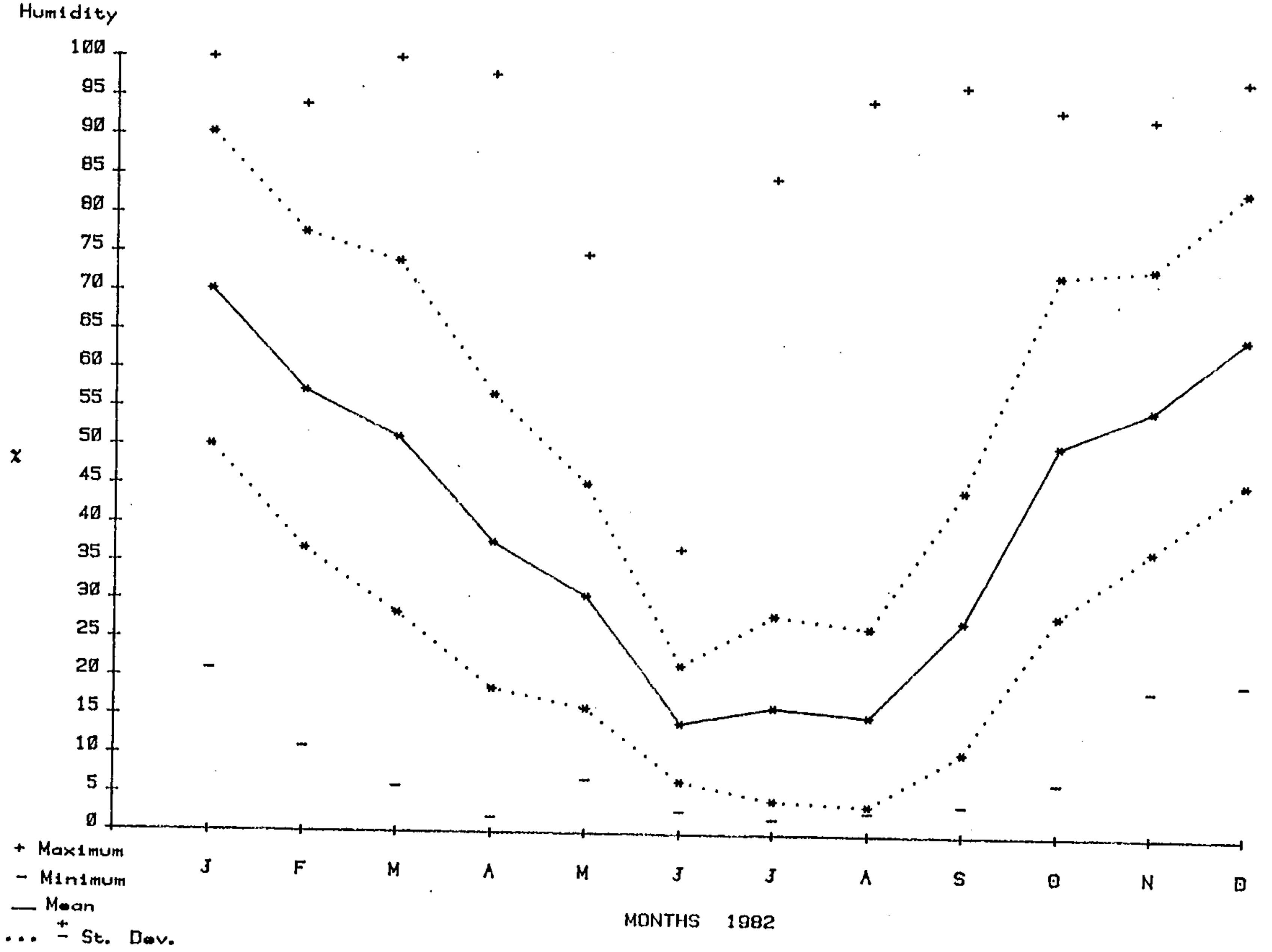
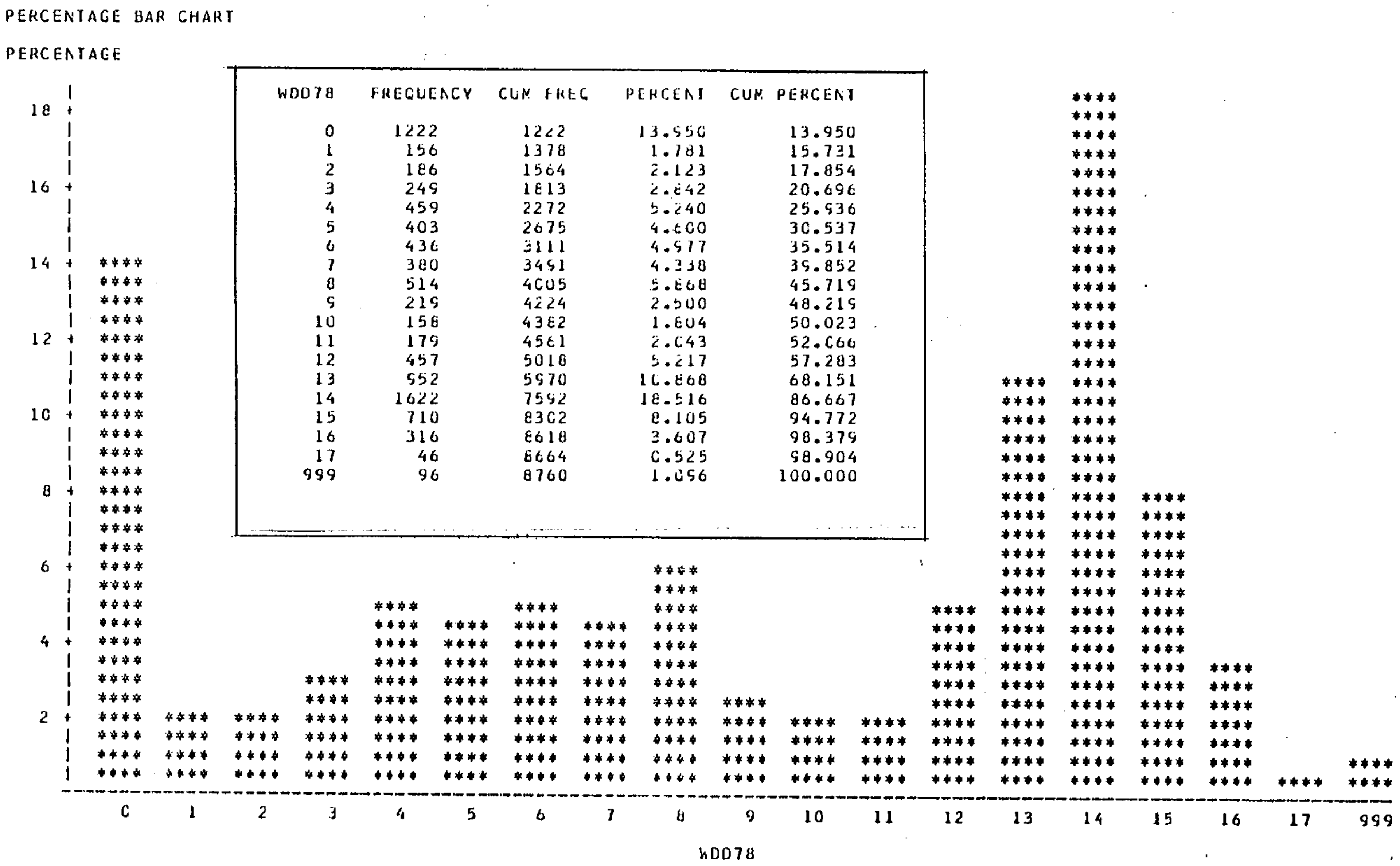


Fig. 6-20. Relative humidity in 1982.

KISRX 8639

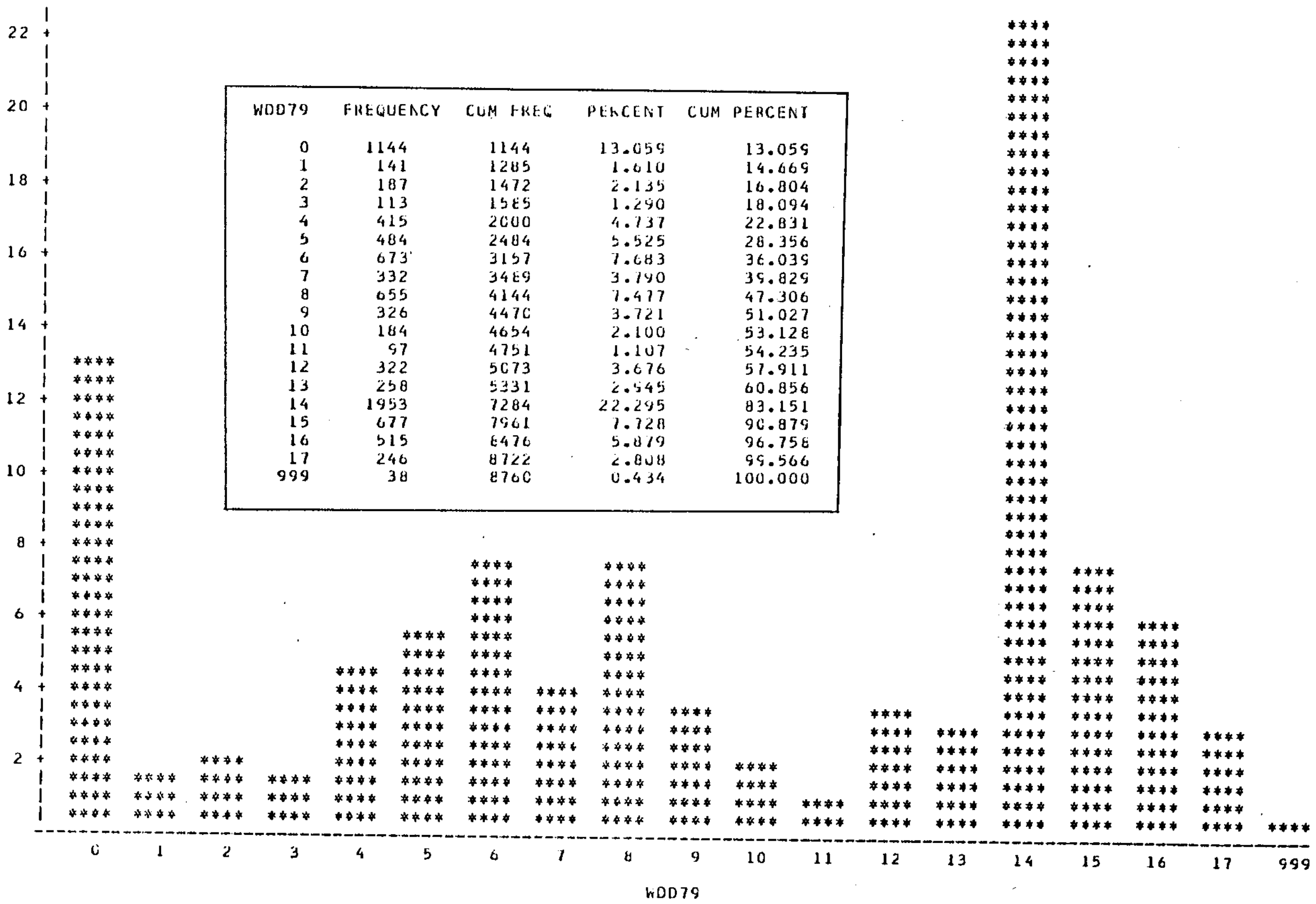


```
 WDD78   FREQUENCY   CUM FREQ   PERCENT  CUM PERCENT

     0       1222       1222     13.950       13.950
     1        156       1378      1.781       15.731
     2        186       1564      2.123       17.854
     3        249       1813      2.842       20.696
     4        459       2272      5.240       25.936
     5        403       2675      4.600       30.537
     6        436       3111      4.977       35.514
     7        380       3491      4.338       39.852
     8        514       4005      5.868       45.719
     9        219       4224      2.500       48.219
    10        158       4382      1.804       50.023
    11        179       4561      2.043       52.066
    12        457       5018      5.217       57.283
    13        952       5970     10.868       68.151
    14       1622       7592     18.516       86.667
    15        710       8302      8.105       94.772
    16        316       8618      3.607       98.379
    17         46       8664      0.525       98.904
   999         96       8760      1.096      100.000
```

KISRX 8640

Fig. 6-21. Wind direction percentages in 1978 (1: wind from N; 2: wind from NNE;.....
16 wind from NNW; 0: calm; 17 variable; 999: missing).

PERCENTAGE BAR CHART



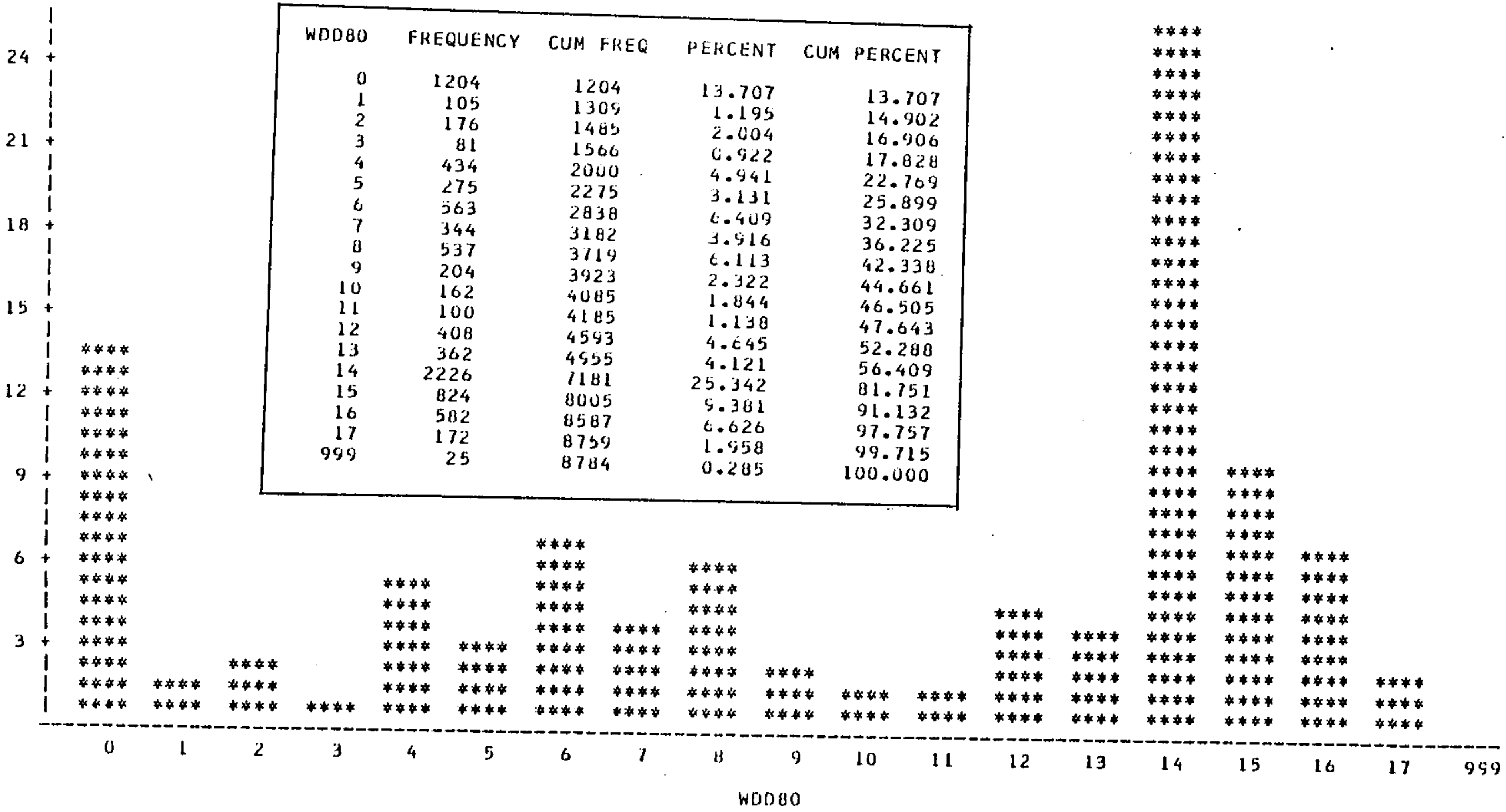
WDD79	FREQUENCY	CUM FREQ	PERCENT	CUM PERCENT
0	1144	1144	13.059	13.059
1	141	1285	1.610	14.669
2	187	1472	2.135	16.804
3	113	1585	1.290	18.094
4	415	2000	4.737	22.831
5	484	2484	5.525	28.356
6	673	3157	7.683	36.039
7	332	3489	3.790	39.829
8	655	4144	7.477	47.306
9	326	4470	3.721	51.027
10	184	4654	2.100	53.128
11	97	4751	1.107	54.235
12	322	5073	3.676	57.911
13	258	5331	2.945	60.856
14	1953	7284	22.295	83.151
15	677	7961	7.728	90.879
16	515	8476	5.879	96.758
17	246	8722	2.808	99.566
999	38	8760	0.434	100.000

Fig. 6-22. Wind direction percentages in 1979.

KISRX 8841

PERCENTAGE BAR CHART

PERCENTAGE

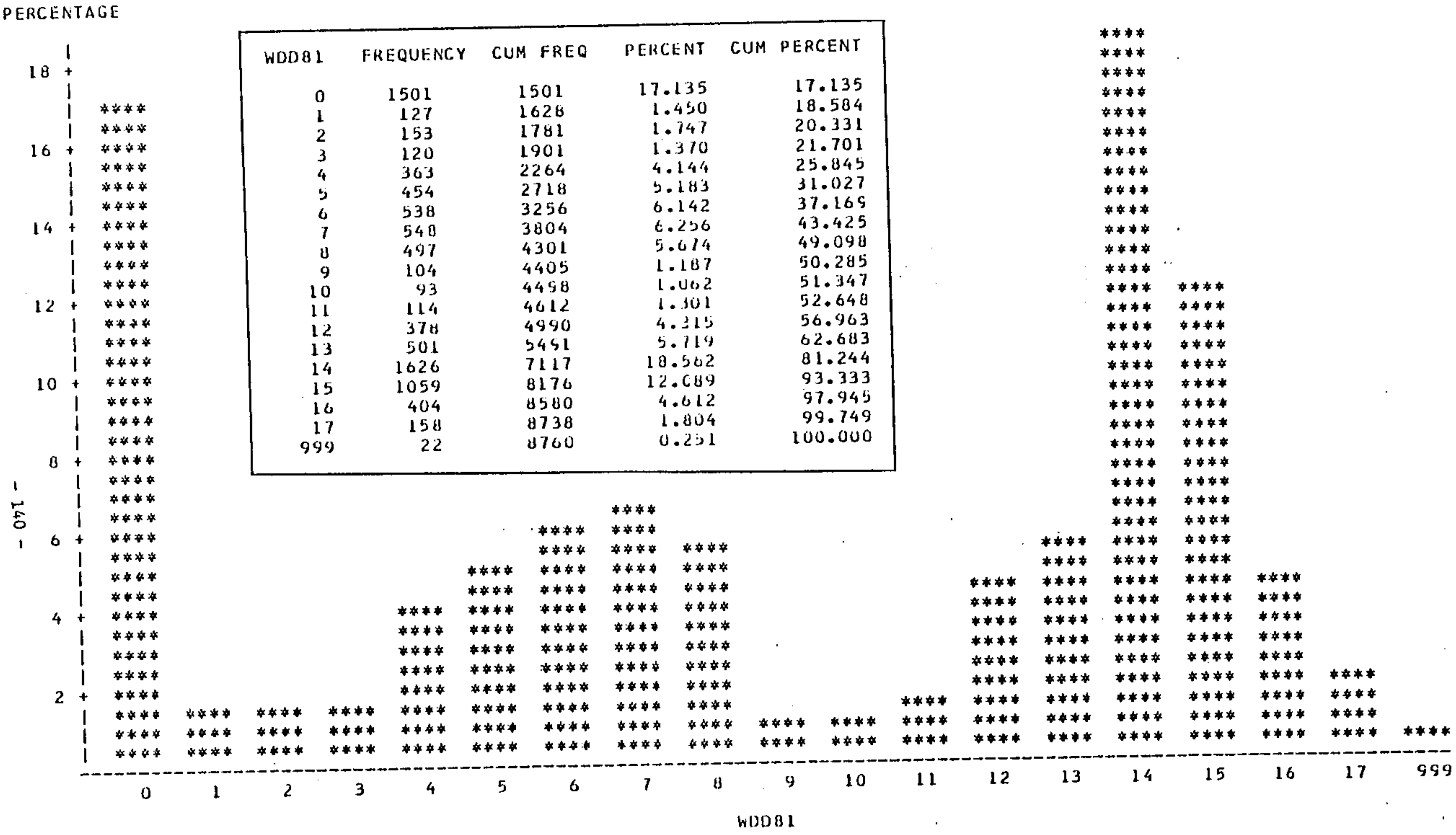


```
WDD80   FREQUENCY  CUM FREQ   PERCENT   CUM PERCENT

   0       1204       1204     13.707      13.707
   1        105       1309      1.195      14.902
   2        176       1485      2.004      16.906
   3         81       1566      0.922      17.828
   4        434       2000      4.941      22.769
   5        275       2275      3.131      25.899
   6        563       2838      6.409      32.309
   7        344       3182      3.916      36.225
   8        537       3719      6.113      42.338
   9        204       3923      2.322      44.661
  10        162       4085      1.844      46.505
  11        100       4185      1.138      47.643
  12        408       4593      4.645      52.288
  13        362       4955      4.121      56.409
  14       2226       7181     25.342      81.751
  15        824       8005      9.381      91.132
  16        582       8587      6.626      97.757
  17        172       8759      1.958      99.715
 999         25       8784      0.285     100.000
```

Fig. 6-23. Wind direction percentages in 1980.

KISRX 8842

PERCENTAGE BAR CHART



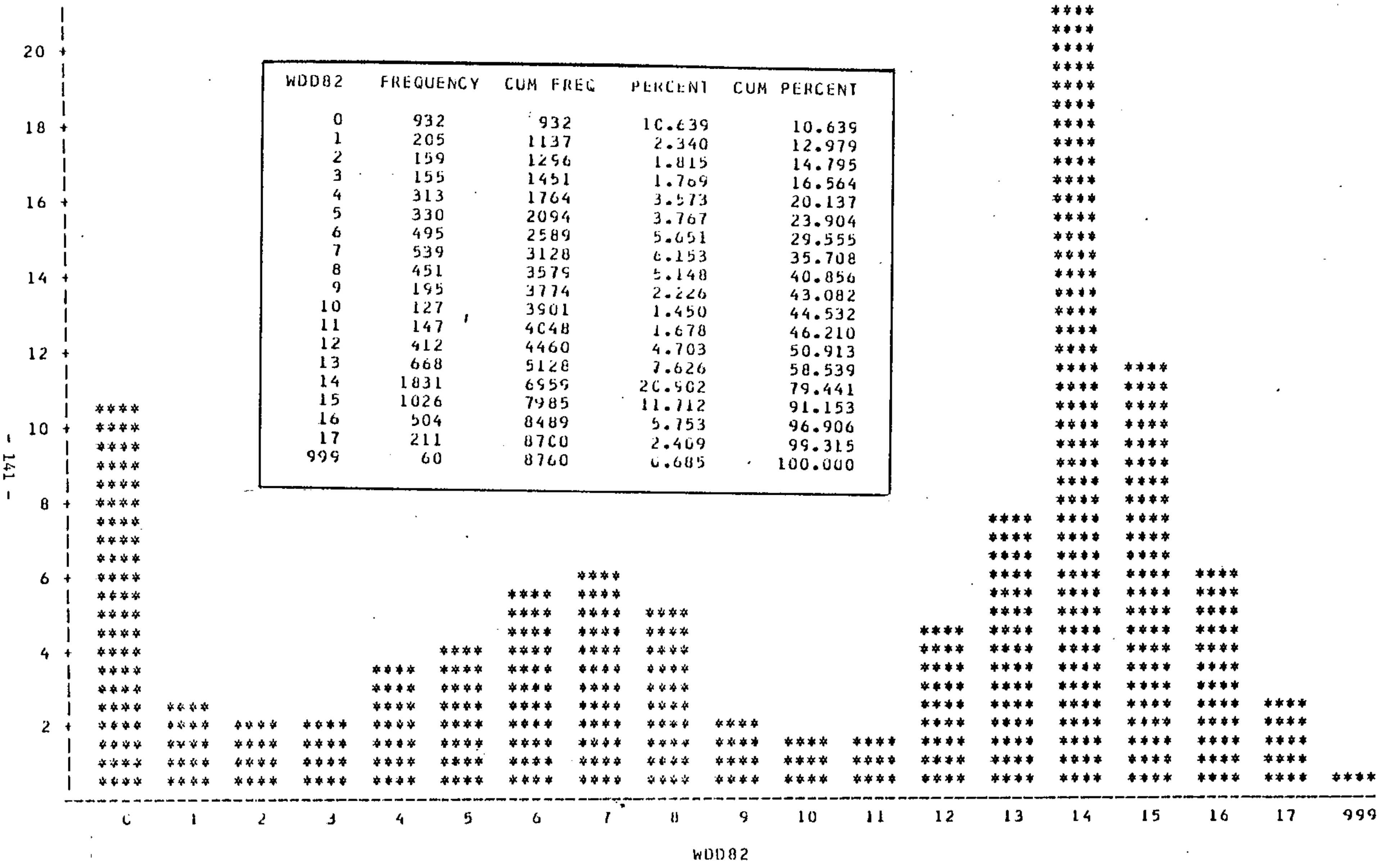
```
WDD81   FREQUENCY   CUM FREQ    PERCENT   CUM PERCENT

    0        1501       1501     17.135        17.135
    1         127       1628      1.450        18.584
    2         153       1781      1.747        20.331
    3         120       1901      1.370        21.701
    4         363       2264      4.144        25.845
    5         454       2718      5.183        31.027
    6         538       3256      6.142        37.169
    7         548       3804      6.256        43.425
    8         497       4301      5.674        49.098
    9         104       4405      1.187        50.285
   10          93       4498      1.062        51.347
   11         114       4612      1.301        52.648
   12         378       4990      4.315        56.963
   13         501       5491      5.719        62.683
   14        1626       7117     18.562        81.244
   15        1059       8176     12.089        93.333
   16         404       8580      4.612        97.945
   17         158       8738      1.804        99.749
  999          22       8760      0.251       100.000
```

Fig. 6-24. Wind direction percentages in 1981.

KISRX 8643

PERCENTAGE BAR CHART

PERCENTAGE



```
WDD82   FREQUENCY  CUM FREQ   PERCENT  CUM PERCENT

    0         932       932    10.639       10.639
    1         205      1137     2.340       12.979
    2         159      1296     1.815       14.795
    3         155      1451     1.769       16.564
    4         313      1764     3.573       20.137
    5         330      2094     3.767       23.904
    6         495      2589     5.651       29.555
    7         539      3128     6.153       35.708
    8         451      3579     5.148       40.856
    9         195      3774     2.226       43.082
   10         127      3901     1.450       44.532
   11         147      4048     1.678       46.210
   12         412      4460     4.703       50.913
   13         668      5128     7.626       58.539
   14        1831      6959    20.902       79.441
   15        1026      7985    11.712       91.153
   16         504      8489     5.753       96.906
   17         211      8700     2.409       99.315
  999          60      8760     0.685      100.000
```

Fig. 6-25. Wind direction percentages in 1982.

KISRX 8644

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PERCENTAGE BAR CHART

PERCENTAGE

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  30 +                                            *****
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  27 +                                            *****
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  24 +                                            *****
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  21 +                                            *****
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  18 +                                *****       *****
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     |                                *****       *****                   *****
  15 +                                *****       *****                   *****
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     |                                *****       *****       *****       *****
  12 +                                *****       *****       *****       *****       *****
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   9 +                                *****       *****       *****       *****       *****
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   6 +                                *****       *****       *****       *****       *****
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   3 +                    *****       *****       *****       *****       *****       *****
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     ---------------------------------------------------------------------------------------
                1           2           3           4           5           6           7

                                               STAB78
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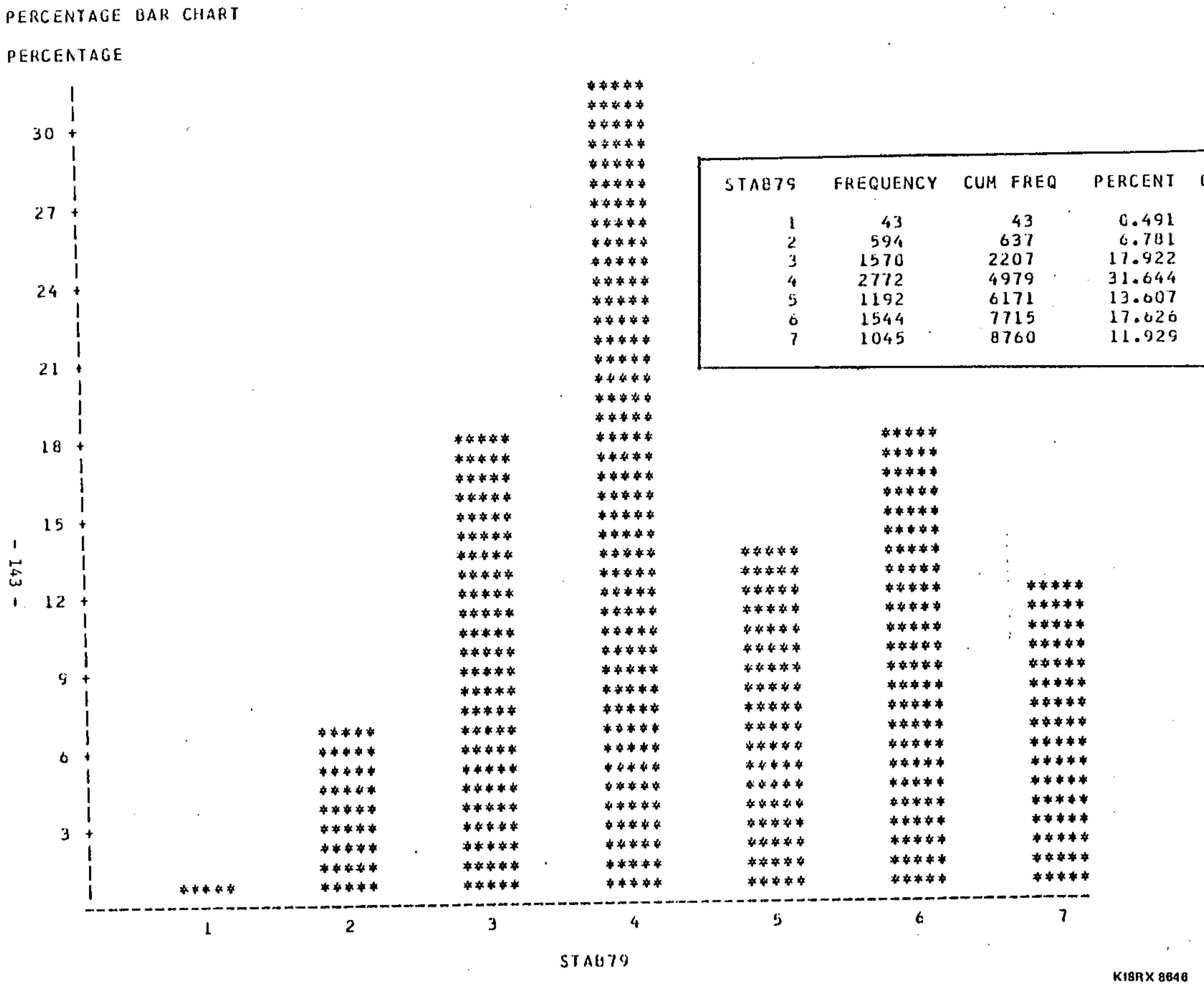
STAB78   FREQUENCY   CUM FREQ   PERCENT   CUM PERCENT

     1          27         27     0.308         0.308
     2         473        500     5.400         5.708
     3        1709       2209    19.509        25.217
     4        2783       4992    31.769        56.986
     5        1255       6247    14.326        71.313
     6        1491       7738    17.021        88.333
     7        1022       8760    11.667       100.000
```

KISRX 8645

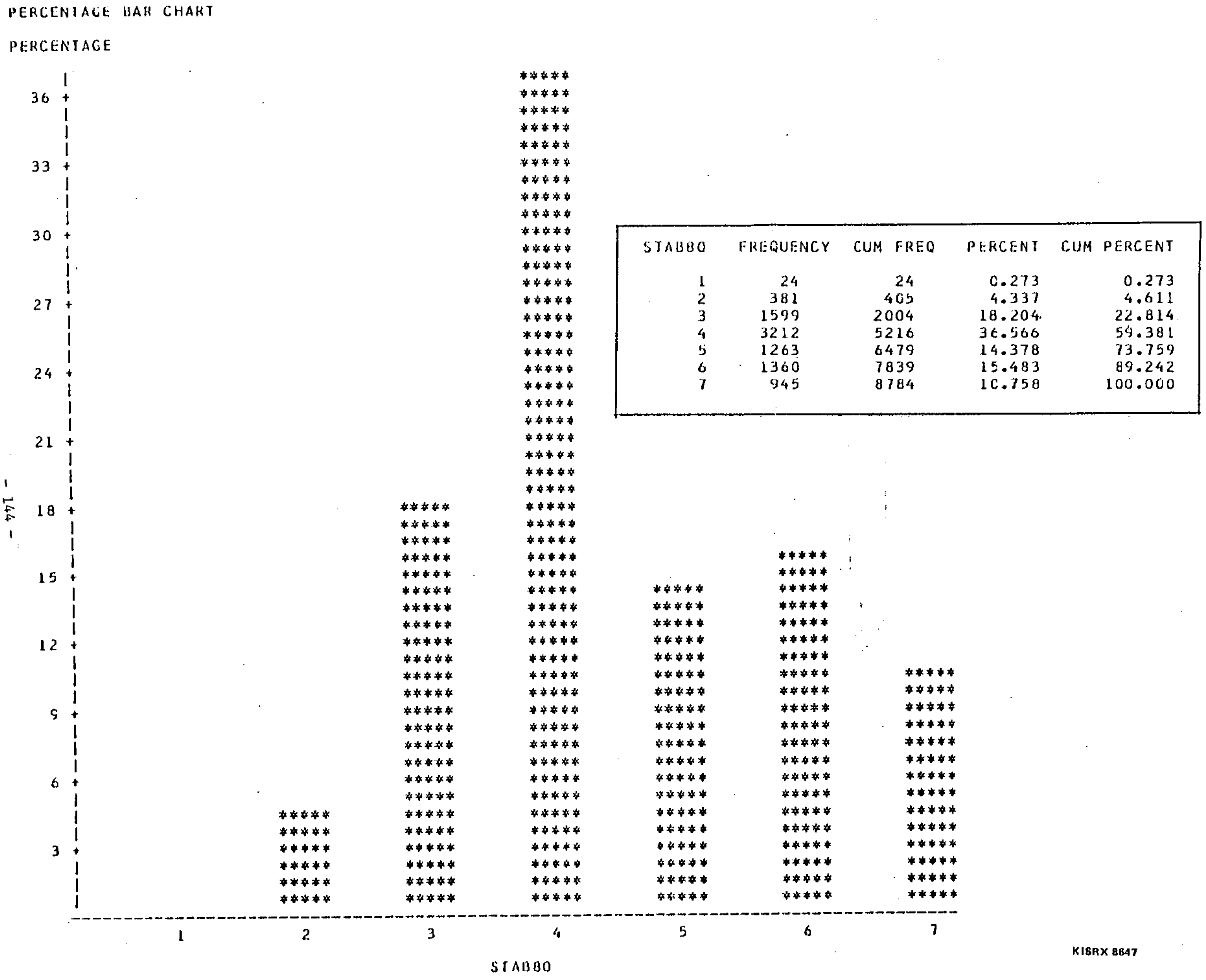
Fig. 6-26. Atmospheric stability percentages in 1978 (1 : very unstable; 2 : unstable; 3 : moderately unstable; 4: neutral; 5 : moderately stable; 6 : stable; 7: very stable).



STAB79	FREQUENCY	CUM FREQ	PERCENT	CUM PERCENT
1	43	43	0.491	0.491
2	594	637	6.781	7.272
3	1570	2207	17.922	25.194
4	2772	4979	31.644	56.838
5	1192	6171	13.607	70.445
6	1544	7715	17.626	88.071
7	1045	8760	11.929	100.000

K18RX 8646

Fig. 6-27. Atmospheric stability percentages in 1979.



STAB80	FREQUENCY	CUM FREQ	PERCENT	CUM PERCENT
1	24	24	0.273	0.273
2	381	405	4.337	4.611
3	1599	2004	18.204	22.814
4	3212	5216	36.566	59.381
5	1263	6479	14.378	73.759
6	1360	7839	15.483	89.242
7	945	8784	10.758	100.000

KISRX 8647

Fig. 6-28. Atmospheric stability percentages in 1980.

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PERCENTAGE BAR CHART

PERCENTAGE

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  27 +                                   *****
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  24 +                                   *****
     |                                   *****
     |                                   *****
     |                                   *****
  21 +                                   *****
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  18 +                         *****     *****
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     |                         *****     *****               *****
  15 +                         *****     *****               *****
     |                         *****     *****               *****     *****
     |                         *****     *****     *****     *****     *****
     |                         *****     *****     *****     *****     *****
  12 +                         *****     *****     *****     *****     *****
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   9 +                         *****     *****     *****     *****     *****
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     |               *****     *****     *****     *****     *****     *****
   6 +               *****     *****     *****     *****     *****     *****
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     |               *****     *****     *****     *****     *****     *****
   3 +               *****     *****     *****     *****     *****     *****
     |               *****     *****     *****     *****     *****     *****
     |               *****     *****     *****     *****     *****     *****
     |     *****     *****     *****     *****     *****     *****     *****
     -----------------------------------------------------------------------
             1         2         3         4         5         6         7

                                        STABBI
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STABBI   FREQUENCY   CUM FREQ    PERCENT   CUM PERCENT

     1          54         54      0.616         0.616
     2         624        678      7.123         7.740
     3        1552       2230     17.717        25.457
     4        2689       4919     30.696        56.153
     5        1213       6132     13.847        70.000
     6        1357       7489     15.491        85.491
     7        1271       8760     14.509       100.000
```
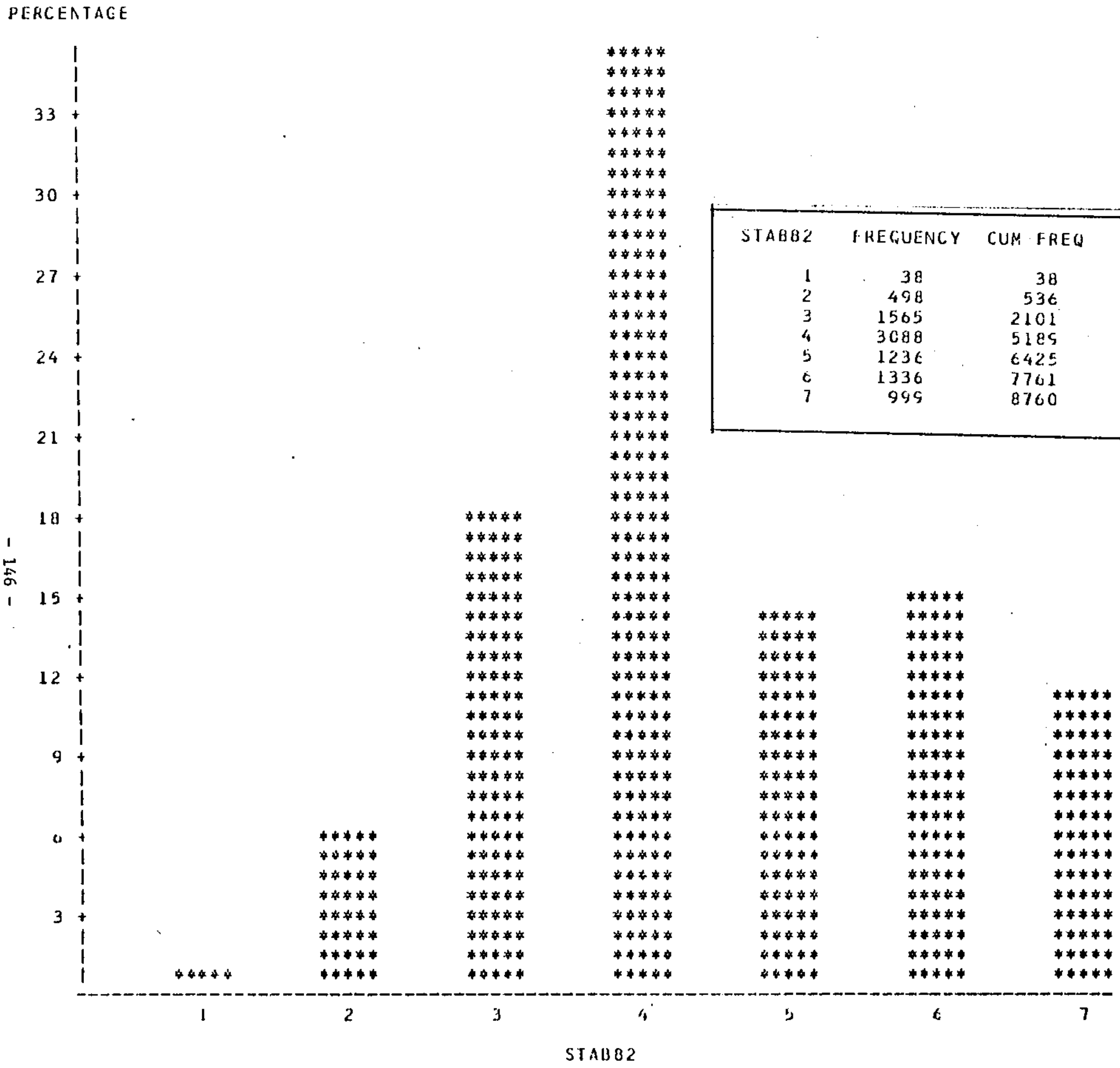

Fig. 6-29. Atmospheric stability percentages in 1981.

KISRX 8648

PERCENTAGE BAR CHART



```
STAB82   FREQUENCY   CUM FREQ    PERCENT   CUM PERCENT

     1          38         38      0.434         0.434
     2         498        536      5.685         6.119
     3        1565       2101     17.865        23.984
     4        3088       5189     35.251        59.235
     5        1236       6425     14.110        73.345
     6        1336       7761     15.251        88.596
     7         999       8760     11.404       100.000
```

KISRX 8649

Fig. 6-30. Atmospheric stability percentages in 1982.

7. Project Results

Four major results were achieved in this project:

1. The computerized collection of important environmental data, their efficient organization in the KISR computer, and their analysis.
2. The special studies and consultants' reports presented in Volume III of this final report.
3. The acquisition, selection, application and development of air pollution modeling techniques for both episode and climatological evaluations.
4. The broadening of SAA personnel capabilities in using the tethersonde instrumentation, performing source sampling activity, and understanding and using computer diffusion models.

These accomplishments are discussed in detail below.

7.1 The Collected Data and their Analysis

Meteorological, air quality and emission data have been collected and stored in the KISR computer, as discussed in Sections 3 and 4. A listing of all the data files collected during the project in Volume V of this final report. Moreover, SAA has been separately provided with a full computer printout of all collected data. All these files are presently stored in the KISR IBM computer and can be provided to SAA on magnetic tape, if required.

Particularly important was the collection of six years (1977-1982) of meteorological data at the KWI and the computerized emission inventory of the industrial stack emissions in the SIA, which updates the previous estimates of Cremer and Warner (1975).

7.2 Special Studies and Consultants' Reports

Several activities were concerned with analyzing the available instrumentation and the collected data. Each of these analyses constituted a special study focussing on a particular specific investigation.

Specialized reports dealing with these special studies were periodically prepared and submitted to SAA. The content, objectives, and results of these special studies are discussed below:

- "A Report on Surface Winds in Kuwait" (provided to SAA as part of this project; KISR 723, Appendix A; abstract enclosed in Section 1 of Volume III of this final report) analyzes five years of wind data recorded at KWI, computing annual and seasonal wind roses. It shows that the most prevalent winds are from the northwesterly quadrant (W, WNW, NW, NNW) with an annual frequency of 42%, but in summer (June, July, August) this frequency reaches 64%.
- "Meteorological Instruments and Practices at the Meteorological Observation Station of the Kuwait International Airport" (provided to SAA as part of this project; KISR 784, Enclosure 1; abstract enclosed in Section 2 of Volume III of this final report) analyses the Kuwait airport instrumentation, its characteristics and accuracy.
- "The Climate of Kuwait" (provided to SAA as part of this project; KISR 844, Appendix A; abstract enclosed in Section 3 of Volume III of this final report) discusses in detail the desert-type features of Kuwait's climate together with the seasonal and daily variation of all major meteorological parameters (pressure, winds, temperature, humidity, dust episodes, temperature inversions).
- "Preliminary Analysis of Wind and Stability Patterns in Kuwait" (provided to SAA as part of this project; KISR 844, Appendix B; abstract enclosed in Section 4 of Volume III of this final report) presents a joint analysis of hourly wind direction and atmospheric stability, where the latter parameter is computed by the CRSTER pre-processor (see Section 4.1.1). It identifies, through automatic computer plotting of wind and stability roses, the main features of atmospheric stability, which is shown to possess a clear seasonal variability. Unstable conditions are more frequent during summer, with a decrease in autumn-winter and a new increase in spring. Stable and neutral conditions are found to prevail in Kuwait, especially when winds blow from the

northwest and south. Unstable conditions, however, are often associated with south-easterly, northerly and easterly winds.

- "Stack Sampling; Summary of Instruments and Methods (Method 1 to Method 5)" (provided to SAA as part of this project; KISR 866, Appendix B; abstract enclosed in Section 5 of Volume III of this final report) provides a detailed description of the instrumentation, methods and computations used for direct stack source evaluation of the emission parameters.
- "A Preliminary Collection of Atmospheric Emission Data in the Shuaiba Industrial Area" (provided to SAA as part of this project; KISR 977A, Appendix A; abstract enclosed in Section 7 of Volume III of this final report) provides a summary, for each emission stack of each company, of source and emission parameters.
- Dr. Boubel's consultant report (provided to SAA as part of this project; KISR 1017A, Appendix A; abstract enclosed in Section 8 of Volume III of this final report) describes the intense activity of Dr. Boubel and Mr. Wellman in training, source evaluation, and source sampling.
- Dr. Tombach's consultant report (Tombach, 1983) describes his review and evaluation of the meteorological and air quality instrumentation used in this project, and precisely: (1) the air pollution monitoring and laboratory facilities of the SAA/EPC; (2) the tethersonde system; and (3) the meteorological station at the KWI. As an overall perspective, this report confirms that EPC has the facilities and equipment for operating a good air monitoring program. The report, however, points out that maintenance, shortage of spare parts and instrument calibration do seem to be a problem.

  Dr. Tombach concludes that, overall, this project represents the first phase of a ambitious program to understand and control air pollution. He points out that initial progress has been uneven, which is a characteristic of any new venture, but the direction seems to be a correct one. He recommends the following specialized activities in the future: (1) the design of an aerosol analysis program to investigate the sources of the dust problem under various meteorological conditions; (2) the design and execution of an intensive study of plume diffusion in the Shuaiba area, using tracer gases, remote sensors, and even aircraft as appropriate; and (3) external audits of the performance and calibration of air pollution measurement stations, emission testing procedures, and laboratory procedures at EPC.

- "Land and Sea Breezes in Kuwait" (provided to SAA as part of this project; KISR 1017A, Appendix B; abstract enclosed in Section 9 of Volume III of this final report) discusses the breeze phenomenon in Kuwait, which represents one of the most important factors in all coastal diffusion studies. This detailed investigation uses the data from two stations (KWI, inland, and Mena Al-Ahmadi, on the coastline) to calculate special breeze roses, and clearly shows the typical characteristics of the breeze effect in the Kuwait region. The daytime phenomenon (sea breeze winds) is found to be stronger than the nighttime one (land breeze winds) and, naturally, this effect is accentuated on the coastline and during the summer season.
- "A Prototype Data Base Structure for Meteorological and Air Quality Data" (fully enclosed in Section 13 of Volume III of this final report) presents a prototype of data base organization of the data collected for this project. Such a huge amount of data, with those that will be added in the future, clearly requires a well-organized set of computer procedures and commands for data organization, selection, and display. This report presents some advanced concepts specifically developed for meteorological/air quality data manipulation, together with selected examples of their practical implementation.
- "Tethersonde Measurements in Shuaiba" (fully enclosed in Section 14 of Volume III of this final report) summarizes the tethersonde measurements performed in the SIA and compares them with radiosonde measurements at the KWI. It shows the important result of the high similarity between the two vertical measurements,

indicating a high degree of horizontal homogeneity in Kuwait's atmospheric structure. This result allows a suitable utilization of KWI radiosonde data for modeling simulations in the SIA.

In addition to these special data analysis and interpretation studies, a fully computerized data analysis has been performed. This analysis is presented in Section 6 (computer plots) and corresponding tables are enclosed in Section 12 of Volume III of this final report.

7.3 Diffusion Models

Diffusion modeling and its results, discussed in Section 5, was the most important activity of this project. Four major accomplishments in this field need to be mentioned:

1. The installation of selected diffusion models in the KISR and SAA/EPC computers.
2 The application of some suitable models for evaluating long-term climatological impacts of SIA emissions.
3. The application of some suitable models for evaluating short-term episode conditions in the SIA.
4. The development and application of an advanced numerical technique (MC-LAGPAR) for special simulations of complex diffusion conditions in the SIA.

As introduced in Section 5.3, six diffusion packages (ISCLT, ISCST, PTMTP, PTMAX, CDM, MC-LAGPAR) were acquired (or developed), installed, tested and applied in this project. A description of their operative use (software user's manuals) is contained in Volume IV. All these packages, except MC-LAGPAR (written in APL), are written in FORTRAN and are easily transferable to any computer large enough to accommodate them. All six programs are currently on-line in the KISR IBM computer, and two of them (PTMTP, PTMAX) were also installed and tested on the SAA/EPC computer, which is still too small for running large diffusion packages. The expected future expansion of the SAA/EPC computer, however, should easily allow the installation of ISCLT, ISCST and CDM.

The availability to SAA of such computer programs, directly on the SAA/EPC computer or through the KISR computer, is the major accomplishment of this study. A detailed discussion on the possible future use of such programs by SAA personnel is presented in Section 8.

The long-term and short-term simulations presented in Section 5 provide an important preliminary planning tool to SIA decision makers. Still, the importance of such planning decisions requires more data collection and model performance evaluation, which are important planned activities for the continuation of this study (see Section 10). The preliminary advanced code MC-LAGPAR represents a first important effort (to be continued in the future) to develop ad hoc techniques for the characterization of the unique diffusion conditions in Kuwait.

In addition to the introductory discussion in Section 5, a specific description of the major modeling approaches used in this project (ISC models and MC-LAGPAR) is presented in Sectons 10 and 11 of Volume III of this final report.

7.4 Improvement of SAA Personnel Capabilities

The improvement of SAA project team capabilities is an important complementary result of this project. A continuous, intense communication between SAA and KISR project teams was a constant characteristic of this study. Through formal and informal meetings, consultants' visits, and official training courses, SAA personnel were exposed to systematic on-the-job training, a valuable asset for future SAA air pollution studies and applications.

In addition to this general improvement of SAA air pollution capabilities, training activities in three specific areas need to be mentioned:

1) tethersonde measurements;
2) source sampling; and,
3) air pollution computer diffusion models.

Two SAA people were trained by KISR to use the tethersonde system after its acquisition. The training results were extremely satisfactory, so that, during the last few tethersonde field data collections (February 1983), SAA personnel were able to fully and properly operate the hardware equipment without active supervision.

Source sampling training was performed by KISR personnel and, especially, by the stack testing consultant, Mr. Eugene Wellman, who gave a one-week source sampling seminar in which several SAA, KISR and local industry people were properly trained in source sampling instrumentation and procedures. Practical field work was an important final part of this training period.

One SAA computer scientist was specifically assigned the task of diffusion model applications. This staff member was trained by KISR in:

1) using the advanced operative system of the KISR IBM computer (CMS, Conversational Monitoring System);
2) understanding the physics behind the computer diffusion models and the operative running options of the computer codes; and,
3) running the selected models on both KISR and SAA/EPC computers.

The outstanding performance of this SAA staff member enabled all planned training objectives to be achieved. In particular, because of the expertise of this trained SAA staff member, SAA/EPC can claim today a full understanding of selected Gaussian computer diffusion codes and the capability of running them without KISR's technical support and supervision.

7.5 Conclusion

Project results of the phase 1 study (1981-83), even though the difficulties were encountered, can be considered important and satisfactory. In spite of the lack of extensive air quality measurements, model results provide important, reliable information. A full model calibration (as recommended in Fig. 1-4) was not possible and this important task must be performed in the future when the new SAA/EPC stations will be fully operative. Nevertheless, the air pollution models selected and applied in this project are state-of-the-art methodologies that are often used in the United States without calibration for multi-million dollar decisions. We therefore feel confident that our model results possess a good degree of reliability, which will be strongly increased by future work in this field.

In conclusion, the foundation for the proper development of SAA-KISR air pollution studies has been successfully built, and, based on existing competence, qualifications and knowledge, the next phases (presented in Section 10) of this scientific collaboration can be properly planned.

8. Possible Future SAA Utilization of Project Results

Several SAA activities may strongly benefit in the near future from project results. Four major topics, in particular, need to be mentioned:

1) the planning of future industrial developments;
2) the determination of industrial emission standards;
3) the simulation of possible accidental releases; and
4) the definition of least-cost emission reduction strategies.

8.1 Industrial Development Planning

New factories, and possible changes to existing ones, will inevitably alter the air pollution emission pattern in the SIA. Appropriate planning for such an evolution is scheduled to be an important SAA activity in the near future. In this respect, the long-term models (CDM and, especially, ISCLT) represent an invaluable tool for assessing in advance the air quality impacts of possible future emission scenarios. In particular, the best locations for a minimum climatological impact of new emission sources can be easily identified using the present results (see Section 5) of the ISCLT model.

On the other hand, short-term episodic conditions may sometimes represent the greatest danger. Some of the developed models (ISCST, PTMTP, and especially MC-LAGPAR) provide reliable simulations of such short-term episodes. The simulations can provide additional suggestions for planning new source locations, based on episode evaluations as well as on climatological considerations.

8.2 Determination of Industrial Emission Standards

Ambient atmospheric standards are pre-fixed concentration values that should not be exceeded in a certain urban or industrial area. There are short-term standards (e.g., hourly averages) to protect the population against pollution episodes, and long-term standards (e.g., yearly averages) to protect against the systematic deterioration of human health or the environment produced by low but persistent pollutant concentrations. Most industrialized countries have adopted laws and regulations fixing suitable values for such ambient standards (see Stern, 1982, for the U.S. standards).

The best guarantee of compliance with the ambient air quality standards is through the implementation of emission standards, since emission parameters can be regulated and controlled by a supervising authority in an industrial area. Diffusion models provide an answer to the following important question: "If the maximum ambient concentration $\chi_{standard}$ is tolerated, what is the maximum emission $Q_{standard}$ that can be allowed to be discharged from a specific source?".

The models developed in this project can answer this and similar questions involving the combined effect of multiple sources, e.g., the existing ones and those planned in the future.

8.3 Simulation of Accidental Releases

Since accidental releases are the only air pollution phenomenon that can be proved without doubt to be potentially lethal, their simulation is especially important. Some models presented in Section 5 (ISCST, PTMTP, and especially the highly sophisticated prototype MC-LAGPAR) can be used for simulating accidental release scenarios. Model outputs can properly help SAA design evacuation plans, intervention strategies, security rules, etc.

8.4 Least-Cost Emission Reduction Strategies

Should SAA consider the present pollutant levels in the SIA too high, a few important questions need to be answered. Which sources need to be reduced? How much reduction is feasible? More importantly, if an air quality goal (e.g., the standards) must be reached, which is the most cost-effective emission reduction strategy? Since the cost of pollution control hardware is staggering, a proper application of diffusion models can help optimal strategies, sometimes with considerable savings.

This least-cost technique, however, requires some additional input data (i.e., the cost of each emission reduction) and suitable computational techniques (i.e., the numerical optimization, under proper constraints, of the cost function).

9. Future Needs in Shuaiba

The extensive analysis of air pollution problems in the SIA performed during the project provided a clear identification of the future needs in the region to accomplish the five APS objectives mentioned in Section 1.1. This section summarizes the four major future requirements:

- routine data collection;
- special intensive data collection campaigns;
- model calibration/evaluation; and,
- development of ad hoc models for the SIA.

9.1 Routine Data Collection

Only through a well-organized continuous collection of meteorological, emission and air quality data can air pollution modeling studies provide those valuable climatological (long-term) simulations that represent the most important air quality planning tool in the SIA. The new automatic monitoring stations, which are being installed by the SAA, represent (if properly maintained and calibrated) a sufficient source of routinely-collected information (air quality and meteorology).

In Tasks 1 and 2, average emission parameters were collected, even though industrial emissions are known to have strong variabilities. Routine periodical information on source variations should be collected, e.g., malfunctioning, shutdowns, installation of new control equipment, changes in production rates, changes in combustion fuels, etc.

9.2 Special Data Collection Campaigns

Routine data collection should be complemented by special intensive campaigns (typically of one-two weeks) for the collection of additional important information. Three major activities should be planned:

1. Sampling the industrial sources in the SIA
2. Performing additional tethersonde measurements.
3. Evaluating atmospheric diffusion rates in the SIA through tracer experiments.

Task 2 of this project pointed out the need for systematic source sampling in the SIA to fully evaluate the emission parameters. Only a few sources in the SIA are now properly equipped for such sampling. It is important, therefore, to prepare the industrial sources for testing (sampling ports, scaffolding, lifts, etc.) and then to perform systematic intensive sampling campaigns.

An important piece of equipment, the tethersonde instrument, was purchased for this phase 1 study. Much still needs to be understood about Kuwait's coastal meteorological patterns. Intensive tethersonde campaigns should, therefore, be planned to facilitate a full evaluation of the time-varying three-dimensional meteorology in the SIA and its surrounding regions.

Available diffusion models, like those used in this study, have built-in diffusion rates that are often not fully representative of the special diffusion conditions encountered in regions different from those in which such diffusion rates were previously evaluated. Therefore, a need often exists for reevaluating these diffusion rates and finding the appropriate local values for the region under examination. Tracer experiments represent the most reliable way to evaluate the diffusion rates in the SIA and are, therefore, strongly recommended for the future.

9.3 Model Calibration and Evaluation

As observed in Section 7.5, the models developed for this study still require a full calibration/evaluation against ambient concentration measurements. This calibration/evaluation should be made as soon as detailed air quality concentration measurements in the SIA are available.

Short-term model calibration should also strongly benefit from the tracer experiment campaigns recommended in Section 9.2, and long-term model calibration is based mainly on long-term average ambient concentration measurements.

Long-term and short-term calibrated models could then be properly used without any reservation for SAA planning/evaluation purposes, as discussed in Section 8.

9.4 Development of Ad-Hoc Models for the SIA

With the increasing data collection activity in the SIA, especially after the performance of tracer experiments and other special monitoring campaigns (Section 9.2), available modeling techniques can be expected to show their limitations in simulating the known complex dispersion conditions in the SIA. At that point, a need will arise for developing and applying more advanced modeling techniques specially designed (or adapted) for the SIA.

The MC-LAGPAR model developed in this phase (see Section 5) is a first step in this direction, but much more is expected to be needed in the future. Three types of models should require special developments for their application in the SIA:

- Gaussian models
- Grid models
- Particle models

Steady-state Gaussian models require, among other things, the appropriate determination of plume dispersion rates, e.g., plume sigmas. The more complex dynamic Gaussian models (segmented plume, puff) may require special adaptations and modifications (as in Zannetti, 1981a).

Grid models are, at least theoretically, a very powerful numerical device for any type of deterministic numerical simulation. They still are the only air pollution simulation method available when complex non-linear chemical reactions between pollutants must be considered. Since chemical especially, photochemical) simulations are expected to be required in the future, the development and application of suitable grid models to the SIA should be considered.

Lagrangian particle models represent today the most appealing numerical technique for the simulation of transport and diffusion processes. The prototype MC-LAGPAR developed for this project showed promising results. This approach is certainly the most flexible in simulating complex diffusion conditions in the SIA, and its future extensive development and application should be considered.

9.5 Conclusion

This section has presented KISR's recommendations for future air pollution activities in the SIA, independently of the possible continuation of this SAA-KISR project. Naturally, this continuation (phase 2) is highly desirable and its proposed structure (described in Section 10) addresses most of the needs identified in this section.

10. The Proposed Continuation of This Study

As stated in the official KISR proposal (Zannetti, 1982b), this final report contains the proposed continuation (phase 2, see Fig. 1-1) of this study during September 1983-June 1985. This new project should aim at the following objectives:

- Computerized collection of additional data.
- Calibration/evaluation of the models developed in phase 1.
- Development of special new models.
- Preliminary evaluation of different future emission scenarios.

This section contains a preliminary description of the study that KISR is recommending for the phase 2 project (1983-1985).

Four tasks are proposed and fully discussed in the work plan to meet these objectives.

10.1 Work Plan

The project will be divided into the following four tasks:

Task 1 - Additional Data Collection, Organization and Analysis
Task 2 - Calibration and Evaluation of Available Diffusion Models
Task 3 - Development and Application of Special New Modeling Techniques
Task 4 - Modeling Simulation of Possible Future Emission Scenarios

Task activities are presented in the following subsections.

10.1.1 Task 1 - Additional Data Collection, Organization and Analysis

Five major (and a sixth optional) data collection activities will be performed in Task 1:

- Subtask 1A: Data will be collected from the new automatic air quality and meteorological stations being installed by the SAA/EPC. These data are extremely valuable for air pollution studies and will, therefore, be collected, checked and organized in computerized form.

- Subtask 1B: Appropriate facilities will be constructed so emission sources in the SIA can be sampled. Stack emission parameters will be sampled, thus providing a final, complete emission inventory of point sources in the SIA. At the same time, all fugitive emission parameters in the SIA will be evaluated.
- Subtask 1C: Using the tethersonde instrumentation purchased in the phase 1 study, systematic meteorological campaigns will be performed to fully evaluate the three-dimensional variation of SIA meteorology.
- Subtask 1D: Early-afternoon ozone concentration measurements, 5-20 km downwind of the SIA, will be collected to evaluate the possible photochemical effects of SIA emissions.
- Subtask 1E: Tracer diffusion experiments (preferably using the SF_6 tracer) will be performed in the SIA to evaluate local diffusion rates during different meteorological conditions and times of the day. Both ground-level and elevated-release experiments will be performed.
- Subtask 1F (optional): A Doppler acoustic sounder instrument will be purchased. This instrument is one of the most advanced types of equipment for air pollution studies and provides a continuous automatic remote sensing, from about 30 m up to 600-1000 m, of wind and turbulent atmospheric structure.

10.1.2 Task 2 - Model Calibration and Evaluation of Available Diffusion Models

With the data collected in Task 1, those models developed in the phase 1 study will be fully calibrated and evaluated. This task will provide completely validated modeling packages for future SAA applications.

10.1.3 Task 3 - Development and Application of Special New Modeling Techniques

Three major modeling activities will be developed in this project:

- Subtask 3A: Development and calibration with tracer data of a fully three-dimensional Lagrangian particle model for the real-time simulation of possible accidental releases in the SIA.

- Subtask 3B: Development of a grid model for short-term (hourly) simulation of pollution episodes in the SIA. Calibration/evaluation of such a model in special selected periods with known emission rates in the SIA. Further final calibration/evaluation using tracer data.
- Subtask 3C: Simulation of chemical and photochemical reactions using appropriate modeling techniques. Assessment of the potential oxidant formation (mainly ozone) that can be attributed to SIA emissions.

10.1.4 Task 4 - Modeling Simulation of Possible Future Emission Scenarios

The SAA will provide different possible future emission scenarios that will then be fully evaluated using selected, well-calibrated diffusion models. This application will allow SAA to make preliminary choices between possible development options in the SIA.

10.2 Expected Results and Deliverables

The following important results are expected from this phase 2 study:

- The completion of the data collection task of the phase 1 study, in particular, the acquisition of suitable and reliable air quality and meteorological measurements inside the SIA.
- The finalization, through extensive source sampling, of the emission inventory in the SIA.
- The validation of selected diffusion models.
- The development of new special diffusion models.
- The preliminary evaluation of future emission scenario impacts in the SIA.

Project deliverables to SAA will be:

- Monthly one-page project status reports (executive summaries).
- Quarterly project reports (technical reports).
- Task reports, at the completion of each task.
- Final report, at the end of the project.
- Computer tapes with all the data and the programs developed during the study.
- User's manuals describing all the computer programs and models developed during the study.

- Installation in the SAA/EPC computer of all the programs that can fit in that computer facility. (if the expected expansion of present computer facilities at SAA/EPC occurs, most of the software developed by this proposed study will be installed in the SAA/EPC computer.)

10.3 Conclusion

This discussion must be considered preliminary working material for SAA's consideration and evaluation. For this reason, no cost or task schedule plans have been included.

11. Final Considerations

This project is the first organized air pollution modeling research study in Kuwait. Like most research studies, especially in new areas, it addresses initial preliminary problems, but, at the same time, identifies the need for further research to both complete previous analyses and develop new ones.

A technological gap in environmental sciences, air pollution, in particular, exists today between Kuwait and Western countries (e.g., Europe and the U.S.). But Kuwait and the SAA are in a very fortunate position. By properly using the lessons gained from experience in the West during the last 15 years, errors and waste can be avoided in the development of air quality studies and air quality intervention or regulation plans.

Future air pollution studies in Kuwait will provide benefits beyond those related to local environmental welfare and industrial development. Air Pollution Studies, with their interdisciplinary structure (physics, chemistry, mathematics, computer science, engineering, electronics, etc.), involve the application of state-of-the-art techniques and represent one of the best ways to develop technical abilities in an emerging country, thus reducing its technological gap.

The detailed discussion of performance, results and possible continuation of this project represents a very specialized study report that opens a new world of applied research and development for Kuwait and has contributed to a real technological jump in local capabilities to deal with air pollution problems and their numerical simulation.

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