STUDIES ON THE CLIMATOLOGICAL ASPECTS OF AIR POLLUTION POTENTIAL OVER TRIVANDRUM

THESIS SUBMITTED TO THE
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
IN
METEOROLOGY

BY
S. S. SUNEELA

PHYSICAL OCEANOGRAPHY AND METEOROLOGY DIVISION
SCHOOL OF MARINE SCIENCES
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY
COCHIN - 682 016

JANUARY 1989

To my beloved parents

CERTIFICATE

This is to certify that this thesis is an authentic record of research work carried out by Ms. S. S. Suneela in the School of Marine Sciences for the Ph.D. degree of the Cochin University of Science and Technology and no part of it has previously formed the basis for the award of any degree in any university.

(D. V. Viswanadham)
Supervising Teacher
Reader in Meteorology
Department of Geophysics
Banaras Hindu University.

Varanasi-221005,

January, 1989.

H.S. Ram Mohan
31/1/89

(H.S. Ram Mohan)
Co-Supervising Teacher
Reader in Meteorology
School of Marine Sciences
Cochin University of
Science & Technology.

Cochin - 682016,

January, 1989.

DECLARATION

I hereby declare that this thesis, entitled 'Studies on the climatological aspects of air pollution potential over Trivandrum' is a genuine record of research work carried out by me in the School of Marine Sciences, Cochin University of Science and Technology and no part of it has previously formed the basis for the award of any degree in any University.

Cochin-682 016,
January, 1989.

(S. S. Suneela)

ACKNOWLEDGEMENTS

I express my profound and heartfelt indebtedness and gratitude to Dr. D. V. Viswanadham, former Lecturer in the School of Marine Sciences, Cochin University of Science and Technology, presently Reader in the Department of Geophysics, Banaras Hindu University for his valuable guidance and constant encouragements.

I wish to express my sincere gratitude to Dr. H. S. Ram Mohan, Reader in the School of Marine Sciences for his suggestions and corrective tips.

I would like to express my appreciation to the authrorities of Cochin University of Science and Technology for providing the necessary facilities. I am also thankful to the former and present Heads of the Physical Oceanography and Meteorology Division and Directors of the School of Marine Sciences.

I gratefully acknowledge the Council of Scientific and Industrial Research for their financial support.

I wish to express my gratitude to Prof. T. Lal, Head, Department of Geophysics, Banaras Hindu University for providing the necessary facilities during my visits to his department.

I am very much thankful to the family of Dr.Viswanadham for their kind hospitality during my stay at Varanasi.

I record my sincere gratitude to my parents and other family members for their constant encouragements.

Last but not least I gratefully acknowledge my well wishers, who helped me by all possible ways.

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PREFACE

The deteriorating air quality especially in urban environments is a cause of serious concern. In spite of being an effective sink, the atmosphere also has its own limitations in effectively dispersing the pollutants being dumped into it continuously by various sources, mainly industries. Many a time, it is not the higher emissions that cause alarming level of pollutants but the unfavourable atmospheric conditions under which the atmosphere is not able to disperse them effectively, leading to accumulation of pollutants near the ground. Hence, it is imperative to have an estimate of the atmospheric potential for dispersal of the substances emitted into it. This requires a knowledge of mixing height, ventilation coefficient, wind and stability of the region under study. Mere estimation of such pollution potential is not adequate, unless the probable distribution of concentration of pollutants is known. This can be obtained by means of mathematical models. The pollution potential coupled with the distribution of concentration provides a good basis for initiating steps to mitigate air pollution in any developing urban area. In this thesis, a fast developing industrial city, namely, Trivandrum is chosen for estimating the pollution potential and determining the spatial distribution of sulphur dioxide concentration. Each of the parameters required for pollution potential is discussed in detail separately. The thesis is divided into nine chapters.

In the first chapter, a brief introduction to the subject along with the statement of the problem is given. An account of the background of the city and the location of various sources are also given.

The second chapter contains a detailed review of the various aspects of air pollution climatology.

In the third chapter, the details of the data used for the present study and their sources are given. The methodology for all the computations carried out in this thesis along with various positive aspects and limitations are also presented.

The analysis of percent frequency of occurrence of inversions, isothermals and lapse conditions form the basis of the fourth chapter.

The fifth chapter deals with the diurnal and monthly variations of mixing heights and ventilation coefficients.

In the sixth chapter, detailed studies on the stability of the atmosphere by the Pasquill's method are carried out. Pollution potential of the atmosphere is studied by developing a new pollution potential index.

Wind fluctuations and their relationships with atmospheric stability and mixing height are studied and presented in the seventh chapter. The diurnal variation of the fluctuations are also presented. Regression equations have been developed between wind fluctuation ranges and mixing height.

In the eighth chapter, spatial distribution of sulphur dioxide concentrations over Trivandrum is studied using multiple stack Gaussian plume model. Suggestions are made for mitigation of pollution and for possible locations of new factories.

The ninth chapter contains the summary and the overall conclusions of the entire study.

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CHAPTER I

INTRODUCTION

1.1 STATEMENT OF THE PROBLEM AND OBJECTIVES

Many of the developmental activities such as industrialisation are directly or indirectly leading to deteriorating air quality because of the dumping of copious amounts of unwanted substances into the atmosphere which has its limitation to effectively absorb them, the great sewage capacity of the atmosphere, notwithstanding. The atmospheric conditions which vary quite considerably with time play a very crucial role in the dispersal of the various pollutants being emitted into the atmosphere. Once pollutants are emitted, the dispersal and the consequent dilution are solely governed by the prevailing meteorological conditions.

A proper planning of any given urban area would help mitigate the problems due to air pollution. Such planning needs the knowledge of the climatology of the area. Irrespective of whether sources are present or not, the capacity or the potential of the atmosphere to dissipate pollutants effectively should be established climatologically, for proper environmental planning. The main objective of the present study is to examine the climatology of the air pollution potential for an industrially developing city, namely, Trivandrum so that effective steps could be initiated before the real industrial boom sets in. The detailed objectives are as follows :

(i) to study the occurrence of inversions, isothermals and lapse conditions,

(ii) to study vertical and horizontal extent of mixing,

(iii) to establish the wind climatology,

(iv) to study the atmospheric stability,

(v) to establish the climatology of wind speed and direction fluctuations,

(vi) to formulate interrelationships among mixing height, stability and wind speed and direction fluctuations,

(vii) to obtain the pollution potential indices,

(viii) to study the ground concentrations of sulphur dioxide by means of multiple stack Gaussian model and

(ix) to suggest the appropriate locations for new industries and other steps for reducing pollution effects.

Trivandrum city is chosen because of the vast natural resources available in the neighbourhood and the commercial potential it has for attracting industrial development. Being the capital of Kerala State, it has various advantages for the development of industries. It is well connected to the rest of the country and to other countries, to facilitate export of the industrial output. At present there are 8 major industries.

1.2 DEFINITIONS, SOURCES, TYPES AND EFFECTS OF AIR POLLUTION

A brief introduction to some of the aspects of air pollution and air pollution climatology is presented in this section.

1.2.1 Definitions

Air pollution generally implies the presence of foreign substances in the air and becomes a cause for serious concern when the concentration of these external substances exceeds certain tolerable limits. A more specific definition of air pollution, advanced by the Engineers Joint Council (Bishop, 1957) is 'Air pollution means the presence in the out door atmosphere of one or more contaminants such as dust, fumes, gas, mist, odour, smoke or vapour, in quantities of characteristics and of duration such as to be injurious to human, plant or animal life or to property, or which unreasonably interfere with the comfortable enjoyment of life and property'.

This all-encompassing definition clearly implies that air is considered to be polluted not necessarily when the effect of foreign substance is felt, but when they tend to cause the effect also.

1.2.2 Sources of air pollution

The sources of pollution can be classified into a) natural and b) man-made sources.

a) Natural sources

Air pollution problems existed even before the industrial era began. The organic compounds from vegetation, ground dust, salt spray from oceans, forest fires and volcanic eruptions are some examples of the various natural sources. The concentrations due to these sources have increased the background pollution levels over years, even over areas far distant from the original sources. Quantitatively, these concentrations are lower compared to those due to man-made sources, owing to their widespread distribution over very large areas extending mostly to uninhabited areas.

b) Man-made sources

These sources can be essentially divided into three categories : (i) Single or point sources, (ii) area sources and (iii) line sources. Common examples of point sources are steel mills, power plants, oil refineries, paper mills, fertilizer plants etc., while residential areas, apartments, office buildings, hospitals etc. are area sources.

Automobiles in motion act as line sources. Among these three, the height of emission is maximum for point and least for line sources.

The major contributor to air pollution is industry. The gaseous and particulate waste caused by the burning of fossil fuels such as coal or oil is dumped into the atmosphere through vertical pipes known as chimneys or stacks. The major ingredients of fossil fuels are carbon, hydrogen and sulphur and consequently the industries discharge oxides of sulphur, carbon particles, carbon monoxide and hydrocarbons. An industry may have one or more stacks. Since a stack is a point in the atmosphere, industries are considered to be point sources.

Whenever there is a cluster of houses or apartments and when the cooking medium is coal or firewood, the smoke from all the houses forms a thick cloud. As the smoke spreads over a given area, where each point cannot be distinguished, this is called as an area source. The smoke can also be due to space heating and refuse disposal.

Motor vehicles emit smoke through an exhaust pipe, and when they move, the smoke forms a line all along the path at a very low level and hence the name, 'line sources'. This is also a very dangerous source because the pollutants are emitted almost at ground level.

1.2.3 Types of air pollution

There are innumerable kinds of air pollutants of which only the major types are pointed out and explained briefly here. The major types are a) Oxides of sulphur, b) Oxides of Nitrogen, c) Carbon compounds, d) Particulate matter and e) Photochemical products.

Sulphur is a constituent in coal and fuel oil. Due to combustion, directly or indirectly, it enters into the atmosphere as sulphur dioxide, hydrogen sulphide, sulphurous and sulphuric acids and various sulphates. The amount of sulphur dioxide emitted into the atmosphere annually from different countries is given by Bach (1972). Globally, an average 80 million tonnes of sulphur dioxide are emitted annually into the atmosphere. If this amount is equally distributed over the globe, it would increase the world's sulphur dioxide concentration by about 0.006ppm. However, Junge and Werby (1958) pointed out that precipitation removes all acids and sulphates within a period of about 43 days.

Nitric oxide, a relatively harmless gas turns into a pungent yellow-brown harmful gas when oxidised to nitrogen dioxide. Man-made nitrogen dioxide originates both from stationary and mobile sources. Ammonia, a pungent gas is emitted into the atmosphere by natural as well as man-made sources.

Carbon compounds include carbon monoxide, carbon dioxide and hydrocarbons. Carbon monoxide, a colourless, odourless and lethal gas, results from incomplete combustion of carbonaceous material. Almost 80 to 90% of it is produced by automobiles. Carbon dioxide, on the other hand, is not considered as an air pollutant directly due to its inherence in all life processes. However, increased level of carbon dioxide may have an indirect impact both locally and globally on changing the climate. Hydrocarbons originate from the combustion of gasoline, coal, oil, natural gas and wood, from evaporation of gasoline and industrial solvents and from natural sources, mainly by the decomposition of vegetation. Among natural and man-made sources, the former far exceeds that due to the latter (Bach, 1972). In air pollution control, the unsaturated hydrocarbons of the olefine group and the compounds belonging to the aromatic or benzene group are of primary importance. Unsaturated olefines react easily with other chemicals. Aromatic compounds have been found to be carcinogenic or cancer producing, the most powerful among them being benzopyrene.

Particulate matter consists of solid and liquid particles of various sizes ranging from less than 0.4^{μ} to about 100^{μ}. Particles larger than 10^{μ} consist mainly of dust, coir-dirt and fly ash from industrial and erosive processes.

Photochemical products can also be called as secondary pollutants. In the presence of reactive hydrocarbons, solar energy is absorbed by nitrogen dioxide to form photochemical smog. During this process, nitric oxide and atomic oxygen are formed. The atomic oxygen (O) reacts with oxygen molecules (O_2) to form colourless and pungent ozone (O_3). Since ozone is an early and continuing product in the smog formation and as such the presence of ozone keeps the oxidising process going, ozone is almost synonymous with the term oxidant, which is a measure of how much smog formation is taking place. Hundreds of chemical processes occur as long as there is sufficient supply of hydrocarbons, nitrogen oxide and nitrogen dioxide from automobiles, ozone and solar radiation. Some of the better known irritating photochemicals are Peroxy Acetyl Nitrate (PAN) and aldehyde.

1.2.4 Effects of air pollution

The effects of air pollution are described in many books with details. (Magill et al, 1956; Faith and Atkinson Jr., 1972; Perkins, 1974 and Stern, 1977). However, the effects are presented very briefly here, to maintain continuity. The most common effects of air pollution are damage to health, visibility reduction, damage to property, annoyance to human senses and substantial changes in the ecosystems.

Damage to health is the cause for primary concern among human beings. Though it is not established as to which particular pollutant causes what type of disease, there have been specific diseases attributed to a single or a group of pollutants. For example, chronic diseases such as bronchitis, asthma, emphysema etc. are aggravated by sufficiently high concentration of sulphur dioxide, nitrogen dioxide, particulate matter and photochemical smog. Cardiovascular and pulmonary diseases are exacerbated by carbon monoxide. Photochemical smog irritates the eyes.

Reduction in visibility is the most widely noticed effect of air pollution. Smoke and dust clouds that are sufficiently dense to darken the skies will obviously limit visibility. Visibility reduction causes considerable difficulties in aviation, shipping and road transportation.

Damage to property includes damage to materials, vegetation and animals. Damage to material is mainly due to corrosive acidic compounds present in the polluted atmosphere. The important acid-forming pollutant is sulphur dioxide. Other damages include rubber cracking, deterioration of painted surfaces, soiling of stuctures and clothes etc. Damage to vegetation is usually in the form of chlorotic marking, banding or silvering or branching of the under side of leaves. In extreme cases, defoliation and death of the plant may result. The economic effect of pollution on animals is normally restricted to effects on domestic animals raised for profit. The most important problem is damage from grazing in areas where grasses are contaminated by fluoride dusts or have absorbed fluoride compounds from the atmosphere.

The next effect of air pollution which causes discomfort to the senses of people includes a multitude of reactions that can be generally divided into two classes, a) Eye, nose, throat and skin irritants and b) Odours. These irritants are emitted into the atmosphere either directly or formed by the reaction of otherwise non-irritating substances. Odour is more difficult to define, as odour obnoxious to one person may be pleasing to another. The common odours which cause discomfort, generally, are from slaughter houses, fish markets, industries emitting hydrogen sulphide and phenolic compounds.

Cloud formation and change in rainfall in areas downwind from large sources of pollution are some of the best examples of ecosystem changes. Temperature changes are also effected by air pollution.

1.3 AIR POLLUTION METEOROLOGY

Every air pollution problem has three requisities: a) there must be a source, b) after emisssion, emittants must be confined to a restricted volume of air and c) the polluted air must interfere with the physical, mental, or social well-being of the people. The first and the third aspects have been discussed in the preceding sections. The second and the most important aspect is the interaction of meteorology with the pollutants. Meteorology plays the most crucial role in determining the concentration of pollutants. The fundamental way in which it can interact is the dispersion or the dilution of pollutants. Meteorology completely governs pollutant dispersal once they are emitted into the atmoshpere. Many of the air pollution episodes are understood to have occurred under adverse meteorological conditions. The elimination of air pollution entails engineering technology and economics for the most part, and forms only a small portion in the scope of meteorological science. But meteorology can and does contribute, in many important ways, to air pollution control activities including research, surveys and operational programmes and in forecasting concentration distribution of air pollutants under normal conditions of pollutant emissions, and with designated levels of controls. An effective air pollution warning can be issued through a meterological forecast from which an abatement strategy can be worked out. Warnings based on air quality alone will be futile if the variable atmospheric processes affecting pollutant dispersal are not taken into account. Abatement of air pollution can be achieved by reducing or eliminating the emission of pollutants from one source after another. One should take into account the influence of meteorological processes that cause pollutants to be dispersed. In urban and industrial development schemes, air pollution climatology should be incorporated to have a long-range air quality management programme. In the following sections, the influence of important meteorological parameters on the dispersion of pollutants are discussed.

The vector wind is the most important meteorological variable used in air pollution studies. The direction and the speed of transport of air pollutants are governed by the wind. The fluctuations of the vector wind can be used to determine stability classes and diffusion coefficients. Winds are usually summarised by classes of speeds and directions and from these, wind roses can be constructed which give the percent frequency of occurrence of 16 (8 primary and 8 secondary) directions with a further subdivision of percent frequency of speed classes in each of these wind directions. These wind roses will be of utmost importance not only for planning purpose but also for determining ambient air quality with the help of models. It is a common observation that wind speed is different in different directions and hence in the air quality modelling, different wind speeds are to be used in various directions; while speed determines the dilution of pollutants in the atmosphere to some extent, direction gives the transport. The study cannot be confined to one or two wind roses per day as the high variability of wind is completely masked, especially in coastal and complex terrains, where mesoscale circulation in the form of land and sea breezes and the orographic influences are predominant. For proper environmental planning, hourly wind roses are essential.

Next to wind, the vertical temperature variations play a very important role in air pollution. The increase of temperature with heights at lower levels, known as 'inversions' is of much concern, as such inversions depending upon the level at which they occur with respect to the stack height can act as lids which inhibit dispersion of pollutants, resulting in enormously high ground level concentrations. The height of the base of the inversion, the intensity of the inversion and the thickness of the inversion play roles in their own way. If the base of the iversion is above the effective stack height (h) it virtually acts as the lid and consequently build up of pollutants takes place. If the top of the inversion lies below h, the inversion does not allow the pollutants to reach the ground and hence a consequent build up takes place from the top of the inversion and above. However, once the inversion breaks or ceases, sudden high doses of pollutant concentration are likely at the ground level. If the base is below h and the top of the inversion is above h, dispersion is completely inhibited and when the inversion ceases to exist or breaks, once again high ground concentrations are likely. Hence, a study of the frequency of inversions is a must for air pollution warning. Usually the inversions are found during nights or in the early morning hours .

Isothermal conditions also have similar effects. The inversions are more stable than the isothermals, but both being stable they have a similar role in inhibiting the dispersion of pollutants. The lapse conditions can also be stable if the atmospheric lapse rate is less than saturated adiabatic lapse rate. Under strong lapse conditions, the air becomes unstable leading to vertical motions, mixing and consequently a tendency for establishment of dry adiabatic lapse rate till the lifting condensation level (LCL). The lapse rate near the ground on sunny afternoons is often superadiabatic. The mixing height (MH) is defined as the top of a surface based layer in which vertical mixing is relatively vigorous and in which the lapse rate is approximately dry adiabatic. The higher the mixing height, the greater the dilution in the vertical and the less is the ground concentration of pollutants. Hence, mixing height along with wind can be taken to represent the atmospheric dispersal capacity. Mixing height is known to exhibit diurnal, seasonal and yearly variations and also known to vary from place to place. The spatial variation of mixing height over any broad area will help to identify the regions of good and poor dispersal capacity of the atmosphere. The spatial variation of mixing height on a much smaller scale, say, for a given station, can be used to identify suitable locations for the industrial development.

The spatial variation of surface temperature also plays a role in air pollution studies. Because of urbanisation, the surface temperature is normally more in cities compared to nearby rural areas. Even within an urban area, differences in temperature exist from point to point. The warm pockets within the city are known as 'urban heat islands' (UHI). These heat islands also exhibit diurnal variation and this phenomenon is taken into consideration to estimate the temperature while computing the urban mixing height which in turn, as already pointed out, influences the dispersion of pollutants.

Stability is another important parameter which governs the pollutant dispersal. Highly unstable conditions result in thorough mixing and dilution and a consequent reduction in the ground level concentration. Stable conditions, on the other hand are characterised by low mixing and are unable to disperse pollutants resulting in the build up of concentrations. Stability, if worked out for every hour, can by itself give an idea of the dispersal capacity. A knowledge of the stability is a must for any air quality modelling. The diffusion coefficients are also dependent on stability and hence the diurnal and the monthly variation of stability should be established for proper environmental planning.

An effluent plume rising from a stack does not immediately move horizontally. In mild wind it may undergo significant rise. This rise of the plume when added to the physical stack height gives the effective stack height. The mixing of the plume and its horizontal propagation takes place from this effective stack height : it appears as though the effluents are emanated from this point. To compute the ground level concentration, it is the effective stack height that is to be used and not the physical stack height. The plume moves in the vertical direction because of the initial momentum and buoyancy. There are a number of empirical formulae developed for determining the plume rise. An appropriate formula is to be chosen for determining the plume rise depending upon the local conditions.

The ground level concentrations of the pollutants emitted from the point sources can be estimated by means of atmospheric dispersion modelling which is a function of emission inventory and meteorological parameters. For proper planning of any urban area, in so far as the location for new industries is concerned, atmospheric dispersion models must be applied. This helps in delineating the industrial and residential sectors. Some abatement schemes can also be suggested with the help of modelling. Such a dispersion model is to be extended for multiple sources to simulate urban air pollution. The application of the model requires the knowledge of mixing height, wind speed and direction, stability and effective stack height, all of which are to be established climatologically.

Air pollution does affect meteorology in some aspects. Changes in precipitation, temperature and visibility are some of the examples. The change in precipitation is mainly effected by providing more particles from industries which can act as condensation nuclei resulting in either decrease or increase in precipitation. As already pointed out earlier, the increased levels of carbon dioxide may result in the increase of temperature due to the so called green house effect. The presence of smoke clouds in local regions, together with the presence of particulate matter, may reduce the albedo and result in decrease of temperature.

1.4 BACKGROUND OF THE CITY

Trivandrum (lat. : 8° 29', lon. : 76° 57'), situated on the coast of the Arabian Sea, is the capital of Kerala State. Blessed with unlimited potentialities for development, it is endowed with natural advantages for expansion. The city is bounded by the Taluks - Kazhakuttam to the north, Nemom to the east and Athiyannoor to the south and the Arabian Sea to the west. Population in the city area of 74.93 square kilometre was about 483000 according to the 1981 census report. The population density in the city area is 5549 persons per square kilometre and during the decade 1971-1981 a population growth of 14.73% has been reported

There are eight major industries in the city and the area covered by them comes to about 0.5 square kilometre. For the present study, three major sources have been selected. Source I comprises of Travancore Titanium Products Ltd, Kochuveli, T. K. Chemicals Ltd, Kochuveli and English Indian Clays Ltd, Veli. Trivandrum Rubber Works, Palkulangara is considered as Source II and Hindustan Latex Ltd, Perurkada as Source III.

CHAPTER II

LITERATURE REVIEW

The detailed objectives of the present study were given in the preceding chapter. In this chapter a systematic literature review is made.

2.1 AIR POLLUTION METEOROLOGY

The most important meteorological parameters affecting the pollution potential are temperature, wind and stability. The ambient value of the temperature and its spatial and temporal variations are important as far as the atmospheric temperature in air pollution study is concerned. The most obvious significance of ambient temperature as an air pollution climatic feature is with respect to its influence on space heating requirements and the attendant discharge of pollutants into the atmosphere. This influence is often expressed in terms of the heating degree days defined as the magnitude of the difference between average daily temperature and 65°C.

It is seen from the spatial variation of temperature that cities are warmer than the nearby rural surroundings, particularly at night during light winds and clear skies. Such conditions lead to wind patterns that would converge toward the centre of the warm pockets. These warm pockets are known as 'heat islands'. As the air moves across the city and is warmed, it becomes less stable. Thus the urban heat island can have a profound effect on the transport and dilution of pollutants. It also plays a major role in the determination of mixing heights. The urban heat island commonly reaches its greatest magnitude at night or around sunrise possibly because the volume of air heated by urban processes is ordinarily smaller during night than during day. However, Findlay and Hirt (1969) and Viswanadham (1983) showed that urban-rural contrast can be large even during maximum temperature epoch. The maximum reported values of urban heat islands are 11.1°C for San Francisco (Duckworth and Sandberg, 1954) and 8.9°C for London (Chandler, 1965). For determining the urban heat island various empirical relations are developed. Mitchell (1961) presented a formula for the nocturnal urban-rural temperature differences, D of the form : $D=(a-b.N)/v$, where N is the percent cloud cover, v is wind speed and a and b are empirically determined constants. To observe the urban micro-climate during moderate wind, night-time conditions Clarke (1964) used helicopters and car traverses to construct the temperature cross section across Cincinnati. Inversions in rural area, adiabatic layer in the downtown area and warm air extending aloft downwind of the city were observed. Urban heat island effect in New York city was studied by Bornstein (1968). Differences in the temperature fields through the lowest 700m of the atmosphere were analysed. Results showed urban surface temperature inversions to be less intense and far less frequent than those in the surrounding non-urban regions. The average intensity of the urban heat island was a maximum near the surface and decreased to zero at 300m.

Analysis of urban-rural differences in tower measured winds at St. Louis by Shreffler (1979) showed that there exists a systematic difference between urban and rural wind speed and direction, at nearly calm conditions. This apparent acceleration of low speed flows was explained as resulting from the dominance of heat island effects over roughness effects. For better estimation of urban influence on local climate Winkler et al (1981) corrected the mean temperature series for biases and heterogeneties. Adjusted temperature data depicted a large heat island that conformed more closely to the urban structure. The mean urban minus rural temperature difference calculated from the adjusted data were as much as 50% larger than the differences calculated from the unadjusted data. Theoretical study of the St.Louis heat island was done by Vukovich and Dunn (1978) and Vukovich and King (1980). To determine the most important factors affecting the heat island circulation, heat island intensity, surface roughness, horizontal diffusion and boundary layer stability were studied using a primitive equation model. The results showed that the heat island intensity and boundary layer stability play the dominant roles in the heat island circulation. Diurnal variation of the urban heat island circulation and associated variations of the ozone distribution were investigated by Vukovich et al (1979). Studies over St.Louis region showed that the daytime heat island effect was relatively weak compared to that during night, but the heat island circulation was more intense during the day. The highest concentration of ozone at the surface was found in the zone of convergence associated with the urban heat island circulation immediately downwind of the centre of the city.

Modelling of the winter urban heat island over Christchurch, New Zealand was done by Tapper et al (1981). The model was tested against surface temperature fields observed over Christchurch under clear winter conditions. A study of the lapse rate or stability at the Meteorological Research Station at Woodbridge and its relation to heat island intensity in Toronto was made by Padmanabhamurthy and Hirt (1974). For clear and partly cloudy conditions with off land winds, the heat island intensity ($\Delta\theta$) was related to lapse rate or stability (x) as $\Delta\theta = 3.81 + 0.88x$. Investigation of urban heat islands using satellite imageries was done by Matson et al (1978). On an unusually cloud-free night-time, thermal infra-red image of the midwestern and northeastern United States from the NOAA 5 satellites enabled detection of more than fifty urban heat islands. Analysis of digital data from the satellites for selected cities yielded maximum urban-rural temperature differences ranging from 2.6 to 6.5°C.

Heat island studies in India are mainly due to Daniel and Krishnamurthy (1972), Philip et al (1974), Bahl and Padmanabhamurthy (1979) and Viswanadham (1983). Bahl and Padmanabhamurthy (1979) conducted mobile temperature surveys in Delhi during the winter months on selected days which showed the formation of the primary and secondary heat islands. The maximum difference in temperature was reported to be 7 °C.

The most important factor in air pollution climatology is the vertical temperature structure as it has profound influence on the dispersal of pollutants. The increase in temperature with height in the troposphere is called inversion and the condition underwhich vertical temperature remains the same is isothermal. In the atmosphere inversion and isothermal are stable conditions, the former being more stable. Both inhibit vertical mixing and act as lids to the atmosphere causing stagnation of pollutants at the level of emission. The base of the inversion, the top of the inversion and the intensity of the inversion are of utmost importance in determining the pollutant dispersal. Detailed studies on the frequency of occurrence of surface based and elevated inversions for different regions were done by various authors. De Marris (1961) published an excellent report on this matter based on temperature data taken on a T. V. tower in downtown Louisville, Kentucky and showed that the average temperature difference between 18 to 160m became super adiabatic lapse rate approximately three hours after sunrise and remained so until about sunset. Not many inversions were reported by him during the night which according to Summers (1967) may be due to the effect of the nocturnal heat island on the vertical structure of temperature. According to Hosler (1961) the greatest frequency of inversions was almost at night or near sunrise, for the studies made by him in the United States.

Using tower data for the period 1 December 1956 to 31 March 1958, time of formation and burn off of nocturnal inversions at Detroit was studied by Baynton (1962) and the results were discussed. A micrometeorological investigation was made by Thompson (1967) of ground level inversion formation, maintenance and dissipation and of the related thermal circulations as they were observed in an area near the mouth of Red Butte Canyon in the Wasatch range of northern Utah. The analysis of the observations taken during the summer of 1957 showed that one basic pattern occurred on 90% of the days. The application of a self-similar profile in the integration of the temperature equation across the stable boundary layer leads to a rate equation for the inversion height. An analytical solution of the resulting equation was derived by Nieuwstadt (1980) and the different conditions were discussed. A low-level inversion over AMTEX area during a period of 'return flow' was studied by Henry and Thompson (1977).

Viswanadham (1980) studied the frequency of ground based and elevated inversions for the four metropolitan cities in India for a five year period on a seasonal basis. Padmanabhamurthy and Mandal (1980) established the climatology of ground based and elevated inversion, multiple inversions and their thickness based on 0000 and 1200 GMT ascents taken during December - March for a five year period for Visakhapatnam, which revealed high frequency of ground based inversions in Delhi compared to that of Visakhapatnam. Das (1987) studied nocturnal radiation at Calcutta airport on clear winter nights.

Mixing height is the vertical extent upto which vigorous mixing takes place in the atmosphere. It varies with vertical as well as the surface temperature. Mainly studies on mixing heights were initiated by Holzworth (1964). Using the radiosonde observations and the mean maximum surface temperature, Holzworth estimated the mean maximum mixing heights for 45 stations in the contiguous United States. The values were presented for each month. Holzworth (1967) studied mixing depth, wind speed and air pollution potential for selected locations in the United States.

A simple model of urban mixing height was developed by Henderson (1980). An equation for the height of the inversion as a function of distance downwind into the city in the case of non-planar topography is also obtained from the model. The model enables rapid calculation of mixed layer depths, ground level concentration and distribution of aerosols. Urban perturbations on the mixing layer airflow over St.Louis were studied as a part of METROMEX by Wong and Dirks (1978). Case studies were conducted on summer days under generally undisturbed synoptic weather conditions. Based on simultaneous airborne wind and temperature measurements, the relative effects of the urban heat island, surface friction and local terrain features were estimated.

Temperature profile, lidar and sodar results for determination of mixing layer heights were compared by Coulter (1979). While the overall agreement was good, systematic differences do appear, particularly in early morning and late afternoon between lidar and sodar results, due to the difference in behaviour of the sensed variables near the capping inversion. By inputing certain surface observations into an estimative model Nozaki (1974) computed mixing heights. Seasonal change of the mixed layer structure at Tsukuba was studied by Gamo (1985), using daily maximum and minimum temperature data. Annual variations of the convective velocity scale, the standard deviation of the vertical velocity fluctuations and the eddy diffusivity were estimated by the surface heat flux and mixed layer height. A generalisation of the mixing height concept was done by Businger (1959), on the fact that convective energy has effect on the mixing length but not on the largest eddies. The theory development on this concept of the mixing length for the diabatic wind profile gives satisfactory agreement with observations over a wide stability range.

Mixing height and ventilation coefficient over India for the four seasons were studied by Vittal Murty et al (1980a, 1980b). While computing mixing height, appropriate heat island effect was applied. The spatial variation of mixing height over India was studied by isopleth analysis. Studies by Sadhuram and Vittal Murty (1984a) showed that the diurnal variation of mixing height of Visakhapatnam city follows $\sigma_{\theta D}$ values which reflect turbulence. Daily estimates of morning and afternoon mixing depths, average wind speed through the mixing layer and ventilation coefficients during clear winter months from 1970 to 1977 were studied by Padmanabhamurthy and Mandal (1979). Thickness and frequency of inversions were also studied. The method of base of first elevated inversion was used by Ramesh (1976) for the estimation of maximum height of mixing layer for Bombay for 1970 and the results were compared with mixing layer using Holzworth's method. Padmanabhamurthy (1984) studied the spatial variation of mixing depths for India taking into account the data from 27 radiosonde station in the country.

Climatology of airflow can be very well expressed in terms of wind roses, which depict the relative frequency with which the wind blows from the various sectors around the compass. Diurnal wind roses on a monthly or seasonal basis are necessary to show systematic variations. Pack et al (1957) drew wind roses for lapse and inversion conditions from June 1955 to May 1957 for shipping port Pennsylvaniya. They pointed out the major differences in the wind features between daytime and nighttime, the former having less calm frequency and stronger winds and the latter having more calm frequency and weak winds. Based on the wind roses the distribution of concentration of pollutants can be depicted. Slade (1968) gave analyses of the persistence of wind direction. During conditions of weak pressure gradient on the macroscale, the description of airflow in cities is complicated because of the heat island effect, the channelling of flows by city 'street canyons' and local aerodynamic influences (Mc Cormic and Holzworth, 1976). True calm conditions rarely exist over any appreciable length of time.

Stability is one of the most important factors in air pollution meteorology since the dispersal of the pollutants are very much affected by it. Stability is a function of temperature and wind speed. Unstable atmospheric conditions help easy dispersal of pollutants while conditions such as stable and neutral cases help to stagnate the pollutants in the atmosphere. There were a number of studies to determine stability using various methods. From the parcel and slice methods, it was shown that stability can be determined purely from the temperature structure in the vertical. Hess (1959) gave a broad categorisation of stability as follows : (a) Absolutely unstable (if atmospheric lapse rate (ALR) is grater than dry adiabatic lapse rate (DALR), (b) conditionally unstable (if ALR is in between DALR and saturated adiabatic lapse rate (SALR)), (c) neutral (dry) (if ALR is equal to DALR), (d) neutral (moist) (if ALR) is less than SALR) and (e) absolutely stable (if ALR is less than SALR)

The absolutely stable conditions do not necessarily include the restricted lapse conditions but can include isothermal and inversion conditions. In air pollution climatology these conditions are more important and to directly apply to air pollution studies, a more specific categorisation is needed. Moreover, the data on vertical thermal structure are not available everywhere which prompted the emergence of a number of schemes for stability with minimum and easily available data.

A subjective classification of the horizontal wind direction fluctuation was given by Singer and Smith (1953) which states that the fluctuation exceeding 90° be classified as highly unstable (A) and that not exceeding 15° be classified as stable (D) with intermediate classes B_1, B_2 and C. Pasquill (1961) proposed six stability categories to describe the diffusive potential of the lower atmosphere. The categories are functions of wind speed, cloudiness and net radiation index. These categories are A (very unstable), B(moderately unstable), C (slightly unstable), D (neutral), E (slightly stable) and F (moderately stable). This was originally developed for open or rural terrain. However, Turner (1961, 1964) modified the above classes so that they can be determined objectively from the routine meteorological data. He successfully applied the above scheme to the urban environment. By far, this scheme is the most popular, probably because many of the diffusion parameters in meteorological models were developed for each of these categories and secondly this is relatively easy to compute with wind speed and cloud amount alone at any given place.

The frequency of occurrence of Pasquill's categories was determined seasonally in Great Britain by Bannon et al (1962). The effect of change of atmospheric stability on the growth rate of puffs used in plume simulation models was examined by Ludwig (1982). The relation between wind speed, atmospheric stability and plume rise at a distance of 2.5km from a multiple source region was investigated by East and

Renaud (1978). By using an integrated form of the Businger Dyer flux-gradient equations, Wang et al (1978) suggested that since the surface wind speed and vertical temperature difference are related to the low level atmospheric turbulence and stability, these parameters can be used directly to determine the plume diffusion parameter for unstable conditions, without using the Pasquill's stability. Boundary layer data from several different geographical locations were analysed by Heald and Mahrt (1981) to document the behaviour of boundary layer shear above the surface giving emphasis to the influence of diurnal variation of stability. Various measures of static stability in the atmosphere were reviewed and their uses were briefly discussed by Gates (1961).

Diurnal and seasonal variation of Pasquill's stability classes at a coastal station were studied by Sadhuram and Vittal Murty (1986) for Visakhapatnam. The study revealed that unstable conditions during night and stable conditions during day were not observed in all the four months, viz. January, April, August and October, typical of the respective season. Neutral condition was present during day and night with high percentage frequencies at the time of just after sunrise and just before sunset. Stability wind roses were also studied and presented. Sadhuram (1986) studied the seasonal variation of $\sigma_{\theta D}$ with wind speed, direction and stability.

Studies on stability in relation to the atmospheric dispersal capacity of air pollutants were carried out by Viswanadham et al (1981). Variations in atmospheric stability serve to explain qualitatively much of the variations in the capacity of the atmosphere to disperse and dilute the pollutants. The studies carried out using the stability categories suggested by Pasquill and modified by Turner (1964), for the four major urban centres in India revealed that the coastal cities and inland cities differed significantly in the percentage occurrence of the stability categories. Pasquill's stability classification was studied by Panchal and Chandrasekharan (1978) for a site influenced by strong sea and land breeze system. It was noted here that the stability categories were not clearly distinguished during on-shore flow. Standard deviations of horizontal wind direction fluctuations both for on-shore and off-shore flow were found to be lower than those suggested by Slade. Bulk Richardson number was found not to be a good stability index at such non-homogeneous terrain conditions.

The interrelationship between the Pasquill's category and horizontal wind direction fluctuation is of interest and despite a number of studies, no universal relationship could be arrived though the trends are maintained. Slade (1968) related $\sigma_{0\theta}$ values (which can be obtained by dividing the wind fluctuation range in 10, 15 or 20 minute interval with 6) to each of the Pasquill's categories as follows : A(25), B(25), C(15), D(10), E(5) and F(2.5). However, Shirvaikar (1975), Padmanabhamurthy and Gupta (1979) and Sadhuram and Vittal Murty (1983) reported different values of $\sigma_{\theta D}$ for each of these categories. Sadhuram (1982) gave an account of seasonal variation also for Visakhapatnam city which showed considerable variation in the relation for unstable classes. In view of the wide variation for $\sigma_{\theta D}$ from author to author the relation between $\sigma_{\theta D}$ and Pasquill's categories was determined for Cochin. The validity of taking 1/6 of the total range was examined by Anilkumar (1986) for Cochin which revealed that half of the range is more representative for $\sigma_{\theta D}$ though it remains to be tested for inland stations. Sadhuram and Vittal Murty (1984a) showed a trend of variation between $\sigma_{\theta D}$ and mixing height for four typical months for Visakhapatnam which showed an excellent relationship between these two.

The climatological occurrence of meteorological conditions associated with extensive and persistent areas of high air pollution potential over the western United States was studied by Holzworth (1962). The most likely large scale synoptic feature conducive to poor air quality was found to be the quasi-stationary anticyclone. Air pollution potential over the Salt Lake Valley of Uttah as related to sability and wind speed were described by Philip (1964). A smoke index was developed to indicate the amount of restriction to visibility due to smoke. The effect of precipitation on the smoke index was also discussed.

Meteorological data from a network set up to study local air pollution problem were used to study local air flow patterns at Louisville by Pooler (1963). Stability conditions are discussed in terms of temperature differences obtained from hygrothermographs installed at different ground elevations. Wanner and Hertig (1984) gave an assessment of the factors that are responsible for urban climate change along with climatological studies and peculiarities of some swiss cities. Heat islands and city-induced air flows, the influence of synoptic winds on boundary layer air flows and the significance of local airflows in complex terrain were studied in detail. Dikaikos (1983) studied the air pollution regime during Halkyon days in Athens. Daily values of air temperature, wind speed, sunshine and cloudiness were analysed and it was seen that the average daily values of smoke and sulphur dioxide concentration at the urban centre of Athens during Halkyon days were much greater than those on the other days.

A study of the pollution potential of Visakhapatnam was done by Sadhuram and Vittal Murty (1984b). It was seen that the winter and the premonsoon season were not favourable for dispersion of pollutants and suggested that the discharge of pollutants should be kept to a minimum in those two seasons. An effective pollution potential index was suggested by Jeevananda Reddy (1974) as a measure of air pollution, for the selected Indian stations, for each month. It was concluded that high pollution potential exists over the stations in different months, which necessitates taking precautionary measures.

Not many indices were proposed which take into consideration all possible parameters. Holzworth (1964) proposed a dilution index based on mixing height and wind speed. Sastry and Vittal Murty (1979) studied another index of pollution potential for Visakhapatnam city by considering the vertical thermal structure alone. Viswanadham (1980) developed another pollution potential index closely following that of Holzworth's .

The magnitude and rate of increase of the diffusion coefficients with distance downwind from a source is strongly influenced by meteorological quantities such as cloudiness, amount of solar radiation and strength of mean wind, all of these affect atmospheric stability. Conditions such as inversions and isothermal layers inhibit the dispersal of the pollutants. Smith (1983) studied the long range transport of air pollution by investigating the nature of emission, the amount of local deposition, the estimation of trajectories and lifetimes of airborne pollutants and their chemistry, relative amounts of dry and wet deposition and background concentration. An analytical study of transport phenomena during the evening transition period in the vicinity of Sacramento, California was done by Myrup et al (1986). The study was based on a network of double theodolite wind stations, aircraft soundings and micrometeorological measurements made in this city. A review was presented by Deardorff (1985) on laboratory modelling of diffusion downwind of a continuous point source within a boundary layer of well defined height with turbulence driven by buoyant convection. Results of the study using mixed layer scaling were summarised and comparisons with atmospheric field measurements were discussed.

Optimal emission control of a transient air pollution source by the method of finite difference was done by Paritosh and Sinha (1987). The meteorological features of a refined air pollution evaluation technique was described by Smith and Singer (1966). Time and space variations of wind speed, dispersion parameters and capping inversions were permitted and it was believed that the estimates of dispersion at large distances from the source were more realistic than those obtained with simple models. An examination of regional pollutant structure in the lower atmosphere was done by Sisterson et al (1979) using diagnostic atmosheric cross section experiments. A stochastic model was developed by Bacci et al (1981) to predict the sulphur dioxide dispersion around a power plant. Precisely the model describes the diurnal dynamics of a variable taken as a representative of ground level pollution. An unsteady two dimensional transport model was used by Viskanta and Daniel (1980) to study the short term effects of elevated pollutant layers on the temperature structure and pollutant dispersion in an urban planetary boundary layer.

A synoptic analysis was carried out by Mc Naugton and Orgill (1980) to identify the source and characteristics of an elevated layer of high airborne sulphate concentrations observed over southeast Wisconsin on 23-24 August 1976. Hourly ground level concentrations of sulphur hexafluoride at downwind distance ranging from 0.5 to 50km were observed by Hanna (1986), to study lateral dispersion from tall stacks and empirical relations were developed. Diurnal variations of carbon monoxide concentrations and traffic density were studied by Mc Cormick and Xintaras (1962). A new technique was suggested for evaluating the effect of changes in traffic desity on carbon monoxide concentrations which may be useful for urban planning purposes and for appreciating the role, wind speed can play to modify these assessments. Photochemical air pollution was studied by Chung (1977) using ozone data. It was seen that fluctuations of ozone were highly dependent on the synoptic, regional and small-scale airflows at low levels. Atmospheric dispersion studies using tracers were done by Hosler (1966), Alkezweeny (1978) and Gryning and Lyck (1984). The influences of different meteorological conditions on the dispersion of those tracers were discussed.

Data from a three dimensional pollutant mapping program, conducted in the Los Angeles basin were analysed by Husar and Patterson (1977) to obtain ground average vertical profile samples on 24 summer days in 1973. Concentration profiles at various locations were discussed. For atmospheric contaminants which decay or react in the atmophere, a first order decay rate was considered to be an appropriate model. The downward concentration from a continuous point source of these decaying contaminants was estimated by multiplying the estimated concentration of an equivalent amount of a conserved pollutant by the factor exp(kx/u) in which k is the first order decay rate, x the downwind distance and u the wind speed. Overcamp (1982) extended the statistical diffusion theory to incorporate first order decay. Long-range pollutant transport and diffusion in the eastern United States were studied by Kao and Yamada (1988) using the 1983 Cross-Appalachian Tracer Experiment (CAPTEX) data.

Time-lapse photography was used to estimate the speed of vortices in condensed plumes by Hanna et al (1978). Median and standard deviation of turbulent fluctuations of tangential speed of the vortices were estimated. Experimental study of an artificial convective plume initiated from the ground was done by Benech (1976). The values of the plume indices, the temperature differences inside the plume and the vertical velocity were measured in terms of atmospheric stability.

Convective downmixing of plume in a coastal environment was studied by Mc Rae et al (1981). The field study demonstrated that materials emitted into an elevated stable layer at night can be transported out over the ocean, fumigated to the surface, and then be returned at ground level by the sea breeze on the next day. Some restrictive meteorological conditions to be considered in the design of stack were presented by Bierly and Hewson (1962). The conditions considered were fumigations, aerodynamic downwash, looping and trapping. Each condition was explained and formulae were given for the computation of ground level concentrations. Methods for determining the percent occrrence of these restrictive conditions from observed data were also discussed very briefly.

2.2 MODEL STUDIES FOR THE DETERMINATION OF POLLUTANT CONCENTRATIONS

Meteorological modelling or urban air quality simulation model is a numerical technique or methodology based upon physical principles, for estimating pollutant concentrations in space and time as a function of the emission distribution and the attendant meteorological and geographical conditions. A review of the past work was made by Wanta (1968), Moses (1969) and Turner (1979). Gaussian plume model is the most popular as it is relatively easy to apply. This model is nothing but the fundamental solution to the classic Fickian diffusion equation. Gifford (1968) gave a detailed discussion of the Gaussian diffusion model. Roberts et al (1970) developed Gaussian puff model for tracking individual pollutant plume. However, there were no extensive application of the puff model due to its large computational requirements. In addition to the Gaussian model there are two other main classes of model based on the equation of mass conservation - Eularian and Lagrangian model. While Gaussian model calculates concentration of pollutants source by source or receptor by receptor, the Eulerian model calculates the concentration throughout a region at one time.

For determining the concentration, Eulerian model was made use of by Mac Cracken et al (1971) for different regions. The Lagrangian models were used by Behar (1970) to investigate photochemical smog in Los Angeles. The Lagrangian models should have many approximations to get the solution and thereby its applicability and the accuracy of solutions are limited (Johnson et al, 1976). Despite the presence of many other models, Gaussian diffusion model is still the most popular, and it was modified considerably. Dispersion from a continuous ground level source was investigated by Gryning (1983) using Monin-Obukhov similarity relations. Mac Cracken et al (1978) developed two air quality models for using in the San Francisco Bay area by using the Eulerian form of the mass conservation equation. Duewer et al (1978) verified the above two models considering the data on topographic, meteorological, source emission and atmospheric pollution concentration.

Overcamp (1983) modified the Gaussian model for continuous elevated sources, which uses a continuous distribution of ground level sources to replace the use of the image source. For the case of the Fickian diffusion with uniform wind, this model is mathematically identical to the conventional Gaussian model with the image source, and therefore, provides a more physically realistic model to justify the use of the image source.

Gaussian plume model parameters for ground level and elevated sources derived from the atmospheric diffusion equation in a neutral case, in which the vertical dispersion coefficient is represented by an experimental law was investigated by Melli and Runca (1979). The results proved that the Gaussian model can approximate very accurately the ground-level concentration profile solution to the atmospheric diffusion equation both for ground-level and elevated sources. A Gaussian plume model of atmospheric dispersion based on second order closure was presented by Sykes et al (1986). The model was comparable with conventional Gaussian plume models in complexity, but still maintained the capability to predict concentration fluctuation variance and to utilise direct measurements of turbulent velocity variences in a consistent manner.

An explicit assumption of the Gaussian plume dispersion model is that the dispersive substance under investigation has neutral buoyancy with respect to the atmosphere. Since the particulate matter has a non-zero sink rate, this assumption must be violated. Davis and Metz (1978) developed a new formulation which deals with surface deposition and reflection in a proper way. According to Penner (1986) smoke from raging fires produced in the aftermath of a major nuclear exchange can cause large decrease in surface temperatures. However, the extent of the decrease and even the sign of the temperature change depend on how the smoke is distributed with altitude. Penner presented a model capable of evaluating the initial distribution of lofted smoke above a massive fire. Several sigma schemes used for estimating plume dispersion were investigated by Irwin (1983).

Numerical optimisation techniques, to determine the spatial distribution of pollutant concentration was discussed by Gustafson et al (1977). Empirical information provided by sparse measurement data was effectively combined with the knowledge of atmospheric dispersion functions of the type commonly used in source-oriented air quality models, to provide improved estimates of the concentration distribution over an extended region. Rheingrover (1981) used multiple regression analysis to study the influence of meteorological variables on the transport and dispersion of stack particulate titanium pollution on the urban scale. The factors studied were wind speed and direction, low level vertical temperature gradient and the standard deviation of the horizontal wind direction fluctuations. For long term regional pollutant transport, a model was developed by Daniel et al (1981). The model had hourly time steps and incorporated a number of simplifying assumptions on mixing heights, horizontal diffusion and emission averaging.

There were some short term models which calculate concentrations for periods of half an hour to one day. Clarke (1964), Turner (1964) and Koogler et al (1967) computed concentrations ranging from two to twenty four hours. All these short term models used a single wind direction for each time period. However, Hilst (1968) developed a regional model that took account of the variations of wind. Studies by Gifford (1973) showed that the estimates from the simple models are as good as those of the more complex models.

The main parameters required for the model computations are effective stack height and dispersion parameters σ_y and σ_z. There were a number of formulae to estimate the effective stack height. For example, the formulae suggested by Lucas et al (1963), Briggs (1975), Slawson and Csanady (1967), Davidson-Bryand (1975) and Holland (1975). These are mostly functions of horizontal wind at the stack height, ambient temperature, plume temperature, vertical velocity of the plume and physical plume parameters. Vittal Murty and Viswanadham (1978) reviewed various plumerise formulae and concluded that no two formulae were giving the same result, suggesting to choose a formula appropriate to the local conditions. A comparative study of plumerise formulae was done by Padmanabhamurthy and Gupta (1980).

Das et al (1973) applied the Gaussian model to study the dispersal of pollutants from the Mathura refinery. Vittal Murty et al (1977) presented a theoretical model for calculating ground concentration of sulphur dioxide at Visakhapatnam. Viswanadham (1980) applied the Gaussian model for multiple source for four major cities in India. To assess the air quality over a short period a model was developed by Gupta and Padmanabhamurthy (1984) utilising the steady state Gaussian equations for point sources and their integration for area sources. Shirvaiker et al (1969) developed a finite plume model based on wind persistence. A one dimensional transport model was developed by Venkatram and Viskanta (1977) for assessing the effects of radiative precipitation of elevated pollutant layers. Manjukumari and Sharma (1987) used profile relationships based on Monin-Obukhov similarity theory to compute turbulence parameter with friction velocity and friction temperature at the surface for applying in air pollution modelling. A detailed discussion on application of turbulence parameters was also given. Multiple Gaussian plume model was used by Santosh (1987) to study the spatial variation of sulphur dioxide concentrations for four major urban centres in South India.

Sachdev and Ramesh (1974) carried out the diffusion studies at Trombay with argon-41 from the cirus stack as a tracer. The downwind concentrations as observed over time intervals were studied as a function of meteorological variables. The implications of these considerations in urban air pollution surveys and the importance of correctly estimating the short term concentrations of effluent toxic gases from industries were then discussed. Particulate deposition due to Indraprastha power plant within 15km of the plant was computed by Padmanabhamurthy and Gupta (1977) employing the long term concentration equation. Isolines delineating zones of low and high deposition were drawn on monthly and annual maps and suggested that particulate pollution in the zone under consideration can be limited by increasing the stack level. Diurnal variation of the vertical mixing of the atmosphere was studied by Viswanadham and Ram Mohan (1980) for Cochin. They found the periods of high and low dispersals and suggested certain abatement steps for mitigation of air pollution problem.

An algorithm was developed by Kothari and Meroney (1981) to estimate field concentrations in the wake of a power plant complex under non-steady meteorological conditions from wind-tunnel experiments. A weighted data methodology developed to predict surface concentrations from stationary wind-tunnel measurement and actual meteorological wind fields was described. Making use of Larsen's mathematical model for correlating concentrations over different averaging periods, the expected maximum hourly concentrations of sulphur dioxide at some of the locations in greater Bombay was calculated by Zutshi and Mahadevan (1975) with the help of monthly average data.

Validating the result of the model is often difficult. However, Pooler (1961) applied a model to determine the monthly concentration of sulphur dioxide at a large number of points at Nashvilla with the help of emission inventory. These estimates were compared with monthly measurements of sulphur dioxide from a network of stations. One half of the observed concentrations were between 80 and 125 percent of predicted value for the five month test period. Martin (1971) formulated a long term model similar to that of Pooler and the same was applied extensively to estimate sulphur dioxide and particulate matter. Many long term models were developed subsequently (Zimmerman, 1971; Turner et al, 1972). There were simple models also by Gifford and Hanna (1973) which upon testing were surprisingly very close second to that complicated models.

CHAPTER III

MATERIALS AND METHODS

In the present chapter, details of the actual data collected and the methods adopted for all the computations carried out in this thesis are presented. The merits and limitations are also discussed.

3.1 DATA AND ITS SOURCES

To study the dispersal capacity of the atmosphere over Trivandrum various meteorological and emission data were collected. The details of meteorological data used are given below. Hourly values of surface temperature, wind speed and direction and three hourly values of low cloud amount on all days of the five year period 1977 to 1981 are made use of. After analysing the daily anemogram charts for wind direction and speed, since the fluctuations are not very high, wind direction and speed fluctuations for every twenty minute interval are noted for all days of the four months January, April, July and October for the above five year period. Surface observations of these meteorological parameters were collected from India Meteorological Department, Trivandrum. Radiosonde data, on all days of the same period of study, for every 50mb interval upto 500mb level were also collected from the India Meteorological Department, Pune.

Data on emission inventory such as stack height, stack diameter, pollutants emitted, rate of emission, plume temperature etc of all the factories in Trivandrum are collected from the Pollution Control Board, Cochin.

3.2 METHODOLOGY

3.2.1 Inversions, isothermals and lapse conditions

These parameters are determined for the layer from surface to 1000 mb and for every layer, 50 mb in thickness, from 1000mb to 500mb level. A further classification is made for inversions and lapse conditions according to their intensities. The various classes are as follows :

For inversions : 0 to 2°C, 2 to 4°C and > 4°C

For lapse conditions : 0 to -2°C, -2 to -4°C, -4 to -6°C and < -6°C

The percent occurrence of the above parameters in each layer are determined using a computer program, the block diagram of which is presented in Fig. 3.1. The input of the program is vertical temperature structure for all the days of the period of study and the output is the percent frequency of inversions, isothermals and lapse conditions in different classes as explained above. To study the monthly variations of these parameters, histograms are drawn for each layer. Taking the total percent occurrence of inversions, isothermals and lapse conditions in all the layers together for each month, pie diagrams are drawn and the monthly

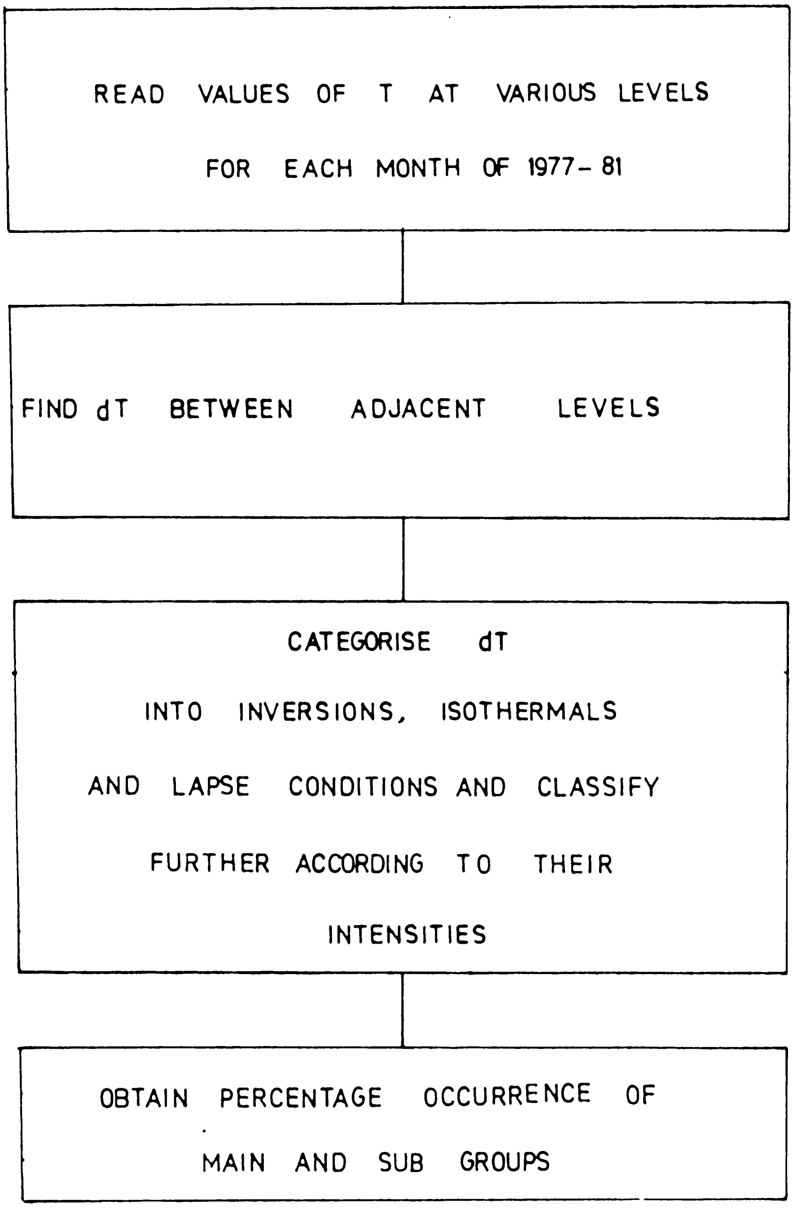


FIG. 3.1. BLOCK DIAGRAM FOR THE COMPUTATION OF ISOTHERMALS, INVERSIONS AND LAPSE CONDITIONS

variation of these parameters are studied.

3.2.2 Mixing heights and Ventilation Coefficients

Mixing height is the height upto which vigorous mixing takes place in the atmosphere. It is computed using the method suggested by Holzworth (1964). Temperature profiles are drawn using the upper air data. A dry adiabat from the surface temperature is extended to intersect the temperature profile. The surface temperature cannot be used straight away without adding the correction factor to account for the urban heat island effect. When the corrected surface temperature is used, the mixing height may be representative of a point in the city where this corrected surface temperature is actually observed. Since the surface temperatures are available from the urban region and the temperature sounding is from its suburb, in the present study, no correction factor is added. The suburban temperature sounding is necessary so that the sounding is free of urban effects. If continuous temperature data from the urban areas is available, the mixing height can be computed at any time by extending a dry adiabat from the surface temperature corresponding to the given times upto lifting condensation level (LCL) and by extending saturated adiabat from LCL onwards to intersect the early morning temperature sounding. The change of dry adiabat to saturated adiabat is necessary because when the parcels move vertically upward, they move dry adiabatically till LCL and saturated adiabatically from LCL onwards because of the condensation that takes place from LCL onwards if the air parcels are moist initially. According to the above method, mixing height is computed for every hour on all days of the five year period and the hourly mean are determined for each month. The diurnal and monthly variations are studied.

Ventilation coefficient at any time can be obtained by multiplying the mixing height at that time and the mean wind speed through the mixing layer. Since the vertical variation of wind is not available for every hour, hourly surface wind speed is used to obtain the hourly ventilation coefficient. This is also determined for every hour on all the days of the five year period and the hourly mean values are calculated for each month and the diurnal and monthly variations are studied.

3.2.3 Atmospheric stability

To determine stability categories the method suggested by Pasquill (1961) and modified by Turner (1964) is made use of. Table 3.1 gives the stability class as a function of wind speed and net radiation index. The net radiation index ranges from 4, the highest positive net radiation (directed towards the ground) to -2, the highest negative net radiation (directed away from the earth).

Instability occurs with high positive net radiation and low wind speeds; stability with high negative net radiation and light winds and neutral conditions with cloudy skies or high wind speeds.

The net radiation index used with wind speed to obtain stability class is determined by the following procedure.

(1) If the total cloud cover is 10/10 and the ceiling is less than or equal to 7000ft, the net radiation index equal to zero is used. (irrespective of the time, whether day or night).

(2) For night-time (night is taken as the period from one hour before sunset to one hour after sunrise).

a) If total cloud cover $\leqslant 4/10$, the net radiation index equal to -2 is used.

b) If total cloud cover $>4/10$, the net radiation index equal to -1 is used.

(3) For day time

a) The insolation class number is determined as a function of solar altitude from table 3.2.

b) If total cloud cover $\leqslant 5/10$, the net radiation index from table 3.1 corresponding to the insolation class number is used without modification.

c) If cloud cover >5/10, the insolation class number is modified as explained below.

i) If ceiling < 7000ft, 2 is subtracted.

ii) If ceiling ⩾ 7000ft, but < 16000ft, 1 is subtracted.

iii) If total cloud cover equals 10/10 and ceiling > 7000ft, 1 is subtracted.

iv) If insolation class number has not been modified by steps (i), (ii) or (iii) above, insolation

Table 3.1

Stability class as a function of net radiation index and wind speed

Wind speed	Net radiation index						
(knots)	4	3	2	1	0	-1	-2
0,1	A	A	B	C	D	E	F
2,3	A	B	B	C	D	F	F
4,5	A	B	C	D	D	E	F
6	B	B	C	D	D	E	F
7	B	B	C	D	D	D	E
8,9	B	C	D	D	D	D	D
10	C	C	D	D	D	D	E
11	C	C	D	D	D	D	D
12	C	D	D	D	D	D	D

class number is assumed to be modified class number.

v) If modified insolation class number is 1, it is taken as 1.

vi) The stability classification is made by taking the modified insolation class number equivalent to net radiation index and using the Table 3.1.

Table 3.2

Insolation as a function of solar altitude

Solar altitude(a) (in degrees)	Insolation class number
$a \geqslant 60$	4
$35 \leqslant a \leqslant 60$	3
$15 \leqslant a \leqslant 35$	2
$a \leqslant 15$	1

A computer program is developed to obtain the stability class for every hour on all days of the period of study, based on the above criteria. The wind speed, cloud amount and cloud type form the input data. The block diagram of the program is shown in Fig. 3.2. The hourly values of stability category and their percent are the output of the program. The percentage frequency of occurrence of the stability classes in each hour are determined for every month and the diurnal and monthly variations are studied.

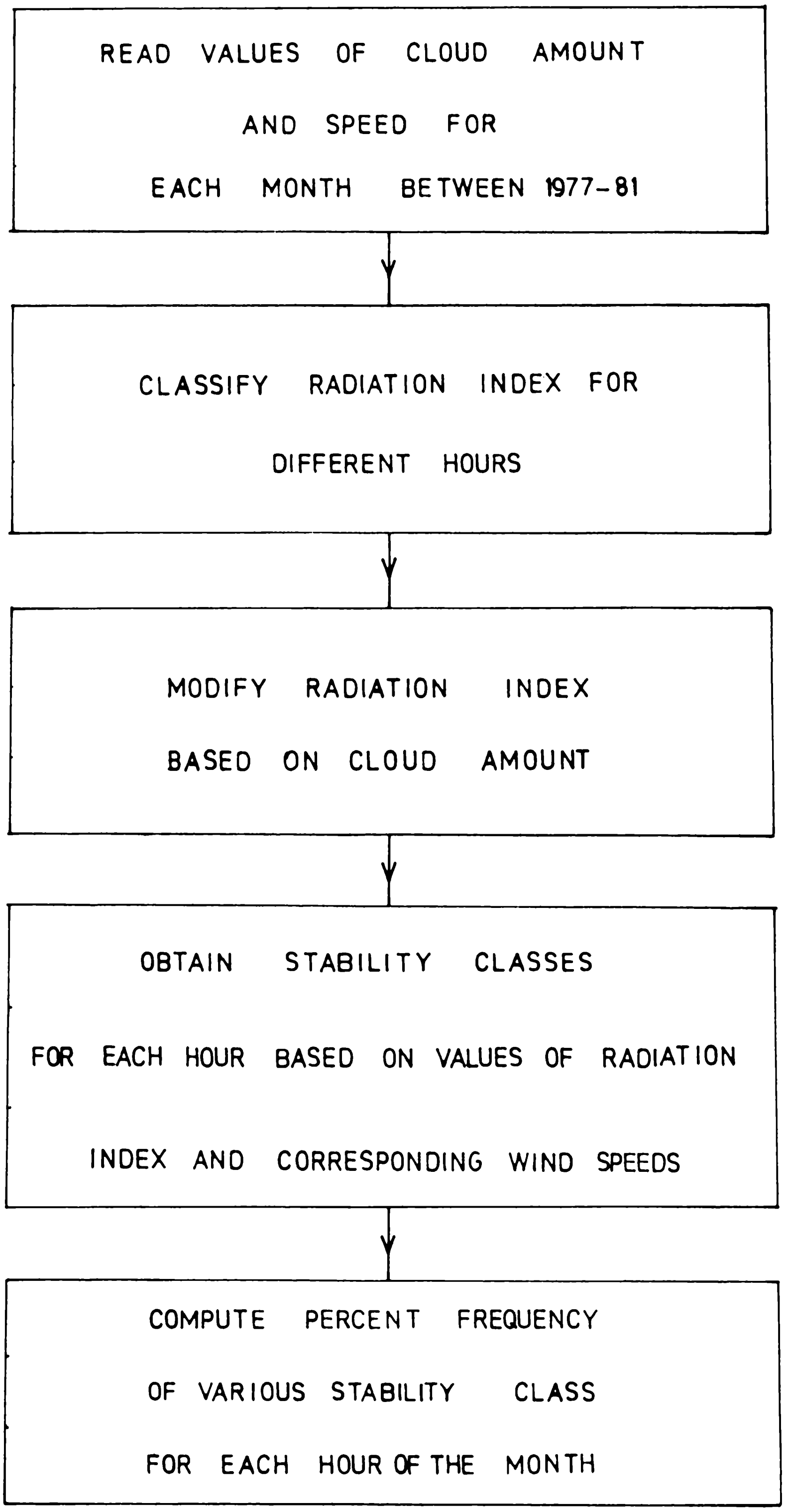


FIG. 3.2. BLOCK DIAGRAM FOR DETERMINING PASQUILL'S STABILITY CLASSES

3.2.4 Pollution Potential Indices

Based on mixing heights, wind speeds and atmospheric stability a new pollution potential index has been developed and applied for Trivandrum city.

Tables 3.3, 3.4 and 3.5 depict the individual indices obtained from mixing height, wind speed and stability class respectively.

Table 3.3

Mixing height in metres	Pollution potential index
0 - 700	3
701 - 1400	6
1401 - 2100	9

Table 3.4

Wind speed in ms^{-1}	Pollution potential index
0.0 - 3.0	3
3.1 - 6.0	6
6.1 - 9.0	9

Table 3.5

Stability class	Pollution potential index
E & F	3
C & D	6
A & B	9

The indices are determined at the given hour from the values of mean mixing height, mean wind speed and the the maximum occurring stability class at the same hour and the mean of the indices is then determined. These mean indices are computed for every hour for all the months. For example, if the mixing height is 1000m, wind speed is 7ms^{-1} and the maximum occuring stability class is C at a particular hour, the pollution potential index at that hour is determined from the tables as, (6+9+6)/3 = 7.

The various categories of pollution potential are very high, moderately high, high, medium, low, moderately low and very low, whose indices are numbered from 3 to 9 respectively. For example, very high pollution potential has the lowest number and very low potential has the highest number. The higher the pollution potential, the more is the possibility of build-up of pollutants. Hence all those conditions such as extremely low mixing, low wind speed and highly stable conditions are given the index 3.

The main purpose of such a categorisation is to pool up all the important parameters so that a unique index could be given which directly reflects the atmospheric capacity to disperse pollutants. Although the numbers in the form of the indices are arbitrary, the categorisation as such is not so. This kind of index development does not need any experimental evidence as this is mainly to help, planners to have an overall idea of the potential.

3.2.5 Wind roses, wind speed and direction fluctuations and their relationships with mixing height and stability

3.2.5.1 Wind roses

The hourly wind speed and direction for all days of the five year period are classified into sixteen direction classes : N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, NNW and five speed classes : 1-5, 6-10, 11-20, 21-30 and >30km per hour. Frequency tables are prepared on an hourly basis for each month, taking the five year period together and the percent frequencies are calculated for direction and speed classes and for calm conditions. A computer program is developed for obtaining the percent frequencies, the block diagram of the program is shown in Fig. 3.3. By taking a suitable scale, wind roses are drawn at six hourly interval. A wind rose consists of a small circle in which normally the calm percentage is indicated and

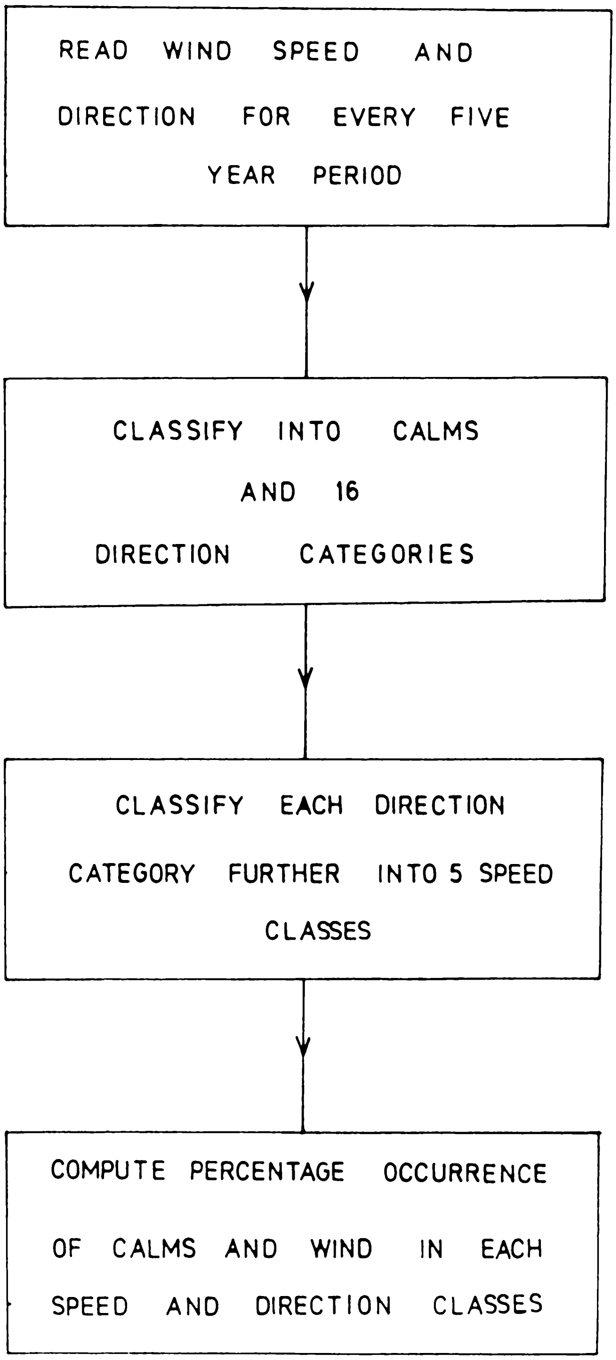


FIG. 3.3. BLOCK DIAGRAM OF THE PROGRAM FOR WIND CLASSIFICATION

shafts in each of the 16 directions from the circle, the length of the shaft representing the percent frequency of wind blowing from that direction. With appropriate notations, the speed classes along each direction, depending upon their relative frequencies, are represented along each of the 16 directions.

3.2.5.2 Wind speed and direction fluctuations and their relationships to mixing height and stability

For computing the standard deviations of wind speed and direction fluctuations ($\sigma_{\theta S}$ and $\sigma_{\theta D}$) the method suggested by Slade (1965) is made use of. The wind speed and direction fluctuations in each hours are conveniently divided into either 10, 15 or 20 minute interval depending upon the degree of fluctuations. For example, for a smooth trace, 20 minute interval can be chosen and for a highly fluctuating case, at least 10 minute interval is to be chosen. After choosing the time interval, the range of fluctuations (difference between the extreme values) within that interval is determined. Then the mean of such ranges in that hour is computed. The mean range is divided by 6 to get $\sigma_{\theta S}$ and $\sigma_{\theta D}$ These values for every hour for all the four months, for the five year period are computed. Computing the mean monthly average for each hour, the diurnal and seasonal variations are studied. The interrelationships among $\sigma_{\theta S}$, $\sigma_{\theta D}$, MH and stability are studied.

3.2.6 Gaussian plume model development and determination of sulphur dioxide concentrations

For the estimation of ground level concentrations both for short term and long term periods, Gaussian model is still the widely used model because of its simplicity and encouraging results compared to more complicated models. The development of the model is presented here very briefly.

3.2.6.1 Model development

As a plume moves downwind from a chimney of effective height h, it grows by action of turbulent eddies. Large eddies simply move the whole plume and diffusion is most effective with eddies of the order of plume size (Perkins, 1974). As the plume moves, it grows in the vertical and across wind directions. The distribution in the vertical and across wind directions is assumed to be Gaussian. Along the wind direction, the convection is greater than diffusion. So, diffusion along wind direction is neglected. The Gausssian function gives a mathematical representation of this physical behaviour. From this function the concentration should be obtained as a function of distance downwind.

As was pointed out earlier, convection dominates diffusion in the wind direction and wind is the only factor affecting the stretching of the plume. The higher the wind speed the faster the dispersion of pollutants in the down wind direction resulting in lower concentrations. Hence it can be written as :

$$\chi \propto \frac{1}{U}$$

where χ is the concentration in gm^{-3} and u is the average wind speed in ms^{-1}.

The distribution in the vertical and cross wind directions are given as Gaussian functions and along the wind direction the concentration is proportional to 1/u. The concentration is proportional to source strength, $Q(gs^{-1})$. So the solution for the plume behaviour can be obtained. We will first see the mathematical form of the Gaussian function in the cross wind direction (y).

$$\chi \propto A \exp\left[-1/2\left(\frac{y}{\sigma_y}\right)^2 \right] \qquad (3.2)$$

where σ_y is the standard deviation, y is the distance cross wind (perpendicular distance to the wind direction x). A is a function of y.

The mathematical form of the Gaussian function in the vertical (Z direction) is

$$\chi \propto B \exp\left[-1/2\left(\frac{Z-h}{\sigma_z}\right)^2 \right] \qquad (3.3)$$

where σ_z is the standard deviation in the vertical

z = is the height in the vertical

h = is the effective height of emission

B = is a function of σ_z .

The equation (3.3) has to be altered accordingly depending upon whether reflection, absorption or deposition takes place at the ground when the plume reaches the ground. No absorption or deposition at the ground is assumed. Instead, perfect reflection is assumed. Then the earth's surface acts as barrier and no further diffusion takes place. An image source can be assumed symmetrically to the actual source with respect to the ground because the concentration at any point downwind space is combination of the concentration contributed by the source directly and that due to the prefect reflection from the ground. So at a height of interest Z, the concentrations due to real source at a height of (Z-h) and that due to image source at a height of (Z+h) are to be combined. This combined effect can be written in the form given below.

$$\chi \propto B\left[\exp(^-1/2(\frac{Z-h}{\sigma_Z})^2) + \exp(^-1/2(\frac{Z+h}{\sigma_Z})^2)\right] \qquad (3.4)$$

The Gaussian function can be normalized so that the area under curve has a unit value. This can be done by taking the value of A and B as $1/\sqrt{2\pi}\,\sigma_y$ and $1/\sqrt{2\pi}\,\sigma_Z$ respectively. This can be clearly seen from the following mathematical operations.

The area under the curve is taken as the integral of

$$\int_{-\infty}^{+\infty} \exp(^-1/2(y/\sigma_y)^2)\,dy = \sqrt{2\pi}\,\sigma_y \qquad (3.5)$$

$$\frac{1}{\sqrt{2\pi}\,\sigma_y}\int_{-\infty}^{+\infty} \exp\left[-1/2\left(\frac{y}{\sigma_y}\right)^2\right] dy = 1 \qquad (3.6)$$

A similar expression can be obtained from the Z direction also as

$$\frac{1}{\sqrt{2\pi}\,\sigma_z}$$

The final solution can be written in the following form by combining the Gaussian functions both in Y and Z directions, source strength, wind speed and replacing A and B by the respective values.

$$\chi_{(x,y,z,h)} = \frac{Q}{2\pi\sigma_y\sigma_z U} \exp(-1/2\,(y/\sigma_y)^2)$$

$$\left[\exp(-1/2\,(\frac{z-h}{\sigma_z})^2) + \exp(-1/2\,(\frac{z+h}{\sigma_y})^2)\right] \qquad (3.7)$$

where Q is given in gs^{-1}, u in ms^{-1}, σ_y and σ_z in metres; h,z,x and y in metres. It should be remembered here that the diffusion along (X) direction is neglected. This assumption facilitates to take the plume emission to be continuous.

Ground level concentration can be observed by putting Z = 0 in the equation (3.7)

$$\chi_{(x,y,0,h)} = \frac{Q}{\pi\sigma_y\sigma_z U} \exp\left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2}\right)\right] \qquad (3.8)$$

The concentration along the plume centre line at the ground can be obtained by putting Y = 0 in the equation (3.8), thus

$$\chi_{(x,0,0,h)} = \frac{Q}{\pi\sigma_y\sigma_z U} \exp(-h^2/2\sigma_z^2) \qquad (3.9)$$

These formulae are applicable for short term concentrations (1 hour).

For long term ground level concentration (of the order of one month or more) the Gaussian function is modified under certain assumptions.

If the wind directions are taken to be 16 points and if it is assumed that the wind directions within each sector are distributed randomly over a period of a month or season, then the effluent is said to be uniformly distributed in the horizontal within the sector. The appropriate equation was given by Turner (1970).

$$\chi = \frac{2Q}{\sqrt{2\pi}\,\sigma_z\,U(2\pi x/16)}\left[\exp(^{-}1/2\,(h/\sigma_z)^2)\right] \qquad (3.10)$$

For long range planning the characteristic number 16 is used to calculate the concentrations in each 22.5° sector of compass.

The equations (3.8) to (3.10) have to be modified if a stable layer exists above. As the plume touches the ground the perfect reflection is assumed. Similarly when a stable layer is present aloft and if the plume touches that layer, a method of incorporating such an effect was given by Turner. The height of the stable layer aloft is taken as L. At a height 2.15 σ_z above the plume centre line, the concentration is one tenth of the plume centre line concentration at the same distance. When one tenth of the plume centre line concentration extends to the stable layer (L), it can be assumed that the distribution starts being affected by 'Lid'.

In such cases σ_z is allowed to increase with distance to a value of L/2.15 or 0.47L. At this distance of X_L, the plume is assumed to have Gaussian distribution in the vertical. If the plume traverses a distance equivalent to $2X_L$, it is assumed that the pollutant is uniformly distributed between the ground and the height L.

Hence for the distance greater than $2X_L$, the concentration at the ground or at any height upto 'L' is constant at a particular distance and is given by

$$\chi_{(x,y,z,h)} = \frac{Q}{\sqrt{2\pi}\,\sigma_y\, LU} \exp(-1/2\,(y/\sigma_y)^2) \qquad (3 \cdot 11)$$

for short term concentrations and as

$$\chi = \frac{Q}{LU\,(2\pi x/16)} \quad \text{or} \quad \frac{2 \cdot 55\,Q}{LUx} \qquad (3 \cdot 12)$$

for long term concentrations.

The height of the stable layer may be the base of an elevated inversion at the top of the mixing layer. Usually this is taken as the top of the mixing layer because the presence of inversions and their effect on mixing are incorporated in determining the layer. The estimation of χ for a particular direction and downwind distance can be accomplished by choosing a representative wind speed for each speed class and solving the appropriate equations (3.10) or (3.12) for all wind speed classes and stabilities.

It is to be noted that a south wind affects a receptor to the north of a source. The average concentration for a given direction and distance can be obtained by summing all the concentrations and weighting each one according to its frequency for the particular stability and wind speed class.

3.2.6.2 Evaluation of parameters in the model

The parameters to be evaluated are σ_y , σ_z , U and h. For the evaluation of σ_y and σ_z , there were many schemes suggested earlier. However, the nomograms presented by Turner (1970) are made use of in the present study.

U stands for the mean wind speed through plume and this is obtained from a height of $h-2\sigma_z$ to $h+2\sigma_z$ (if $2\sigma_z > h$, then the wind can be averaged from surface to $h+2\sigma_z$). This height difference varies with downwind distance and so does the mean wind speed. Hence for each distance downwind U has to be computed. However, the wind variation in the vertical are seldom available. So an estimate of the variation of wind has to be made which is a function of stability. A simple power law profile has been used for this purpose.

$$U_z = U_1(z/z_1)^{1/p}$$

where U_z is the wind at any heights z, U_1 is the wind at height Z_1 . P having values of 9 (unstable conditions) 7 (neutral conditions) and 3 (stable conditions). In the present study for A, B and C classes the value of 9, for D the value of 7 and for E and F the value of 3 are used for P. At every downwind distance depending upon the stability, the mean winds are obtained between $h-2\overline{\sigma_z}$ to $h+2\overline{\sigma_z}$. Representative wind speed in different wind directions are used. For the computation of effective stack height the formula suggested by Slawson and Csanady (1967) is used. The formula is

$$H = 250 F_T / U^3$$

where

$$F_T = g w_o R_o (T / T_a)$$

where

H = plume rise

u = mean horizontal wind speed

w_o = stack gas velocity at the exit

T = temperature difference between plume and ambient air

and T_a = ambient air temperature.

This formula does not require the knowledge of heat emission and is preferred here, as the value of heat emission is not available.

3.2.6.3 Application of the model for multiple sources

The pollutant under consideration here is sulphur dioxide from industrial sources. The ground concentration of sulphur dioxide at each hour for all these stability classes are computed. The χ is distributed among the sixteen directions depending upon their relative frequencies. The χ is divided with the respective mean wind speeds in each direction to get the concentration due to one source. The city area is divided into 2km X 2km grids and the concentration in each grid due to all the three sources are added together and isolines are drawn. The location of the three sources are shown in the map of the city (Fig. 3.4)

3.2.6.4 Computer program

Fig. 3.5 shows the flow diagram of the numerical scheme in fortran used to obtain spatial distribution of sulphur dioxide concentration for Trivandrum city. The hourly percent frequencies of wind and stability, the hourly values of mixing height, stack parameters and rate of emission and data on the dispersive coefficient in the vertical for different downwind distance form the input of the program. The weighted mean wind speed is computed using the hourly percent frequency tables of wind. The maximum occurring stability class for the hour is considered while taking the dispersive coefficient. For convenience, these computations are incorporated in the main program as separate subroutines. The output of the program is concentration at different downwind distance.

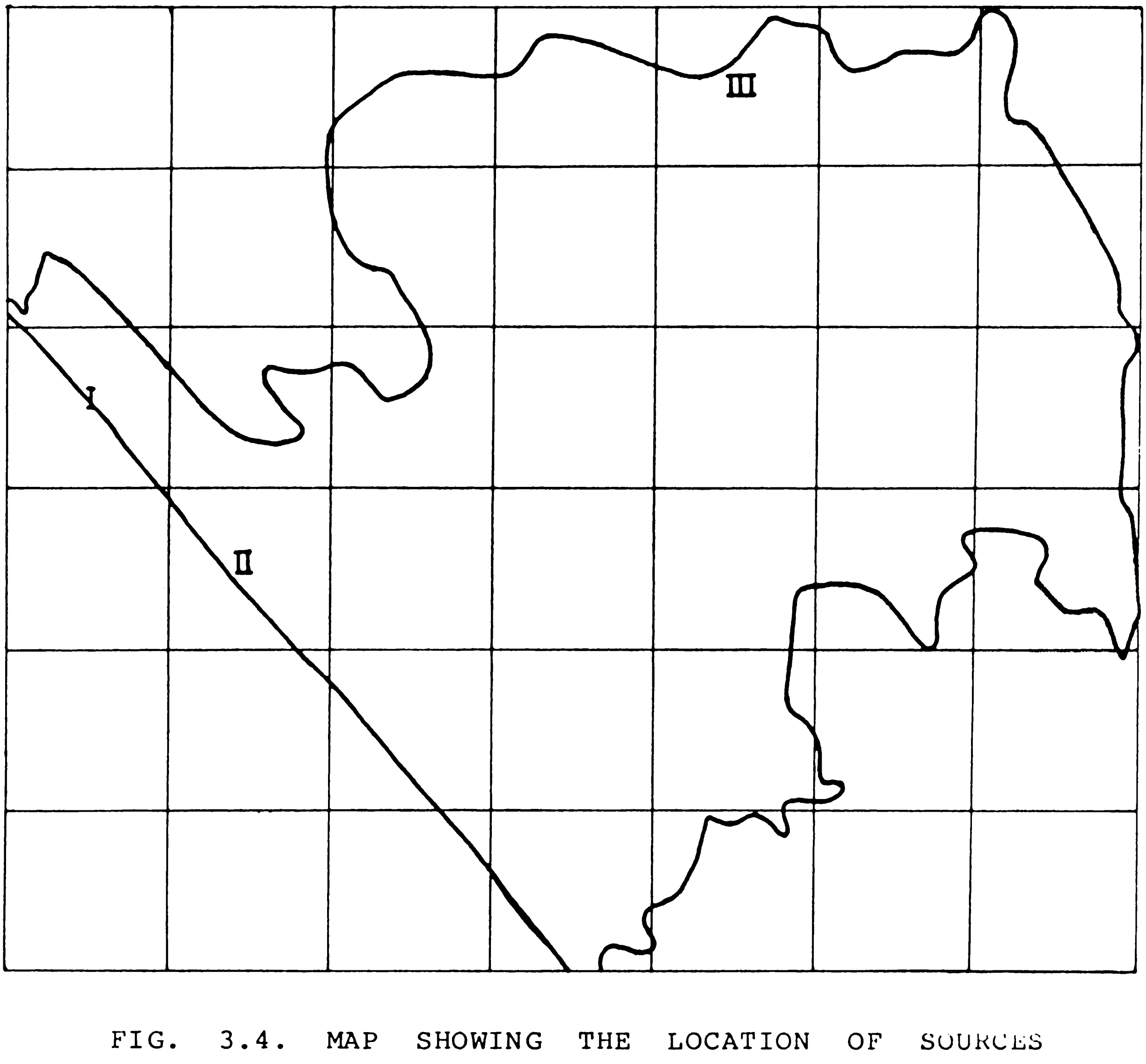
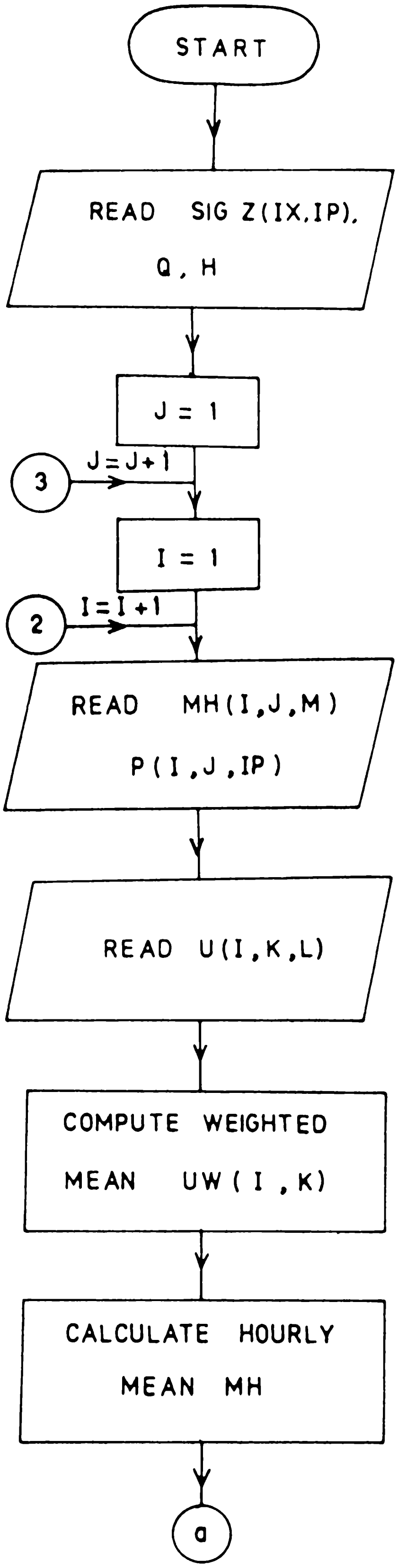


FIG. 3.4. MAP SHOWING THE LOCATION OF SOURCES



SIG Z(IX,IP) = DISPERSION COEFFICIENT IN THE VERTICAL

IX = DOWNWIND DISTANCE

IP = STABILITY CLASS

Q = RATE OF EMISSION

H = EFFECTIVE STACK HEIGHT

J = MONTH

I = HOUR

MH(I,J,M) = MIXING HEIGHT

M = DAY

P(I,J,IP) = PERCENT FREQUENCY OF STABILITY

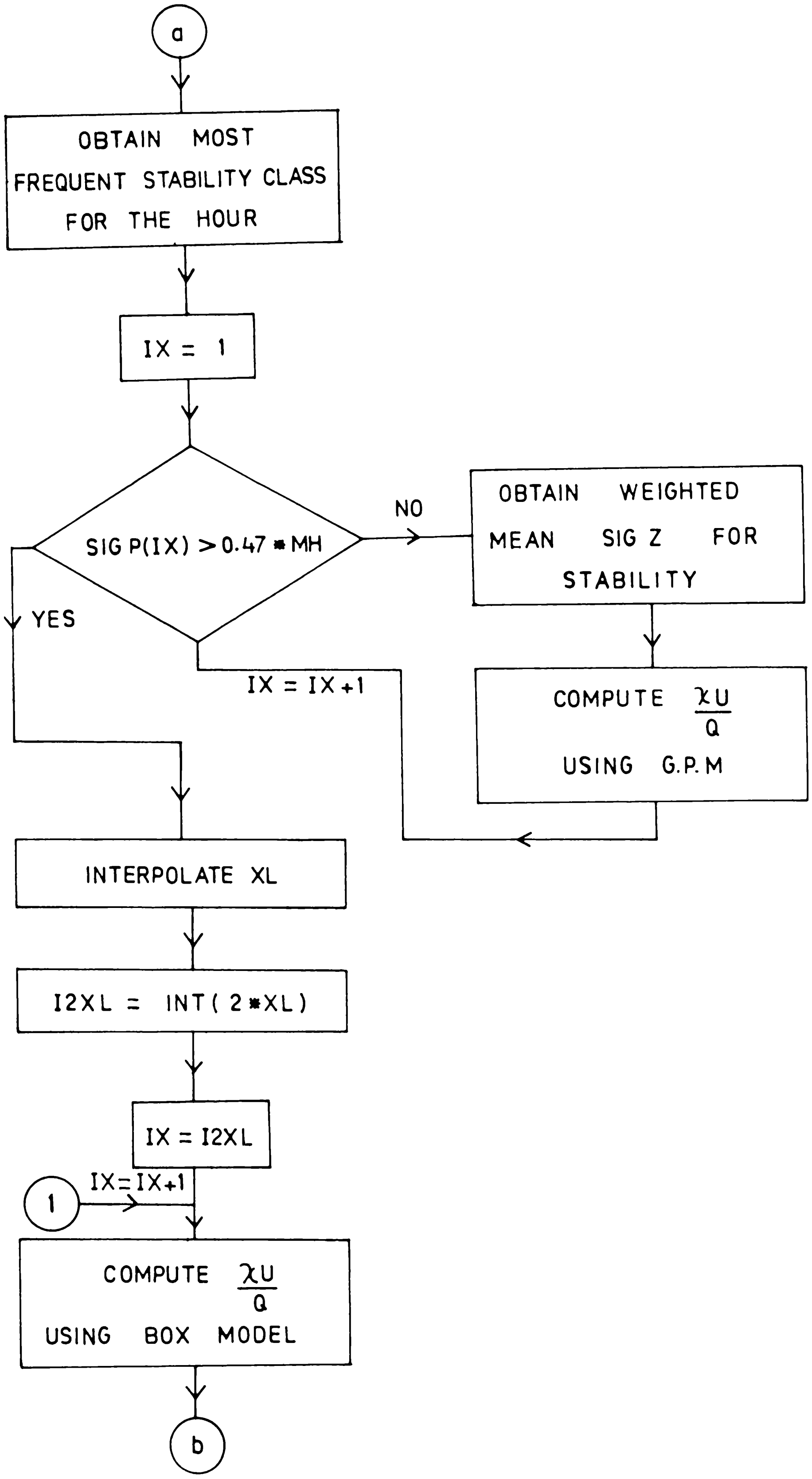
U(I,K,L) = PERCENT FREQUENCY OF WIND

L = SPEED CLASS

K = DIRECTION CLASS

UW(I,K) = WEIGHTED MEAN WIND

SIG P(IX) = DISPERSION COEFFICIENT FOR MAX. OCCURRING STABILITY CLASS


a
OBTAIN MOST FREQUENT STABILITY CLASS FOR THE HOUR
IX = 1
SIG P(IX) > 0.47 * MH
NO
YES
OBTAIN WEIGHTED MEAN SIG Z FOR STABILITY
COMPUTE $\frac{\chi U}{Q}$ USING G.P.M
IX = IX + 1
INTERPOLATE XL
I2XL = INT(2 * XL)
IX = I2XL
1
IX = IX+1
COMPUTE $\frac{\chi U}{Q}$ USING BOX MODEL
b

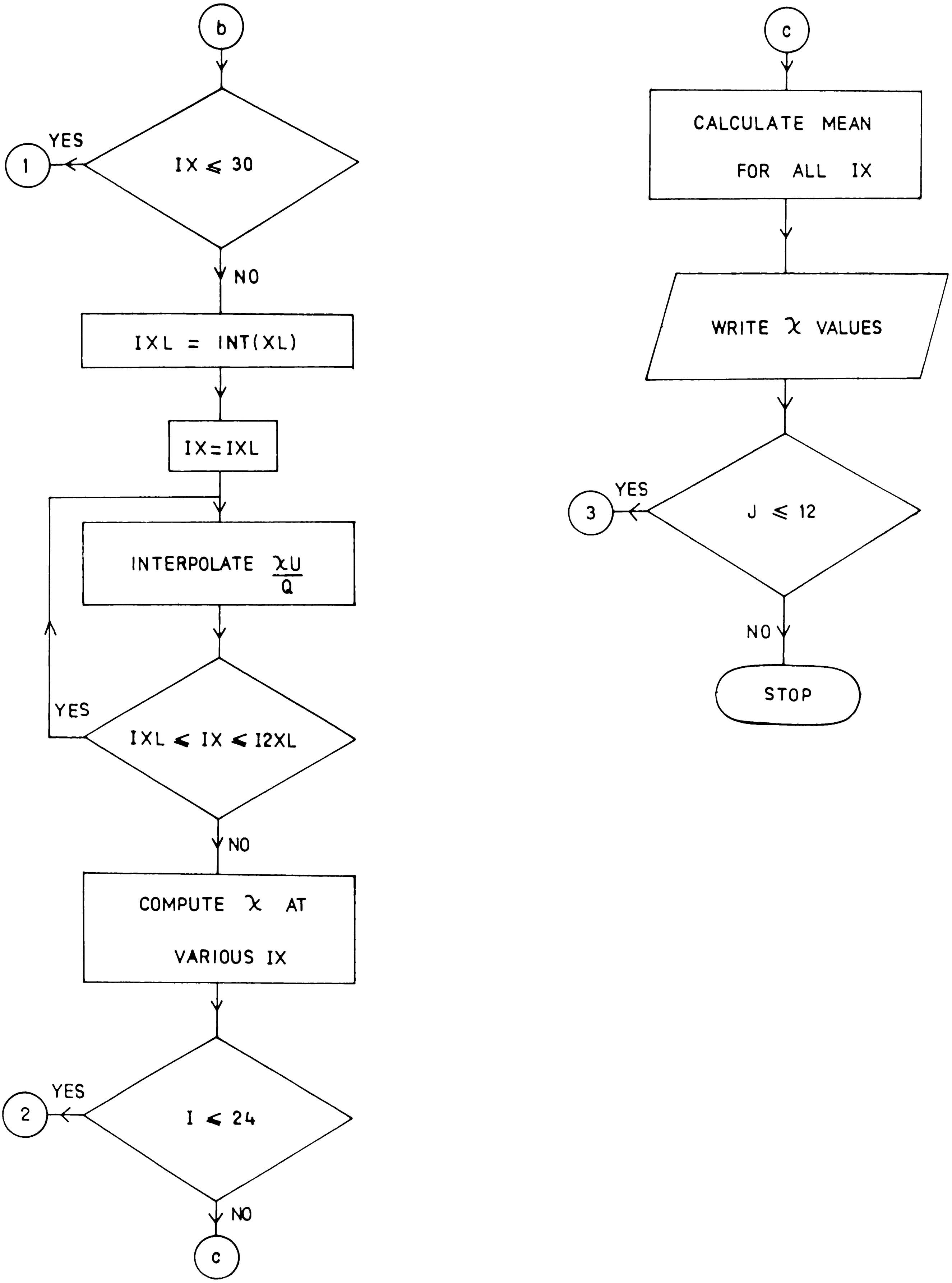


FIG. 3.5. FLOW CHART OF THE PROGRAM FOR SULPHUR DIOXIDE CONCENTRATIONS USING GAUSSIAN PLUME MODEL

3.3 MERITS AND LIMITATIONS

3.3.1 MERITS

(1) The frequency of occurrence of inversions, isothermals and lapse conditions are computed for every 50mb thickness upto 500mb level for all the months.

(2) Mixing heights and ventilation coefficients are computed for every hour for all months in all the five years.

(3) Frequency tables are prepared for every hour using hourly wind and wind roses are drawn for every six hours for all months.

(4) For the first time a comprehensive index of pollution potential is developed by taking the vertical thermal structure, winds and atmosheric stability into consideration.

(5) The wind direction fluctuation range and wind speed fluctuation range are computed by taking continuous recording graphs. Nearly 2000 such graphs are made use of to compute these parameters and a relation between these two is obtained.

(6) The representative values of $\sigma_{\theta D}$ and $\sigma_{\theta S}$ are obtained

for Pasquill's categories and mixing heights.

(7) The spatial distribution of sulphur dioxide concentration over Trivandrum is studied for every month.

(8) The possible locations for new industries are suggested.

3.3.2 LIMITATIONS

(1) The computed ventilation coefficients are likely to be underestimates since only the surface wind is multiplied with the mixing height. Strictly speaking it is the mean wind through the mixing layer that is to be considered.

(2) The index of pollution developed in the present thesis does give a fair indication of the atmospheric ability to disperse pollutants. But this categorisation appears to be arbitrary. It does not have experimental evidence. However, this cannot be overlooked because it is an arbitrary consideration, since this index gives all the information at a given time about the mixing height, wind speed and stability in the simplest way.

(3) In applying the model, the calm conditions could not be taken into account.

(4) The model could not be validated with the actual observed concentrations due to their non-availability.

(5) The assumptions such as perfect reflection at the ground and flat terrain really pose some restrictions for the application of the model, more so to Trivandrum city since the roughness length in Trivandrum is not inconsiderable in view of the slight irregular terrain features.

(6) The automobiles which contribute substantially to the pollution are not considered in the present study. As such the concentrations obtained from the model are likely to be underestimates.

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CHAPTER IV

INVERSIONS, ISOTHERMALS AND LAPSE CONDITIONS

The types and the sources of data and the detailed methodology along with the merits and demerits were presented in the preceding chapter. In the present chapter, the results and the discussions of the studies on inversions, isothermals and lapse conditions are presented, separately.

4.1 RELATIVE FREQUENCIES OF INVERSIONS, ISOTHERMALS AND LAPSE CONDITIONS

The percent frequencies of the total inversions isothermals and lapse conditions, irrespective of their intensities, are computed for all the months and presented in Fig. 4.1. Lapse conditions dominate in all the cases followed by isothermals and inversions. The lapse conditions are around 90% in all the cases and rest is dominated by isothermals (about 6%).

The extremely high frequency of lapse conditions can be explained as due to the heating of the atmosphere from below. The dominance of lapse conditions cannot be taken to represent unstable conditions since mere presence of lapse conditions is not sufficient, although it is necessary, for instability to be present. In spite of this, the atmospheric temperature some times remains constant or increases with height which is normally called as isothermal and inversion respectively. Inversions are more during the early morning

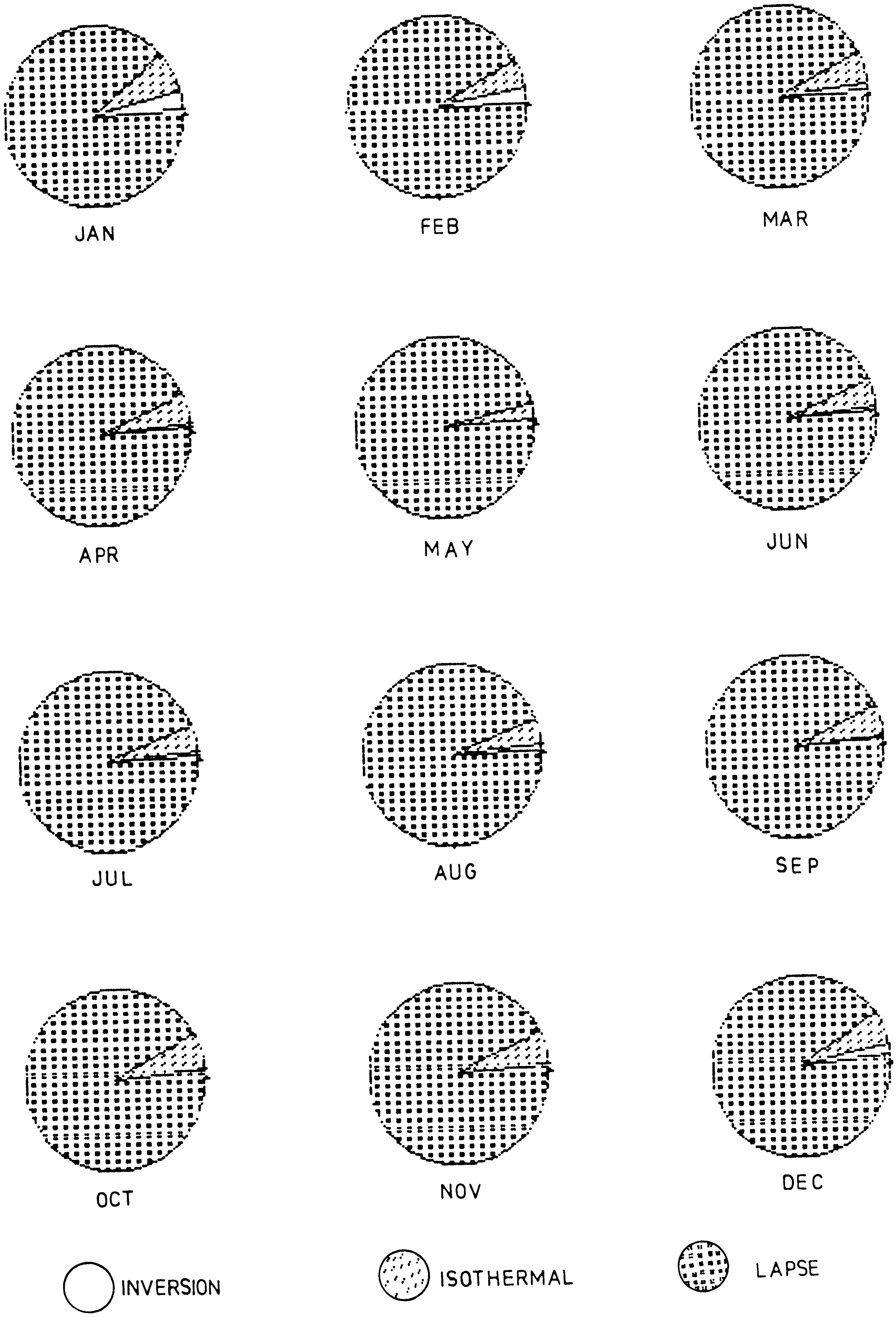


FIG. 4.1. PERCENT FREQUENCY OF INVERSIONS, ISOTHERMALS AND LAPSE CONDITIONS

hours of January followed by February and December. Although the figure does not show any frequencies of inversions in many of the months it cannot be construed as the case of no inversions at all. In fact when compared to the lapse conditions the frequency of inversions is so low that it can be represented properly in these diagrams. The isothermal conditions are also found to be maximum in January. The minimum isothermal frequencies are noticed in the month of May. The month of May represents typical summer conditions for Trivandrum and as such the isothermals and inversions are expected to be extremely low in this month.

The percent frequencies of different intensities of inversions and lapse conditions and isothermals in various layers in the atmosphere are presented separately hereunder.

4.2 INVERSIONS

The percent frequencies of intensities of inversions in various layers are depicted in Figs. 4.2(a) and 4.2(b) for all the months at 0000 GMT. For the present study, the atmospheric layer from the surface upto 950mb is considered as the surface layer and all other layers as upper layers. Surface based inversions dominate (about 60%) in all the months. Intense inversions, though infrequent are observed only in the upper layers in as many as seven months. Although surface based inversions are relatively high in frequency

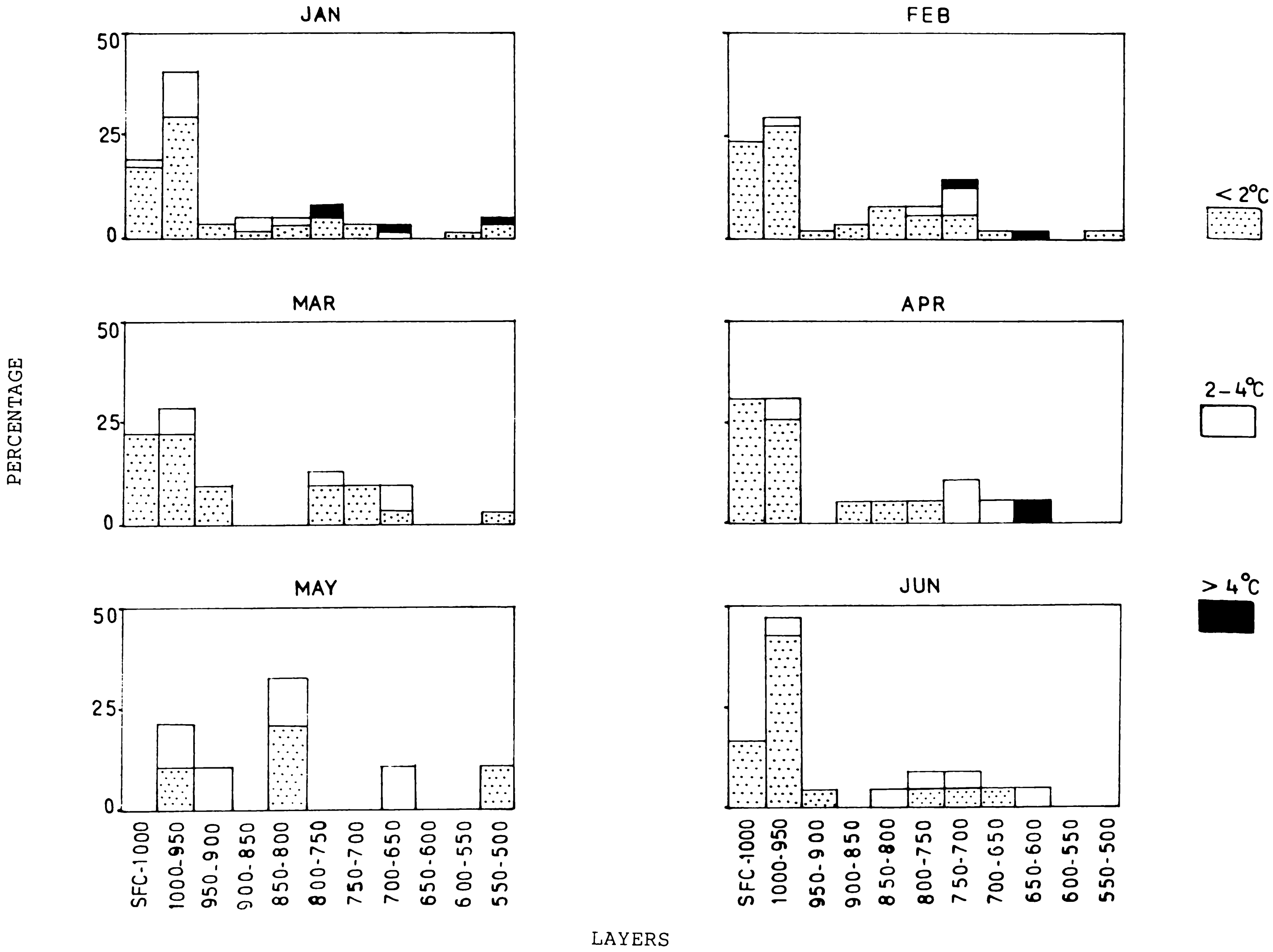


FIG. 4.2(a). PERCENT FREQUENCY OF INVERSIONS

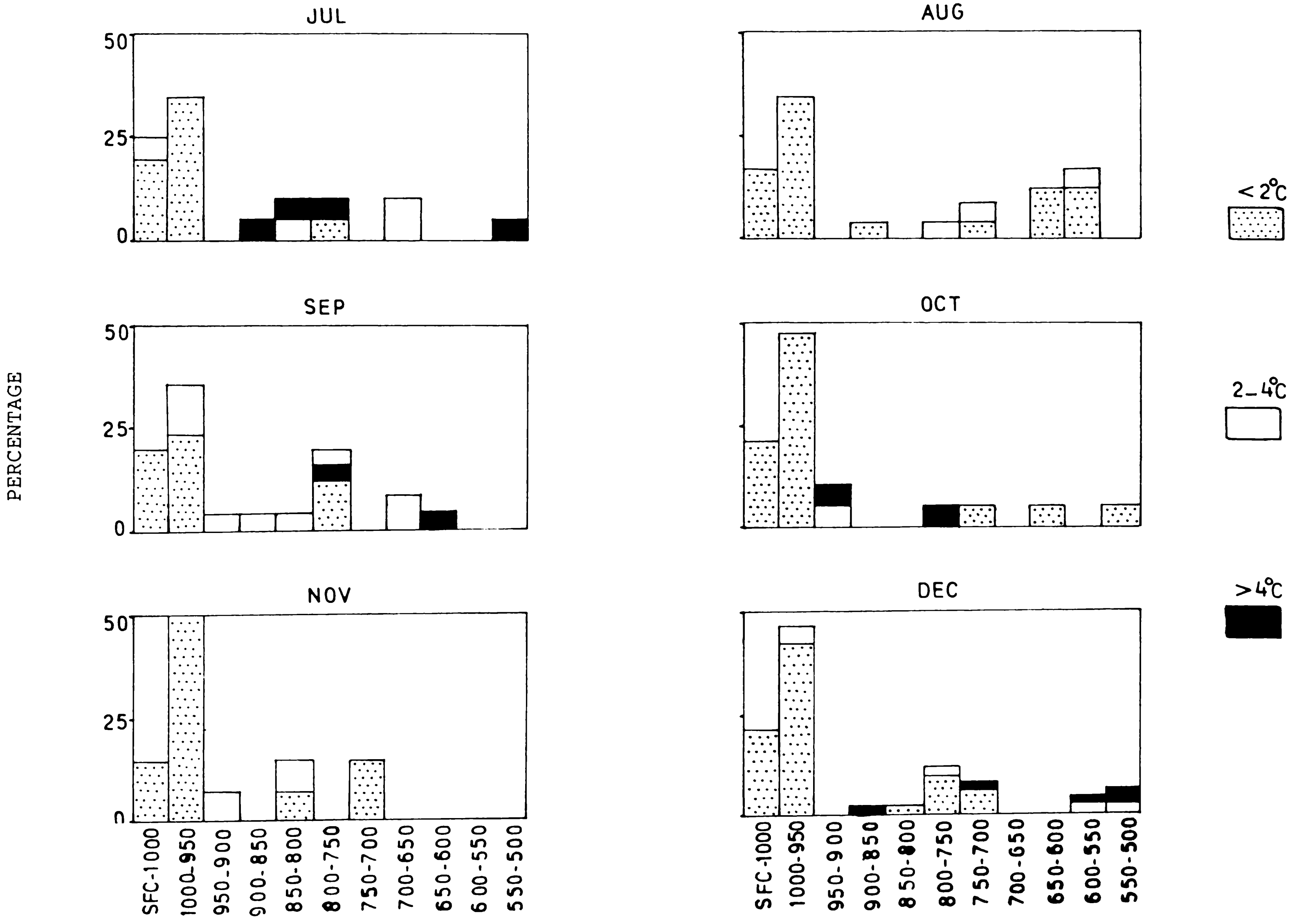


FIG. 4.2(b). PERCENT FREQUENCY OF INVERSIONS

(about 60%), they are found to be weak in intensity. Frequency of strong inversions is highest (20%) in July. It is to be noted here that these frequencies are relative to the total number of inversions present and the total frequency of inversion itself is extremely small. The presence of inversions on any given day has its own impact on the dispersal of atmospheric pollutants. The 0-2 °C per 50mb intensity is the dominating one in all the cases of surface inversions. The very first layer shows the intensity to be 0-2°C but the intensity in the literal sense is much higher mainly because of the small thicknesses there.

In general, the presence of inversions does not seem to cause much anxiety as far as air pollution is concerned, since its percentage occurrence is extremely low, because of the coastal characteristics of the station. There is only one instance of the elevated inversions being high in frequency in the entire case and that is in the month of May, where the 850 - 800mb layer has more frequency of inversions. The insignificant monthly variation is also due to the coastal characteristics.

4.3 ISOTHERMALS

The isothermal frequencies in different layers are presented in Figs. 4.3(a) and 4.3(b). Once again the surface based isothermals dominate in all the cases. The monthly variation is insignificant. The elevated isothermals are in

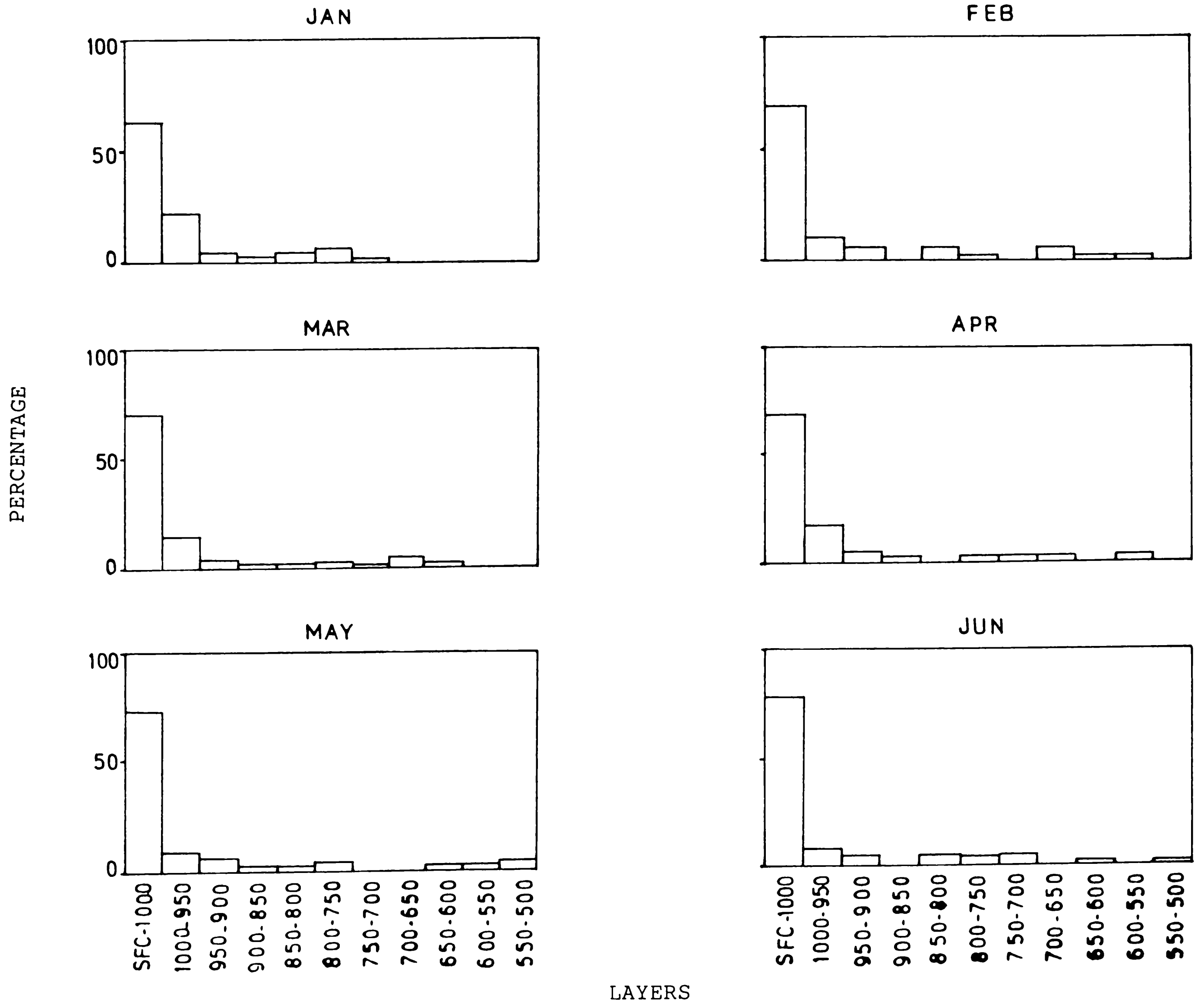


FIG. 4.3(a). PERCENT FREQUENCY OF ISOTHERMALS

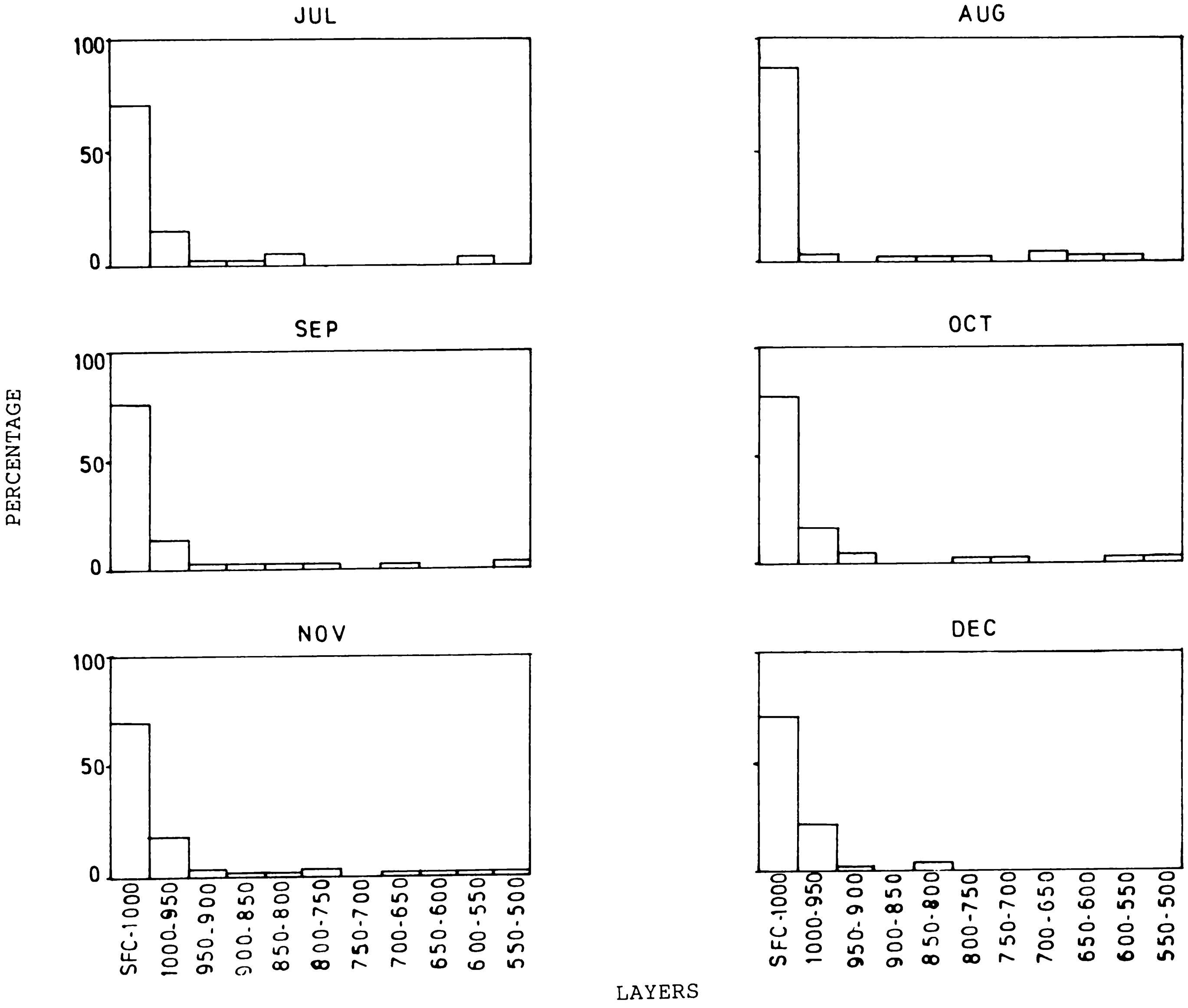


FIG. 4.3(b). PERCENT FREQUENCY OF ISOTHERMALS

extremely low frequency in all the cases without any exception. Since they are all relative frequencies, they cannot be compared with the frequency of inversions in Figs.4.2(a) and 4.2(b). The isothermals represent moderately stable conditions and as such the higher percent frequency cannot be overlooked : they may act as lids in the atmosphere and not allow the pollutants to penetrate into them, although, not as effectively as inversions.

4.4 LAPSE CONDITIONS

Figs. 4.4(a) and 4.4(b) represent the percent frequencies of lapse conditions in every 50mb layer for all the months. The lapse conditions near the surface are low while the elevated lapse conditions are more in frequency. There are some layers which show all intensity classes, although with different frequencies. Apparently, the intensity increases from surface to the topmost level under consideration in all the cases. Utmost caution should be exercised in interpreting this aspect, since the intensities are taken for pressure intervals of 50mb whose thickness in gpm increases with elevation. As such the lapse rates may not differ that significantly as depicted in the figure. The systematic decrease of -2 to -4°C per 50mb intensity and the consequent increase of -4 to -6°C per 50mb intensity with elevation in all the cases is a notable feature. Most of the layers except near the surface and the topmost layers, are

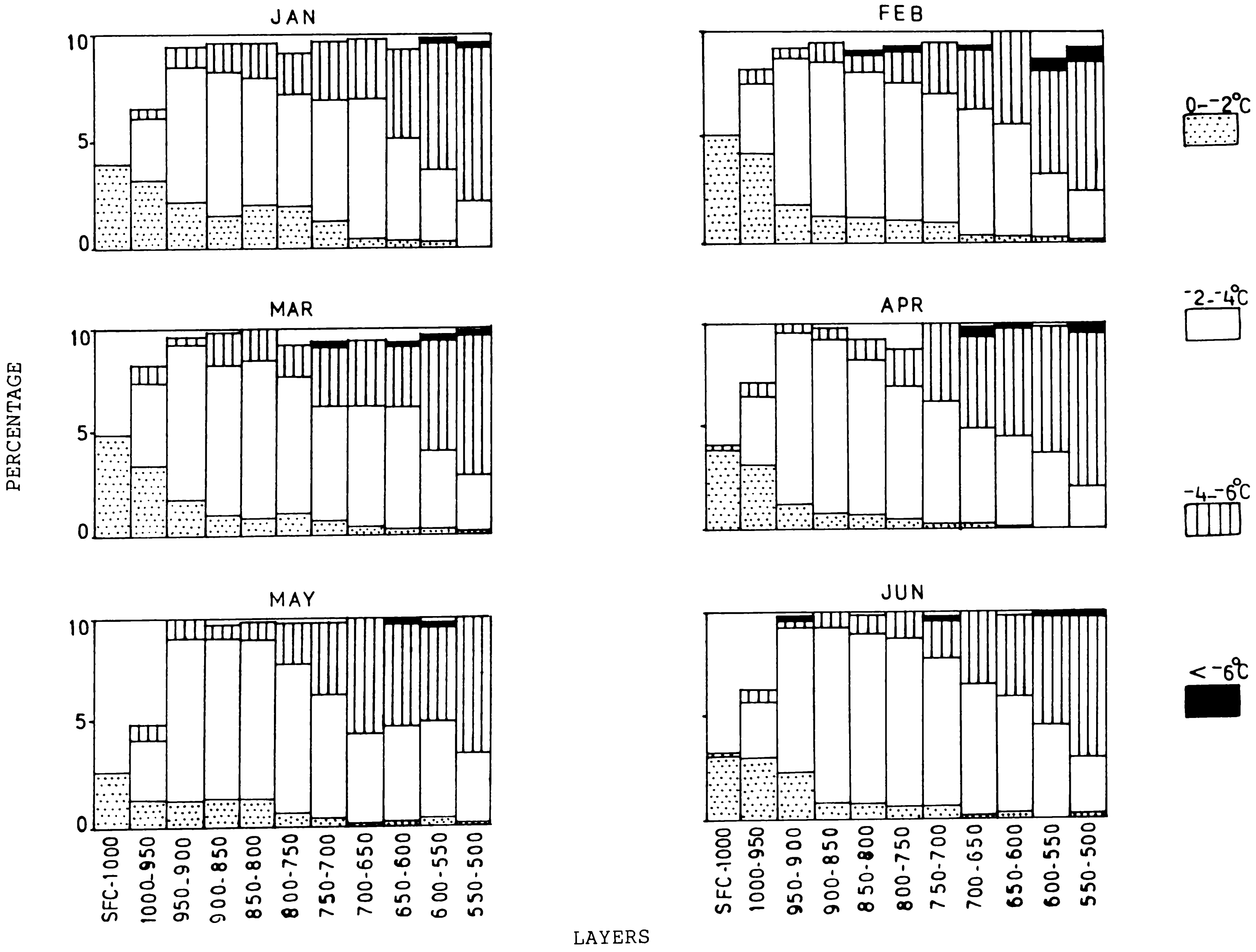


FIG. 4.4(a). PERCENT FREQUENCY OF LAPSE CONDITIONS

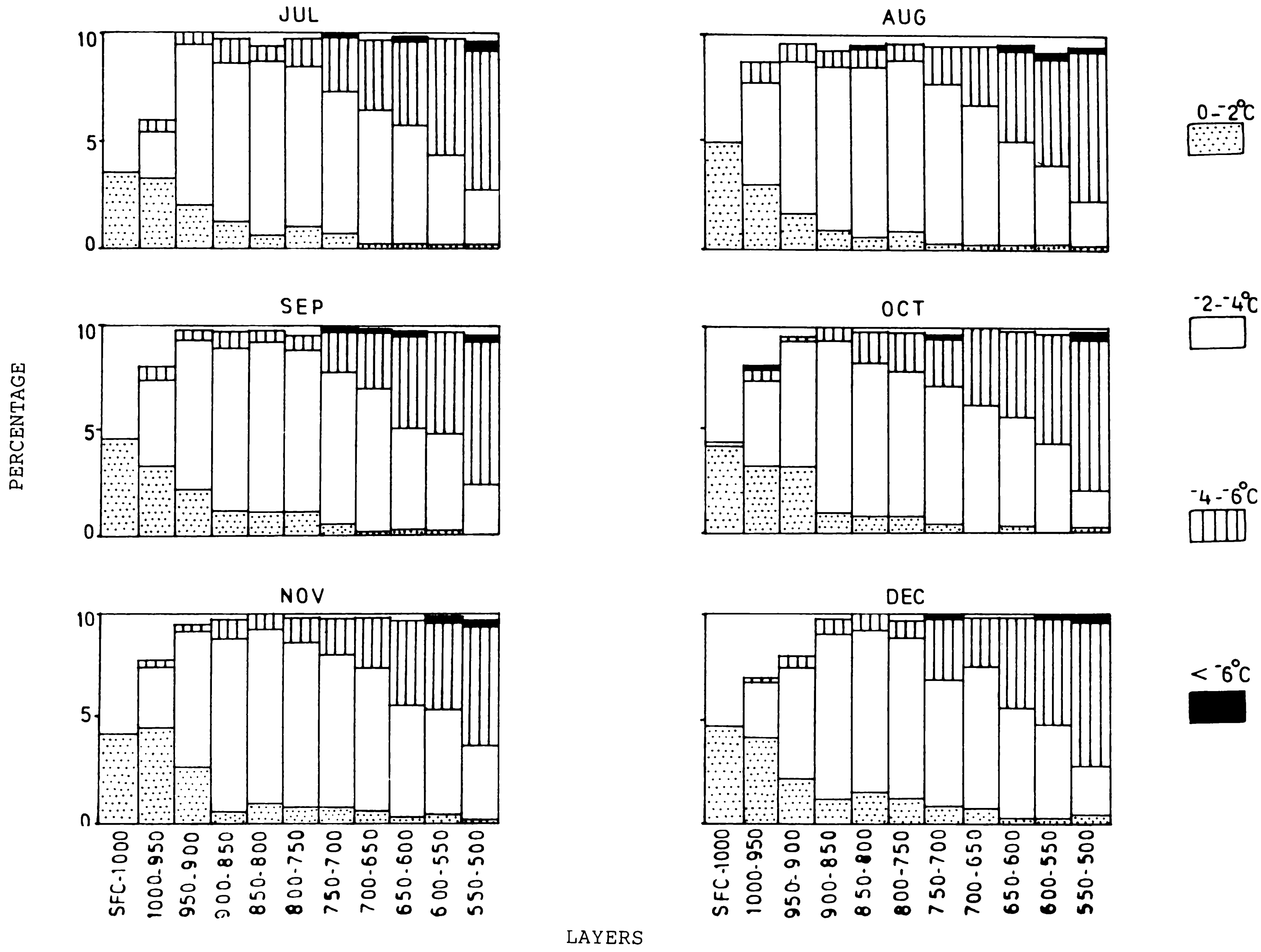


FIG. 4.4(b). PERCENT FREQUENCY OF LAPSE CONDITIONS

dominated by -2 to -4°C intensity. The elevated frequencies of lapse conditions in each of the layers do not differ significantly, although the individual intensities differ from layer to layer.

As mentioned before, these lapse conditions should never be construed as superadiabatic or unstable conditions both of which cannot persist for a considerable length of time. In fact these are more predominant during the afternoon times when the excess heat input near the surface causes steep lapse rate resulting in superdiabatic conditions. On the whole, the lapse conditions are found to be dominating in all the months compared to inversions and isothermals. The monthly variation is not so significant.

Although these conditions provide some insight, the extent to which pollutants get mixed cannot be inferred from this, unless the mixing heights and prevailing winds at the different hours in all the months are known. Studies of these aspects form the basis of the next chapter.

CHAPTER VI

MIXING HEIGHTS AND VENTILATION COEFFICIENTS

The study of inversions, isothermals and lapse conditions which actually represent the vertical thermal structure was presented in the preceding chapter. However, that does not provide the actual extent of mixing, unless some additional information is provided. In this chapter, the vertical and horizontal extents and their variations are presented.

5.1 MIXING HEIGHT

The diurnal variation of mixing height for all the months is presented in Figs. 5.1(a) and 5.1(b). The pattern closely follows the diurnal variation of surface temperature. In about 6 months the minimum mixing height is very near to zero. The highest value (1463m) is observed in February at 1400 hours. The maximum mixing height in June is only 855m. Both the night-time and day time values are generally higher from January to April. The maximum mixing height decreases from February to July, then increases upto September, decreases thereafter till November followed by an increase upto February. The largest range is noticed February and March while the monsoonal months experience the lowest ranges.

The high values from December to April are mainly because of strong heat input near the surface. Although part

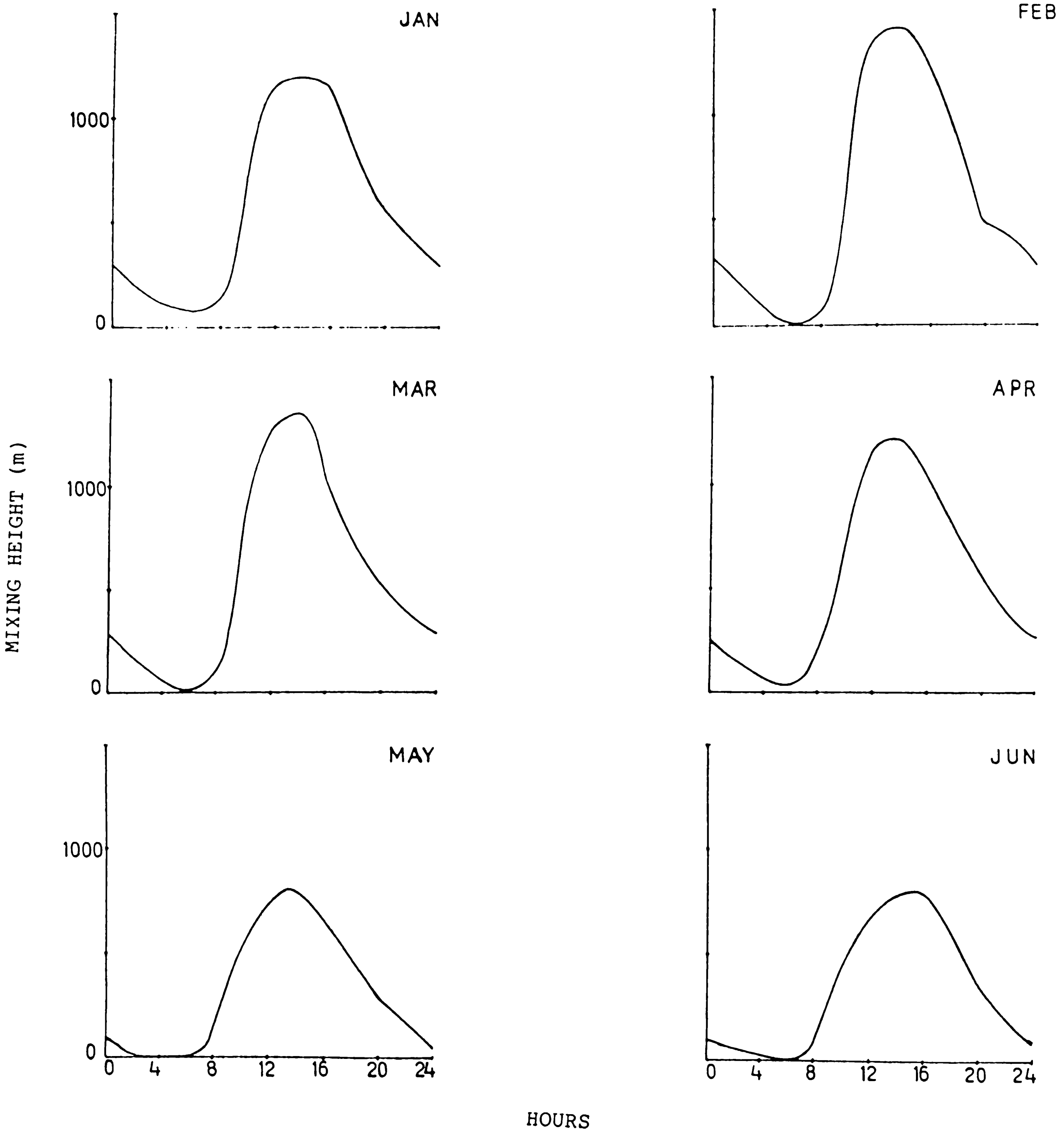


FIG. 5.1(a). DIURNAL VARIATION OF MIXING HEIGHT

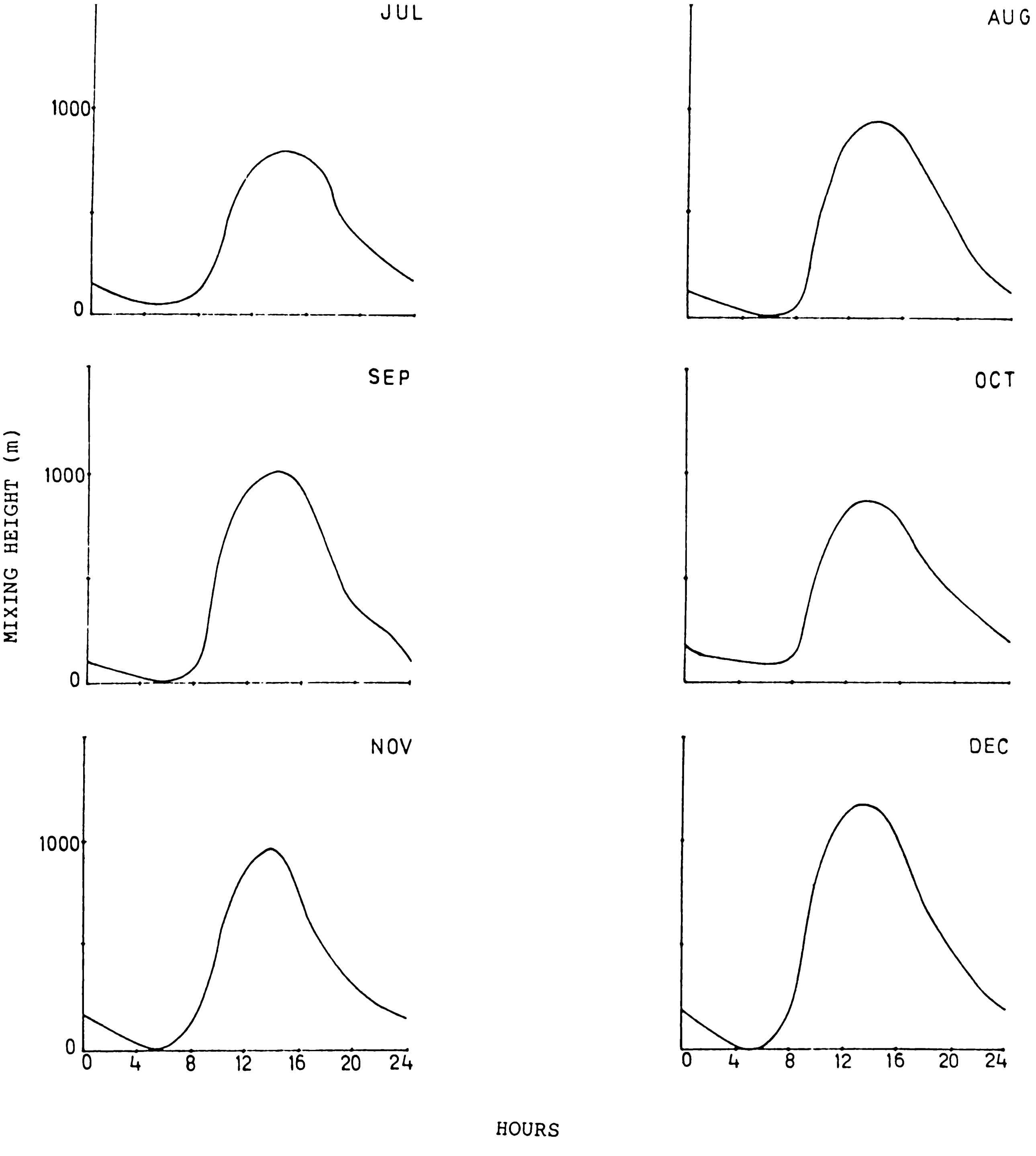


FIG. 5.1(b). DIURNAL VARIATION OF MIXING HEIGHT

of these months is considered as winter, the real winter effects are not actually felt in the station. Incidentally if one looks at the surface temperature pattern it comes to light that lowest surface temperatures (around 26°C) are recorded during monsoon season and the highest (around 28°C) in February and March. An interesting speculation is that whether Trivandrum has any winter at all. These so called winter months are characterised by clear skies and subsequent good heat input at the surface which generate convection, at the levels and later extending upto as high as 1.5km. Even the night-time mixing is high in these months, further corroborating the earlier view of no winter features in this season. April also shows higher mixing height if not the highest. In the normal circumstances April being typical of premonsoon season should have maximum heat input at the surface giving rise to highest mixing. But the frequent thunder showers which are very common in this month do not allow the surface temperature to rise beyond a limit and consequently the mixing height cannot be the highest in this month.

The lowest values in the monsoon season are mainly because of the continuous precipitation and overcast conditions with lot of moisture, all of which reduce the surface temperature considerably resulting in the lowest mixing height, which do not allow the pollutants to get diluted resulting in higher concentrations. The night-time situation is much worse when the mixing height are absolutely low.

The monthly variation of mixing height for each of the 24 hours is presented in Figs. 5.2(a) and 5.2(b) for day time and night-time respectively. During night-time it is generally invariant.

5.2 VENTILATION COEFFICIENT

The diurnal variation of ventilation coefficient is presented in Figs. 5.3(a) and 5.3(b), for all months. The diurnal variation is well marked in all the cases showing a near perfect normal distribution. The peak value is noticed at 1400 hours in almost all the cases except in July and September when it is noticed at 1500 hours. The values and the variation are almost similar in the months of February, March, April, August and September. The ventilation coefficient values in the afternoon hours during these months are higher than in the other months. The peak values vary from 2500 to 6100 $m^2 s^{-1}$. The high values in February, March and April are mainly because of the higher mixing height, whereas they are due to higher wind speeds in August and September. However, negligibily small values of ventilation coefficients are absent during night-time in all these months. These extremely small values are a matter of serious concern since the pollutants can neither get mixed up in the

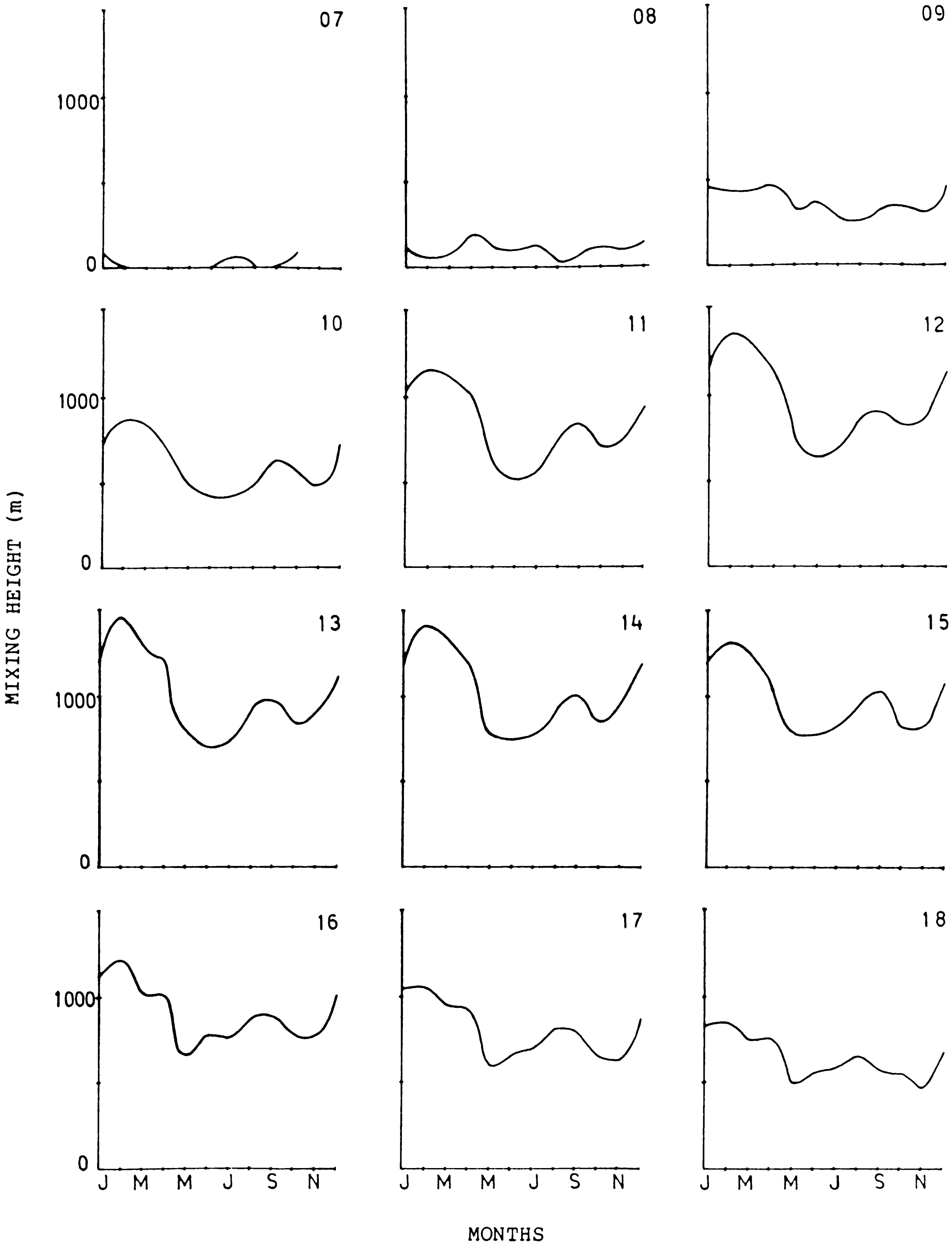


FIG. 5.2(a). MONTHLY VARIATION OF MIXING HEIGHT DURING DAY TIME

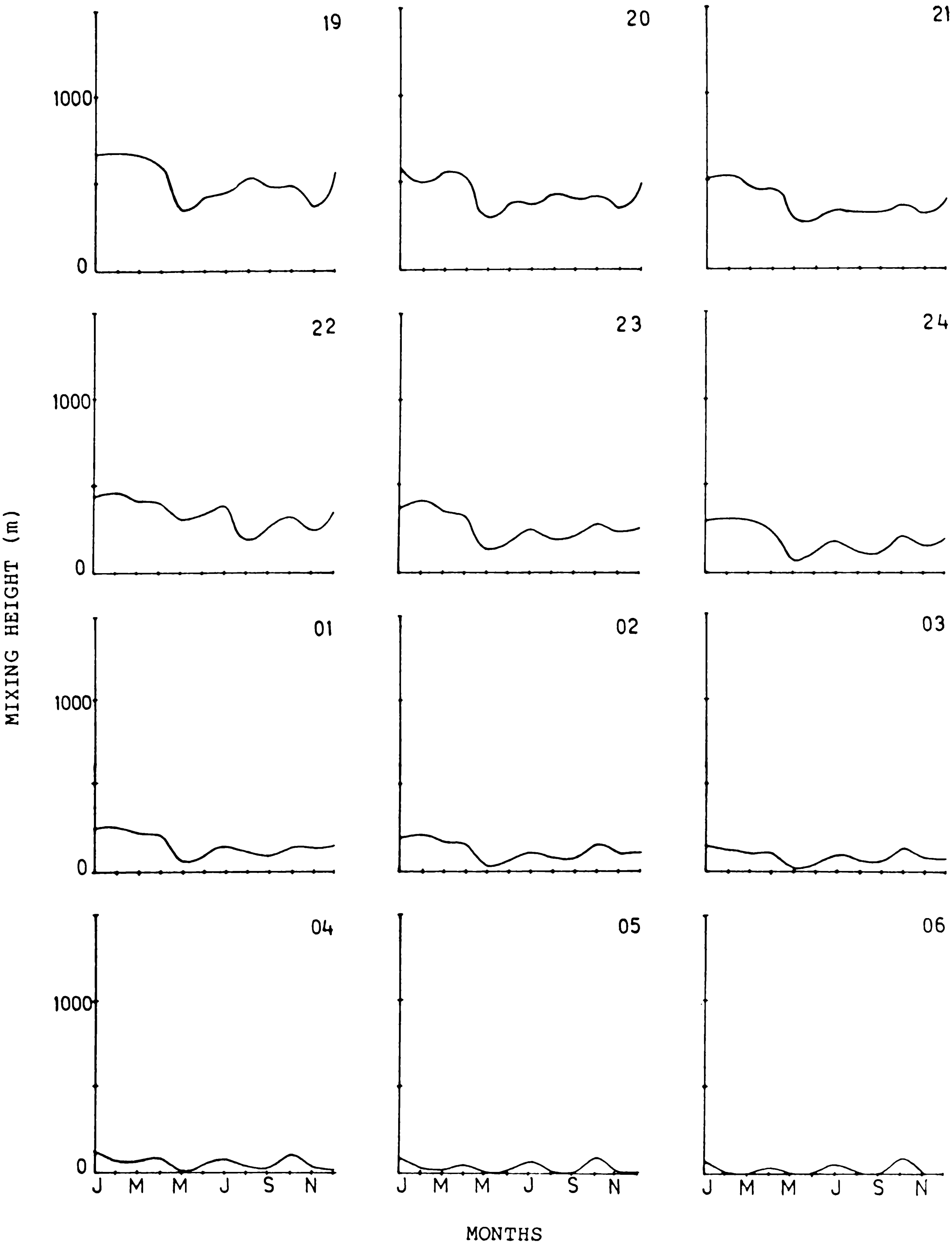


FIG. 5.2(b). MONTHLY VARIATION OF MIXING HEIGHT DURING NIGHT-TIME

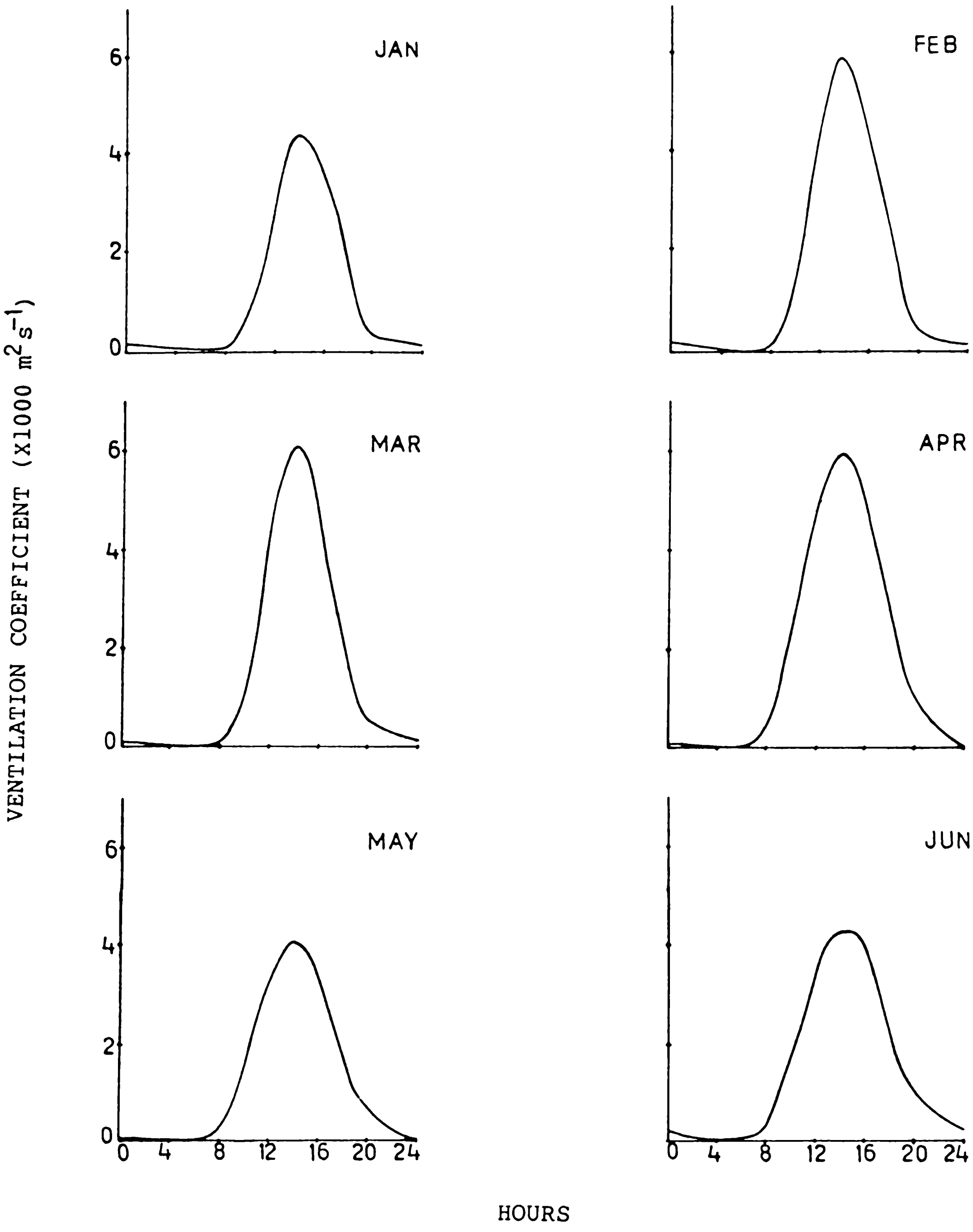


FIG. 5.3(a). DIURNAL VARIATION OF VENTILATION COEFFICIENT

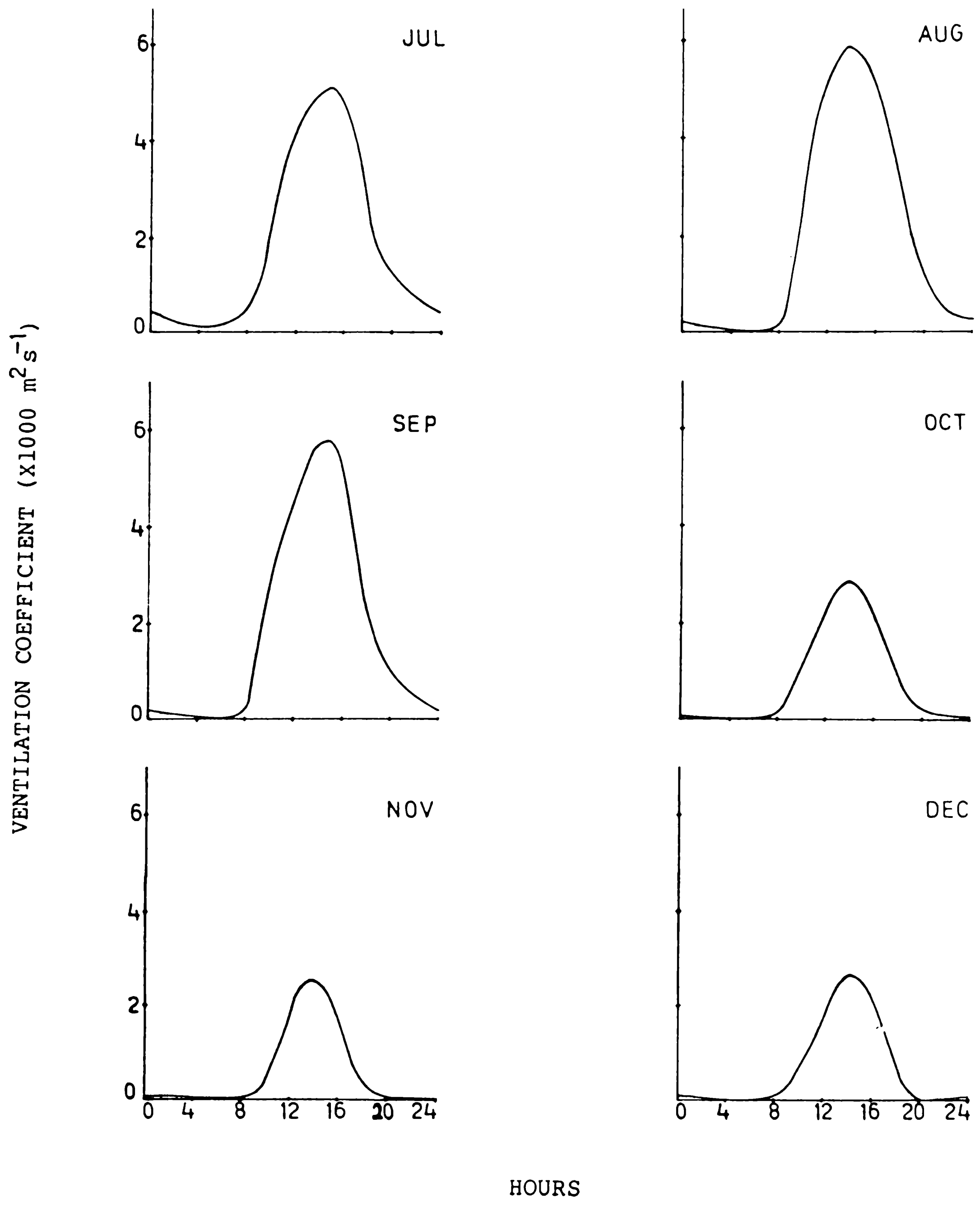


FIG. 5.3(b). DIURNAL VARIATION OF VENTILATION COEFFICIENT

vertical nor can get dispersed in the horizontal. It would result in the accumulation of pollutants leading to very high doses of concentration. The night-time situation is equally bad in the other months too. Moreover, the day time values add to the concern in these months since the values are very low (around 2500 $m^2 s^{-1}$)especially from October to December. In fact, the low values during day time are because of the low mixing heights and relatively lower wind speeds.

The monthly variation of ventilation coefficient is depicted for every hour in Figs. 5.4(a) and 5.4(b) for day time and night-time respectively. Once again two maxima and minima are noticed during day time when the monthly variation is at its peak, closely following the pattern of mixing height. Although the mixing is very low in the monsoonal months the wind speed is so high that the ventilation coefficient exceeds the corresponding values from February to March during most of the day time.

The very strong winds from July to September are mainly due to the southwest monsoon which, in addition, brings in copious amounts of rainfall in these months. This may be one of the reasons for the low heat input near the surface in these months giving rise to extremely low mixing height. Although the concern is expressed, it must be noted that the heavy rainfall washes out most of the pollutants in the atmosphere making it to be free from pollution, at least,

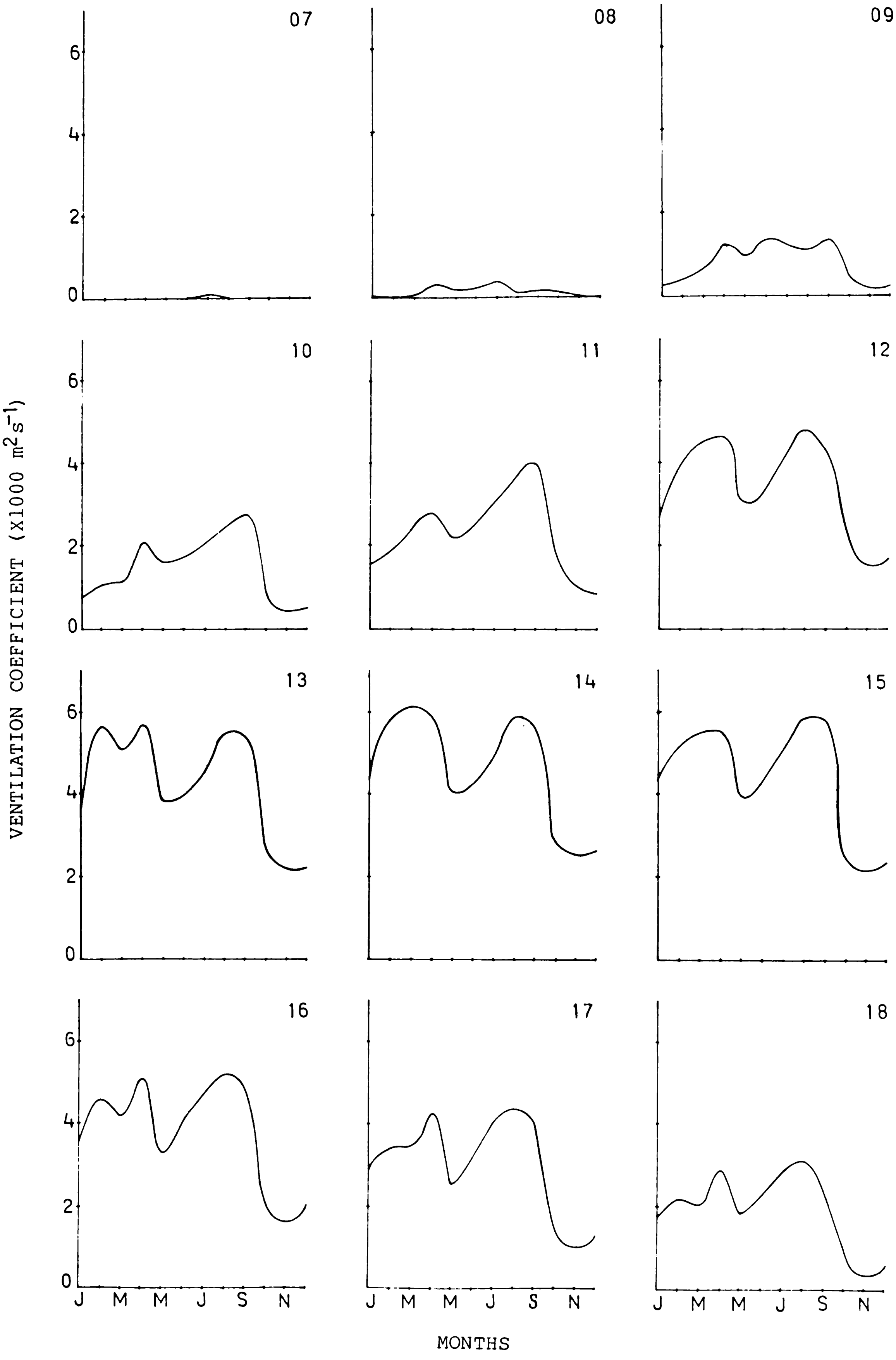


FIG. 5.4(a). MONTHLY VARIATION OF VENTILATION COEFFICIENT DURING DAY TIME

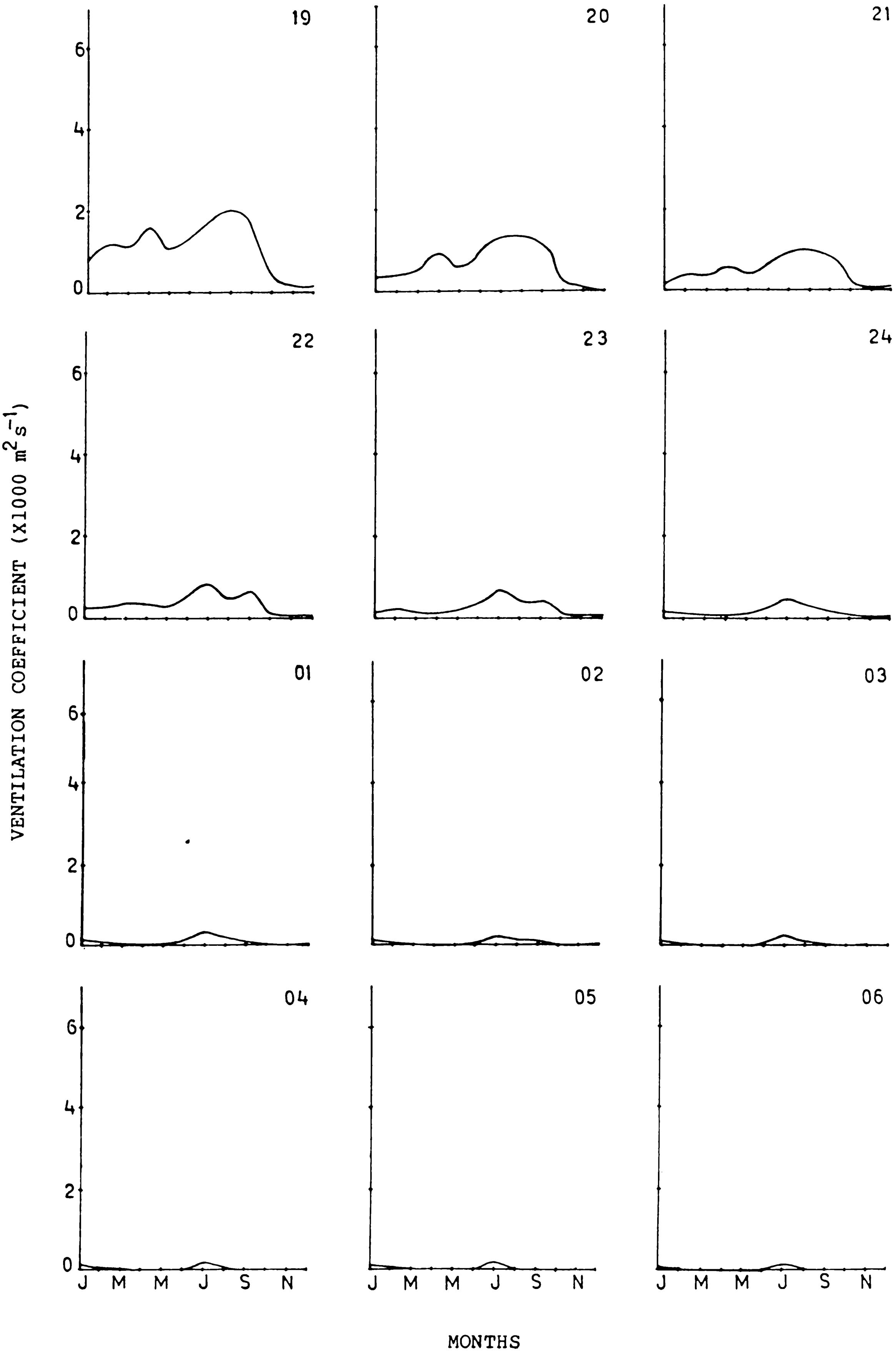


FIG. 5.4(b). MONTHLY VARIATION OF VENTILATION COEFFICIENT DURING NIGHT-TIME

temporarily. As such the concern due to the low value during the night time in these months is offset because of the washout due to rainfall. However, it should be remembered that although the atmosphere is clear after washout, all the pollutants reach the earth's surface in dissolved form which also is a matter of concern but in a different sense. Now the real concern is confined to the non-rainy months. The relatively low ventilation coefficient are also partly due to the non-inclusion of wind variation with height. As such all the values reported are likely to be underestimates. Inclusion of wind variation with height may result in a large increase of the existing values especially during day time.

The night-time situation as far as both the mixing height and ventilation coefficient are concerned is pretty bad since low values of both these parameters inhibit the dispersal of pollutants in the vertical as well as horizontal leading to large accumulation of pollutants. As such the emissions from the various sources should be correspondingly reduced in order to keep the concentration of pollutants within the permissible limits. However, this is not the only thing which influences the dispersal of pollutants and hence the conclusions are deferred till the study of other influencing factors, is made.

CHAPTER VI

PASQUILL'S STABILITY AND WIND

In the present chapter one of the most important parameters, namely, atmospheric stability which has a direct bearing on the pollutant dispersal, is studied along with the wind roses. The pollution potential indices are also discussed in this chapter.

6.1 ATMOSPHERIC STABILITY

The method of computing stability by Pasquill's technique is given in chapter 3. The percent frequency of occurrence of Pasquill's stability classes is studied for every hour for all the months. The diurnal variation of the maximum occurring stability class is also studied for every month.

The diurnal variation of percent frequency of occurrence of each of the Pasquill's stability categories for every hour is presented in Figs. 6.1(a) and 6.1(b) for all the months. Here day time is considered as 0700 to 1800 hours and night-time as 1800 to 0700 hours. Highly stable conditions (F class) are observed during night-time and all classes of unstable conditions (A, B and C classes) are observed during day time in January. During the transition periods from night to day and day to night, one can notice the presence of neutral (D class) and slightly unstable (C class) conditions. Most of the day time all the three

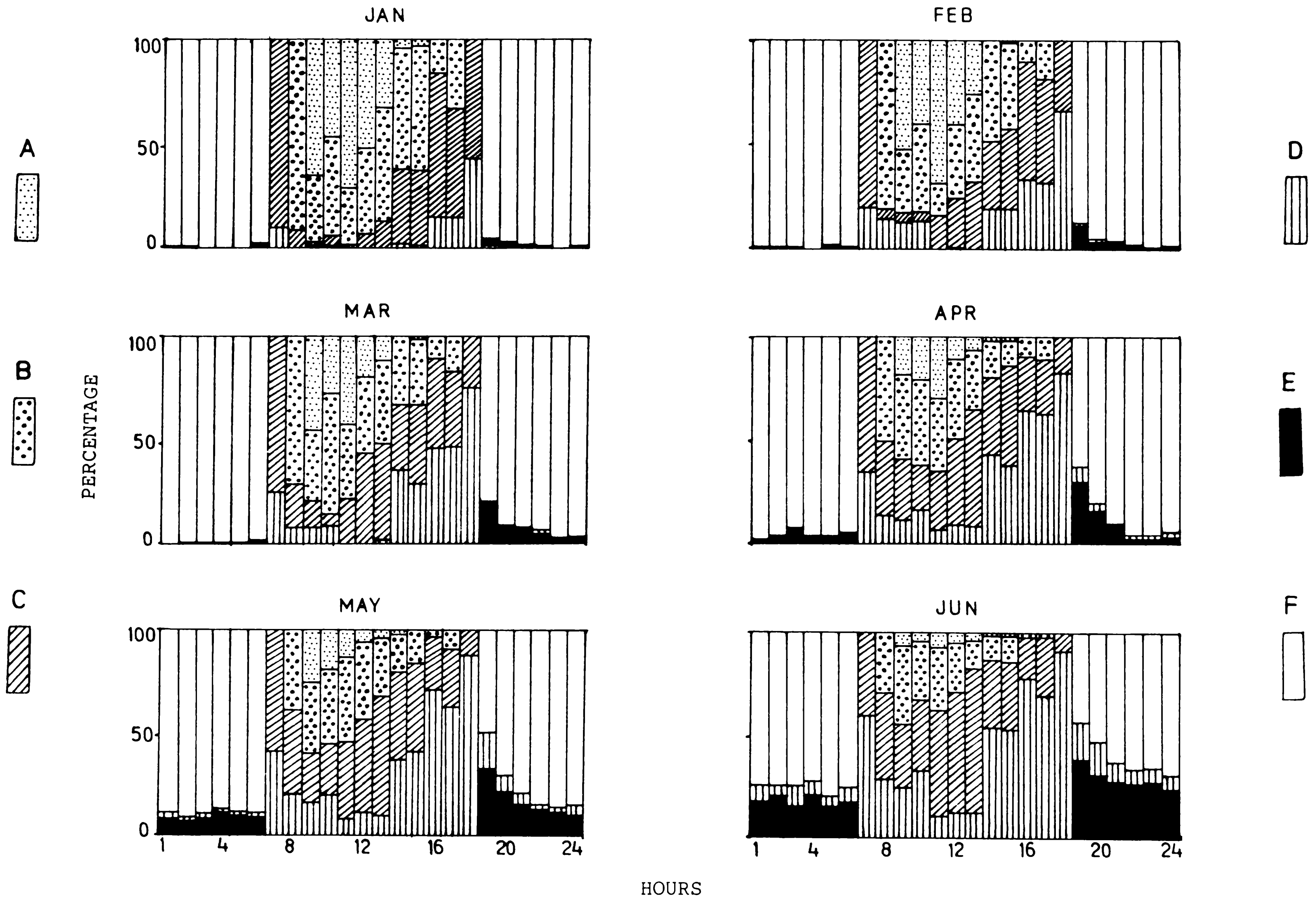


FIG. 6.1(a). DIURNAL VARIATION OF PERCENT FREQUENCY OF PASQUILL'S STABILITY CLASSES

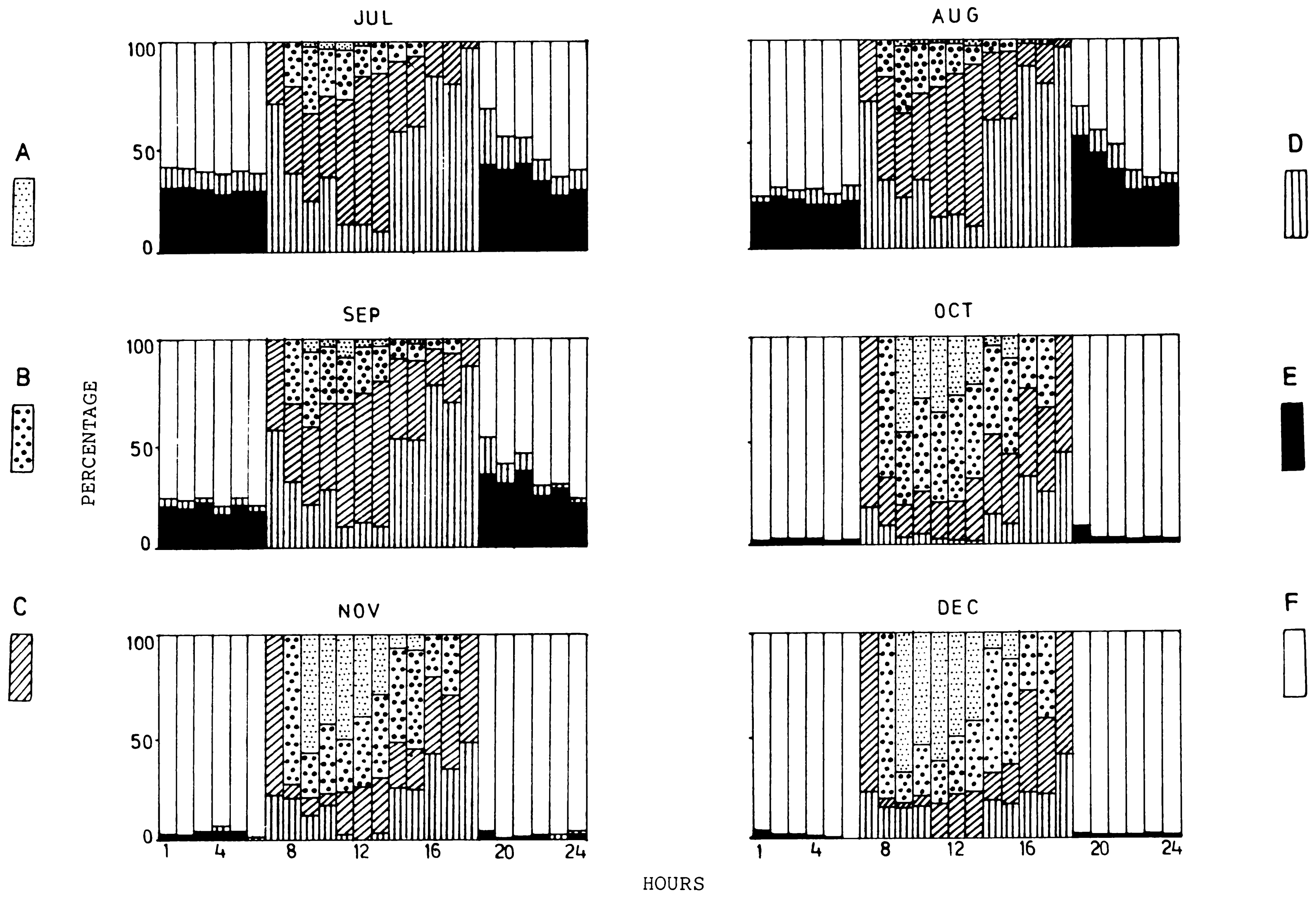


FIG. 6.1(b). DIURNAL VARIATION OF PERCENT FREQUENCY OF PASQUILL'S STABILITY CLASSES

unstable classes are noticed although with variable frequencies. During night-time slightly stable (E class) conditions are in considerable frequency. The case of February is more or less same but for an increase of neutral conditions during day time and slightly stable conditions during night-time. One can see a systematic increase of neutral conditions from January to September, with a consequent decrease of highly unstable conditions during day time. There is a steady increase of slightly stable conditions from January to August. The presence of highly unstable conditions during October to April is mainly due to relatively clear skies which result in direct solar radiation to reach the surface of the earth which according to Pasquill's technique should lead to highly unstable conditions, provided the wind is not that high. The decrease of these unstable conditions from January onwards is because the wind gradually increases and also the sky becomes more and more cloudy month after month, both of which lead to less intense stabilities. The presence of neutral conditions mainly during day time is explained as due to the strong winds and to some extent overcast conditions. During night time the winds are very weak which allow the extreme cases to establish and prevent the so called neutral conditions, which require strong winds and overcast conditions. During the monsoonal months neutral conditions should have been in considerable frequencies even during night-time but it results only in the increase of slightly stable conditions mainly because, although the skies are cloudy, winds are not strong enough to bring the highly stable conditions to neutrality. In general, all classes of unstable conditions are observed in the day time and stable conditions only at night-time.

It is of interest to see how each of these stabilities varies from month to month at a given time. Fig. 6.2 shows the monthly variation of Pasquill's stability classes at 1200 hours. One can see the systematic decrease of highly unstable conditions from January to July followed by an increase thereafter. The moderately unstable conditions although remaining constant till April, there is a systematic decrease from April onwards till August followed by an increase till October and a decrease thereafter. The cases of slightly unstable and neutral conditions are entirely different almost following the reversal in trend compared to that of highly unstable and moderately unstable conditions. In fact, the highly unstable and slightly unstable conditions show the reversal trend very exactly. The systematic increase of neutral conditions till August and the decrease thereafter is a noticeable feature. This time of 1200 hours is chosen for representing this variation mainly because all the four possible categories would appear.

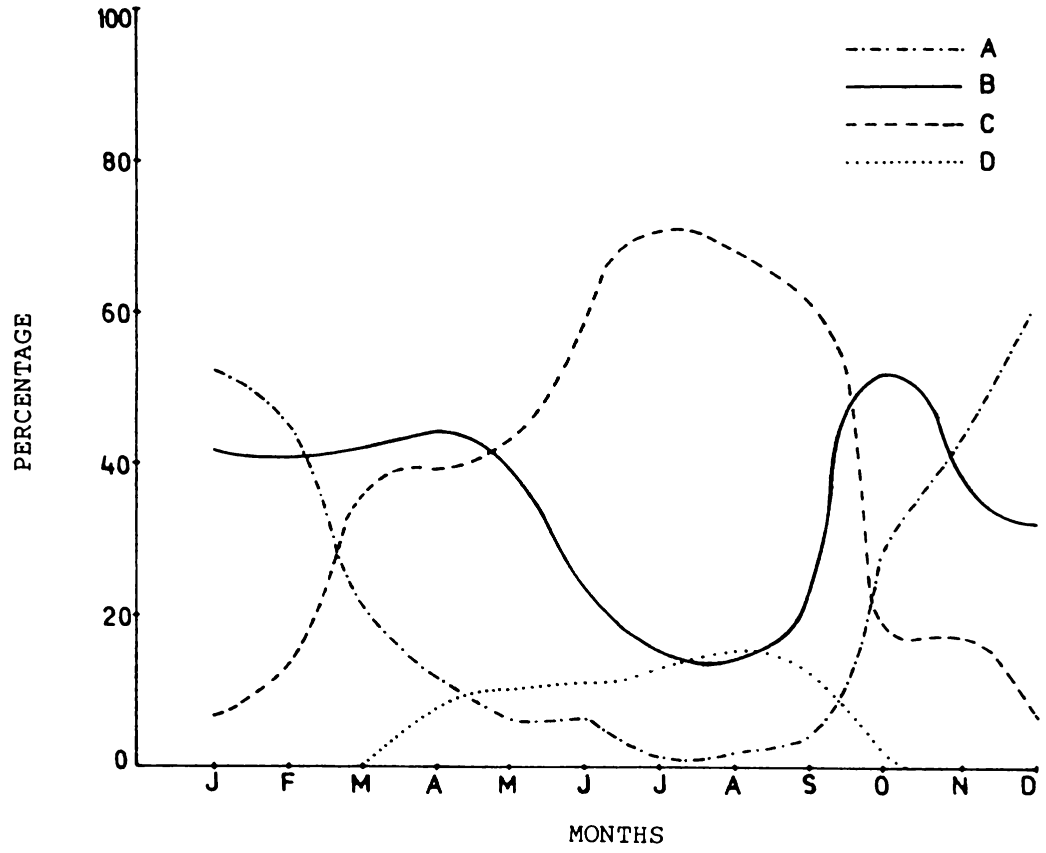


FIG. 6.2. MONTHLY VARIATION OF PERCENT FREQUENCY OF OF PASQUILL'S STABILITY CLASSES AT 1200 HOURS

It should be noted that whatever the circumstances would be according to the present criteria of Pasquill it is impossible to think of any stable conditions during day time and any unstable conditions in night-time. Now the reversal in trend among the possible trend is understandable.

Figs. 6.3(a) and 6.3(b) depict the percent frequency of maximum occurring stability at every hour for all the months. Undoubtedly category F is the maximum during the entire night-time in all the months except July and August, where E class dominates for a few hours in the early night. One can see the dominance of the highly unstable class to be the maximum in December followed by November, January, February, March and October. During the monsoonal months, it is never maximum at any time.

The very high frequency of highly stable conditions during night-time causes concern again. In fact, even during monsoonal months highly stable conditions are dominating during most of the night-time. These highly stable conditions do not allow the pollutants to get dispersed thereby resulting in higher concentrations slightly away from the source. The entire night-time conditions are really gloomy since neither the mixing height and ventilation coefficient nor the atmospheric stability helps in a good dispersal of pollutants. Although wind is included in driving all these parameters, a study of the wind roses separately

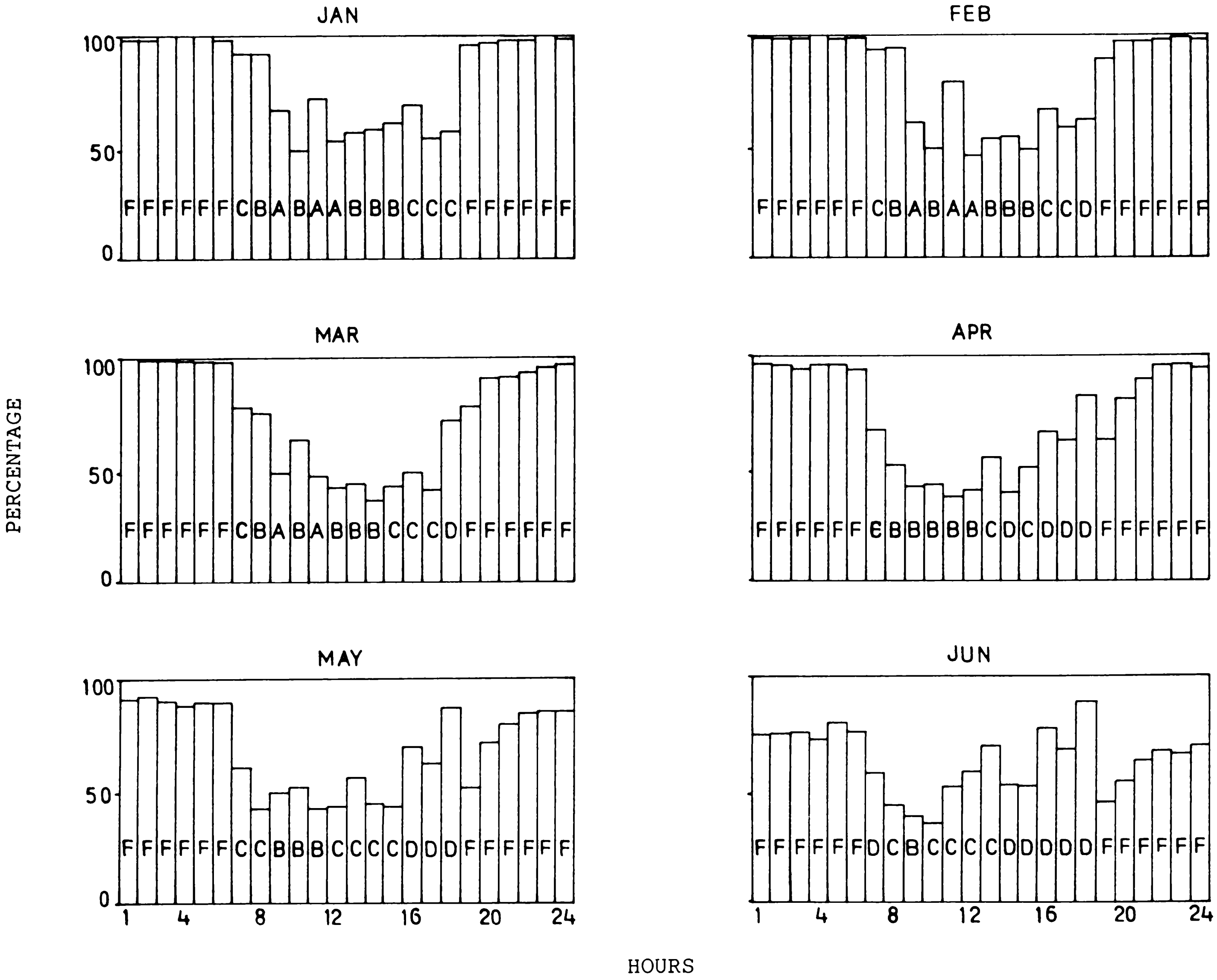


FIG. 6.3(a). DIURNAL VARIATION OF PERCENT FREQUENCY OF MAXIMUM

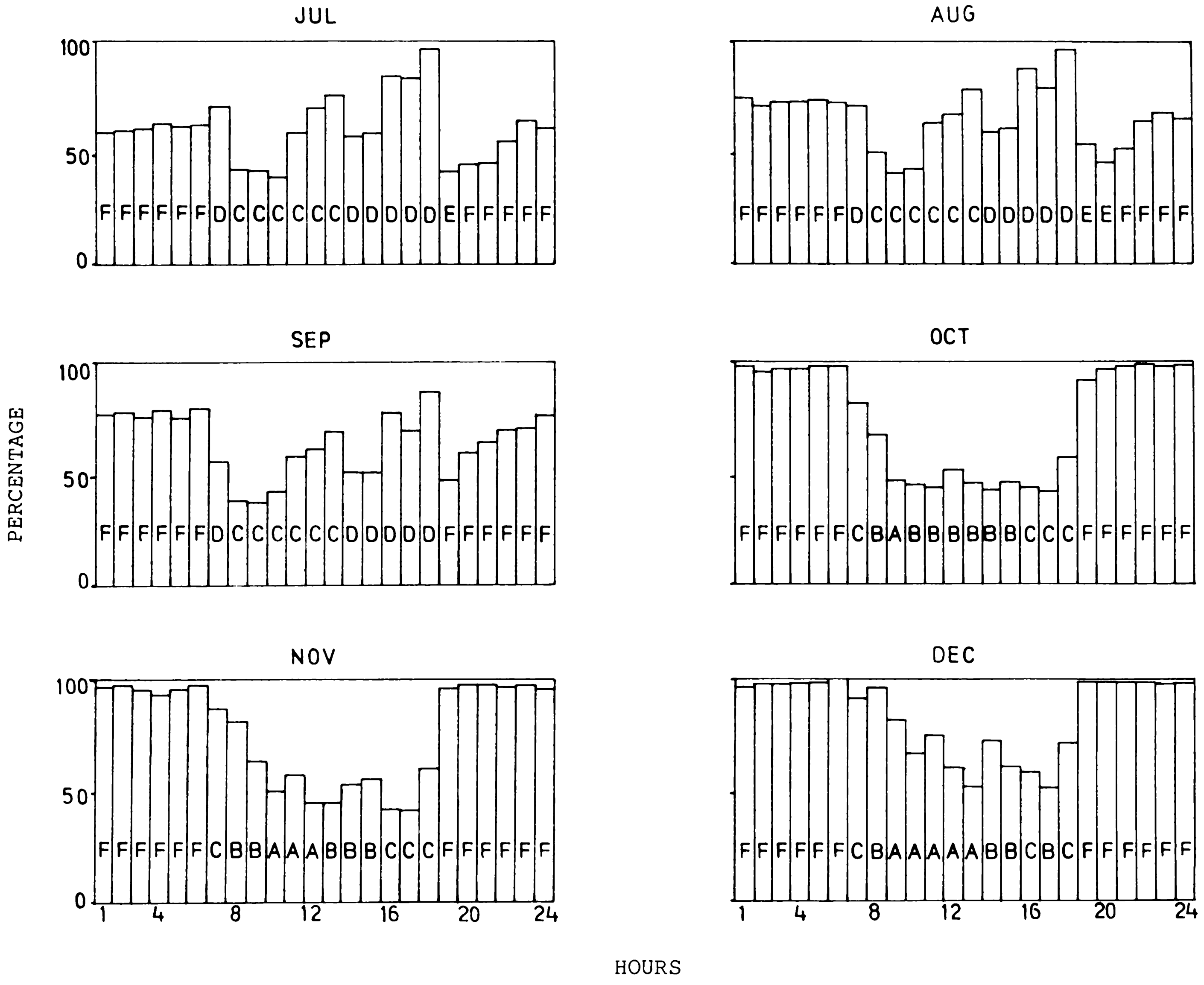


FIG. 6.3(b). DIURNAL VARIATION OF PERCENT FREQUENCY OF MAXIMUM OCCURRING PASQUILL'S STABILITY CLASSES

would make the picture clearer.

6.2 WIND ROSES

The six-hourly wind roses for 0000, 0600, 1200 and 1800 hours are represented in Figs. 6.4(a) to 6.4(f) for all the months.

From October to April, calm conditions dominate (frequency more than 70%) at 0000 and 0600 hours. At 1200 and 1800 hours, the frequency of calm conditions decreases and prevailing wind directions are northwesterlies and westerlies. During these times the wind speed is never greater than 30 km per hour except in April, when westerlies greater than 30 km per hour are some times experienced. In May, the calm conditions are around 50% at 0000 and 0006 hours and the winds are very weak. At 1200 and 1800 hours winds become stronger and northwesterlies prevail. From June to September, calm conditions are less than 30% at 0000 and 0600 hours and wind speeds in the range 21-30 km per hour are noticed. Also, they are generally from the northern sector only. At 1200 and 1800 hours calm conditions are never greater than 5%. Wind speeds greater than 30km per hour are observed in these months.

The night-time winds are very weak in most of the cases except during monsoonal months. The calm frequency is also high during night-time accounting for more than 75% in

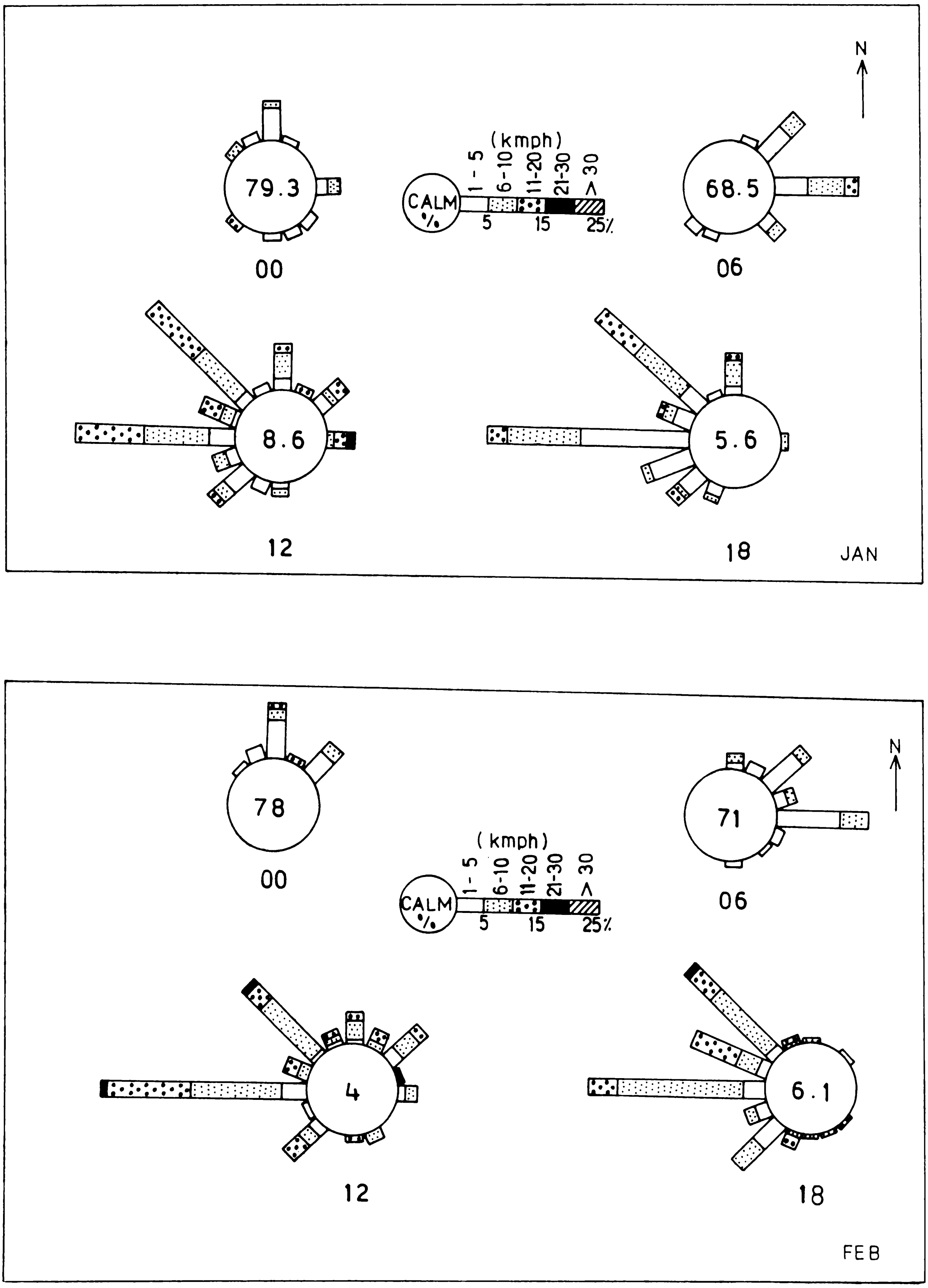
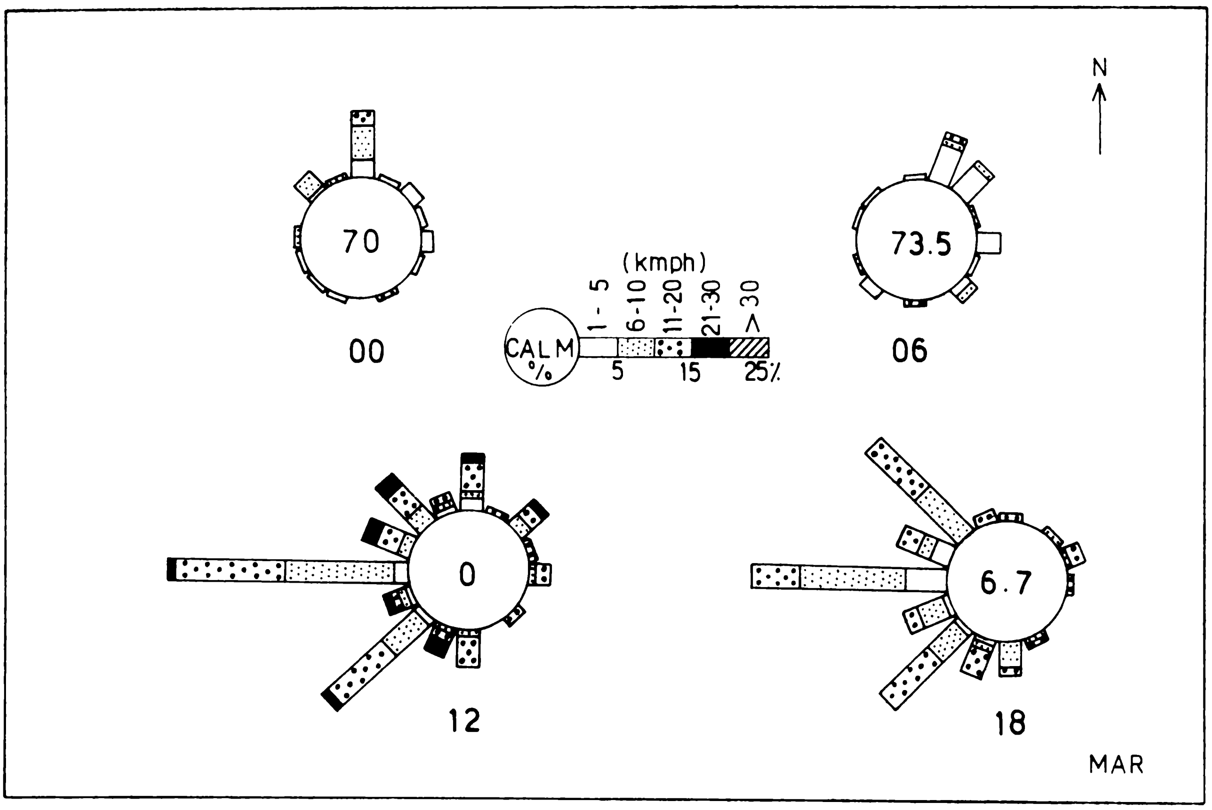


FIG. 6.4(a) WIND ROSES FOR THE MONTHS OF JANUARY AND FEBRUARY



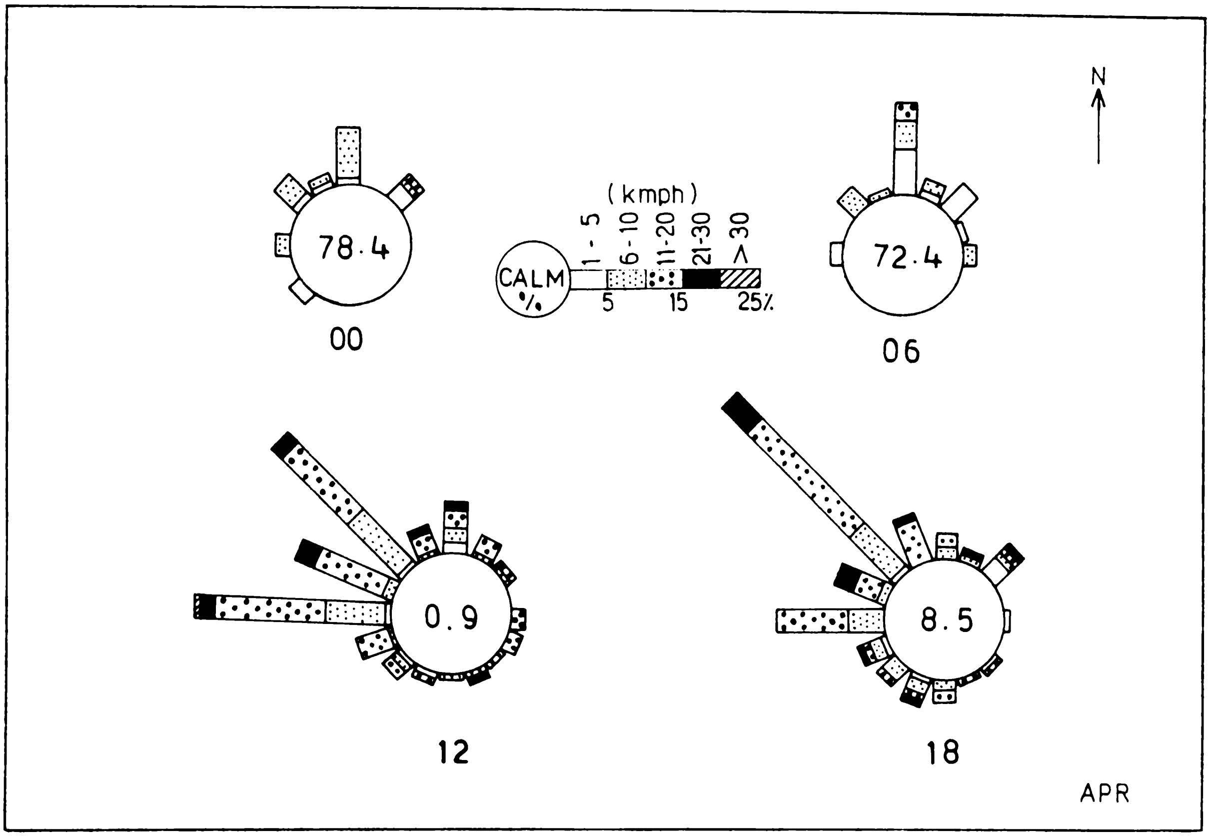


FIG. 6.4(b) WIND ROSES FOR THE MONTHS OF MARCH AND APRIL

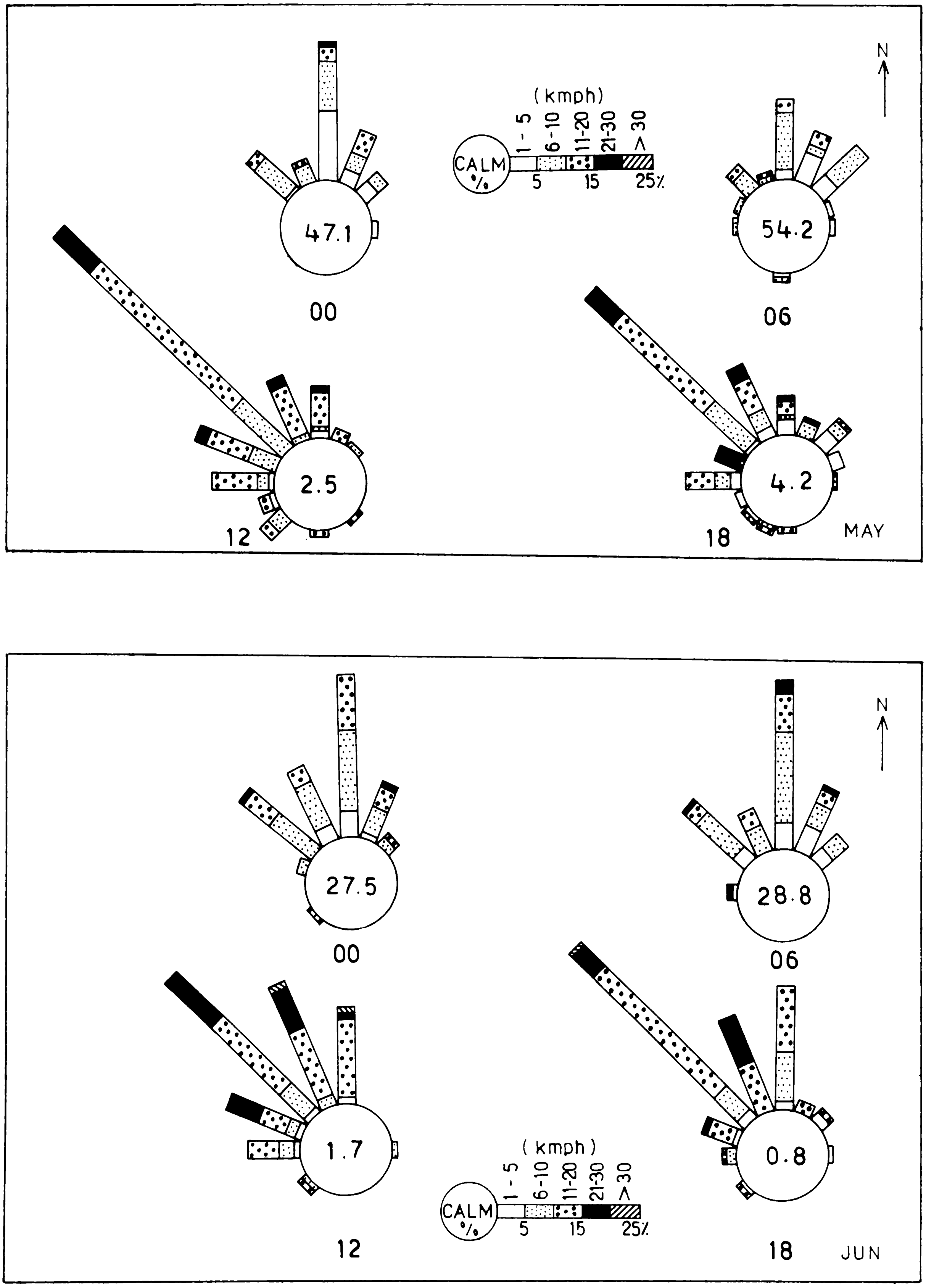


FIG. 6.4(c) WIND ROSES FOR THE MONTHS OF MAY AND JUNE

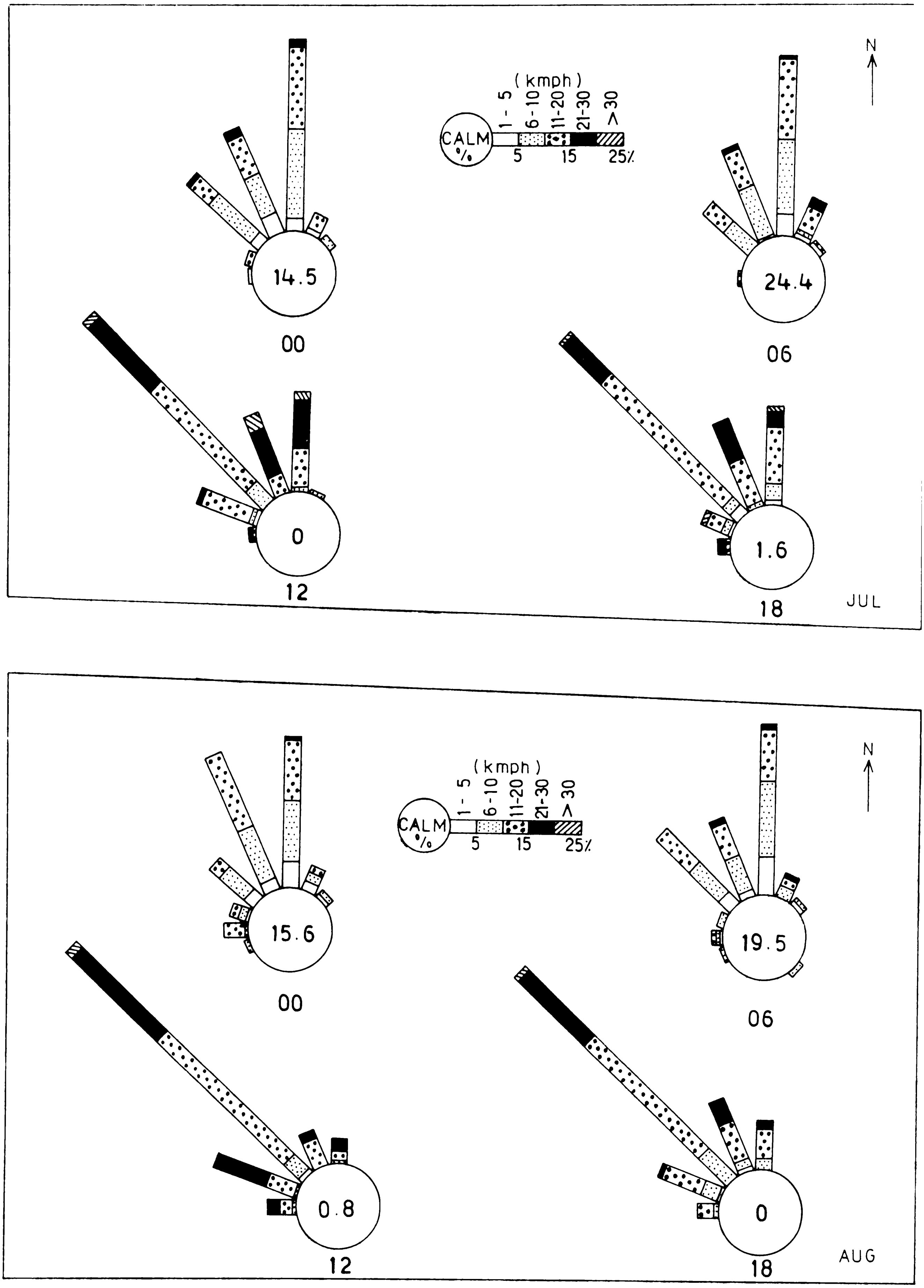
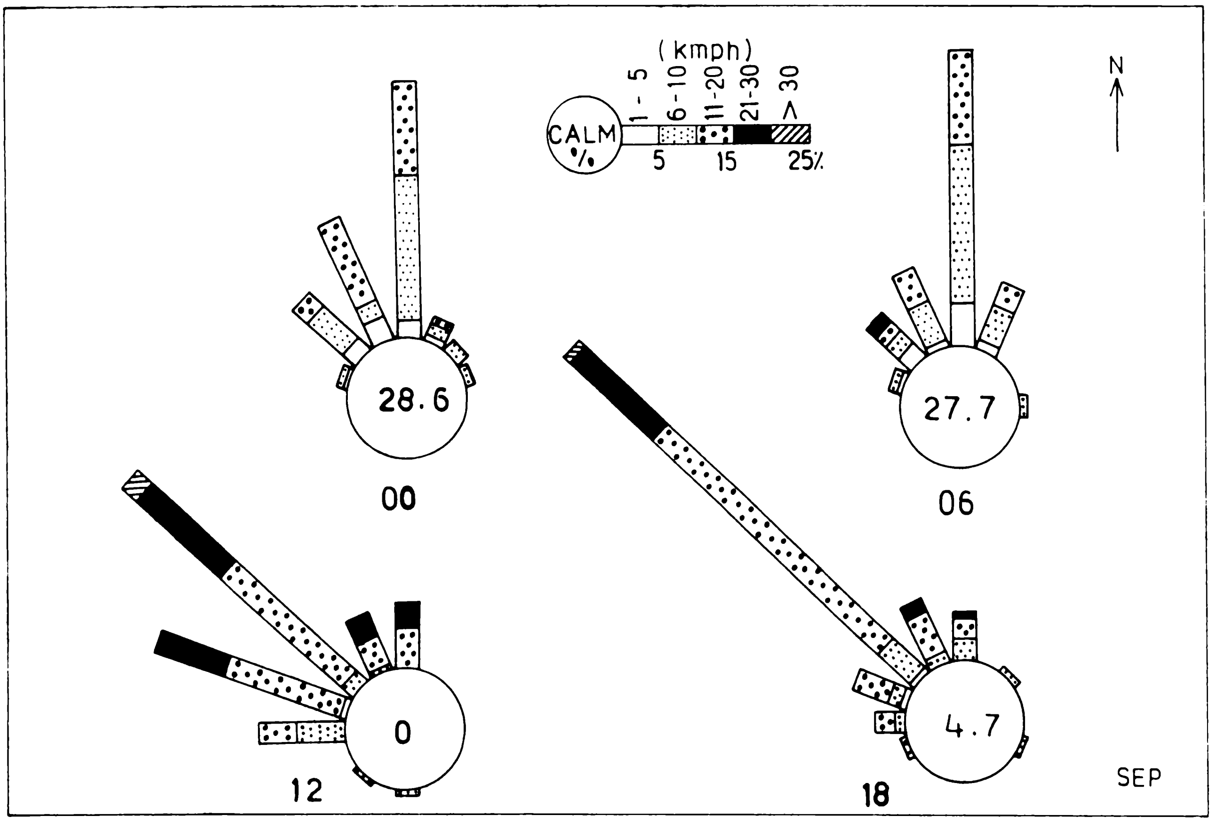


FIG. 6.4(d) WIND ROSES FOR THE MONTHS OF JULY AND AUGUST



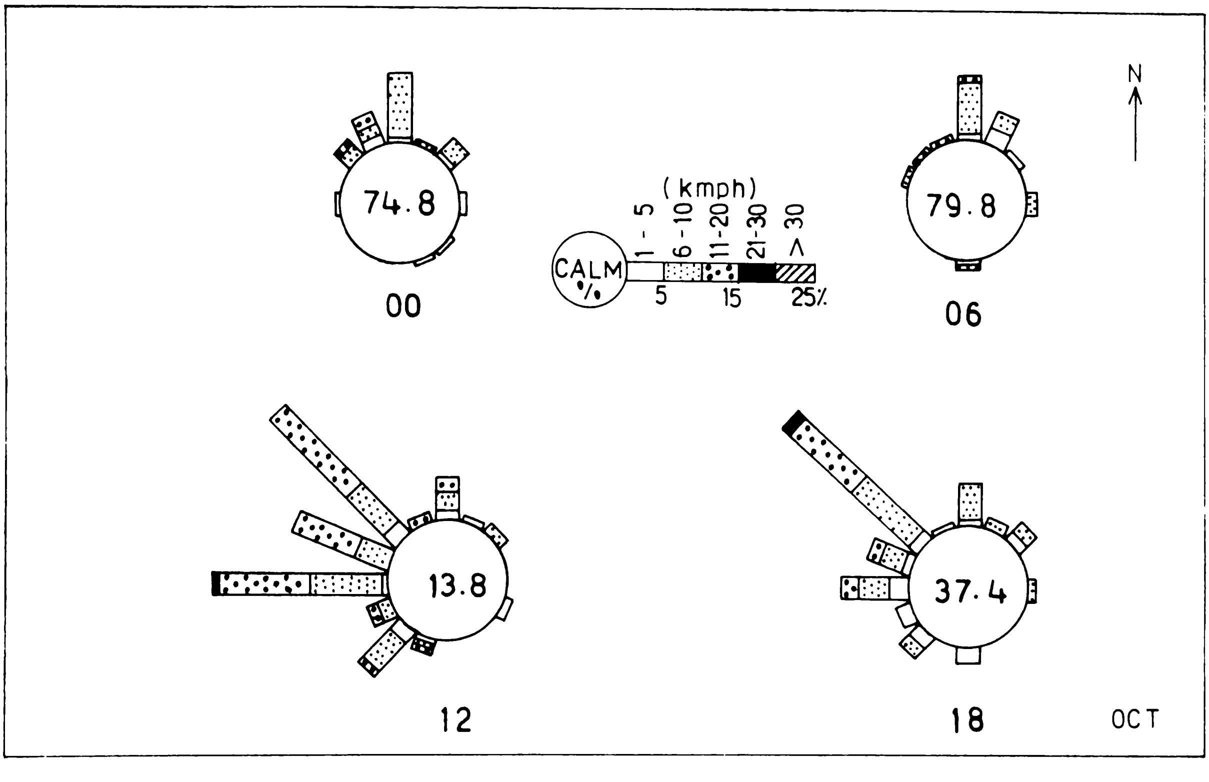


FIG. 6.4(e) WIND ROSES FOR THE MONTHS OF SEPTEMBER AND OCTOBER

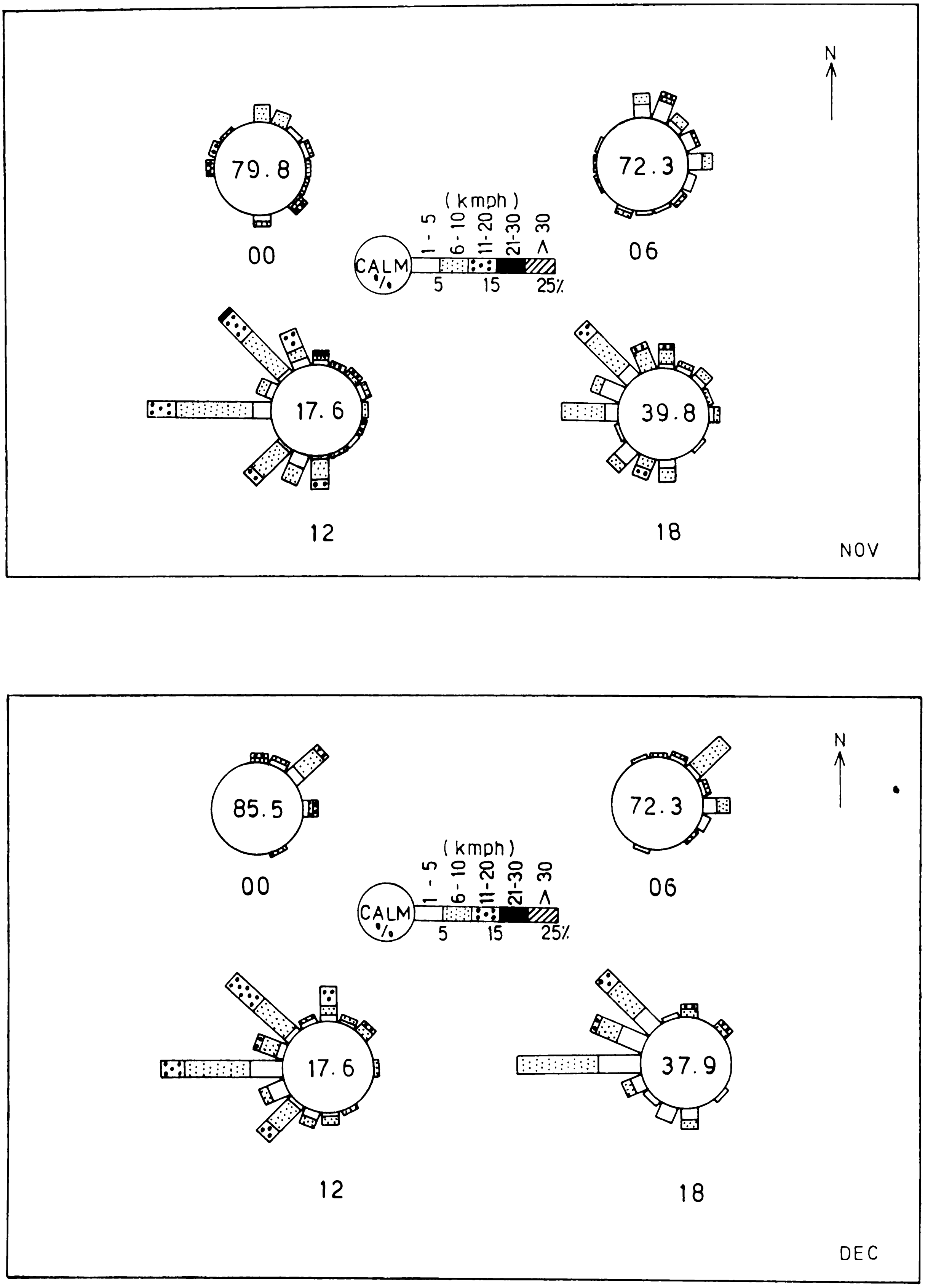


FIG. 6.4(f) WIND ROSES FOR THE MONTHS OF NOVEMBER AND DECEMBER

most of the cases. This is a serious matter which one has to really worry about. Consistently the winds become stronger and stronger till the monsoonal months when they are the strongest. Another interesting feature is that during day time in no month does the wind blow from the eastern sector, while the westerly domination during day time in the non-monsoonal months may be explained to a large extent as due to the sea breeze phenomenon, the strong winds from the northwestern sector in the monsoonal months are due to the southwest monsoon. It is rather intriguing to note that during the southwest monsoon season the winds are mostly from the northwest even during night-time. This may be due to the fact that the monsoonal winds enter the coast as westerlies but on account of the presence of Western Ghats not far away from the city make the surface winds to deflect towards southeast in making the westerlies to become northwesterlies. In other words it is the orgraphic forcing which mainly may be responsible for the dominating wind direction to be northwesterly. The deflecting coriolis force also helps the westerlies to become northwesterlies. As far as the pollutant dispersal is concerned the monsoonal months seem to be more favourable from the point of view of strong winds. At night-time utmost caution must be exercised in view of the extremely high calm frequencies. It is evident that at night-time none of the conditions or parameters discussed so far seem to be favourable for the pollutant dispersal.

6.3 POLLUTION POTENTIAL INDICES

Fig. 6.5 shows the diurnal variation of the pollution pontential indices for all the months. The highest value of pollution pontential index (8) is observed in February at 1400 hours, which means that there would be a good dispersal of pollutants in this month. The maximum variation is seen in August and the minimum in May. During night-time, the index is always 3 in all the months except in July and August, when the value of 4 is also seen. Generally the index is greater than or equal to 6 in the afternoon hours.The systematic increase of the index from early morning hours to around maximum temperature epoch and the decrease thereafter is the consistent feature of the figure although on quite a few occasions the index is constant as for example in the case of night-time. Since this index takes into consideration all the possible parameters including stability this could be considered as a comprehensive index directly revealing the atmospheric abilities to disperse the pollutants. A minimum index of 6 is suggested for a good dispersal of pollutants. However, 6 number as the permissible limit has no experimental sanctity. It should be noted here that the extreme index of 9 does not appear anywhere mainly because of the coastal characteristics. Since this index takes into consideration all the possible

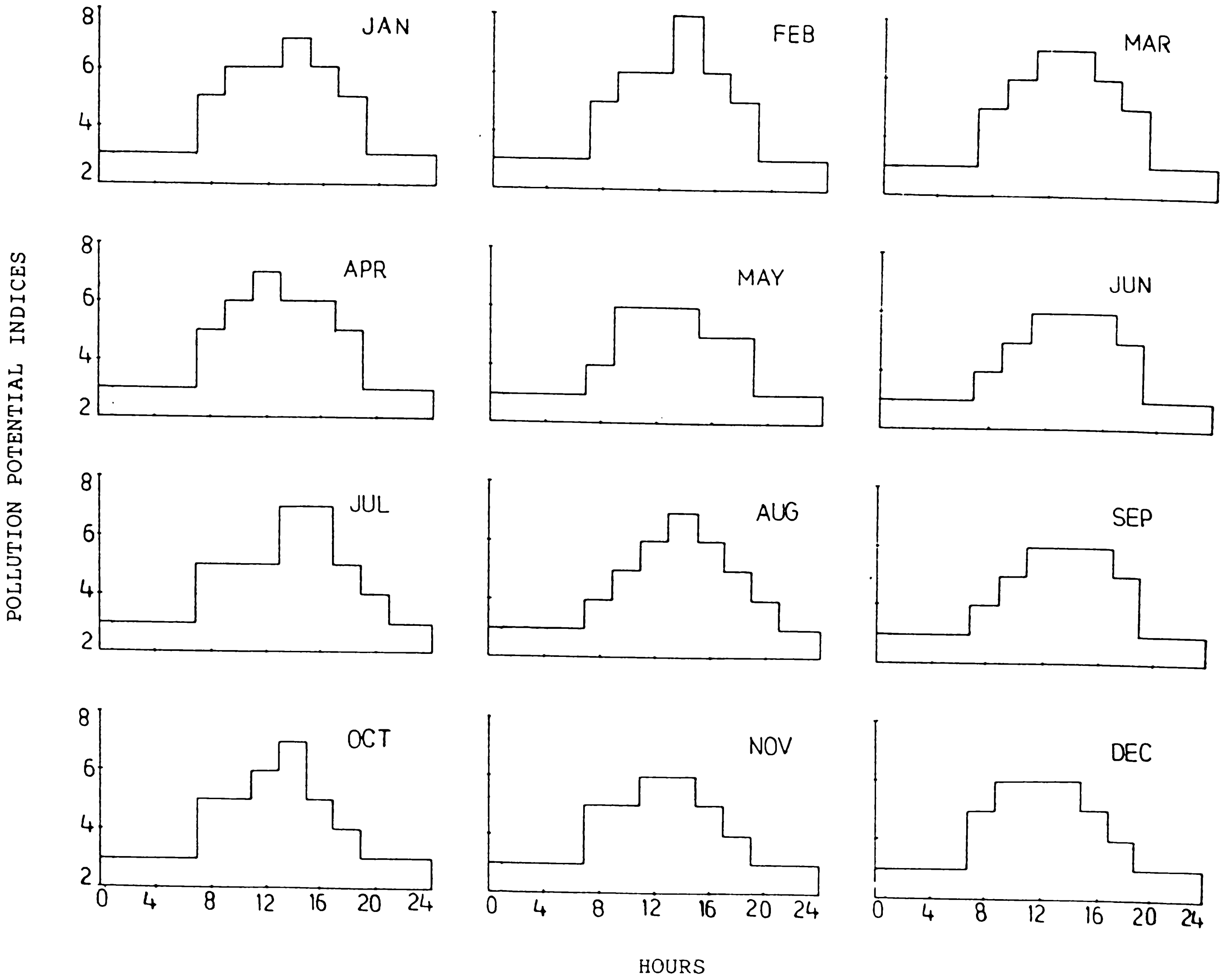


FIG. 6.5. DIURNAL VARIATION OF POLLUTION POTENTIAL INDICES

parameters including stability this could be considered as a comprehensive index directly revealing the atmospheric abilities to disperse the pollutants. The night-time situation is very grim as has been noted in the earlier cases, and as such utmost precautions must be taken to bring down the concentration of pollutants.

CHAPTER VII

WIND FLUCTUATIONS AND THEIR RELATIONSHIPS WITH ATMOSPHERIC STABILITY AND MIXING HEIGHT

In this chapter the diurnal and seasonal variation of wind direction and wind speed fluctuations are studied. Attempts are also made to relate these fluctuation ranges with stability and mixing height in addition to the relation between them, so that if any one of these parameters is known others could be easily obtained.

7.1 WIND DIRECTION FLUCTUATION RANGE ($\sigma_{\theta D}$)

The diurnal variation of $\sigma_{\theta D}$ for the four typical months is presented in Fig. 7.1. The diurnal variation is very striking in all the cases. In January $\sigma_{\theta D}$ increases rather slowly from around midnight till 0900 hours and suddenly shoots up to reach the maximum at 1500 hours followed by a very steep decrease. The average of $\sigma_{\theta D}$ is very high in this month. In April the night-time values are more than their counter parts in January while the maximum is slightly less than that of January, consequently, the range comes down in this month. In this case the values decrease from mid-night till around 0600 hours and starts increasing thereafter unlike in the case of January where it is found to increase from 2200 hours onwards till around 1400 hours. In the case of July, the range of $\sigma_{\theta D}$ has come down considerably with night-time values being the highest compared to any of

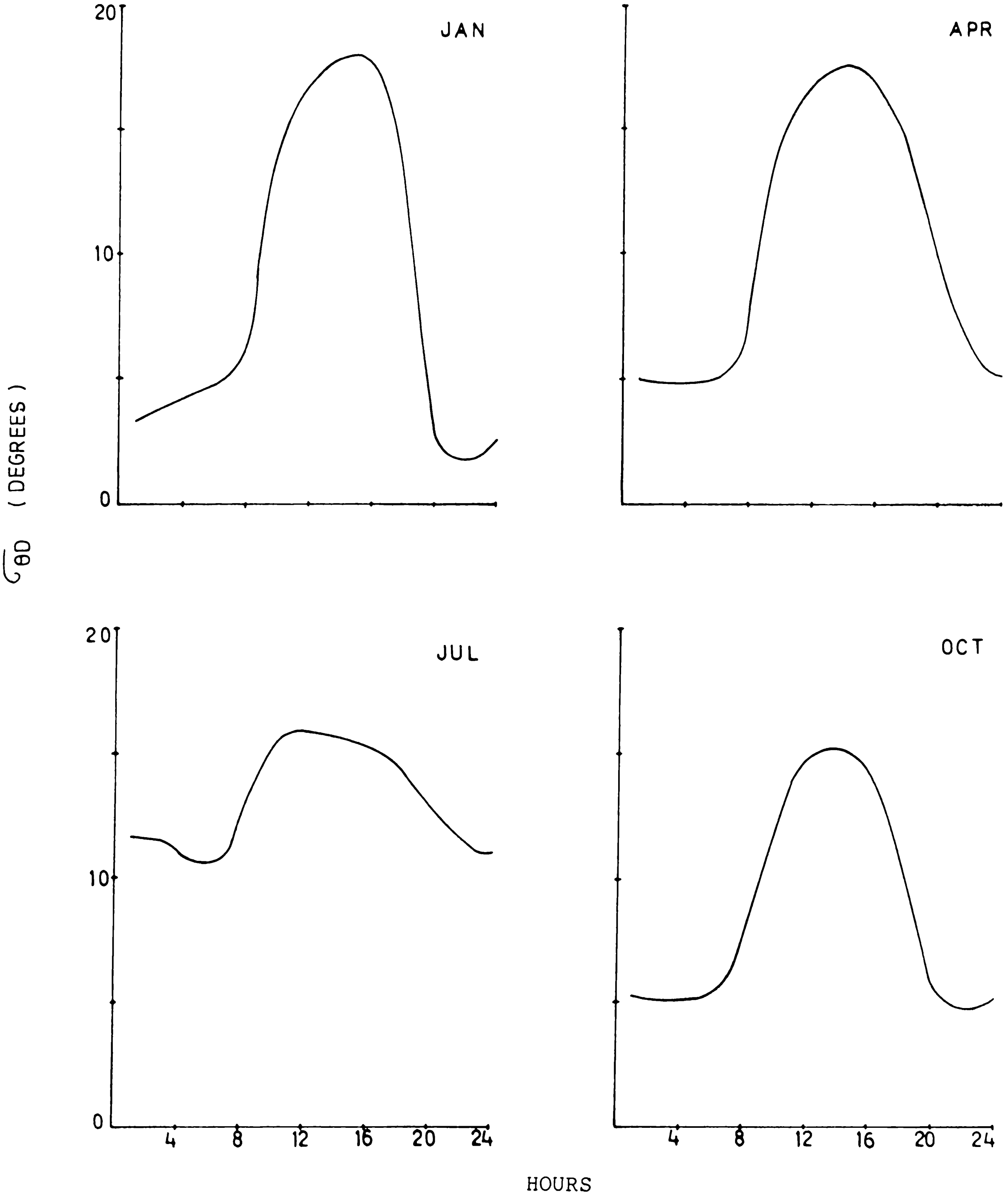


FIG. 7.1. DIURNAL VARIATION OF $\sigma_{\theta D}$

their counterparts. However, the day time values are less than those in January and April. The range of $\sigma_{\theta D}$ is only about 5° compared to around 16° in January. In October although the range of $\sigma_{\theta D}$ has gone up the maximum value is the lowest in this month.

In all these cases it reveals that $\sigma_{\theta D}$ exhibits a good diurnal variation and as such can be taken as a measure of surface turbulence, which also exhibits typical diurnal variation showing low values during night-time and high values during day time. The larger the values of $\sigma_{\theta D}$ the more is the turbulence. From the figure, it is evident that the maximum turbulence is in January rather than in April. This is mainly because although January represents the winter season for most part of the country this is not so in the case of Trivandrum : in fact January is the hottest month among the four considered. However, at night-time considerable cooling leads to lower surface turbulence. April, on the other hand experiences premonsoon thundershowers which lead to slightly lower day temperatures than in January. The low values during day time in July are mainly due to the low temperatures recorded in this month. However, night-time is different where the high values are observed, because of the strong southwest monsoon wind. If the turbulence is divided into mechanical and thermal turbulence, the night-time case in July can be attributed to mechanical turbulence.

7.2 WIND SPEED FLUCTUATION RANGE ($\sigma_{\theta S}$)

Fig 7.2 depicts the diurnal variation of $\sigma_{\theta S}$ for the four months, January, April, July and October. The diurnal variation is rather low in January. During most of the night time the value is invariant in this month. The maximum variation is noticed in April. The values are extremely high in July. In fact the minimum in July is more than the maximum in January, while it is comparable to the maximum in October. The relatively higher values in April can be explained as due to thermal turbulence while the highest values in July can be attributed to mechanical turbulence. The extremely high values in July do cause some doubts regarding the $\sigma_{\theta S}$ to be taken as a measure of surface turbulence. The more the wind speeds, the more are the fluctuations. This is precisely what happens in the monsoonal months where the strongest winds during day time and night-time lead to higher values of $\sigma_{\theta S}$.

The diurnal variation of $\sigma_{\theta D}$ varies from that of $\sigma_{\theta S}$ in so far as its seasonal variation is concerned. This poses an important question as to which of these could be taken as a measure of surface turbulence, the clear diurnal variation of both the parameters notwithstanding. $\sigma_{\theta S}$ shows unusually high turbulence in July while $\sigma_{\theta D}$ shows reasonably high values. $\sigma_{\theta S}$ shows relatively low values in this month. This leads one to conclude that $\sigma_{\theta D}$ should be taken as a measure

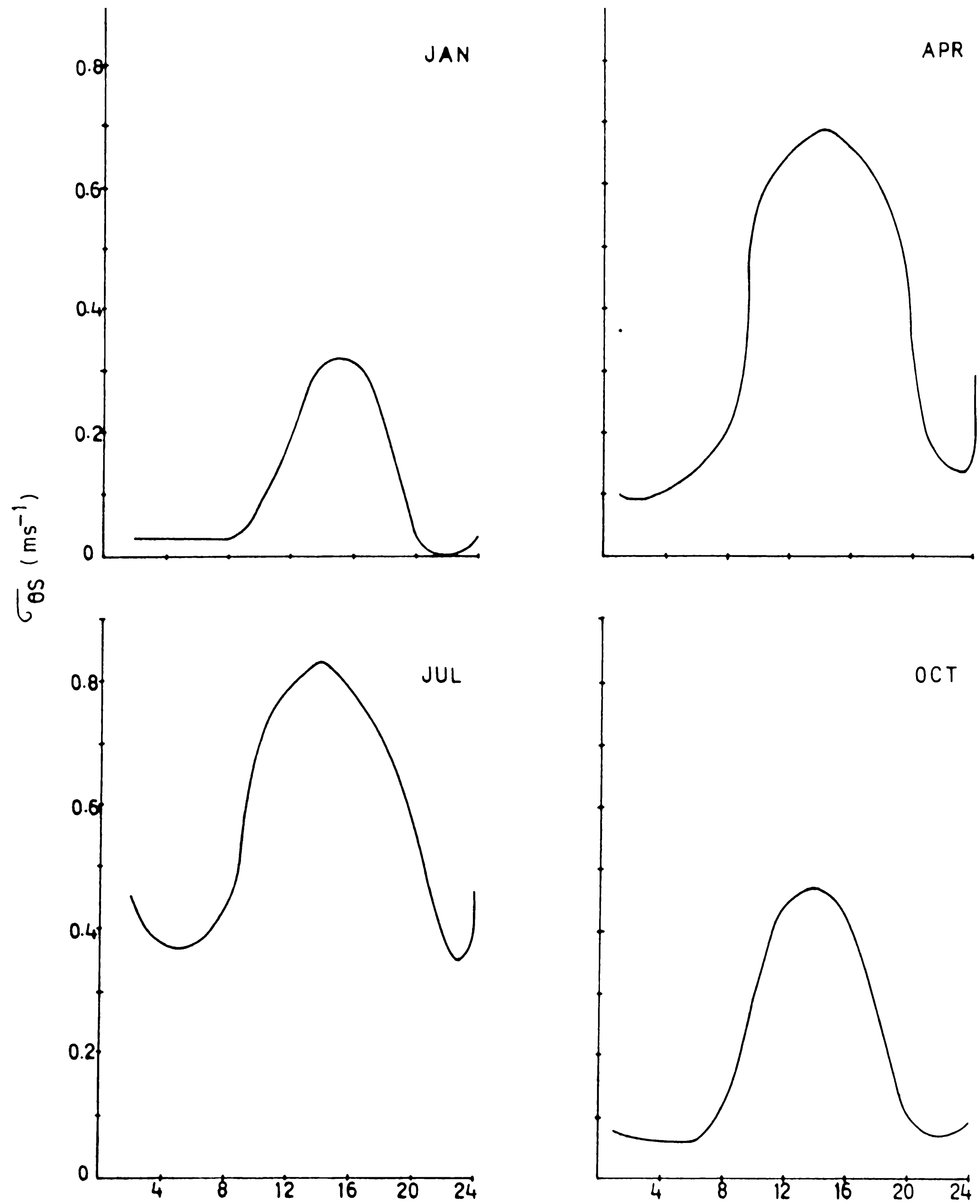


FIG. 7.2. DIURNAL VARIATION OF $\sigma_{\overline{\theta S}}$

of turbulence. However, the studies of the interrelationships may throw further light into this aspect.

7.3 INTERRELATIONSHIPS AMONG PASQUILL'S STABILITY, $\sigma_{\theta D}$ AND $\sigma_{\theta S}$

The mean values of $\sigma_{\theta D}$ and $\sigma_{\theta S}$ are obtained for each of the Pasquill's stability classes for the four typical months. Linear regression equations are developed for $\sigma_{\theta D}$ and $\sigma_{\theta S}$, $\sigma_{\theta D}$ and mixing height and $\sigma_{\theta S}$ and mixing height.

7.3.1 Stability vs $\sigma_{\theta D}$

Tables 7.1 to 7.4 show the representative statistical parameters for each of the Pasquill's stability categories,

Table 7.1

Statistical parameters of $\sigma_{\theta D}$

in different stability classes for January

	MEAN	MEDIAN	MODE	SD	MD	CV
A	13.38	14.1	17.5	9.30	8.03	69.5
B	15.67	19.1	20.0	9.58	8.45	61.1
C	15.21	16.6	11.6	8.69	7.47	57.1
D	16.96	17.5	17.5	5.42	3.86	31.9
E	7.40	9.1	12.5	5.10	4.62	68.9
F	3.88	2.5	5.0	4.52	3.80	116.5

Table 7.2

Statistical parameters of $\sigma_{\theta D}$ in different stability classes for April

	MEAN	MEDIAN	MODE	SD	MD	CV
A	12.42	14.1	11.6	7.01	5.73	56.4
B	12.33	12.5	15.0	6.66	5.28	54.0
C	12.82	13.3	10.0	6.55	5.23	51.1
D	14.70	15.0	16.6	5.70	4.50	38.8
E	12.17	12.5	12.5	4.27	3.28	35.1
F	5.54	5.8	6.6	4.81	4.03	86.8

Table 7.3

Statistical parameters of $\sigma_{\theta D}$ in different stability classes for July

	MEAN	MEDIAN	MODE	SD	MD	CV
A	13.13	13.3	12.5	5.07	3.35	38.6
B	13.33	13.3	15.8	3.72	2.96	27.9
C	14.24	15.0	15.0	4.00	3.36	28.1
D	15.23	15.8	15.8	3.91	3.09	25.7
E	12.81	13.3	14.1	2.86	2.26	22.3
F	10.2	10.0	9.1	3.43	2.55	33.6

for the months of January, April, July and October respectively. There is no systematic variation of the mean $\sigma_{\theta D}$ values for any stability category from A to F. Neither the median nor the modal values show any reasonable relationship. The coefficient of variation is generally very high in all the cases. Since all the important statistical parameters of $\sigma_{\theta D}$ for the various stability categories are inconsistent in almost all the cases, they are not useful in distinguishing stable and unstable conditions.

Table 7.4

Statistical parameters of $\sigma_{\theta D}$

in different stability classes for October

	MEAN	MEDIAN	MODE	SD	MD	CV
A	10.4	11.6	14.0	7.6	6.52	73.0
B	12.9	13.3	13.3	6.8	5.4	52.5
C	11.4	11.6	10.0	5.9	4.7	52.1
D	12.0	10.8	10.0	5.3	4.2	44.4
E	8.9	9.1	8.3	2.9	2.0	32.3
F	5.2	5.0	7.5	4.9	4.2	94.0

7.3.2 Stability vs $\sigma_{\theta S}$

The same statistical parameters are obtained for each of the Pasquill's stability classes and are presented in

Table 7.5

Statistical parameters of $\sigma_{\theta S}$

in different stability classes for January

	MEAN	MEDIAN	MODE	SD	MD	CV
A	0.10	0.08	0.06	0.10	0.08	100.1
B	0.20	0.23	0.23	0.14	0.12	68.9
C	0.22	0.23	0.32	0.16	0.13	71.9
D	0.25	0.26	0.45	0.11	0.09	41.7
E	0.15	0.14	0.23	0.07	0.06	43.9
F	0.03	0.02	0.02	0.05	0.04	146.4

Table 7.6

Statistical parameters of $\sigma_{\theta S}$

in different stability classes for April

	MEAN	MEDIAN	MODE	SD	MD	CV
A	0.30	0.26	0.06	0.25	0.21	83.7
B	0.50	0.49	0.49	0.59	0.28	112.5
C	0.54	0.60	0.77	0.31	0.26	57.3
D	0.65	0.66	0.69	0.26	0.19	40.6
E	0.52	0.51	0.57	0.21	0.16	41.1
F	0.17	0.09	0.06	0.26	0.17	150.73

Table 7.7

Statistical parameters of $\sigma_{\theta S}$
in different stability classes for July

	MEAN	MEDIAN	MODE	SD	MD	CV
A	0.37	0.31	0.29	0.36	0.31	95.6
B	0.56	0.60	0.51	0.29	0.24	52.2
C	0.68	0.69	0.69	0.31	0.23	45.4
D	0.78	0.74	0.80	0.34	0.26	44.3
E	0.51	0.49	0.49	0.27	0.21	53.7
F	0.29	0.23	0.09	0.25	0.19	85.6

Table 7.8

Statistical parameters of $\sigma_{\theta S}$
in different stability classes for October

	MEAN	MEDIAN	MODE	SD	MD	CV
A	0.19	0.11	0.03	0.20	0.16	105.8
B	0.35	0.34	0.37	0.26	0.22	73.5
C	0.33	0.31	0.34	0.27	0.23	81.5
D	0.39	0.34	0.26	0.28	0.23	70.3
E	0.43	0.51	0.60	0.26	0.23	61.0
F	0.07	0.00	0.03	0.13	0.09	175.9

tables 7.5 to 7.8. Here again, the ralationship is inconsistent and random and hence not useful. A similar study of the relationship between Pasquill's stability and mixing height has also been inconclusive. These results are presented here so that this would act as a guideline for not taking up these rigorous exercises in future.

7.3.3 $\sigma_{\theta S}$ vs mixing height

The linear regression equations 7.1 to 7.4 are developed to compute mixing height from $\sigma_{\theta S}$ for the months of January, April, July and October respectively.

$$MH = 3380\,\sigma_{\theta S} + 213 \qquad (7.1)$$

$$MH = 1688\,\sigma_{\theta S} - 93 \qquad (7.2)$$

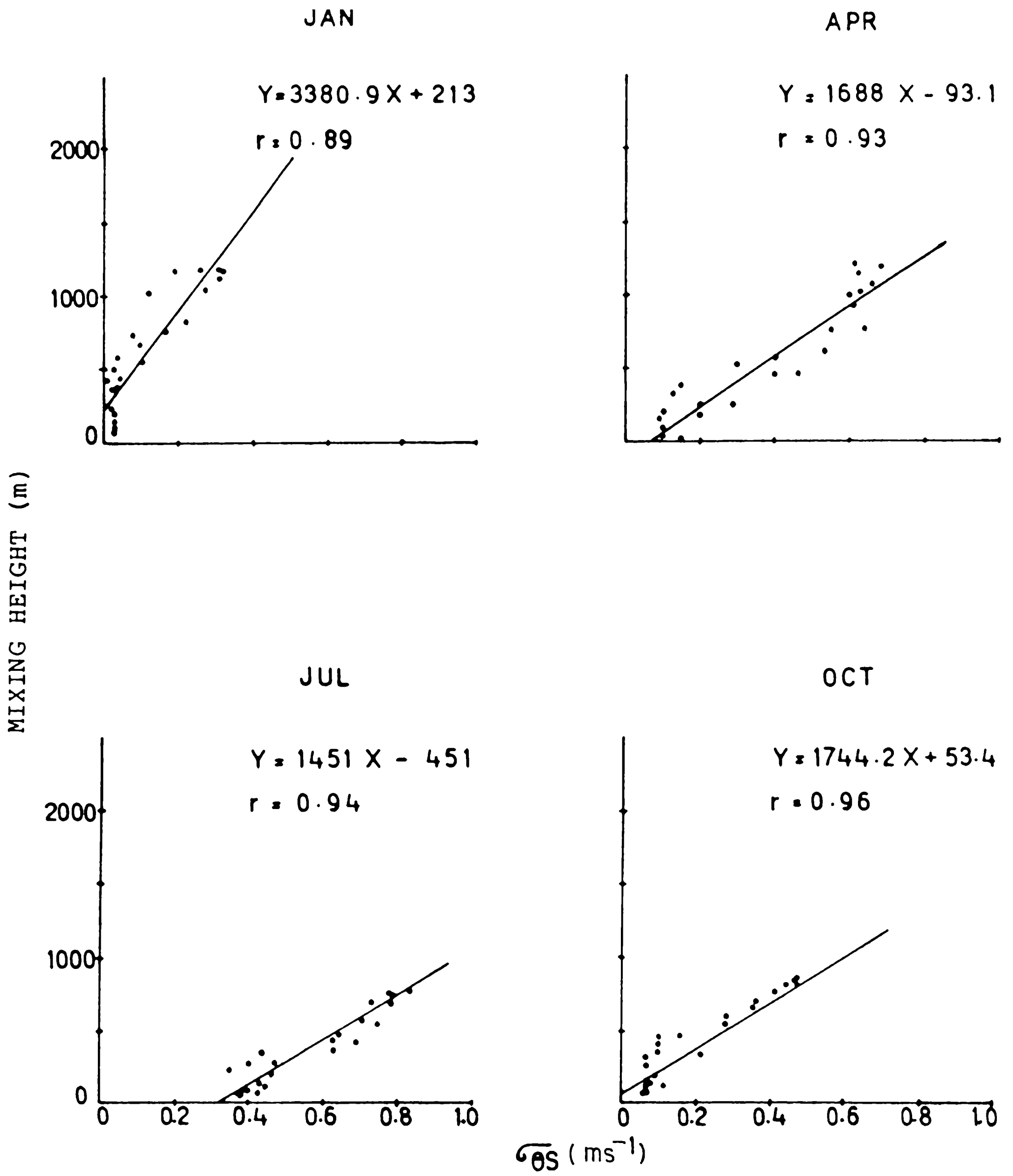
$$MH = 1451\,\sigma_{\theta S} - 451 \qquad (7.3)$$

$$MH = 1744\,\sigma_{\theta S} + 53 \qquad (7.4)$$

The correlation coefficients between mixing height and $\sigma_{\theta S}$ are extremely high. From the scatter diagram (Fig. 7.3) it appears that mixing height can be determined with fair degree of accuracy from $\sigma_{\theta S}$ and it is found that this relationship is statistically significant at the 1% level.

7.3.4 $\sigma_{\theta D}$ vs mixing height

The regression equations 7.5 to 7.8 developed for


JAN

APR

JUL

OCT

FIG. 7.3. SCATTER DIAGRAM BETWEEN MIXING HEIGHT AND $\sigma_{\theta S}$

computing mixing height from $\sigma_{\theta D}$ are given hereunder for the months January, April, July and October respectively.

$$MH = 63.8\ \sigma_{\theta D} + 33.9 \qquad (7.5)$$

$$MH = 79\ \sigma_{\theta D} - 265 \qquad (7.6)$$

$$MH = 128.4\ \sigma_{\theta D} - 1315 \qquad (7.7)$$

$$MH = 65\ \sigma_{\theta D} - 160.3 \qquad (7.8)$$

In this case also high correlations are observed that are statistically significant at 1% level. Even the scatter diagram (Fig.7.4) shows a good linear relation between these two. Except in January, the other equations show negative constants which means that there would always be $\sigma_{\theta D}$ even if mixing height is zero. It is already seen that on many occasions the mixing is zero in July and the minimum value of $\sigma_{\theta D}$ is above 10°. Hence it is not inconsistent to get the negative constants in the equations. Since the scatter is good and the correlations are very high mixing height can be obtained from $\sigma_{\theta D}$. Further, the variations in $\sigma_{\theta D}$ are larger compared to that of $\sigma_{\theta S}$ and as such the mixing height obtained from $\sigma_{\theta D}$ are likely to be more accurate. However, it is individuals's choice to choose any one of these parameters since both of these have extremely high correlations, with mixing height.

7.3.5 $\sigma_{\theta S}$ vs $\sigma_{\theta D}$

It is logical interest to see the relation between

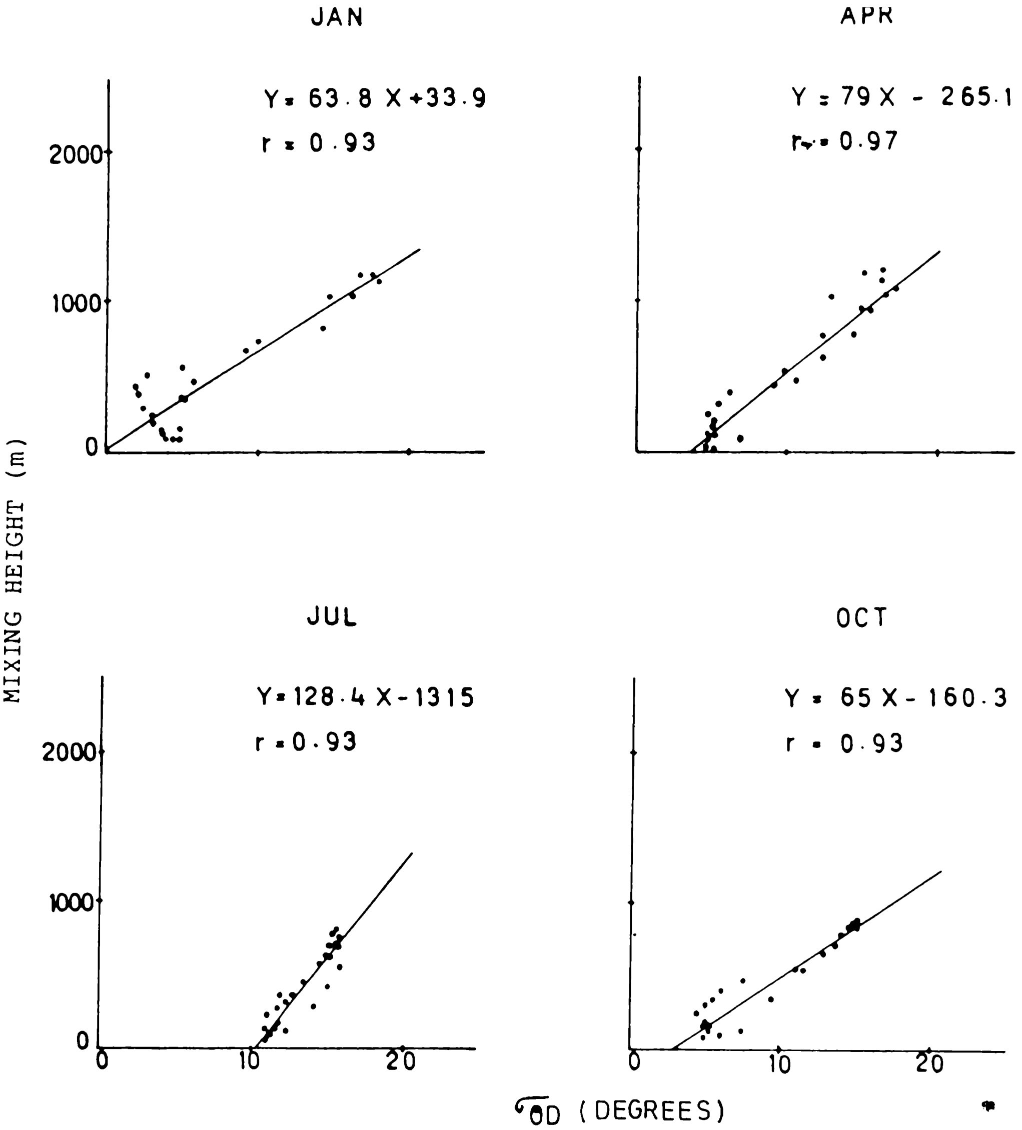


FIG. 7.4. SCATTER DIAGRAM BETWEEN MIXING HEIGHT AND $\sigma_{\theta D}$

$\sigma_{\theta D}$ and $\sigma_{\theta S}$. The regression equations developed are given below.

$$\sigma_{\theta D} = 52.5\,\sigma_{\theta S} + 2.86 \tag{7.9}$$

$$\sigma_{\theta D} = 21.6\,\sigma_{\theta S} + 2.28 \tag{7.10}$$

$$\sigma_{\theta D} = 10.96\,\sigma_{\theta S} + 6.92 \tag{7.11}$$

$$\sigma_{\theta D} = 25.9\,\sigma_{\theta S} + 3.48 \tag{7.12}$$

The correlations are very high and the level of significance is 1% once again showing that these two are very intimately connected. The corresponding scatter diagram is presented in Fig. 7.5. The interesting feature of this figure is the presence of $\sigma_{\theta D}$ values even when $\sigma_{\theta S}$ is zero. Zero values of $\sigma_{\theta S}$ do not always mean no wind but the speed may remain uniform in which case the directions can vary. This is precisely what is reflected in the diagram. However, as indicated earlier $\sigma_{\theta D}$ would be more appropriate for computing mixing height and also being taken as a measure of surface turbulence.

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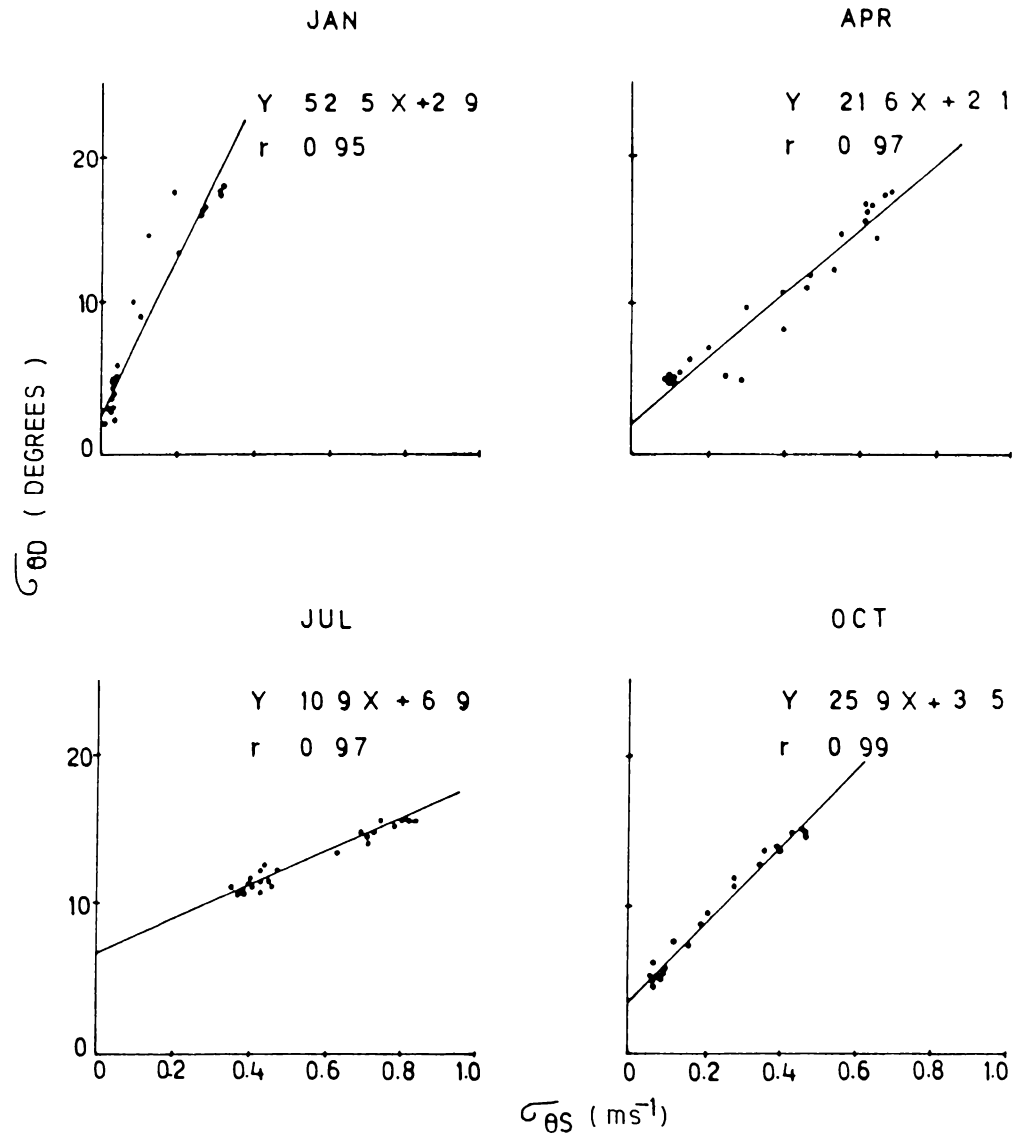

FIG. 7.5. SCATTER DIAGRAM BETWEEN $\sigma_{\theta D}$ AND $\sigma_{\theta S}$

CHAPTER VIII

SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS BY MEANS OF GAUSSIAN PLUME MODEL

This chapter presents the spatial distribution of sulphur dioxide (SO_2) concentrations by means of multiple stack Gaussian plume model, by taking the actual emission inventory into consideration. The various possibilities of mitigating the pollutant levels are also discussed in addition to suggesting the optimum locations for new industries. A map of the city and neighbourhood showing various locations are presented in Fig. 8.1.

8.1 SPATIAL DISTRIBUTION OF SO_2 CONCENTRATION

The total emission of SO_2 from all the three sources is a little less than $10 gs^{-1}$. The isolines of the ground level concentratons of SO_2 are depicted in Figs. 8.2(a) to 8.2(l) for the months from January to December respectively.

January

The maximum sulphur dioxide concentrations ($12 \mu gm^{-3}$) is observed over the Vettukadu area of the northeastern sector of the city. The values decrease away from the region in all directions over the city. Values less than $2 \mu gm^{-3}$ are observed over the southern, northeastern and northern portions of the city.

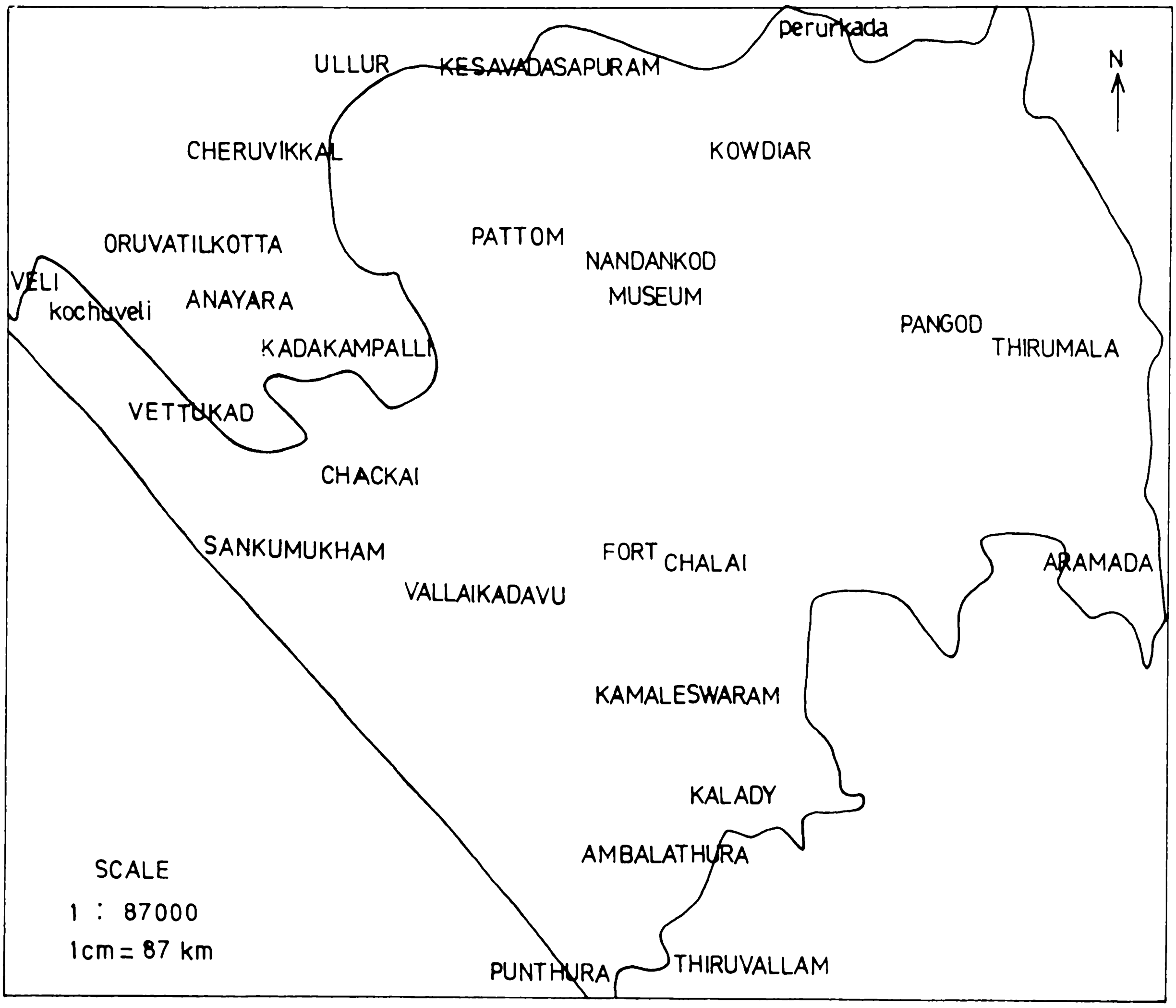

FIG. 8.1. MAP OF TRIVANDRUM CITY

FIG. 8.2(a). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR JANUARY ($\mu g m^{-3}$)

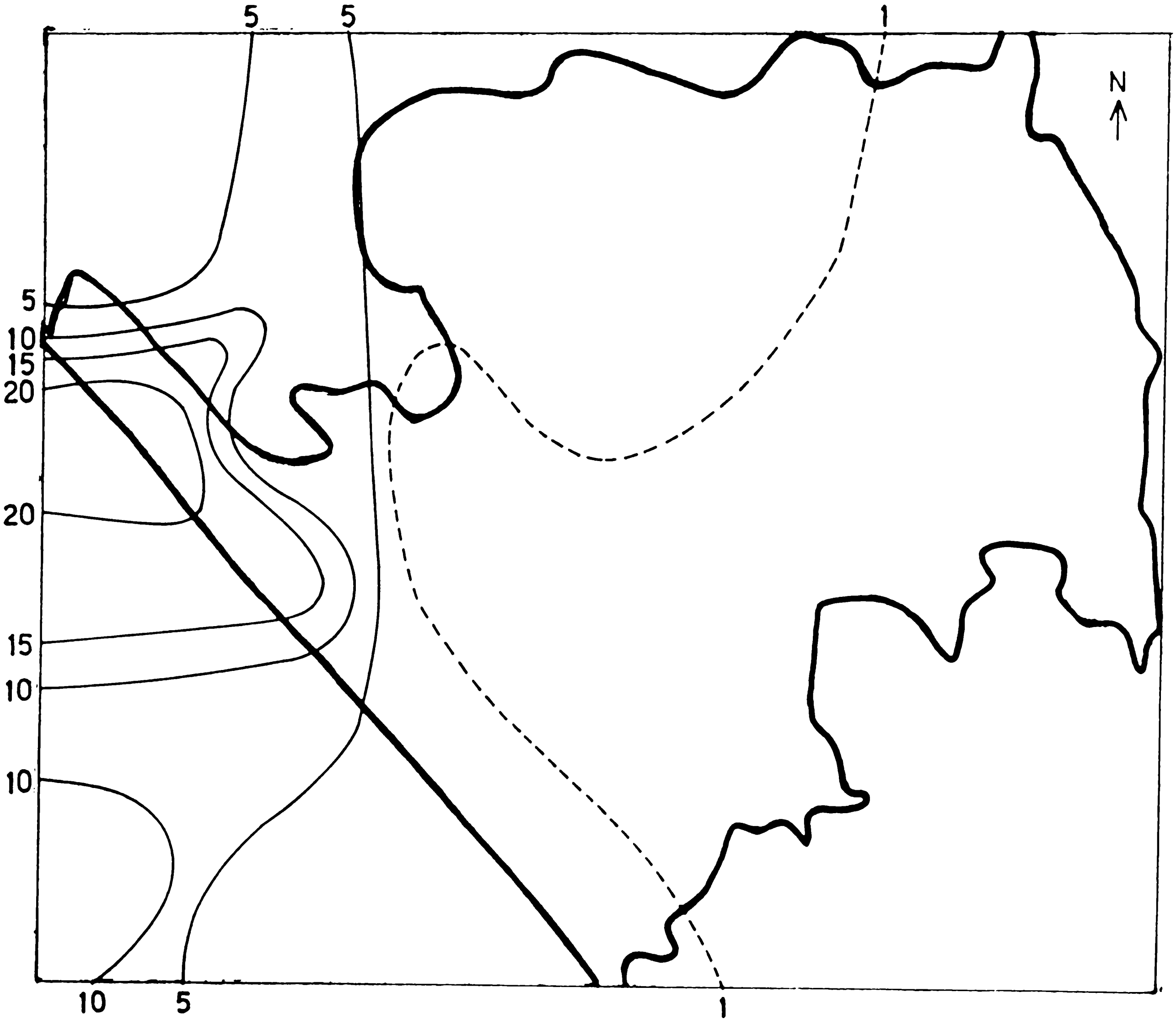

FIG. 8.2(b). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR FEBRUARY (μgm^{-3})

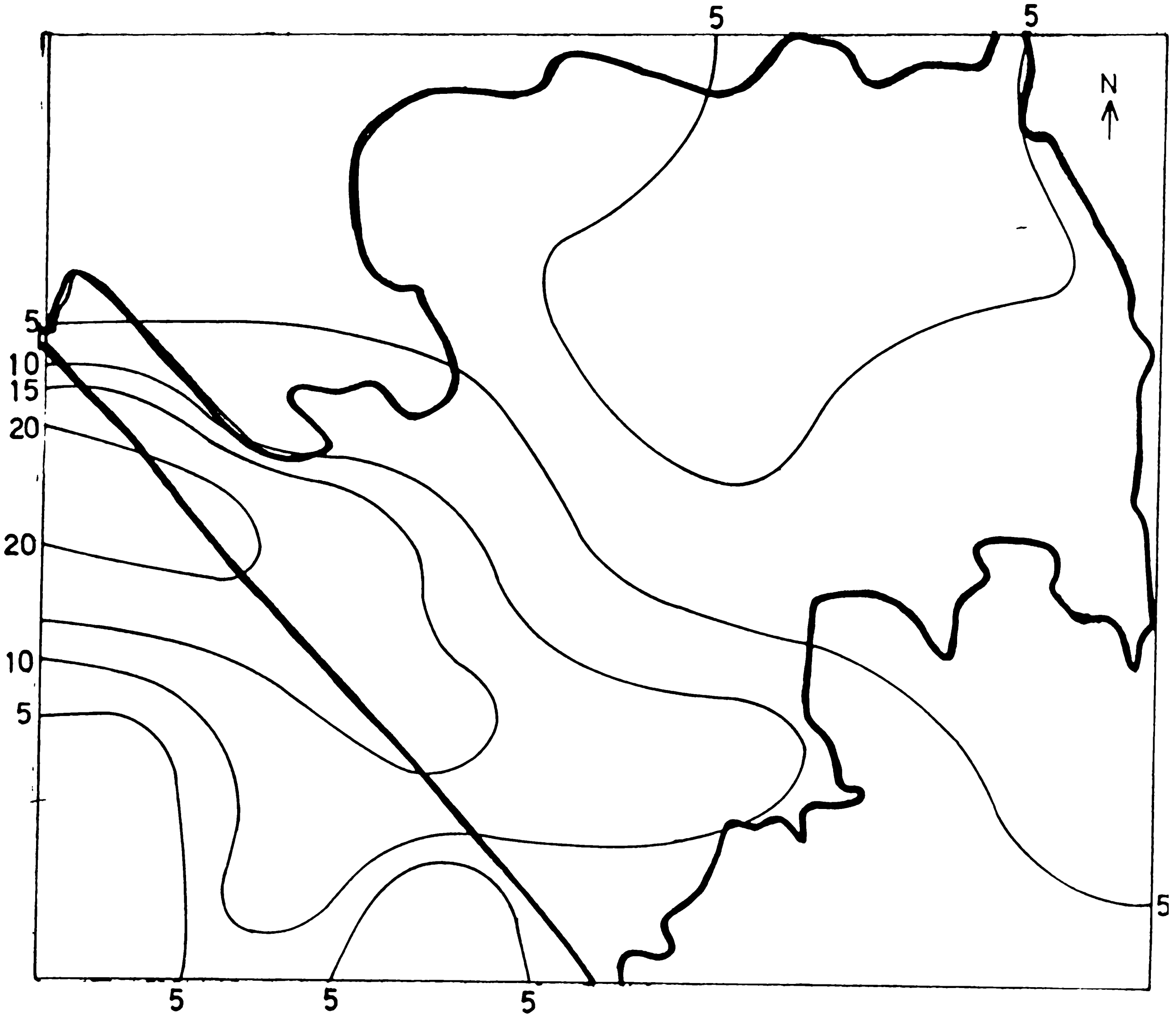

FIG. 8.2(c). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR MARCH (μgm^{-3})

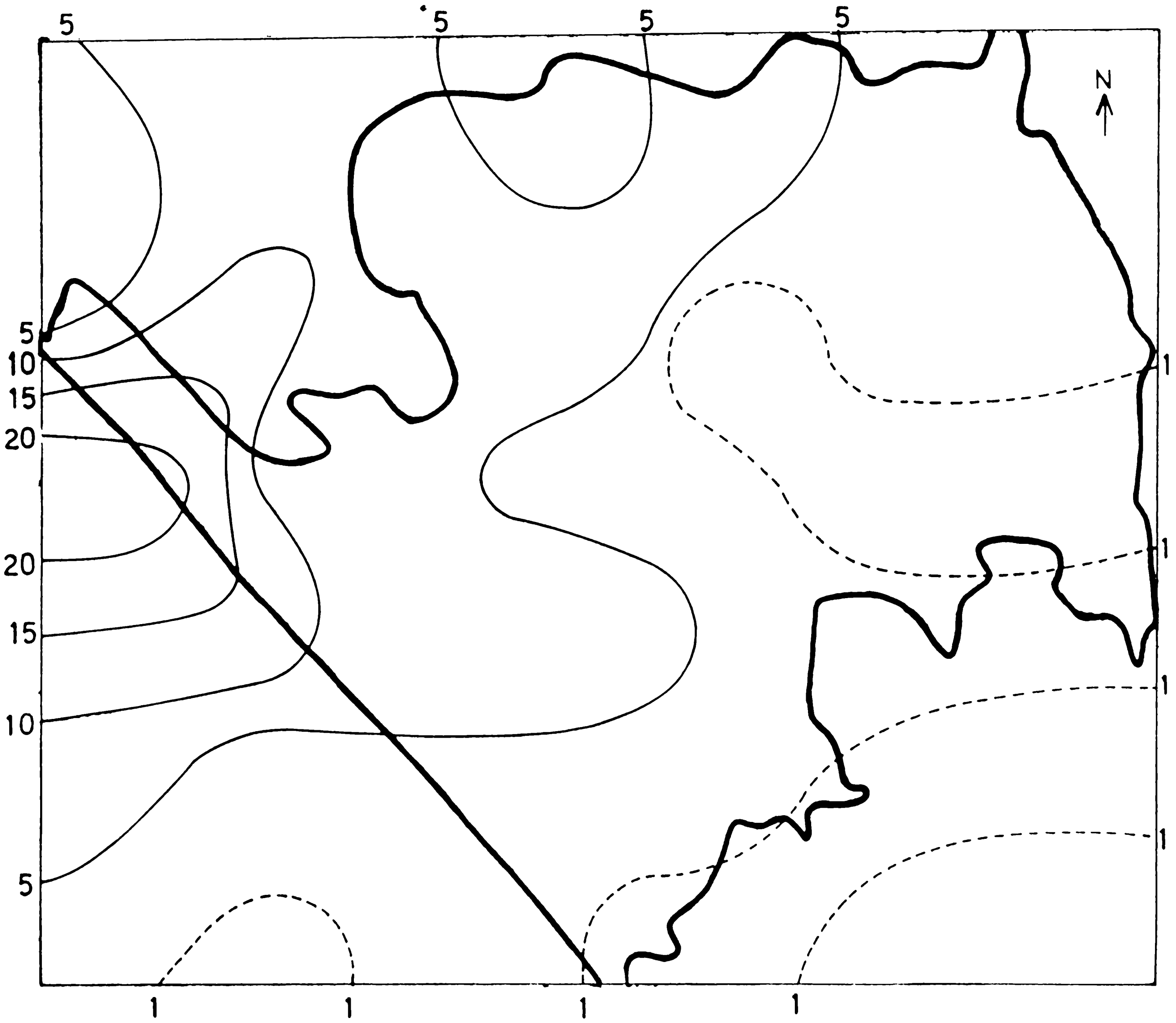

FIG. 8.2(d). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR APRIL (μgm^{-3})

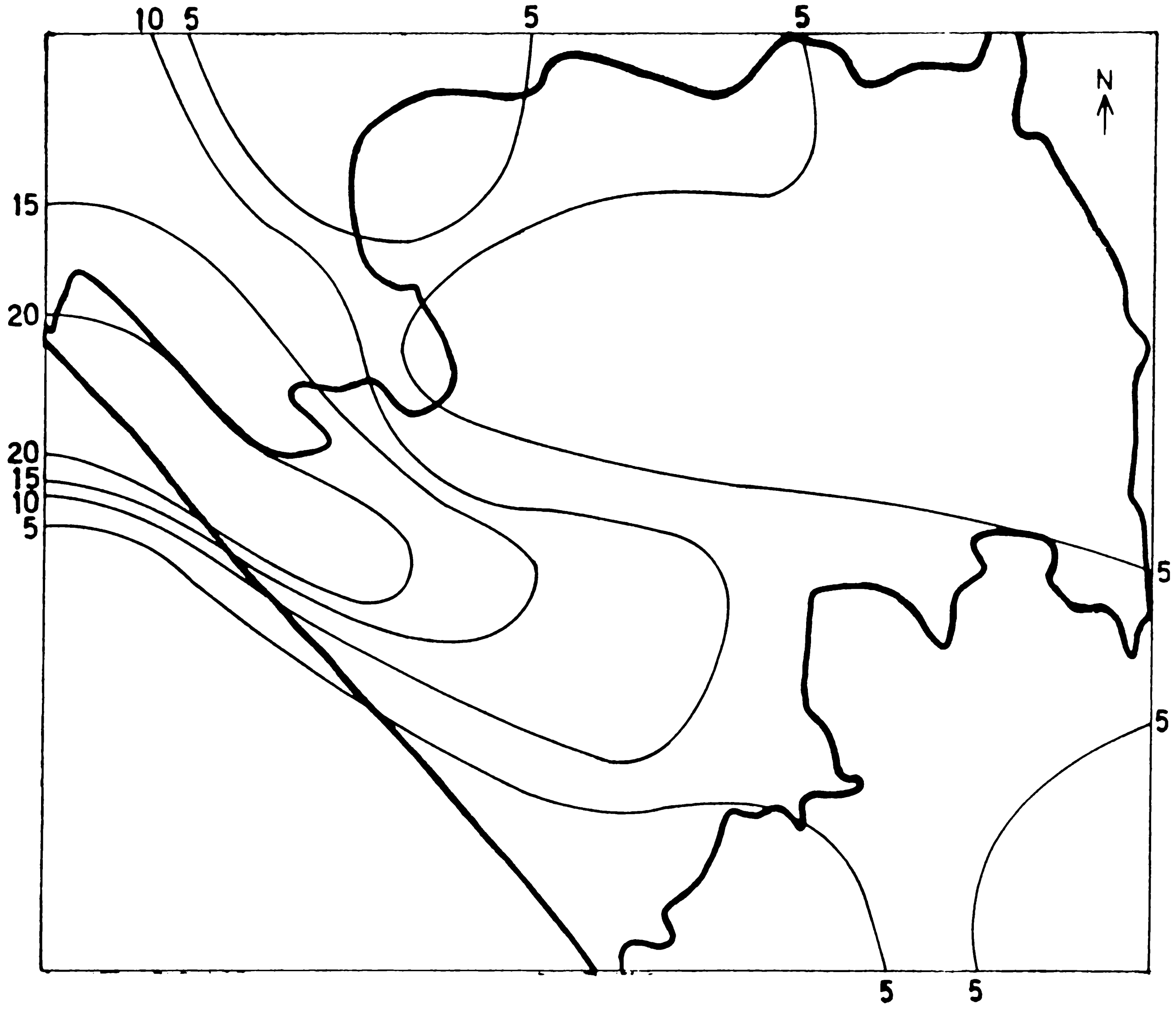

FIG. 8.2(e). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR MAY (μgm^{-3})

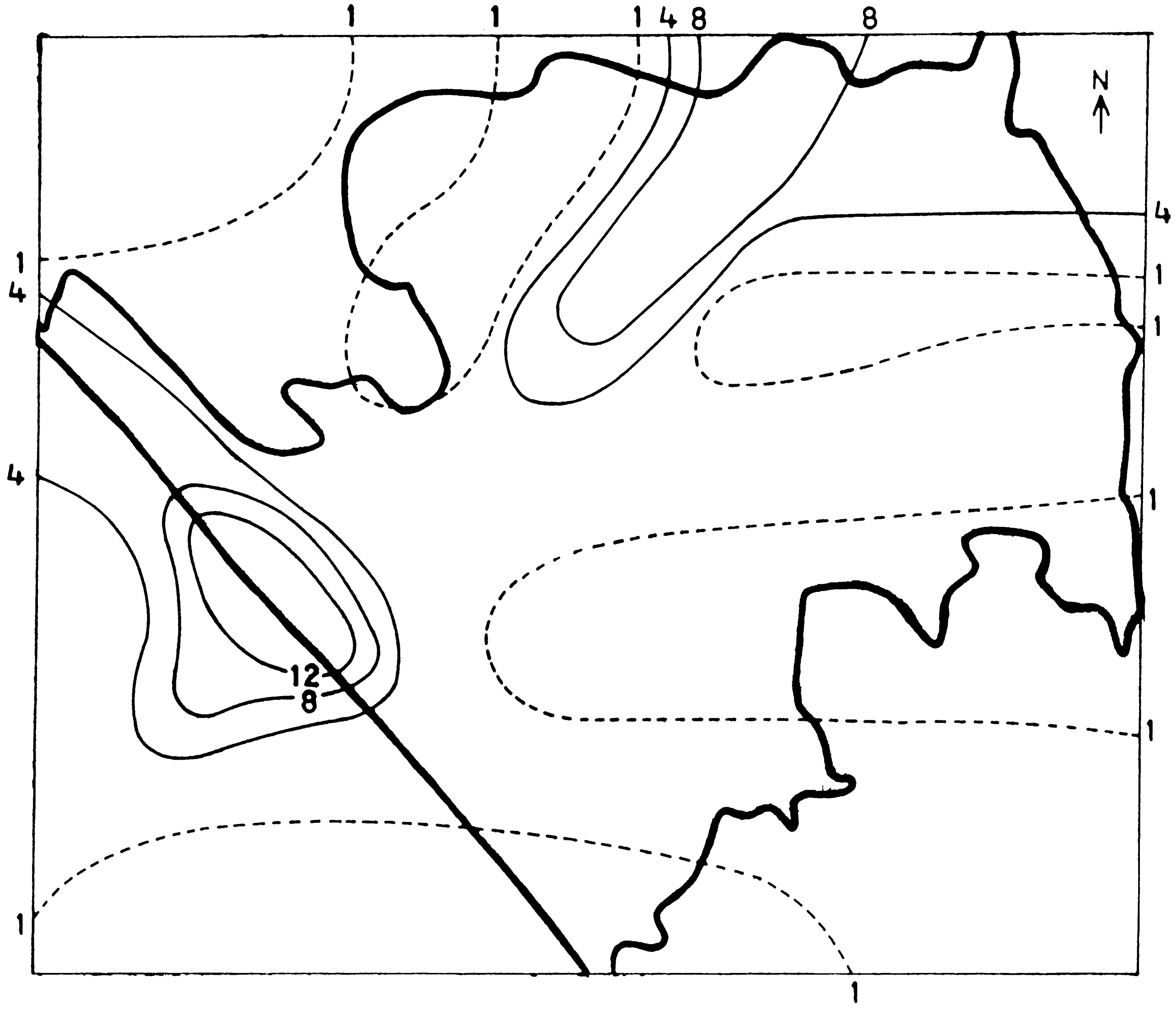

FIG. 8.2(f). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR JUNE (μgm^{-3})

FIG. 8.2(g). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR JULY (μgm^{-3})

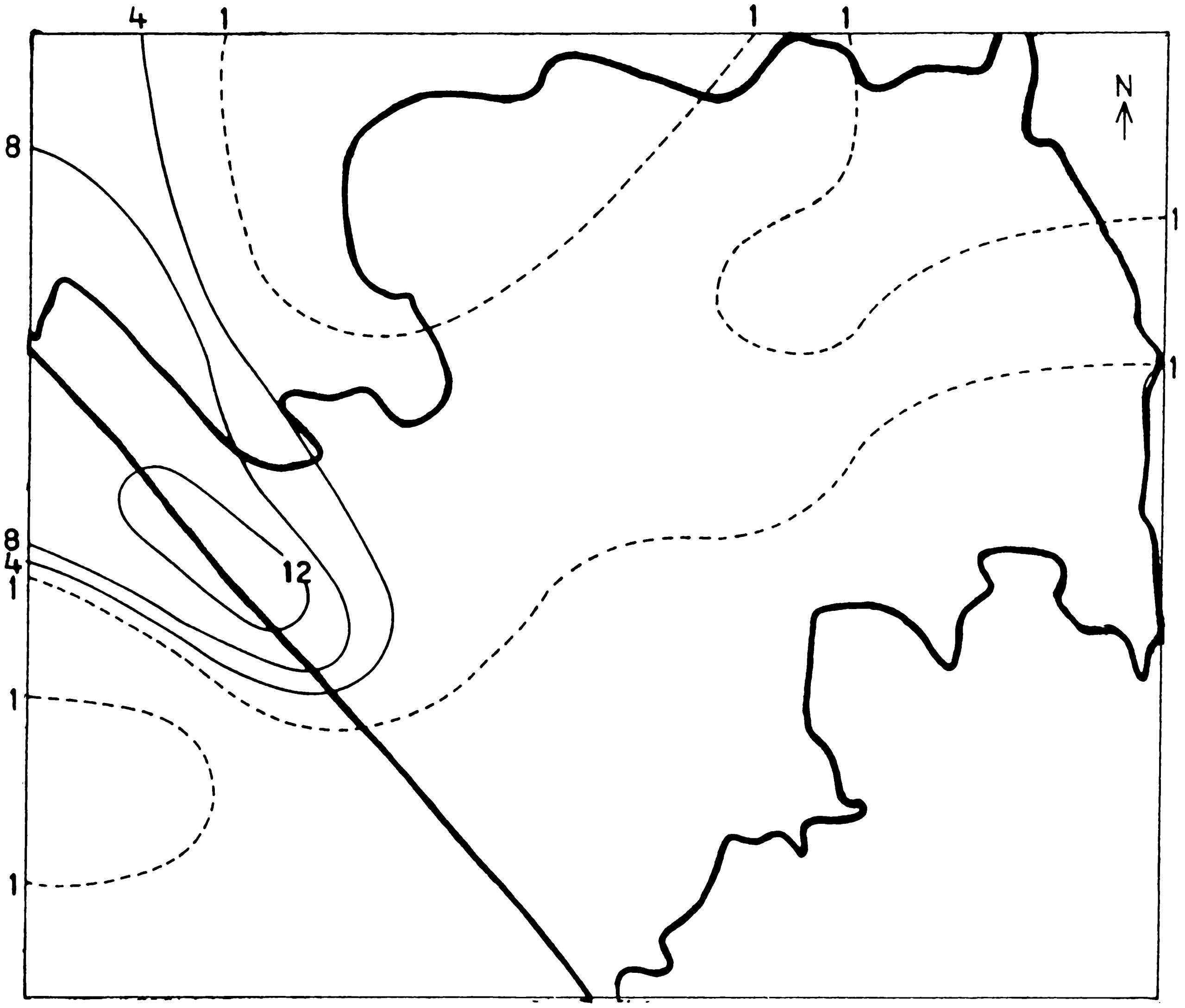

FIG. 8.2(h). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR AUGUST (μgm^{-3})

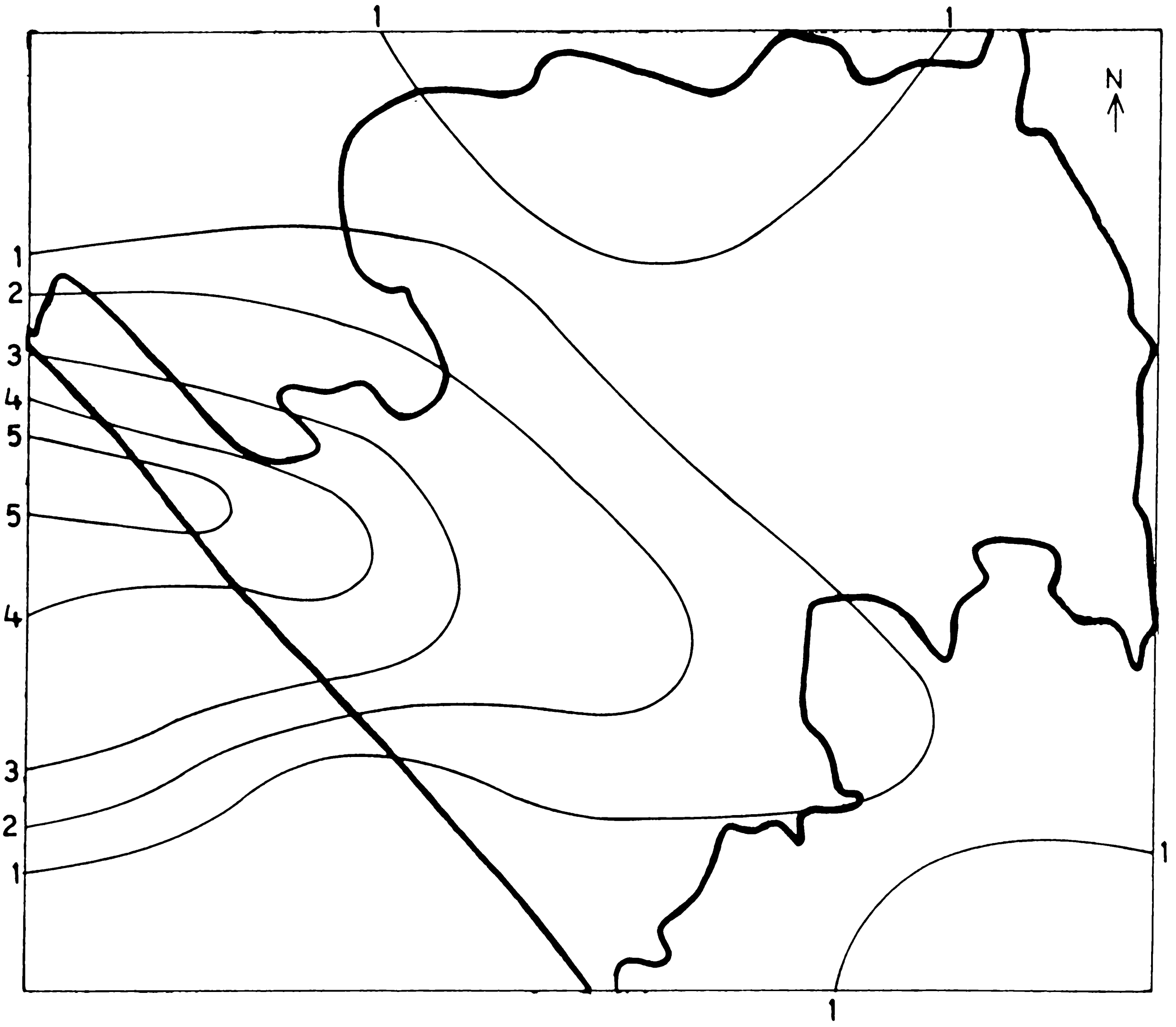

FIG. 8.2(i). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR SEPTEMBER (μgm^{-3})

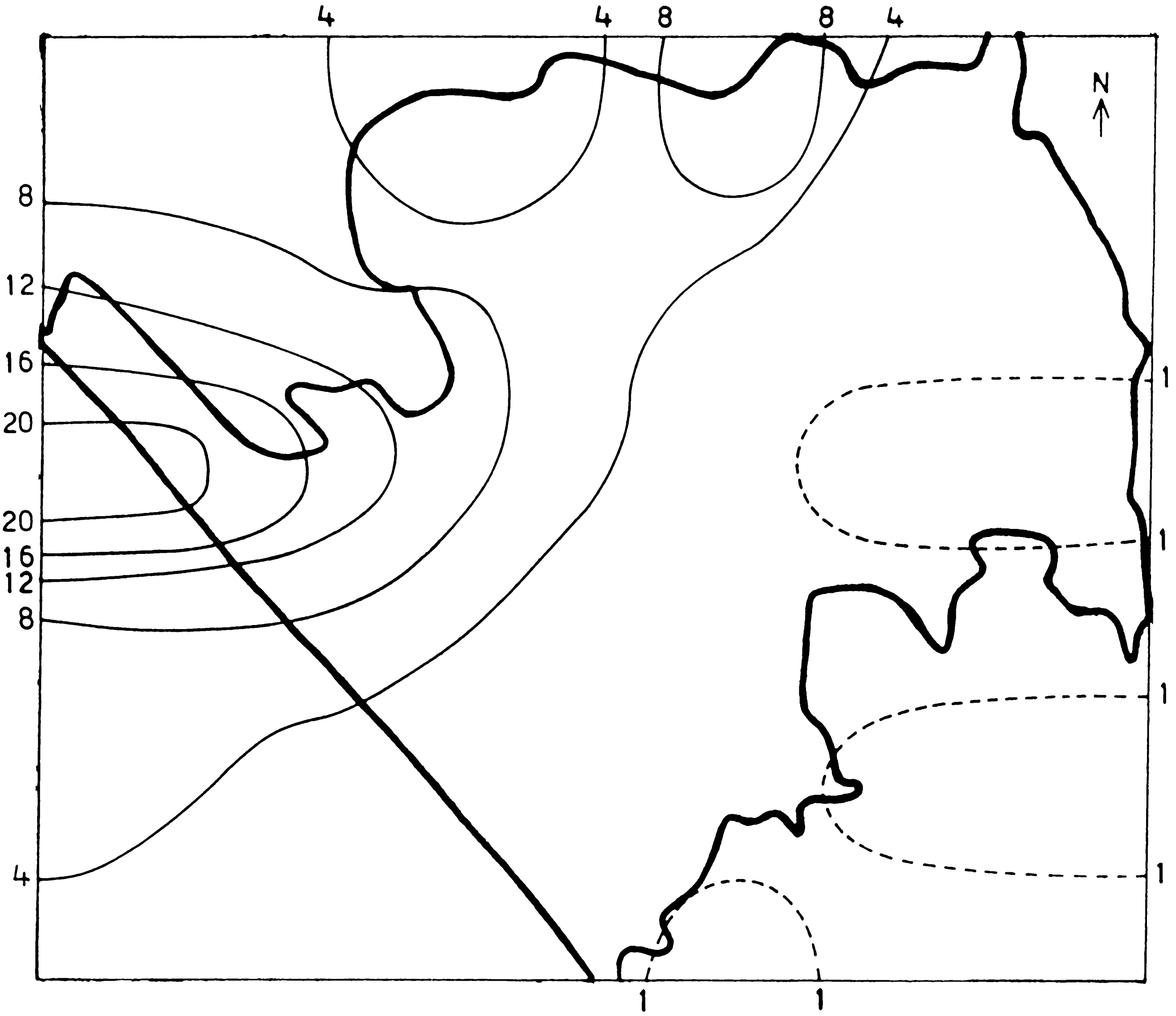

FIG. 8.2(j). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR OCTOBER (μgm^{-3})

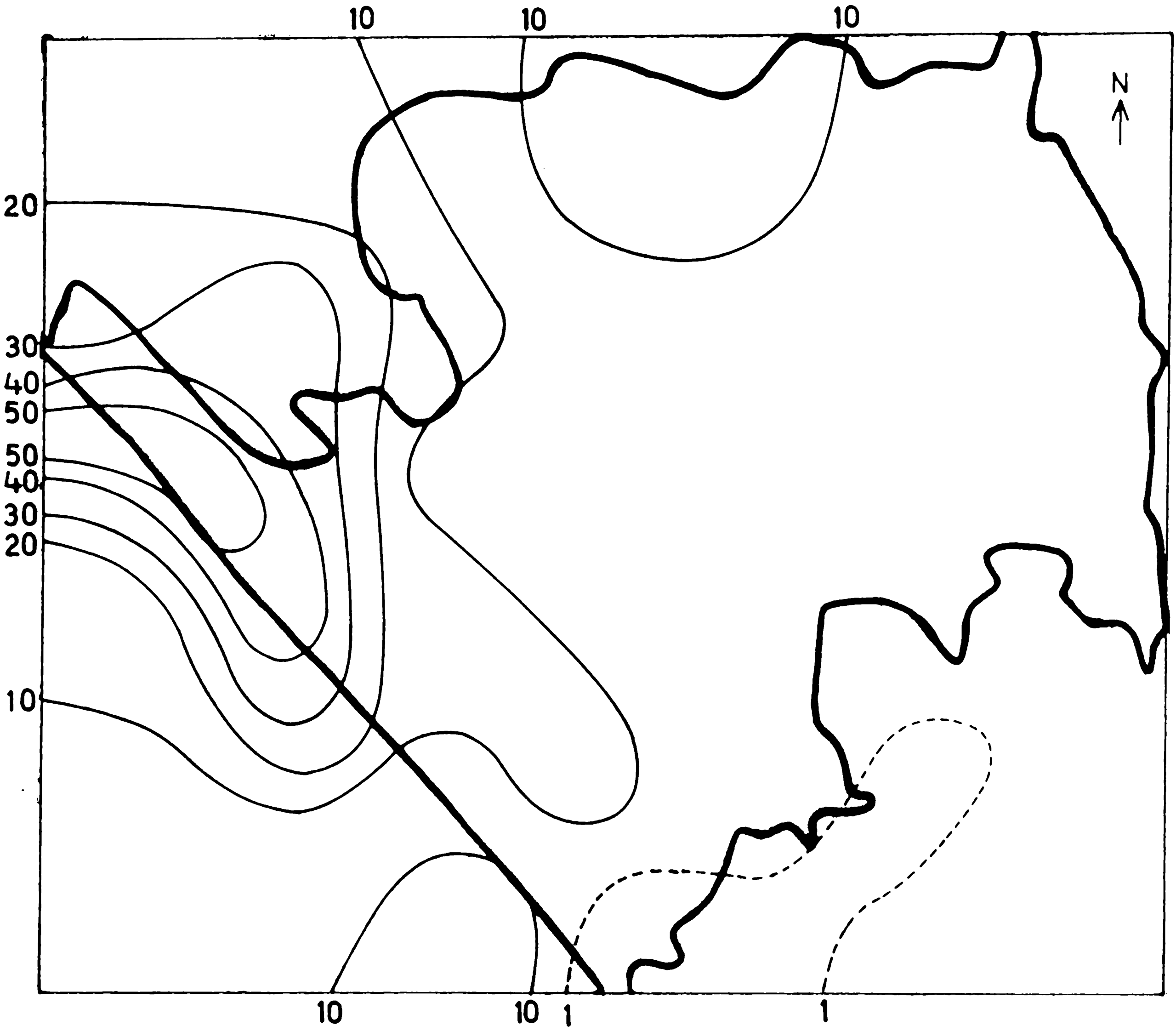

FIG. 8.2(k). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR NOVEMBER (μgm^{-3})

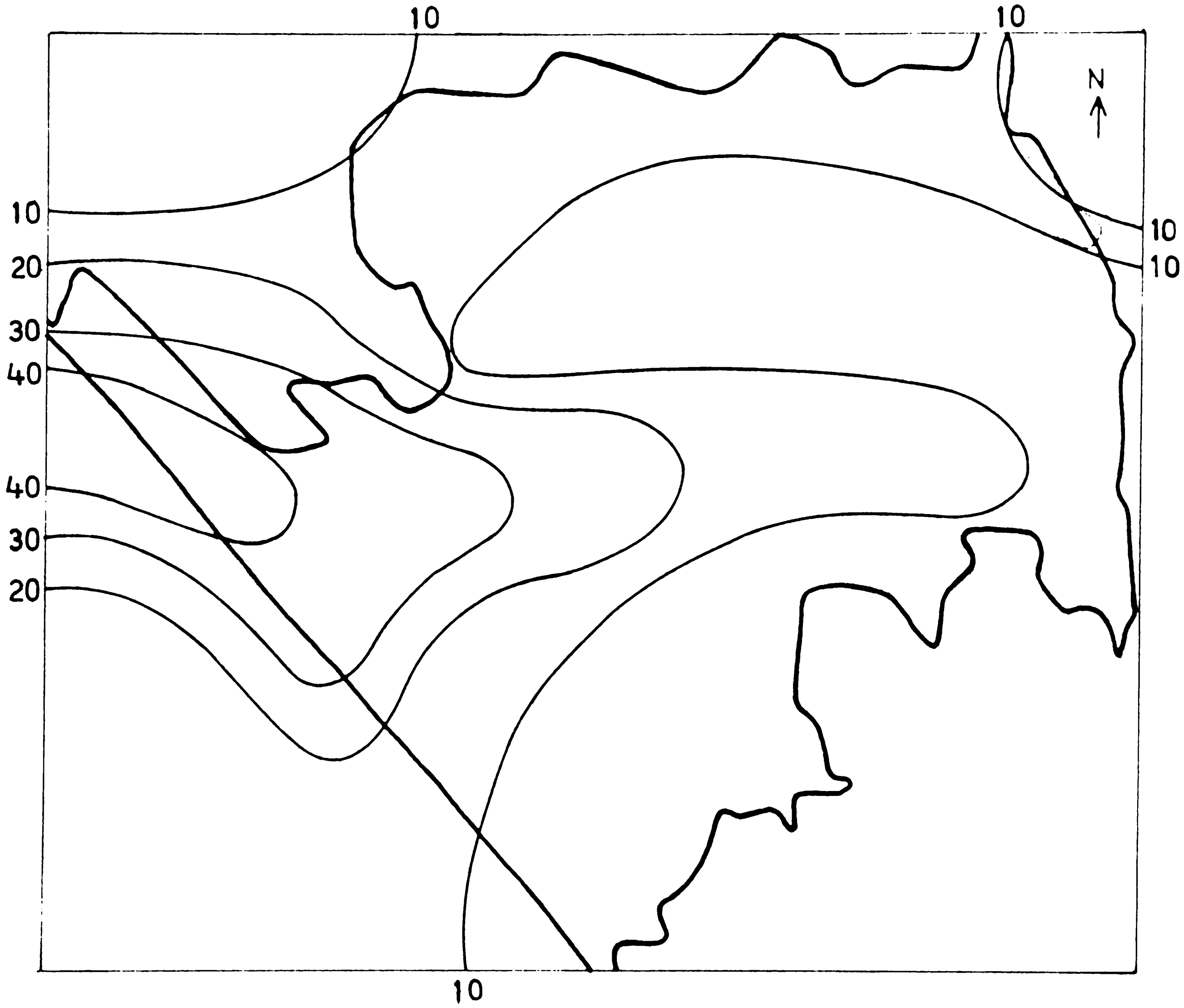

FIG. 8.2(1). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR DECEMBER (μgm^{-3})

February

The values near the first source in the Vettukadu region are much higher ($20 \mu gm^{-3}$) than in the previous month. The entire northwestern sector has values higher than $10 \mu gm^{-3}$. In contrast over the rest of the city the values have decreased to very low values. Over more than half the city, the values are less than $1 \mu gm^{-3}$. This is because most of the pollutants are carried westward over the sea from the source.

March

During this month too, the concentrations are very high near the source I. However, the concentrations show a substantial increase over the other areas of the city. The isopleths exhibit a slight northwest-southeast orientation, resulting in larger concentrations in the southern sector too.

April

The distribution in this month is similar to that of March except that in the extreme southern and eastern sectors, where the values are much lower now. The highest concentrations of $15\text{-}20 \mu gm^{-3}$ continue to be near the Titanium factory. Most of the city has concentration around $5 \mu gm^{-3}$.

May

The concentrations in May over the city are around

$5\mu gm^{-3}$. The values over the northwestern sector are higher in this month ($20\mu gm^{-3}$). The isopleths show a northwest-southeast orientation as in March.

June

The distribution is extremely different in this month. Two pockets of high concentrations are observed-one over the coastal area near Sankumukham (around $12\mu gm^{-3}$) and the other in the northern parts of the city, covering Perurkada, Kowdiar and Nandankode areas. This second cell of high concentrations is due to the source III and is observed only during this month. The concentrations in the rest of the city area are low.

July

During this month too, the concentrations are high near the source I. The isopleths are oriented in southwest-northeast direction. The southern and eastern parts of the city have very low values.

August

Most of the city area is almost free from pollution, the values being around $1\mu gm^{-3}$. Only the northwestern sector has values more than $4\mu gm^{-3}$ with the coastal area near Vettukadu having a maximum of $12\mu gm^{-3}$ near the source II. The pollutants seem to be confined to the area close to the source.

September

The sulphur dioxide concentrations even near the source is much lower (around $5\mu gm^{-3}$) during this month. But there appears to be a considerable spread towards the southeastern regions of the city, since the winds are predominantly northwesterlies during the day time. In general, the concentrations are low over most of the city.

October

The maximum concentration in this month shoots up to $20\mu gm^{-3}$ (the same values earlier observed in May) over the northwestern region. The northern region (Kowdiar, Perurkada) near Hindustan Latex Ltd experiences values of $8\mu gm^{-3}$, while the neighbouring area north of Pattom has values around $4\mu gm^{-3}$. During this month too, the southern and eastern portions show low sulphur dioxide concentrations.

November

The sulphur dioxide concentrations register their highest values during this month. The entire western areas of the city have values more than $10\mu gm^{-3}$. The maximum concentrations of $50\mu gm^{-3}$ is noticed near Vettukadu region.

The values decrease away from this source and the minimum values are less than 1μgm^{-3} in the extreme southern parts of the city.

December

During this month, the concentrations are slightly lower than in November, but still very high. Although the maximum values observed (40μgm^{-3}) is lower than in November, the city shows generally higher values above 10μgm^{-3}. Concentrations are greater than 1μgm^{-3} over the whole city area.

It is thus seen that the months December and November show the highest concentrations while the monsoonal months show the lowest. Higher values of mixing heights do not seem to have as much impact as the wind has on the concentration of pollutants. The months December to March show relatively higher mixing heights but the concentrations are not low. But in the monsoonal months, the strong winds are the main cause for the lower values. This may probably be explained as due to the direct inverse proportionality of wind to the concentration. The mixing height involvement in the model comes only after a certain distance from the source and as such the concentration will not be affected in the first few kilometres. But the wind has an increased involvement throughout the distance upto which the concentration is calculated.

The very large concentration in November (highest in the year) may be due to the very low wind speeds coupled with lower mixing height. In any case one can notice that despite the strong unidirectionality of the wind in many cases the pollutant distribution does not follow that pattern. This is mainly because whenever the winds are unidirectional they are extremely strong as a result of which the concentration in the downwind direction is bound to be low compared to the case of low frequency but weak winds from any other direction. The latter, in view of its very low wind speed, results in higher concentration and the effect is seen for a considerable distance. Whether the weak winds are persistent enough to carry pollutants to such great distances is a debatable point. But the model does not take into account such persistence of the winds and as such the pattern discussed above appears.

It should also be noted that the monsoon brings in lot of rainfall resulting in a possible washout of pollutants leaving the concentration to be further low. The presesnce of huge amounts of moisture in the atmosphere cannot be left untouched becuase of a possible conversion of sulphur dioxide to sulphurous acid or sulphuric acid in which case also the concentration of ground becomes further low. However, although the moisture and rain act as sinks of sulphur dioxide, this is not a matter over which one can be happy in view of the possible acid rain which has its own deleterious effects. In any case, from all counts monsoon season appears to be very safe in view of the low concentration.

These long term concentrations give some insight into choosing the appropriate locations for further industries. Except on a couple of occasions, it appears that most of the city area is relatively free from pollution. Especially, the southeastern and eastern sectors are free from pollution in most months. As such, the present location of industries are not inappropriate. However, one cannot think of a cluster of industries and hence other locations are to be chosen keeping the existing levels in view. The extreme northeastern parts appear to be very plausible for further industrial development since the contribution from the north side is not significant. One can see the rapid decrease of concentration towards south. This is the main point on which the northeastern locations is suggested. Although, the southeastern parts are free from pollution, it must be kept in mind that in most of the cases the spread is in the northwest-southeast direction and that would result in heavy doses of concentration in the central parts if southeastern parts are chosen for further industries. In any case it depends upon the amount of emission also. To some extent the northwestern parts also seem to be appropriate for further industries. But it does result in rather high concentration in central northern parts. However, the city interior is not affected that much.

In addition to the location of the industries, one should also see the concentration variation diurnally. Although, not depicted here, the night-time concentrations are even higher, mainly because of low wind speeds. In certain months such as November and December the night-time concentration would be undoubtedly very high and hence one has to think of regulating the emissions. In fact if the night emssions are brought down, the effective concentration for day and night put together also would automatically come down. The emissions during night-time can be brought down with a corresponding increase during day time which then would also lead to lowering of effective concentrations. A fifty percent reduction in the night-time emission would lead to an almost fifty percent decrease in night-time concentration. However, fifty percent of additional emissions during day time would lead only to a marginal increase because of high wind speeds and hence the average concentration comes down considerably. In addition the effective stack height would also be raised but this does not seem to have any considerable impact on the concentration of pollutants.

It must be noted that the concentrations are only due to the industries and the vehicular traffic is not included. This would mean that the present levels of pollutants reported here are underestimates.

CHAPTER IX

SUMMARY AND CONCLUSIONS

The study of air pollution potential is essential for any urban area in order to initiate remedial measures for the mitigation of air pollution. The main objective of the thesis is to provide the climatology of air pollution potential and to give the spatial distribution of sulphur dioxide concentration for Trivandrum. The effects of air pollution are well known and so are the sources. Sulphur dioxide is the single most important contaminant and is very effective even at low concentrations. Once the pollutants are emitted into the atmosphere their subsequent dispersion and dilution is governed solely by the atmospheric conditions. Some unfavourable conditions such as presence of inversions and highly stable conditions, low mixing and weak wind conditions, quite often lead to unsatisfactory air quality levels. Hence a detailed study of atmospheric conditions for any urban area is essential.

The extensive literature survey (Chapter II) shows that the above is indeed the case. It also shows the necessity of studying the climatological occurrence of inversions, isothermals,lapse conditions, mixing heights, ventillation coefficients, winds and stability. The study of surface turbulence and its relationship with the other parameters is also shown to be important. The estimation of ground concentration of sulphur dioxide has been made by many with the help of various mathematical models. The survey reveals that inspite of the pesence of various mathematical models, Guassian plume model is the widely used one. The various methods of computation and their limitations are spelt out.

These studies are carried out extensively for Trivandrum, an industrially developing city, where there is a lot of potential, otherwise, for further industries. The climatology of air pollution potential is discussed in detail giving equal importance to each of the parameters involved. The isopleth analysis is applied for studying the spatial distribution of sulphur dioxide concentration and the regions of high and low concentrations are identified. Based on these studies and the subsequent discussions, the main conclusions drawn are given hereunder.

The studies of occurrence of inversions, isothermals and lapse conditions (Chapter IV) show that lapse conditions dominate in all the months followed by isothermals and inversions. Inversions and isothermals are found to be most frequent in the month of January. While considering the intensities of inversions and lapse conditions, in every 50mb layer, presence of former do not seem to cause much anxiety as far as air pollution is concerned, since its percentage of occurrence is extremely low. The above three factors do not show significant monthly variations because of the coastal characteristics.

To get a clear idea about the vertical and horizontal extent of mixing, mixing heights and ventilation coefficients have been studied in detail (Chapter V). Mixing height values are maximum during the afternoon hours and minimum during early morning hours. The highest mixing heights are observed in the months of February and March.Day time mixing heights are lower in the monsoonal months than in the rest of the year. The very low mixing heights during night-time all through the year and during day time in the months of May, June, July and October could result higher concentrations as any pollutants emitted into the atmosphere would not be allowed to get dispersed.

Ventilation coefficients which determine the horizontal mixing are found to be high in the monsoonal months. The monthly variation of ventilation coefficients almost follows the pattern of mixing heights : During night-time the values are extremely low. The emission from various sources should be reduced during night-time in order to keep the concentration of pollutants within the permissible levels.

Atmospheric stability is one of the most important parameters affecting the dispersal of pollutants. It is seen that highly stable conditions are observed during night-time and unstable conditions only in day time. Unstable conditions are more frequent in the non-monsoonal months with its maximum being in December and January. Neutral conditions are more frequent during day time. There is a systematic increase of neutral conditions from January to September with a consequent decrease of highly unstable conditions during day time. While considering the entire night-time, highly stable conditions are most dominant in all the months. These conditions do not allow pollutants to get dispersed thereby resulting in higher concentrations slightly away from the source.

To study the effect of wind on the dispersal capacity of the atmosphere, six hourly wind roses are analysed. During night-time winds are extremely weak in most of the cases except in the monsoonal months, with the calm frequency reaching above 75%. Winds are strongest in the monsoonal months and more frequent from the northwestern sector. During day time in the monsoonal months westerlies dominate. As far as the dispersion of pollutants is concerned, the monsoonal months seem to be more favourable.

Studies on pollution potential indices show that the index is highest in the month of February revealing good dispersal capacity in this month. The index is highest during day time and lowest during night-time. The indices are highly variable from month to month and hour to hour with maximum variation in August and minimum in May. There is a systematic increase of the index from early morning hours to around maximum temperature epoch and a decrease thereafter, in all the months. As in earlier cases, here also the night-time seems to be less favourable for the dispersal of pollutants.

$\overline{\sigma_{\theta D}}$, which shows a good diurnal variation with lowest values during night-time and highest values during day time can be taken as a measure of surface turbulence. Surface turbulence is maximum in the month of Janauary amongst the four typical seasonal months. During day time turbulence is minimum in July but during night-time it is more in this month. $\overline{\sigma_{\theta S}}$ values are maximum in the month of July and minimum in the month of January, with its maximum diurnal variation occuring in April. $\overline{\sigma_{\theta D}}$ is more appropriate being taken as a measure of surface turbulence.

Linear regression equations are developed between mixing height and $\overline{\sigma_{\theta D}}$, mixing height and $\overline{\sigma_{\theta S}}$ and $\overline{\sigma_{\theta D}}$ and $\overline{\sigma_{\theta S}}$. All of these show very high correlation coefficients. Since the variations in $\overline{\sigma_{\theta D}}$ are larger compared to that of $\overline{\sigma_{\theta S}}$, mixing height obtained from $\overline{\sigma_{\theta D}}$ are likely to be more accurate. It is also seen that even when mixing height values are zero $\overline{\sigma_{\theta D}}$ values exist.

Investigation of the spatial distribution of sulphur dioxide concentrations by means of multiple stack Gaussian plume model reveals that the months of November and December show the highest concentrations while the monsoonal months show the lowest concentrations. Higher values of mixing height do not seem to have as much impact as the wind has on the dispersal of pollutants. It is seen that the distribution of pollutants does not follow the unidirectionality of the wind pattern in many cases. Therefore most of the factors studied suggest that monsoon season appears to be safe in view of the low concentrations.

Most of the city area is found to be free from pollution, especially, the southeastern and the eastern sectors. Therefore, the present location of factories are not inappropriate. To avoid any clustering of industries, appropriate locations of new industries can be chosen in the extreme northeastern parts, since the spreading of the pollutants towards south is insignificant. Any further establishment of industries in the northwestern parts will result in rather high concentrations in central northern part.

Also, it seems that if the night-time emissions are brought down, the effective concentration for the whole day would automatically come down.

It is shown that a considerable reduction during night-time and a consequent increase during day time would bring down the concentrations effectively.

It is already pointed out that some improvements are necessary for the model in order that it would be more effective. The vehicular sources also should be taken into consideration for further studies.

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