STUDIES ON AIR POLLUTION METEOROLOGY WITH SPECIAL REFERENCE TO MADRAS CITY

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C E R T I F I C A T E

This is to certify that this thesis is an authentic record of research work carried out by Mr. C. A. Babu 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.

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D E C L A R A T I O N

I hereby declare that this thesis, entitled 'Studies on air pollution meteorology with special reference to Madras city' 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.

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C O N T E N T S

P R E F A C E

The meteorological consequences of urbanisation and industrialisation have been noted since the turn of the century. In the last few decades, detailed observations and analyses have made air pollution meteorology an established branch of science. These studies have indicated beyond any doubt that environmental planning is essential to help reduce pollution wherever urbanisation and industrialisation are envisaged. Such planning requires comprehensive studies of the meteorological conditions prevailing over the area. The main idea behind the present study is to provide a complete picture of the atmospheric potential for the dispersal of pollutants over Madras city and neighbourhood, to enable planning to improve the air quality standard over the area. The emphasis is on the application of a numerical model to study the spatial distribution of pollutants emitted by multiple sources. The various meteorological parameters affecting the dispersion of pollutants are studied in great detail, since they would provide clues on the abatement steps to be taken.

The thesis is divided into six chapters. The first chapter presents the objectives of the study. A description of air pollution and its effects together with the various meteorological factors affecting it are also discussed in this chapter. The second chapter is completely devoted to literature review and methodology. As a first step, the research work carried in the field of air pollution meteorology is reviewed. A detailed methodology of the concepts and techniques employed in the present study, along with their merits and demerits is presented.

Chapter 3 is mainly concerned with the air pollution climatology of Madras city. This includes the vertical thermal structure of the lower troposhere upto 500mb level and the surface wind climatology. The diurnal and monthly variations of mixing height and ventilation coefficient are presented in this chapter. Atmospheric stability, classified according to the Pasquill's scheme is discussed here. The variations in wind direction fluctuation range ($\sigma_{\theta D}$) and wind speed fluctuation range ($\sigma_{\theta S}$) are presented in chapter 4 which also contains interrelationships among Pasquill's stability, mixing height, $\sigma_{\theta D}$ and $\sigma_{\theta S}$.

Spatial distribution of sulphur dioxide concentrations is studied by means of Gaussian plume model for multiple industrial sources for all the months for Madras metropolitan area and presented in the fifth chapter. Steps needed to reduce air pollution over Madras are also suggested. The overall summary and conclusions are presented in the sixth and final chapter.

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 PROBLEMS AND OBJECTIVES

Clean air is essential for the survival of mankind. Due to developmental activities such as industrialisation, urbanisation etc, the air is almost always contaminated, though this phenomenon has been going on through the ages due to natural processes. The level of contamination has risen so alarmingly, that unless proper effective control and abatement steps are taken, it would lead to a complete deterioration of the environment. Many of the problems encountered in this regard are due to improper planning. In this connection, it must be emphasised that meteorology plays a pivotal role and must be considered not only for urban and industrial planning but also for operational purposes. Idealistically one would like to see all pollution prevented at the source, but realistically one should attempt to minimise it. In places which are just developing, there is opportunity and need to do all the planning before hand. Detailed studies are, therefore, needed for these areas to incorporate meteorological concepts into planning of locations of new industries and residential areas. One such important developing metropolis, namely Madras, is chosen for undertaking such a study.

The main objective of the present study is to give a clear picture of various meteorological factors affecting the dispersal of pollutants. The results of the investigation will help proper and effective planning so as to minimise the effects of air pollution due to industries in Madras. The detailed objectives are :

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

(ii) to establish the vertical and horizontal extent of mixing of pollutants.

(iii) to study the wind climatology.

(iv) to study the atomospheric stability and its variation.

(v) to study the surface turbulence in terms of wind direction as well as speed fluctuations.

(vi) to establish the interrelationships among mixing height, stability, wind speed fluctuation and wind direction fluctuation.

(vii) to obtain the spatial distribution of sulphur dioxide concentration using the Gaussian plume model, which accounts for various industrial sources.

(viii) to suggest optimum locations for industries.

Madras (Latitude 13°05'N, Longitude 80°18'E) is a fast developing industrial city situated on the southeast coast of India. Highly metropolitan in nature, the city is often regarded as the capital of South India. In view of the facilities (mainly transportation by sea, road and air) existing in this city, Madras is the natural first choice of many to establish new industries. Hence this city is chosen for the present study.

1.2 INTRODUCTION TO AIR POLLUTION

Although this topic is well known and is available in literature, it is presented below for the purpose of continuity.

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 0.4μ to about 100μ. Particles larger than 10μ 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 dispersion 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.

CHAPTER II

LITERATURE REVIEW AND METHODOLOGY

The objective of the present work and a brief introduction to air pollution meteorology were presented in the preceding chapter. In this chapter, a review of literature pertaining to the various studies and methodologies involved is presented. The methodology adopted for the present study along with the sources of the data are given. The limitations of the present study are included at the end of this chapter.

2.1 LITERATURE REVIEW

The important meteorological parameters which determine the dispersal of pollutants are temperature, wind and stability. The ambient value of the temperature and its spatial and vertical variations are important in air pollution studies. The most obvious significance of ambient temperature is 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 the average daily temperature and 65°F.

The spatial variation of temperature normally shows that cities are warmer than nearby rural surroundings, particularly at nights with 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. There have been a number of studies on heat islands (for example : Chandler, 1965; Okita, 1965; Bornstein et al, 1968, and Georgii, 1969). 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. Besides, it 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 at night than at day time. However, as shown by Findlay and Hirt (1969) and Viswanadham (1983), the urban-rural contrasts can be large even during maximum temperature epoch. The maximum reported values of urban heat islands are 8.9°C for London (Chandler, 1965) and 11.1°C for San Franscisco (Duckworth and Sandberg, 1954). There are empirical relationships for determining the urban heat islands, based on cloud cover, wind speed, population, etc. Mitchell (1961) presented a formula for the nocturnal urban-rural temperature difference, D of the form $D=(a-b.N)/v$ where N is the percent cloud cover, v is the wind speed and a and b are empirically determined constants. Ludwig and Kealoha (1968) made extensive investigations of the urban heat island and developed equations for the magnitude of urban heat island as a function of variation of temperature with height in the nearby urban area. Oke (1972) developed an equation for the maximum value of urban heat island as a function of population. Padmanabhamurthy and Hirt (1974) studied the heat island in relation to the pollution distribution for Toronto. Urban heat island effect in New York city was studied by Bornstein et al (1968) in which, differences in the temperature field through the lowest 700m of the atmosphere in and around New York city during the hours before and after sunrise were analysed. Urban surface temperature inversions were found less intense and less frequent than those in the surrounding non-urban regions. The average intensity of the urban heat island was maximum near the surface and decreased to zero at 300m. At mornings, with relatively strong urban elevated inversion layers, the heat island extended well over 500m.

A theoretical study of the St.Louis heat island was done by Vukovich and Dunn (1978) and Vukovich and King (1980). A sensitivity analysis was performed to determine more important parameters affecting the urban heat island circulation in St.Louis, Missouri. The effects of heat island intensity, surface roughness, horizontal diffusion and boundary layer stability on the heat island circulation were studied using a three-dimensional primitive equation model. The results indicated that the heat island intensity and boundary layer stability play a dominant role in the heat island circulation. Using the model, the early afternoon wind velocity field over St.Louis, was predicted and it was compared with observed data from the METROMEX network. With proper initialisation, the model very closely simulated actual conditions, the main feature of which was the urban heat island circulation.

Nkemdirim (1980) investigated a lapse rate-wind speed model for estimating heat island magnitude in an urban airshed, Calgary. Regression analysis showed that the model based on the ratio of lapse rate to wind speed was not that effective in estimating urban heat island intensity though it was superior to ones based on wind speed alone. Heat island studies for Athens, Greece were made by Katsoulis and Theoharatos (1985) using air temperature data analysis for a period of 22 years. The effect of urban heat island was clearly evident and its intensity varied according to the season and maximum and minimum temperatures. In particular, the analysis of the data pointed out the variations caused by natural processes and anthropogenic activities.

Diurnal variation of the urban heat island circulation and associated variations of the ozone distribution over St.Louis region was studied by Vukovich et al (1979). The results showed that the day time heat island effect (1-2°C) was relatively weak compared to that at night (approximately 5°C). In contrast, the urban heat island circulation was more intense during day, probably, due to the heat being distributed through a deeper layer. The highest concentrations of ozone at the surface were found in the zone of convergence associated with the urban heat island circulation immediately downwind of the centre of the city.

Draxler (1986) studied the influence of the nocturnal urban heat island on the local wind field. The influence of Washington DC urban area on the local airflow was to enhance the vertical mixing due to the increased low level instability as the air approached the warmer city centre. This resulted in anticyclonic turning of low level winds from upwind values.

High spatial resolution thermal infrared data at times of day appropriate for the study of the urban heat island effect, obtained from a NASA satellite was studied by Price (1979). Quantitative estimates of the extent and intensity of urban surface heating were made.

Wong and Dirks (1978) studied the urban perturbations on the mixing layer airflow over St.Louis as part of METROMEX. Based on simultaneous airborne wind and temperature measurements, the relative effects of the urban heat island, surface friction and local terrain features were estimated. Their studies revealed that when the heat island was strong and the winds were light, the thermally induced pressure perturbation was the dominant force and accelerated the airflow as it converged into the heat island. With strong winds and weak thermal fields, frictional drag was dominant which decrease the wind speed over the city.

Ackerman (1985) used twenty years of records from Midway Airport located within the city of Chicago and from Argonne National Laboratory, as the rural site, 23km southwest of the airport, to study the diurnal and seasonal variation in the Chicago urban heat island. There was an elevation in temperature within the city most of the time, at an average of 1.85°C during non-precipitation hours. The magnitude of the heat island was characterised by diurnal and seasonal cycles, which were modulated by cloud and wind conditions. Studies by Kukla et al (1986) showed that meteorological stations located in an urban environment in North America warmed between 1941-1980, compared to the countryside and the average rate was approximately 0.12°C per decade.

Studies for some of the Indian cities were carried out by Daniel and Krishnamurthy (1972), Philip et al (1974) and Viswanadham (1983). Bahl and Padmanabhamurthy (1979) conducted mobile temperature surveys in Delhi during 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 vertical temperature structure is one of the most important elements in air pollution climatology as it has a direct impact on the vertical extent of dispersal of pollutants. The increase of temperature with height, known as inversion, inhibits the mixing of pollutants. 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. Much light was thrown on the frequency of occurrence of surface based and elevated inversions for different regions by various authors. De Marris (1961) published an excellent report on this matter based on temperature data taken on a T.V. tower in down-town Louisville, Kentucky and showed that the average lapse rate between 18 to 160m became super adiabatic (greater than the dry adiabatic value of 9.78°C per km) approximately 3 hours after sunrise and remained so until about sunset. Not many inversions were reported by him during the night-time which according to Summers (1967) may be due to the effect of the nocturnal heat island on the vertical temperature structure.

The analysis of low level temperature data obtained by radiosonde is common despite a few limitations, which are (1) some loss of resolution of temperature profile occurs as the response of the temperature sensor is relatively slow with respect to the ascent rate of the balloon; consequently the small excursions in the temperature profiles are not necessarily reported and (2) the radiosonde launching sites are usually at airports in rural or sub-urban surroundings, so that the low level data need not necessarily be representative of urban conditions. Szepesi (1967) made detailed studies of radiosonde data by using five year soundings for each of six different observational hours. He analysed the monthly distributions of stability conditions and frequency and duration of the inversions. Hosler (1961) studied the low level inversion frequency for the United States based on radiosonde observations at four synoptic hours. He reported that the observation time with the greatest frequency of inversions was almost at night or near sunrise. Bilello (1966) presented information on inversions at eleven Arctic and Sub-Arctic radiosonde stations in Canada, Greenland and Alaska. He computed the frequency, base height, thickness, base temperature and the intensity of inversions at 0000 GMT. Inversions at Point Arguello, California were related to surface wind direction and speed and surface temperatures by Baynton et al (1965). Nocturnal inversions based below 1000ft, have their maximum frequency in winter and their minimum in summer. Most of them occur with downslope surface winds. Afternoon inversions were most frequent in July and least frequent in January. Time series analysis of observations of inversion base and top height and inversion strength at urban and non-urban sites in St.Louis, Missouri was done by Godowitch et al (1985). The time dependent behaviour of each inversion parameter was presented from statistical and least square regression analyses.

Differences in inversion evolution between these sites were discussed.

A simple prognostic equation for predicting the development of the nocturnal surface inversion height was constructed from the thermal energy equation by Yamada (1979). A significant improvement of this model over previous simple models was the inclusion of atmospheric cooling due to long wave radiation. Another important difference, which considerably simplified the model, was the adoption of an empirical expression for the particular temperature profile. Predictions agreed quite well with the data of the Wangara experiment.

The meteorological conditions associated with the high inversion fog episode during 23-28 December, 1978 near Chico, California were described by Stephen (1981). Pilot and Swanson reports of the fog top (inversion base) were also discussed. These meteorological conditions were typical of other high inversion episodes from 1954-80 in the central valley.

Fog over Madras airport was studied by Manikiam (1983). In this study an attempt was made to calculate the time of occurrence of fog by applying Jacob's diagram, which was based on Brunt's formula. Das (1987) studied nocturnal radiation at Calcutta airport on clear winter nights.

Padmanabhamurthy and Mandal (1976,1979) studied the frequency of inversions for Delhi. 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 inversions, multiple inversions and their thickness, based on 0000 and 1200 GMT ascents during December-March for a five year period for Visakhapatnam. They made a comparison for Delhi and Visakhapatnam which revealed high frequency of ground based inversions in Delhi compared to Visakhapatnam.

Mixing height is the vertical extent of convective activity in the atmosphere, or it is the top of the layer in which vertical mixing is vigorous, and varies with surface temperature as well as vertical temperature structures. Studies on mixing height are mainly due to Holzworth (1964). He estimated the mean maximum mixing heights for 45 stations in the contiguous United States based on the radiosonde observations and normal maximum surface temperatures. The isopleth analyses of mean maximum mixing height were presented for each month. Holzworth (1967, 1972) estimated morning and afternoon mixing heights and average wind speeds through the mixing layer. He put forward the procedure to include the heat island effect and suggested that a value of 5°C be added to the minimum temperature to get the minimum mixing height.

A concept for the mixing length in diabatic conditions was introduced and elaborated by Businger (1959). Convective energy has effect on the mixing length but not on largest eddies. The theory developed on this concept of the mixing length for the diabatic wind profile gave satisfactory agreement with observations over a wide stability range. An atmospheric mixed layer model for a coastal region was studied by Davidson et al (1984) to predict changes in the inversion and mixed layer temperature and humidity, using data from the Los Angeles-San Diego Basin. The model microphysics and initialisation methods were evaluated separately.

Persistent horizontal rolls in the urban mixed layer were investigated by Kropfli and Kohu (1978) for the St.Louis region using a Dual-Doppler Radar. It was demonstrated that aircraft dispersed chaff could be used to trace the air motion over a several hundred kilometres area and through the entire depth of the developed mixing layer. The mechanism of energy exchange of a flow regime moving from water to heated land was studied in the laboratory under controlled conditions by Lai (1978). The results of the study indicated that the development of the thermal mixing layer was strongly dependent on local shear stress and heat flux. To estimate hourly mixing depth Benkley and

Schulman (1979) developed a one-dimensional operation model making use of 0000 GMT and 1200 GMT temperature soundings and hourly surface wind speed and temperature. By statistical comparisons with available acoustic sounder and radiosonde data, it was shown that, for one month of data at a central Illinois site, the proposed model demonstrated more skill than presently operational schemes.

The diurnal variation of mixing height over White Sands Missile Range, New Mexico was studied by Norton and Hoidale (1976), based on radiosonde observations. The results were displayed graphically and discussed. The laboratory experiments of Deardorff (1985) showed that the dispersion from a low-level source under convective conditions follows mixed layer similarity. The convective runs of the Prairie Grass dispersion experiment were reanalysed by Nieuwstadt (1980). It was seen that mixed layer similarity scaling also worked well for this classic field experiment. The observed cross-wind intergrated concentration closely matched the laboratory results.

Vittal Murty et al (1980a, 1980b) studied the mixing heights and ventilation coefficients over India for the four seasons namely winter, premonsoon, monsoon and postmonsoon. While computing mixing heights, appropriate heat island effect was applied. The spatial variation of mean maximum mixing heights over India was also studied by the isopleth analysis. Diurnal variation of mixing height and standard deviation of horizontal wind direction fluctuation ($\sigma_{\theta D}$) were studied for Visakhapatnam city by Sadhuram and Vittal Murty (1984). The study showed that the variation of mixing height almost followed values which reflect turbulence.

Daily estimates of morning and afternoon mixing depths, average wind speeds through mixing layer and ventilation coefficients during clear winter months for a period from 1970 to 1977 were studied by Padmanabhamurthy and Mandal (1979). Thickness and frequency of inversion were also studied. Padmanabhamurthy (1984) studied the spatial variation of mixing heights for India taking into account the data from 27 radiosonde stations in the country.

Some of the most useful expressions of the climatology of airflow are 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 Pennsylvania. They pointed out the major differences in the wind features between day time and night-time, the former having less calm frequency and strong winds and the later having more calm frequency and weak winds. The distributions of concentrations of the pollutants can also be depicted using wind roses. Slade (1968) presented the analysis of the persistence of wind direction. During conditions of weak pressure gradient on the macroscale, the description of airflow in cities was complicated because of the heat island effect, the channelling of flows by city 'street canyons' and local aerodynamic influences (Mc Cormick and Holzworth, 1976). True calm conditions rarely existed over any appreciable length of time. Stability wind roses were reported by Viswanadham (1980) and Sadhuram (1982).

Atmospheric stability is one of the most important elements in air pollution studies. Although wind, temperature and stability are studied separately, they are interrelated. In fact stability is a function of temperature, wind etc. A number of studies to determine the stability using various methods are presently available. It was shown that stability can be determined purely from the vertical temperature structure. A broad categorisation based upon vertical temperature structure is as follows (Hess, 1959) : (1) Absolutely unstable (if atmospheric lapse rate (ELR) is greater than dry adiabatic lapse rate (DALR). (2) Conditionally unstable (if ELR is in between DALR and saturated adiabatic lapse rate (SALR). (3) Neutral (Dry) (if ELR is equal to DALR). (4) Neutral (Moist) (if ELR is equal to SALR. (5) Absolutely stable (if ELR is less than SALR).

In air pollution climatology, these conditions are important since they determine the vertical extent of mixing. But for applying directly to pollution studies, the vertical temperature structure is not available everywhere and every time. This necessitated a more specific categorisation of stability conditions. Pasquill (1961) developed a method to classify stability with minimum available data. He proposed six stability categories to describe the diffusive potential of lower atmosphere in estimating the dispersion of pollutants. The categories are functions of wind speed, cloudiness and intensities of incoming and outgoing radiations. These are A (very stable), B (moderately unstable), C (slightly unstable), D (neutral), E (slightly stable) and F (moderately stable).

Turner (1961,1964) modified the above scheme, which was developed for rural areas and successfully applied 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 it 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 frequency of occurrence of the stability category, D in each direction and speed class was computed for Birmingham, Alabana by Mc Cormick and Holzworth

(1976). Sadhuram (1982) computed Pasquill's categories for Visakhapatnam for a 10 year period.

Wang (1981) developed analytical relations to determine the surface layer stability and eddy fluxes using wind speed and vertical temperature gradient measurements. Analytical relations are determined between Monin-Obukhov parameter and modified bulk Richardson number expressed in terms of measured wind speed and vertical temperature difference. Measured Monin-Obukhov parameters and Richardson number were compared with those calculated using these relations as well as those using the conventional schemes developed earlier by Golder (1972). Effects of different choices of parameters in flux profile relationship with respect to the predicted stability parameter and to the plume dispersion parameter were discussed. The role of atmospheric stability in the lowest 30m in characterising the dispersion of the primary pollutants, Carbon monoxide, nitric oxide and hydrocarbons was investigated by Remsberg and Woodberg (1983) using the 1976 air quality data set for St.Loius. Stability was determined in three separate ways (1) from tower measurements of the vertical temperature gradient, dT, (2) tower measurements of wind speed u and (3) an approximation to the bulk Richardson number B, based only on dT and u in the surface layer. High positive correlation coefficients were obtained between area averages of dT and each of the species for the inner urban area of St. Louis.

The influence of atmospheric stability on the growth rate of puffs used in plume simulation models was studied by Ludwig (1982). The dependence of plume growth rate on plume size was discussed. It was shown that growth rates estimated by the techniques used in some widely distributed puff models can be in error by as much as two orders of magnitude, although the errors were more commonly in range of 10%. The concept of vertical travel distance was shown to provide a more realistic representation of the physical processes involved in plume growth after a change in atmospheric stability. The dependence of boundary layer shear on diurnal variation of stability was studied by Heald and Mahrt (1981). The applicability of the power law for use in shear estimate was examined. Temperature and wind speed measurements over a 6 year period from a 32m tower located in a primarily rural area were used to assess the pollutant dispersive characteristics of a rural site by Takle et al (1976). A monthly comparison of a crude pollution-trapping index showed July through September, the most favourable and December through February the least favourable months for trapping contaminants emitted from ground-based sources in rural areas.

Diurnal and seasonal variation of Pasquill's stability classes at a coastal station were studied by

Sadhuram and Vittal Murty (1983, 1986). The studies revealed that unstable conditions during day time were not always observed in the four months, viz. January, April, August and October, typical of the respective seasons. Neutral conditions were present during day and night, sometimes with high percentage frequencies just after sunrise and before sunset. The study of stability wind roses indicated highly and moderately unstable conditions and stable conditions were associated with low wind speeds and slightly unstable and neutral conditions were associated with high wind speeds. Studies by the same authors regarding the seasonal variation of $\sigma_{\theta D}$ vs Pasquill's stabilities over complex terrain showed that the values of $\sigma_{\theta D}$ were quite high in the months of April in contrast with other months. Values were also high when compared with those estimated over flat terrain and at coastal sites.

Stability of the atmosphere is an important tool in determining the dispersion and thereby the resulting concentration of the pollutants. The stability categories suggested by Pasquill and modified by Turner (1964) were computed for four major urban centres in India by Viswanadham et al (1981). The percentage occurrence of these stability categories was worked out and a relative comparison among the four cities was made.

Horizontal wind direction fluctuation studies were carried out by Panchal and Chandrasekharan (1983) for Madras Atomic Power Project, Kalpakkam. Values of $\sigma_{\theta D}$ showed as high as three fold variation for the same atmospheric stability depending on the effective roughness length of the upwind sector. Average $\sigma_{\theta D}$ values separated for sea and land breeze conditions, when correlated with Pasquill's stability categories showed a monotonic decrease with increasing stability for land breeze but found to increase for change from D to F category during sea breezes presumably due to the influence of an internal boundary layer development. Studies were carried out to obtain values corresponding to different stability classes by Shirvaikar (1975), Padmanabhamurthy and Gupta (1979), and Sadhuram and Vittal Murty (1983). Sadhuram (1982) gave an account of seasonal variation of $\sigma_{\theta D}$ for Visakhapatnam city which showed considerable variation in the relation for unstable classes. Sadhuram and Vittal Murty (1984), however, showed a trend of variation between $\sigma_{\theta D}$ and mixing height for 4 typical months for Visakhapatnam which showed an excellent relationship between these two.

The capability of the lower layers of the atmosphere to transport and disperse pollutants from their source depends primarily on the average speed of the wind near the surface and the degree or intensity of the air turbulence. Smith (1983) studied the long range transport of air pollution. The nature of emissions, 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 were investigated. An account of computer modelling was also presented.

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 the city. Mitchell (1984) discussed the physical process through which certain gases influence climate and summarised those constituents which are most likely to make a significant contribution to the climatic change over the next few decades and illustrated how numerical models are being used to estimate details of such changes in climate. For diffusion studies, atmospheric dispersion measurements were done by Norman (1961) and Albert (1963). Plume dispersion coefficients were discussed by Sheih et al (1980) in terms of single particle and relative diffusion and were investigated as functions of averaging time. Air pollution transport studies in a coastal zone using kinematic diagnostic analyses were done by Keen et al (1979) and the computed three-dimensional trajectories were presented using computer graphics displays. Brock and Hewson (1963) used the analog computer to obtain solutions to the diffusion equation for the case of continuous point source aloft. The basic model used was that of a source located between an inversion and the ground where the wind speed and eddy diffusivity were constant over the diffusing region.

Results of urban pollutants measurements made during an aircraft flight downwind of St.Louis were presented by Alkezweeny and Drewes (1977). Decrease in the levels of sulphur dioxide, nitrogen dioxide, nitric oxide and aerosols were noted, while ozone was observed to increase to more than 200ppb at 150km downwind. Vertical ozone distribution in the lower troposphere over Point Mugu, California was investigated by Duane (1968) using ozonesondes. The sounding showed a pronounced tendency for maximum ozone to occur above the base of the low level temperature inversion. It seems likely that ozone stored therein can at times reach the surface and contribute to localised pollution.

Lidar observation of elevated pollution layers over Los Angeles was done by Wakimoto and Mc Elroy (1986) using an aircraft. Detailed ancillary upper air kinematic and thermodynamic data were collected simultaneously to aid in the interpolation of those elevated layers. Lebedeff and Hameed (1976) solved a two dimensional diffusion equation by an integral method to obtain the distribution of ground level concentration of an alert effluent emitted from a semi-infinite area source in a steady state and horizontally homogeneous atmospheric surface layer. 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.

Particulate deposition due to Indraprastha power plant within 15km of the plant was computed by Padmanabhamurthy and Gupta (1977) employing the long period 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. The dispersal of pollutants from an elevated point source was computed by a numerical method by Gupta (1980). The computations were made with forward time differences. But backward space differences were used for computing the horizontal advection of pollutants. A comparison between a numerical solution of the diffusion equation and the Gaussian plume model for different atmospheric conditions were done.

Diurnal and seasonal variations of the atmospheric contents of sulphur dioxide, nitrogen dioxide, nitric oxide and aldehydes at BARC, Bombay during 1973 was investigated by Zutshi et al (1976) who found that the four hourly average concentration during 1972 and 1973 were logarithmic normally distributed. Diurnal variations of vertical mixing of the atmosphere were studied by Viswanadham and Ram Mohan (1980) for Cochin. They determined the periods of high and low dispersals and suggested certain abatement steps for mitigation of air pollution problem.

Thermodynamic properties and aerosol patterns in the plume downwind of St.Louis were studied by Shea and Aner (1978) using an instrumented aircraft equipped to measure temperature, humidity, turbulence, aitken nuclei and wind speed and direction. A conceptual model describing various urban influences on the mid-day mixing layer downwind of metropolitan areas was synthesised. The height of buoyant plumes in a stably stratified environment was studied by Todd and Leonard (1962).

In order to study the behaviour of the plume emitted from the air-cooled nuclear reactor at Brookhaven National Laboratory on central Long Island, radioactive argon-41 was measured by Peterson (1968) using an airborne gamma-ray spectrometer as far as 160 nautical miles downwind on a day with neutral stability. Cooling tower plumes from energy centres were studied by Hanna (1977). Average annual plume rise was estimated. The predicted plume rise, visible plume length and cloud formation were given as functions of time of day, year and weather type.

A large data set containing the measurements of the rise of plumes emitted by five Tennesse Valley Authority steam plants was examined by Domenico (1985). Plume merging was studied in detail in neutral and stable conditions. The existence of a critical angle for merging was suggested by Briggs (1975). He proposed a formula to describe plume rise in the transitional and final phases, both in neutral and stable conditions. The plume rise equations of Briggs were described and applied for hypothetical short and very tall chimneys at five National Weather Service rawinsonde stations across the United States, by Holzworth (1978). It was seen that the effluent from tall chimneys remains airborne longer than that from short chimneys hence transported over greater distances and has more probability to undergo chemical transformations before reaching the ground.

An improved puff algorithm for simulating plume behaviour was discussed by Zannetti (1981). Modifications to the basic methodologies were introduced which make it more generally applicable to non-stationary and non-homogeneous conditions, as well as calm wind situation. The model accurately reproduced the analytical solution to the steady state Gaussian plume equation. Radar observations of a plume of microwave reflecting chaff was reported by Moninger and Kropfli (1982). The advantages and disadvantages of radar acquired transport and diffusion data were discussed and the data on the horizontal and vertical spread of the plume was compared with other atmospheric experiments.

Lateral turbulence intensity and plume meandering during stable conditions were investigated by Hanna (1983). When no turbulence data are available, an empirical formula was suggested which predicts the hourly average lateral turbulence intensity as a function of wind speed and hour to hour variations in wind directions. Experimental study of an artificial thermal plume in the boundary layer was done by Benech et al (1986) and Noilhan and Benech (1986). Flow characteristics near the heat source and thermodynamic and dynamic structure within the plume were studied. Padmanabhamurthy and Gupta (1980) made a comparative study of various plume rise formulae.

Meteorological model 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 prevailing meteorological as well as geophysical conditions. A review of the past work was made by Wanta (1968), Moses (1969) and Turner (1979). Gaussian diffusion model is the most popular and is easy to apply. This model is based on the Fickian diffusion equation. Gifford (1968) gave a complete discussion on the Gaussian diffusion model.

In addition to Gaussian type of formulation there is another fundamental type which is based on the equation of mass conservation. There are two main classes of models in this category : (i) Eularian model and (ii) Lagrangian model.

While Gaussian model calculates concentration of pollutants source by source or receptor by receptor, the Eulerian model calculates concentration throughout a region at one time. Mac Cracken et al (1971) made use of the above models in the San Francisco Bay area. The Lagrangian model was used by Behar (1970) to investigate Los Angeles photochemical smog. In the box models, a complete vertical mixing is assumed and diffusion between boxes is neglected, which could possibly lead to erroneous results. The Lagrangian models were based on many approximations and the accuracy of the solutions were limited (Johnson et al 1976). Despite the presence of many other models, Gaussian diffusion model is still the most popular model and there are considerable modifications to improve the validity of the model.

It is often difficult to validate the model. However, Pooler (1961) applied a model to determine the monthly concentration of sulphur dioxide at 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, which were simpler (Zimmerman, 1971; Turner et al 1972). Gifford and Hanna (1973) tested a simple model and found that the results were very close to complicated models.

There were some short term models which calculate concentrations for time periods of half an hour to one day. Turner (1964), Clarke (1964) and Koogler et al (1967) computed concentrations ranging from two to twentyfour hours. All these short term models use a single wind direction for each period. Hilst (1968) developed a regional model that took account of the variation of wind. Gifford (1973) evaluated the performance of several simple models with available data to compare the performance, revealed that the estimates from the simple models are often as good as those from the more complex models.

For the model computations, the main parameters required are effective stack height and dispersion parameters σ_y and σ_z. Effective stack height is the sum of physical stack height and plume rise. A knowledge of effective stack height is a must for the evaluation of any model. There are a number of formulae to estimate the effective stack height. Lucas et al (1963), Slawson and Csanady (1967), Briggs (1969), Davidson-Bryand (1975) and Holland (1975) suggested formulae to estimate effective stack height, most of which are functions of horizontal wind at the physical stack height, ambient temperature, plume temperature, vertical velocity of the plume and physical stack parameters. Vittal Murty and Viswanadham (1978) reviewed various plume rise formulae and concluded that no two formulae yielded the same result, and suggested that a formula suitable to the local conditions be chosen.

Pasquill (1962) revealed the diffusion coefficients in terms of standard deviations. Mc Elroy (1969) proposed the relation between σ_y and σ_z in terms of downwind distances as follows. $y = bx^p$, $z = ax^k$ where a,b,p and k are constants whose values are functions of stability. Turner (1970) prepared nomograms for computing σ_y and σ_z as a function of downwind distance and Pasquill's stability category. Das et al (1973) applied Gaussian plume model to study the dispersal of pollutants from Mathura refinery in two stages : (i) the short period concentrations were computed under the vast meteorological conditions, to estimate the peak concentrations and (ii) the long period concentrations were studied for planning purposes. Vittal Murty et al (1977) presented a theoretical model for calculating ground concentrations of sulphur dioxide at Visakhapatnam. The seasonal and annual variations were studied. Viswanadham (1980) applied the Gaussian model for multiple source for the 4 major cities in India. Shirvaiker et al (1969) developed a finite plume model based on wind persistence. Gupta (1980) suggested a numerical solution for the dispersal of pollutants from an elevated point source. He compared the results with that of Gaussian plume model and reported that the latter did not provide correct estimates at larger distances downstream as the horizontal advection was not taken into account. Despite the presence of many models, current models are based upon the concept of Gaussian plume model. A Gaussian model for continuous elevated sources was developed by Overcamp (1983) 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. A statistical plume model with first order decay was developed by Overcamp (1982) to estimate the downwind concentrations from a continuous point source of certain radioactive contaminants.

Using the Eulerian form of the mass conservation equation integrated vertically from the surface to the base of inversion, Mac Cracken et al (1978) developed two regional air quality models (LIRAQ-1 and LIRAQ-2) for use in San Francisco Bay area. These models consider the complex topography, changing meteorology and detailed source emission pattern in generating surface and vertical average pollutant concentrations. The focus of LIRAQ-1 is the treatment of transport and dispersion of relatively non-reactive species whereas LIRAQ-2 treats photochemically active pollutants. Duewer et al (1978) used topographical, meteorological source emission and atmospheric pollution concentration data, to verify the LIRAQ-1 and LIRAQ-2 models. It was seen that the temporal and spatial phasing for concentrations of carbon monoxide, ozone and oxides of nitrogen can be adequately represented by the models. Sensitivity studies indicated that initial and horizontal boundary layer conditions as well as grid size and subgrid scale effects are less significant than emissions, meteorological and vertical boundary conditions in dealing with regional concentrations of pollutants.

The theory of concentration fluctuations by non-Gaussian and Gaussian particle separation probability density functions were explored by Sawford (1983), using two Lagrangian Monte Carlo models. He found that the non-Gaussian model predictions are in agreement with observation, whereas the Gaussian model incorrectly predicts concentration fluctuations. The reason for the failure of the latter is the large time intervals, which accounts only for the meandering contribution to fluctuations and smoothens all interval structure of the cloud, eliminating relative fluctuations. With the assumption of Gaussian subgrid scale distributions, Shannon (1979) developed a new method of solution of the advection diffusion equation. The Gaussian moment conservation technique is found to be computationally rapid and applicable to telescoping grid systems and to model diffusion accurately.

A three-dimensional hydrostatic meteorological model was developed by Anthes and Warner (1978). The model contains provisions for variable terrain, a moisture cycle, sensible heat addition at the earth's surface and high and low resolution boundary layer physics. Sheih (1978) developed a scheme to minimise the pseudo diffusion which arises in numerical solution and transport. In this model, the subgrid distribution of pollutant concentration was parameterised by a Gaussian puff and at each time step the concentration within each grid volume was characterised by a Lagrangian puff.

Markov chain model that simulates the trajectories of fluid particles in turbulent flow was described by Legg (1983). It incorporated fluctuations in vertical streamwise velocity and can be used with velocities that have a skewed probability distribution. The model was used to estimate the distribution of heat downwind of an elevated line source in the boundary layer above a rough surface and the results were compared with those from a wind tunnel experiment.

The various approaches to long-range transport modelling were outlined by Eliassen (1980) and some of their virtues and shortcomings were discussed. It was seen that the long term deposition and concentration patterns can be estimated reasonably well, whereas agreement between calculated and observed daily concentrations was more variable. The various aspects of statistical measures for evaluating the urban air quality models were discussed by Downtown and Dennis (1985) and a procedure for evaluation of air quality models for regular use was suggested.

Factors such as diffusion in the convective boundary layer (CBL), convective scaling parameters and non-Gaussian nature of vertical diffusion were usually incorporated in some applied models. Weil (1985) suggested that the most important suggestions were the use of the convective velocity scale and the CBL height directly in expressions for the dispersion parameters (σ_y and σ_z).

A model was developed by Gupta and Padmanabhamurthy (1984) to assess the air quality over short periods of the order of an hour to a day of relatively stable pollutants over an urban area. The steady state Gaussian diffusion equations for point sources and their integration for area sources were utilised. The average 24 hour concentration of sulphur dioxide by this model during any of the four seasons at Delhi due to area and point sources did not exceed the United States Environmental Protection Agency's (USEPA) primary air quality standards. However, for some pockets in Delhi around industrial areas, the values exceeded the USEPA secondary standards. Vittal Murty et al (1977) determined the spatial distribution of sulphur dioxide concentrations using a model and suggested optimum locations for setting up of new industrial complexes.

A one dimensional transport model was developed by Venkatram and Viskanta (1977) to study the effects of radiative precipitation of elevated pollutant layers. Special features of the model include a turbulent kinetic energy model and a two-stream solar radiation model. Pollutants were assumed to consist of aerosols and pollutant gases. Their studies showed that elevated layers of pollutants would control mixed layer expansion by modifying the stability of the capping stable layer.

Turbulence parameters for application in air pollution modelling were estimated by Manjukumari and Sharma (1987). Profile relationships based on Monin-Obukhov similarity theory were used to estimate friction velocity and friction temperature at the surface with available routine meteorological data for Delhi. In order, to make the method more realistic a radiation model was coupled with an iterative procedure adopted for the similarity theory approach. The various applications of turbulence parameters were presented and discussed.

2.2 MATERIALS AND METHODS

This section deals with the details of the data used for the present study and its source and the computational procedure of mixing height, ventilation coefficient, wind rose, Pasquill's stability, $\sigma_{\theta D}$ and $\sigma_{\theta S}$. Evaluation and application of the Gaussian model to study the spread of sulphur dioxide from multiple sources are also discussed.

2.2.1 Materials

The present study is carried out using a five year period data from 1977 to 1981 for all the months pertaining to Madras station. The data used for the study are of two types, which are : (i) Meteorological data and (ii) Emission inventory. The meteorological data collected are hourly surface temperature, hourly surface wind speed and direction, vertical temperature at an interval of 50mb from surface to 500mb, three hourly cloud type, amount and height, and wind direction and speed fluctuations for every 15 minutes interval for the months of January, April, July and October, which are considered to be typical of winter, premonsoon, monsoon and postmonsoon seasons respectively. The sources of the above data are India Meteorological Department, Pune and Regional Centre of I. M. D., Madras.

The various pollution data collected are the physical stack heights, emission rates, stack diameters, temperature of effluents, types of fuel used, rates of consumption of fuel and composition effluents for all the industries in Madras city.

2.2.2 Methodology

2.2.2.1 Inversions, isothermals and lapse conditions

These parameters are determined for the layer from surface to 1000mb and for every layer, 50mb 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. 2.1. 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,

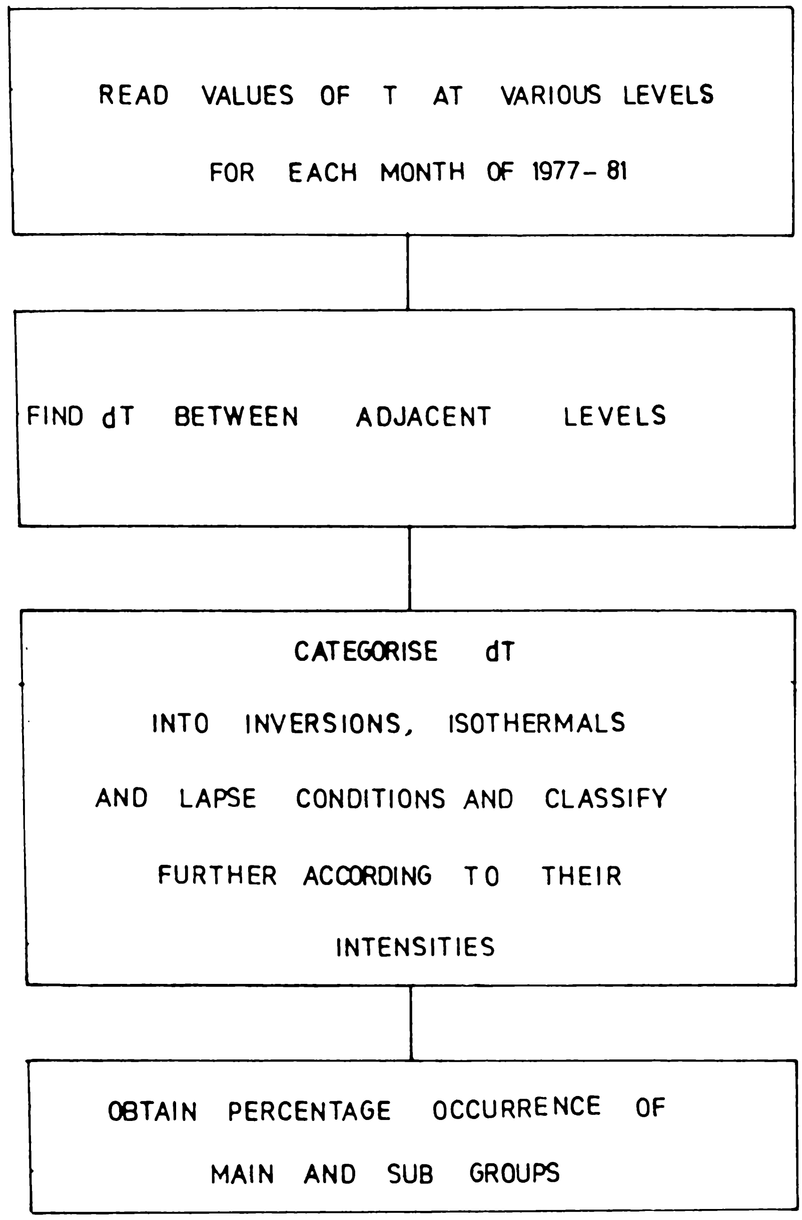


FIG. 2.1. BLOCK DIAGRAM FOR THE COMPUTATION OF ISOTHERMALS, INVERSIONS AND LAPSE CONDITIONS

isothermals and lapse conditions in all the layers together for each month, pie diagrams are drawn and the monthly variation of these parameters are studied.

2.2.2.2 Mixing height and Ventilation coefficient

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 days of the five year period and the hourly mean values are calculated for each month and the diurnal and monthly variations are studied.

2.2.2.3 Atmospheric stability

To determine stability categories the method suggested by Pasquill (1961) and modified by Turner (1964) is made use of. Table 2.1 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 2.2.

b) If total cloud cover $\leqslant 5/10$, the net radiation index from table 2.1 corresponding to the insolation class number is used without modification.

Table 2.1

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

Wind speed (knots)	Net radiation index 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

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 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 2.1.

Table 2.2

Insolation as a function of solar altitude

Solar altitude(a) (in degrees)	Insolation class number
$a \geq 60$	4
$35 \leq a \leq 60$	3
$15 \leq a \leq 35$	2
$a \leq 15$	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. 2.2. The hourly values of

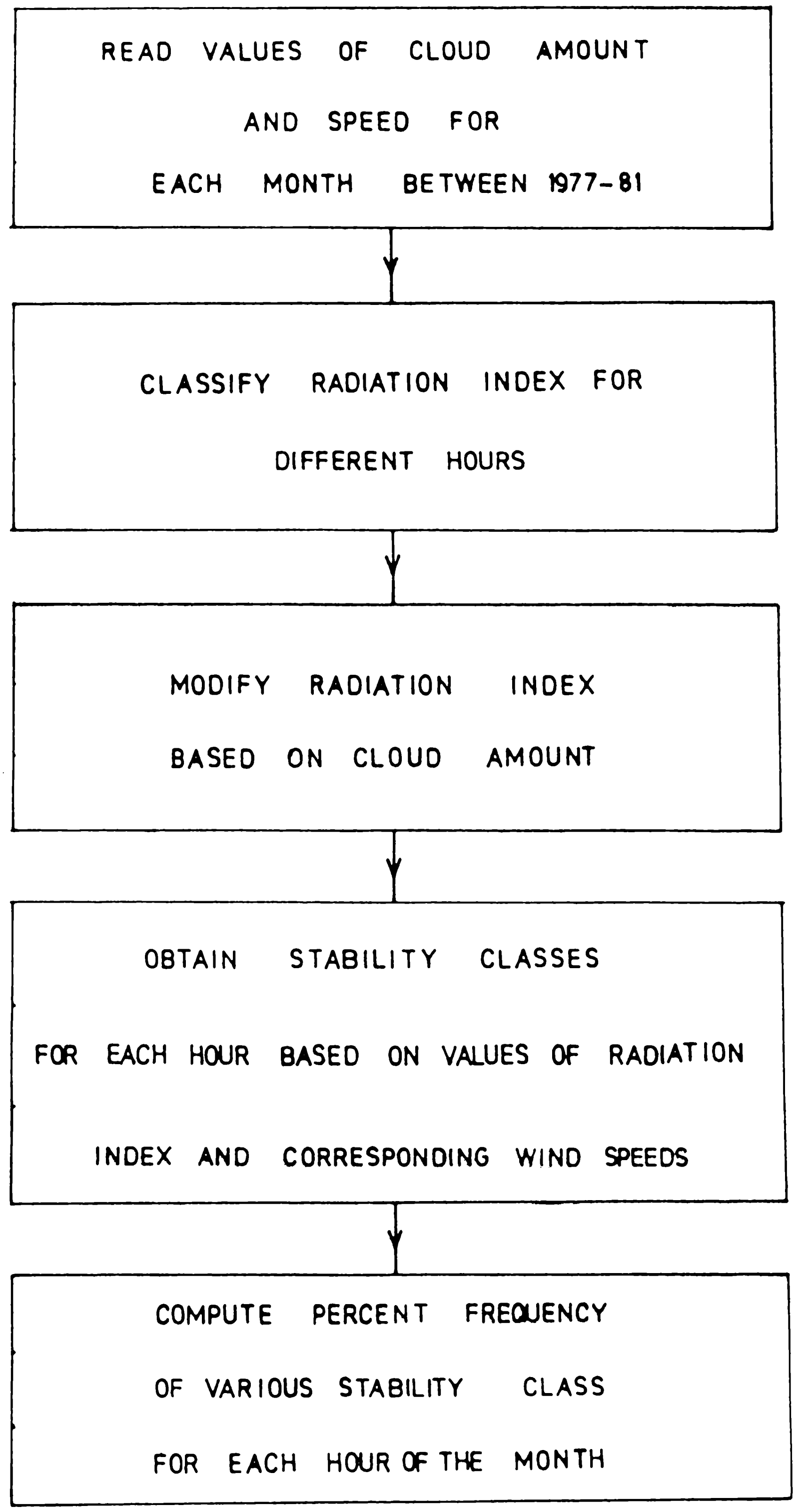


FIG. 2.2. BLOCK DIAGRAM FOR DETERMINING PASQUILL'S STABILITY CLASSES

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.

2.2.2.4 Wind roses

The hourly wind speed and direction for all days of 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. 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. 2.3. By taking a suitable scale, wind roses are drawn at six hourly intervals. A wind rose consists of a small circle in which normally the calm percentage is indicated and 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.

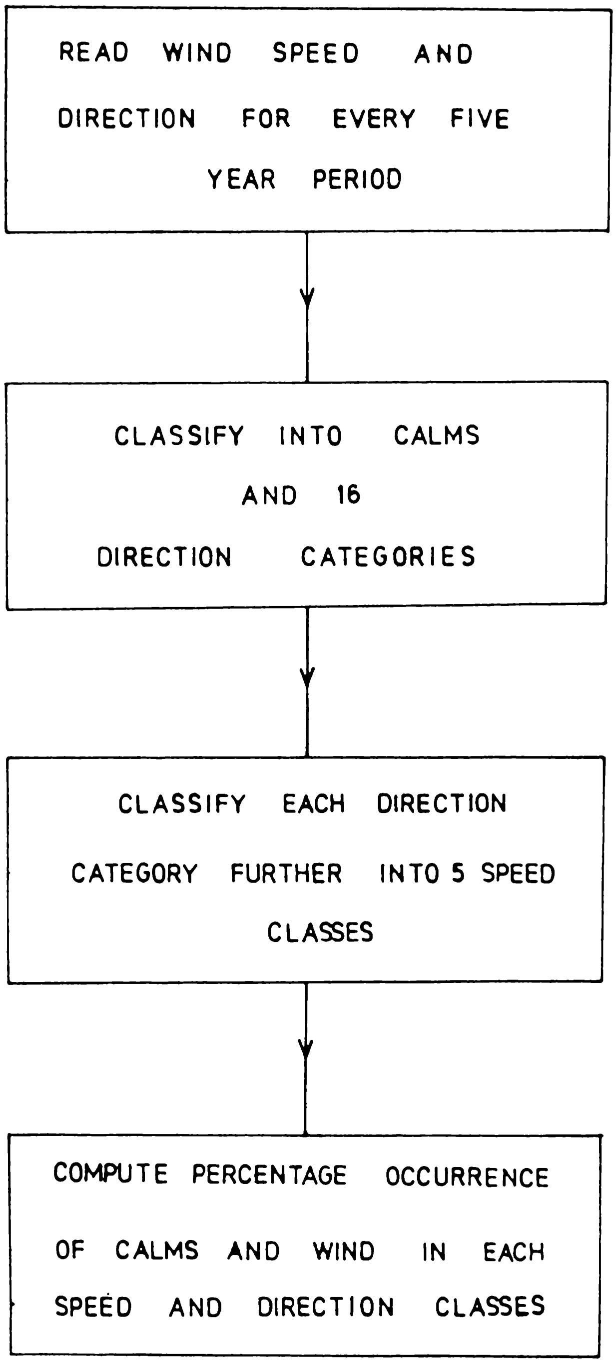


FIG. 2.3. BLOCK DIAGRAM OF THE PROGRAM FOR WIND CLASSIFICATION

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

For computing the standard deviations of wind speed and direction fluctuations ($\sigma_{\theta D}$ and $\sigma_{\theta S}$), the method suggested by Slade (1965) is made use of. The wind speed and direction fluctuations in each hour 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 $\sigma_{\theta D}$ and $\sigma_{\theta S}$ 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 $\sigma_{\theta D}$, $\sigma_{\theta S}$, mixing height and stability are studied.

2.2.2.6 Gaussian plume model development and determination of sulphur dioxide concentrations

(i) Application of the model to Madras city

There are many small scale and large scale industries in Madras. The major industries include a refinery, a

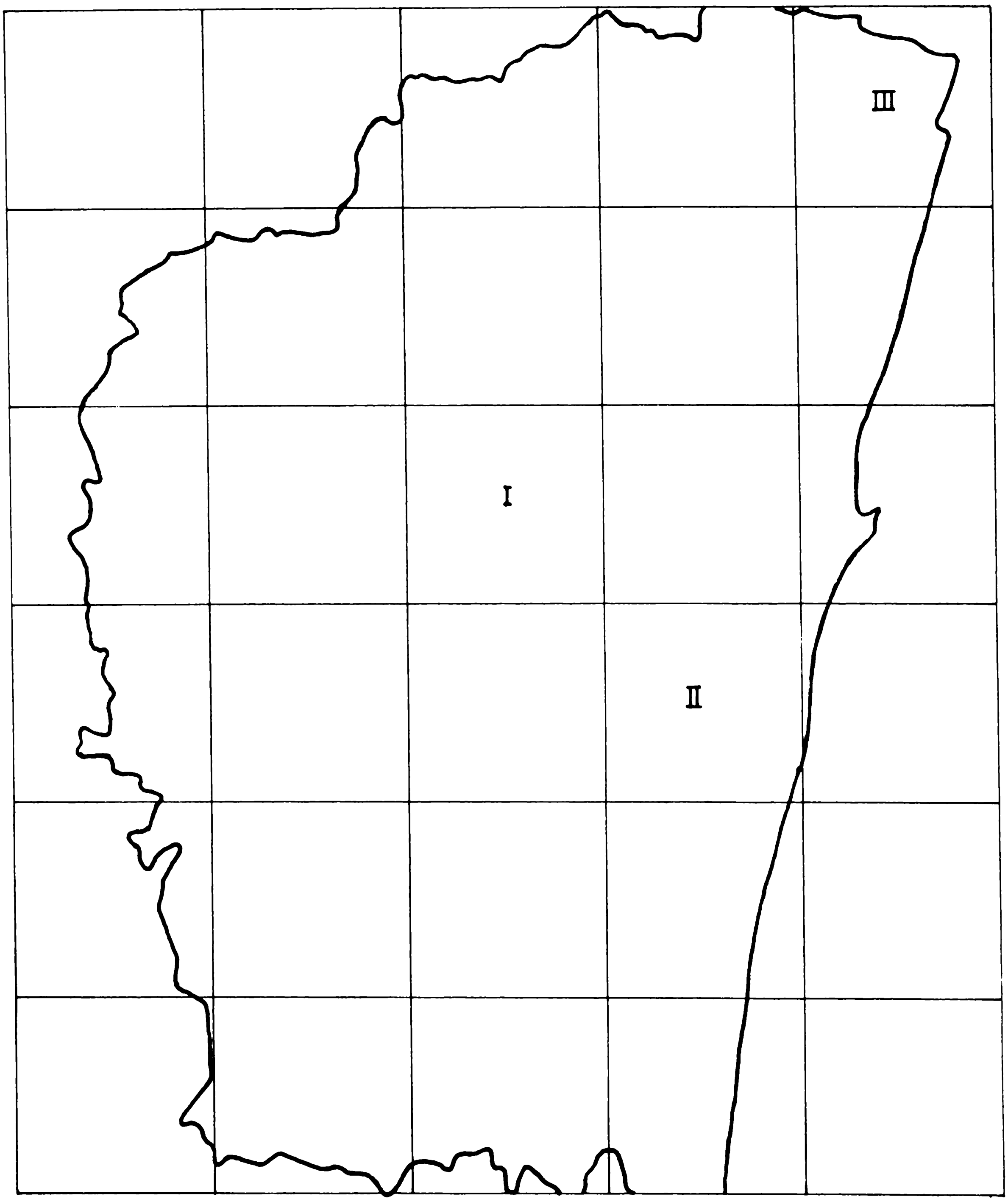


FIG. 2.4. MAP SHOWING THE LOCATION OF SOURCES

fertilizer plant and a thermal power plant. Subsidiary industries are many and there are altogether more than 200 industries in the city and neighbourhood. However, their major sources are identified according to the clustering of industries. They are (1) Ennore, (2) Ambattur and (3) Guindy. The rate of emission of suphur dioxide from these sources is worked out as 34.72, 23.15 and 23.15 gs^{-1} respectively. Locations of these sources are shown in Fig. 2.4.

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.

a) 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 cross wind directions. The distribution in the vertical and cross 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 downwind direction resulting in lower concentrations. Hence it can be written as

$$\chi \propto \frac{1}{U} \qquad (2.2)$$

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).

$$\chi \propto A \exp\left[-1/2\,(y/\sigma_y)^2\right] \qquad (2.2)$$

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

$$\chi \propto B \exp\left[-1/2\left(\frac{z-h}{\sigma_z}\right)^2\right] \qquad (2.3)$$

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 (2.3) 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 a 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 perfect 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.

$$\chi \propto B\left[\exp\left(-1/2\left(\frac{z-h}{\sigma_z}\right)^2\right)+\exp\left(-1/2\left(\frac{z+h}{\sigma_z}\right)^2\right)\right] \qquad (2.4)$$

The Gaussian function can be normalised 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

$$\int_{-\infty}^{+\infty} \exp\left[-1/2\,(y/\sigma_y)^2\right] dy = \sqrt{2\pi}\,\sigma_y \qquad (2.5)$$

So,

$$\frac{1}{\sqrt{2\pi}\,\sigma_y} \int_{-\infty}^{+\infty} \exp\left[-1/2\,(y/\sigma_y)^2\right] dy = 1 \qquad (2.6)$$

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 and wind speed and by replacing A and B with the respective values.

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

$$\left[\exp\left(-1/2\,(\frac{z-h}{\sigma_z})^2\right) + \exp\left(-1/2\,(\frac{z+h}{\sigma_z})^2\right)\right] \qquad (2.7)$$

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 (2.7).

$$\chi_{(x,y,0,h)} = \frac{Q}{\pi \sigma_y \sigma_z U} \exp\left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{y^2}{2\sigma_z^2}\right)\right] \quad (2.8)$$

The concentration along the plume centre line at the ground can be obtained by putting Y = 0 in the equation (2.8), thus

$$\chi_{(x,0,0,h)} = \frac{Q}{\pi \sigma_y \sigma_z U} \exp\left(\frac{h^2}{2\sigma_z^2}\right) \quad (2.9)$$

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).

$$\chi = \frac{2Q}{2\pi \sigma_z U (2\pi x/16)} \left(\exp\left(-1/2 \left(h/\sigma_z\right)^2\right)\right) \quad (2.10)$$

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

The equations (2.8) to (2.10) 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

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

for short term concentrations and as

$$\chi \quad \frac{Q}{LU\,(2\pi x/16)} \quad \text{or} \quad \frac{2.55\,Q}{LUx} \qquad (2.12)$$

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 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 (2.10) or (2.12) 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.

b) 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-2σ_z to h+2σ_z (if 2σ_z > h, then the wind can be averaged from surface to h+2σ_z). This height difference varies with downwind distance and so does the mean wind speed. Hence for each downwind distace 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 $h-2\sigma_z$ to $h+2\sigma_z$ 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.

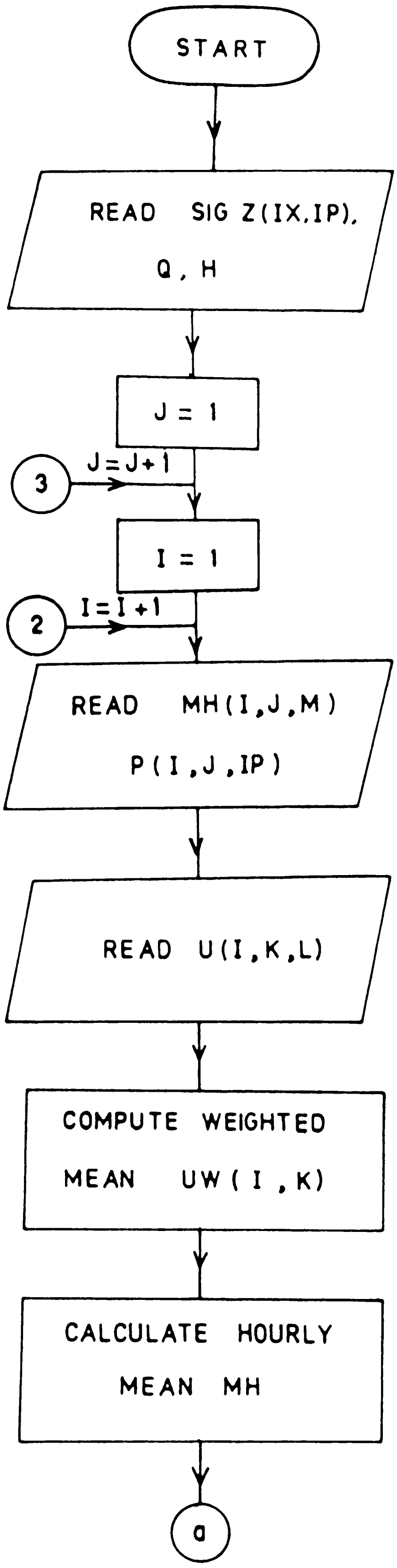
This formula does not require the knowledge of heat emission and is preferred, as the value of heat emission is not available.

c) 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 4km X 4km grids and the concentration in each grid due to all the three sources are added together and isolines are drawn.

d) Computer program

Fig. 2.5 shows the flow diagram of the numerical scheme in fortran used to obtain spatial distribution of sulphur dioxide concentration for Madras 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



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

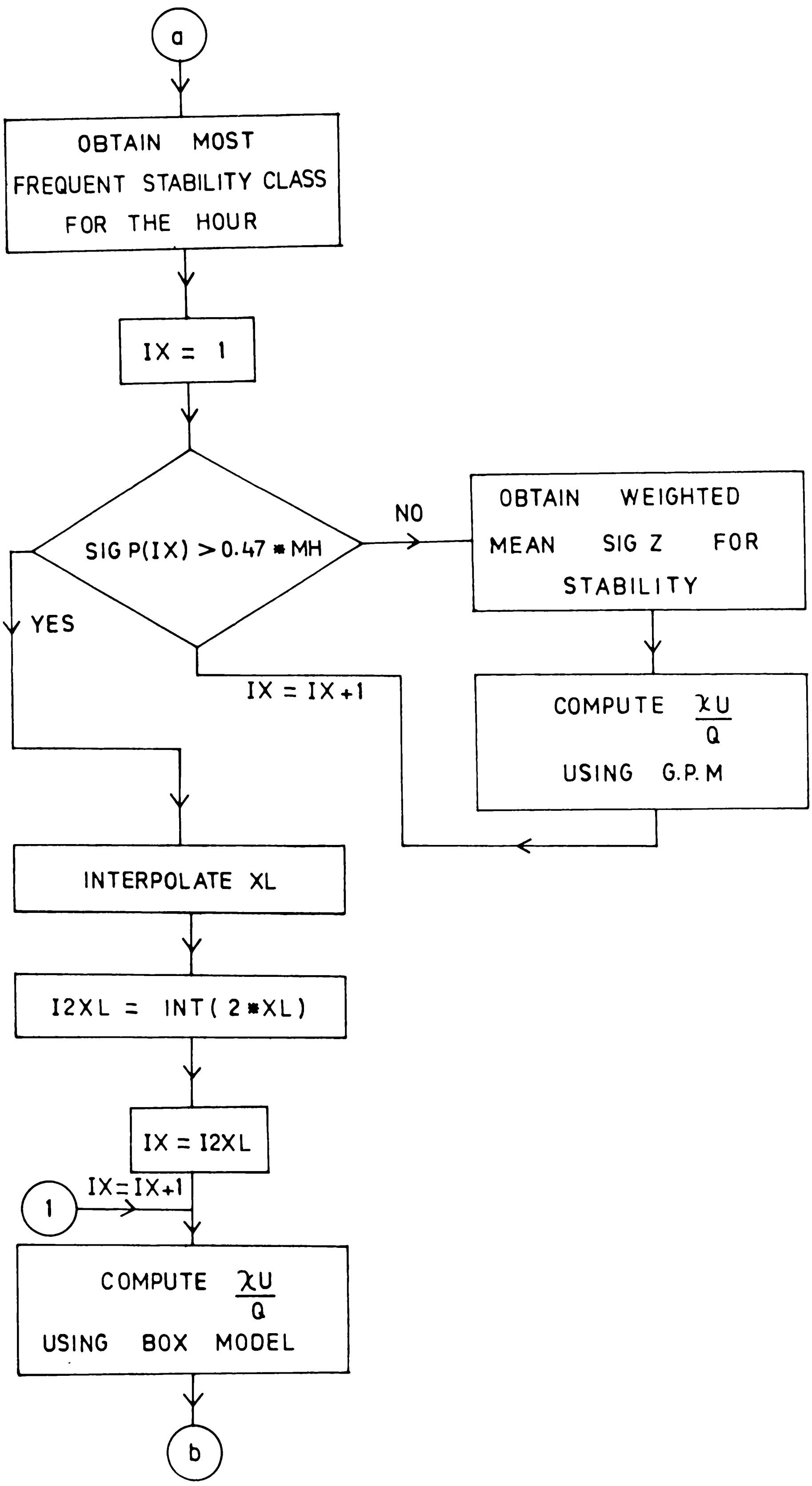
U(I,K,L) = PERCENT FREQUENCY OF WIND

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 χU/Q USING G.P.M
IX = IX + 1
INTERPOLATE XL
I2XL = INT(2 * XL)
IX = I2XL
IX=IX+1
1
COMPUTE χU/Q USING BOX MODEL
b

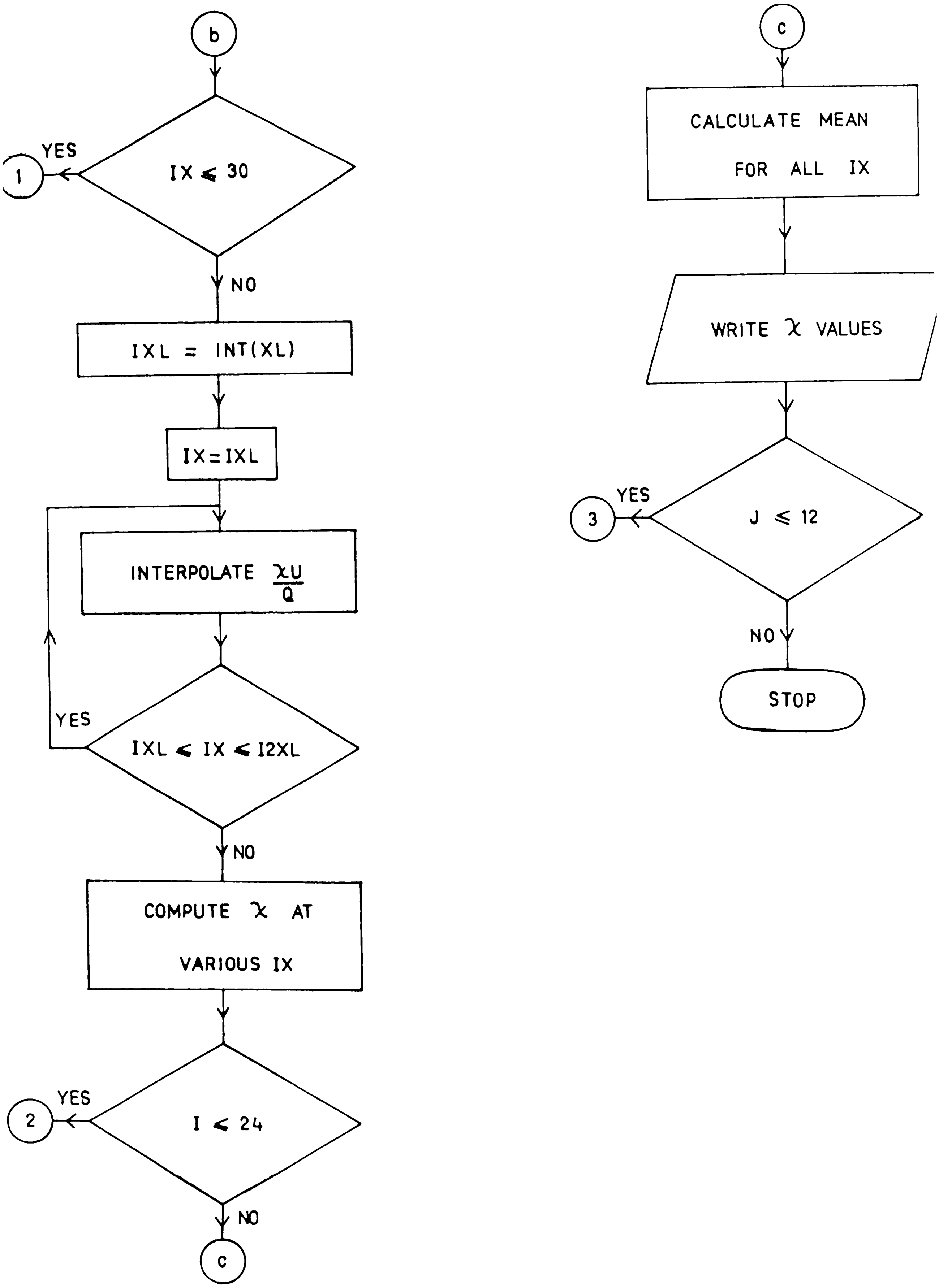


FIG. 2.5. FLOW CHART OF THE PROGRAM FOR SULPHUR DIOXIDE CONCENTRATIONS USING GAUSSIAN PLUME MODEL

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.

2.2.2.7 Merits and limitations

Merits

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

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

(3) The hourly wind frequency tables are prepared and the wind roses are drawn for every six hours for all the months.

(4) The wind direction fluctuation range ($\sigma_{\theta D}$) and wind speed fluctuation range ($\sigma_{\theta S}$) are computed taking continuous record of graphs. Nearly 2000 such graphs are made use of to compute both $\sigma_{\theta D}$ and $\sigma_{\theta S}$.

(5) For the first time a relation between these two is obtained.

(6) The representative values of $\sigma_{\theta D}$ and $\sigma_{\theta S}$ are obtained for Pasquill's stability categories and mixing heights.

(7) The monthly distribution of sulphur dioxide concentration is studied spatially for Madras.

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

Limitations

(1) In the computation of ventilation coefficients, only surface wind is considered instead of mean wind through the mixing layer.

(2) The calm conditions could not be considered in the application of the model.

(3) The validation of the model also could not be taken up for want of information regarding the observed levels of pollutants.

(4) The non-inclusion of vehicular traffic is also one of the drawbacks, whose contribution is considerable.

(5) The assumption of perfect reflection of pollutants at the ground, in the model is not completely correct.

CHAPTER III

ATMOSPHERIC DISPERSAL CAPACITY FOR MADRAS

In the present chapter inversions, isothermals, lapse conditions, mixing heights, ventilation coefficients, wind roses and stability of the atmosphere are presented.

3.1 INVERSIONS, ISOTHERMALS AND LAPSE CONDITIONS

The computational procedure for finding the percent frequency of inversions, isothermals and lapse conditions are outlined in the preceding chapter. The relative percent frequency of occurrence of these three conditions are represented in Fig. 3.1 for all the months. The lapse conditions are extremely high in all the months accounting for more than 80%. Inversions and isothermals constitute the other 20%. The percent frequency of inversions is relatively high during the period from December to March with a maximum of 10.7 in January.

The high frequency of lapse condition is natural due to the reason that earth gets heated from surface and as such the atmospheric temperature should decrease with height in the atmosphere. However, due to various other reasons, this is not always so, because sometimes the temperature remains constant with height or increases with height, both of which are very important events as far as air pollution is concerned, since they inhibit the dispersion of pollutants. The relatively high frequency of inversions from December to

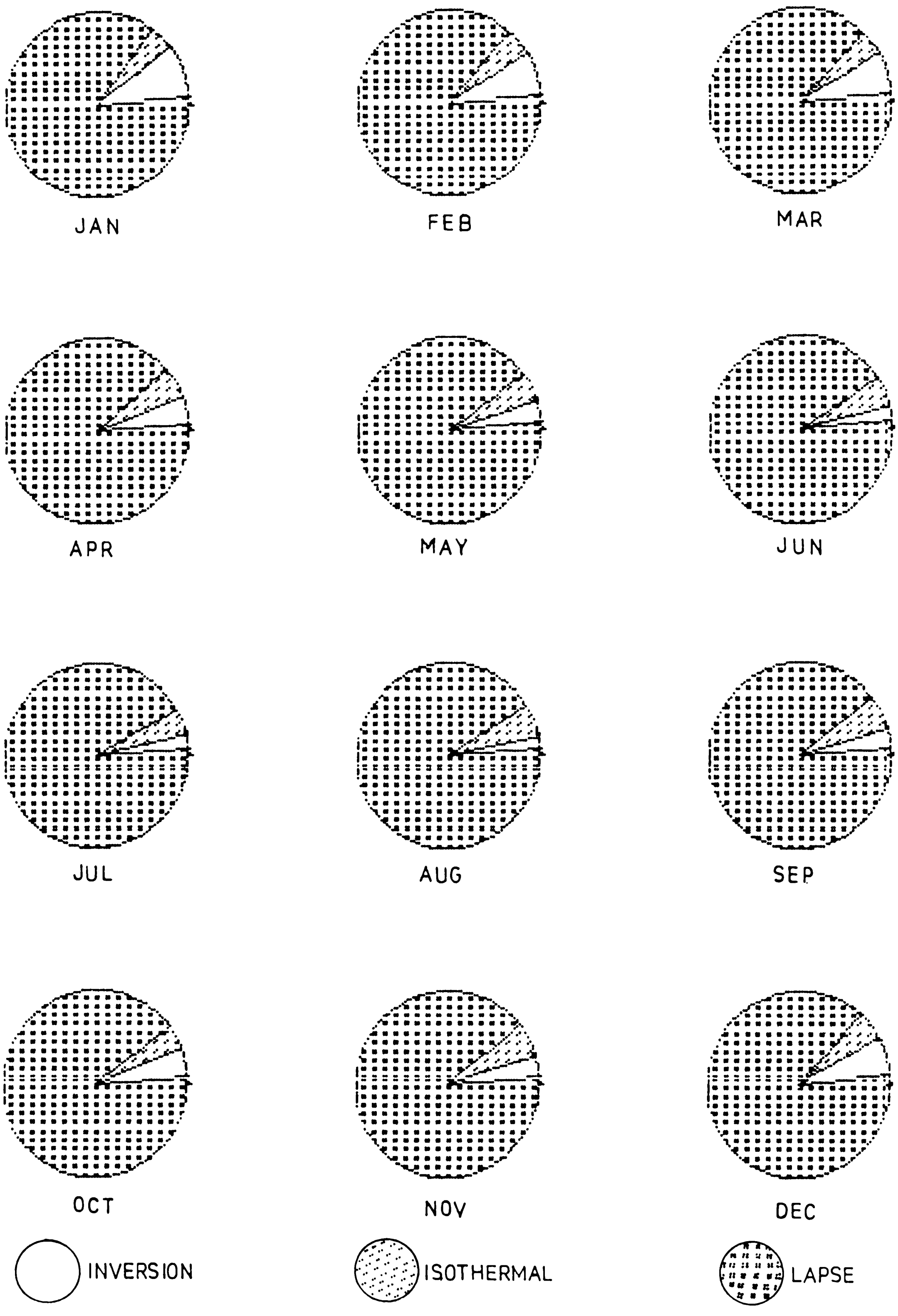


FIG. 3.1. PERCENT FREQUENCY OF INVERSIONS, ISOTHERMALS AND LAPSE CONDITIONS

March is understandable since this period falls in winter season, although the winter effects are not felt acutely because of the coastal characteristics. The extremely low values of inversions in the southwest monsoon season are due to the summer characteristics in this season as this monsoon does not affect Madras very much. It is important to note that either inversions or isothermals are present in all the months.

3.1.1 Inversions

Figs. 3.2(a) and 3.2(b) depict the percent frequency of occurrence of inversions in different layers of the atmosphere. The surface based inversions are more in 50% of the cases while the rest of the 50% shows more inversions from 1000 to 950mb layer. However, much cannot be read between the lines for surface to 1000mb and 1000 to 950mb layer frequencies, since the thickness of the former is extremely small and variable too. For the present study, the layer from surface to 950mb is considered as surface layer and layers above 950mb as elevated layers.

One of the important features is the very high frequency of elevated inversions especially in the ninth layer (650 to 600mb) in the month of June. It is equally interesting to know that the elevated inversions are extremely strong compared to the surface based inversions. Many a time the strong elevated inversions are a big handicap

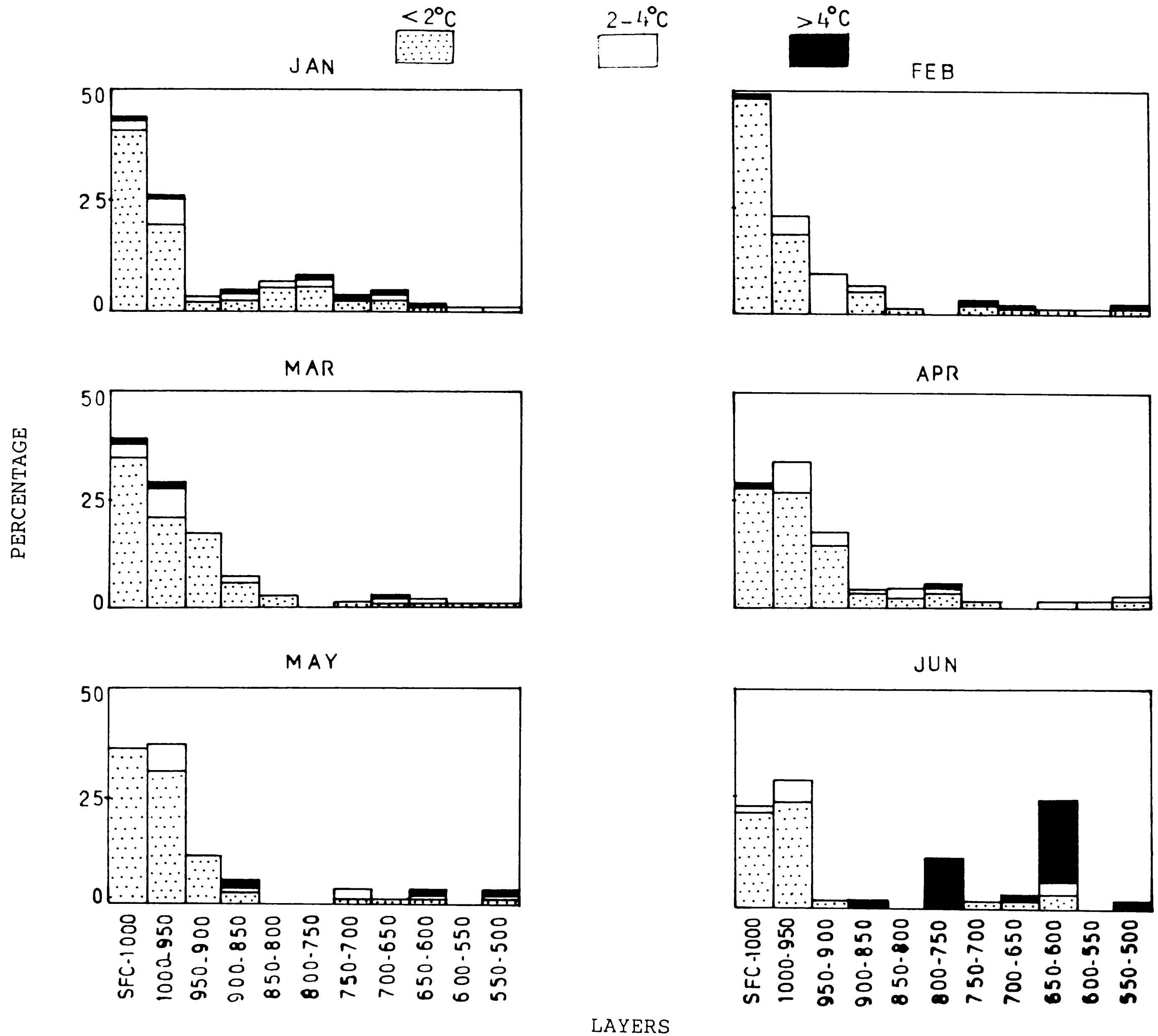


FIG. 3.2(a). PERCENT FREQUENCY OF INVERSIONS

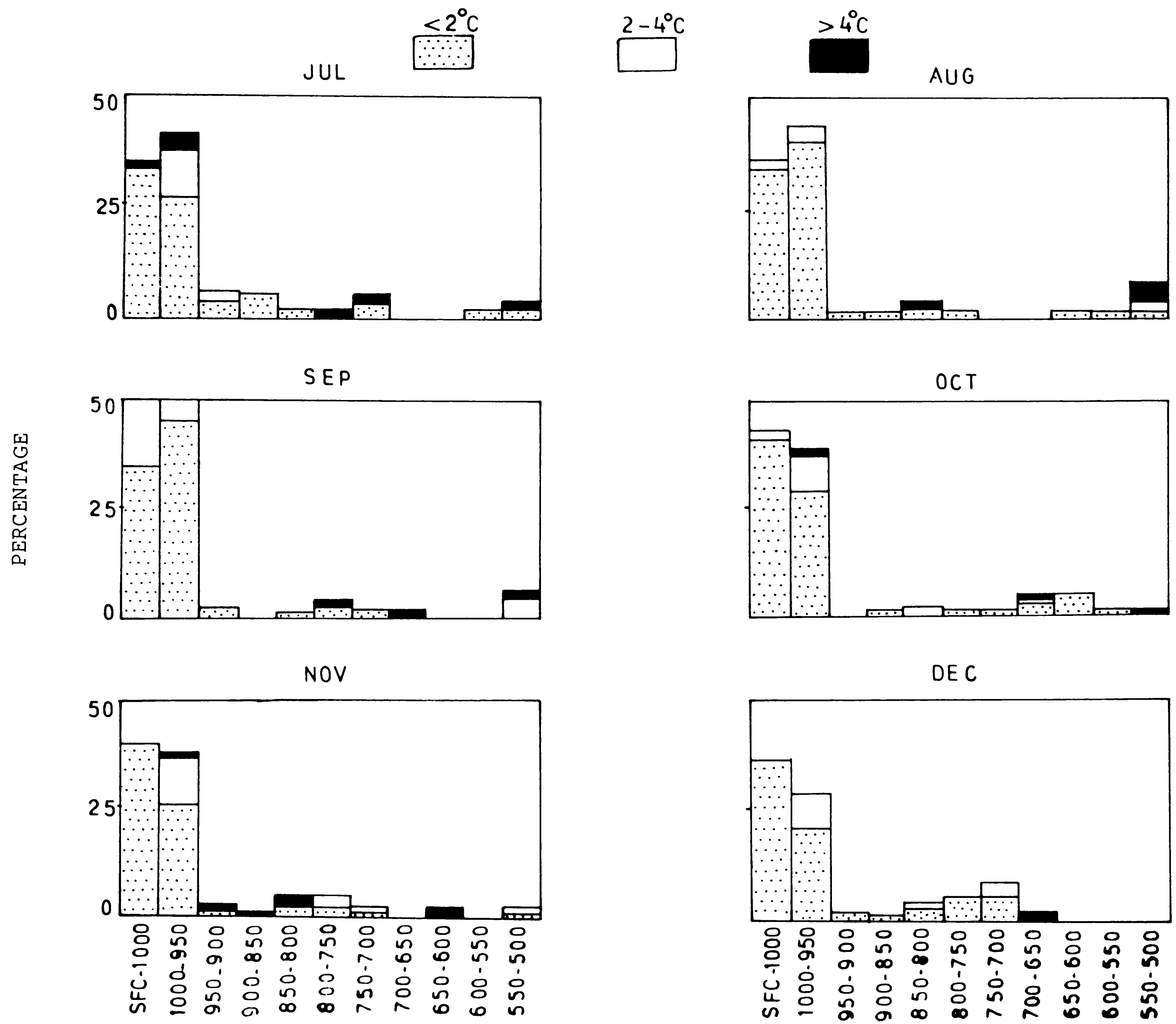


FIG. 3.2(b). PERCENT FREQUENCY OF INVERSIONS

for the dispersal of pollutants, since the bases of such inversions act as lids and do not allow pollutants to penetrate high into atmosphere, but help in accumulation of pollutants near the ground. However, in the present case, this is not a matter of serious concern since this month is a typical summer month and as such there will be thorough mixing in the lower layers, which allow pollutants to get diluted quickly in the atmosphere; consequently the resulting ground concentration would be low.

3.1.2 Isothermals

Figs. 3.3(a) and 3.3(b) show the percent frequency of occurrence of isothermals in different layers of the atmosphere. In this case also the surface based isothermals are more frequent than those which are elevated. The monthly variation is not significant. They are more in frequency only upto 900mb level.

3.1.3 Lapse conditions

The percent frequency of occurrence of lapse conditions of different intensities in various layers are presented in Figs. 3.4(a) and 3.4(b). As is to be expected the frequencies are low near the surface and high in the elevated cases. The lapse condition of intensity -2 to -4°C per 50mb generally dominates in all the cases except in the surface layer and the layers 650-600mb and above in almost

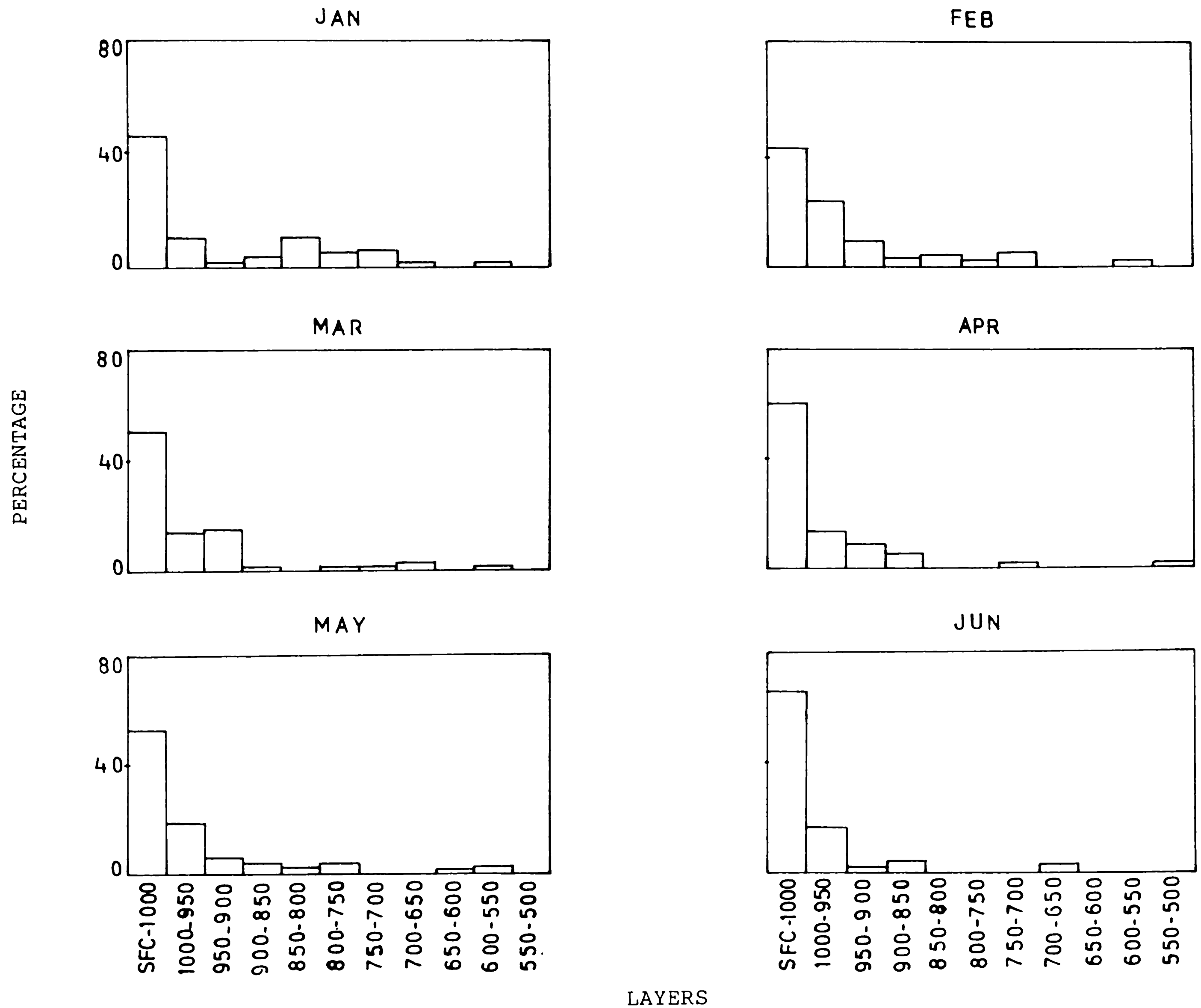


FIG. 3.3(a). PERCENT FREQUENCY OF ISOTHERMALS

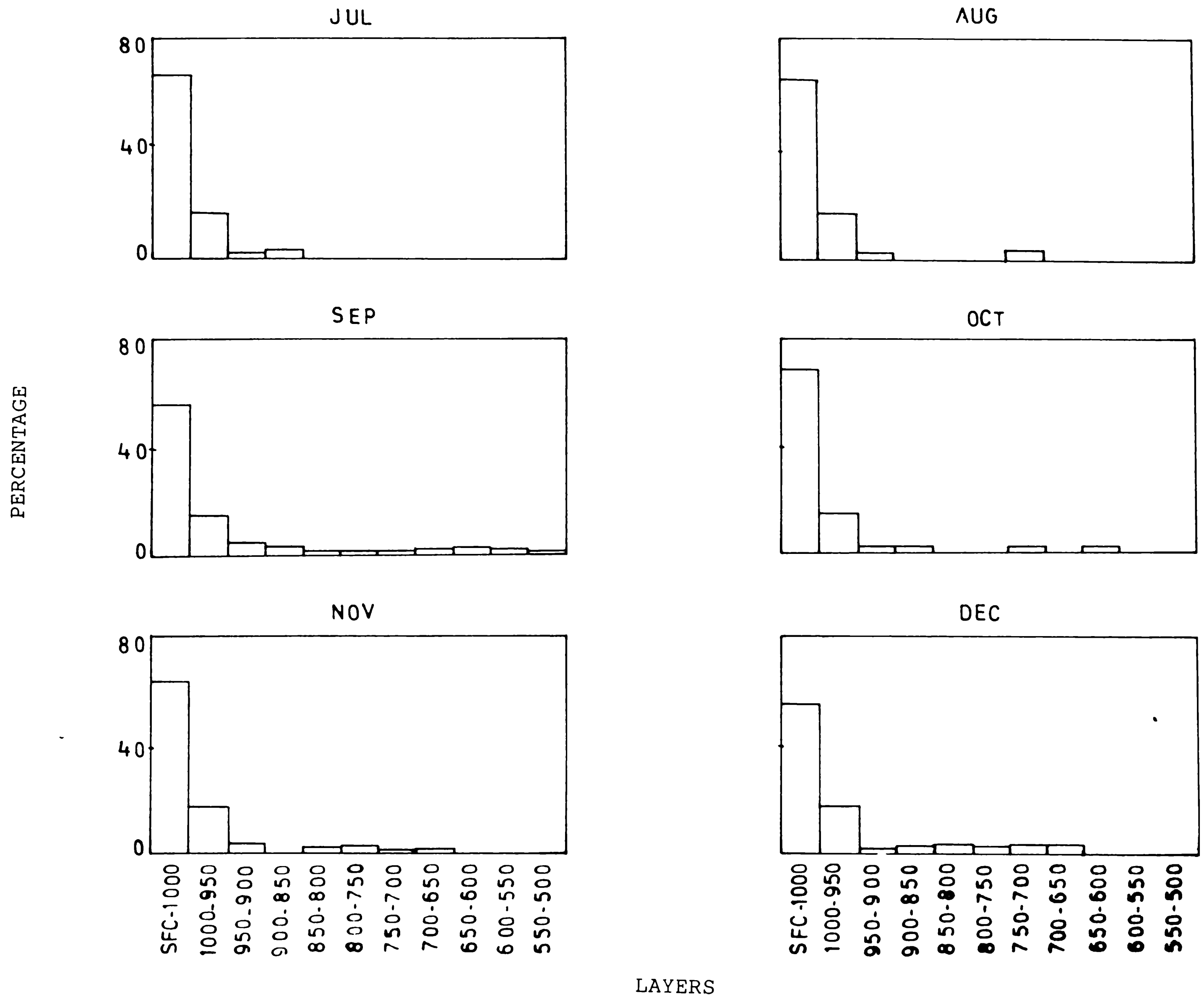


FIG. 3.3(b). PERCENT FREQUENCY OF ISOTHERMALS

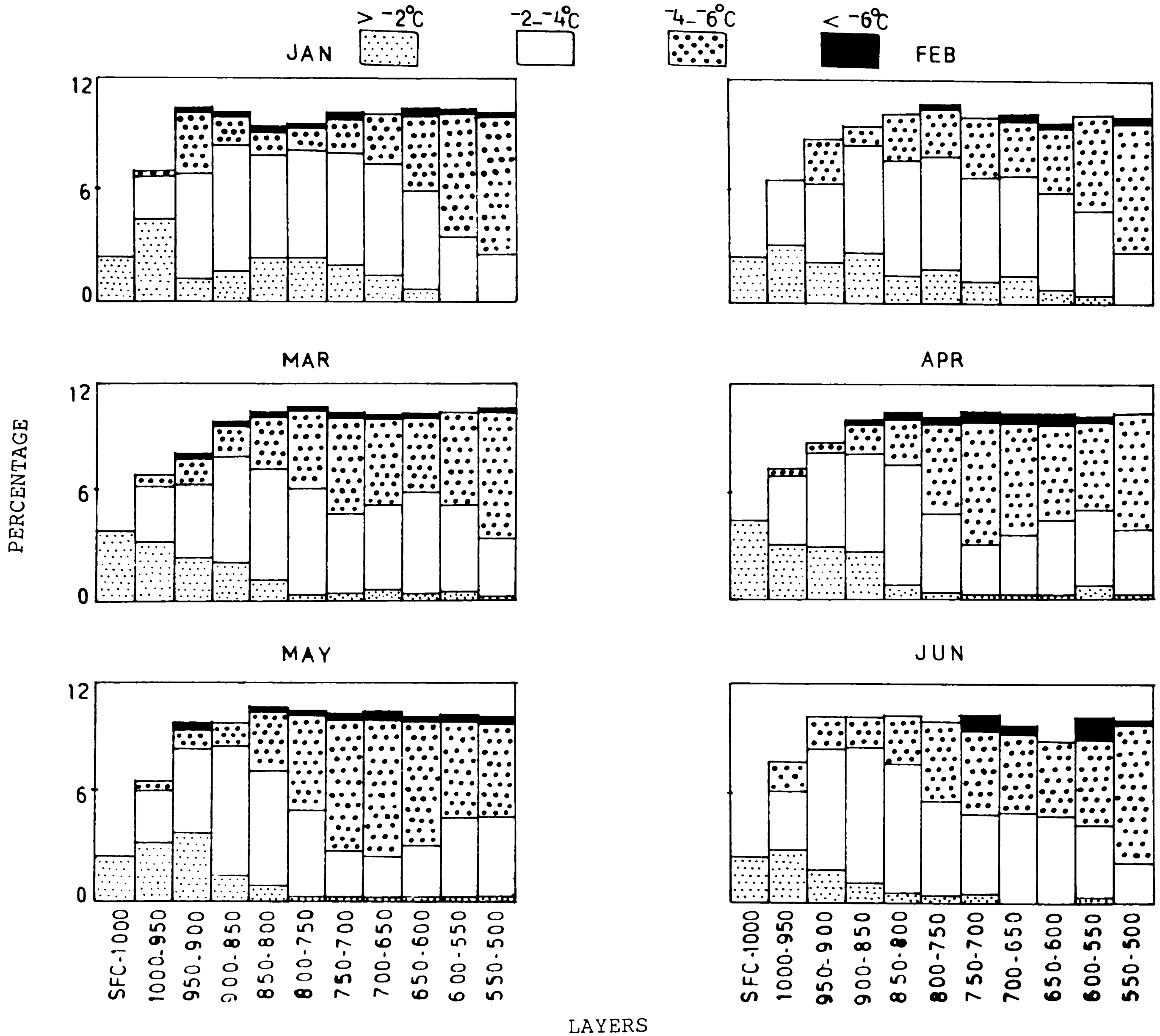


FIG. 3.4(a). PERCENT FREQUENCY OF LAPSE CONDITIONS

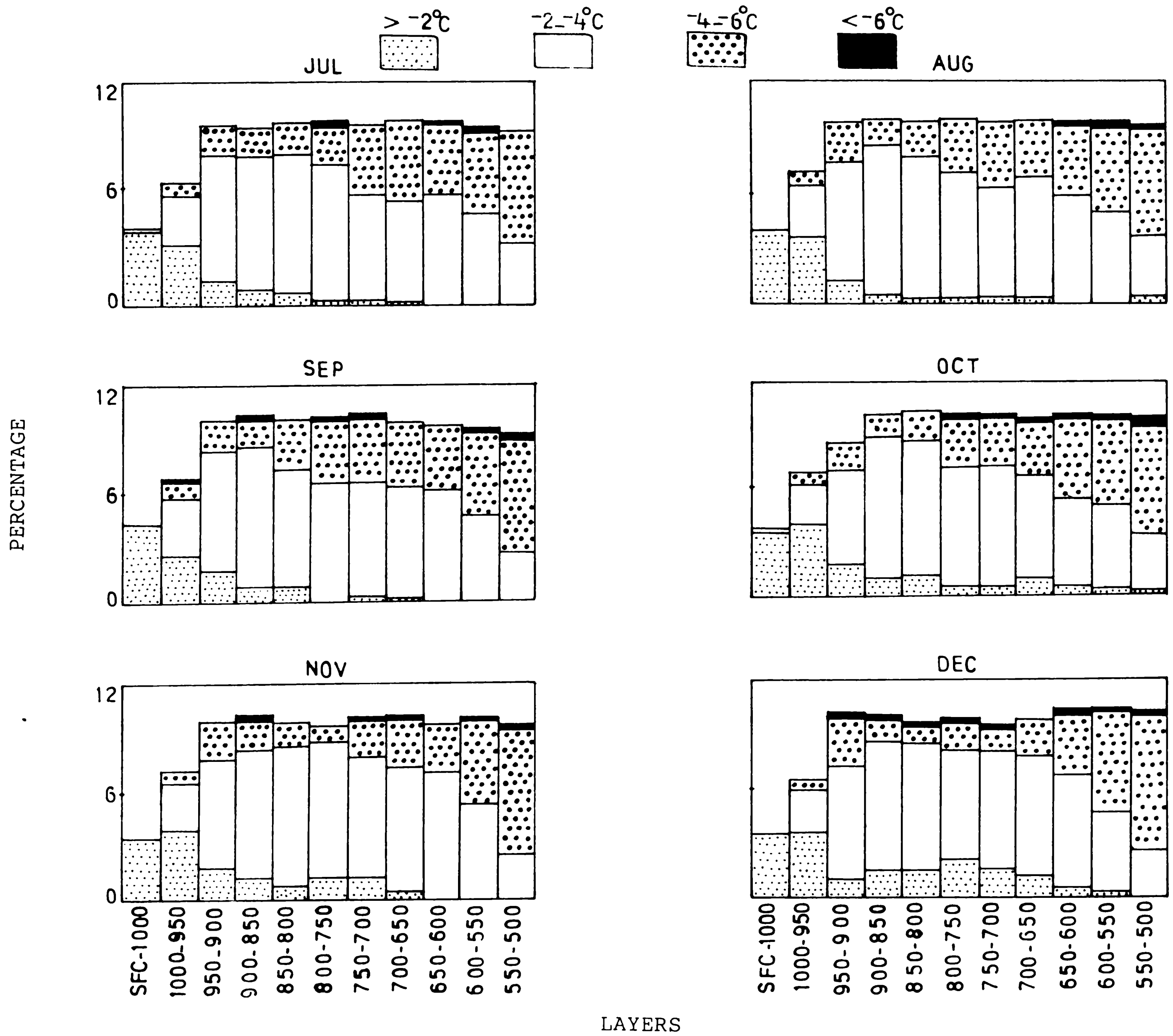


FIG. 3.4(b). PERCENT FREQUENCY OF LAPSE CONDITIONS

all months. The surface based lapse condition is very mild in intensity where the elevated conditions are relatively strong. Near-adiabatic conditions (9.8°C per km) are very low in frequency. The lapse conditions increase from surface to certain level and become more or less uniform thereafter, although the individual intensities may differ with their percent frequencies. The relatively high frequency of 4 to 6°C per 50mb at higher level cannot be construed as dry adiabatic lapse rates, since the thickness of 50mb which would be around 500m near the surface goes up considerably at high levels making the lapse rates to be sub-adiabatic.

The reversal in trend of the variations of lapse conditions and inversions in each of these layers is but natural. The ninth layer in the month of June shows strong inversions and relatively weak lapse conditions. The lapse intensities are relatively weak from October to January while they are more from March to June. It may be noted here that not all the lapse conditions are favourable for good dispersal of pollutants since the atmosphere under sub-adiabatic conditions cannot disperse pollutants effectively because of the prevailing density gradients and the consequent stable conditions. While it is emphasised that the isothermal and inversion conditions are undesirable for good dispersal of pollutants, the lapse conditions of low intensity are equally undesirable.

3.2 MIXING HEIGHT

Figs. 3.5(a) and 3.5(b) show the diurnal variation of mixing height for the months of January to December. A clear-cut diurnal variation is noticed in all the months. The minimum values are observed during early morning hours and the maximum values are noticed in the after noon hours. The variation is quite rapid from around 0800 hours till noon and from about 1600 hours to 2000 hours. During the rest of the time the variation is not that marked. The diurnal range is minimum in November and maximum in June. The minimum mixing heights are lowest in February and highest in June.

As is to be expected, the mixing heights are low during early morning hours which coincide with the minimum temperature epoch and high during afternoon hours coinciding with the maximum temperature epoch. It should be noted here that the diurnal variation more or less follows the diurnal temperature march mainly because it is the surface heat input in the form of temperature which triggers the convective activity in the vertical leading to the vertical mixing height. As such one expects low mixing during minimum temperature and high mixing during maximum temperature epoch. Another interesting feature is that the maximum values of mixing heights are higher (greater than 1500m) during the months February to August. This reflects the coastal characteristic features of Madras wherein the mean maximum

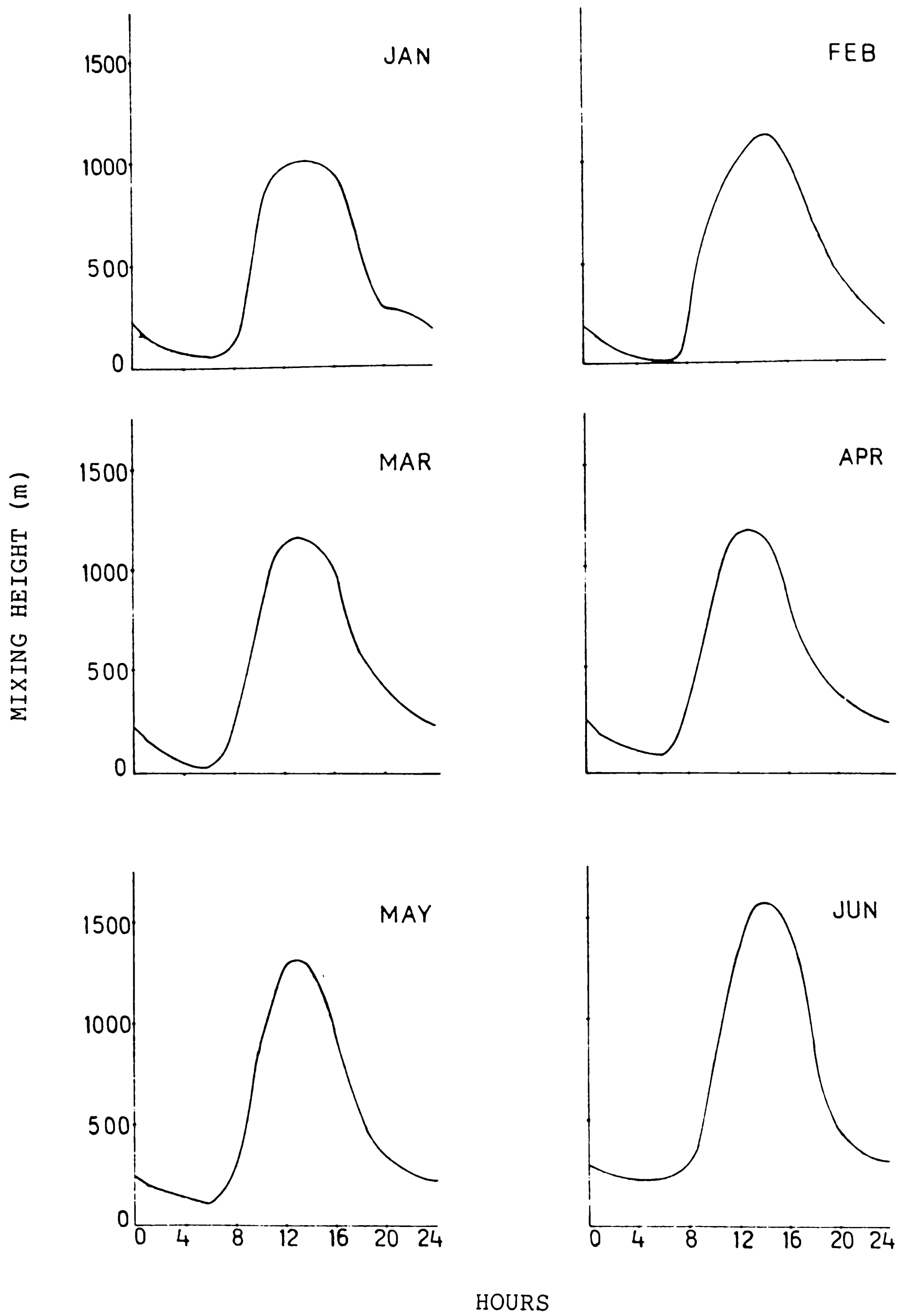


FIG. 3.5(a). DIURNAL VARIATION OF MIXING HEIGHT

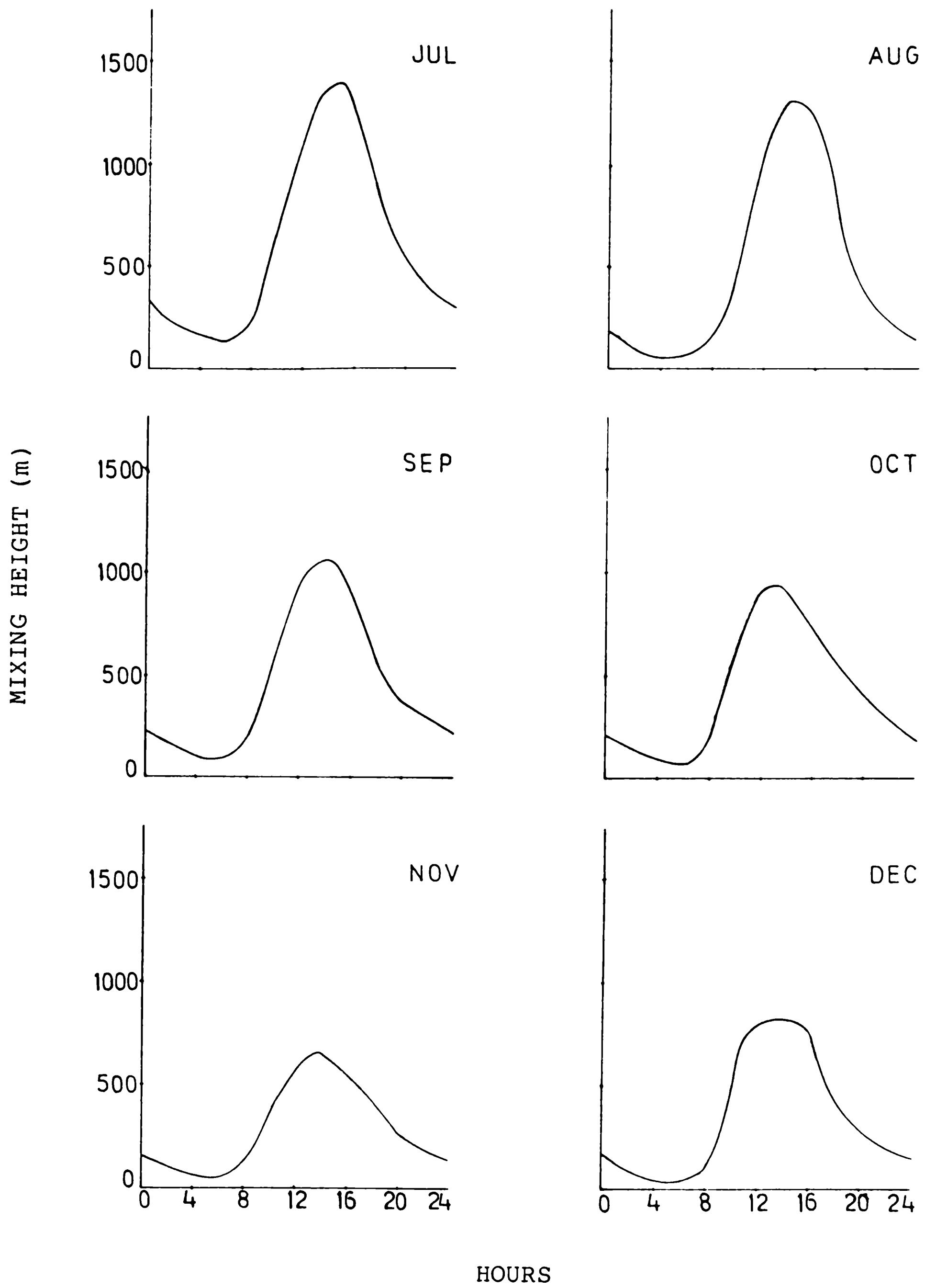


FIG. 3.5(b). DIURNAL VARIATION OF MIXING HEIGHT

temperature does not vary very significantly from month to month. It is not surprising to note that the maximum values are found during the peak southwest monsoon mainly because Madras, does not receive significant rainfall during this season. As such the so called monsoon effects such as overcast conditions are not felt in this station and the temperatures are rather high in this season resulting in higher mixing heights. However, the temperatures recorded are not that high as they are moderated by sea breeze phenomenon.

The lower values of mixing heights from October to December are partly due to the northeast monsoon. This monsoon results in overcast conditions and brings in a lot of rainfall to this city. It is these overcast conditions that are actually responsible for the lower temperatures and consequent lower mixing heights. It cannot be construed as due to winter alone, since the winter effects are offset by the coastal characteristics.

Figs.3.6(a) and 3.6(b) depict the monthly variation of mixing heights for every hour, for day and night conditions respectively. The month to month variation of mixing height is very striking in the afternoon hours. For example, at 1500 hours the mixing height in June is 1560m whereas in November it is 620m. This variation is not prominant during night-time.

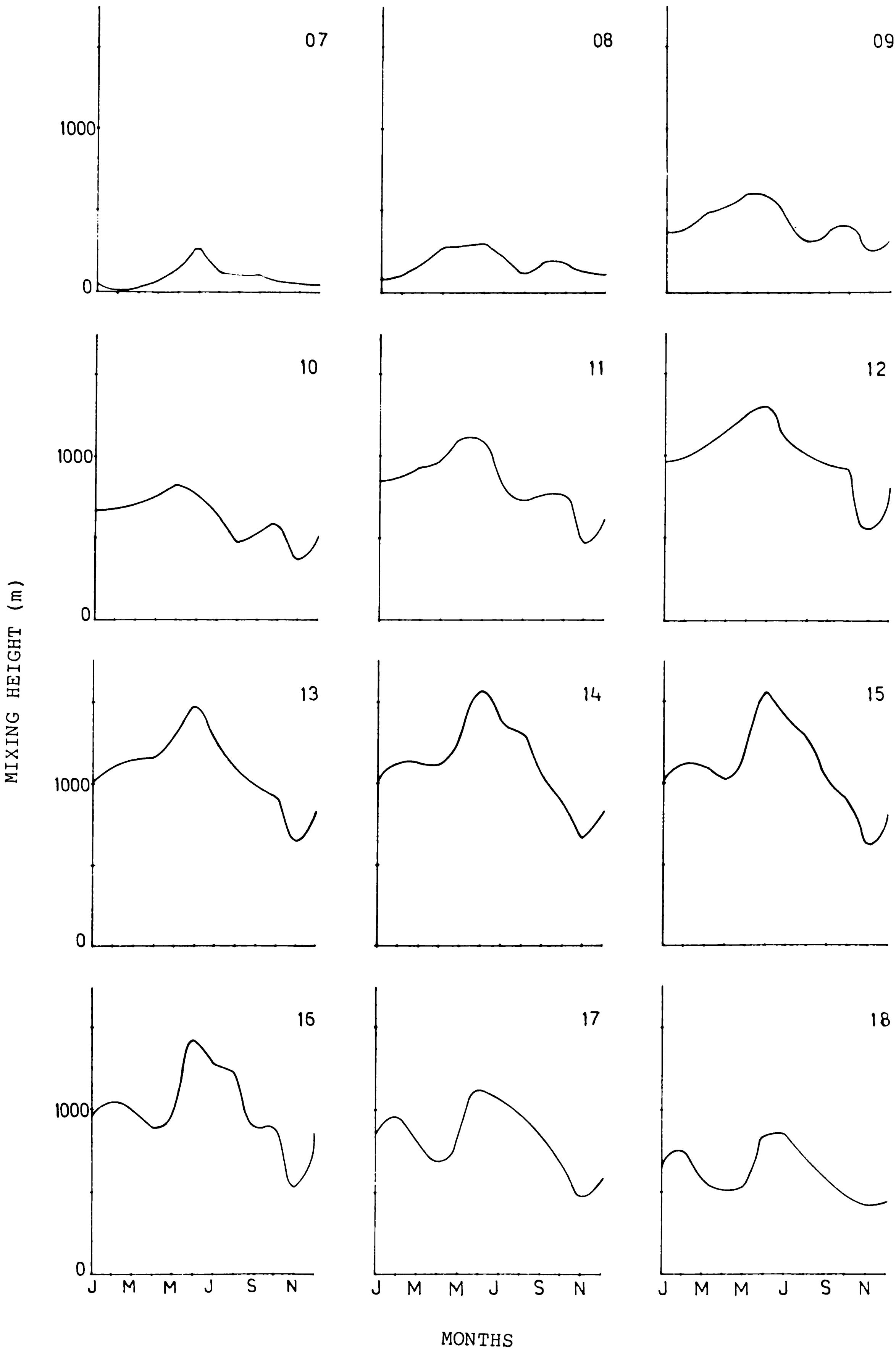


FIG. 3.6(a). MONTHLY VARIATION OF MIXING HEIGHT DURING DAY TIME

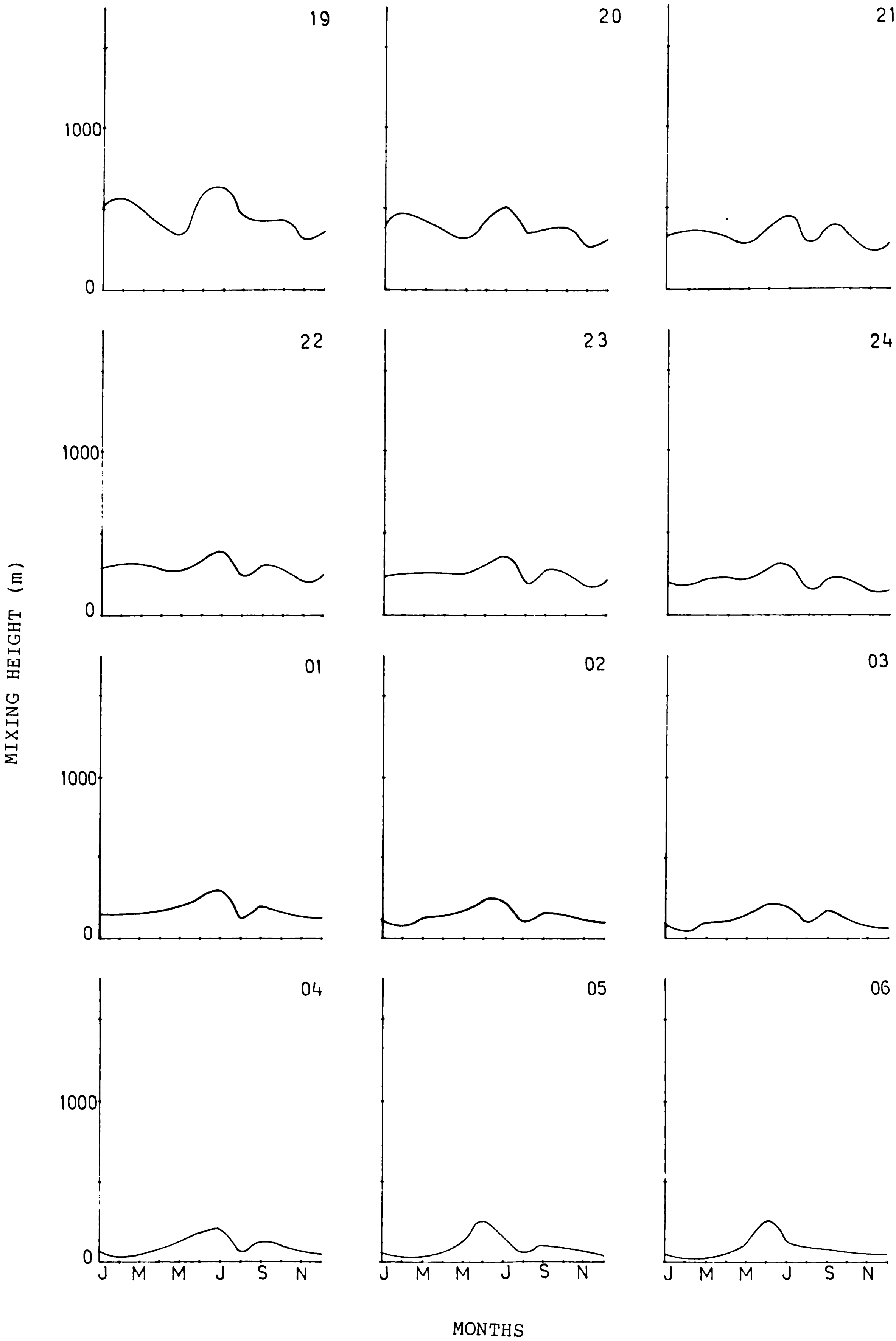


FIG. 3.6(b). MONTHLY VARIATION OF MIXING HEIGHT DURING NIGHT-TIME

3.3 VENTILATION COEFFICIENT

The diurnal variation of the ventilation coefficient is shown in Figs. 3.7(a) and 3.7(b) for all the months. The variation is very striking as in the case of mixing height. It shows a near normal distribution, the highest values occurring during the afternoons with a maximum of about $8000 m^2 s^{-1}$ around 1600 hours in June. During night-time, the values are always less than $1000 m^2 s^{-1}$. Ventilation coefficient may even reach zero at 0500 or 0600 hours between August and April. In all the cases, the values increase rapidly from early morning upto around 1400 hours followed by steep fall upto around 2000 hours and then a steady decrease till the early morning hours.

As in the case of mixing heights, ventilation coefficients at all hours are higher in June and July than in the other months. This may be explained as due to higher mixing as well as higher wind speeds. It is to be noted here that although the southwest monsoon does not cause overcast conditions and consequent rainfall, it brings in strong winds which together with the higher mixing causes the ventilation coefficients to be relatively high in this season. The extremely low values of ventilation coefficients in November caused by low values of mixing height are a matter of serious concern.

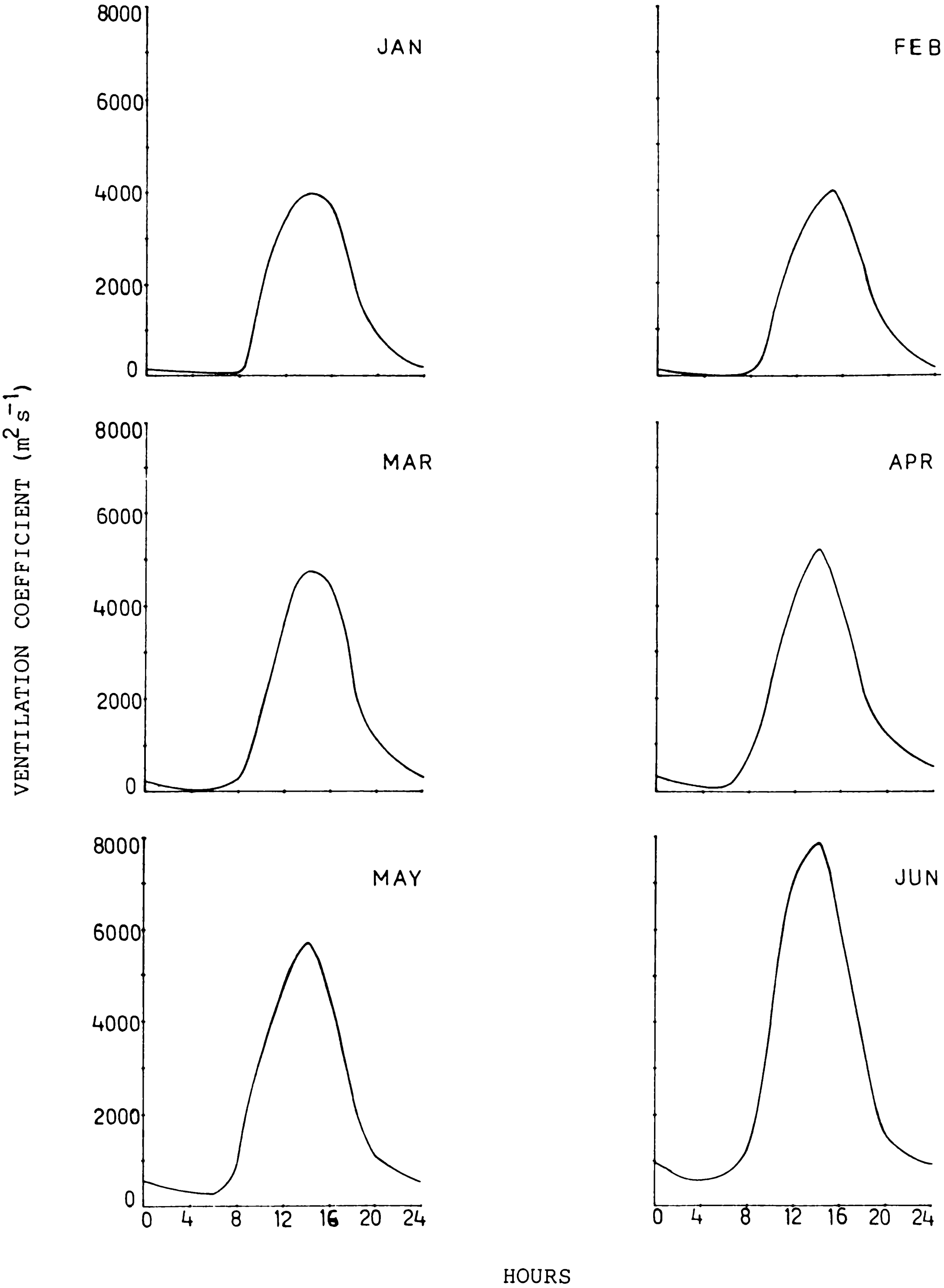


FIG. 3.7(a). DIURNAL VARIATION OF VENTILATION COEFFICIENT

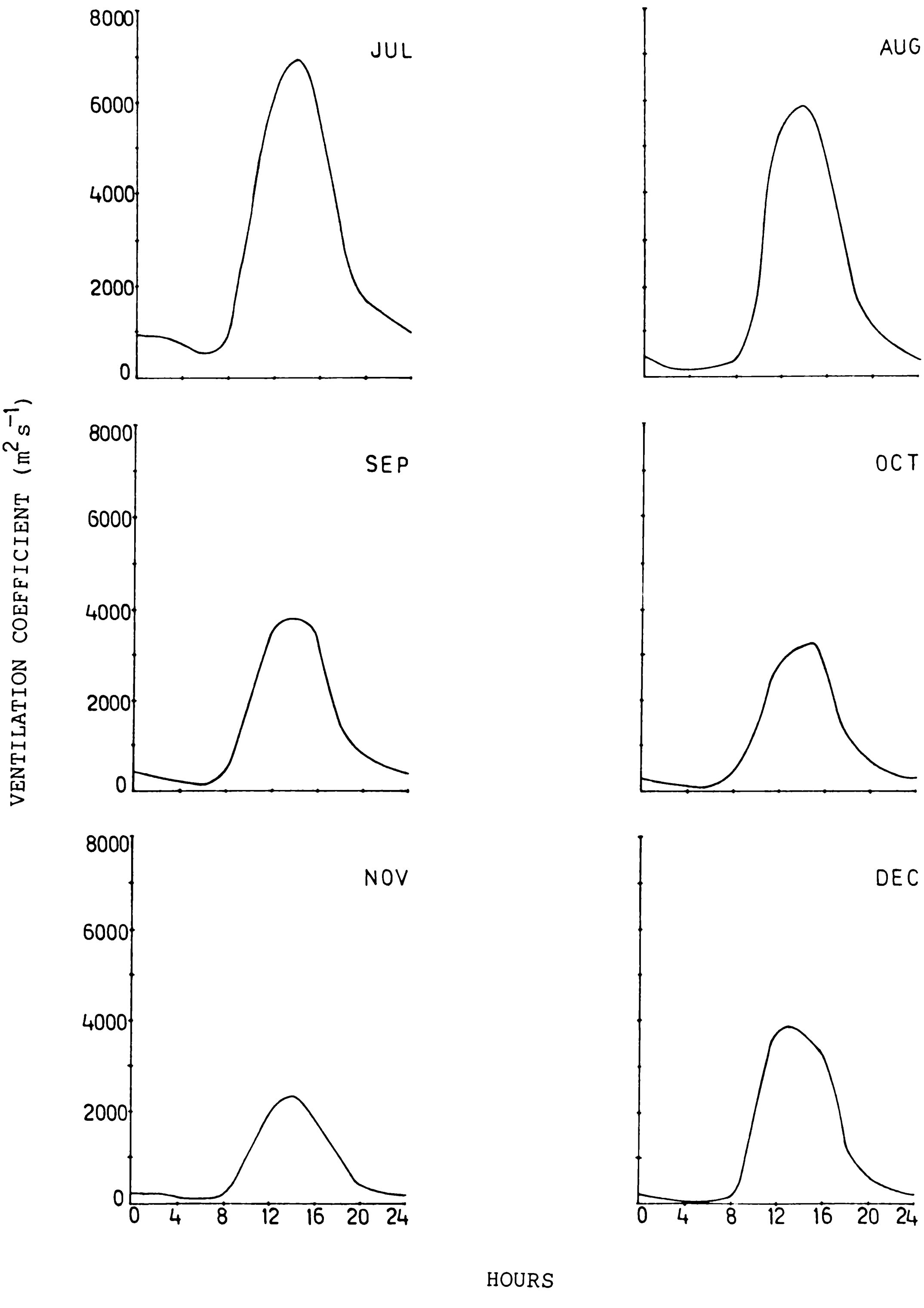


FIG. 3.7(b). DIURNAL VARIATION OF VENTILATION COEFFICIENT

The period from September to February is not conducive for a good dispersal of pollutants and as such this particular period may be viewed with caution. However, it should be noted here that these ventilation coefficients are computed using the surface wind speed alone, as a consequence of which, the values are likely to be underestimates. In fact, one would expect Madras, a coastal station, to have higher ventilation coefficients, but the non-inclusion of average wind through the mixing layer may be the cause of lower values. Even with the inclusion of variation of wind, the situation in the night-time need not necessarily brighten, since the average wind is to be computed within the first few hundred metres, which would make the wind speeds to be at the most 2 or 3 times of the surface value. Added to this, the prevailing stable conditions also do not permit steep increase in wind speed with height.

The monthly variation of ventilation coefficient for every hour is shown in Figs. 3.8(a) and 3.9(b) for day time and night-time conditions respectively. As in the case of mixing height, the month to month variation of ventilation coefficient is much larger in day time than during night-time. At night-time, the values are always below $1000 m^2 s^{-1}$ as already noted and as such the variation is smaller.

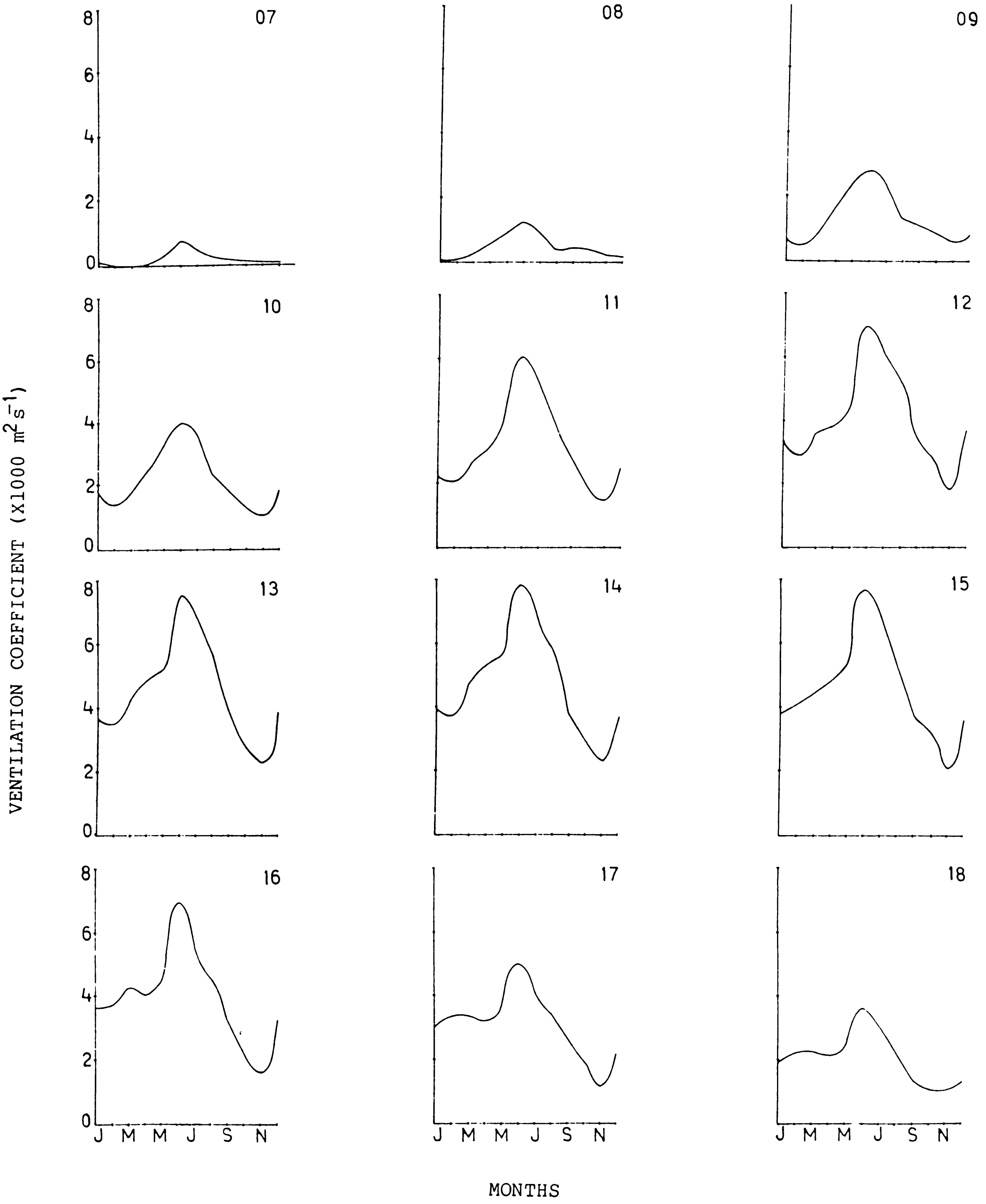


FIG. 3.8(a). MONTHLY VARIATION OF VENTILATION COEFFICIENT DURING DAY TIME

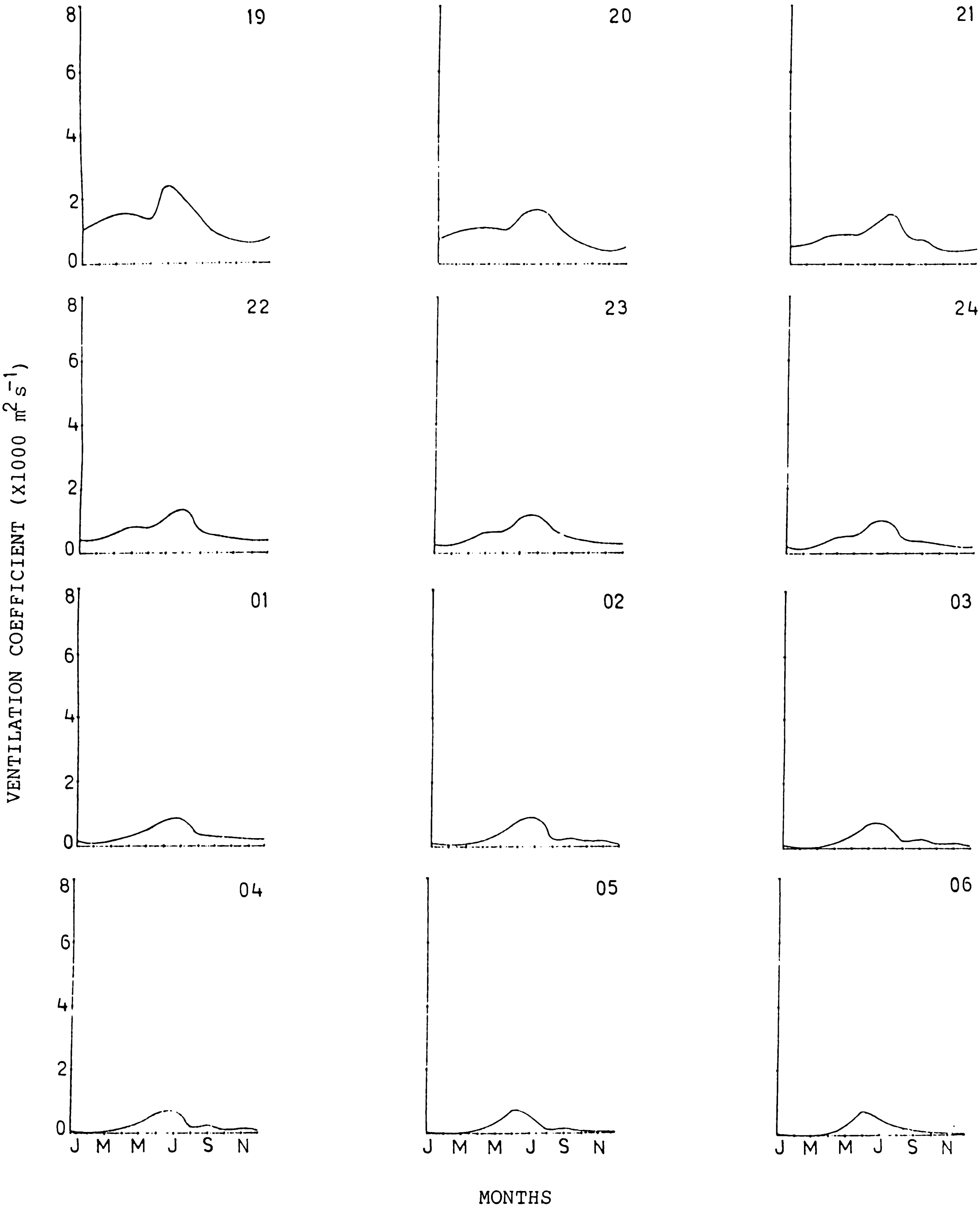


FIG. 3.8(b). MONTHLY VARIATION OF VENTILATION COEFFICIENT DURING NIGHT-TIME

3.4 ATMOSPHERIC STABILITY

The various Pasquill's stability classes from A to F are computed for every hour for all the days and for all the months for the five year period. The percent frequency of occurrence of each of these stability categories are represented for every hour for all the months in Figs. 3.9(a) and 3.9(b). In most of the cases, category F is highly predominant. Highly stable conditions during night-time and neutral to unstable conditions during day time, are the predominant features in the months of January and February. The percent frequency of category E increases from January to July and decreases thereafter especially from evening to midnight hours. Day time stabilities also change from month to month. For example, category A decreases from January to July and increases till October and again decreases thereafter. During day time, in June neutral category, D is maximum and in almost all other months either category B or category C dominates. The rest of the day time hours are dominated by categories A and B from January to May. This is mainly because of the clear skies and a good heat input near the surface. Although the heat input is enough in June and July the strong winds offset the dominance of the extreme conditions such as A and F. The relatively high frequency of C and D during day time especially in November and December is mainly due to the overcast conditions.

Figs. 3.10(a) and 3.10(b) show the frequency of that

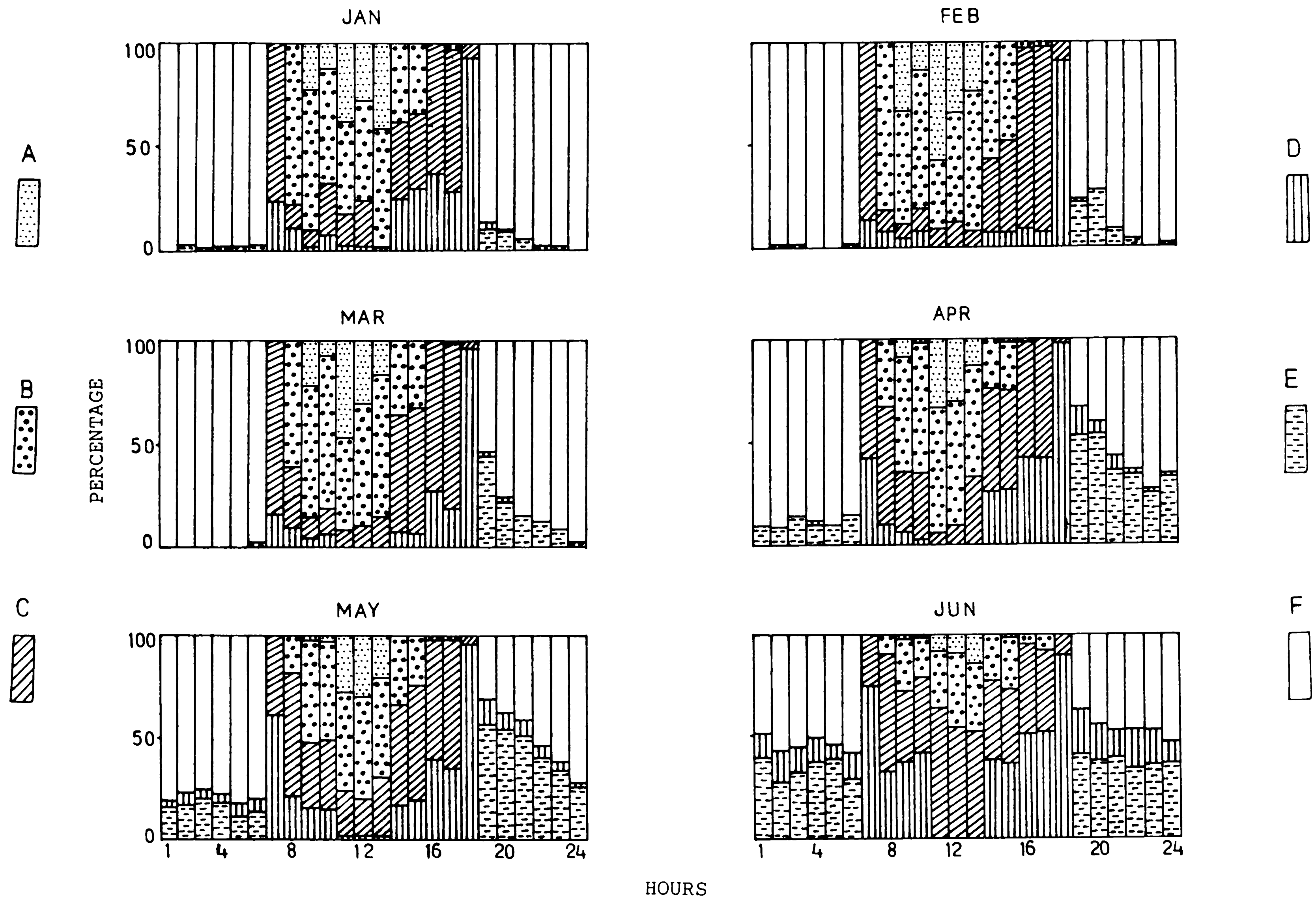


FIG. 3.9(a). DIURNAL VARIATION OF PERCENT FREQUENCY OF PASQUILL'S STABILITY CLASSES

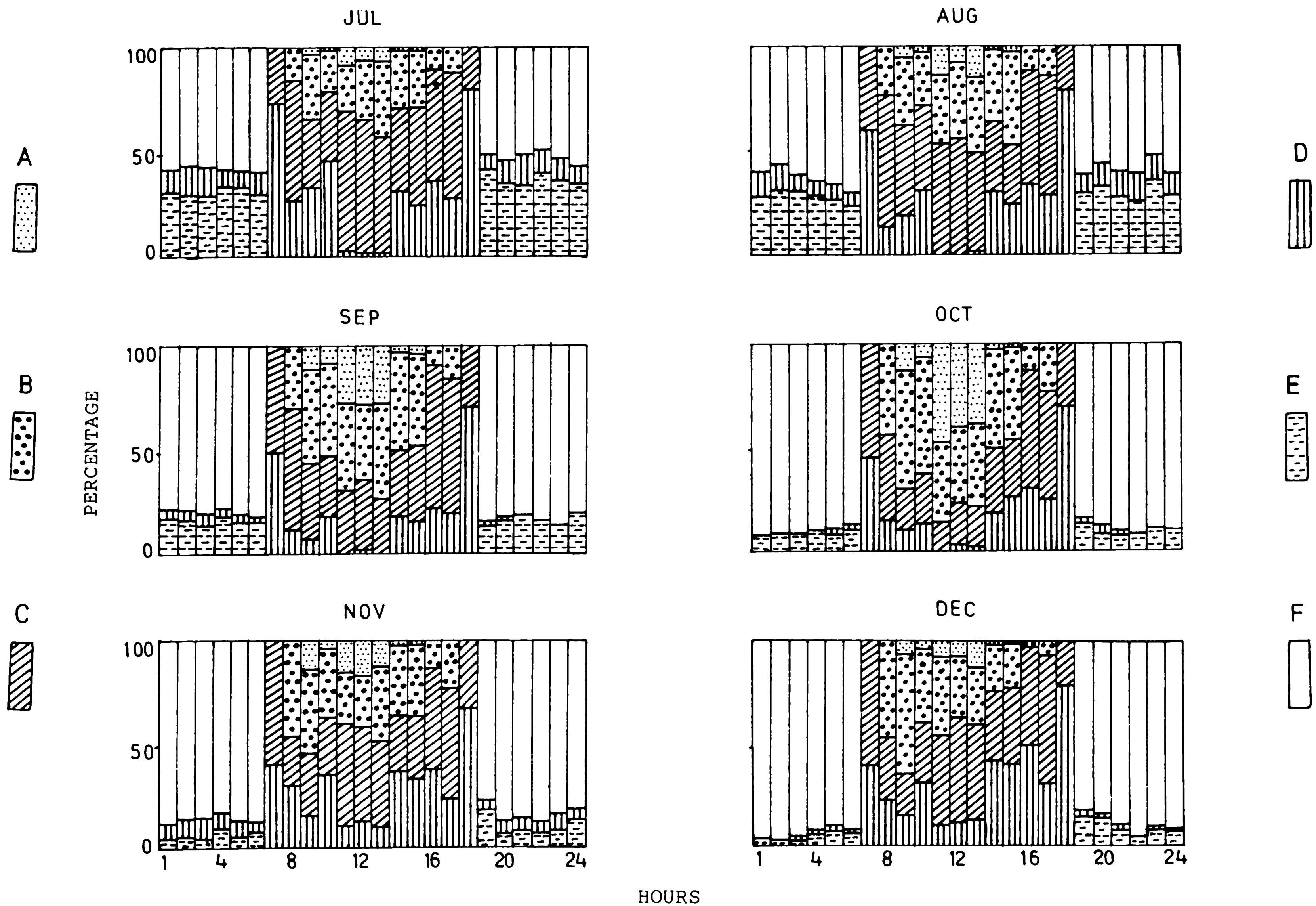


FIG. 3.9(b). DIURNAL VARIATION OF PERCENT FREQUENCY OF PASQUILL'S STABILITY CLASSES

category of stability whose frequency is maximum in the given hour for all the months. Undoubtedly the frequency of F category is maximum during night-time in all the months with a few exceptions. The extremely unstable conditions are dominant for a few hours in February, March and October. One can notice the lowering of frequencies from May to August. During transition periods either slightly unstable or neutral conditions are dominant. Fig. 3.11 indicates the monthly variation of the percent frequencies of all the categories at 1200 hours. The reversal in trend between categories B and C and to some extent A and C is the dominant feature of this figure. The southwest monsoon season is dominated mostly by C category followed by categories B, A and D, whereas from January to June B is dominating followed by A and C. The neutral category does not show significant variation in any of these months.

In all these cases, it is evident that the entire night-time is dominated by highly stable conditions, while the day time shows considerable variation in the unstable category. The extremely low winds and the continuous cooling of the earth's surface during night-time are the principal causes for the highly stable conditions during night-time. With the advent of sun's rays in the early morning, convection begins at the earth's surface leading to unstable conditions with the peak around the maximum temperature epoch. The predominance of highly stable

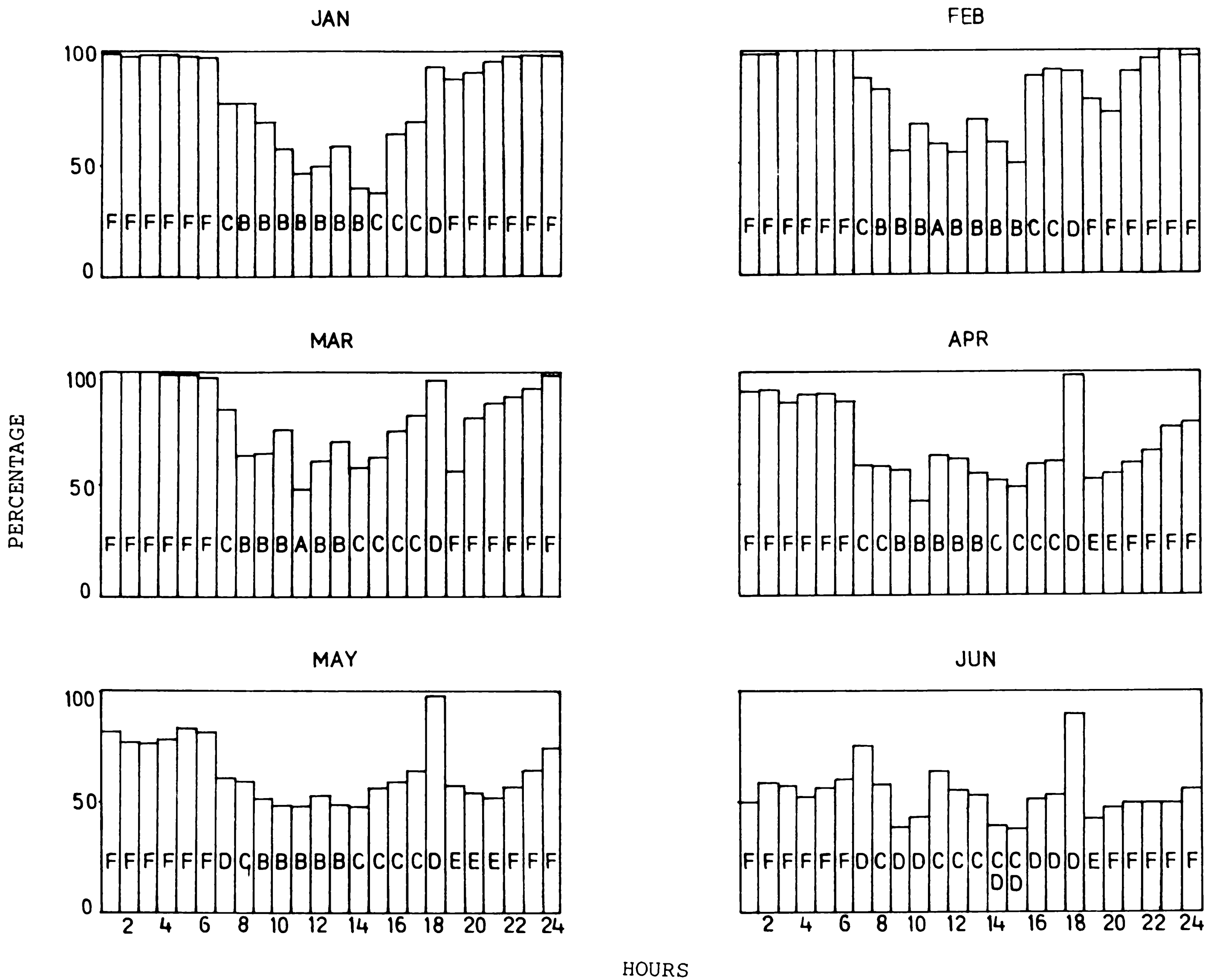


FIG. 3.10(a). DIURNAL VARIATION OF PERCENT FREQUENCY OF MAXIMUM OCCURRING PASQUILL'S STABILITY CLASSES

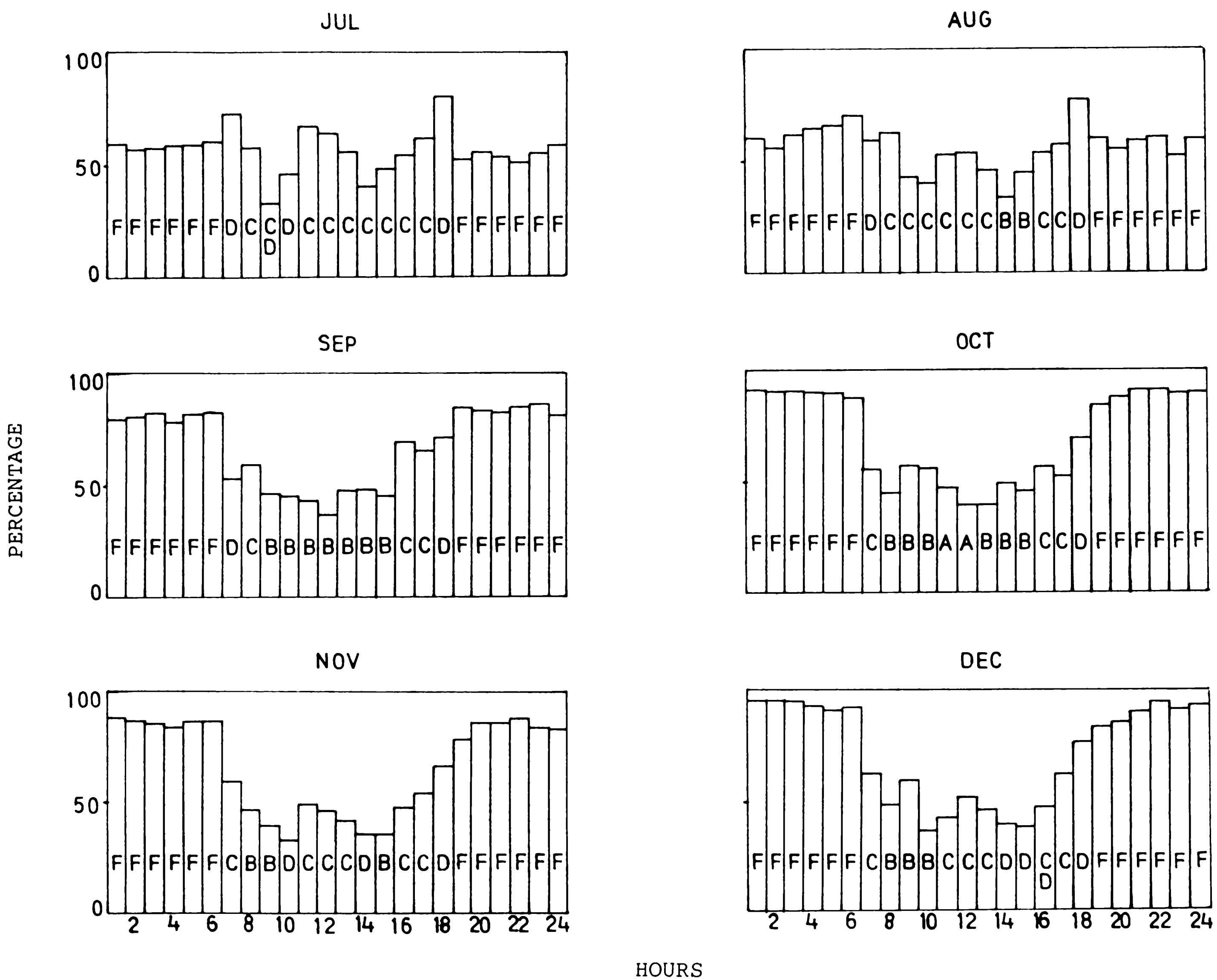


FIG. 3.10(b). DIURNAL VARIATION OF PERCENT FREQUENCY OF MAXIMUM OCCURRING PASQUILL'S STABILITY CLASSES

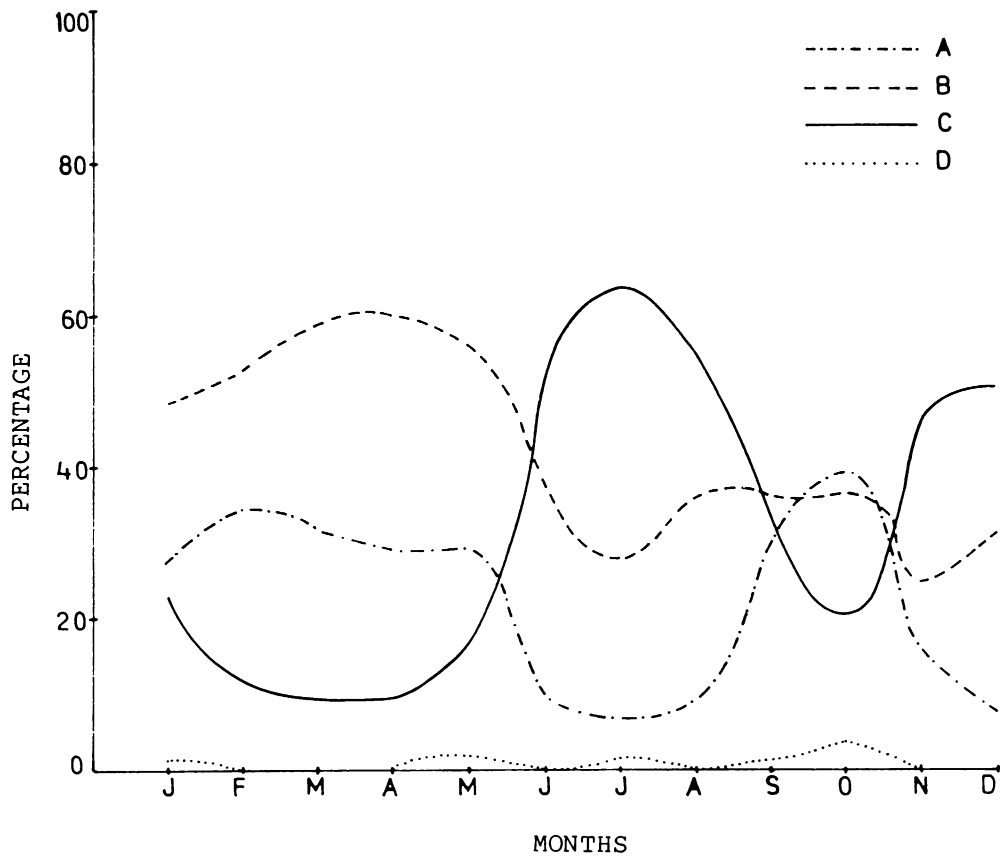
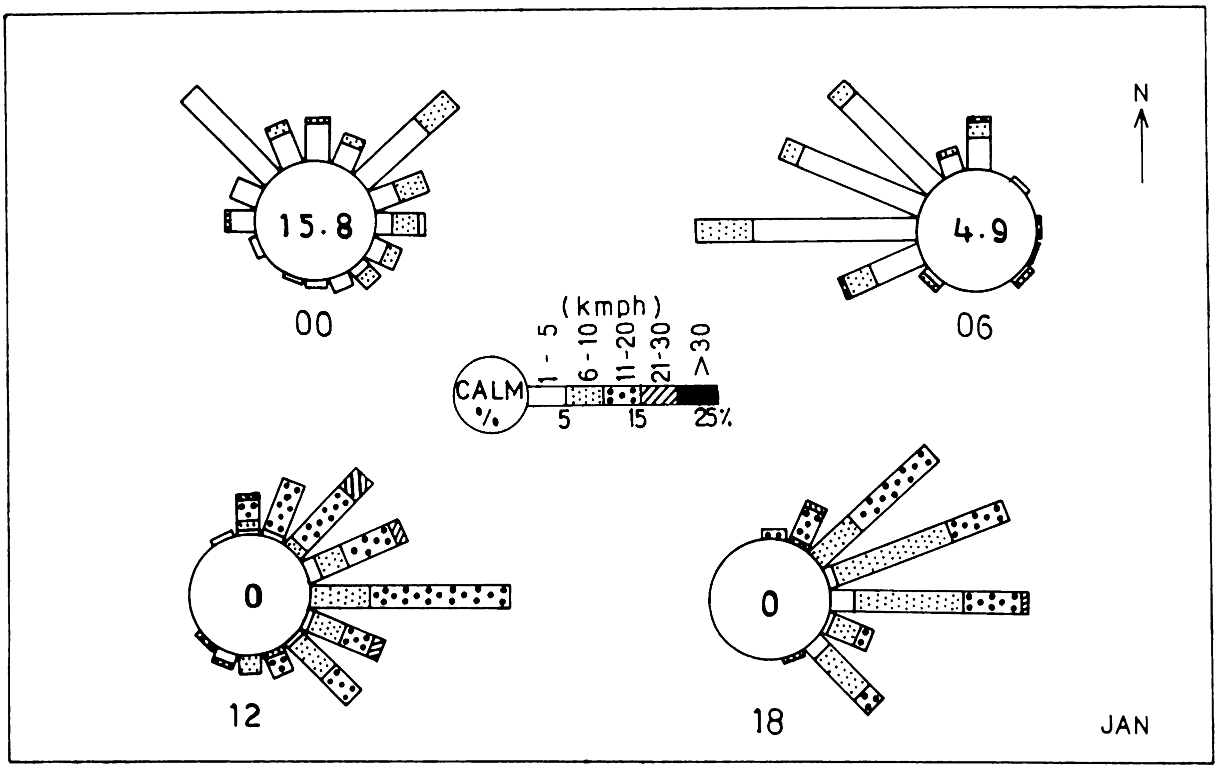


FIG. 3.11. MONTHLY VARIATION OF PERCENT FREQUENCY OF OF PASQUILL'S STABILITY CLASSES AT 1200 HOURS

conditions during night-time is a matter of serious concern since in these conditions pollutants, if present, cannot get dispersed or diluted, resulting in the heavy doses of concentrations. Hence emissions during night-time should be regulated so as to avoid this accumulation of pollutants.

3.5 WIND ROSES

The wind roses for 0000, 0600, 1200 and 1800 hours for all the months are presented in Figs. 3.12(a) to 3.12(f) The calm percent is indicated in the circles. In January, at 1200 and 1800 hours, the winds are completely from the eastern sectors with the dominating direction being easterly or northeasterly. During the other hours especially in the early morning hours, the prominent direction is westerly. The winds are relatively low or calm during night-time (represented by 0000 and 0600 hours) and strong during day time (represented by 1200 and 1800 hours). The more or less uniform distribution of the various directions at midnight is a notable feature. The situation in February is similar to January with an exception at 0000 hours, where the dominant direction is from southeast. During day time, the dominant direction is from the eastern sector. The reversal of wind direction from night-time to day time is noticeable in this month too as in the case of January. The calm percentage has gone up considerably especially at 0000 hours. The south easterlies dominate in this month during day time compared to



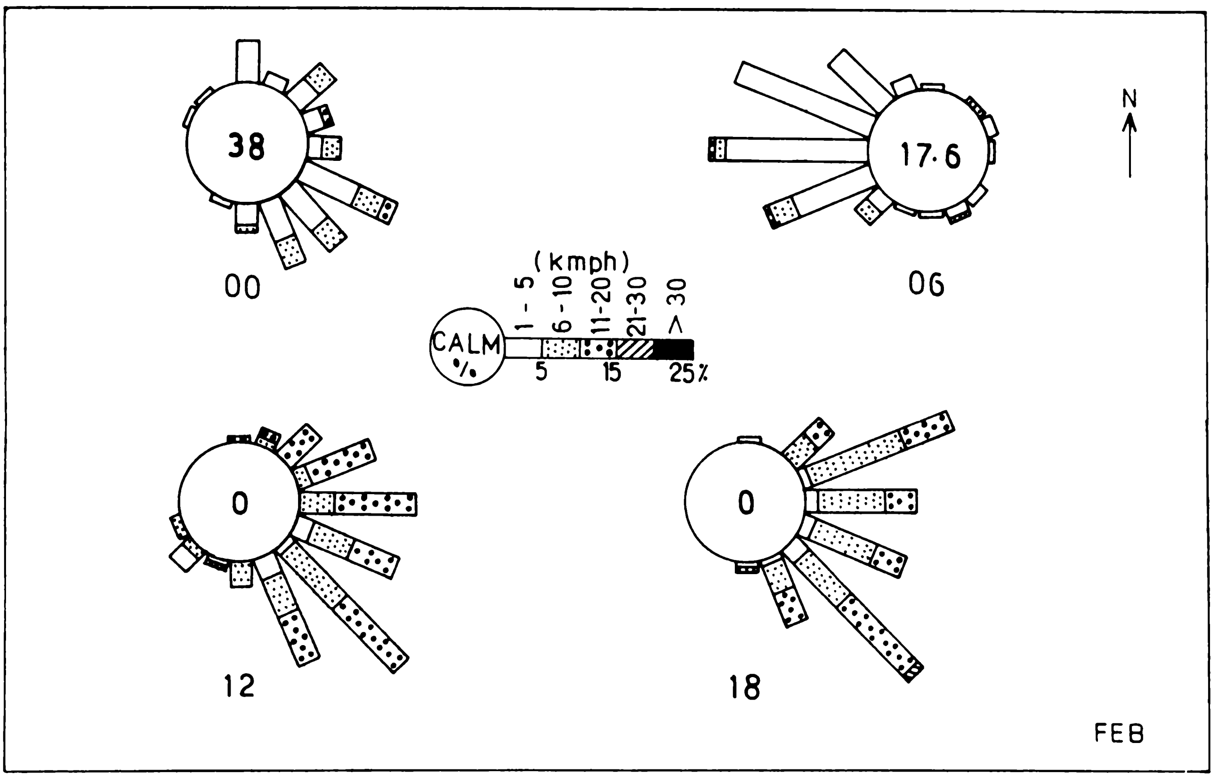
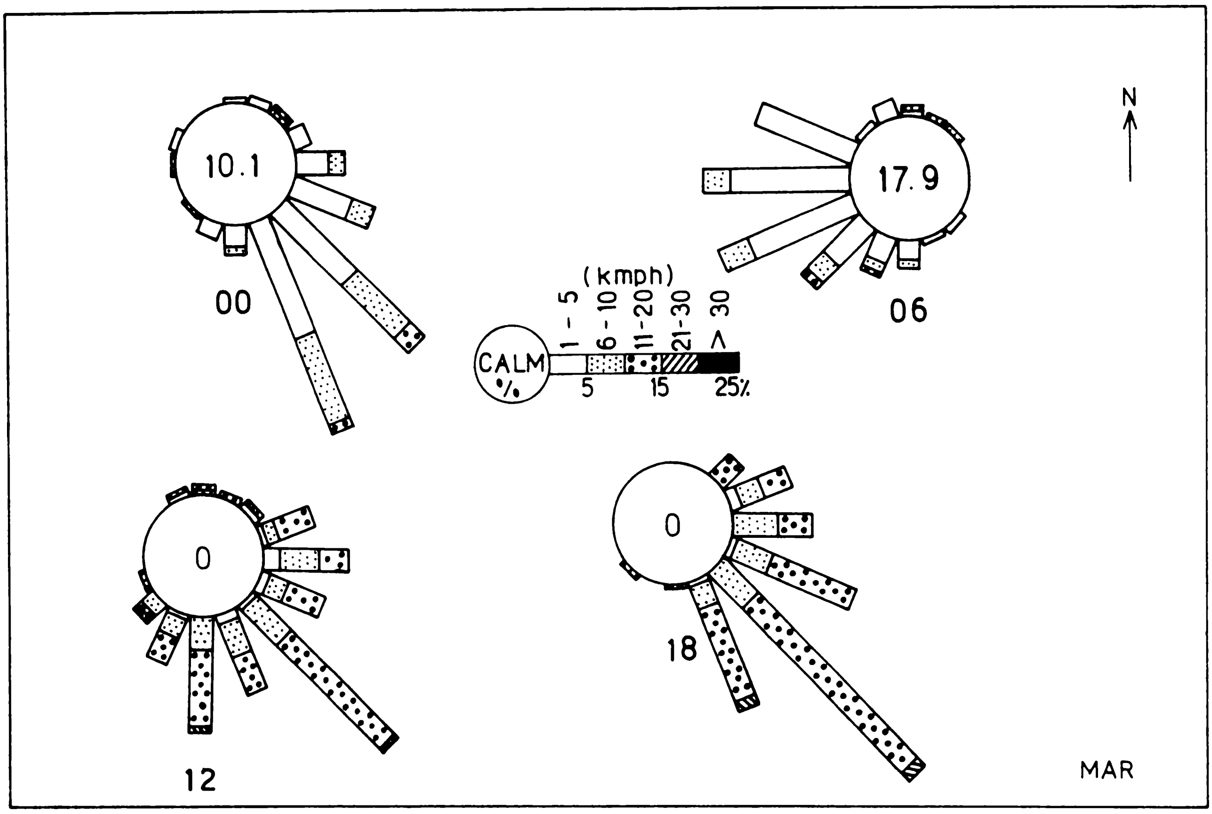


FIG. 3.12(a). WIND ROSES FOR THE MONTHS OF JANUARY AND FEBRUARY



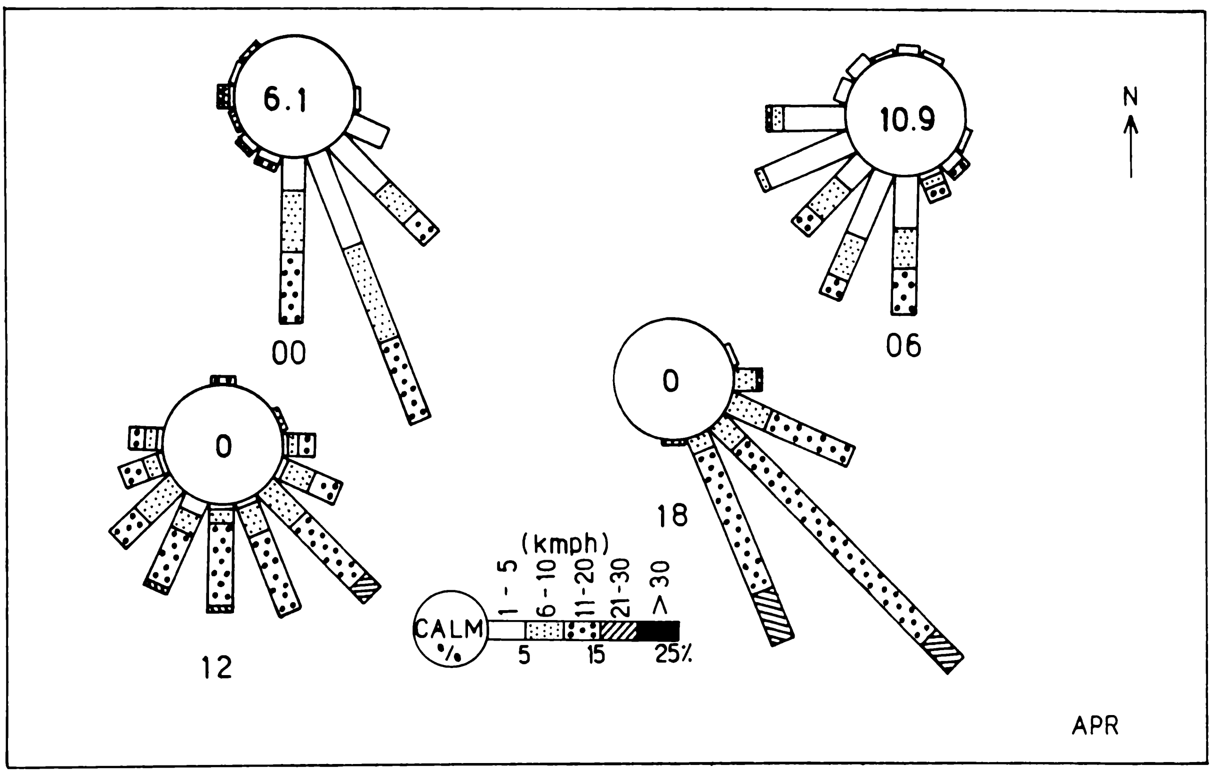


FIG. 3.12(b). WIND ROSES FOR THE MONTHS OF MARCH AND APRIL

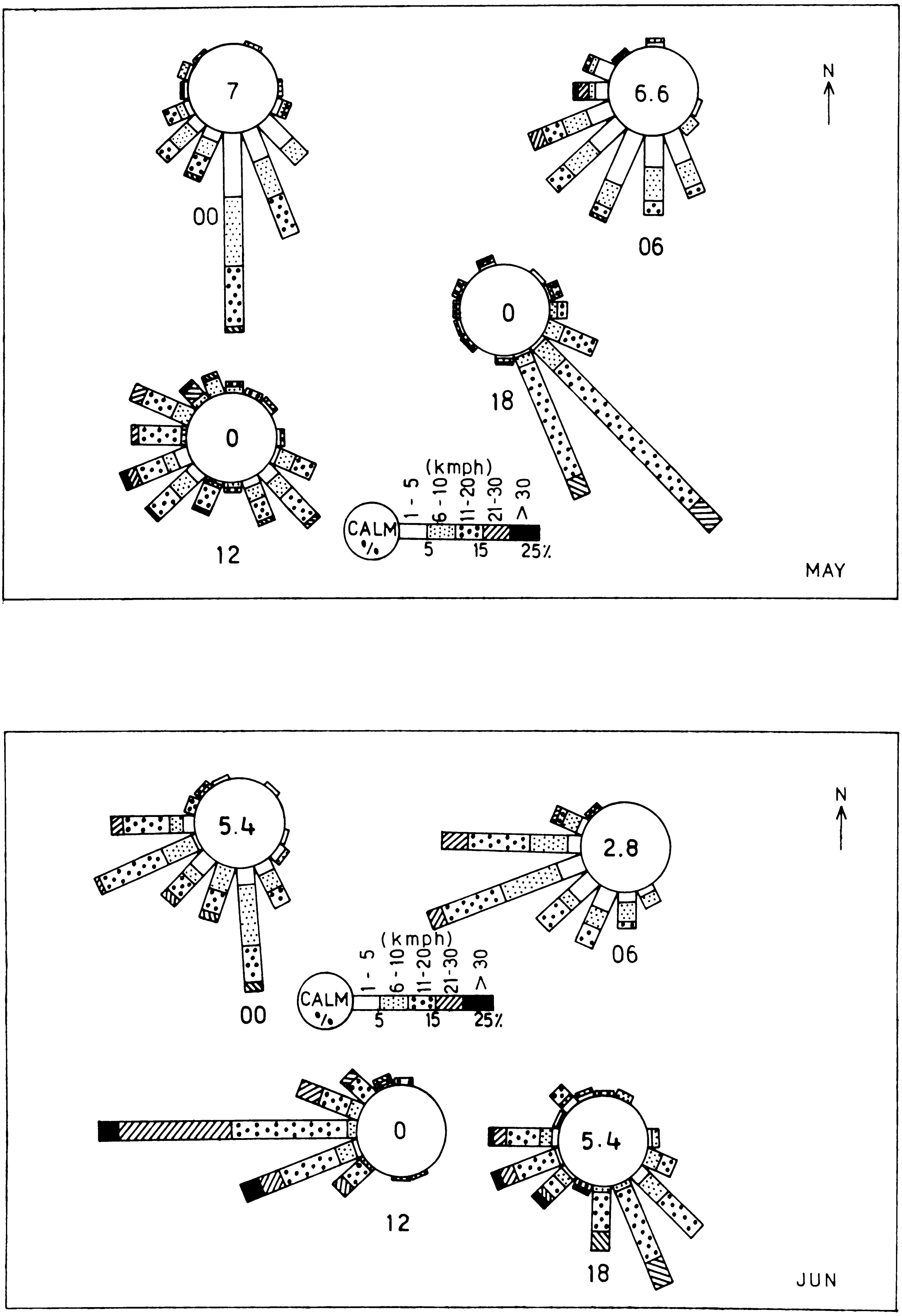
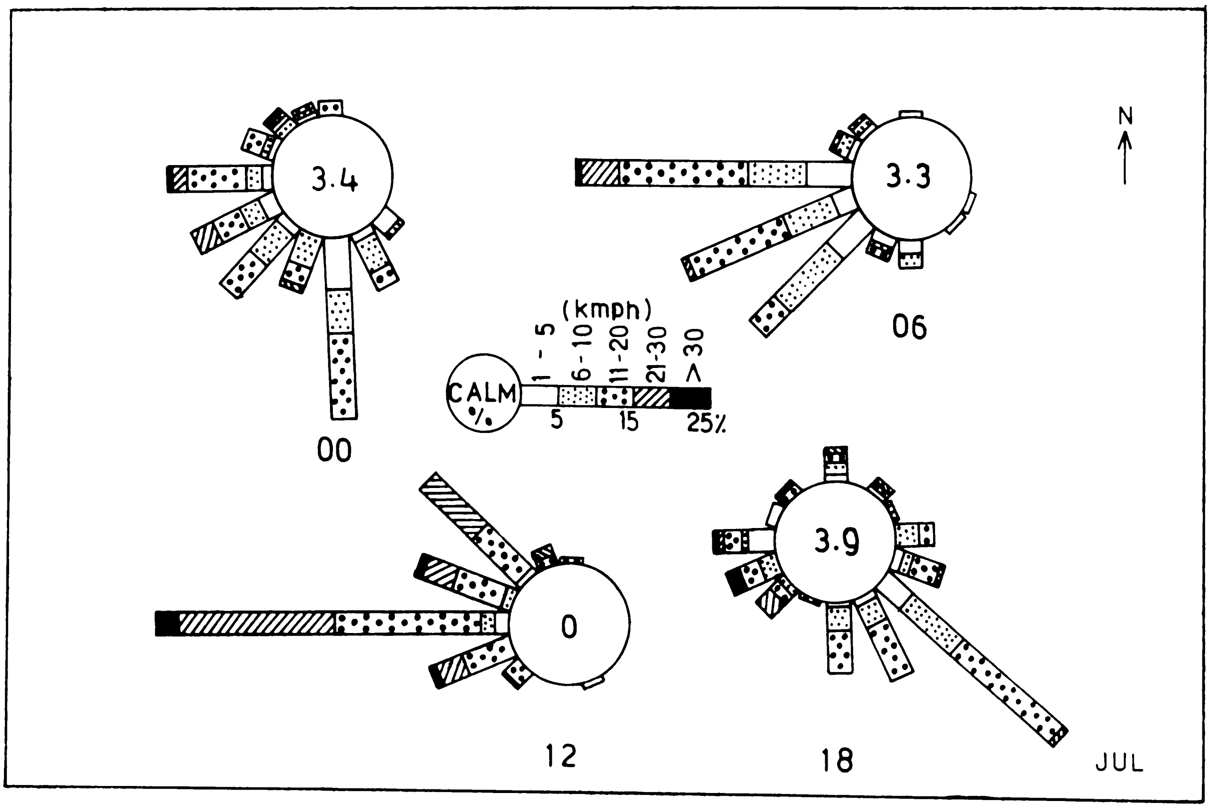


FIG. 3.12(c). WIND ROSES FOR THE MONTHS OF MAY AND JUNE



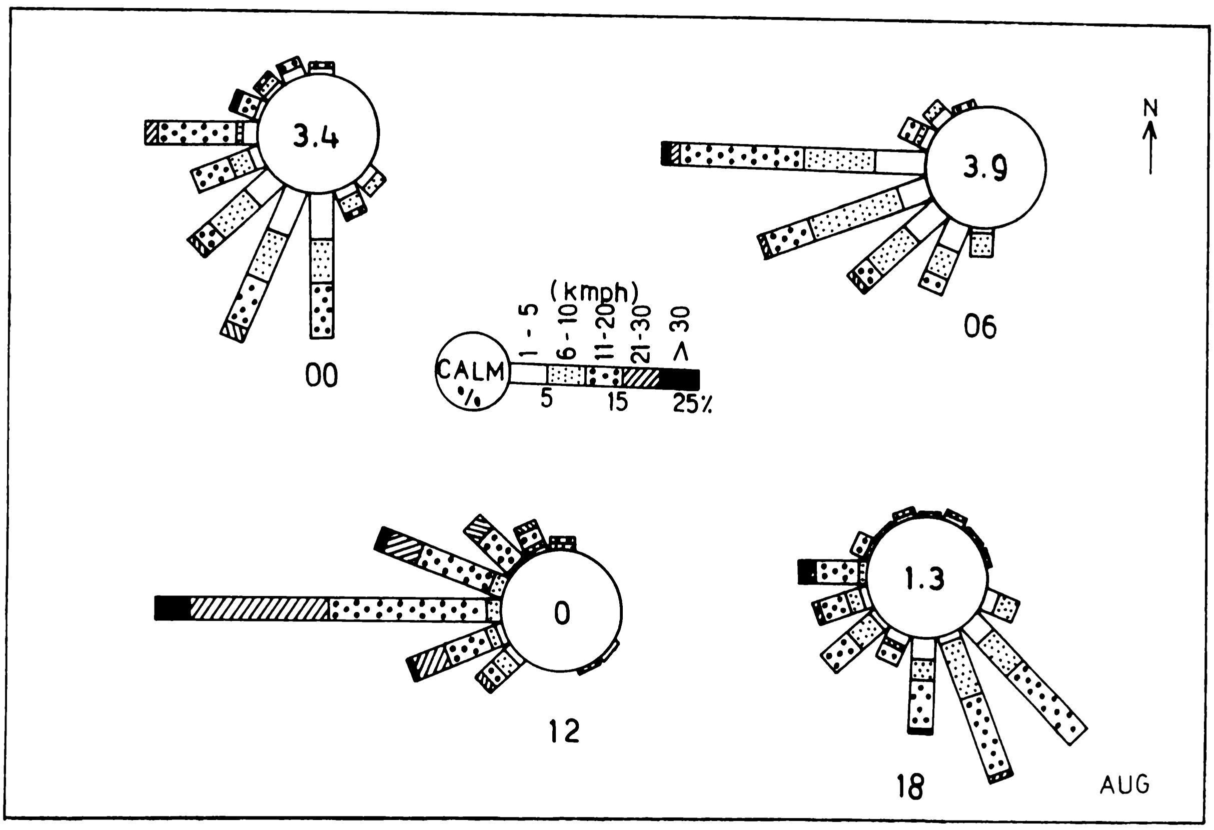


FIG. 3.12(d). WIND ROSES FOR THE MONTHS OF JULY AND AUGUST

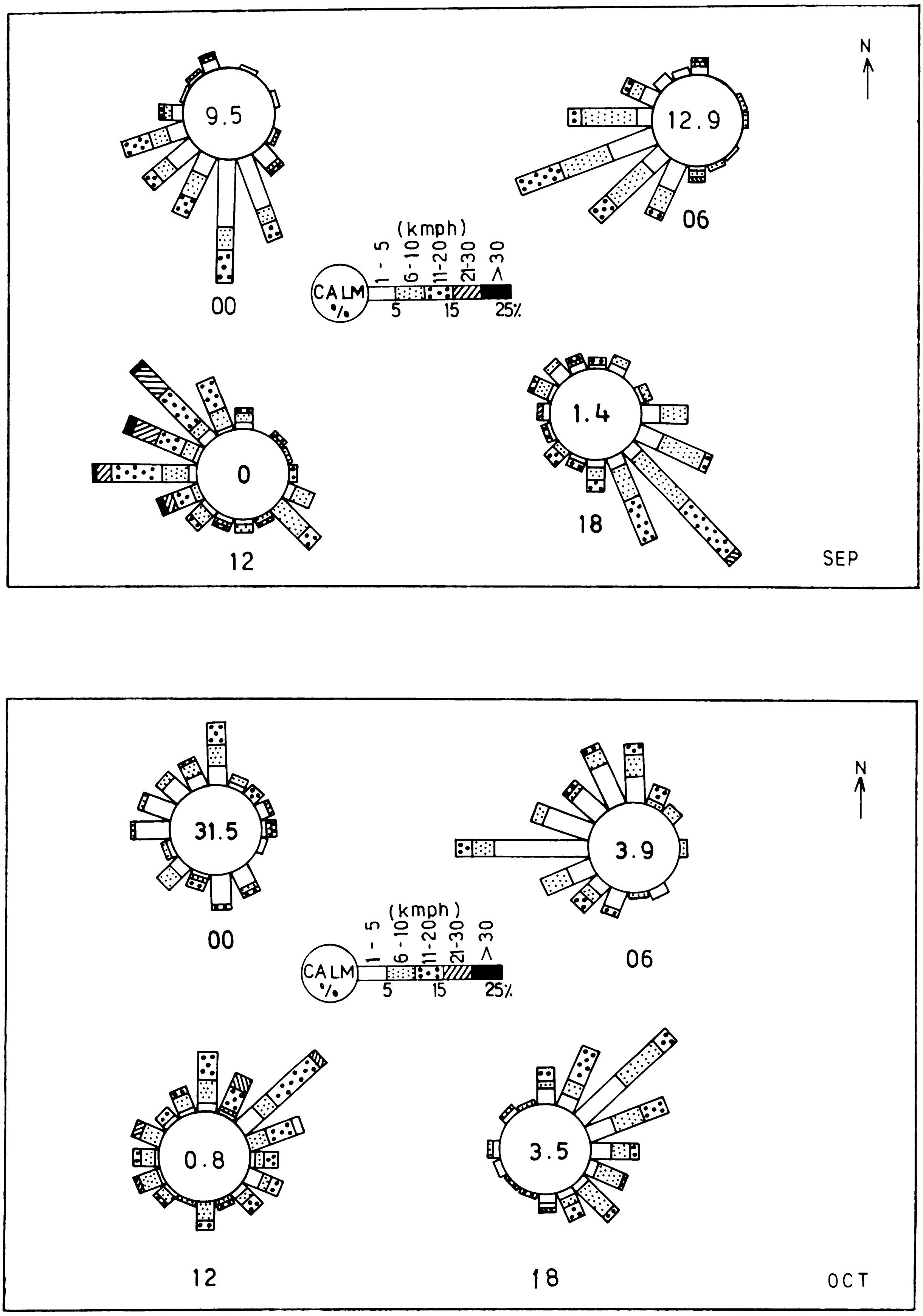
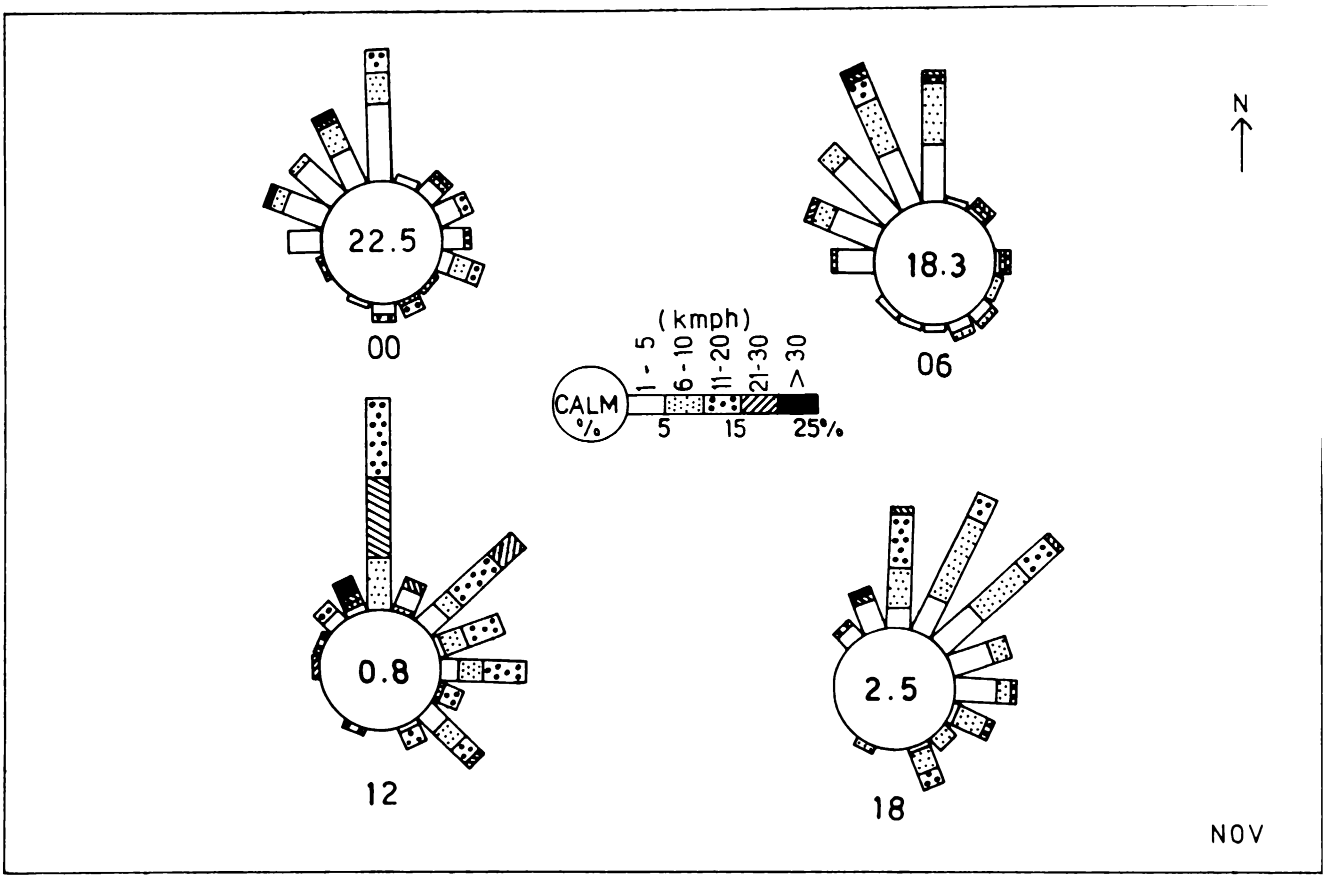


FIG. 3.12(e). WIND ROSES FOR THE MONTHS OF SEPTEMBER AND OCTOBER



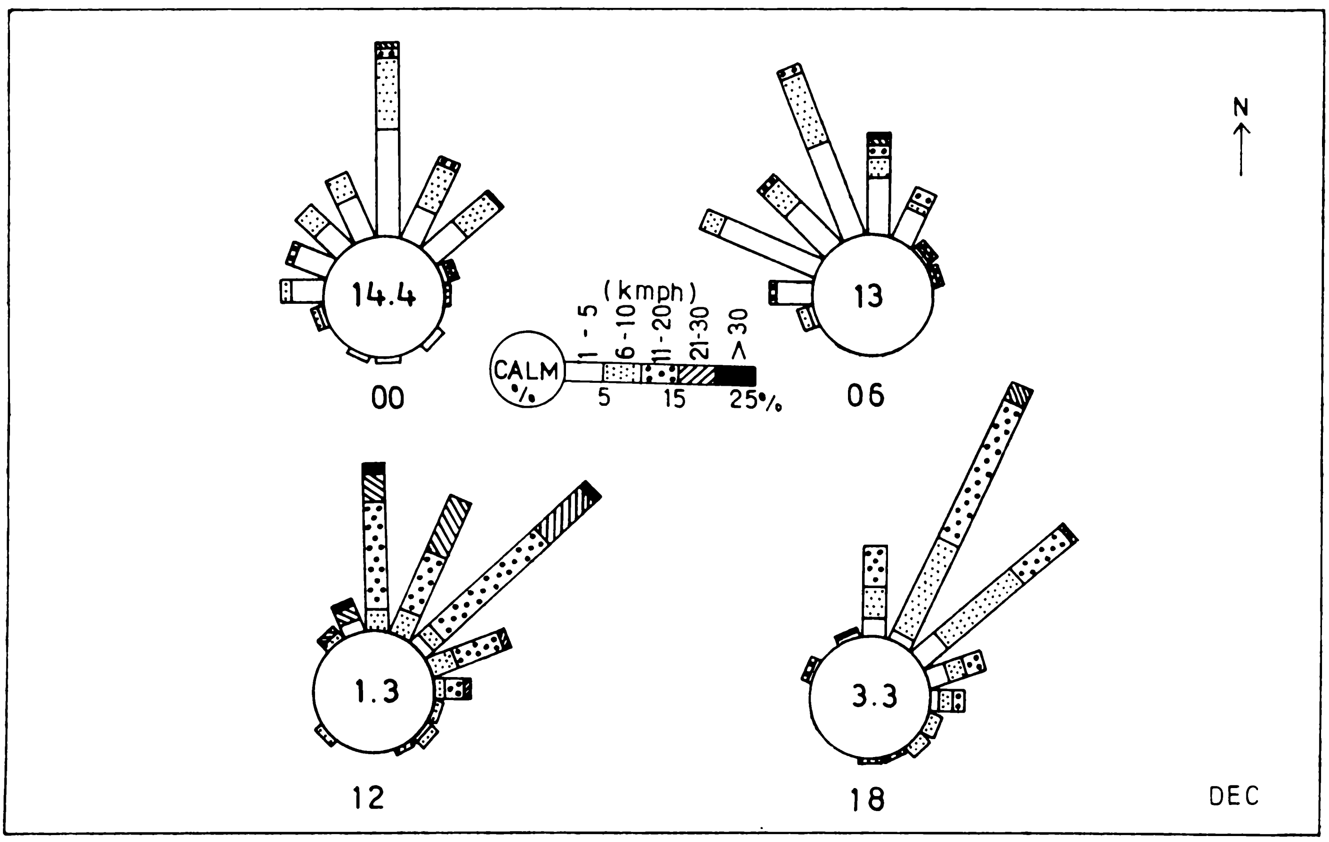


FIG. 3.12(f). WIND ROSES FOR THE MONTHS OF NOVEMBER AND DECEMBER

January, where the northeasterlies dominate.

The wind pattern of March differs from those of the previous months. The frequency of calms has come down substantially at 0000 hours while a moderate increase is noticed at 0600 hours. The northeasterly component has come further in this month and the northeasterlies even at 0000 hours is a noticeable feature. The southeasterly component is increasing consistently from January onwards at 0600 hours. In April, during night-time also the winds are strong. The northeasterly winds are almost negligible during day time as well as midnight. At 0600 hours, the winds are mostly from the southwestern sector and are strong. At 1200 hours the winds are uniformly distributed in the entire southern sector. The reversal of wind from day to night is not prominent. In May, the northerly and northeasterly components are more or less absent. The dominating winds are from southeast to southwest sectors at all the hours. Winds have become stronger in this month compared to those in the earlier months.

The situation in June is similar to that of May except that the winds are stronger in this month than in the former. During day time, appreciable changes are observed. For example, the southeasterly components have come down and a consequent increase in westerly is observed at 1800 hours. Although the westerly frequency at 1800 hours is not predominant, it is considerable. Strong westerlies at 1200 hours are fully established in this month. In July, the westerly domination is observed at most of the times except at 1800 hours, in which case southeasterlies dominate. The wind is widely distributed at 1800 hours. The winds have become stronger at 0600 hours compared to that of June. The case of August is not much different from that of July. In September, however, the dominance of westerly ceases and the wind is widely distributed. The southeasterlies continue to dominate at 1800 hours.

In October, the wind is uniformly distributed with northeasterlies prevailing during day time. Generally, the winds are from northern sector. In the month of November, the frequency of calms has gone up. The winds from northern sector dominate again - easterly during day time and westerly during night-time. A similar situation is observed in December, with the northeastrlies further dominating during day time. The diurnal reversal is not present in December.

All these figures show a consistent change of prominent wind direction from season to season. From October to February, the day time winds are northeasterlies or northerlies and from March to May, they are southeasterlies while they are from western sector during the rest of the months. This shows a complete cycle of wind direction change which means a 360° change. The two monsoons which affect the city are the southwest and the northeast, although the former is not as important as the latter as far as the rainfall is concerned. However, the wind speeds in the southwest monsoon season are slightly higher. This reflects the name 'land of two monsoons' to Tamil Nadu in general and to Madras, in particular. Another important aspect is the presence of southeasterlies at 1800 hours during summer when the southwest direction is predominant at almost all the hours. This may probably be explained as due to the sea breeze phenomenon. Sea breeze should be easterlies in Madras and because of the action of Coriolis force they become southeasterlies. This phenomenon should normally set in around 9 hours or 10 hours, but because of the strong large scale westerlies, this local phenomenon cannot appear until it becomes strong enough to dominate over these westerlies which may take place around 1500 hours.

In any case, the winds are widely distributed from all the directions, if one looks broadly over the entire year. The night-time winds are relatively stronger than what they should normally be, is mainly due to the presence of the strong seasonal winds on a large scale.

CHAPTER IV

WIND SPEED AND DIRECTION FLUCTUATIONS AND THEIR RELATIONSHIPS WITH STABILITY AND MIXING HEIGHT

The various aspects of vertical temperature structure of the atmosphere, mixing heights, ventilation coefficients, wind and atmospheric stability were discussed in the previous chapter. In the present chapter, the surface turbulence in the form of wind direction fluctuation range ($\sigma_{\theta D}$) and wind speed fluctuation range ($\sigma_{\theta D}$) are studied together with their diurnal and seasonal variation. The relationships among stability , mixing height, $\sigma_{\theta D}$ and $\sigma_{\theta S}$ are studied and regression equations are developed between mixing height, $\sigma_{\theta D}$ and $\sigma_{\theta S}$. These three aspects are discussed separately here under.

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

The diurnal variation of $\sigma_{\theta D}$ for the months of January, April, July and October is depicted in Fig. 4.1 representing the four seasonal months - which are typical of winter, premonsoon, monsoon and postmonsoon seasons respectively. In January, the value decreases till early morning and rises thereafter attaining the peak around noon and decreases thereafter till around 2100 hours. The maximum is 12.5°. The diurnal variation is very striking in this month. In April, the range of $\sigma_{\theta D}$ has come down with the maximum being observed around noon. The absolute values are

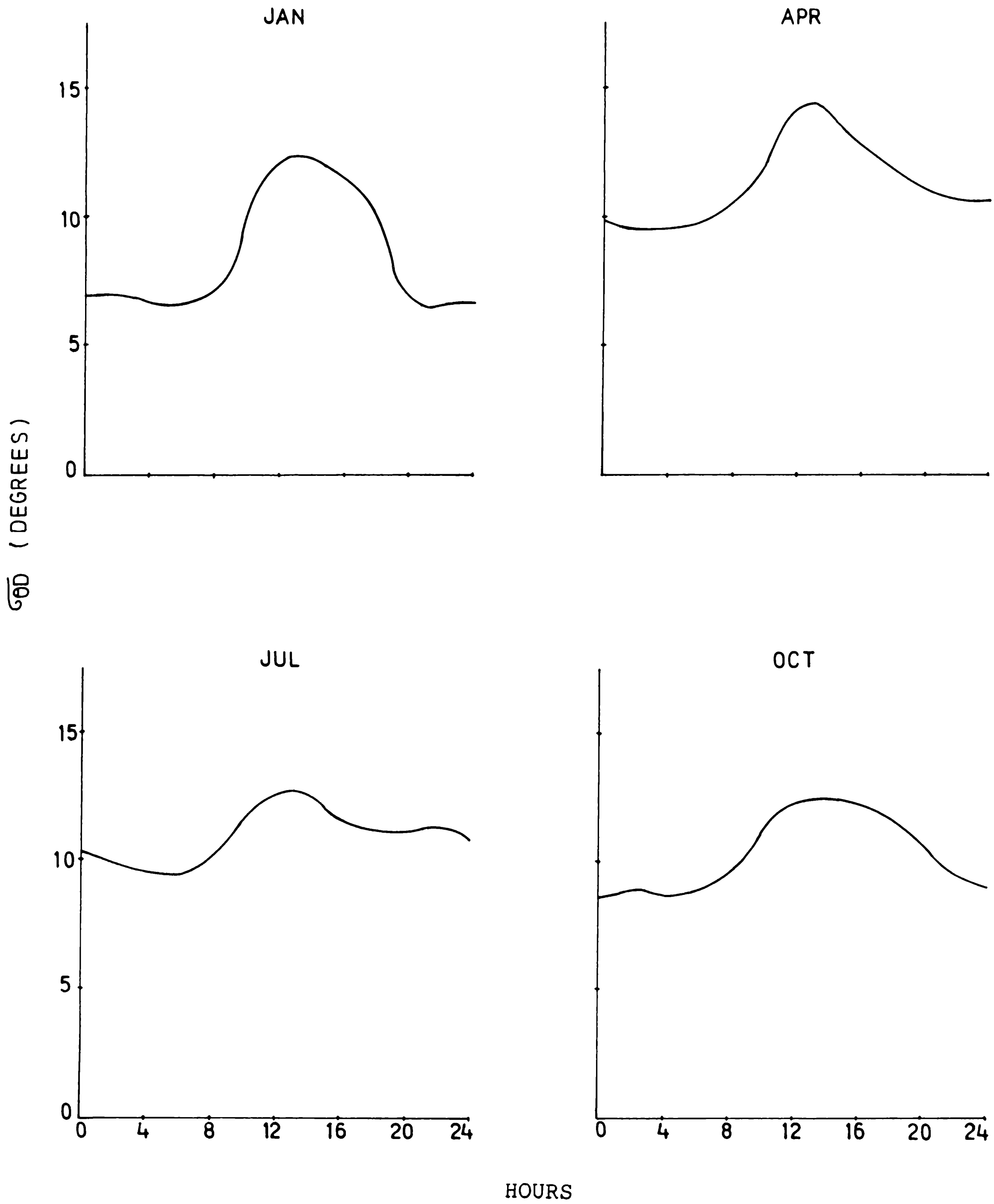


FIG. 4.1. DIURNAL VARIATION OF $\sigma_{\theta D}$

higher at any given time in this month compared to the respective values in January. In the month of July the diurnal variation is not very striking although it is present. The diurnal range has further come down compared to that of April. The peak, once again, is observed at noon and the minimum in morning. In the month of October, the diurnal variation is relatively striking compared to that of July. The peak value is observed for a considerable period of time (1200 hours to 1600 hours). The diurnal variation is found to be maximum in January followed by April, October and July. The absolute values are maximum in April at all the hours with a few exceptions than those values in the other months. The minimum values in the early morning hours can be explained to be due to the most undisturbed conditions prevailing at that time. By undisturbed conditions, it is implied that the atmosphere is absent from external heating. The moment it starts getting heated up, the convection sets in and the wind direction keeps changing quite rapidly indicating the establishment of turbulence in the atmosphere. The maximum value in April can be set due to the intense convection present in this season. The lowest values during night time in January are explained because of the calm conditions likely to prevail in this season. However, it clearly shows $\sigma_{\theta D}$ can be taken to represent the surface turbulence, in view of its attaining minimum values in night time and maximum in day time.

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

The diurnal variation of $\sigma_{\theta S}$ for the months of January, April, July and October are presented in Fig. 4.2. A clear cut diurnal variation is observed in all the months. The minimum is once again observed in early morning hours and the maximum in the afternoon hours with its peak changing from month to month as far as its time of occurrence is concerned. For example, the maximum in January is at 1500 hours, while it is at 1100 hours in July. The diurnal variation of $\sigma_{\theta S}$ does not differ so significantly from month to month. The absolute values are high in July and April while they are relatively low in January and October. Maximum noticed is less than $1 ms^{-1}$. The higher values in April can be explained once again due to intense convection. The most striking feature is the perfect diurnal variation indicating that this could also be taken as a measure of atmospheric turbulence.

It is of interest to note that the diurnal variation of $\sigma_{\theta S}$ is relatively more striking than that of $\sigma_{\theta D}$ which means that either of these two or both together may be taken as a measure of turbulence. The perfect diurnal variation of both $\sigma_{\theta D}$ and $\sigma_{\theta S}$ suggests a strong relation between these two. It is only a matter of choice as to which parameter $\sigma_{\theta S}$ or $\sigma_{\theta D}$ is taken as a measure of turbulence. Since the computation of any one of these two is relatively easy, the

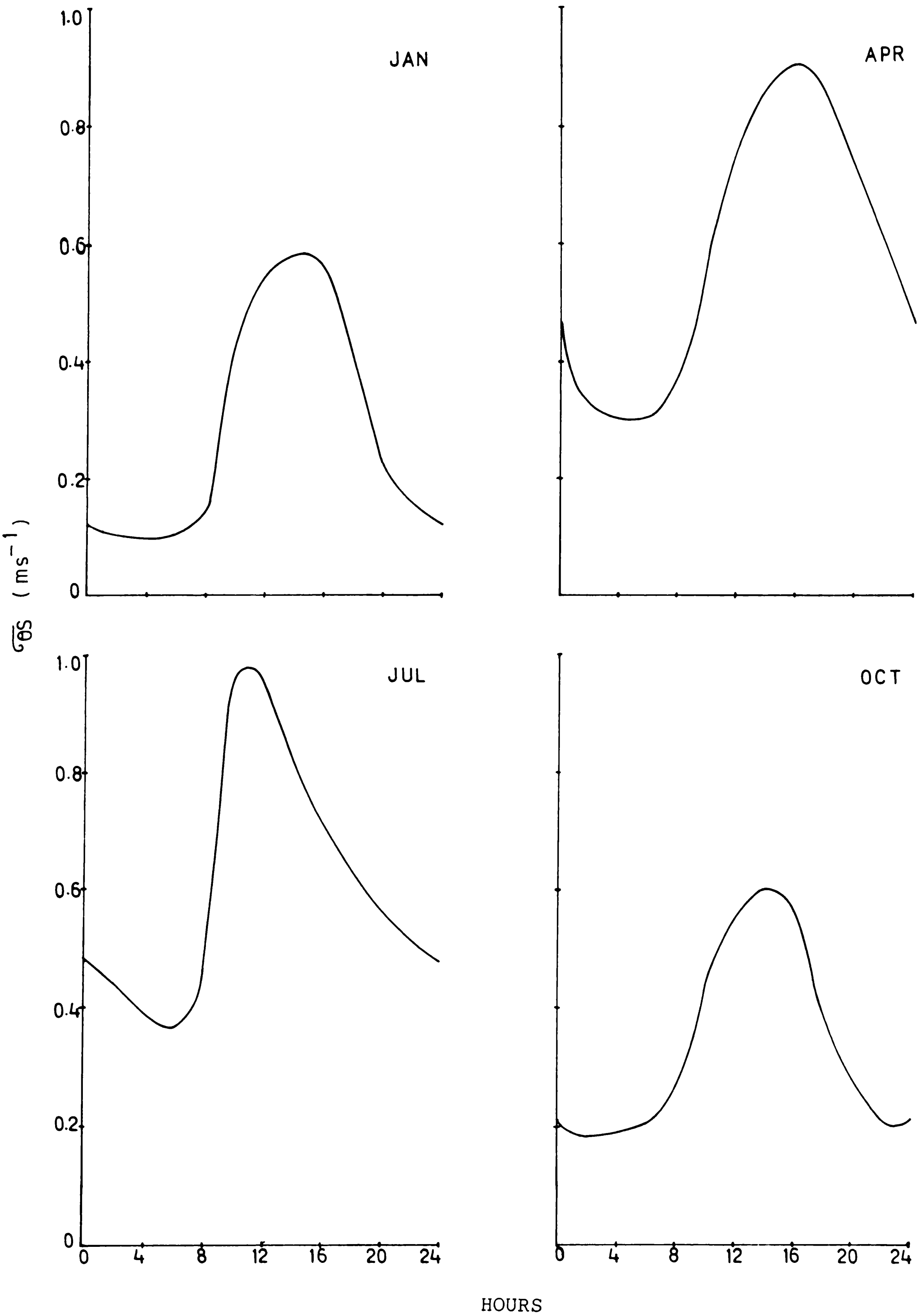


FIG. 4.2. DIURNAL VARIATION OF $\sigma_{\theta s}$

other important parameters in air pollution such as mixing height and stability whose diurnal variation is equally striking could be determined from the values of $\sigma_{\theta D}$ and $\sigma_{\theta S}$ provided the relation among them is established.

4.3 INTERRELATIONSHIPS AMONG STABILITY, MIXING HEIGHT, $\sigma_{\theta D}$ AND $\sigma_{\theta S}$

The main purpose of this section is to establish a relationship for all possible combinations of $\sigma_{\theta D}$, $\sigma_{\theta S}$, mixing height and Pasquill's stability.

4.3.1 Pasquill's stability vs $\sigma_{\theta D}$

Table 4.1 to 4.4 show various statistical parameters of $\sigma_{\theta D}$ for each of the Pasquill's stability classes for January, April, July and October respectively. In almost all the cases $\sigma_{\theta D}$ decreases from A to F categories as far as arithmetic mean is concerned. Median and modal values do not show any systematic variation with different stability categories. The coefficient of variation too does not provide any encouraging result to identify different stability classes. It is evident from these four tables that the identification of stability class with unique value of $\sigma_{\theta D}$ is difficult. The month to month variation in various statistical parameters is neither high nor realible as an indicator of stability class. This is perhaps because extreme conditions are not experienced in this coastal city.

Table 4.1

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

in different stability classes for January

	MEAN	MEDIAN	MODE	SD	MD	CV
A	12.24	11.7	10.0	4.03	3.23	32.9
B	10.24	10.0	10.0	3.98	3.14	38.9
C	9.96	10.0	10.0	3.33	2.50	33.4
D	10.11	10.0	10.0	3.27	2.59	32.4
E	8.80	8.3	8.3	2.90	2.49	33.0
F	6.73	6.7	5.0	2.88	2.05	42.7

Table 4.2

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

in different stability calsses for April

	MEAN	MEDIAN	MODE	SD	MD	CV
A	13.69	14.2	13.3	3.78	2.92	27.6
B	12.62	11.7	10.0	3.96	3.13	31.4
C	12.11	11.7	10.0	3.48	2.79	28.8
D	12.31	11.7	10.0	3.02	2.48	24.5
E	11.56	11.7	10.0	2.89	2.27	25.0
F	9.93	10.0	10.0	2.68	2.07	27.0

Table 4.3

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

in different stability classes for July

	MEAN	MEDIAN	MODE	SD	MD	CV
A	13.03	12.1	12.5	2.77	2.39	21.3
B	11.91	11.7	10.0	3.93	3.18	33.0
C	11.36	10.8	10.0	3.76	3.06	33.1
D	10.73	q0.0	10.0	3.60	2.91	33.6
E	10.73	10.0	10.0	3.43	2.77	32.0
F	10.37	10.0	10.0	2.90	2.26	28.0

Table 4.4

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

in different stability classes for October

	MEAN	MEDIAN	MODE	SD	MD	CV
A	13.05	13.3	10.0	3.91	3.24	30.0
B	11.83	11.7	10.0	3.68	2.99	31.1
C	10.76	10.0	10.0	3.46	2.63	32.2
D	10.53	10.0	10.0	3.14	2.46	29.8
E	9.08	8.3	11.7	2.19	1.79	24.1
F	9.21	10.0	8.3	2.84	2.26	30.9

4.3.2 Pasquill's stability vs $\sigma_{\theta S}$

The same statistical parameters of $\sigma_{\theta S}$ are presented for different stability classes in tables 4.5 to 4.8 for the months January, April, July and October respectively. In this case too, the relationship is rather inconsistent and hence $\sigma_{\theta S}$ cannot be used for identifying different stability categories with any degree of certainity.

Table 4.5

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

in different stability classes for January

	MEAN	MEDIAN	MODE	SD	MD	CV
A	0.37	0.37	0.37	0.18	0.15	49.9
B	0.40	0.42	0.56	0.21	0.18	53.4
C	0.45	0.49	0.56	0.22	0.18	49.8
D	0.44	0.46	0.56	0.18	0.14	41.0
E	0.36	0.35	0.38	0.12	0.17	33.5
F	0.14	0.09	0.05	0.11	0.09	82.9

Table 4.6

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

in different stability classes for April

	MEAN	MEDIAN	MODE	SD	MD	CV
A	0.53	0.51	0.58	0.21	0.16	38.8
B	0.60	0.58	0.56	0.25	0.20	41.9
C	0.70	0.74	0.83	0.32	0.27	45.7
D	0.85	0.83	1.11	0.31	0.26	36.7
E	0.80	0.83	0.93	0.25	0.21	31.2
F	0.34	0.30	0.05	0.23	0.18	67.7

Table 4.7

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

in different stability classes for July

	MEAN	MEDIAN	MODE	SD	MD	CV
A	0.48	0.42	0.56	0.28	0.23	58.6
B	0.65	0.58	0.37	0.35	0.28	54.5
C	0.75	0.67	0.46	0.41	0.34	55.3
D	0.77	0.69	0.65	0.36	0.29	47.4
E	0.58	0.53	0.46	0.25	0.20	42.9
F	0.37	0.32	0.28	0.22	0.17	60.0

Table 4.8

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

in different stability classes for October

	MEAN	MEDIAN	MODE	SD	MD	CV
A	0.39	0.39	0.46	0.17	0.13	43.9
B	0.45	0.44	0.46	0.22	0.17	49.8
C	0.46	0.46	0.46	0.23	0.18	51.0
D	0.48	0.44	0.37	0.26	0.20	53.6
E	0.52	0.44	0.28	0.30	0.25	60.4
F	0.19	0.16	0.05	0.15	0.12	76.7

4.3.3 Pasquill's stability vs mixing height

The same statistical parameters of mixing heights are presented for different stability classes in tables 4.9 to 4.12 for the months of January, April, July and October respectively. A systematic decrease of mixing height from A to F categories is noticed in almost all the cases. The modal values however fail to have any distinguishing feature for any of the stability classes, while the coefficients of variation are fairly high in all the months. In spite of this, it is still possible to clearly distinguish the mixing height values between stable and unstable conditions. The

Table 4.9

Statistical parameters of mixing height in different stability classes for January

	MEAN	MEDIAN	MODE	SD	MD	CV
A	766	773	450	392	332	51.4
B	675	595	650	485	422	71.8
C	730	780	535	490	423	67.2
D	721	730	820	443	280	61.4
E	331	275	350	270	224	81.4
F	204	155	180	240	158	105.2

Table 4.10

Statistical parameters of mixing height in different stability classes for April

	MEAN	MEDIAN	MODE	SD	MD	CV
A	994	977	805	414	336	41.7
B	890	850	785	456	360	51.3
C	705	720	680	472	389	66.9
D	582	500	520	395	325	68.0
E	276	255	295	190	149	68.9
F	178	140	160	158	126	87.6

Table 4.11

Statistical parameters of mixing height in different stability classes for July

	MEAN	MEDIAN	MODE	SD	MD	CV
A	848	800	785	582	466	68.6
B	935	845	895	636	529	68.1
C	911	842	885	623	522	68.4
D	717	500	695	655	525	91.3
E	329	245	315	317	232	96.6
F	293	190	310	322	236	109.8

Table 4.12

Statistical parameters of mixing height in different stability classes for October

	MEAN	MEDIAN	MODE	SD	MD	CV
A	799	695	680	601	488	75.2
B	697	475	620	584	480	83.9
C	597	415	605	522	440	87.4
D	536	380	590	495	398	92.4
E	196	140	205	202	152	102.9
F	223	150	250	237	170	106.1

main purpose of this particular study is to help estimate mixing heights within a reasonable range from stability-a parameter which does not require radiosonde data. It is not out of context to mention here that an error of 100 to 200m in mixing heights is not generally critical either for forecasting or planning purposes.

4.3.4 Direction fluctuation ($\sigma_{\theta D}$) vs Mixing height

The following linear regression equations, 4.1 to 4.4 are developed for obtaining mixing heights from $\sigma_{\theta D}$ for the four typical months January, April, July and October respectively.

$$MH = 158\ \sigma_{\theta D} - 909 \quad (4.1)$$

$$MH = 246\ \sigma_{\theta D} - 2312 \quad (4.2)$$

$$MH = 361\ \sigma_{\theta D} - 3340 \quad (4.3)$$

$$MH = 202\ \sigma_{\theta D} - 1822 \quad (4.4)$$

The above equations show a considerable monthly variation. The negative constants indicate that even if there is no mixing height, $\sigma_{\theta D}$ can be present. The unusually high degree of correlation coefficients suggests that strong and close relationship between mixing heights and $\sigma_{\theta D}$. The negative intercepts are understandable in view of the fact that many a time the mixing heights are extremely low during night time while $\sigma_{\theta D}$ is almost always present. This may probably imply that the mere presence of the surface turbulence may not trigger the vertical convections. Fig. 4.3 shows the scatter diagram between $\sigma_{\theta D}$ and mixing height. It can be concluded that mixing height can be computed with a very fair degree of accuracy from $\sigma_{\theta D}$. The case of $\sigma_{\theta D}$ being zero, if at all arises, causes mixing height to be a negative value. Although apparently this seems to be a paradox, since negative mixing height has not been defined, the present case of negative mixing height may be considered to be one of very strong inversion where only subsidence is present. In the normal mixing case, there will be upward as well as downward motions, leading to thorough mixing , which is a case of positive mixing height. Moreover, the probability of getting negative values with the range of $\sigma_{\theta D}$ observed for this city is rather low.

4.3.5 Speed fluctuation ($\sigma_{\theta S}$) vs Mixing height

The following linear regression equations, 4.5 to 4.8 are developed for obtaining mixing height from $\sigma_{\theta S}$ for the four typical months January, April, July and October respectively.

$$MH = 1917\ \sigma_{\theta S} - 84 \qquad (4.5)$$

$$MH = 1374\ \sigma_{\theta S} - 307 \qquad (4.6)$$

$$MH = 1814\ \sigma_{\theta S} - 498 \qquad (4.7)$$

$$MH = 1918\ \sigma_{\theta S} - 214 \qquad (4.8)$$

Unlike in the case of $\sigma_{\theta D}$ vs mixing height, the

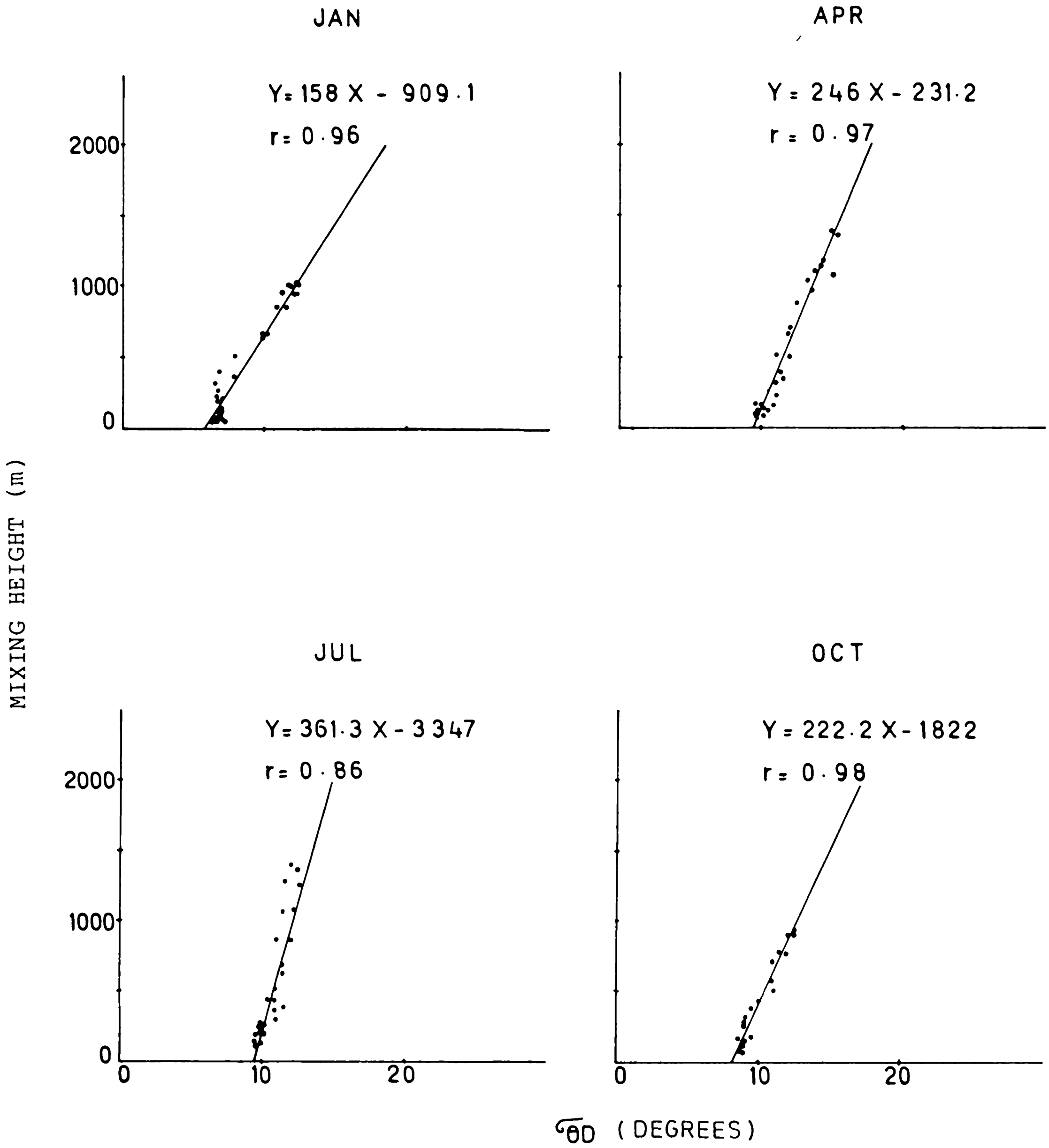


FIG. 4.3. SCATTER DIAGRAM BETWEEN MIXING HEIGHT AND $\sigma_{\theta D}$

equations do not differ significantly except for April where it is relatively poorly correlated, absolutely high correlation coefficient notwithstanding. Once again the negative constants are present which show that for zero value of $\sigma_{\theta S}$, negative mixing height would result. Fig. 4.4 shows the scatter of $\sigma_{\theta S}$ and mixing height. The cases of January and October are near perfect while for April and July it is not so perfect although the correlations are around 0.8. It is evident that one can easily obtain the mixing height from the values of $\sigma_{\theta S}$ also. For negative values, the same explanation that was offered in the case of $\sigma_{\theta D}$ and mixing height could be offered.

4.3.6 $\sigma_{\theta D}$ vs $\sigma_{\theta S}$

The following linear regression equations, 4.9 to 4.12 are developed for $\sigma_{\theta D}$ and $\sigma_{\theta S}$ for the months of January, April, July and October respectively.

$$\sigma_{\theta D} = 11.8\ \sigma_{\theta S} + 5.2 \qquad (4.9)$$

$$\sigma_{\theta D} = 5.7\ \sigma_{\theta S} + 8.1 \qquad (4.10)$$

$$\sigma_{\theta D} = 5.0\ \sigma_{\theta S} + 7.9 \qquad (4.11)$$

$$\sigma_{\theta D} = 8.9\ \sigma_{\theta S} + 7.1 \qquad (4.12)$$

The positive constants in the equation indicate that when $\sigma_{\theta S}$ is zero $\sigma_{\theta D}$ is present. The case of $\sigma_{\theta S}$ zero need not not necessary mean zero wind speed, but may indicate uniform values of wind speed. As such it is not inconsistent

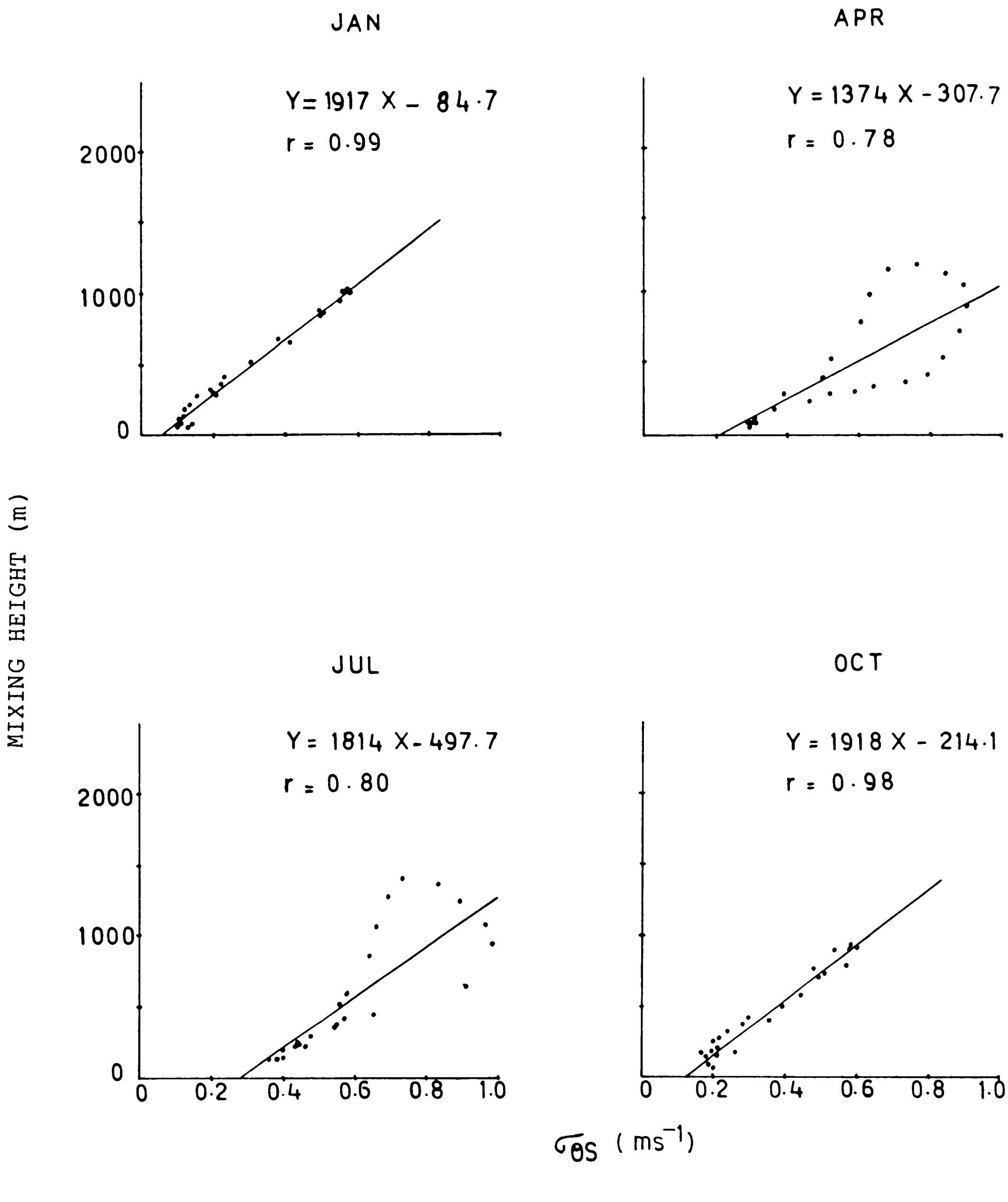


FIG. 4.4. SCATTER DIAGRAM BETWEEN MIXING HEIGHT AND $\sigma_{\theta S}$

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to get values of $\sigma_{\theta D}$ for zero values of $\sigma_{\theta S}$. This also shows that wind direction is highly variable compared to that of wind speed. The scatter between $\sigma_{\theta D}$ and $\sigma_{\theta S}$ is shown in Fig. 4.5. Once again, amazingly, the correlations are absolutely high, showing a near perfect relationship between these two. If one is known the other can be computed. However, the question that arises is which one of these two should be taken. In view of the relatively higher values of the possible errors likely to be encountered would be small in percentage while it becomes the same order of magnitude for $\sigma_{\theta D}$, especially when at lower values. Hence, $\sigma_{\theta D}$ may represent the surface turbulence better. Even for the purposes of relating the various parameters ie mixing height, stability etc. is likely to be the better choice. The level of significance of most of the above cases is 1%.

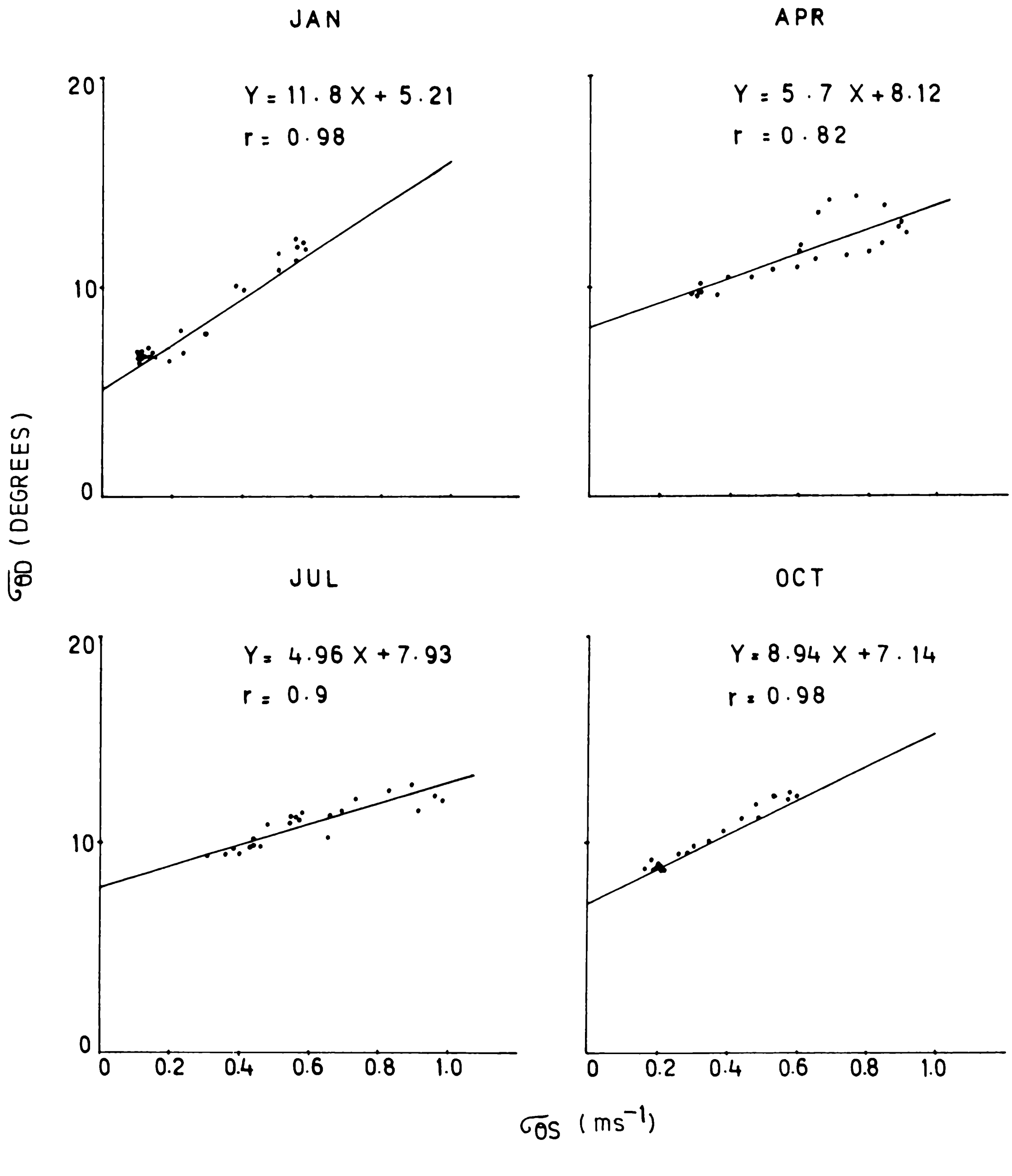

FIG. 4.5. SCATTER DIAGRAM BETWEEN $\sigma_{\theta D}$ AND $\sigma_{\theta S}$

CHAPTER V

MODEL STUDIES OF SULPHUR DIOXIDE CONCENTRATIONS

In the preceding chapters, the parameters which affect dispersal of airborne pollutants were discussed in detail. This chapter is completely devoted for estimating spatial distribution of sulphur dioxide concentrations using Gaussian plume model. All the parameters discussed earlier and the actual emission from various industries are incorporated in the model. Various steps to reduce pollution and locations for new industries are discussed in this chapter. A map of Madras city and neighbourhood is shown in Fig. 5.1.

5.1 SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS

The spatial distribution of sulphur dioxide concentrations at the surface, obtained by means of Gaussian plume model for multiple industrial sources over Madras, is presented in Figs. 5.2(a) to 5.2(l) for the months from January to December respectively.

January

The concentration is maximum ($60 \mu gm^{-3}$) near Ennore in the northeastern sector with a secondary maximum ($40 \mu gm^{-3}$) in the central parts, extending from Ambathur to Royapettah in the heart of the city. The entire western belt has lower concentrations (less than $20 \mu gm^{-3}$). Steep gradients of

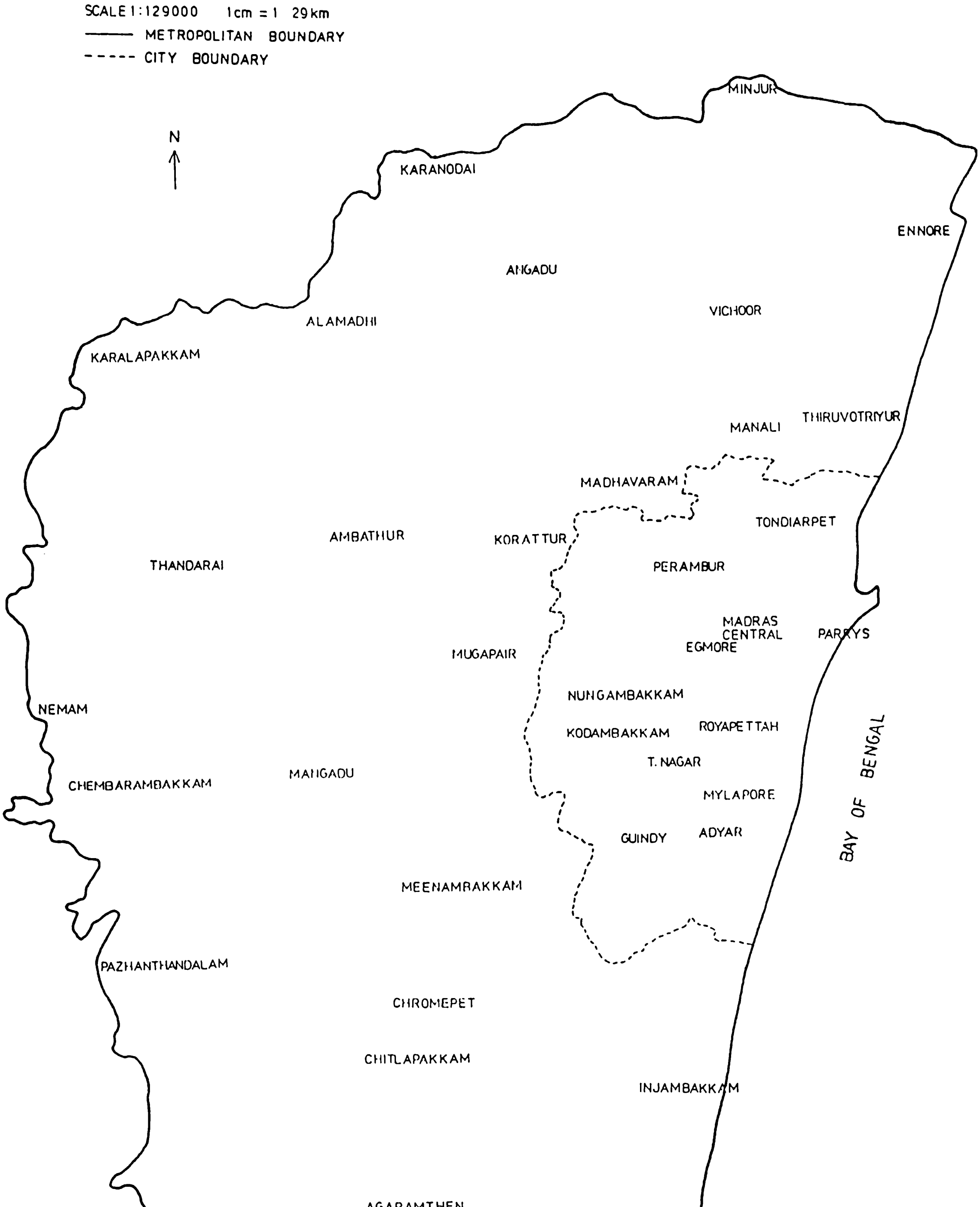

FIG. 5.1. MAP OF MADRAS CITY AND NEIGHBOURHOOD

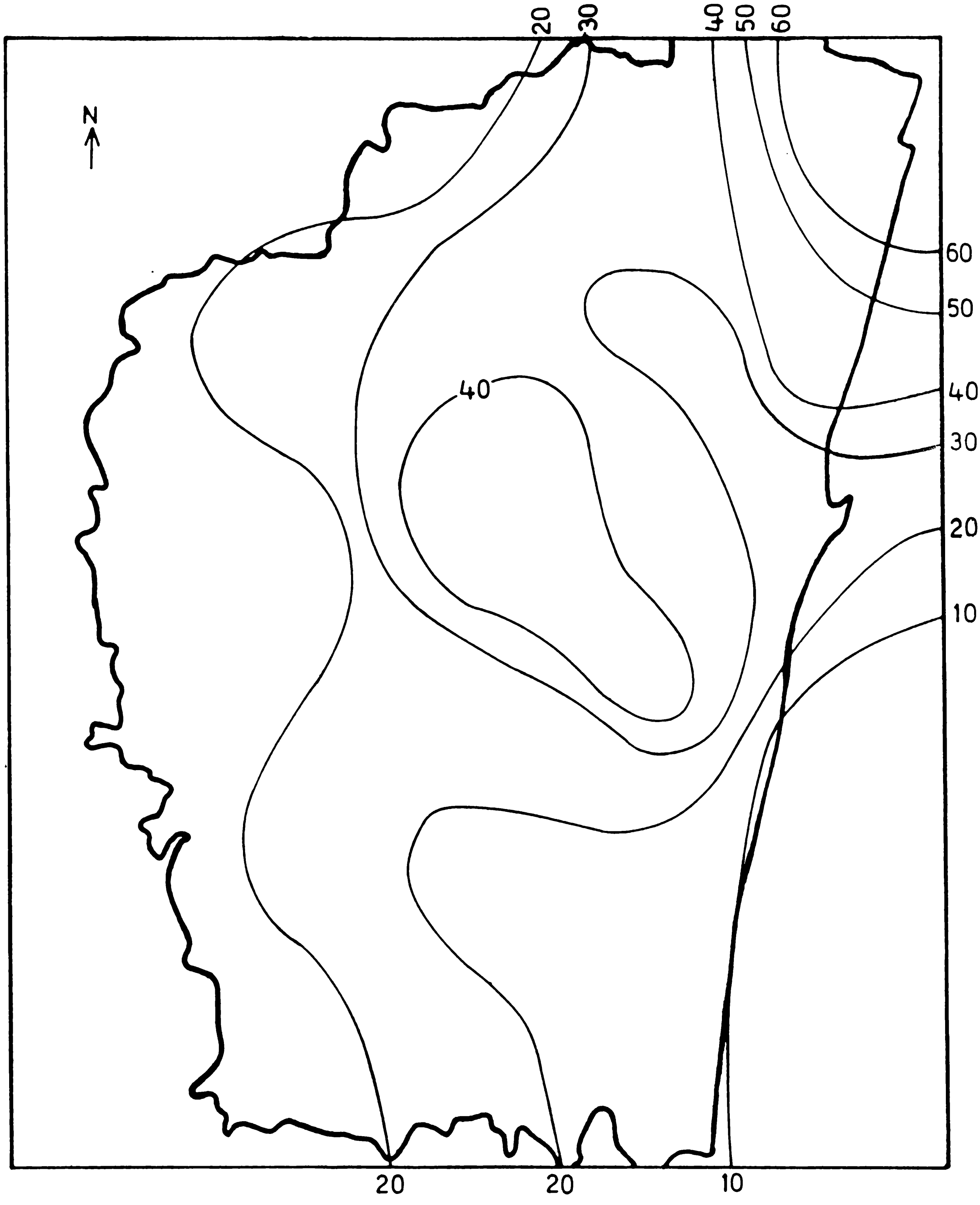

FIG. 5.2(a). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR JANUARY (μgm^{-3})

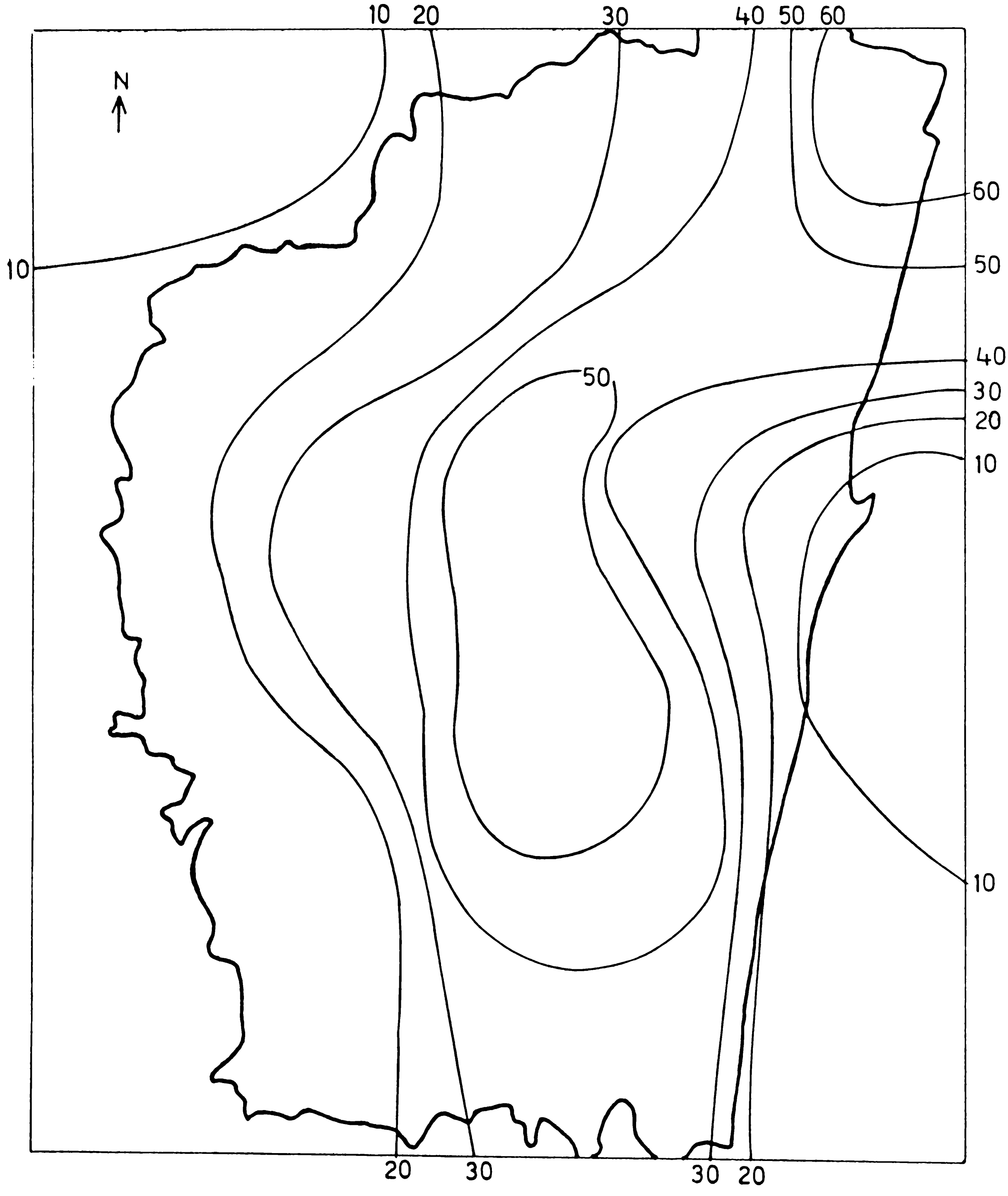

FIG. 5.2(b). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR FEBRUARY (μgm^{-3})

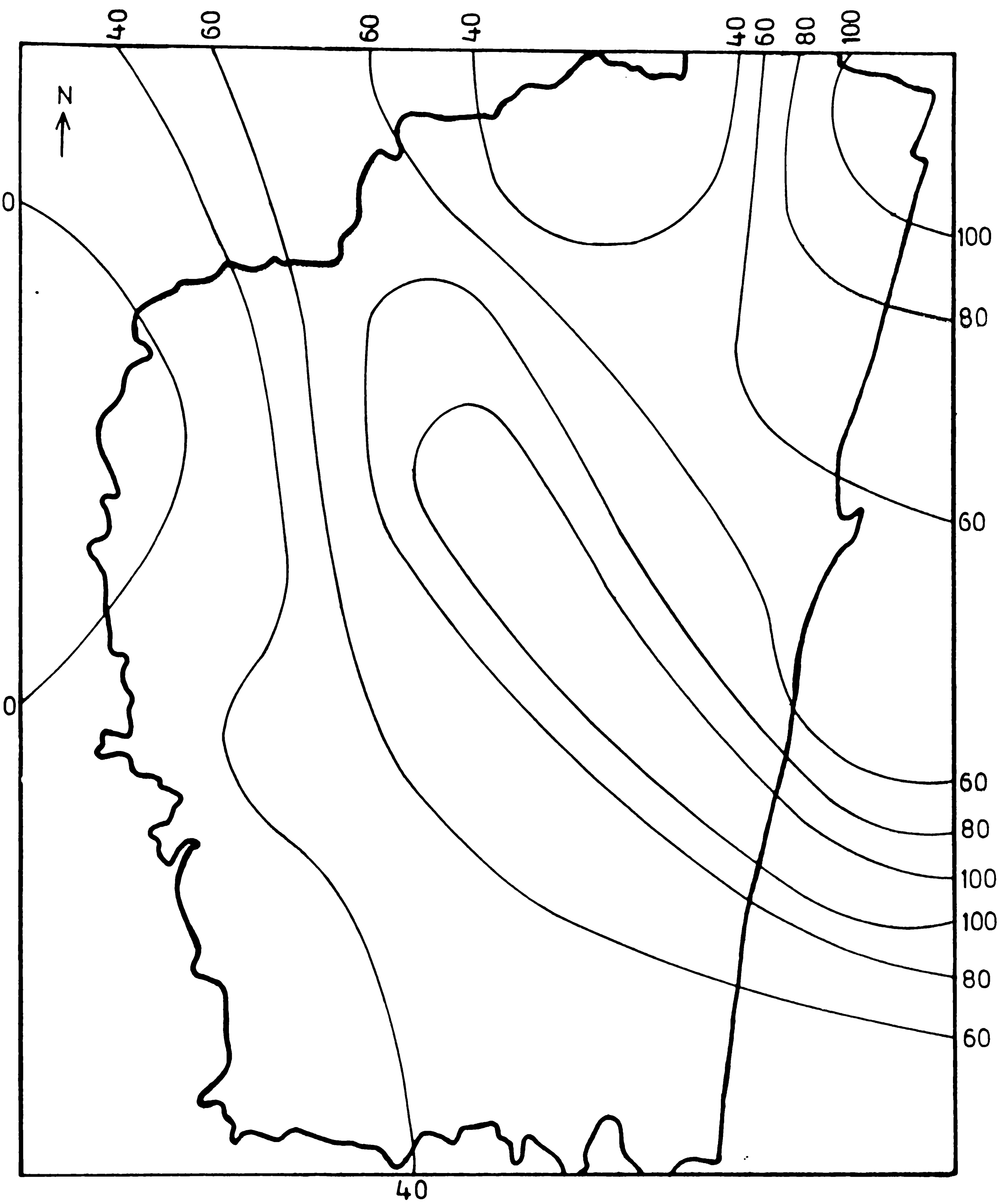

FIG. 5.2(c). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR MARCH (μgm^{-3})

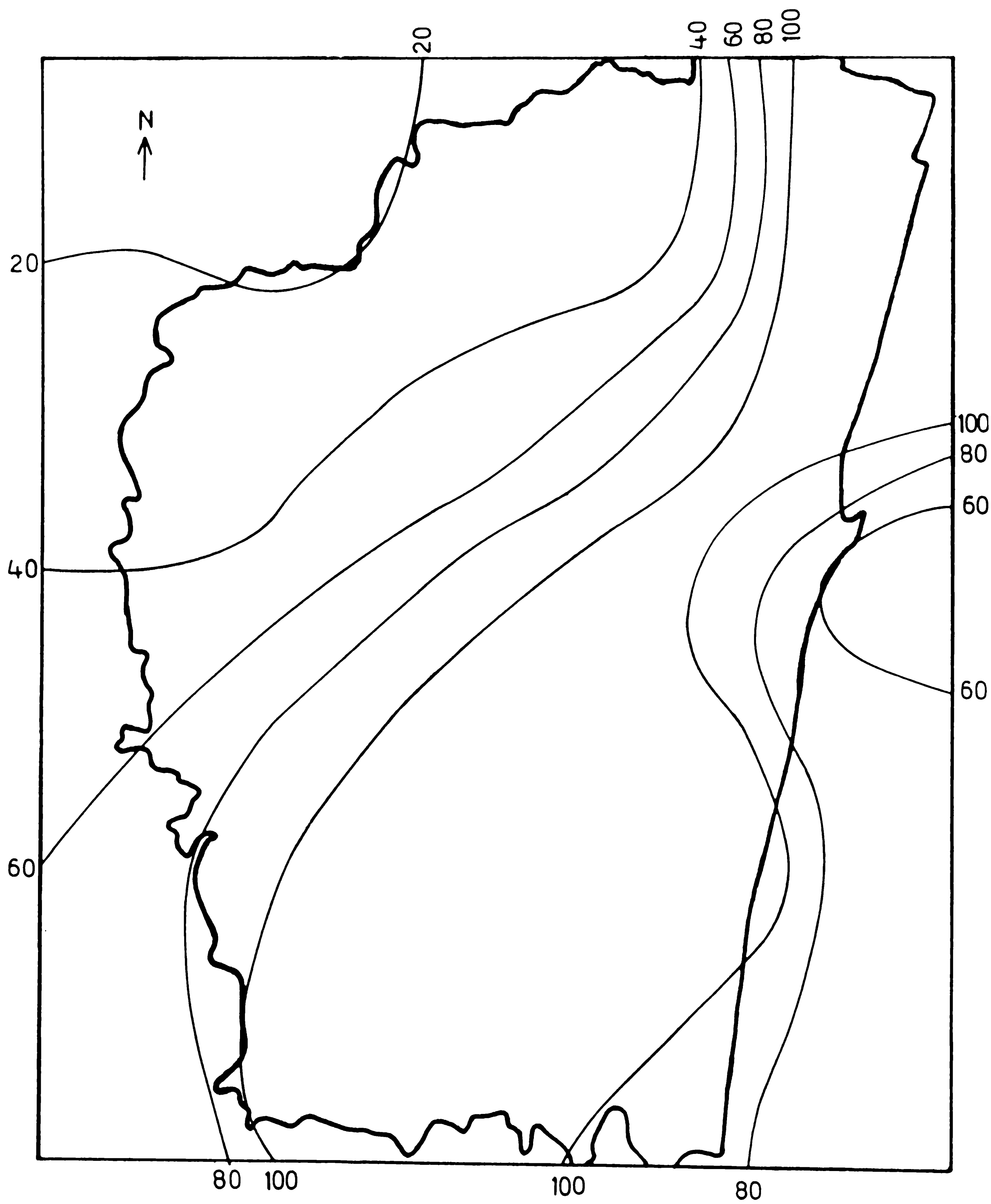

FIG. 5.2(d). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR APRIL (μgm^{-3})

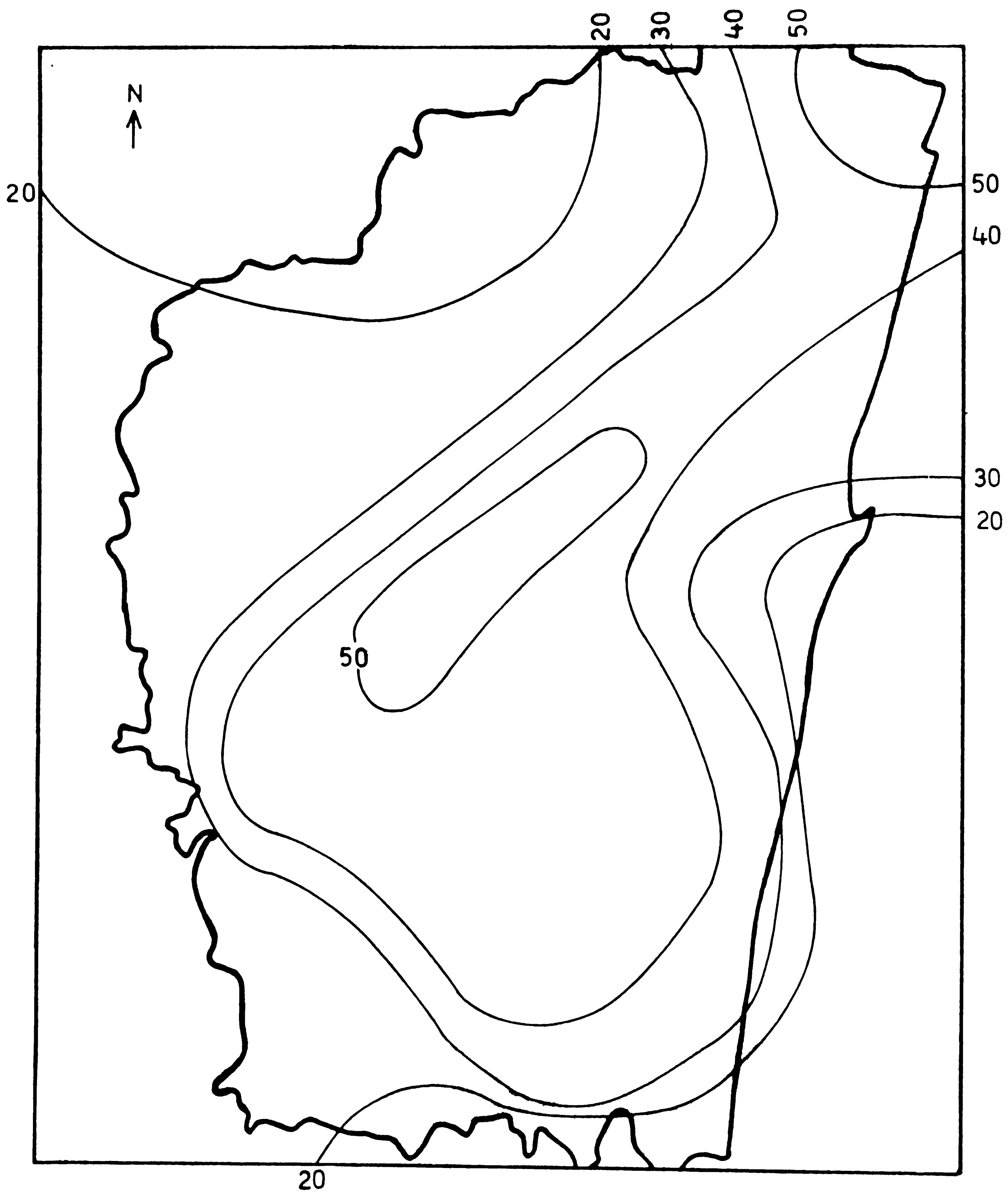

FIG. 5.2(e). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR MAY (μgm^{-3})

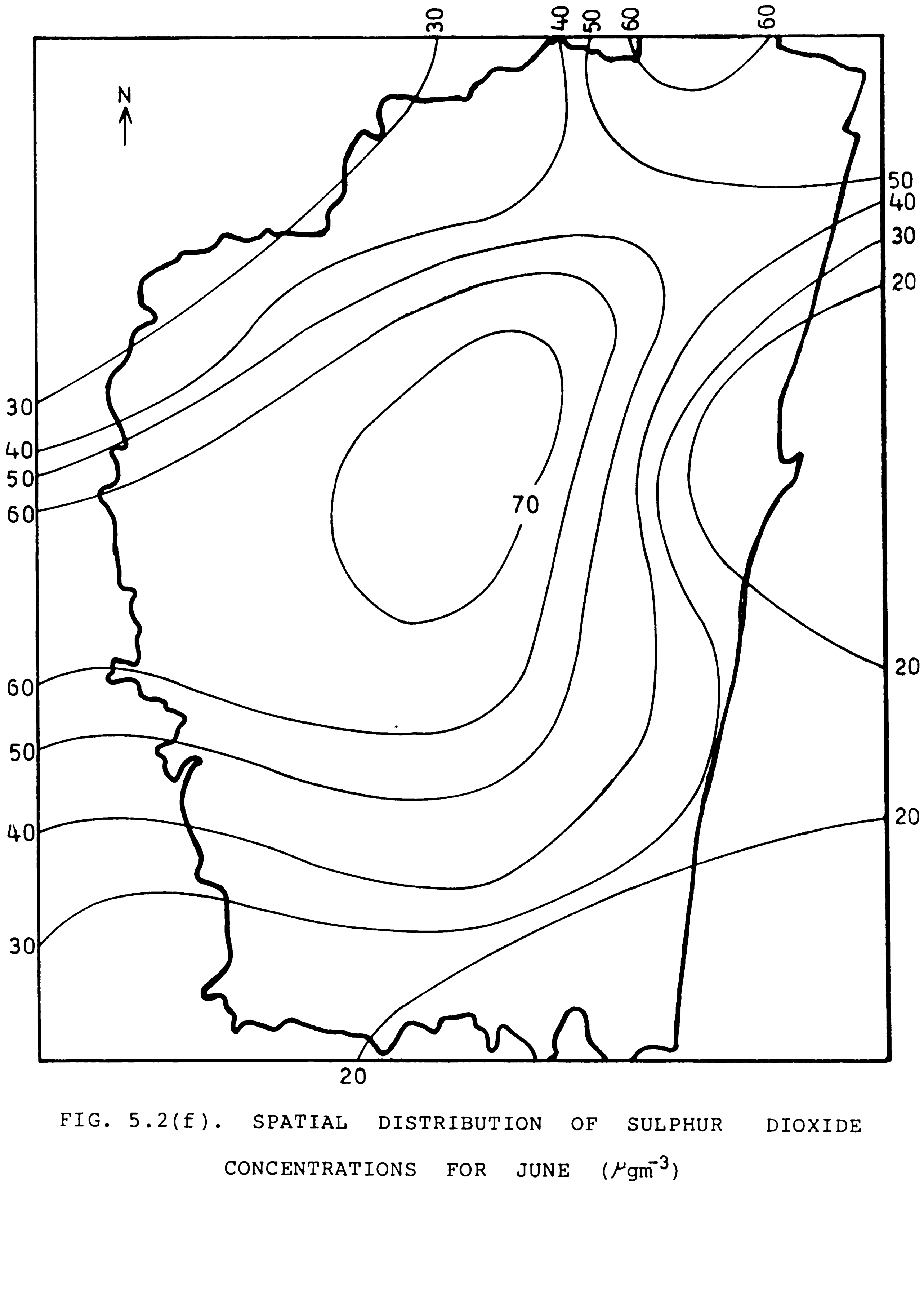

FIG. 5.2(f). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR JUNE (μgm^{-3})

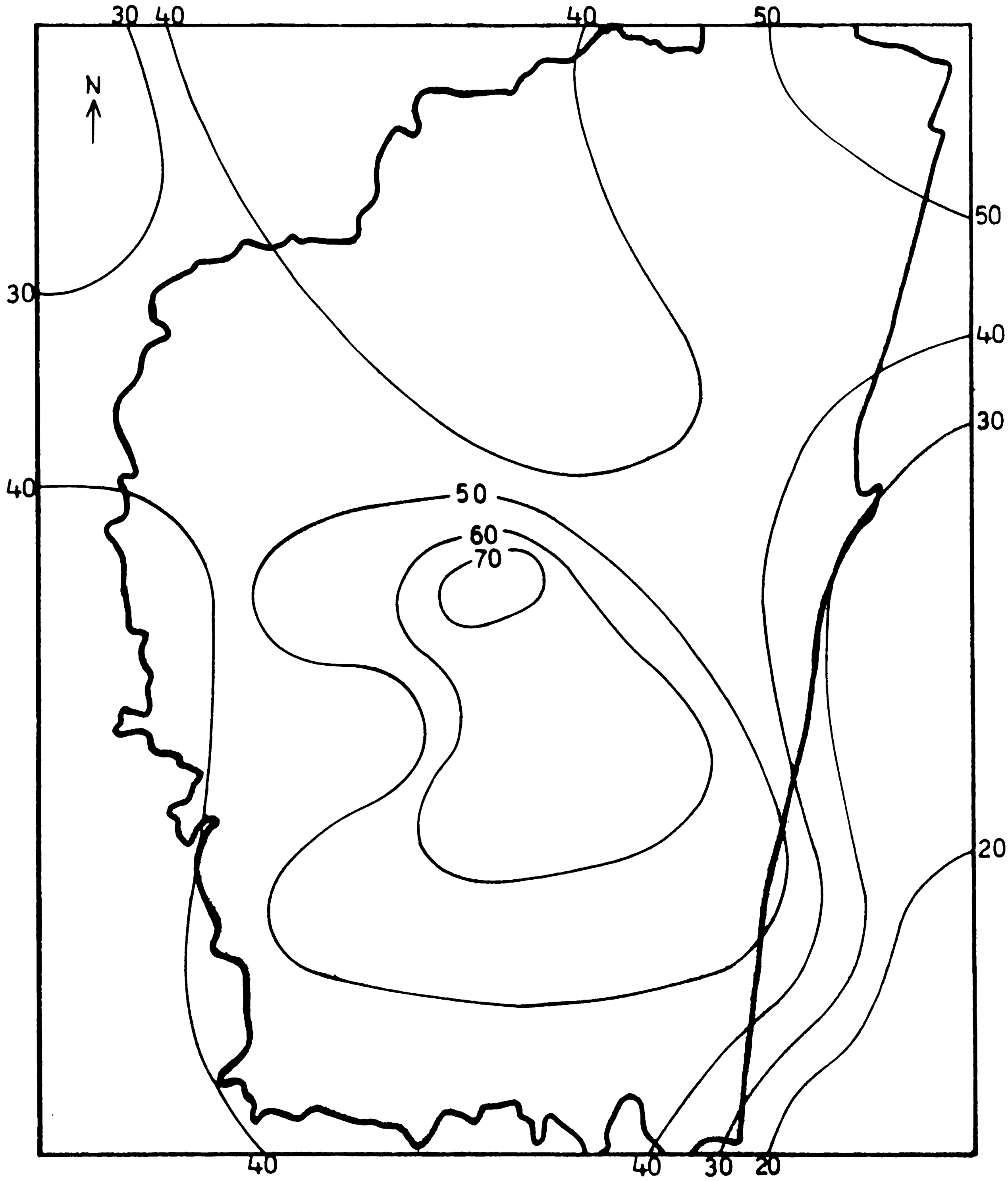

FIG. 5.2(g). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR JULY (μgm^{-3})

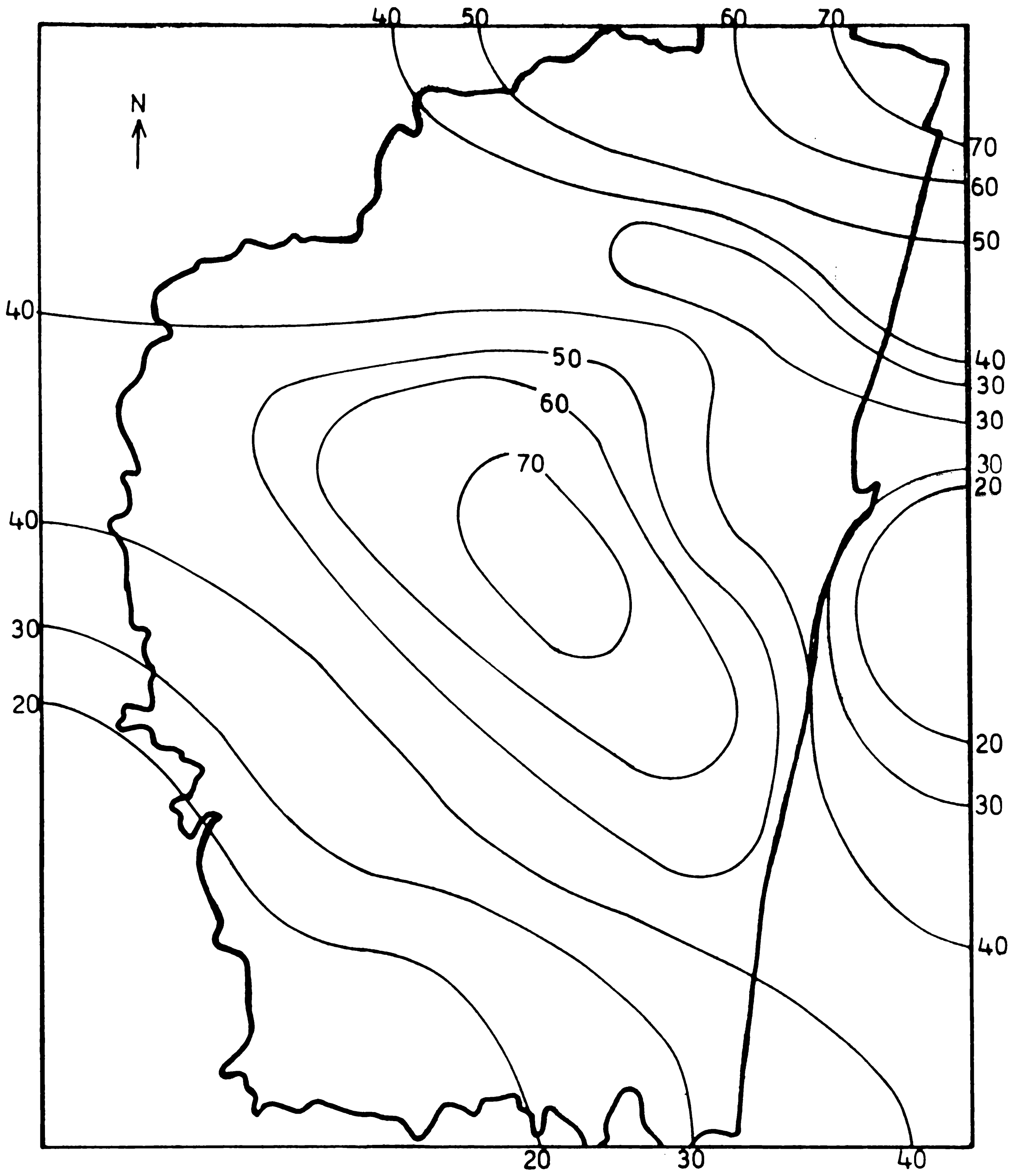

FIG. 5.2(h). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR AUGUST (μgm^{-3})

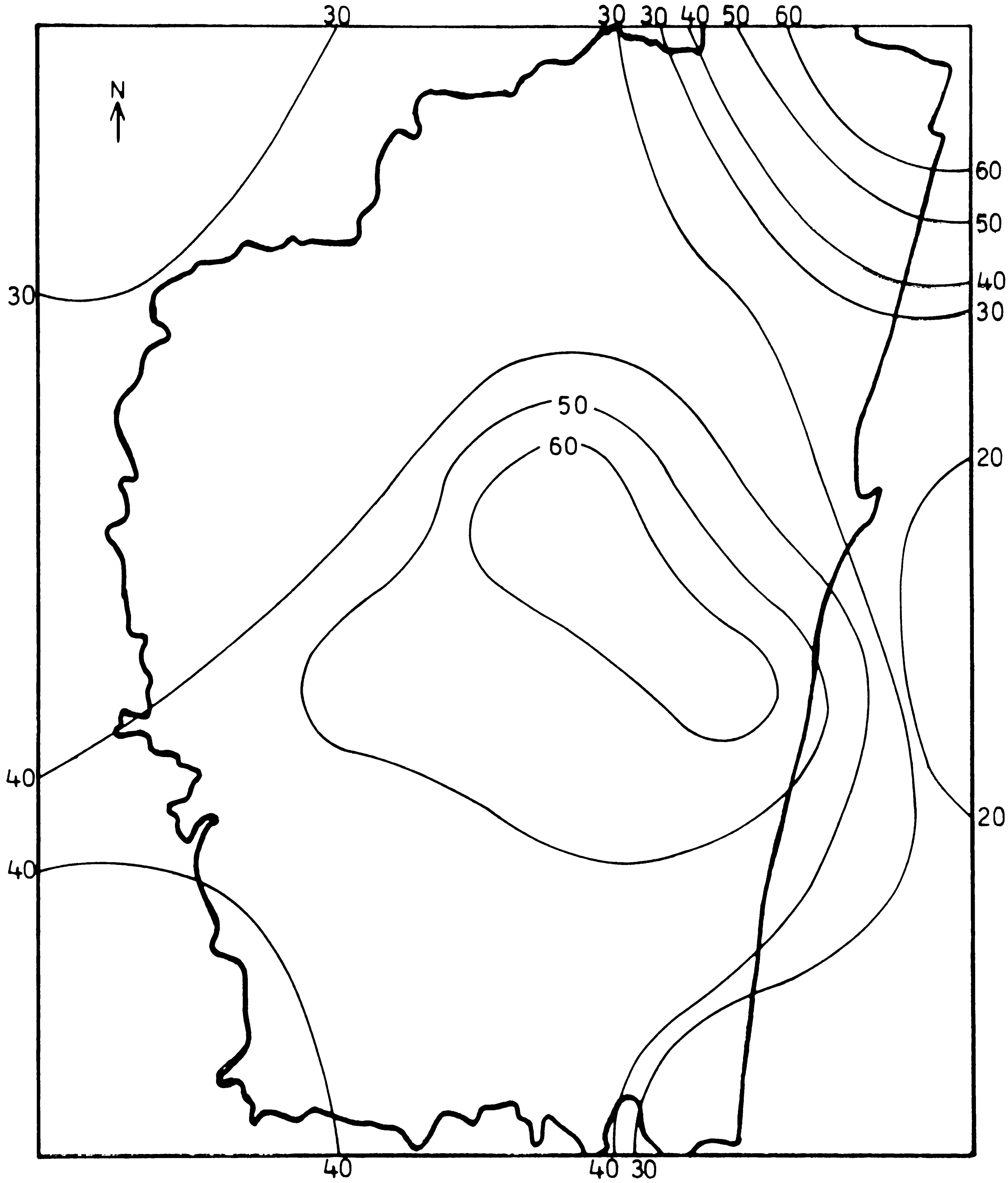

FIG. 5.2(i). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR SEPTEMBER (μgm^{-3})

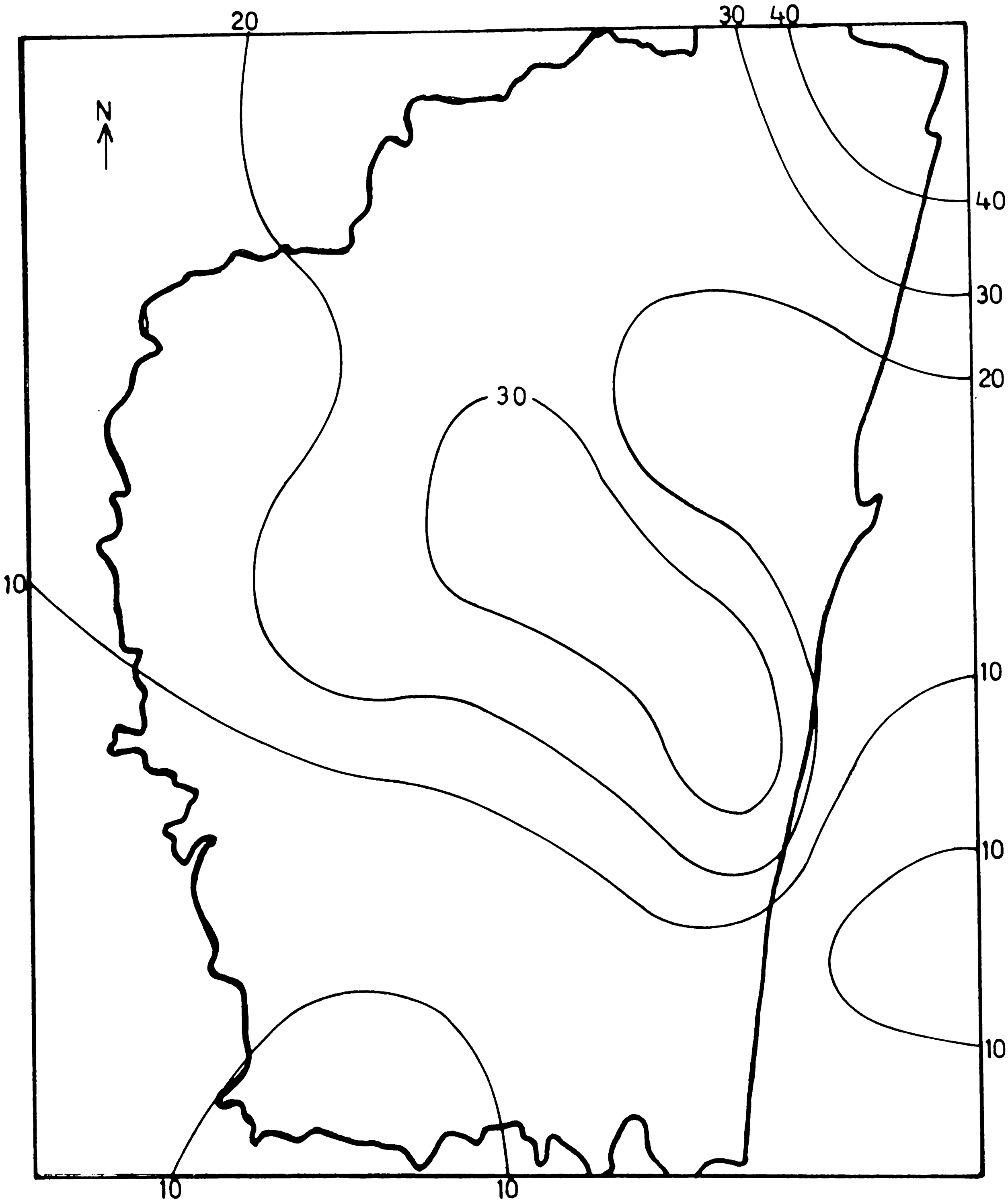

FIG. 5.2(j). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR OCTOBER (μgm^{-3})

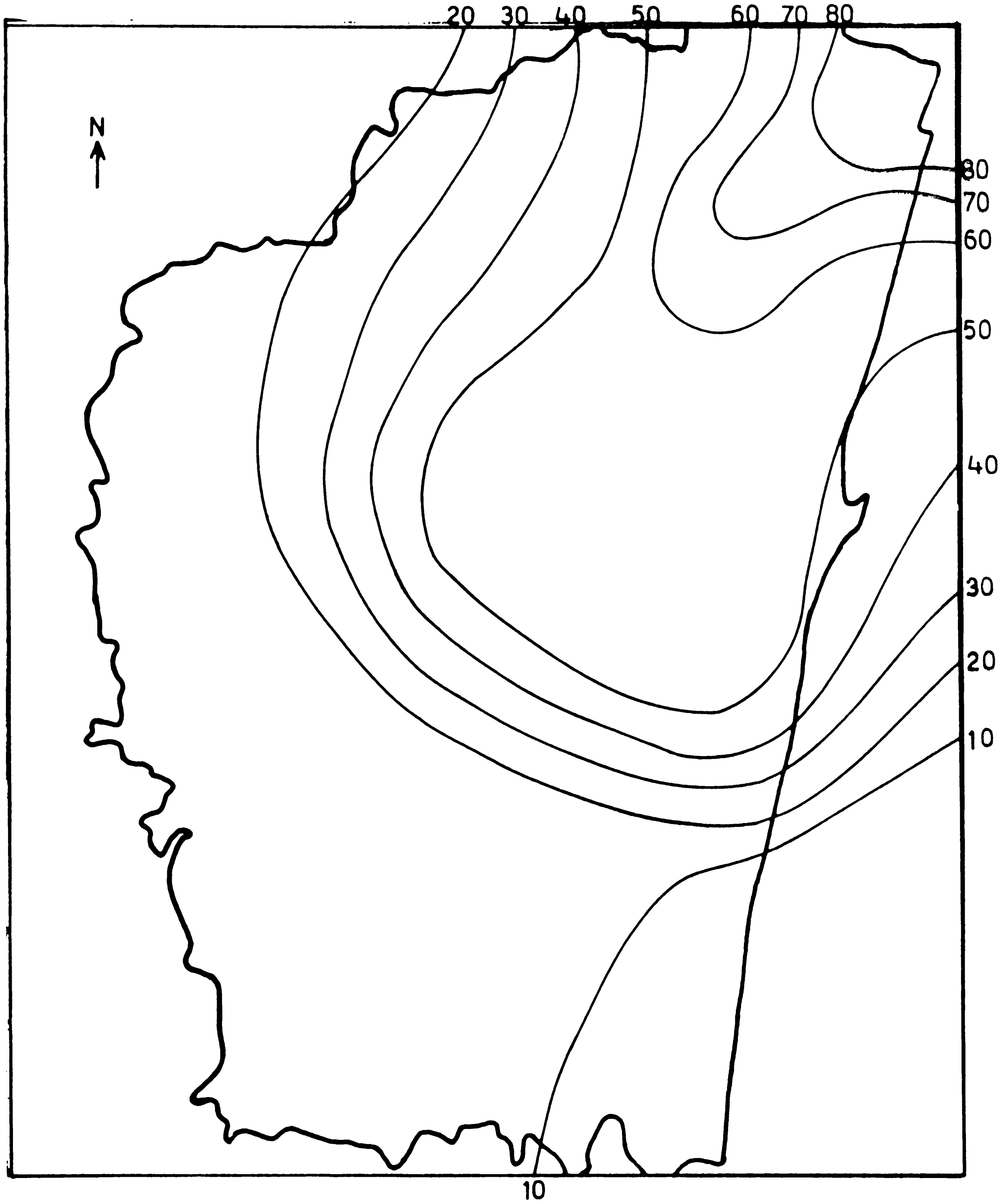

FIG. 5.2(k). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR NOVEMBER (μgm^{-3})

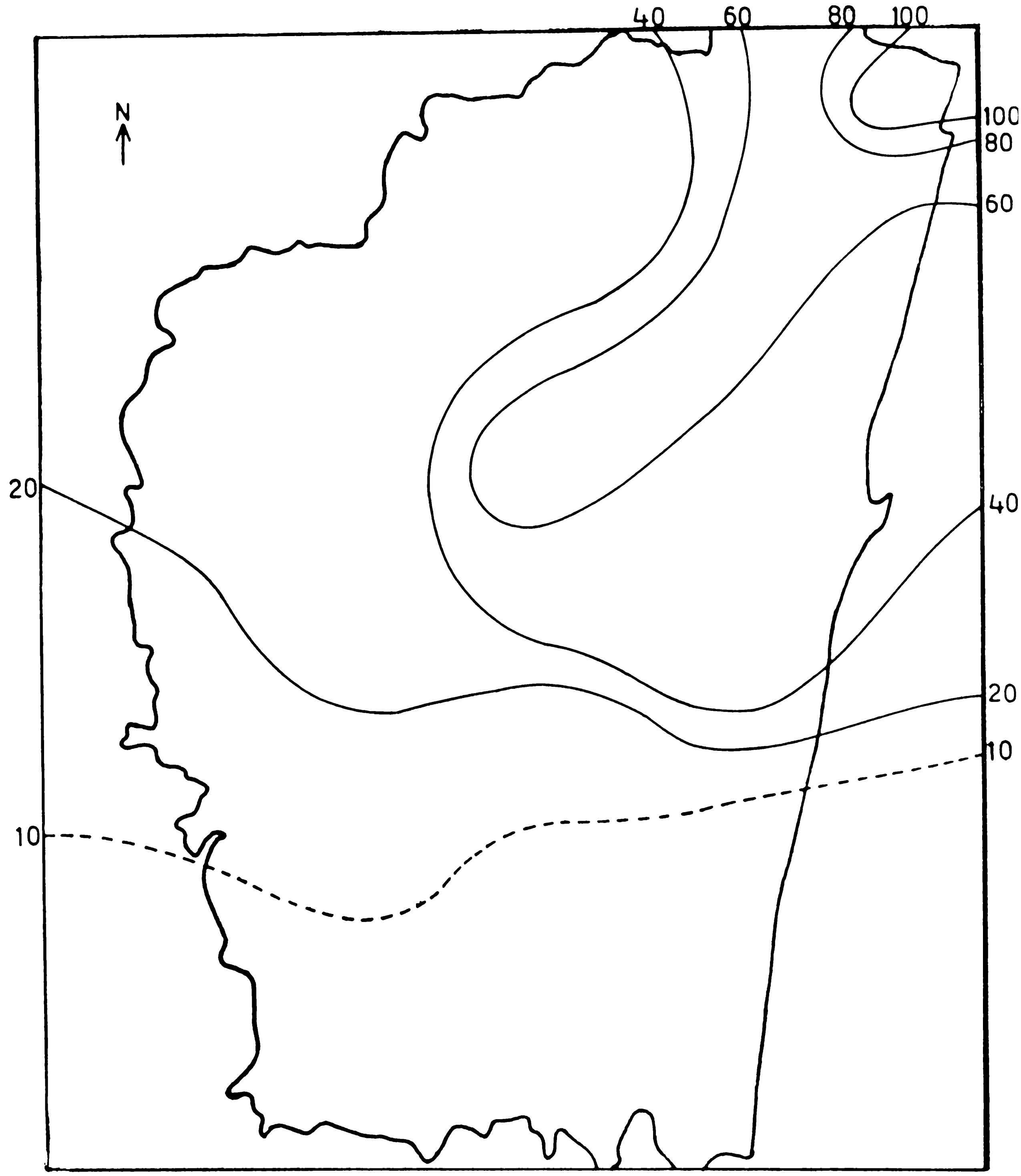

FIG. 5.2(1). SPATIAL DISTRIBUTION OF SULPHUR DIOXIDE CONCENTRATIONS FOR DECEMBER (μgm^{-3})

concentrations are observed near the primary pollutant source, Ennore. The minimum values ($10 \mu gm^{-3}$) are recorded in the southeastern coastal region.

February

In this month too, the highest values of concentration ($60 \mu gm^{-3}$) are observed in the northeastern region. A secondary maximum ($50 \mu gm^{-3}$) is noticed in the central region, which extends from Korattur to Guindy in the north-south direction. A narrow belt of low concentration (less than $20 \mu gm^{-3}$) extends from Karanodai on the western border. Compared to January, a much larger area is affected by high sulphur dioxide concentrations in this month.

March

The concentrations are found to have further gone up in this month. Ennore and neighbourhood exhibit values upto $100 \mu gm^{-3}$. In addition, a narrow belt extending southeastward from Ambathur through the city upto the coast also has concentrations $100 \mu gm^{-3}$. More than 75% of the city area suffers concentrations above $50 \mu gm^{-3}$. As in earlier months, the western parts show lower concentrations than the eastern, but the values are higher ($20 \mu gm^{-3}$) comparatively.

April

The distribution is contrastingly different in this month. The entire southern sector is under the grip of high concentrations with a maximum of 100μgm^{-3}. Such high values extend to central and northeastern regions too. The concentration is higher than that in earlier months at all places. The isopleths are generally oriented southwest to northeast with a minimum (20μgm^{-3}) in the northwestern region. More than 40% of the area records concentrations above 100μgm^{-3}.

May

The concentrations are considerably lower in this month with a maximum of 50μgm^{-3} occurring in the neighbourhood of Ennore and in the central region from Chembarambakkam to Madhavaram. The northwest sector (northwest of Angadu) and the extreme southeastern region have minimum concentrations (20μgm^{-3}). Although the maximum concentration is 50μgm^{-3}, this isopleth covers a very small area.

June

In this month, the maximum concentration (70μgm^{-3}) is recorded in the central region covering Mugapair, Ambathur and Madhavaram with a secondary maximum (60μgm^{-3}) on the northern extreme. More than 30% of the area has concentration above 50μgm^{-3}. The minimum concentration (20μgm^{-3}) is recorded in the southeast and in the coastal area, east of Madras Central. The area of maximum concentration shifts westward compared to that in the previous months.

July

The maximum concentration ($70\mu gm^{-3}$) is seen in a small area near Mugapair. An isopleth of $50\mu gm^{-3}$ covers a large area in the central region, southwards from Korattur to Chromepet and Injambakkam. Another isopleth of $50\mu gm^{-3}$ covers the northeast region near Ennore. Although the maximum concentration in this month is $70\mu gm^{-3}$, the minimum isopleth is $40\mu gm^{-3}$.

August

In this month, the maximum concentration ($70\mu gm^{-3}$) is observed in the northeast region near Ennore and the central region southeast of Korattur. The minimum values ($20\mu gm^{-3}$) are observed in the extreme southwestern sector, southwest of Chromepet, encompassing about 15% of the area. All other parts of the city suffer concentrations more than $20\mu gm^{-3}$. About 50% of the metropolitan area experiences concentrations greater than $40\mu gm^{-3}$.

September

Once again the maximum concentration is noticed in the central and northeastern parts of the city. The extreme southeastern coastal region shows the minimum concentration

($30\mu gm^{-3}$). Although the maximum in this month is lower than that in August, the concentrations along the boundary are equally high, indicating the weak dispersal of sulphur dioxide from the areas of maximum concentration.

October

The interesting feature of this month is the considerable decrease of concentration at all points in the city and neighbourhood. The maximum concentration recorded in the northeast region near Ennore ($40\mu gm^{-3}$) with a secondary maximum ($30\mu gm^{-3}$) in the region extending southeast from Korattur. The minimum concentration ($10\mu gm^{-3}$) is observed in the region south of Chromepet. More than 75% of the area has concentrations less than $30\mu gm^{-3}$.

November

The maximum concentration ($80\mu gm^{-3}$) recorded near Ennore, is higher than that in October. The regions in the west and south experience concentrations less than $20\mu gm^{-3}$.

December

The spatial distribution of sulphur dioxide in this month resembles that in November - the maximum is over the northeastern sector and the concentration decreases monotonically towards the southwest. The maximum concentration ($100\mu gm^{-3}$) is however higher and equals the maxima in March and April. The entire southern half of the area has concentrations less than 20μgm^{-3}.

As is noted from the discussions above, April records highest concentrations, since most of the city area has values around 100μgm^{-3}. The lowest values are recorded in October. The occurrence of very high concentrations in the northeastern and the central parts is mainly because the sources are located there. In most of the cases, the western and southeastern parts seem to be relatively free from pollution. The entire northeastern sector is almost always polluted and hence is not suited for any further industrial development.

If Madras city and suburbs are to be least affected by pollution from industries, the optimum location could have been the extreme southeastern parts since most of the pollutants then would spread on to the sea, or further away from the city. However, it is impractical to think of it at this stage when already industries have been developed in the northeastern and central regions. The levels of pollution as such no doubt are high enough, albeit not exceeding the permissible limits. So, the problem now is two-fold : (i) how to reduce the existing levels of pollutants and (ii) where to locate any further industries. The first one can be tackled in many ways. One obvious answer to such problems is to reduce the emissions, although this is not possible. However, this should be the case in the months March and April. A 25% reduction in the emission would bring the values on par with those in the other months. The usage of the wetscrubbers or any such system would suffice instead of actually reducing the emissions. An immediate necessity would be to deploy such control systems at the source itself.

Another way is to raise the stack height either by increasing the physical stack height or giving additional buoyancy to the plume. Although the reduction in concentration is accomplished by raising the stack height, it must be borne in mind that the effect of stack height on the downwind concentration is limited to certain distance which varies from as low 3 to 4km in highly unstable conditions to as high as 25km in highly stable conditions. Since the concentrations are determined using weighted means of stability, the dependence of the concentrations on stack height is felt upto 5 to 6km from the source. Within this distance the concentration can be reduced by about 50%, but for long distances the increase in effective stack height cannot result in any reduction in concentration. This is mainly because once the pollutants reach the top of the mixing layer and start getting mixed thoroughly in the vertical, the normal distribution does not hold good any longer. In fact, it amounts to a simple box model, where the effective height of emission does not enter into the picture.

However, all this holds good only for long term concentrations. If one takes into consideration the short term concentrations, which are of greater importance in suggesting emission schedules, the stack height has a very strong influence, which extends upto a distance of 20 to 30km in the night-time and a distance of 5km during day time. In most of the night-time cases, the low wind speeds and high calm conditions are a cause for serious concern. It is in this context that one can think of bringing down the levels of concentrations by raising the stack height, which can result in a reduction of concentration upto 50%. In fact, with the increase of stack height, the distance of influence also increases accordingly.

The second problem of choosing the optimum location of any further industries can be tackled only keeping in view of the existing levels of pollution. If it is assumed that the pollutant levels are really brought down with the above method then further industrial development is possible. The extreme southwestern part seems to be more appropriate for further industrial development, since pollutant spread would be away from the city. The southeastern part also can be another choice, since the concentration decreases quite rapidly towards northwest. However, in the immediate vicinity of the sources, the levels of pollutants are high but they do not spread further to the interior areas. The third possible choice of location could be the extreme western parts, since the spread towards east is rather sluggish and hence does not result in substantial increase of levels in the city interior.

It must be noted that only the sulphur dioxide concentration is considered in this model. There are various pollutants whose emission could be much higher, but are not taken into account in the present model. So, before the conclusions are drawn, it is better to have an estimate of all types of pollutants. The actual levels of pollutants could be higher in the city than those reported here. This is because of the non-inclusion of vehicular traffic and also because of the small industries situated at various locations and not considered here. Although the verification is not made with the actual observed values (which could not be obtained), it is strongly felt that the concentrations are underestimates and hence further precautions are necessary.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The main objective of the thesis is to provide a comprehensive picture of the atmospheric potential for the dispersal of pollutants over Madras city and neighbourhood. This includes spatial distribution of sulphur dioxide concentration due to industrial sources in addition to the establishment of climatology of atmospheric dispersal capacity. It is well known that air pollution has deleterious effects on human beings, plants and animals. Any unwanted substance present in the atmosphere can be regarded as air pollution. The sources of air pollution are both natural as well as man-made. Of the various pollutants, sulphur dioxide is the one which has received a lot of attention because of its undesirable effects even at very low concentration.

Meteorology plays the most dominant role as far as the pollutant dispersal is concerned, once it is emitted into the atmosphere by myriad sources, the dilution and the subsequent concentration of the pollutants is solely governed by prevailing meteorological condition. If the conditions are not favourable for dispersion, the concentration would shoot up leading to the so called pollution episodes. Such conditions include prevailing anticyclones, low wind speeds, low mixing and highly stable conditions. Conditions favourable for dispersion include high mixing heights, high wind speeds and unstable conditions, all of which help to disperse the pollutants very effectively in the atmosphere leading to relatively low concentration. These low and high concentrations data discussed in the preceding chapter correspond to the same sources and emissions. The surface temperature, the vertical thermal structure of the atmosphere, wind speed and direction are the most important meteorological parameters that have a direct bearing on the pollutant dispersal.

Proper environmental planning is necessary to keep the pollution level within the tolerable limits, when new industries are going to be set up. Many a time, their location has a profound influence on the dispersal of pollutants. Hence, keeping in view the mistakes committed in developed countries, comprehensive planning is needed for developing countries such as India. Such planning requires a knowledge of the pollutant distribution over any region, which could be obtained by means of theoretical models, provided the emission inventory is known in addition to the meteorology of the area.

The review of literature reveals that for any urban area the study of inversions, isothermals, lapse conditions, mixing heights, ventilation coefficients, wind roses and atmospheric stability is vital. It also reveals that despite the presence of various mathematical models, Gaussian plume model is the widely used one because of its simplicity and easy adaptability. Keeping this in view fast developing metropolis, Madras situated on the east coast of India, is chosen for a comprehensive study of the atmospheric dispersal capacity and the spatial distribution of sulphur dioxide by means of Gaussian model.

The relative percent frequency of occurrence of lapse conditions is extremely high in all the months accounting for more than 80% of the total cases. The high frequency of lapse conditions is natural as the heat input is from the earth's surface. The other 20% frequency is shared by inversions and isothermals. One of the noticeable features is either inversion or isothermal occurs in all the months however small the frequency may be, which are important as both inhibit vertical dispersion of pollutants. The relatively high frequency of inversions from December to March is due to the reason that this period falls in the winter season. There is not much of a variation in the isothermal conditions.

The surface based inversions are very large in number compared to elevated inversions in all the months except in June. The frequency of elevated inversions is very high especially in the layer 650-600mb for the month of June. The elevated inversions are extremely strong compared to the surface based inversions. The percent frequency of occurrence of isothermals is more near the surface than in the upper levels and marks a sudden decrease from 900mb level. In case of lapse conditions, the percent frequency of occurrence is low near the surface and high in the elevated cases. The lapse condition of the intensity -2 to -4°C per 50mb is generally dominating in almost all the cases. The lapse conditions increase from surface to certain level and become more or less uniform thereafter, although the individual intensities may differ with their percent frequencies.

The hourly values of mixing heights show a clear cut diurnal variation. The minimum values are observed during the early morning hours and the maxima are noticed in the afternoon hours. The annual range is minimum in November and maximum in June. The maximum mixing height is highest in June and lowest in November, while minimum mixing height is lowest in February and highest once again in June. The diurnal march of mixing height more or less follows the diurnal temperature march. The maximum mixing heights are in the order of 1800m except from October to December.

The diurnal variation of ventilation coefficient shows a near normal distribution, the highest value occurring in the afternoon hours. The maximum value decreases from January to June and increases thereafter till November. The values are highest in the month of June . In all the cases, one can notice steep increase of values from about 0800 hours upto around 1400 followed by a rapid fall upto around 2000 hours, then gradual decrease upto 0600 hours and gradual increase upto 0800 hours.

The percent frequency of occurrence of various Pasquill's stability classes from A to F shows that the most predominant category is F. Highly stable conditions during night-time and neutral to unstable conditions during day time are the important features in the months of January and February. The percent frequency of E category increases from January to July and decreases thereafter especially from evening to midnight hours. Day time stability also changes month to month. From January to May, either category A or category B is dominant mainly because of clear skies and the resultant large thermal input near the surface.

The study of wind roses reveals two prominent wind directions in the entire year namely southwesterlies and northeasterlies. The sea breeze and the land breeze are also seen in some of the cases. A consistent change of wind direction from month to month at any given time is also noticed. From October to February, winds are northeasterlies or easterlies and from March to May, they are southerlies.

The diurnal variation of the wind direction fluctuations show near-normal distribution with the maximum around noon. In October, the peak value is observed for a considerable period of time. The diurnal variation is found to be maximum in January followed by April, October and July. The absolute values are maximum in April at most of the hours.

A clear-cut diurnal variation of wind speed fluctuation is observed in all the months. The minimum is observed in the early morning hours and the maximum in the afternoon hours with its peak changing from month to month as far as its time of occurrence is concerned. The diurnal range of $\sigma_{\theta S}$ does not differ significantly from month to month. Maximum $\sigma_{\theta S}$ noticed is less than $1ms^{-1}$. The diurnal variation of $\sigma_{\theta S}$ is relatively more striking than that of $\sigma_{\theta D}$.

The interrelationships among all the parameters show a reasonable representation of $\sigma_{\theta D}$ for various Pasquill's classes. $\sigma_{\theta D}$ is found to be more appropriate than $\sigma_{\theta S}$, for reprensenting the Pasquill's classes and computing mixing height. $\sigma_{\theta D}$ is found to be good measure of surface turbulence. The mixing height can be computed even in the absence of vertical temperature structure with the knowledge of $\sigma_{\theta D}$ with a fair degree of accuracy. Some inconsistencies are observed in providing the representative values of all the parameters for various Pasquill stability classes.

The spatial distribution of sulphurdioxide concentrations, obtained by means of multiple Gaussian plume model shows a considerable difference in the pattern from month to month according to the variations of different meteorological parameters. In general, April records highest concentrations, and October, the minimum. In most of the cases the western and southern parts of Madras metropolitan area appear to be relatively free from pollution with a few exceptions. The entire northeastern sector is almost always polluted and hence it is not suited for any further industrial development. It is suggested that a 25% reduction in the emission which could be accomplished in many ways, will bring down the concentrations. It is felt that instead of reducing the emission, the stack height could be raised by 20% which could reduce the concentrations by 50% within the first few kilometres. The extreme southwestern part would be the first choice followed by southeastern and extreme western parts, for further industrial development. It is also felt that the present concentrations are likely to be underestimates.

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