STUDIES ON THE METEOROLOGICAL ASPECTS OF AIR POLLUTION OVER COCHIN

Thesis Submitted to the Cochin University of Science and Technology for the Degree of

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In

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By

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'To my beloved parents'

PREFACE

Rapid industrialisation and the subsequent urbanization have lead to severe doses of air pollution causing widespread damage to life and property. The deterioration of the environment due to air pollution assumes much greater proportions, even to the extent of global scale, if it continues unabated. In fact, the atmosphere is well equipped to effectively disperse and dilute the pollutants under certain favourable conditions. Many historical air pollution episodes have clearly demonstrated the profound influence of meteorology in the dispersion of air pollutants. Once the pollutants enter the atmosphere, their dispersion is solely governed by the prevailing meteorological conditions.

A study of the prevailing meteorological conditions for any locality is necessary as it aids the planners to choose appropriate locations for industries so as to minimize the effects of pollution and also to regulate the emissions depending upon the meteorological conditions prevailing from time to time. In the present thesis the meteorological aspects of air pollution for Cochin, a fast growing industrial and commercial capital of Kerala, have been studied with a view to suggest some abatement steps and to suggest the optimum locations for new industries in order to keep the effects to a minimum.

For the sake of convenience, the thesis has been divided into six chapters. Chapter I deals with the problem, objectives of the present study, fundamentals of air pollution and importance of meteorology in air pollution studies together with a brief description of Cochin region.

Chapter II is mainly devoted to the literature survey and the methodology of the present work. The merits and demerits of the methodology are also given in this chapter.

Chapter III deals with air pollution climatology for Cochin, that includes the study of inversion, mixing heights, ventilation coefficients and wind climatology.

In view of special importance of stability in air pollution studies, one full chapter has been devoted. Chapter IV deals with the stability of the atmosphere for Cochin and the relations between stability, σ_θ and mixing height. This chapter also deals with the climatology of σ_θ.

The application of the Gaussian plume model for multiple industrial sources for Cochin is dealt with in chapter V.

The overall summary and conclusions are given in the sixth chapter.

An appendix is also given which deals with the relation between σ_θ and wind direction fluctuation range.

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I will fail if I do not express my sincere thanks to my friends who helped me during the different phases of the study and its completion.

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 Sri K.G.Anil Kumar, M.Sc., under my supervision and guidance 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 other degree in any University.

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CHAPTER - 1

1. INTRODUCTION

1.1. Pollution problem

The earth's atmosphere has served man in two fundamental ways throughout his existence; it has provided him with life-sustaining air to breath and it has acted as a medium for disposing of his refuse. On an average man breathes 22,000 times a day and takes in approximately 20 kilograms of air. The consumption of air by man far exceeds that of food and water. Man, on an average, can survive for five weeks without food, five days without water but not even for five minutes without air. That shows the utmost importance of air for human being Every human being on this earth has got a right to have clean air. However, the air is almost always contaminated to some extent, despite the fact that the atmosphere is equipped to efficiently dispose of reasonable quantities of the wastes associated with human activity in addition to those associated with some natural processes. The indiscriminate use of the atmosphere as a great sewer by the human elements has led to severe, though isolated, air pollution episodes and ultimately to a global deterioration of the quality of the ambient air. The technological advancement, industrial development, population explosion, urbanisation etc. have contributed to a great extent to the erection of the current air pollution crisis.

The economy of any country naturally depends on the extent to which the natural resources could be exploited. However, the consumers do not worry about the wastes that the exploitation of the resources inevitably produce. In his anxiety to have the technological advancement and the industrial development as quickly as possible, no serious thought was given to deal with the refuse from the industries. Of late not only the scientists and engineers but the administrators as well have realized the gross consequences of such unprecedented expansion of the industries, probably because of the severe air pollution disasters that have occurred mostly due to improper planning and due to the inefficiency of the atmosphere to disperse the refuse emitted into it effectively beyond a certain limit. The search is on to find out the means not only to reduce the occurrence of air pollution episodes but also to reduce effectively the levels of contamination, in general.

Control and abatement of air pollution are receiving the utmost attention in view of the threat of a complete deterioration of the environment, if action is not initiated in time.

Most of the earlier problems were due to improper planning, beginning from the siting of industries to the irregular emissions into the atmosphere. A proper planning of any urban area is an essential first step, in so far as the optimum location of the industries is concerned, to minimize the pollution to some extent. This necessitates a thorough study of the dispersal capacity of the atmosphere over that region, the spatial distribution of the pollutant concentration by means of a model and the variation of the meteorological parameters in that region.

The main objective of the present thesis is to give a comprehensive planning of one rapidly developing industrial area, namely, Cochin. The detailed objectives are listed below:

1. To study the spatial variation of the atmospheric dispersion capacity.
2. To establish the climatology of the wind for different hours.
3. To find the diurnal, monthly, and the yearly variation of atmospheric stability.
4. To find the relationship between mixing heights, stability and $\sigma\theta$.
5. To find the spatial distribution of a particular pollutant, namely, Sulphur dioxide (SO_2) by means

of a meteorological model taking the industrial sources into consideration.

6. To suggest the optimum locations for the new industries and to suggest some abatement steps.

It is worthwhile to examine the measuring of air pollution, its sources, types and effects and the role of meteorology in air pollution very briefly.

1.2. Definitions, sources, types and effects of air pollution

1.2.1. Definitions

Basically air pollution is the presence of foreign substances in the air. The problem arises only when the concentration of the external substances exceeds certain tolerable limits. A more specific definition of air pollution has been developed by the engineers joint council (Bishop, C.A., 1957). '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 is a very broad definition covering all aspects of air pollution. It shows clearly that air is said to be polluted not necessarily when the effect is felt, but even when they tend to cause the effect also.

1.2.2. Sources of air pollution

The sources of pollution can be divided into two broad types. 1. Natural and 2. Man made.

1.2.2.1. Natural sources

The air pollution problem was there, well before the industrial era began. The organic compound 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 increase the background pollution levels over years, even at points far distant from the original sources. Quantitatively the concentrations are much below compared to those of man made sources, probably because of the wide spread distribution of these quantities over very large area extending mostly to uninhabited areas.

1.2.2.2. Man made sources

These sources can be essentially divided into three categories. 1. Single or point sources 2. Area sources and 3. Line sources. The examples of point sources are steel mills, power plants, oil refineries, paper mills, fertilizer plants etc. Examples of area sources are residential areas, apartments, office buildings, hospitals etc. Examples of line sources are motor vehicles while moving. Comparing the height of emission of the pollutants from these sources, the lowest is line sources followed by area sources and point sources.

The gaseous and particulate waste is dumped into the atmosphere through vertical pipes known as chimneys or stacks. Each industry may have one or more stacks. The emission from such a stack gives an impression that the source is the stack exit itself which appears as a point in the atmosphere and hence the name.

The major contributor to air pollution is industry. Most of the air pollution from the industry is caused by burning the fossil fuels such as coal and oil. Because sulphur is one of the major ingredients of these fuels, industries are the greatest contributors to sulphur dioxide pollution.

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

Motor vehicles emit the smoke through a small pipe and when they move the smoke forms as a line all along the road at a very very low level and hence the name, line sources. This is also a very dangerous source because the pollutants are emitted almost at the ground level and so without getting much diluted in the atmosphere, they will be inhaled causing more problems.

1.2.3. Types of air pollution

There are innumerable number of air pollutants of which only the major types are pointed out briefly here. The major types are

1. Oxides of sulphur
2. Oxides of nitrogen
3. Carbon compounds
4. Particulate matter and
5. Photochemical products.

Sulphur is an impurity in coal and fuel oil. Due to combustion it enters the atmosphere as sulphur dioxide, hydrogen sulphide, sulphurous and sulphuric acid and various sulphates. The amount of sulphur oxides emitted into the atmosphere annually from different countries is given by Wilfrid Bach (1972). On an average 80 million tonnes of sulphur oxides are emitted annually into the atmosphere in the whole world. If this amount is equally distributed over the globe it would increase the world sulphur dioxide concentration by about 0.006 ppm. However, Jaunge 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 oxidized to nitrogen dioxide. Man-made nitrogen dioxide originates from stationary sources and from mobile sources.

Carbon compounds include carbon monoxide, carbon dioxide and hydrocarbon. Carbon monoxide, a colourless, odourless and a 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 essentiality 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, wood, from evaporation of gasoline and industrial solvents and from natural sources, mainly by the decomposition of vegetation. The contribution from the natural sources far exceeds than that of from man-made (Wilfrid Bach, 1972). In air pollution control the unsaturated hydrocarbon of the olefin group and the compounds belonging to the aromatic or benzene group are of greatest concern. The unsaturated olefins react easily with other chemicals. For instance, only a few tenths of 1 ppm of nitrogen oxides and less than 1 ppm unsaturated and hence highly reactive hydrocarbon together with sunlight have been found to initiate the Los Angeles type smog. The aromatic havé been found to be carcinogenic or cancer-producing. The most powerful of these is benzopyrene.

Particulate matter consists of solid and liquid particles of various sizes ranging from less than 0.1μ to about 100μ. Particles larger than 10 μ consists 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 the usually present oxygen molecules (O_2) to form the colourless and pungent gas ozone (O_3). Since O_3 is an early and continuing product in the smog formation, and since the presence of O_3 keeps the oxydizing process going, O_3 is almost inter changeable 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, and O_3 and solar radiation. Some of the better known irritating photochemicals are PAN (peroxy acetyl nitrate) and aldehydes.

1.2.4. Effects of air pollution

There have been a number of books which have given the effects of air pollution in detail (Stern, A.C. 1976; Faith, W.L. and A.A. Atkisson Jr. 1972; Perkins, H.C. 1974 and Magill, P.L. et al. 1956). However the effects are presented very briefly here, in order to have the continuity. The most common effect of air pollution are damage to health, visibility reduction, damage to property annoyance to human senses and substantive changes in the ecology of the natural environment.

Of all air pollution effects, damage to health is the foremost in peoples' mind. Though it is not established as to which particular pollutant causes what type of disease, there have been some specific diseases attributed to a single or a group of pollutants. For example chronic diseases such as bronchites, asthma, emphysema etc. are aggravated by sufficiently high concentration of sulphur dioxide, nitrogen dioxide, particulate matter and photochemical smog. Cardiovascular and pulmonary diseases are aggravated by carbonmonomide. Photochemical smog irritates the eyes.

Restriction of 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. The visibility reduction causes considerable transportation hazards, the most important thing being air craft landing.

Damage to property includes damage to materials, vegetation and animals. Damage to materials is evident by the corrosion of metals presumably from acidic compounds in polluted atmosphere. The important acid forming pollutant is sulphur dioxide. Other damages include rubber cracking, deterioration of the painted surfaces, soiling of structures and clothes etc. Damage to vegetation is usually in the form of chlorotic marking, banding or silvering or bronching of the under side of the 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 floride dusts or have absorbed floride compounds from the atmosphere.

Annoyance to the senses of people include a multitude of reaction that can be generally divided into two classes. 1. Eye, nose and throat irritation and 2. Odours. Eye irritation is caused by the emission of an irritating substance into the atmosphere and by the formation of an eye irritant in the atmosphere by reaction of otherwise non-irritating pollutants. Similarly nose and throat irritation have often been reported as effects of air pollution in the same way as that of eye irritation. Odour is more difficult to define, as odour objectionable to one person may be pleasing to another. The common odours which cause discomfort, generally, are from slaughter house, fish market, from industries emitting hydrogen sulphide and phenolic compounds.

Cloud formation, change in rainfall in areas downwind from large sources of pollution are the best examples of eco system changes. The temperature changes are also effected by the air pollution such as the increase of carbon dioxide.

1.3. Air pollution meteorology

Every air pollution problem has three requisites. 1. There must be a source. 2. After emission it must be confined to a restricted volume of air and 3. The polluted air must interfere with the physical, mental, or social well being of the people. One and three have been discussed in the preceeding sections. The second one brings in the most important aspect, i.e. the interaction of meteorology with the pollutants. Meteorology plays the most crucial role in determining the concentrations of the pollutants. The fundamental way in which it can interact is the dispersion or the dilution of the pollutants. Meteorology governs the pollutant dispersal completely once they are emitted into the atmosphere. 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 is only to a small degree within the scope of meteorological science. But meteorology can and does contribute in many important ways to air pollution control activities including research, surveys and to operational programmes and forecasting concentration distribution of air pollutants on significant time and space scales under normal conditions of pollutant emissions, and with designated levels of control. An effective air pollution warning can be through a meteorological forecast from which an abatement strategy can be worked out. Warnings based on air quality alone will be futile if the variable atmospheric processes of pollutants dispersal is not taken into account. Abatement or air pollution can be achieved by reducing or eliminating the emission of pollutants source by source. One should take into account the influence of meteorological processes that cause pollutants to be dispersed quantitatively. In urban and industrial development schemes the air pollution climatology should be incorporated to have a long range air quality management programme. It is attempted in the following sections to discuss the influence of important meteorological parameters and its quantifications.

The vector wind is the single most meteorological variable for use 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 summarized by classes of speeds and directions. Making use of these, the wind roses can be constructed which give the percent frequency of occurrence of each of the 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, if drawn hourly or three hourly climatologically, are of utmost importance not only for the planning purposes but also for determining the ambient air quality with the help of models. It is a common observation that the 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 to some extent the dilution of the pollutants in the atmosphere, the direction gives the transport. The study cannot be confined to one or two wind roses per day as the highly variable wind is completely masked especially in coastal and complex regions where the mesoscale circulation in the form of land and sea breezes and the orographic influences are predominant. For a proper environmental planning hourly wind roses should be constructed.

Next to wind the vertical temperature variation plays a very important role in air pollution. The increase of temperature with height in the low level, known as 'inversion' is of much concern because such inversion, depending upon the level at which it occurs with respect to the stack height can act as lid and does not allow the dispersion to take place 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 their role in each one of its own ways. If the base of the inversion is above the effective stack height (H) then that inversion 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, a sudden high dose of concentrations are likely at the ground level. If the base is below h and the top of the inversion is above h, the dispersion is completely inhibited and once the inversion ceases to exist or breaks, once again high ground concentrations are likely. Hence a study of the frequency of inversion is a must for air pollution warnings. Usually the inversions are found during night or 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 dondensation level (L.C.L.). The lapse rate near the ground on sunny afternoon is often super adiabatic but in equilibrium it becomes more nearly adiabatic. 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 more the MH, the more the dilution in the vertical and the less is the ground concentration. Hence, MH along with wind can be taken to represent the atmospheric dispersal capacity. MH is known to exhibit diurnal, seasonal and yearly variation and also known to vary from place to place. The spatial variation of MH over any broad area will help to identify the regions of good and poor dispersal capacity of the atmosphere. The spatial variation on a much smaller scale, say, for a given station, can be used to identify the locations for the industrial developments.

The spatial variation of surface temperature also plays a role in air pollution studies. Because of the urbanization, the surface temperature is normally more in the cities compared to the 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). The UHI also exhibits diurnal variations and is usually maximum at the minimum temperature epoch. This UHI is used in computing the urban MH which in turn, as already pointed out, influences the dispersion of the pollutants.

Stability is another important parameter which governs the pollutants 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 characterized by low mixing and cannot disperse the pollutants resulting in the build up of pollutants. The stability should be worked out for every hour which itself can 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 dependant on stability and hence the diurnal and the monthly variation of stability should be established for a proper environmental planning.

An effluent plume rising from a stack does not immediately move horizontally. In a 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 is at this point that it appears as though the effluents are emanated from that point. To compute the ground level concentration it is the effective stack height that is to be used but not the physical stack height. The plume moves in the vertical direction because of the initial momentum and buoyancy dominates. 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 concentration 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 a proper planning of any urban area,in so far as the siting of location for the new industries is concerned, atmospheric dispersion model must be applied. This helps in delineating the industrial and residential sectors. Some of the abatement schemes can be suggested with the help of the 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 MH, wind speed and direction, stability and effective stack height all of which are to be established climatologically for long term planning.

Air pollution does affect meteorology in some aspects. The change 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 nucleii resulting in either decrease or increase in precipitation. As already pointed out earlier the increased levels of carbondioxide 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. The visibility aspect is discussed earlier.

1.4. Background of Cochin region

Cochin is basically a coastal station bounded between $9^{o}49'$ and $10^{o}14'N$ and $76^{o}10'$ and $76^{o}31'E$. The region includes Cochin and Kanayannur taluks and portion of Alwaye, Kunnathunadu and Parur taluks in Ernakulam district of Kerala State. The total area of the region is approximately 700 sq. km. The region has a population of over 16 lakhs by 1981 and is expected to go beyond 22 lakhs by 1991. This region which is considered as the nerve centre of industrial and commercial activity in the state, witnessed unprecedented and phenomenal growth during the last three decades in all fronts.

The industrial awakening of the region started with the establishment of FACT in 1947. This place was almost the ideal because of the factors such as availability of cheap land, power, skilled labour, abundance of water supply, nearness to the all-weather port of Cochin and the facility of a navigable canal connection to the port. The utilization of the products and by-products of FACT contributed to the subsequent establishment of a number of chemical industries in its immediate environs. Major establishments such as HMT, Cochin Refineries, Premier Tyres, Indian Aluminium Company, Toshiba Anand Lamps and

Dry Cell Factory, Carborandum Universal Limited etc. have sprung up and boosted the industrialisation of the region. With the industrial boom, the inevitable pollution problems have started becoming a real concern.

Since the prospects of further industrialisation are very high in this region, a planning, so as to investigate the levels of air pollution, is necessary in so far as not only their optimum locations are concerned but also the regulation of emissions are concerned.

1.5. Summary

Clear or unpolluted air is a must to avoid deterioration of environment. A proper planning is necessary to mitigate air pollution. The main objective of the present work is to give a comprehensive planning for Cochin. The definition, sources of air pollution are brought out briefly together with various types of pollutants. The main contributing sources to air pollution are industries. The role of some of the meteorological parameters in air pollution is given briefly. The effects of air pollution on meteorology are also brought out. Finally, the description of Cochin region is presented.

The problem and the objectives of the present work are presented in the preceeding chapter. In this chapter the work done on this field by various authors has been reviewed sequentially. The source of data, the methods of computations and the procedures adopted for the work carried out are completely given in this chapter. In addition, the merits and the demerits of the methods adopted are also presented here.

2.1. Literature survey

Review of literature on (1) Air pollution climatology (2) Atmospheric stability and (3) Meteorological modelling has been made separately.

2.1.1. Air pollution climatology

Air pollution climatology is concerned with the aggregate of weather as it may affect the atmospheric concentrations of pollutants. This includes temperature, wind, stability and atmospheric turbulence. However, stability is discussed in the subsequent sections separately and hence the review in this section is confined to wind and temperature.

Temperature comes into picture in three ways, namely, (1) Ambient value (2) Spatial variation and

C H A P T E R - 2

2. EXISTING LITERATURE AND METHODOLOGY

2.1. Literature survey

2.1.1. Air pollution climatology

2.1.2. Atmospheric stability

2.1.3. Meteorological modelling

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2.2.2. Computation of frequency of inversions, mixing heights and ventilation coefficients and construction of wind roses.

2.2.2.1. Frequency of inversions

2.2.2.2. Mixing heights

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2.2.5.1. Merits

2.2.5.2. Demerits

2.3. Summary

(3) Vertical variation. The most obvious significance of ambient temperature as an air pollution climatic feature is with respect to their influence on space heating requirements and the attendant discharge of pollutants into the atmosphere. This influence is often expressed in terms of heating degree-days defined as the magnitude of the difference between the average daily temperature and 65^{o}F. Turner (1968) developed empirical relationship between hourly temperature and fuel used by residential and commercial establishments during winter in St. Louis, Missouri, which showed that in addition to temperature effect the diurnal variation of fuel usage was also influenced by socio-economic factors. Bulfalini and Allsehuller (1963) indicated that air temperature is an important factor in the formation of photochemical air pollution, and that seasonal and diurnal temperature variation can cause significant changes in photo oxidation rates.

The spatial variation of temperature ordinarily shows that cities are warmer, than the nearby rural surroundings, particularly at night during light winds and clear skies. Such conditions lead to wind patterns that would converge toward the centre of the warm pockets. These warm pockets are known as 'heat islands'. There were a number of studies on heat island (Chandler, 1962;

Okita, 1965; Georgie, 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 in the day time. However, as was shown by Findly and Hirt (1969) and Viswanadham (1983) that urban rural contrasts can be large even during maximum temperature epoch. The maximum reported values of urban heat islands are 8.9^{o}C for London (Chandler, 1963) and 11.1^{o}C for San Fransisco (Duckworth and Sandbord, 1954). There were some empirical relations also for determining the urban heat islands, based on cloud cover, wind speed, population etc. Mitchell (1961) has 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 wind speed and a and b are empirically determined constants. Ludwig and Kealoha (1968) have made extensive investigation of the urban heat island and developed equations for the magnitude of the urban heat island as a function of the variation of temperature with height in the nearby non urban area. Oke (1972) has developed 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 Torento.

Studies for some of the Indian cities are due to Bahl and Padmanabhamurthy (1979), Daniel and Krishnamurthy (1972), Philip et al. (1974) and Viswanadham (1983). Bahl and Padmanabhamurthy (1979) conducted mobile temperature surveys in Delhi during the winter months on selected days which showed the formation of the primary and secondary heat islands. The maximum difference in temperature was reported to be 7^{o}C. There were reports of heat island studies for Pune, Bombay, Visakhapatnam and Cochin, as well, where the maximum difference is reported to be within 5^{o}C.

The vertical temperature structure is the most important element in air pollution climatology as this has a direct impact on the vertical extent of dispersal of pollutants. The increase of temperature with height, known as inversion, inhibit 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 Marrais (1961) has 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 temperature difference between 18 and 160 m became super adiabatic (lapse rate greater than the adiabatic value of 9.78°C/km) approximately 3 hours after sunrise and remains 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 structure of temperature.

The analysis of low level temperature data obtained by radiosonde is common despite a few limitations on such data. The limitations are (1) Some loss of resolution of temperature profile occurs because,the response of the temperature sensor is relatively slow with respect to the ascent rate of the balloon, so that small excursions in the temperature profile are not necessarily reported and (2) The radiosonde launching site are usually at airports in rural or sub-urban surroundings, so that the low level data are not necessarily be representative of urban conditions. However, these observations are used because the data are collected mostly from these radio sonde. Szepesi (1967) has made detailed studies of radio sonde data by taking 5 years of soundings for each of 6 different observational hours. He made analysis of the monthly distributions of stability conditions, frequency of the inversions and its duration. Hosler (1961) studied the low level inversion frequency for U.S. based on radio sonde observations at 4 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 radio sonde stations in Canada, Greenland, and Alaska. He computed the frequency, base height, thickness, base temperature and the intensity of inversions at 00 GMT.

Padmanabhamurthy and Mandal (1976,1979) have studied the frequency of inversions for Delhi. Viswanadham (1980) has studied the frequency of ground based and elevated inversions for the four metropolitan cities in India for a 5 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 00 and 12 GMT ascents during December-March for a 5 year period for Visakhapatnam. They made a comparison for Delhi and Visakhapatnam which revealed high frequency of ground based inversions in Delhi compared to that of Visakhapatnam.

Mixing height gives a good estimate of the vertical extent in the atmosphere to which thorough mixing occurs. Studies on the mixing height were mainly due to

Holzworth. Holzworth (1964) estimated the mean maximum mixing height for 45 stations in the Contiguous United States based on the radio sonde 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 brought forward the procedure to include the heat island effect and suggested that a value of 5^{o}C be added to the minimum temperature to get the minimum mixing height. Vittal Murty et al. (1980 a) computed mixing heights and ventilation coefficients for India and pointed the regions of good and poor dispersal of pollutants. The diurnal, seasonal and spatial variation of these has been studied in detail by them. Vittal Murty et al. (1980 b) studied the yearly variation of mixing heights for all the Indian radio sonde stations during the period 1959 to 1961. Vittal Murty et al. (1980 c) computed for Visakhapatnam, the mixing heights at two points in the city under different stability conditions. Padmanabhamurthy and Mandal (1980) studied the mixing heights for the winter season for Visakhapatnam. Sadhuram (1982) computed the mixing height for a 10 year period for Visakhapatnam. Padmanabhamurthy (1984) has studied the spatial variation of mixing heights for India taking into account the data from 27 radio sonde stations in the country. However, the spatial variation within a given city has not been attempted so far.

Some of the most useful expressions of the climatology of air flow 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) have drawn wind roses for lapse and inversion conditions from June 1955 to May 1957 for shipping port Pennsylevaniya. They pointed out the major differences in the wind features between day time and night time, the former having less calm frequency and stronger winds and the latter having more calm frequency and weak winds. Based on the wind roses the distributions of concentration of the pollutants can also be depicted. Singer and Nagle (1970) have prepared maps of recurrence interval for wind direction persistence of 2,4 and 6 days based on hourly wind data at 35 locations in U.S. They found that the regimes of most persistent direction occurred along coast lines and was associated with strong winds, with lowest persistence in mountaneous regions. Slade (1968) gave analyses of the persistence of wind direction. During conditions of weak pressure gradient on the macro scale, the description of air flow in cities is 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 exist over any appreciable length of time. The reports on the wind roses for every three hours are rare. Stability wind roses, however, have been reported (Viswanadham, 1980 and Sadhuram, 1982).

2.1.2. Atmospheric stability

Atmospheric stability is the most important element in air pollution studies. Though, wind, temperature and stability are studied separately they are interrelated. In fact stability is a function of temperature structure, wind etc. There were a number of studies to determine stability using various methods and to relate them with wind speed and directional fluctuations. From the parcel and the slice methods, it was shown that stability can be determined purely from the temperature structure in the vertical. Broadly, the following categorisations can be made (Hess, 1959).

1. Absolutely unstable (if atmospheric lapse rate (ALR) is greater than dry adiabatic lapse rate (DALR)
2. Conditionally unstable (if ALR is in between DALR and saturated adiabatic lapse rate (SALR)
3. Neutral (Dry) (if ALR is equal to DALR)
4. Neutral (Moist) (if ALR is equal to SALR)
5. Absolutely stable (if ALR is less than SALR).

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

Singer and Smith (1953) gave a subjective classification of horizontal wind direction fluctuations which states the fluctuations exceeding 90^o be classified as highly unstable (A) and fluctuations not exceeding 15^o be classified as stable (D) with intermediate classes B_2, B_1 and C in between. This classification was found to be a useful tool for the development of diffusion climatology (Baulch, 1962). Smith (1956) related the above classes to wind speed and vertical differences of temperature which showed super adiabatic conditions for 'A', 'B_2' and 'B_1' and sub adiabatic condition for 'C' and inversion conditions for D. However wind direction fluctuation measurements may not be available often, Pasquill (1961) proposed 6 stability categories to describe the diffusive potential of the lower atmosphere in estimating the dispersion of air pollutants. The categories are functions of wind speed, cloudiness, incoming solar and out going terrestrial radiation intensities. These are A (very stable), B (moderately unstable, C (slightly unstable), D (neutral), E (slightly stable) and F (moderately stable).

This was originally developed for open or rural terrain. However, Turner (1961,1964) modified slightly the above classes so that they can be determined objectively from the routine meteorological data. He successfully applied the above scheme to the urban environment. By far, this scheme is the most popular, probably because many of the diffusion parameters in meteorological models were developed for each of these categories and secondly this is relatively easy to compute with wind speed and cloud amount alone at any given place. The frequency of the occurrence of Pasquill categories has been determined seasonally in Great Britain by Bannon et al. (1962). The frequency of occurrence of D in each direction and speed class is computed for Birmingham, Alabama (Mc Cormick and Holzworth, 1976). Viswanadham (1980) and Viswanadham et al. (1981 a and 1981 b) studied the Pasquill categories, their percent frequencies, and their variations for four major urban centres in India namely Bombay, Calcutta, Madras and Delhi. According to them unstable conditions during day time with B and C are the most dominating classes for Bombay, Madras and New Delhi. The seasonal variation was reported to be well marked for the above places. Sadhuram (1982) computed Pasquill categories for Visakhapatnam for a 10 year period.

The interrelationship between the Pasquill category and horizontal wind direction fluctuations is of interest and despite a number of studies no universal relationship could be arrived though the trends are maintained. Slade (1968) related $\sigma\theta$ values (which can be obtained by dividing the wind fluctuation range in 10, 15 or 20 minutes interval with six).to each of the Pasquill categories as follows: A (25), B (20), C (15), D (10), E (5) and F (2.5). However Shirvaikar (1965), Padmanabhamurthy and Gupta (1979) and Sadhuram and Vittal Murty (1983) have reported different values of $\sigma\theta$ for each of these categories. Sadhuram (1982) gave an account of seasonal variation also for Visakhapatnam city which showed considerable variation in the relation for unstable classes. In view of the wide variation from author to author the relation between $\sigma\theta$ and Pasquill categories is determined for Cochin. The validity of taking 1/6 of the total range has been examined for Cochin which yielded a different value as can be seen in the subsequent chapters.

The relation between either mixing height and stability or mixing height and $\sigma\Theta$ has not been reported so far. Sadhuram and Vittal Murty (1984), however, showed a trend of variation between $\sigma\Theta$ and mixing height for 4 typical months for Visakhapatnam which showed an excellent relationship between these two. But the numerical relation has not been found and an attempt is made in the present work to give the same.

2.1.3. Meteorological modelling

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 attendant meteorological and geophysical conditions. A review of the past work was made earlier by Stern (1970), Wanta (1968), Moses (1969), Seienfield et al. (1972), Eschenvoeder and Mastinez (1972) and Fan and Horia (1971). Gaussian diffusion model is the most popular and is easy, relatively, to apply. This model is nothing but the fundamental solution to the classic Fickian diffusion equation. Sifford (1968) gave a complete discussion of the Gaussian diffusion model. Robertz et al. (1970) developed Gaussian puff model which track individual pollutant plume element as they move along wind trajectories and diffuse in Gaussian fashion. This, according to them, is to overcome some of the drawbacks. However, there were no extensive application of puff model due to its large computational requirements.

In addition to the Gaussion type of formulation there is another fundamental approach which is based on the equation of mass conservation. There are two main classes of model in this category.

1) Eularian model and (2) Lagrangian model. While Gaussian model calculates concentration of pollutants source by source or receptor by receptor, the Eularian model calculates concentration throughout a region at one time. Ulbrack (1968) made use of Eularian model and computed concentrations in Los Angeles. Reiquam (1970) computed concentrations with the help of the same model for Willamatte Valley, Oregon. Moecracken et al. (1971) also made use of the same model in the San Francisco Bay area. The Langrangian models were used by Wayne et al. (1971) and Behar (1970) to investigate Los Angeles photochemical smog. Leahey (1972) used the same model for SO_2 in New York. However, the box models assume complete vertical mixing, neglect diffusion between boxes and use first order differencing. These would result in errors. The Langrangian models should have many approximations to

get the solution and thereby its applicability and the accuracy of solutions are limited (Johnson et al., 1976). Despite the presence of many other models Gaussian diffusion model is still the most popular model, and there have been considerable modification to improve the validity of the model.

It is often difficult to test the model. However, Pooler (1961) applied a model to determine the monthly concentration of SO_2 at a large number of points at Nashvilla with the help of emission inventory. These estimates were compared with monthly measurements of SO_2 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 has been applied extensively to estimate SO_2 and particulate matter. Many long term models were developed subsequently (Zimmerman, 1971; Turner et al., 1972). There were simple models also by Gifford and Hanne (1973) which upon testing were surprisingly very close second to the complicated models.

Simultaneously, there were some short term models which calculate concentrations for time periods of half hour to one day. Turner (1964), Claske (1964), Koogler et al., (1967) have all computed concentrations ranging from two to twenty four hours. All these short term models use a single wind direction for each time period. However, Hilst (1968) developed a regional model that took account of the variations of wind. Gifford (1973) evaluated the performance of several simple models with available data to test other models which revealed that the estimates from the simple models are often as good as those of the more complex models.

The main parameters required for the model computations are effective stack height and dispersion parameters σy and σz. 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 models. There were a number of formulae to estimate the effective stack height. To name a few, Briggs(1965), Holland (1975), Davidson and Bryand (1975), Luccas et al. (1963) and Slawson and Csanady (1967). The formulae suggested by them are mostly functions of horizontal wind at stack height, ambient temperature, plume temperature, vertical velocity of the plume and physical stack parameters.

Vittal Murty and Viswanadham (1978) have reviewed various plume rise formulae and concluded that no two formulae are giving the same result suggesting to choose a formula apposite to the local conditions.

The crux of the model evaluation lies in estimating the dispersion parameters namely σy and σz. Pasquill (1962) expressed the diffusion coefficients in terms of standard deviations. Mc Elroy (1969) proposed the relation between σy and σz in terms of downwind distance as follows. $\sigma y = bx^P$, $\sigma z = ax^k$ where a,b,p and k are constants whose values are functions of stability and are given by him. Turner (1970) prepared nomograms for computing σy and σz as a function of downwind distance and Pasquill stability category.

In India there were some studies applying the Gaussian models making use of one of the plume rise formulae and one of the techniques to estimate σy and σz. Das et al. (1973) applied the model to study the dispersal of pollutants from the Madhura refinery in two parts (1) The short period concentrations have been computed under the vast meteorological conditions, to estimate the peak concentrations. (2) The long period concentrations has been studied for the planning purposes. Vittal Murty et al. (1977) presented a theoretical model for calculating ground concentration of SO_2 at Visakhapatnam. The seasonal and annual variations were studied. Viswanadham (1980) applied the Gaussian model for multiple sources for the 4 major cities in India. Sirvaiker et al. (1969) developed a finite plume model based on wind persistence. Padmanabhamurthy and Gupta (1968) applied Gaussian model at Borgoli, Salakati and at Madhura. They suggested optimum stack height for any proposed industry and optimum emission for the existing stack height. 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 very larger distances downstream because it neglected the horizontal advection of pollutants. Despite the presence of a number of models, most of the current models in use are based upon Gaussian plume concept (Turner, 1979).

2.2. Materials and methods

This section deals with the data and its sources and the computational procedures of mixing heights, ventilation coefficients, wind roses, Pasquill stability, $\sigma\theta$, evaluation of the model and its parameters and application of the model to multiple sources. Also, this part deals with the relative merits and demerits of the methods applied.

2.2.1. Data and its sources, and the period of study

The period of data is 10 years from 1973 to 1982. The data collected is two fold. (1) Meteorological data and (2) Emission inventory. The meteorological data collected is three hourly surface temperature, daily values of temperature and wind at various levels in the vertical during the early morning period, three hourly cloud type, amount and height and hourly surface wind speed and direction on all the days in all the months for all the 10 years mentioned above. The hourly values of surface temperature at 9 points in the city were collected for 3 days each in the months of December, January and February for the years 1981 and 1982. The anemogram charts numbering 3,650 were collected to analyse and compute the range of the wind direction fluctuations, spanning over the whole 10 year period. The source of the above data is IMD Pune and Trivandrum.

The physical stack heights, emission rates, stack diameter and stack gas temperatures, types of fuel used, consumption of fuel, composition of various gases contained in the plume for all the major industries in the city were gathered.

2.2.2. Computation of frequency of inversions, mixing heights and ventilation coefficients and construction of wind roses.

2.2.2.1. Frequency of inversions

The surface based and elevated inversions and the isothermal conditions are noted from the radiosonde data for each month and the frequencies are computed and presented in tabular form.

2.2.2.2. Mixing heights

MHs can be determined by extending a dry adiabat from the surface temperature to its intersection with the early morning temperature soundings (Holzworth, 1967). The height of the point of intersection from the ground is termed as MH. The surface temperature cannot be used straight away without adding the correction factor to account for the urban heat island effect. Holzworth suggested a value of 5°C to be added to the rural surface minimum temperature to compute the minimum MH at the minimum temperature epoch. The value of 5°C was found to be rather high for Indian conditions, especially for coastal stations where a different value was proposed by Vittal Murty et al. (1980). These assumptions are necessary in the absence of any observational evidence. If the data is collected from airports the MHs computed also are representative for that part unless the correction factor is added. When the corrected surface temperature is used this MH may be representative at a point in the city where this corrected surface temperature is actually observed. However, if the surface temperatures are available from the urban regions and the temperature soundings is from its suburb, the MH can be computed without adding any correction factor, since the observed temperature is from the urban area where the MH is to be found out. The suburban temperature sounding is necessary so that the sounding is free of the urban effects. If continuous temperature data in the urban area is available, the MH can be computed at anytime by extending the dry adiabat from the surface temperature corresponding to the given time to 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. The MH thus computed, will be representative only at a particular point. However, as the surface temperature is known to vary spatially within a given city, MH computed at a single point cannot be representative for the whole city. In addition, the spatial variation of MH within a given city can serve to delineate the regions of good and poor dispersal of pollutants. While the spatial variation of MH over a country gives broadly, the possible regions for the industrial development, the microlevel spatial variation of MH gives the specific locations within a given city. However, such studies require a knowledge of spatial distribution of surface temperature within a given city which are seldom available. Hence, such distributions of temperature have to be obtained either from some empirical relationships or from the actual observations made for short periods but are extendable to longer periods as well. For the present computations the latter is adopted. The surface observations were made hourly by Viswanadham (1983) in the winter period in 1981 and 1982. Nine points were selected to record the observations with whirling psychrometers. The differences in temperature at each of the nine points in the city and at every hour from the corresponding value at the airport are noted and the same differences in temperature are made use of to get the spatial temperature variations for the other months and for the rest of the period. Table 2.1 gives the differences in temperatures. This approximation at the first instance may appear to be crude, but certainly it is a relatively better approximation than that obtained from the empirical methods because it has some experimental evidence. Moreover, in the absence of a good observational net work of surface temperature observations within a given city, this can certainly serve the purpose. Accordingly, the MH is computed with the method outlined above daily for every three hours for all the months for the 10 year period; at all the 9 points in the city. The monthly means for

Table 2.1

Correction factors (^{o}C) added to the Naval Base surface temperature to get surface temperatures at various points at different timings for Cochin

	Time (I.S.T)							
	00	03	06	09	12	15	18	21
Fort Cochin	+0.2	+1.2	+1.5	+0	+0	+0	+0.8	+0.5
Kacherippady	+2.0	+3.0	+3.5	+0.2	+0	+0	+1.0	+1.0
Menaka Junction	-0.5	+0	+0	+0.2	+0	+0.5	+0	-1.0
Mattancherry	-1.0	+0	+0	+1.7	+1.5	+1.0	+0	+0.5
Tripunithura	-0.5	+0.5	+0.5	-0.3	+1.0	+1.0	+1.0	+0
Trikkakara	+0.3	+1.5	+1.3	-0.6	+1.5	-0.1	+1.1	+0
Valanjambalam	+0.2	+0	+0	+0.4	+0.2	+0	+0.2	+1.0
Vypeen	+0.1	+1.0	+1.2	-0.6	-0.8	-0.4	+1.3	-0.2

every three hours are obtained for each of the month and the isolines of MHs are drawn on the map of Cochin. The diurnal, monthly and yearly variations at selected points and for selected timings have been studied.

2.2.2.3. Ventilation coefficient

Ventilation coefficient (VC) at any time can be obtained by multiplying the MH at that time and the mean wind speed through the mixing layer. Since the MHs are already computed for every three hours, the winds and their vertical variation at those timings is necessary to compute the mean wind to multiply with the corresponding MH. However, neither the spatial variation of wind within the city nor the vertical variation of wind at the airport for all the hours is available to compute the VC. The vertical wind structure is available only twice a day at the airport. Hence, the surface wind, which is available at every hour is multiplied with the MH to get VC. Accordingly, the VCs are computed daily for every three hours for all the months for the ten year period. The monthly means are obtained. The diurnal and the monthly variation has been studied.

2.2.2.4. Wind roses

The hourly wind speed and direction for all the days in all the months for the 10 year period are utilized to prepare the frequency table for every hour. The wind speed and direction are split into 5 and 16 classes respectively. The five speed classes are 1-5, 6-10, 11-20, 21-30 and >30 kmph and the 16 directions are N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW and NNW. For every hour in each month the frequency tables are prepared for the five speed classes in all the 16 directions. The calm conditions are also noted. By taking a suitable scale the wind roses for every hour have been drawn for all the months. The 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 the appropriate notation, the speed classes along each directions, depending upon their relative frequencies, are represented along each of the 16 directions. The wind roses for every three hours have been presented and the diurnal and the monthly variation have been studied.

2.2.3. Computation of stability

The methodology of computing Pasquill stability and $\sigma\theta$ is presented here.

2.2.3.1. Pasquill stability

Pasquill suggested a scheme for computing the six stability categories ranging from A to F. Table 2.2

Table 2.2

Stability class as a function of net radiation 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	E
11	C	C	D	D	D	D	D
12	C	D	D	D	D	D	D

gives the stability class as a function of wind speed and net radiation index. The net radiation index ranges from 4, highest positive net radiation (directed towards the ground) to - 2 highest negative net radiation (directed away from the earth). Instability occurs with high positive net radiation and low wind speed, stability with high negative net radiation and light wind 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 7000 feet use net radiation index equal to 0 (whether day or night).

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

   a) If total cloud cover $<$ 4/10, use net radiation index equal to -2.

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

(3) For day time

   a) Determine the insolation class number as a function of solar altitude from Table 2.3.

   b) If total cloud cover $<$ 5/10, use the net radiation index in Table 2.1 corresponding to the insolation class number.

Table 2.3

Insolation as a function of solar altitude

Solar altitude (a)	Insolation class number
$60^\circ < a$	4
$35^\circ < a < 60^\circ$	3
$15^\circ < a < 35^\circ$	2
$a < 15^\circ$	1

c) If cloud cover > 5/10, modify the insolation class number by following these six steps:

i) Ceiling < 7000 ft., subtract 2.

ii) Ceiling > 7000 ft., but < 16000 ft., subtract 1.

iii) Total cloud cover equal 10/10, subtract 1. (This will only apply to ceilings > 7000 ft. since cases with 10/10 coverage below 7000 ft. are considered in item 1 above).

iv) If insolation class number has not been modified by steps (1), (2) or (3) above, assume modified class number equal to insolation class number.

v) If modified insolation class number is less than 1, let it equal 1.

vi) Use the net radiation index in Table 2.1 corresponding to the modified insolation class number.

Accordingly, the stability for every hour on all days for all the months are computed. The percentage frequenc of occurrence of each of the stability classes for each hour are computed for all the months. The diurnal, monthly and yearly variation have been studied.

2.2.3.2. $\sigma\theta$

Slade (1968) has proposed a simple method to computed σ_θ. The wind direction fluctuation in each hour are conveniently divided into either 10, 15 or 20 minutes intervals depending upon the degree of variation of wind direction. For example, for a smooth direction trace 20 minutes interval can be chosen and for a highly fluctuating case, at least 10 minutes interval is to be chosen. After choosing the time interval the range of the fluctuations (difference between the extreme values) within that interval is determined. Then the mean of such ranges in that hour is computed to get the mean range in that hour. The mean range is divided by 6 to get $\sigma\theta$. 12 anemograms in 1974 were examined in detail to compute $\sigma\theta$ from the conventio statistical techniques for every 10 minutes for all the 12 days. 3 days are chosen each for the months of January, April, July and October. The $\sigma\theta$ thus computed are arranged in each hour. The ranges for 10 minutes interval are also noted from the same charts and related the same to $\sigma\theta$. To establish this, $\sigma\theta$ was computed nearly 3000 times. In order t make the computation of $\sigma\theta$ easier, regression equations of th form Y = mX are developed. However, to have a relative comparison of $\sigma\theta$ with those computed by other scientists, the value of $\sigma\theta$ obtained by multiplying 1/6 with wind direction fluctuation range only has been used. Although very laborious, all the 3650 anemograms are analysed to compute climatologically the values of $\sigma\theta$ for every three hours for all the months. The diurnal, monthly and yearly variation has been studied. The values of $\sigma\theta$. corresponding to each of these 6 stability classes have also been computed for January, April, July and October, typical of winter, pre-monsoon, monsoon and post-monsoon seasons respectively. The relation between $\sigma\theta$ and MH has also been found out for the same four months.

2.2.4. Application of model

For the estimation of ground level concentrations both for short term and long term periods, Gaussion 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.

2.2.4.1. Model development

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

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

$$\chi \propto \frac{1}{u} \qquad \text{------}\rightarrow (1)$$

where χ is the concentration in g/m^3 and U is the average wind speed in m/sec.

The distribution in the vertical and cross wind directions are given as Gaussian functions and along the wind direction the concentration is proportional to . The concentration is proportional to source strength Q(g/sec). 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)

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

where σy 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

$$\chi \propto B \exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma z}\right)^2\right] \text{--------} \rightarrow (3)$$

where σz 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 σz.

The equation (3) has to be altered accordingly depending upon whether reflection, absorption or deposition takes place at the ground when the plume reaches the ground. No absorption or deposition at the ground is assumed. Instead, perfect reflection is assumed. Then the earth's surface acts as barrier and no further diffusion takes place. An image source can be assumed symmetrically to the actual source with respect to the ground because the concentration at any point down wind in 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 continued effect can be written in the form given below:

$$\chi \propto B\left[\exp\left(-\frac{1}{2}\left(\frac{z-h}{\sigma_z}\right)^2\right) + \exp\left(-\frac{1}{2}\left(\frac{z+h}{\sigma_z}\right)^2\right)\right] \quad \text{----------} \rightarrow (4)$$

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

The area under the curve is taken as the integral of

$$\int_{-\infty}^{+\infty} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] dy = \sqrt{2\pi}\;\sigma_y \quad \text{----} \rightarrow (5)$$

$$\text{so} \quad \frac{1}{\sqrt{2\pi}\,\sigma_y} \int_{-\infty}^{+\infty} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] dy = 1 \quad \text{-------} \rightarrow (6)$$

A similar expression can be obtained from the 'Z' direction also as $\frac{1}{\sqrt{2\pi}\,\sigma_z}$.

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

$$\chi(x,y,z;h) = \frac{Q}{2\pi \sigma_y \sigma_z U} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{\exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+h}{\sigma_z}\right)^2\right]\right\}$$

---------→(7)

where Q is given in grams/sec, U in m/sec, σy and σz in metres; h,,z,x,y in metres. It should be remembered here that the diffusion in the along with (X) direction is neglected. This assumption facilitates to take the plume emission to be continuous.

Ground level concentrations can be observed by putting Z = 0 in equation (7)

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

---------→(8)

The concentrations along the plume centre line at the ground can be obtained by putting Y = 0 in equation (8), thus

$$\chi(x,0,0;h) = \frac{Q}{\pi \sigma_y \sigma_z U} \exp\left[-\frac{h^2}{2\sigma_z^2}\right]$$

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

$$\chi = \frac{2Q}{\sqrt{2\pi}\,\sigma_z U \left(\frac{2\pi x}{16}\right)} \exp\left[-\frac{1}{2}\left(\frac{h}{\sigma_z}\right)^2\right] \quad \text{-----------} \rightarrow (10)$$

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

The equations (8) and (10) have to be modified if a stable layer exists above. As the plume touches the ground 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 σz 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 σz is allowed to increase with distance to a value of L/2.15 or 0.47 L. 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 2 X_L, it is assumed that the pollutant is uniformly distributed between the ground and the height L.

So for the distances greater than 2 X_L, the concentration at the ground or at any height upto 'L' is constant at a particular distance and is given as

$$\chi(x, y, z; h) = \frac{Q}{\sqrt{2\pi}\,\sigma_y\, L U} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \quad \text{-----------} \rightarrow (11)$$

for short term concentrations and as

$$\chi = \frac{Q}{LU\left(\frac{2\pi x}{16}\right)} \quad \text{or} \quad \frac{2.55\,Q}{LU\,x} \quad \text{---------} \rightarrow (12)$$

for long term concentrations.

The height of the stable layer may be the base of an elevated inversion or 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. In the present case the representative MH for Cochin has been used. The representative value has been obtained by taking the spatial mean of MH computed at various points in Cochin. The estimation of for a particular direction and downwind distance can be accompolished by choosing a representative wind speed for each speed class and solving the appropriate equations (10) or (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.

2.2.4.2. Evaluation of parameters in the model

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

$$U_z = U_l \left(\frac{Z}{Zl} \right)^{\frac{1}{P}}$$

where U_z is the wind at any height 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 Slawsen and Csandy has been used. The formula is

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

where $F_T = gw_O\ R_O\ (\frac{T}{T_a})$,

where ΔH = plume rise

U = mean horizontal wind speed

W_O = stack gas velocity at the exist

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 hence preferred as the value of heat emission is not available.

2.2.4.3. Application of the model for multiple sources

The pollutant under consideration here is SO_2 from the industrial sources. The ground concentrations of SO_2 at each hour for all these stability classes are computed. Depending upon the percent frequency of occurrence of stability classes the cumulative concentration is computed. The χ is distributed among the 16 wind directions depending upon their relative frequencies. The χ is divided with the respective mean wind speeds at each distance in each direction to get the concentration χ due to one source.

The inclusion of calm conditions is a ticklish problem. However, a simple way is suggested to incorporate calm conditions in the model. Normally, less than one kmph is reported as calm conditions. Never does one find wind to be absolutely calm for a length of time. So an average wind of 1/2 kmph is used as the wind speed and the concentrations are obtained accordingly. The concentration is distributed along the wind directions observed at that hour depending upon their relative frequencies. This is because the pollutants which get accumulated during the calm conditions will have to be dispersed when the wind blows. Instead of distributing this concentration equally in all directions, it is distributed proportionately depending upon the relative frequencies of wind directions at that hour. The incorporation of calm conditions is necessitated in view of the very high frequency of calms during night time, sometimes accounting for more than 50%. Having found out the concentrations at every hour, after incorporating the calm condition, the 24 hour cumulative values are obtained.

The Cochin and its suburbs are conveniently divided into 4 km x 4 km grids. Three major sources have been identified. The concentrations in each of the grids due to all the three sources are stored and added.

The isolines of 24 hour values of χ are drawn on the map for each month.

2.2.5. Merits and demerits

2.2.5.1. Merits

The spatial variation of MH within a given city has been done for the first time by making use of the actual urban heat island studies for few months. For the first time, the diurnal variation, by taking MHs for every three hours, has been studied. Hitherto studies were confined mainly to compute maximum MH and minimum MH only, atleast for India.

For the first time the three hourly wind roses for all the months for a 10 year period are reported.

The climatological values of Pasquill stability and their distribution are established for every hour in all the months for Cochin.

In order to establish the diurnal and monthly variation of $\sigma\theta$ on a climatological basis, all the daily charts for all the months for the period 1973 to 1982 numbering to nearly 3650 charts, are analysed. Hitherto studies were confined to compute seasonal values for 10 years (Sadhuram, 1982). The analysis on such a large scale was never reported. This climatology of σ_θ is an asset for the turbulence studies as well.

Though very laborious, the actual standard deviation from the conventional statistics has been computed for every hour to verify the validity of taking 1/6 of the range as σ_θ. Since Slade reported in 1968, there were no attempts to verify this value. With a view to establish firmly the numerical value to be multiplied with the range, σ_θ is computed from both the methods for the four typical months.

For the first time an exact relation between σ_θ and MH is obtained in the form of regression equations for the four typical months.

The incorporation of the calm conditions in the model and taking a representative MH for the whole city to be used in the model and the inclusion of wind variation with height at each downwind distance and stability are the prominent features in the evaluation of the model.

2.2.5.2. Demerits

The drawback in the study of spatial distribution of MH is the extension of the observations made for few days in few months to all the remaining months and for the rest of the years. This has to be necessitated because there is no continuous net work of observational system to measure surface temperature spatially. Another drawback is the computation of MH in the monsoon season. Normally the days with rainfall are to be deleted. However, from June through September the rainy days are more than 50%. The other part may not represent the conditions in those month. So an alternative is to delete these months. But is is felt that MH be computed in those month also irrespective of whether it rains or not, mainly to have the continuity. The question, however, remains as to whether MH can be computed or not disregarding whether it rains or not. In drawing the isolines the watermasses present in Cochin are not taken into account. The MH over the land may not be the same as over the water body. As Cochin consists of islands, the water body in between two land masses is a common feature, but no correction is made to that effect.

The Gaussian model is applied with the assumptions such as (1) Flat terrain (2) The pollutant should be physically and chemically inactive (3) Perfect reflection of the plume at the ground (4) Neglecting the diffusion in the downwind direction. In the evaluation of the parameters in the model power law profile for the vertical wind variation is assumed, which may not be appropriate because this law is applicable only in the surface layer extending to a height of 100 to 200 meters. There is ample scope for the thickness between $h - 2\sigma z$ to $h + 2\sigma z$ to exceed hundred meters, far away from the source, especially in unstable conditions. However, this problem is partly overcome inherently because of the following reasons: (1) In unstable conditions, the pollutant is uniformly distributed in the vertical very close to the source and hence the thickness between $h - 2\sigma z$ to $h + 2\sigma z$ may not exceed few hundred meters (2) In stable conditions the thickness increases with downwind distance very slowly and hence the possibility of the thickness exceeding few hundred meters is rare.

The incorporation of the calm conditions in the model may have few limitations, because, the pollutants that get accumulated due to calm conditions may get dispersed with the winds which blow at a later time rather than that at the same time. However, even in the subsequent hours calms are prominent, especially during night time and hence the proposed distribution along the prominent wind direction at that time is partly justified. Taking 1/2 kmph as the wind speed also may not sound appropriate. But, for the zero wind the model gives the concentration to be infinity which is absurd. An average value between zero and one kmph which is 1/2 kmph, would give a finite result, which will be certainly a higher concentration than for higher wind speeds and hence justified partly, despite the short coming.

The emission from industries alone is considered. The line sources which do contribute to the pollution, are not taken into consideration. Hence the concentrations may under estimate the actual values.

2.3. Summary

A review of air pollution climatology, atmospheric stability and meteorological modelling is presented which showed that till todate the first two are to be established and the last to be applied for any developing city. The study of MH, inversions, VC, and winds, form air pollution climatology. Holzworth's method of computing MH and VC are widely used. It is shown that the spatial variation of MH within a given city has not been attempted so far. It is also shown that how, for the first time, it is attempted in the present work. Pasquill's stability classification is by far the most popular scheme of computing atmospheric stability, despite the presence of many other stability schemes. Gaussian model for estimating the ground concentration of pollutants is the widely used and the simplest ever. Many of the recent developments in the modelling still have Gaussian model as the basis. The comparison with many other complicated models showed a very little deviation from the actual and hence preferred.

The data and its sources and the period of study are also shown. The detailed computational procedures of MH, VC, wind rose, stability, $\sigma\theta$ and the model for multiple source are brought out clearly. The procedure for spatial variation of MH within a given city is also presented. It is also shown how enormous the data is, to establish the monthly variation of $\sigma\theta$. For the first time, 3650 anemograms are analysed. The actual standard deviation of the wind direction fluctuations and $\sigma\theta$ computed by Slade's method are compared to see whether the factor of 1/6 is to be altered. The method of multiple sources, in addition to the model evaluation, is presented in detail. Some of the points superior to others such as spatial variation of MH for a given city incorporating the observed heat island studies, the climatology of the diurnal variation of wind roses, analysing 3650 anemograms, the alteration of the factor 1/6 to compute $\sigma\theta$ and the inclusion of calm conditions in the model are listed. At the same time the drawbacks such as extending the observed heat islands in December, January and February to other months, the non inclusion of effect of precipitation in computing MH and those pertaining to the evaluation of the model are clearly brought out, though some justifications are offered to partly compensate the effects of the drawbacks listed.

C H A P T E R - 3

3. AIR POLLUTION CLIMATOLOGY

3.1. Introduction

3.2. Results and discussion

3.2.1. Frequency of inversions

3.2.2. Mixing heights

3.2.2.1. Spatial variation

3.2.2.2. Diurnal variation

3.2.2.3. Monthly variation

3.2.2.4. Yearly variation

3.2.3. Ventilation coefficients

3.2.3.1. Diurnal variation

3.2.3.2. Monthly variation

3.2.4. Wind climatology

3.2.4.1. Wind roses

3.2.4.2. Diurnal variation

3.3. Summary

3.1. Introduction

The importance of air pollution climatology is brought out in the preceeding chapters. In the present chapter the results and the discussion of the study on air pollution climatology for Cochin are presented.

3.2. Results and discussion

The results and discussion of the study of inversion, MH, VC and Wind roses are presented separately.

3.2.1. Frequency of inversions

The percent frequency of ground based and elevated inversions and isothermals for each month are given in Table 3.1. The thickness of the ground based inversions (GI) is 100 metres, while that for elevated inversion (EI) is 500 metres. For isothermals also the thicknesses are similar to those of inversions i.e. for surface based isothermals (IS), it is 100 metres, for elevated isothermals (EIS), it is 500 metres. Both EI and EIS are observed from a height of 100 metres only. The intensity of inversion is in three classes, namely, $<2^{o}$, 2^{o}-4^{o}, and 4^{o}-6^{o}C. Mostly the intensity of inversion is 2^{o}C. GI frequency is maximum in January and

Table 3.1

Percent frequency of occurrence of inversions and isothermals over Cochin

		J	F	M	A	M	J	J	A	S	O	N	D
Surface based inversion	$0^o - 2^o$	7.1	4.1	2.6	3.7	0.6	1.3	1.3	0.3	1.0	0.3	2	4
	$2^o - 4^o$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0	0
	$4^o - 6^o$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0
Elevated inversion	$0^o - 2^o$	1.3	0.0	0.6	0.3	0.3	0.3	1.0	0.6	1.0	0.0	0	1.3
	$2^o - 4^o$	0.3	0.7	0.0	0.6	0.0	0.7	0.0	0.0	0.0	0.3	0	0.0
	$4^o - 6^o$	0.6	0.7	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0
Isothermal	Surface based	28.1	16.9	21.0	23.5	21.9	22.0	31.3	23.9	19.7	25.2	29.3	25.2
	Elevated	1.0	3.1	4.2	4.2	4.5	4.0	4.8	2.6	2.3	4.2	4.7	3.2

less than 1% in May, August and October. The maximum GI in January is 7.1%. Only in April, December and February, the GI frequency is more than 3%. These are all in negligible quantities. Even the maximum in January shows, on an average, only 2 days with GI. The case of EI is still worse. The maximum frequency is only 1.3% and hence need not be taken very seriously.

The case of IS is different. IS frequency minimum itself is 16.9% and the maximum is 31.3%. Irrespective of the season, IS are present in considerable frequency, maximum being in July and the minimum in February. EIS frequency once again is in negligible percentage.

In general, both GI and EI are in negligible quantities. If isothermals are combined with inversion frequency, as is done in most of the cases, then the occurrence of inversions can be shown to be having considerable frequencies. Cochin being a coastal station normally does not show many inversions as compared to that of inland stations. Even those inversions which are present do not have much intensity. The non availability of the data for every hundred meters upto 1 km **may** have masked the elevated inversions. However in the absence of any such information it is to be concluded that it does not have considerable frequency of EI and EIS. Even the percent frequency of isothermals and inversions combined, the maximum is 35% only. 30 to 35% frequency of inversion-isothermal conditions in winter is not very alarming. Though the combined frequency is more in January, the average surface temperatures are not minimum in these months. The interesting speculation is whether December, January and February can be taken to represent the winter season. In any case, the situation is not very serious as far as air pollution dispersion is concerned.

3.2.2. Mixing heights

3.2.2.1. Spatial variation of MH

The MHs are computed at 9 locations in the city from the method outlined in Chapter 2. Fig. 3.1 shows the locations of the 9 points in the city. MHs are computed for every 3 hrs for all the years in all the months. At a given time the monthly mean values are

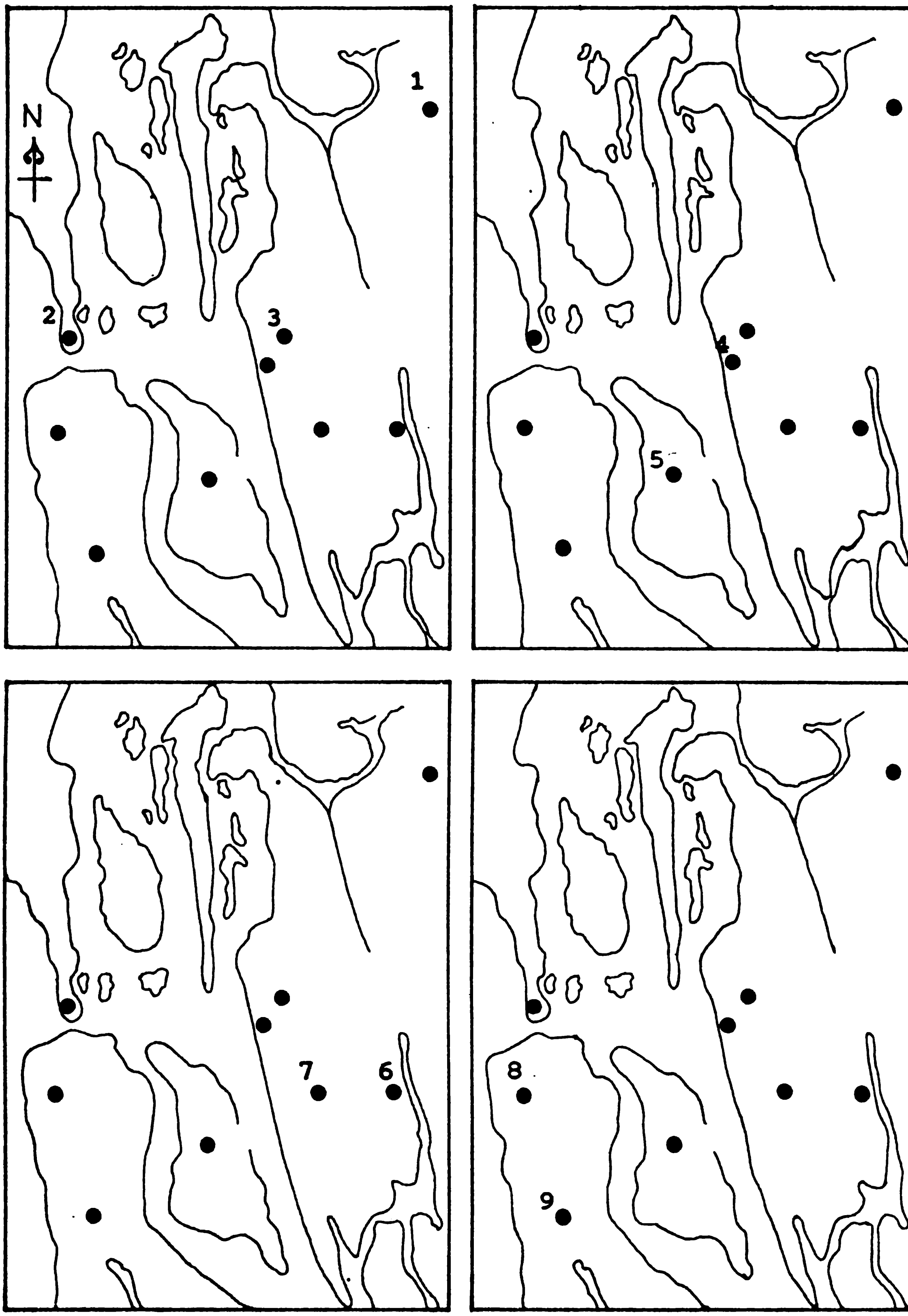


Fig.3.1. MAP OF COCHIN SHOWING THE POINTS OF OBSERVATION.

1.Trikkakara 2.Vypeen 3.Kacherippady 4.Menaka 5.Naval Base
6.Tripunithura 7.Valanjambalam 8.Fort Cochin 9.Mattanchery

obtained at each of the 9 locations for the 10 year period. The isolines of MHs for four selected timings namely 06, 12, 18 and 24 hrs IST, are drawn for each of the 12 months. Figures 3.2 to 3.13 depict the spatial distribution of MHs for Cochin for the four timings mentioned earlier, respectively for the months from January to December.

January

Enormous gradients are noticed at 06 and 24 hrs at the central parts of the city. They decrease as one moves towards north or northeast except at 18 hrs when they increase towards north. Relatively higher values are observed in the ESE portions at 12 hrs, while the converse appears to be true for the other timings. The SW portions have shown maximum values and NE portions minimum at 12 hrs while the pattern is different at other timings.
For example at 18 hrs higher values in the NE and minimum in the SW portion are noticed with a small cell of maximum in the western portion. At 06 hrs the entire southern parts of the city have shown very low values (<100 mts.).

February

Figure 3.3 represents spatial distribution of MH for February. The pattern is almost the same except that

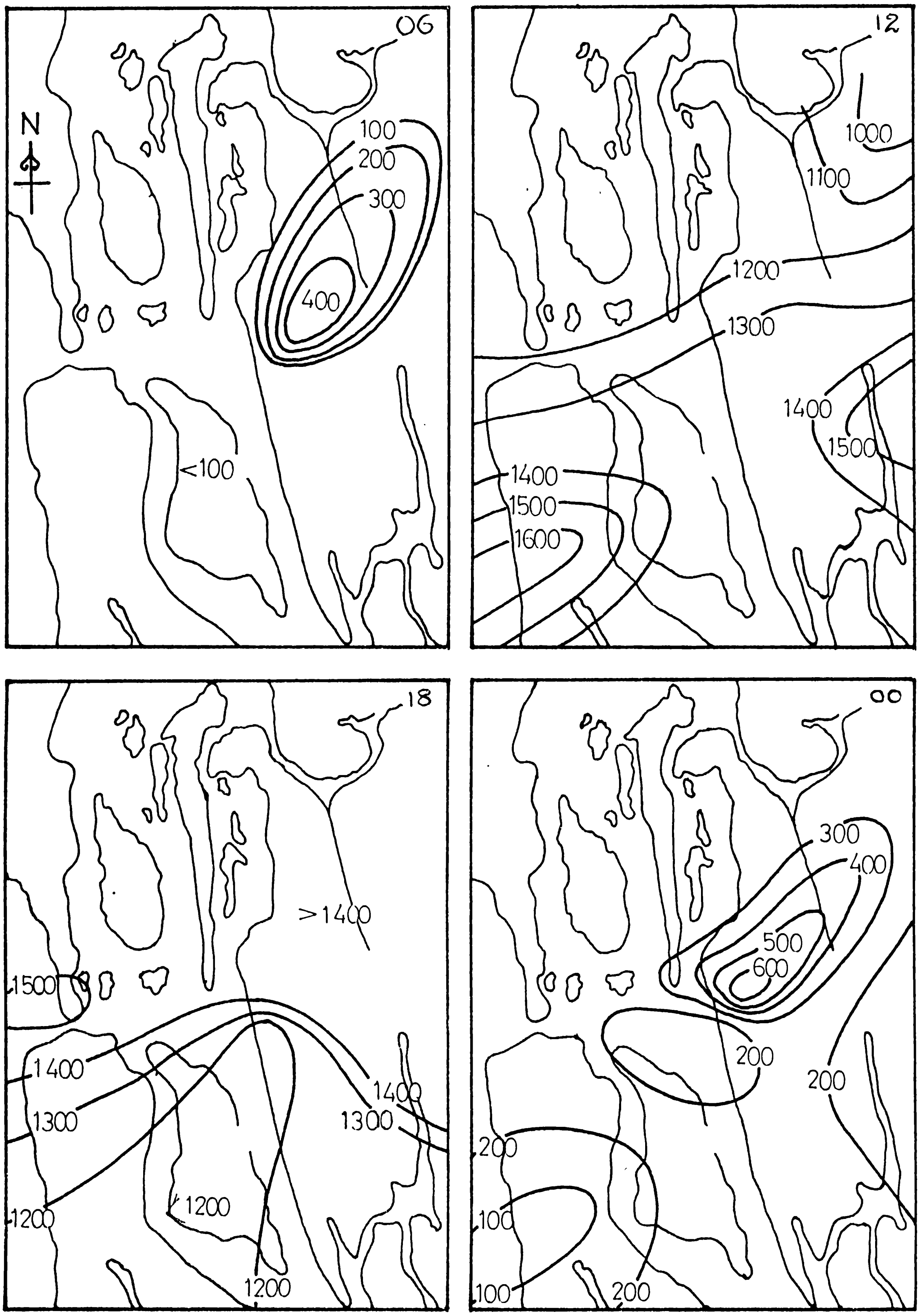


Fig.3.2. SPATIAL VARIATION OF MIXING HEIGHT AT 00,06,12 AND 18 Hrs IN JANUARY. (IN METRES)

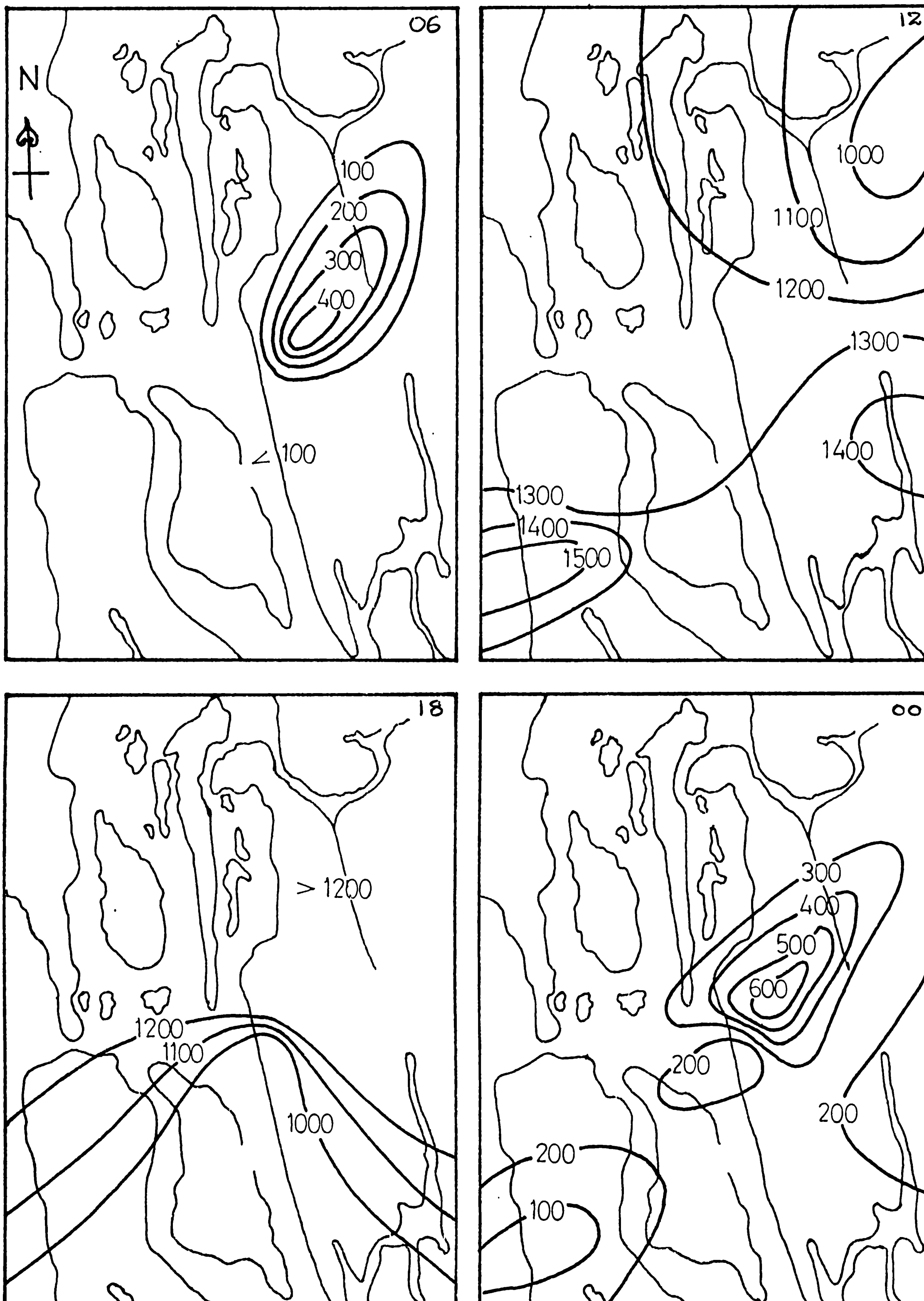


Fig.3.3. SPATIAL VARIATION OF MIXING HEIGHT AT 00,06, 12 AND 18 Hrs IN FEBRUARY. (IN METRES).

the MHs are relatively lower in this month compared to those in January.

March

Maximum MH is observed in the central parts at 06 and 24 hrs, towards NE at 18 hrs and towards SW at 12 hrs. Minimum values are observed in the southern parts at 06 hrs and at 18 hrs, the extreme southeastern parts at 12 hrs and extreme southwestern parts at 24 hrs. The spatial range is maximum at 6 hrs followed by at 24 hrs, 12 hrs and 8 hrs.

April

The maximum at 06 and 24 hrs are once again observed at the central parts. At 12 hrs the southern parts have shown maximum values and the NE parts have shown the minimum values. Mostly in the central parts MH varied between 12 and 13 hundred metres. The spatial range is maximum at 06 hrs followed by 12 hrs, 24 and 18 hrs. The maximum range is of the order of little over 600 metres.

May

The spatial range is almost same at 6, 12 and 24 hrs. At 18 hrs it is minimum. The maximum at 12 and 18 hrs have shown the reverse trend while, the same at

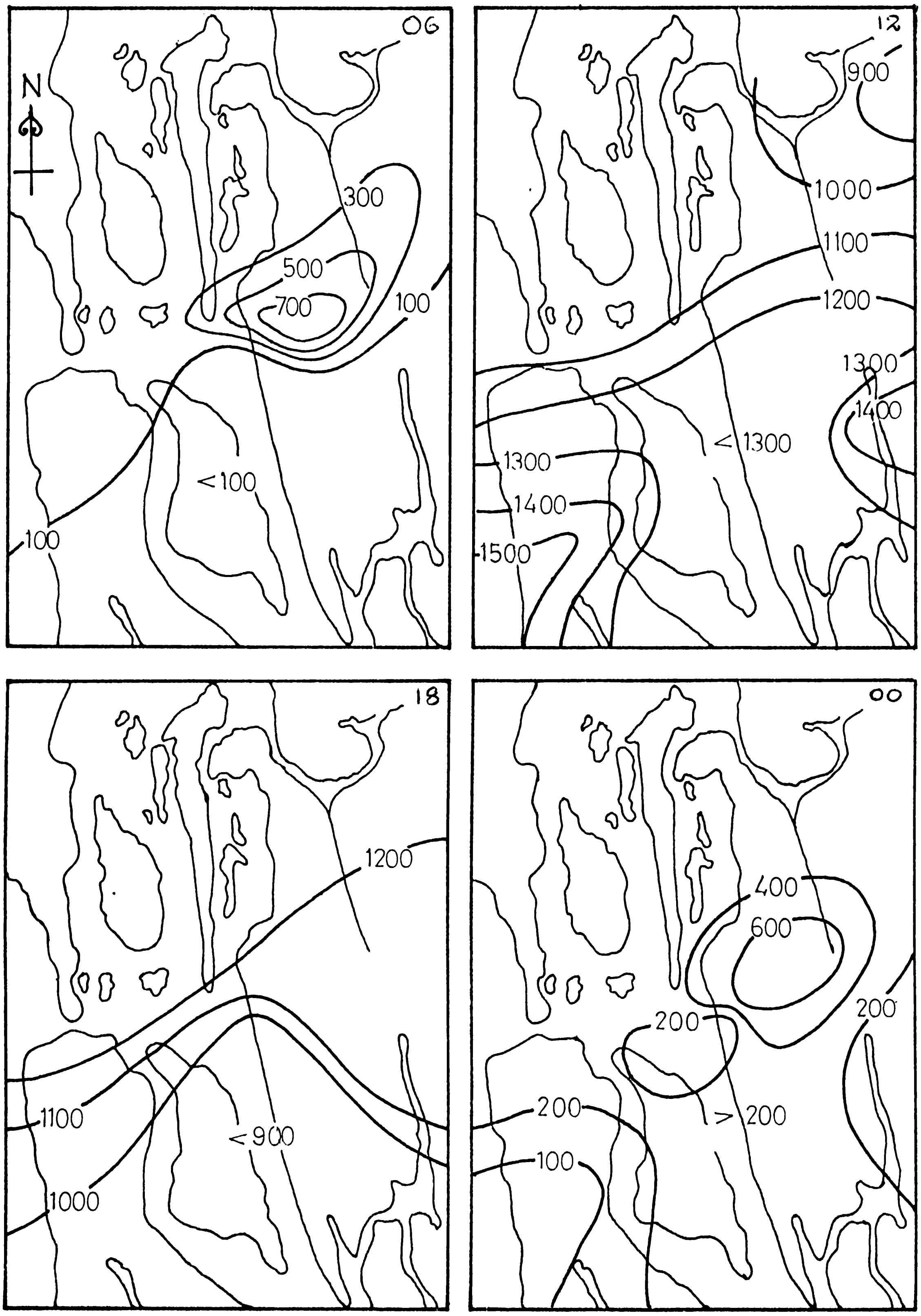


Fig.3.4. SPATIAL VARIATION OF MIXING HEIGHT AT 00, 06, 12 AND 18 Hrs IN MARCH.
(Isopleths are in 200 m intervals at 00 and 06 hours)

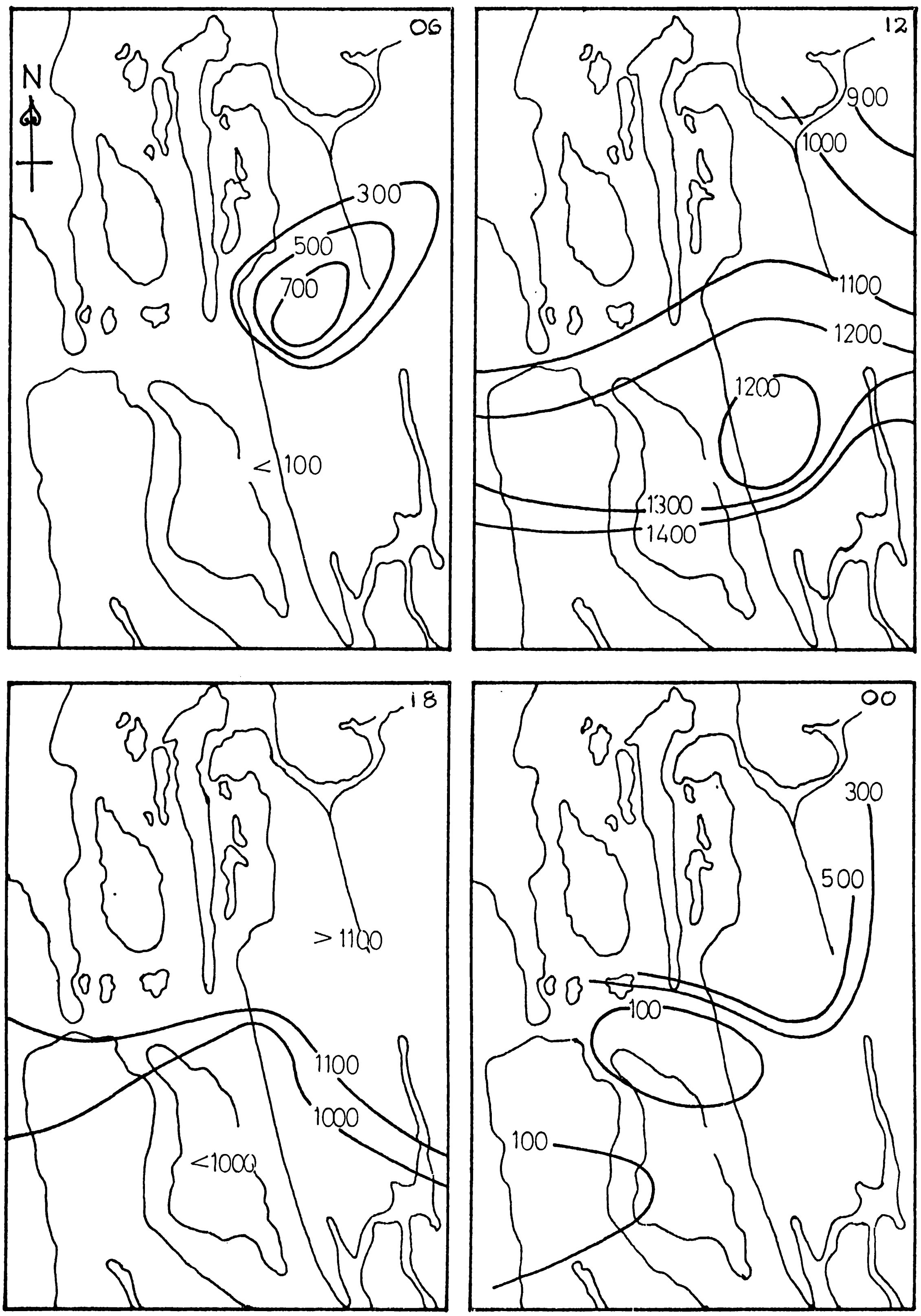


Fig.3.5. SPATIAL VARIATION OF MIXING HEIGHT AT 00, 06, 12 AND 18 Hrs IN APRIL.
(Isopleths are in 200 m intervals at 00 and 06 hours)

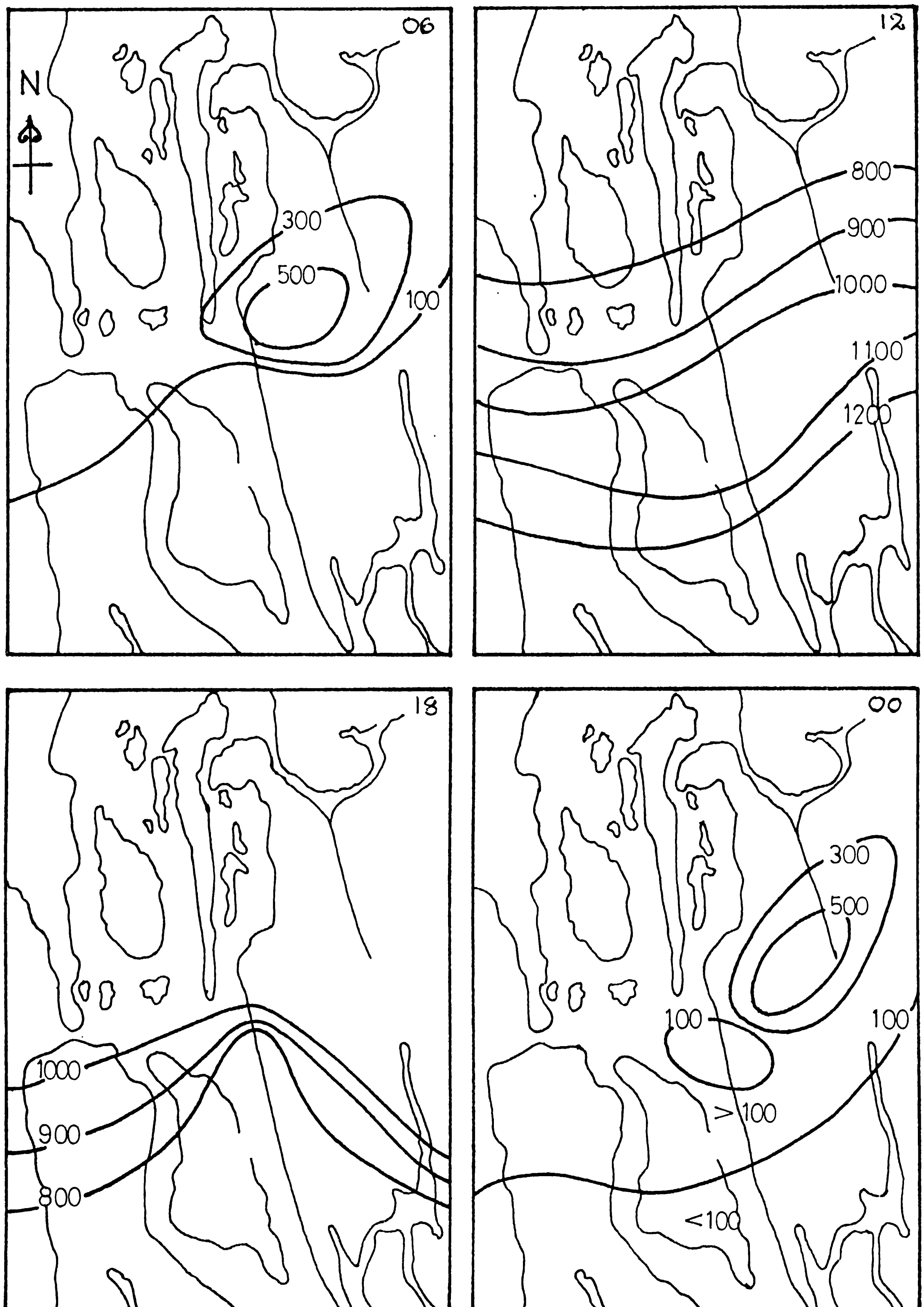


Fig.3.6. SPATIAL VARIATION OF MIXING HEIGHT AT 00, 06, 12 AND 18 Hrs IN MAY.
(Isopleths are in 200 m intervals at 00 and 06 hours)

6 and 24 hrs maintained the same trend. Except at 12 hrs the southern parts have shown very low values.

June

The maximum is observed at the central parts at all the hours. The values first increased and then decreased from SW to NE at 12 hrs. The spatial range is more at 12 hrs followed by 06, 24 and 18 hrs. At all these timings the southern portions have shown the minimum values.

July

The maximum values are observed in the central parts at 6 and 24 hrs and in the western parts at 18 hrs and in the southwestern parts at 12 hrs. The spatial range is maximum once again at 12 hrs. The spatial range is same at the remaining hours. The extreme southern parts have once again shown minimum values except at 12 hrs.

August

The pattern is almost the same as that in July with a profoundly higher values at the central parts at 06 hrs in this month compared to that in July. The spatial range is maximum at 6 hrs followed by 12, 24 and 18 hrs. At 06 and 24 hrs the mixing is confined only to the central parts.

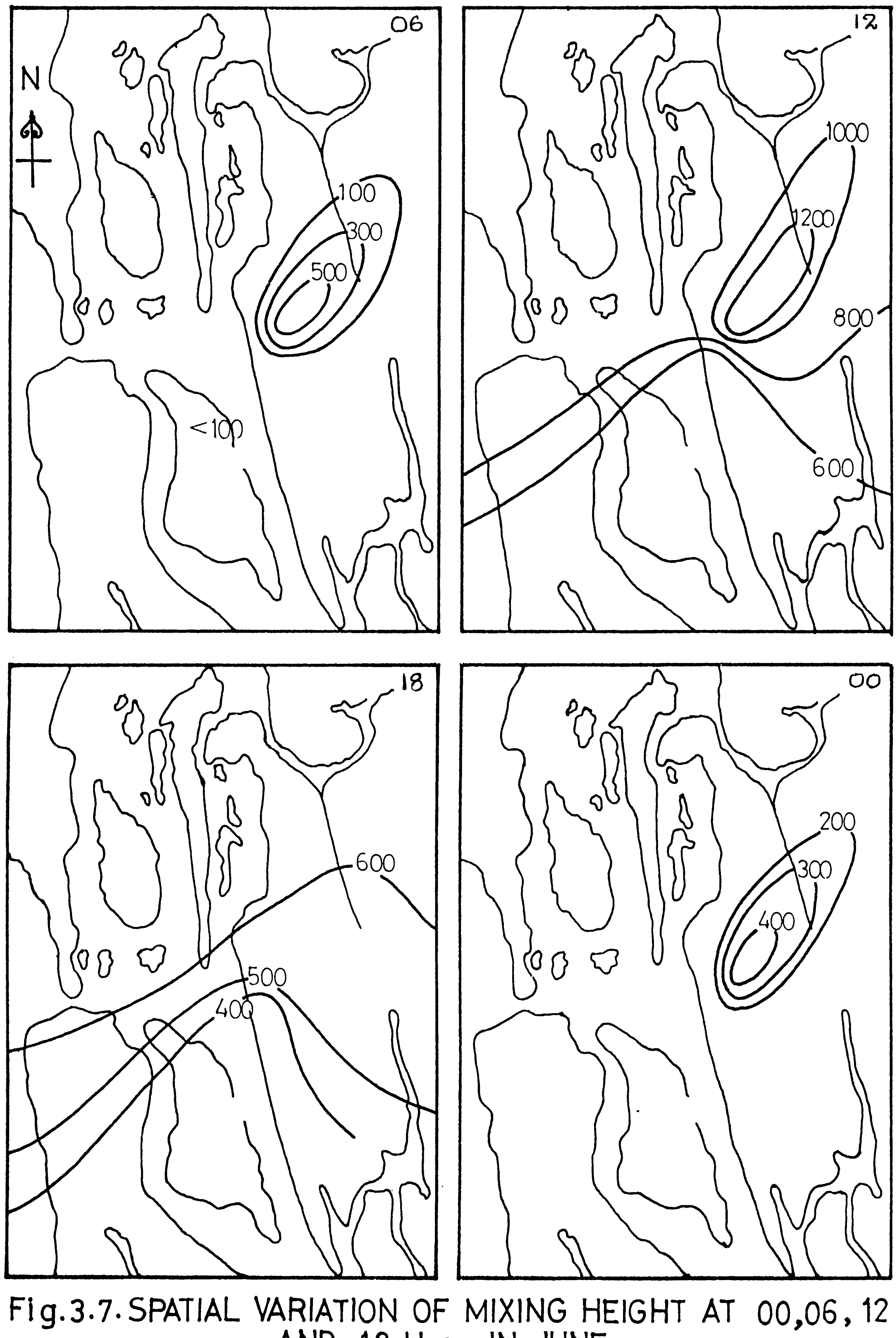


Fig.3.7. SPATIAL VARIATION OF MIXING HEIGHT AT 00,06, 12 AND 18 Hrs IN JUNE.
(Isopleths are in 200 m intervals at 12 and 06 hours)

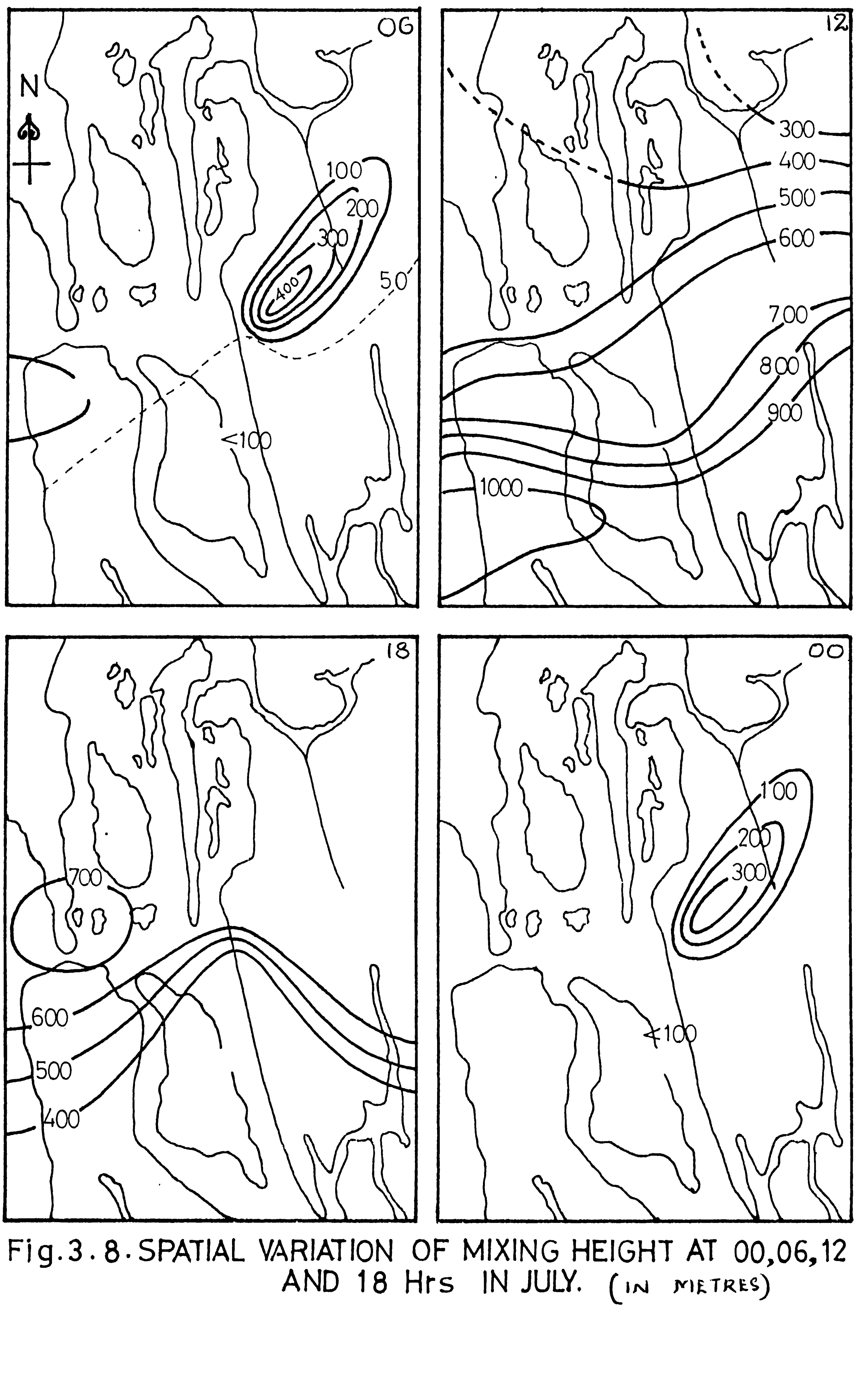


Fig.3.8. SPATIAL VARIATION OF MIXING HEIGHT AT 00,06,12 AND 18 Hrs IN JULY. (IN METRES)

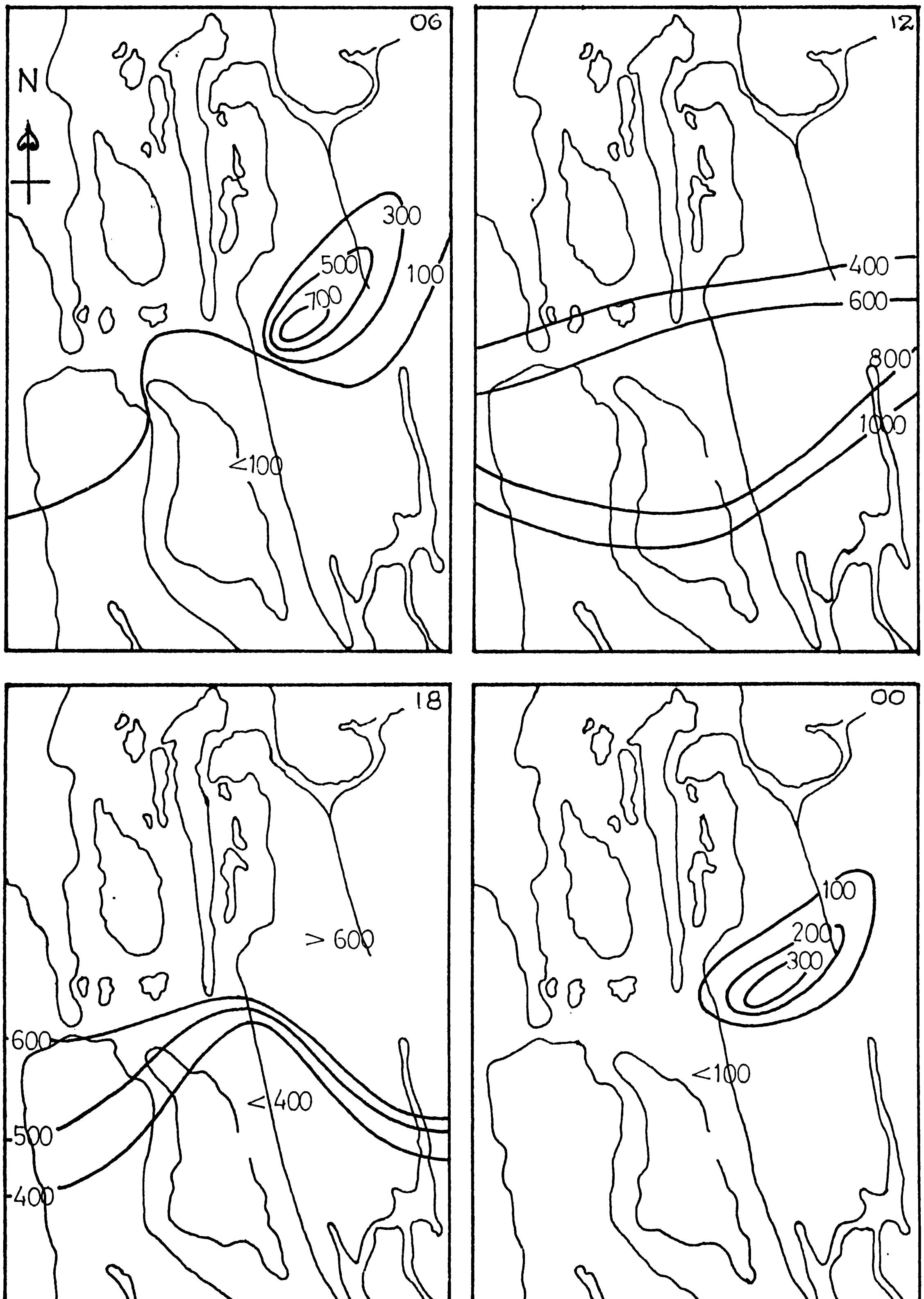


Fig. 3.9. SPATIAL VARIATION OF MIXING HEIGHT AT 00,06,12 AND 18 Hrs IN AUGUST.
(Isopleths are in 200 m intervals at 12 and 06 hours)

September

Relatively higher values at 12 and 18 hrs, same values at 24 hrs and relatively low values at 06 hrs are observed compared to those in August. The spatial range has attained maximum at 12 hrs followed by at 06, 24 and 18 hrs.

October

Maximum values are observed in the central parts at 06 and 24 hrs in southern parts at 12 hrs and the east west portions of the city. The spatial range has followed the same pattern as that in September.

November

While the maxima and minima are observed at the same places as that in October, the values have gone up relatively except at 06 hrs in this month compared to that in October. The spatial range once again followed the same pattern except for the fact that at 06 and 24 hrs it is the same.

December

Relatively higher values compared to that in

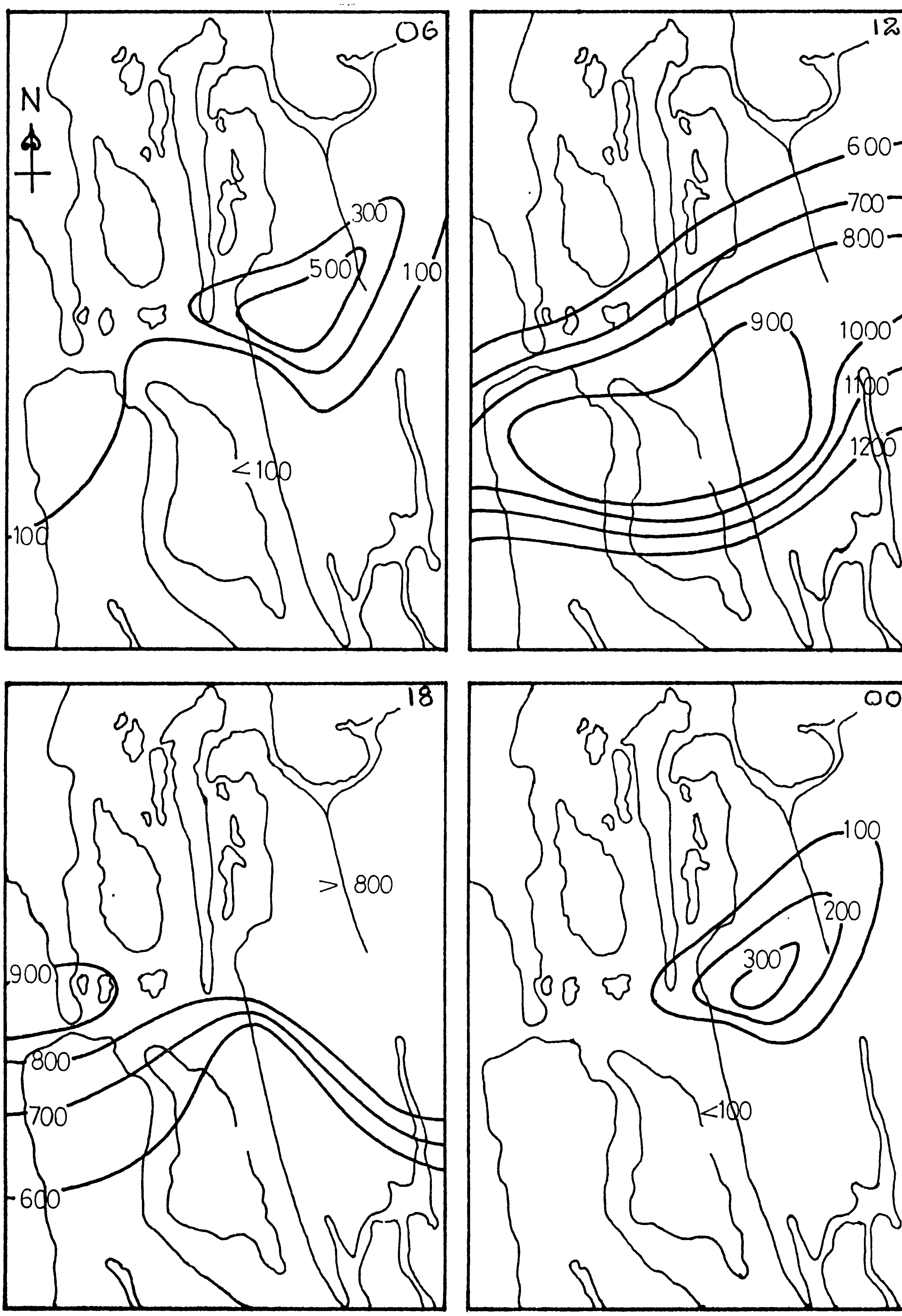


Fig. 3.10. SPATIAL VARIATION OF MIXING HEIGHT AT 00,06,12 AND 18 Hrs IN SEPTEMBER.
(Isopleths are in 200 m intervals at 06 hours)

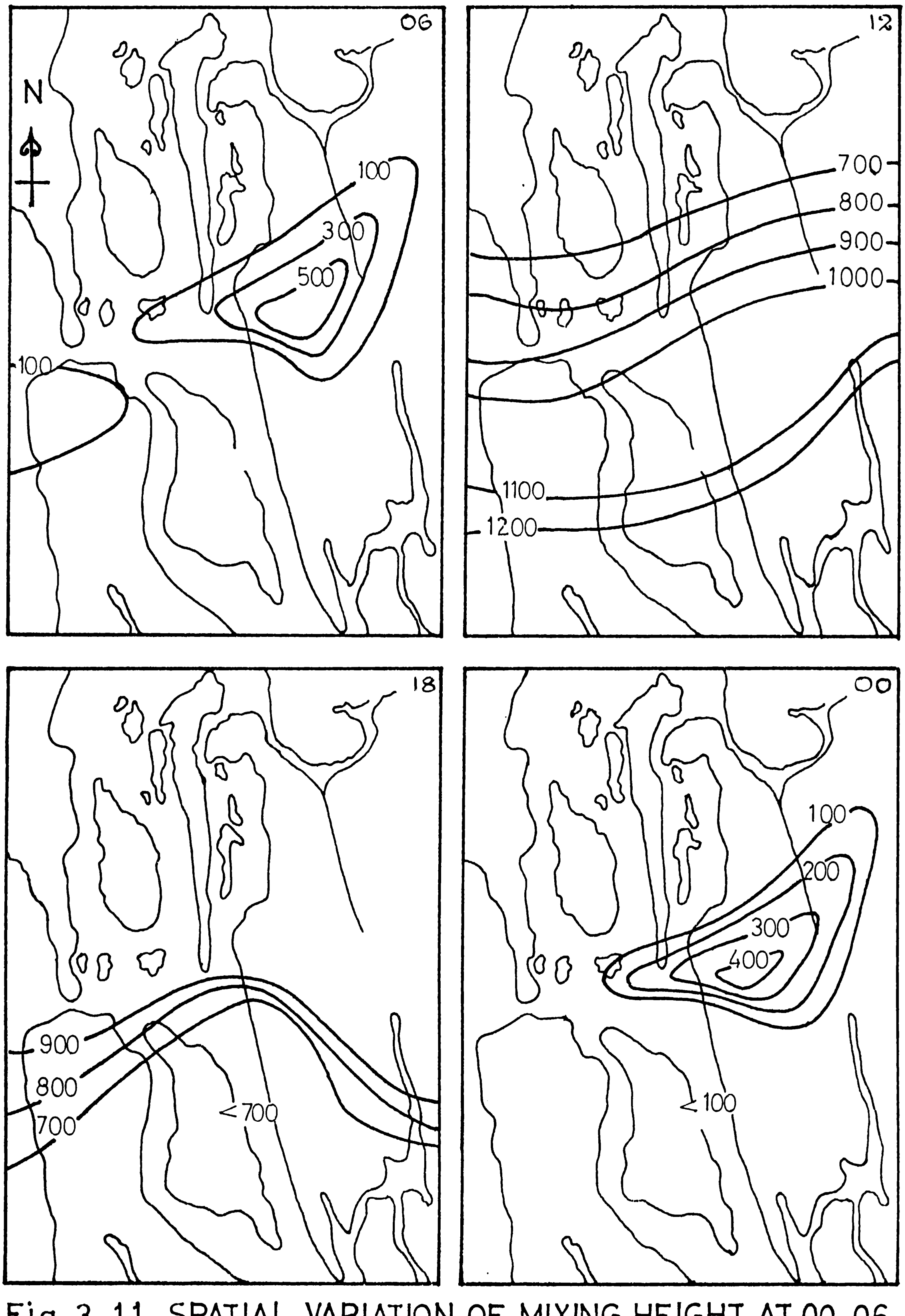


Fig.3.11. SPATIAL VARIATION OF MIXING HEIGHT AT 00,06, 12 AND 18 Hrs IN OCTOBER.
(Isopleths are in 200 m intervals at 06 hours)

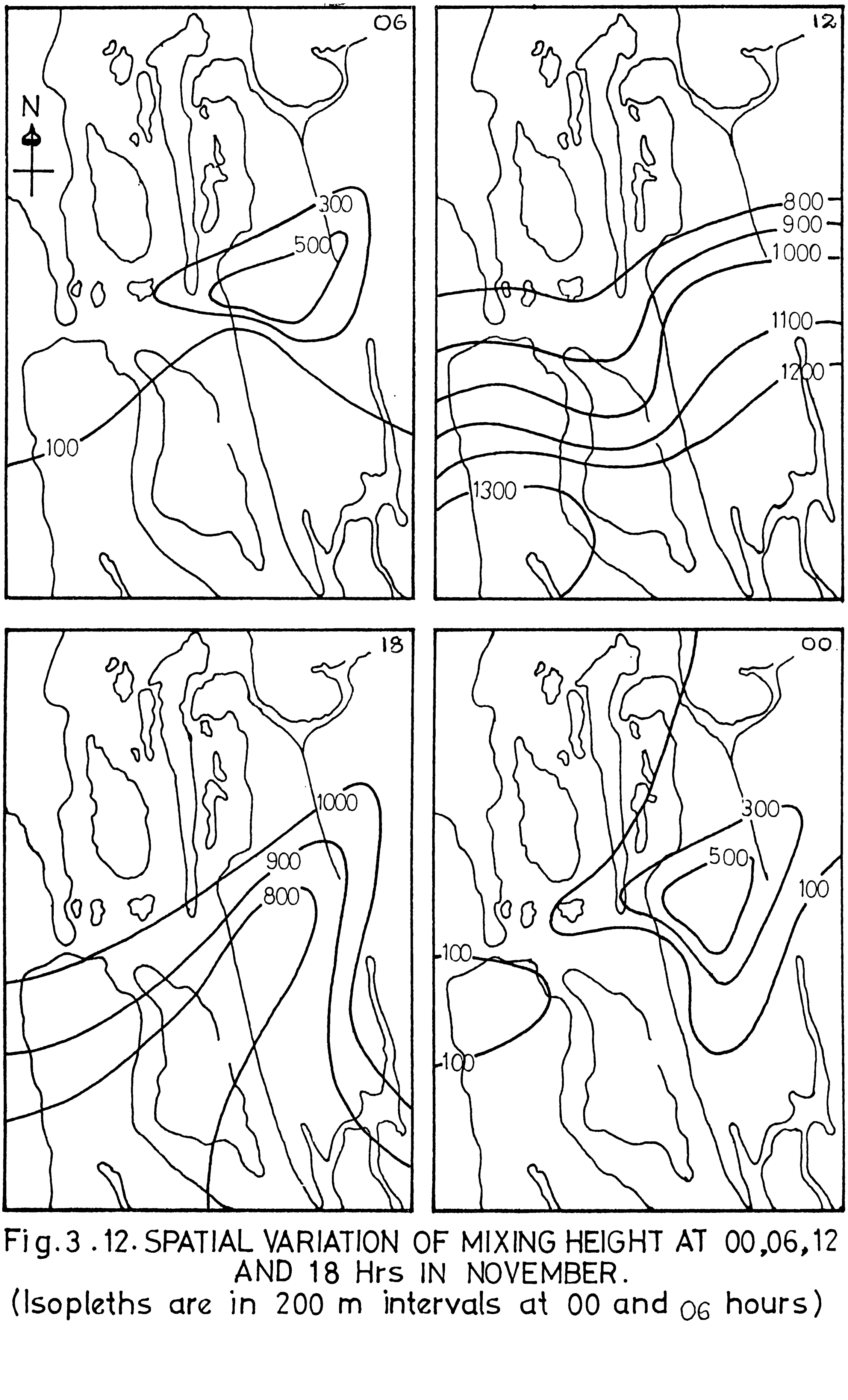


Fig.3 .12. SPATIAL VARIATION OF MIXING HEIGHT AT 00,06,12 AND 18 Hrs IN NOVEMBER.
(Isopleths are in 200 m intervals at 00 and 06 hours)

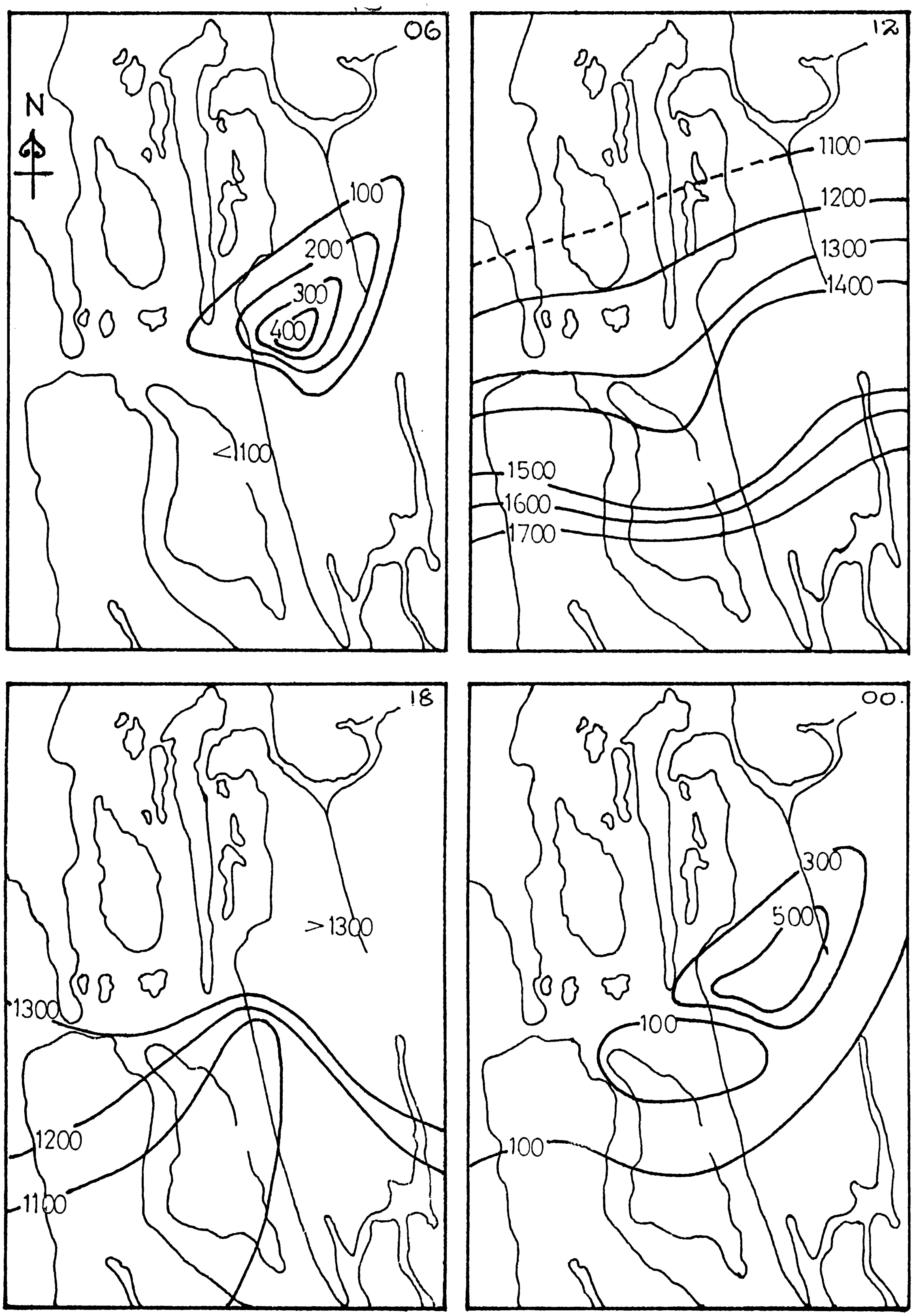


Fig. 3.13. SPATIAL VARIATION OF MIXING HEIGHT AT 00,06,12 AND 18 Hrs IN DECEMBER.
(Isopleths are in 200 m intervals at 00 hours)

November are observed on all the places at all the hours except at 06 when the values are low and at 24 hrs when they are the same. The range is maximum at 12 hrs followed by 24, 06 and 18 hrs.

The extreme southern portions are observed to have the least MH in almost all the months and all the timings except at 12 hrs. At 06 and 24 hrs, once again in all the months, the MH is less than 100 metres except near the central parts. The reason is that there is a prominent heat island near the Kacherippady junction. The enormous gradients in the central parts are also explained as due to the heat island at Kacherippady and a very low temperature recorded at Menaka junction which faces the sea. Viswanadham (1983) offered an explanation for such sharp difference in temperature between those two points which are very close by. The effect of sea is felt more at Menaka junction than at Kacherippady because of the former's direct exposure to sea as compared to the non-exposure of the latter because of the multistoried concrete buildings situated right on the coast obstructing the wind from and to sea. Since the MH follows the surface heat input the same explanation can be offered.

Another interesting feature is the wide variation of MHs spatially during day time. In other words the spatia range is maximum at 12 hrs. This brings out an important fact that there are wide variations of surface temperature even during day time. So if one wishes to compute the maximum MH a correction factor should be added to the maximum temperature. Holzworth's (1967) contention that the rural surface maximum and the urban maximum do not differ significantly is debatable as the present study has clearly shown the large variation of temperature within a city.

In the absence of the spatial distribution one gets the MH at only one point where the observations are recorded, which certainly can not represent the value for Cochin city. An average value of MH only, can be taken to be representative for the given city. There appears to be every possibility for the build up of air pollutants in the southern parts, especially during night time because of a very low mixing.

Southern portions of the city can perhaps be treated as suburban areas and are very close to the water bodies, which may explain the extremely low mixing during night time and relatively low mixing during day time. However, at 12 hrs the southwestern portions are showing higher values because in the Mattancherry area the effect of land is felt more because, the points of observations are in the midst of this huge island. The months of June through September are to be viewed with caution because of the possibility of the wash out of pollutants by the monsoonal rainfall.

Although the mixing is low in this months, the continuous rains with the scavenging effect overshadow the implications of low mixing.

3.2.2.2. Diurnal variation of MH

In view of the fact that the MH at a single point can not be a representative value for the whole city as explained in the section 3.2.2.1, the average of the MH at all the 9 points in the city is computed for every 3 hrs. The diurnal variation of such spatially averaged MH, hereafter referred to as Mean Mixing Height (MMH), for all the months is represented in Fig. 3.14. The figure also gives the average of MMH of all the hours and its standard deviation for each month.

In January, the minimum MMH is observed at 06 hrs and the maximum at 15 hrs. The mean value for the whole day is 697 metres with the standard deviation (S.D.) of 578 metres making the coefficient of variation more than 80%. There is a steep rise from 09 hrs to 15 hrs and a steep fall thereafter.

The diurnal range of MMH is of the order of little over 1500 metres.

In February, the minimum is observed at 06 hrs with a very steep rise from 09 hrs reaching a maximum at 12 hrs followed by a very gradual fall upto 18 hrs. The diurnal range is of the order of 1200 metres. The coefficient of variation is 77.8%.

In March, the pattern is in between that of January and February with a range of little over 1100 metres. The coefficient of variation has also come down to 70%.

In April, the range has further come down and the coefficient of variation has gone up little. The maximum is observed between 12 and 15 hrs and the distribution more or less resembles a normal distribution.

In May, a similar distribution is observed with a further lowering of the range with more or less the same coefficient of variation though the mean value is lower in this month compared to that in April.

In June, however, there is a sharp decrease of not only the range but also the mean value. The MH is more or less same upto 09 hrs followed by a very steep rise upto 12 hrs and a gradual fall thereafter.

In July not only the mean value but also the range attain the least. A primary peak at 15 hrs and a secondary peak at 03 hrs are observed. The coefficient of variation has also gone upto 90% nearly.

In August though the peak value is more or less same as that of July, the mean value has risen slightly. A gradual rise upto 09 hrs followed by a steep rise upto 12 hrs and a normal fall thereafter are the observed features. The coefficient of variations has come down to nearly 76%.

An increase of range and the mean value, the same coefficient of variation as in August are the features observed in September. From 09 hrs onwards it resembles the normal distribution with the peak at 15 hrs.

In October again a similar pattern with a consequent rise in the peak value and the range, is observed. The coefficient of variation is shot up again to 85%.

In November the peak value remained the same, but the mean has gone up with a reduction in the coefficient of variation. The range is also same,more or less.

In December, the peak as well as the range have shot up very steeply with a rise in coefficient of variation also. This variation resembles that of January.

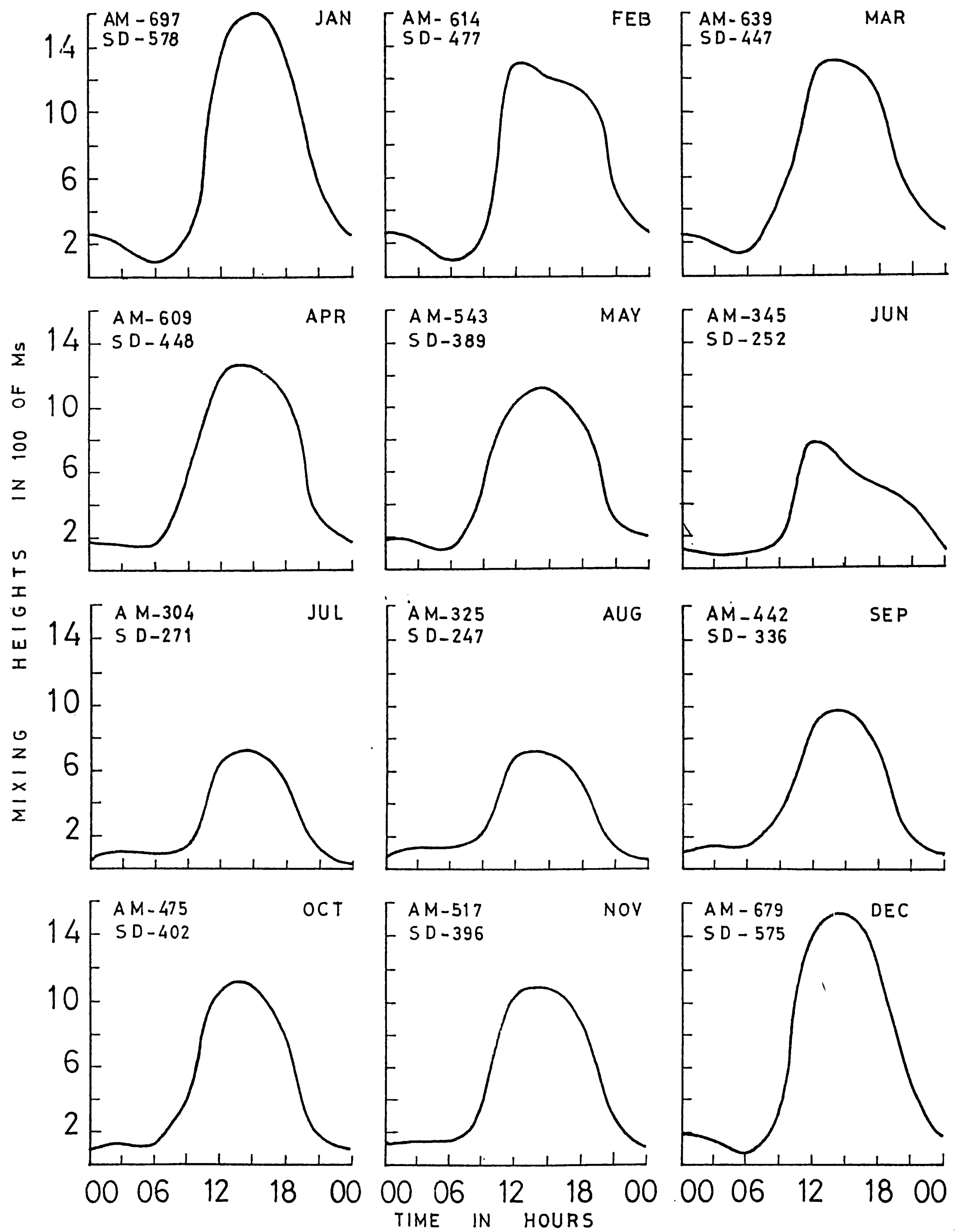


Fig. 3- 14. DIURNAL VARIATION OF MEAN MIXING HEIGHT FOR COCHIN.

Except in February an excellent and clearcut reduction of the mean values from January, which recorded the maximum, to July, which recorded the minimum followed by rise from July to December are observed. The mean temperature follows more or less a similar pattern which must be the reason for such a variation.

3.2.2.3. Monthly variation of MMH

The monthly variation of MMH for 00, 06, 12 and 18 hrs is depicted in Fig. 3.15. The variation is almost negligible at 00 and 06 hrs, though there are few undulations in the values. At 12 hrs and 18 hrs there are large variations. The values are decreasing from January to July and increasing from July onwards. At 18 hrs there is a sudden fall from January to February followed by more or less same value till April and a steep fall thereafter till June. It increased slightly from June to July and decreased slightly till August followed by a rise till November with a steep rise thereafter. At 06 hrs the peaks are in April, August and November though the variation is of the order of 100 metres only. As explained earlier, the lower temperatures in the monsoon season must be responsible for the low values in that season. The predominency of the variation at 12 and 18 hrs may be explained as due to the complete overcast conditions in the monsoon season which remarkably, reduce the surface

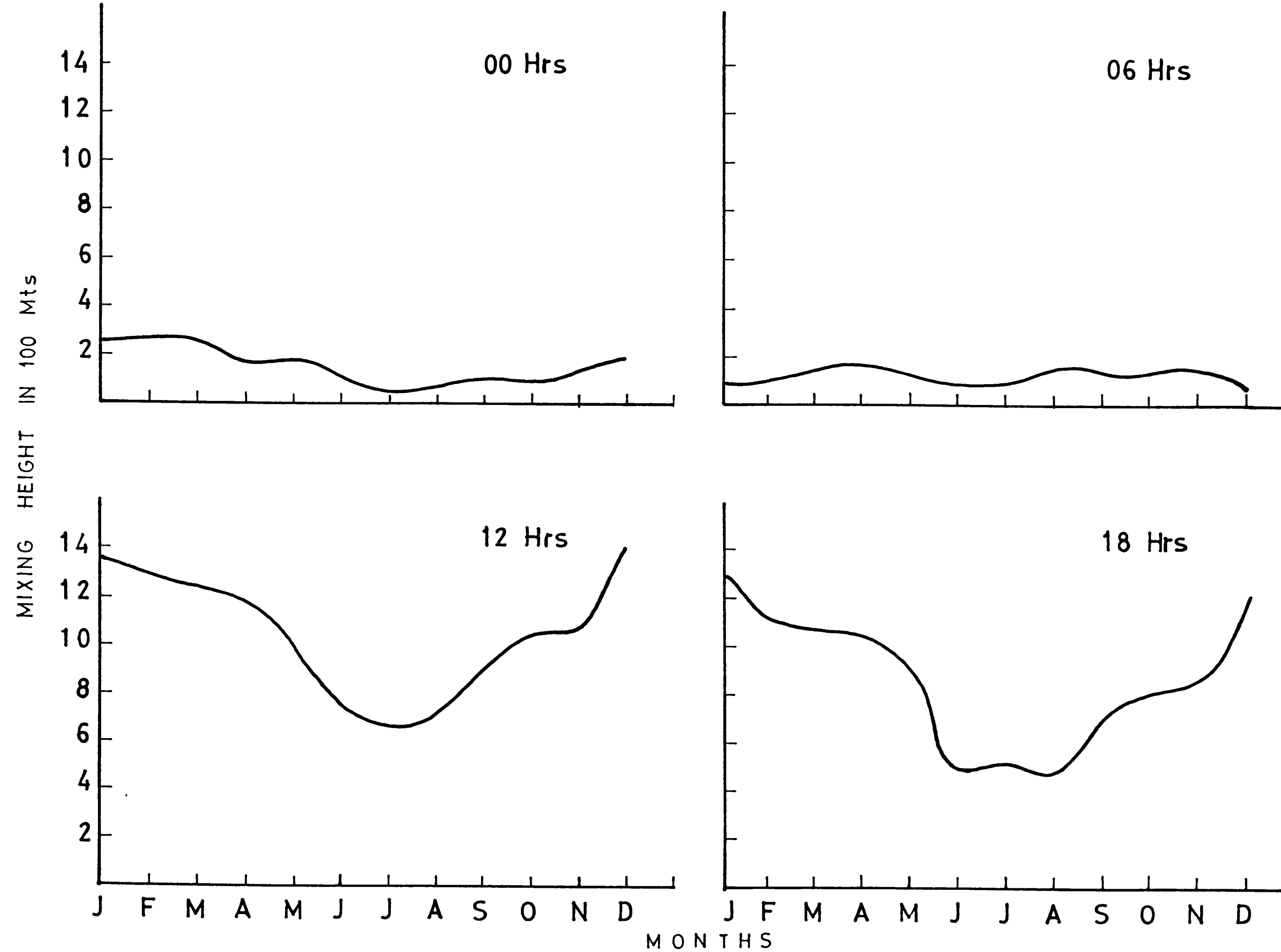


Fig. 3-15. MONTHLY VARIATION OF MEAN MIXING HEIGHTS FOR COCHIN AT 00,06,12 AND 18 Hrs.

temperatures during day time and increase the surface temperature during night time. With the latter effect the relatively higher values in the monsoon season at 06 hrs can be explained.

3.2.2.4. Yearly variation

The yearly variation is presented in Fig. 3.16 for the values at 06 and 15 hrs and for the daily mean MMH (DMMMH). The DMMMH is the mean of MMH at all the hours in the days for that particular month.

In January at 15 hrs the minimum is observed in 1975 and the maximum in 1982. The trend appears as though it is rising, though, the variation of the DMMMH shows an increasing trend to 1980 and decrease thereafter. There is no specific trend observed at 06 hrs.

In February, there is an increase from 1973 to 1975 and a decrease from 1975 to 1976 and a steep decrease between 1978 and 1979 at 15 hrs. Rapid increase from 1979 to 1980 followed by a fall thereafter is also observed at 15 hrs. There is no specific trend observed though it is found to oscillate about a MH of 1200 metres. The DMMMH and the variation at 06 hrs are also not showing any specific trends. However, the maximum values for all the three cases are recorded in 1980.

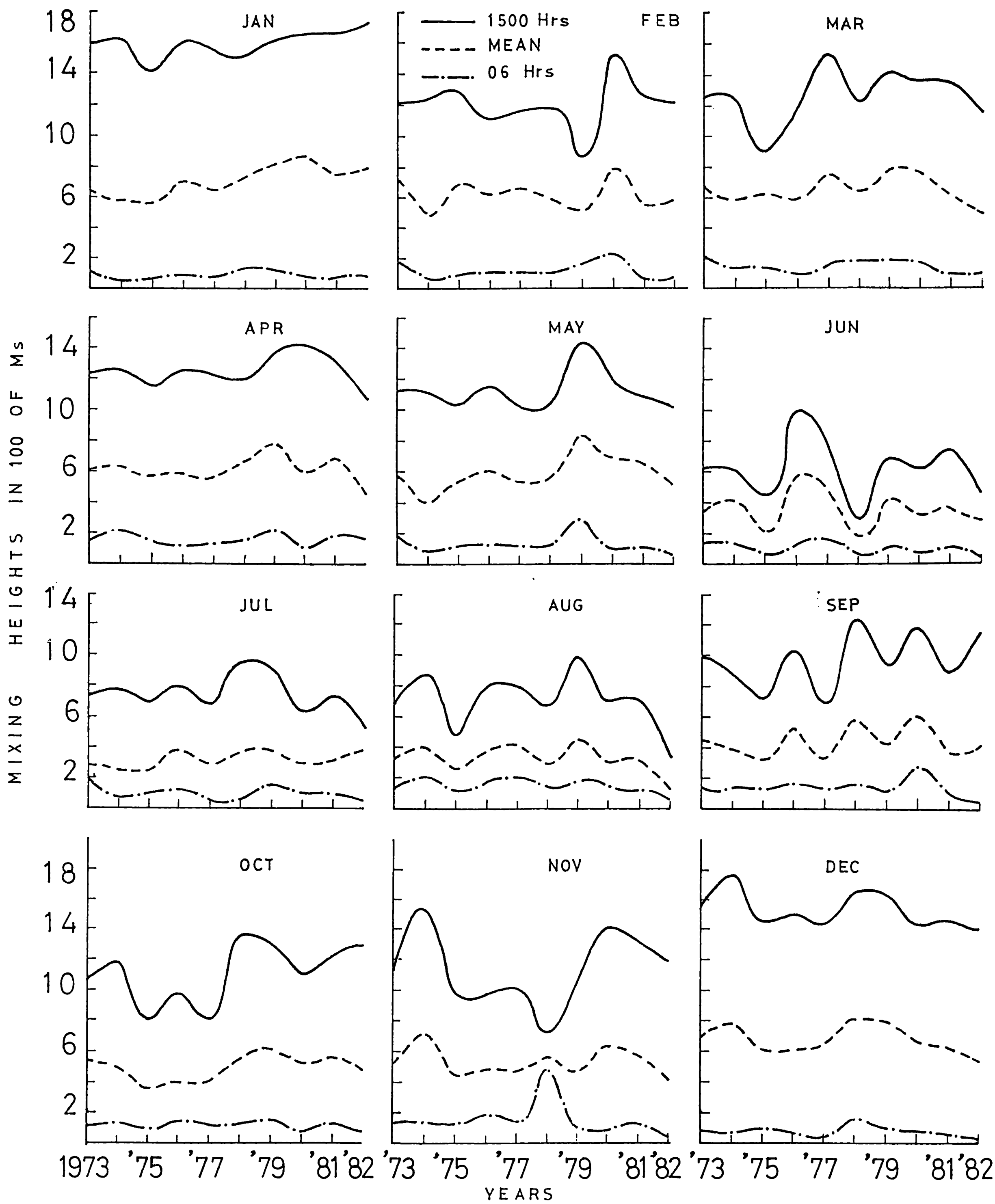


Fig. 3-16. YEARLY VARIATION OF MIXING HEIGHTS IN DIFFERENT MONTHS FOR COCHIN.

In March the minimum and maximum are observed in 1975 and 1977 respectively at 15 hrs. The DMMMH and MMH at 15 hrs are showing a slight rise in trend till 1979 and a decrease in the same thereafter. The MMH at 06 hrs shows a decreasing trend till 1976 and a slight increase till 1977 with more or less the same value till 1980 followed by a decreasing trend thereafter.

In April the amplitude of the variation appears to be increasing at 15 hrs. For the DMMMH the maximum at 15 hrs and at 06 hrs is observed in 1980 and in 1979 respectively. There are two peaks in the case of MMH at 06 hrs, namely, 1974 and 1979.

In May the amplitude of the variation is increasing in all the three cases. There is an increasing trend in DMMMH till 1979 and a decrease thereafter. The maximum in all the three cases is observed in 1979.

In June, the amplitude of variation is decreasing in all the three cases. There is neither an increase nor a decrease in trend in any of the cases. The maximum is observed in 1976 and the minimum in 1978 once again in all the cases. All the 3 curves are showing more or less same pattern.

A slight decrease in trend at 15 hrs and a slight increase in trend for DMMMH are noticed in July. While, no specific trend is noticed at 06 hrs. The peak values occurred in 1978 and 1979.

Though the trend is more or less unchanged till 1979, there is a clear decreasing trend from then onwards in all the three cases in August. 1979 showed once again the maximum values in all the cases.

A clear cut rise in trend at 15 hrs is the prominent feature in September while, the DMMMH and MMH at 06 hrs have no specific trend. The maximum occurred in 1978 for MMH at 15 hrs and in 1980 for both at 06 hrs.

A similar increase in trend both for MMH at 15 hrs and for DMMMH is observed in October. The maximum is observed at 15 hrs in 1978 and 1979 for DMMMH and for MMH at 06 hrs.

Two prominent peaks at 15 hrs and for DMMMH and a single prominent peak at 06 hrs are the stricking features in November. The two peaks for MMH at 15 hrs and for DMMMH are in 1974 and 1980, while the single peak of MMH at 06 hrs is in 1978 when the minimum MMH at 15 hrs is recorded.

In December there is a decreasing trend for the MMH at 16 hrs as well as for the DMMMH while no specific trend was noticed at 06 hrs. The maximum MMH at 15 hrs is observed in 1974 while the maxima for DMMH and for MMH at 06 hrs is in 1978 when the secondary maximum of MMH at 15 hrs is also noticed.

Barring a few cases the maximum MMH are noticed in the period between 1978 and 1980. To know the actual variations the standard deviation and the coefficient of variation at 15 hrs and at 06 hrs are given in Table 3.2 which shows that in general the coefficient of variation is more at 06 hrs (the value was never below 25%) than that at 15 hrs (the values was never above 31%). The ranges of MMH are well marked in March, June, September, October and November at 15 hrs. While at 06 hrs they are not well marked except in November though the coefficient of variation is more at 06 hrs.

A comparison of the MH of Cochin with other coastal stations is made. The MH for Bombay, Madras, Trivandrum, Visakhapatnam were computed by Viswanadham (1980). Bombay recorded lower values in January and April compared to that for Cochin while showed the same values for August and October as far as the maximum MH is concerned. The minimum MH in Cochin are always less than 200 metres compared

Table 3.2

Standard deviation and coefficient of variation of yearly variation of MH for various months for Cochin

Month	Standard deviation		Coefficient of variation in %	
	06 hrs	15 hrs	06 hrs	15 hrs
January	26.6	84.5	33.0	5.0
February	53.7	156.0	51.0	13.0
March	38.2	169.0	25.5	13.3
April	41.6	95.8	26.0	7.7
May	62.2	118.8	49.3	10.6
June	36.6	190.0	35.4	30.2
July	43.4	121.3	44.7	16.3
August	40.2	177.6	27.3	25.3
September	36.3	180.9	26.3	18.7
October	29.4	187.0	26.0	16.9
November	117.0	229.6	74.0	20.3
December	41.3	116.8	51.1	7.6

to little higher values in Bombay, Madras, Trivandrum and Visakhapatnam. It is reported (Viswanadham, 1980) that the diurnal range of MH is small for coastal stations compared to that of inland stations and the range was found to be maximum in April for the inland station. However, the diurnal range of MH in December through March resembles that of an inland station to have a very high range. The only comparable coastal station in this respect is Madras which showed the maximum range range among the coastal stations (Vittal Murty et al., 1980). Another interesting deviation is that maximum mixing in Cochin is observed in January as compared to the same for other coastal station. Bombay and Trivandrum have shown similar trends to that of Cochin. The values decreased from January to August and Increased thereafter. In general the values are comparable to those in other coastal stations.

3.2.3. Ventilation coefficients

For computing VC the MMH and the surface wind speed are used. In order to have uniformity for the purpose of comparison the surface wind alone is used since the vertical structure of wind is available only twice a day. Hence the VC presented here may underestimate the actual value. The diurnal and the monthly variation of VC for Cochin is presented here.

3.2.3.1. Diurnal variation of VC

The diurnal variation of VC for each month is presented in Fig. 3.17. The diurnal variation follows the same pattern as that of MMH in January. The maximum occurred at 15 hrs and the minimum at 06 hrs. There is a steep increase from 09 to 15 hrs followed by a steep fall, the peak value being 4567 m^2/s. The coefficient of variation is more than 100%.

The pattern slightly differs from that of MMH in February. The maximum value is observed at 15 hrs as compared to the maximum of MMH at 12 hrs. On either side of the peak there is a steep change unlike in the case of MMH. The coefficient of variation is more than 100%.

In March, once again the variation is similar to that of MMH with the peak occurrence at 15 hrs and minimum at 06 hrs and the steep changes on either side of the peak. Once again the coefficient of variation exceeded 100% with the daily mean value exceeding that of February.

In April also, a similar pattern is observed with peak occurring at 15 hrs, minimum at 06 hrs, steep changes on either side and the coefficient of variation exceeding 100%. The daily mean value exceeded that of March.

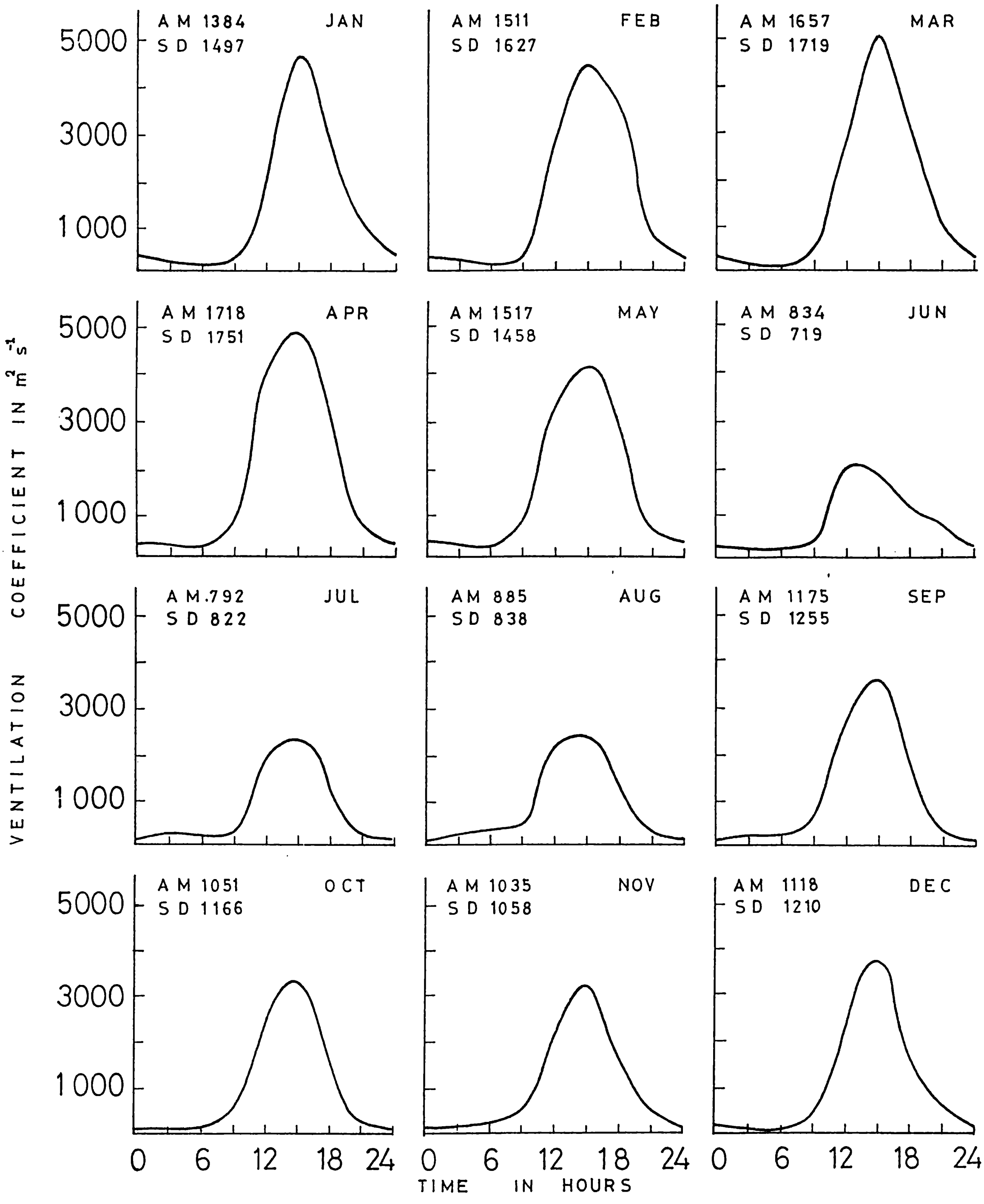


Fig. 3-17. DIURNAL VARIATION OF VENTILATION COEFFICIENTS FOR COCHIN.

In May, similar variation is observed as that of April excepting that the peak value is lower and the coefficient of variation is less than 100%.

In June, however, there is a sharp change in that the absolute values have come down by half of what is observed in May. The range of VC is also reduced considerably with the coefficient of variation attaining its lowest value of 86%. The maximum occurred at 12 hrs. The rise to the peak is steeper than the fall from the peak.

In July, situation similar to that of June is observed excepting that peak is observed at 15 hrs, the coefficient of variation exceeded 100% and the normal distribution on either side of the peak is observed. The daily mean has attained its lowest value of 792 m^2/s though the peak value is slightly higher than that in June.

In August, there is a gradual increase from 00 hrs to 09 hrs and a steep rise at 12 hrs, followed, once again, by gradual rise to 15 hrs with a steep fall thereafter till 21 hrs. The coefficient of variation is slightly less than 100%. The daily mean as well as the peak value have gone up slightly than compared to those in July.

In September, once again, a sharp change is noticed. The peak is observed at 15 hrs with a steep change on either side. The daily mean value is shot up while, the coefficient of variation exceeded 100%. The diurnal range also has gone up compared to that in August.

In October, however, the daily mean and the diurnal range have come down compared to that in September. Although the coefficient of variation exceeded 100%. The peak is lower than that in September.

In November, exactly similar variation is noticed on all accounts, excepting that the daily mean and the peak are slightly lower than those in October.

In December, however, the diurnal range and the peak value have gone up from that of November. The coefficient of variation has exceeded 100%. The daily mean also has gone up. The peak is observed at 15 hrs and the minimum at 06 hrs.

In all, the diurnal variation is well marked with the coefficient of variation exceeding 100% in most of the cases which shows the pronounced diurnal variation of wind speed also. The daily means have in general increased from January to April, July to September and from November to December and decreased from April to July and from September

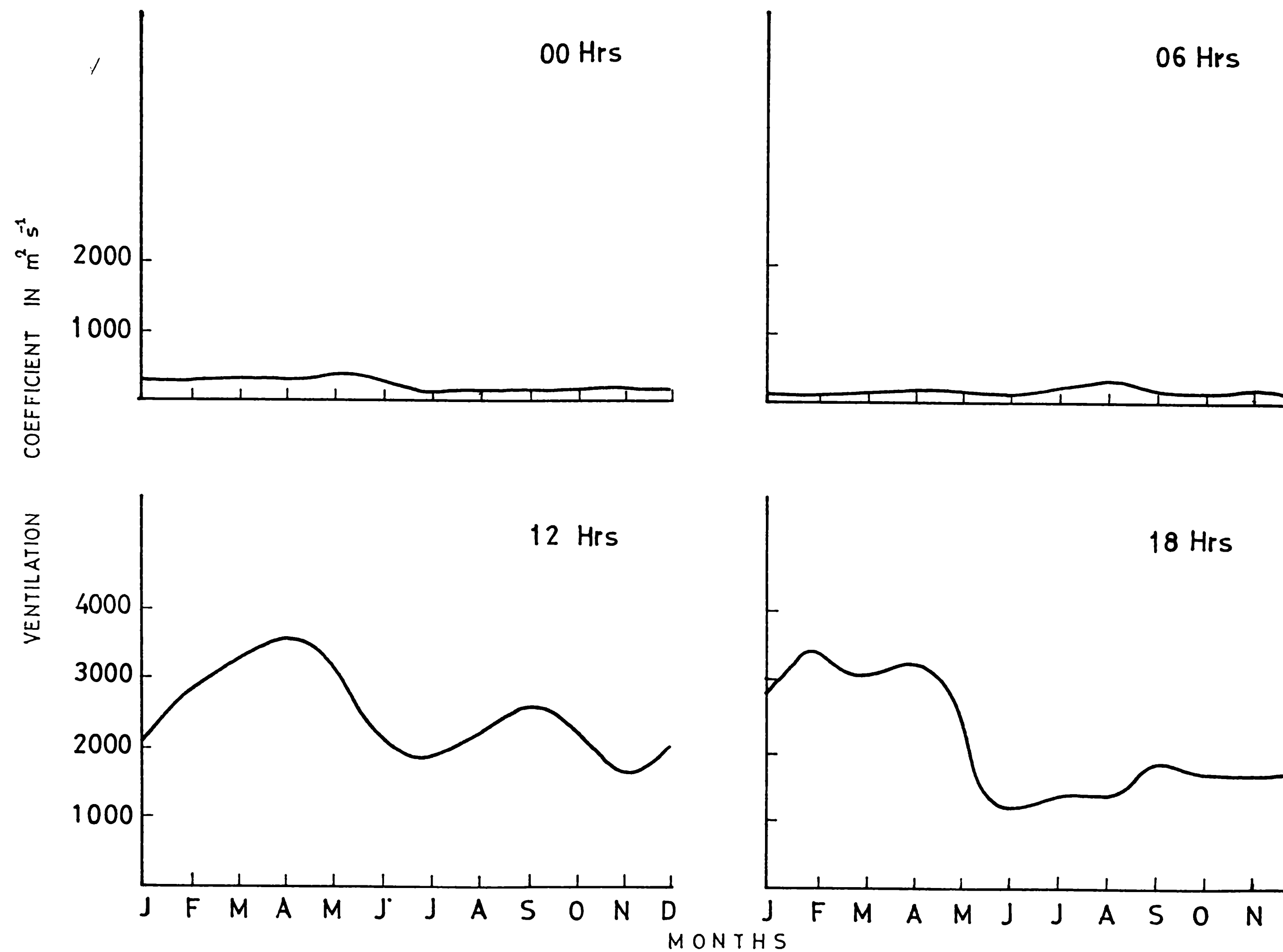


Fig. 3-18. MONTHLY VARIATION OF VENTILATION COEFFICIENTS AT 00, 06,12 AND 18 Hrs.

to November. The peak values also showed more or less the same trend except in February. Another interesting feature of this diurnal variation is that the maximum always occurred at 15 hrs. except in June, when it is observed at 12 hrs. The high values from January to May are attributed due to large MH and strong winds. However, from June to September comprising of the monsoon season, the VCs are considerably lower mostly because of very low mixing in this season despite equally strong winds compared to those in March and April.

As it is, never did the value of VC exceed 6000 m^2/s, a minimum value suggested by Environmental Protection Agency for a fairly good dispersal of pollutants (Holzworth, 1972). However, it should be noted that the wind variation in the vertical (normally increases with height) has not been taken into consideration which would certainly under estimate the values presented here as already mentioned in the beginning of this section. The winds on the other hand are not very strong enough to change a low mixing to a high VC.

3.2.3.2. Monthly variation

The monthly variation of VC at 00, 06, 12 and 18 hrs is depicted in Fig. 3.18. The monthly variation is not well marked at 00, and 06 hrs while, considerable variation is observed at 12 and 18 hrs. At 12 hrs it increases from

January to April, July to September and November to December and decrease from April to July and September to November. It differed significantly from the variation of MMH. At 18 hrs the values are high till May and low from June to December. The maximum is observed in February the secondary peak in April. This also differs significantly from the variation of MMH. This shows the influence of wind on the variation of VC.

A comparison of VC for Cochin with those for other stations is made. The VC computed by Vittal Murty et al (1980) for 11 Indian stations are compared with those computed for Cochin. The afternoon VCs (AVC) are more than 6000 m^2/s for the coastal stations, Madras, Trivandrum and Visakhapatnam while, Bombay showed values below 6000 m^2/s. The values of Bombay are comparable with those of Cochin though the trends are entirely different. In Bombay the AVC increased from January to August and decreased thereafter. Whereas in Cochin the values increased from January to April and decreased considerably and is minimum in August and increased thereafter. The winds appear to be stronger in Madras, Trivandrum and Visakhapatnam compared to that in Cochin which must be one of the reasons for a lower VC in the latter. The maximum AVC is observed in August for all the coastal stations according to Viswanadham (1980) whereas, it is minimum in August in Cochin. The reason is the stronger winds at those places in August as compared to those in Cochin and also due to the very low mixing in August in Cochin. Another fact which should be borne in mind is that the VCs are computed for only two times a day by Viswanadham (1980) and as such the vertical variation of wind was also considered. Hence the values may be relatively higher in those stations. As already mentioned the present values for Cochin are under estimates.

3.2.4. Wind climatology

The frequency tables of wind are prepared for every hour for each month for the period under study. The speed intervals are 1-5, 6-10, 11-20, 21-30 and >30 kmph. Speeds <1 kmph are included in the calm conditions and their frequency is also computed. From the tables the wind roses are drawn for every 3 hrs namely 00, 03, 06, 09, 12, 15, 18 and 21 hrs IST. The diurnal variation of the percent frequency of occurrence of each of the 16 wind directions has also been studied for the 4 typical months, namely, January, April, July and October representative for the seasons, winter, premonsoon, monsoon, post-monsoon respectively.

3.2.4.1. Wind roses

The 3 hourly wind roses are drawn for all the months and depicted in the figures from 3.19 to 3.30 for the 12 months from January to December respectively.

January (Fig. 3.19)

The calm frequency is very high in this month starting from 21 hrs with 68.3% to 12 hrs with 41.6%. Maximum calm is observed at 00 hrs, the value being 84.4% followed by 03 hrs with 69.4%, 06 hrs with 64.5% and 09 hrs with 64.0%. From 03 hrs onwards NE starts increasing reaching a maximum at 09 hrs. At 12 hrs the winds are relatively stronger but are almost uniformly distributed in all directions. Suddenly from 15 hrs one could see the predominant winds from the SW sector with the strongest winds of the day. At 18 hrs the predominancy of winds from SW sector continued, though less vigorously, and the winds are less strong. The reversal of wind direction from night time to day time is very much evident with the transition taking place after 09 hrs and after 21 hrs.

February (Fig. 3.20)

Almost similar conditions as in January are prevailing in this month. At 00hr, though 75.6% is calm,

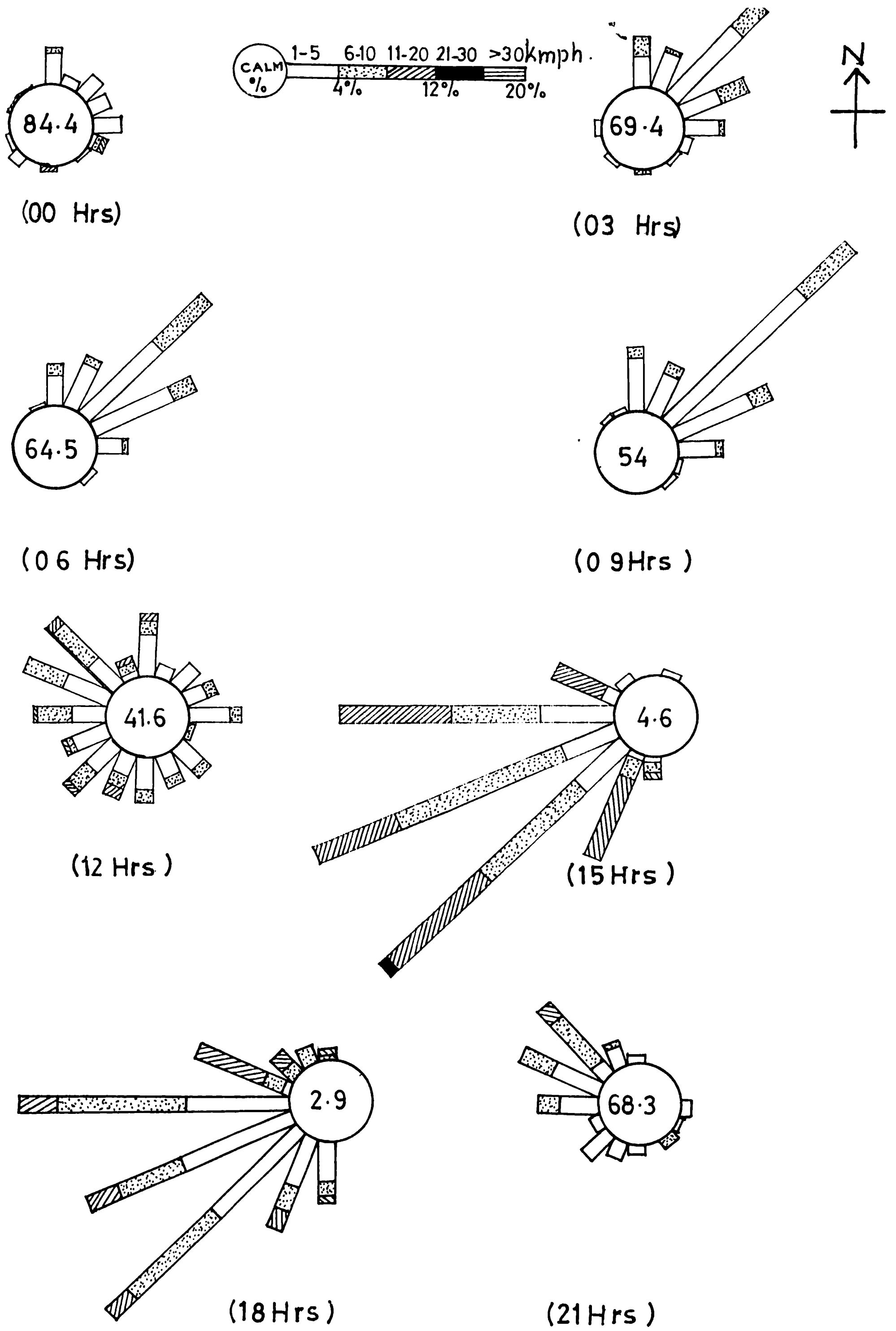


FIG.3 19.WIND ROSES OVER COCHIN FOR JANUARY.

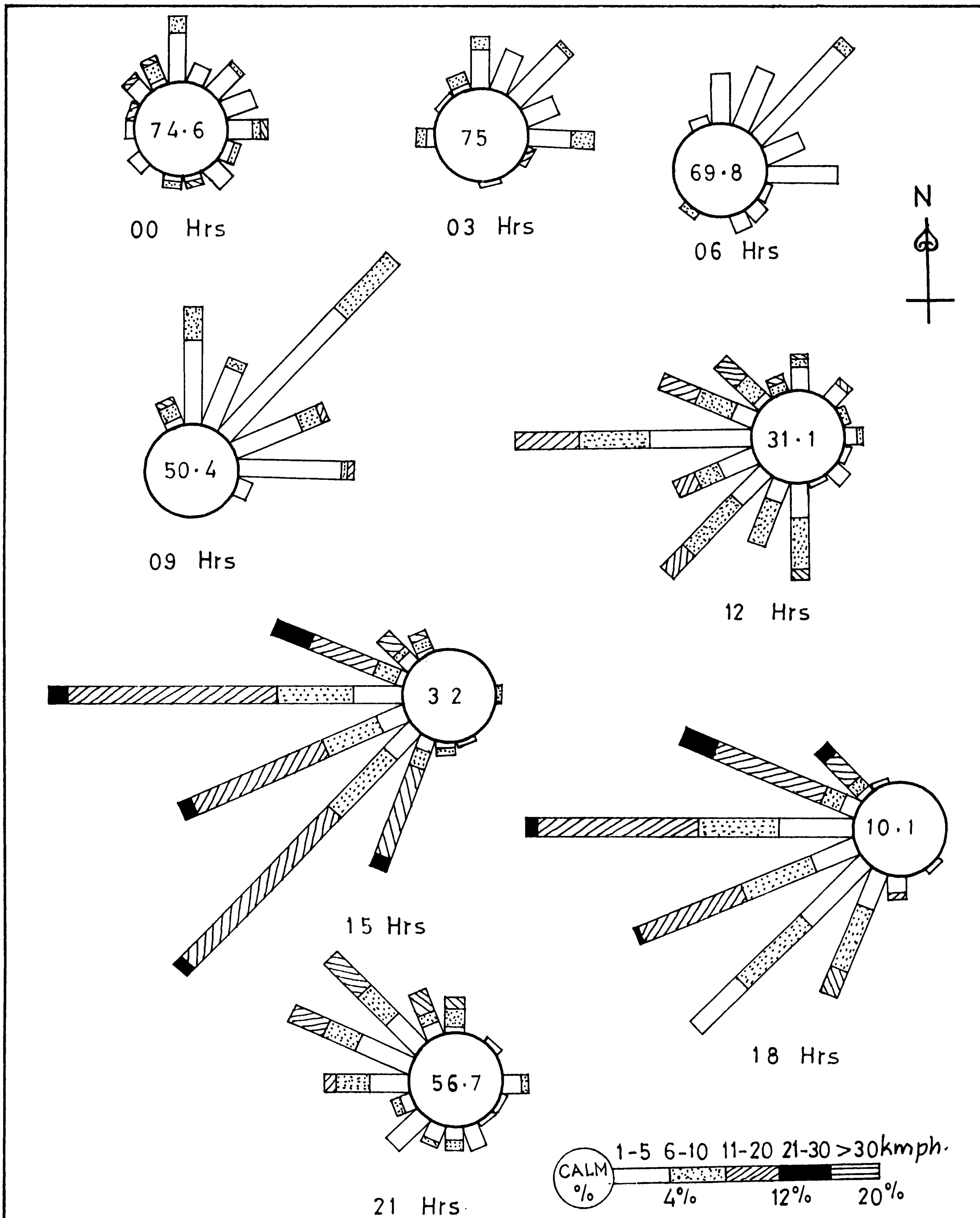


FIG. 3.20. WIND ROSES OVER COCHIN FOR FEBRUARY.

the winds are relatively stronger compared to those in January at the same time. There is a slight N wind turning gradually from N to NE and reaching maximum at 09 hrs. At 12 hrs W, SW and NW are predominant and the same are maximum at 15 hrs with the strongest winds of the day and minimum calm frequency which continued even at 18 hrs but with relatively less strong winds. At 21 hrs one can still see the NW components with considerable wind speed which turns to N at 00 hrs. The calm has decreased from 03 hrs to 15 hrs and increased thereafter. The reversal of winds from night to day time and relatively stronger winds both during night and day time compared to those in January are the features to be noted. The predominancy of westerlies started from 12 hrs as compared to 15 hrs in January. A sudden transition from 09 to 12 hrs is the notable feature.

March (Fig. 3.21)

The wind is equally distributed from W through N to NE at 00 hrs. The northerly and the northeasterly winds are predominant at 03 and 06 and 09 hrs. From 09 to 12 hrs the winds have become W, SW and NW. At 15 hrs the winds are the strongest and are W, SW and NNW. More or less the same frequency distribution but with weak winds relatively, are observed at 18 hrs. The winds at 21 hrs

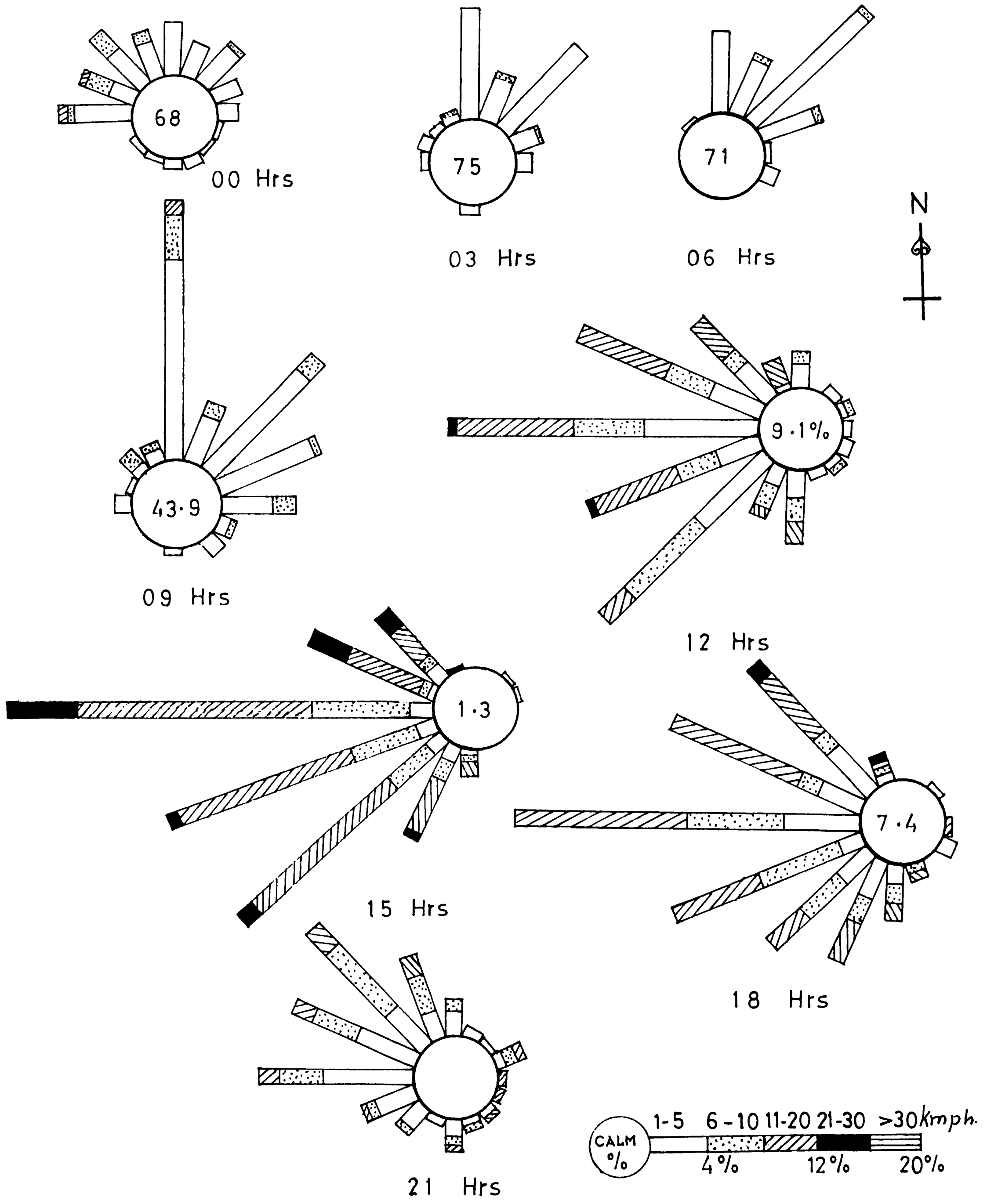


FIG. 3.21. WIND ROSES OVER COCHIN FOR MARCH.

are from NW sector. The calm frequency once again is more than 50% during night time with a maximum at 03 hrs and decreasing thereafter to 15 hrs. The same increases from 15 hrs onwards to 03 hrs. NE during night time and W and SW during day time are the prominent features.

April (Fig. 3.22)

The situation in this month is slightly different from those observed earlier and that there is no predominancy of NE winds during night time. At 00 hrs the winds are from E and W. N wind prevails slightly at 03 and reaches maximum at 09 hrs. At 12 hrs one can see the W dominating with components from SW and NNW sectors. The same situation with the strongest winds of the day are noticed at 15 hrs. At 18 hrs the W continue to dominate. The winds from W and NW are still in considerable frequency at 21 hrs. The calm frequency is maximum at 06 hrs reaching a minimum at 15 hrs and increasing upto 06 hrs.

May (Fig. 3.23)

Winds are almost uniformly distributed from 00 to 06 hrs. At 09 hrs N and E are dominating though the wind has considerable frequency in other directions. The WSW wind, though very small in frequency appears to have stronger winds at this hour. At 12, 15 and 18 hrs

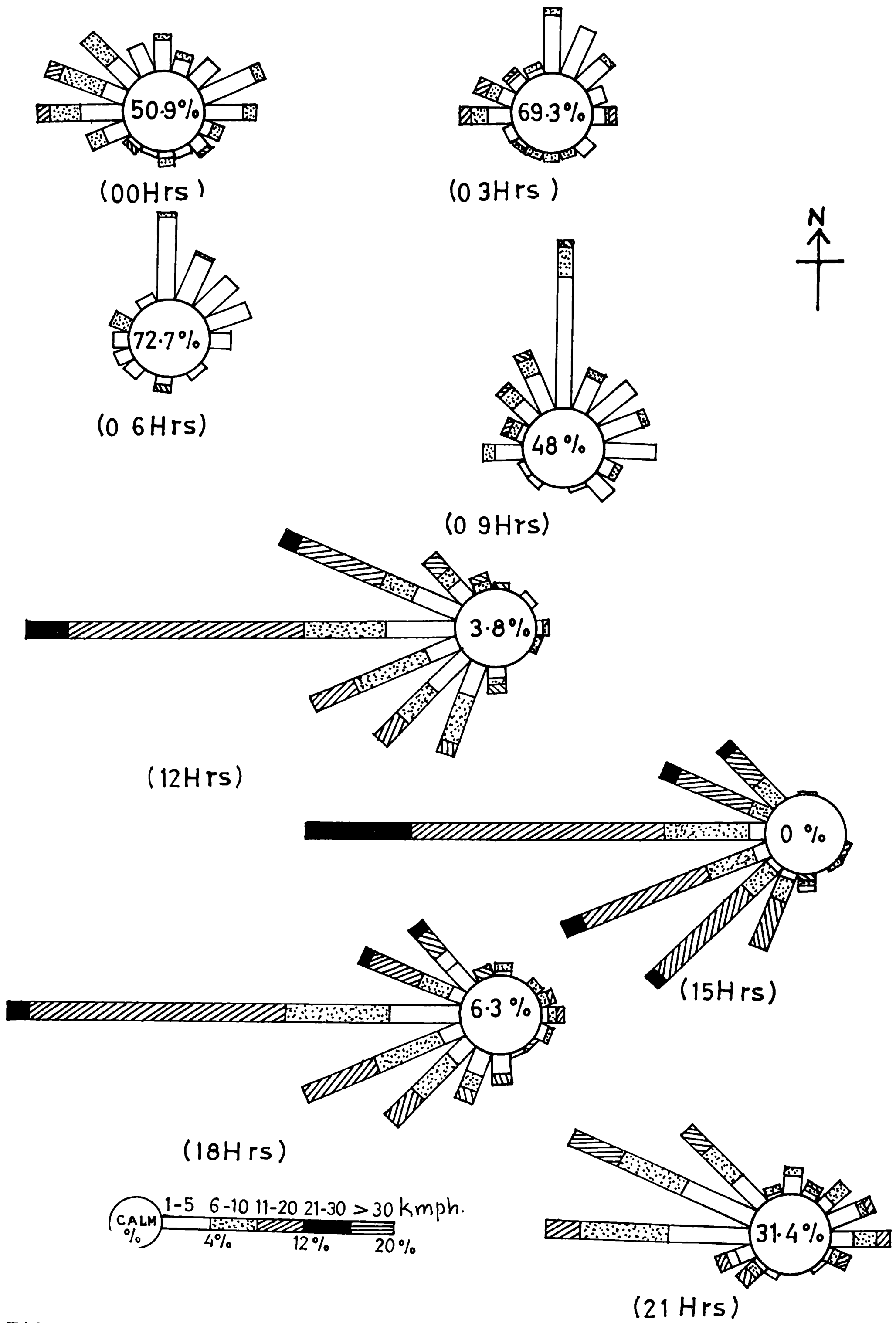


FIG.3 22 WIND ROSES OVER COCHIN FOR APRIL

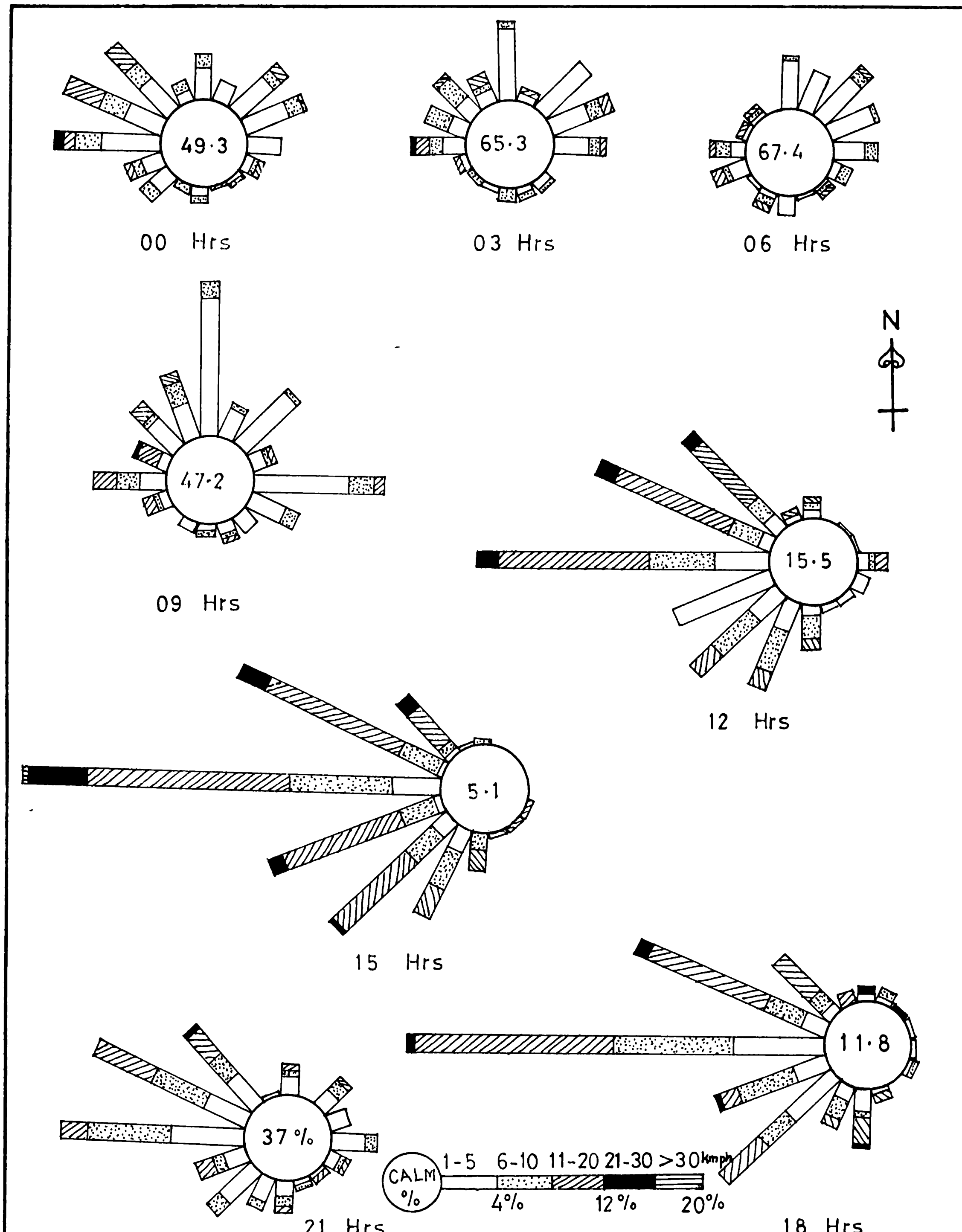


FIG. 3·23. WIND ROSES OVER COCHIN FOR MAY.

the winds are W, NW and SW. At 21 hrs the winds from WNW sector are dominating. The winds from W, whenever they occur, appear to be stronger than those from other directions. The calm frequency is once again maximum at 06 hrs but with the less value than that in April is observed and the same trend followed.

June (Fig. 3.24)

Irrespective of the day and night, the winds appear to be stronger always compared to those in the previous months. From 00 to 09 hrs the winds are from all the major directions excepting SE sector. At 12 hrs the domination of W wind can be seen though there is considerable frequency of winds from NW and SW sectors also. A similar situation is prevailing at 15 and 18 hrs. At 21 hrs again the wind is uniformly distributed with a slightly higher frequency for W. The calm frequency is maximum at 06 hrs with 60.2% and decreases upto 15 hrs and increases thereafter upto 00 hrs. From 00 to 03 hrs it again decreases.

July (Fig. 3.25)

Similar conditions as in June are noticed in this month with the wind distributed almost in all the directions during night time. The winds from 12 to 18 hrs are completely from SW, W and NW sectors. It may be noted here

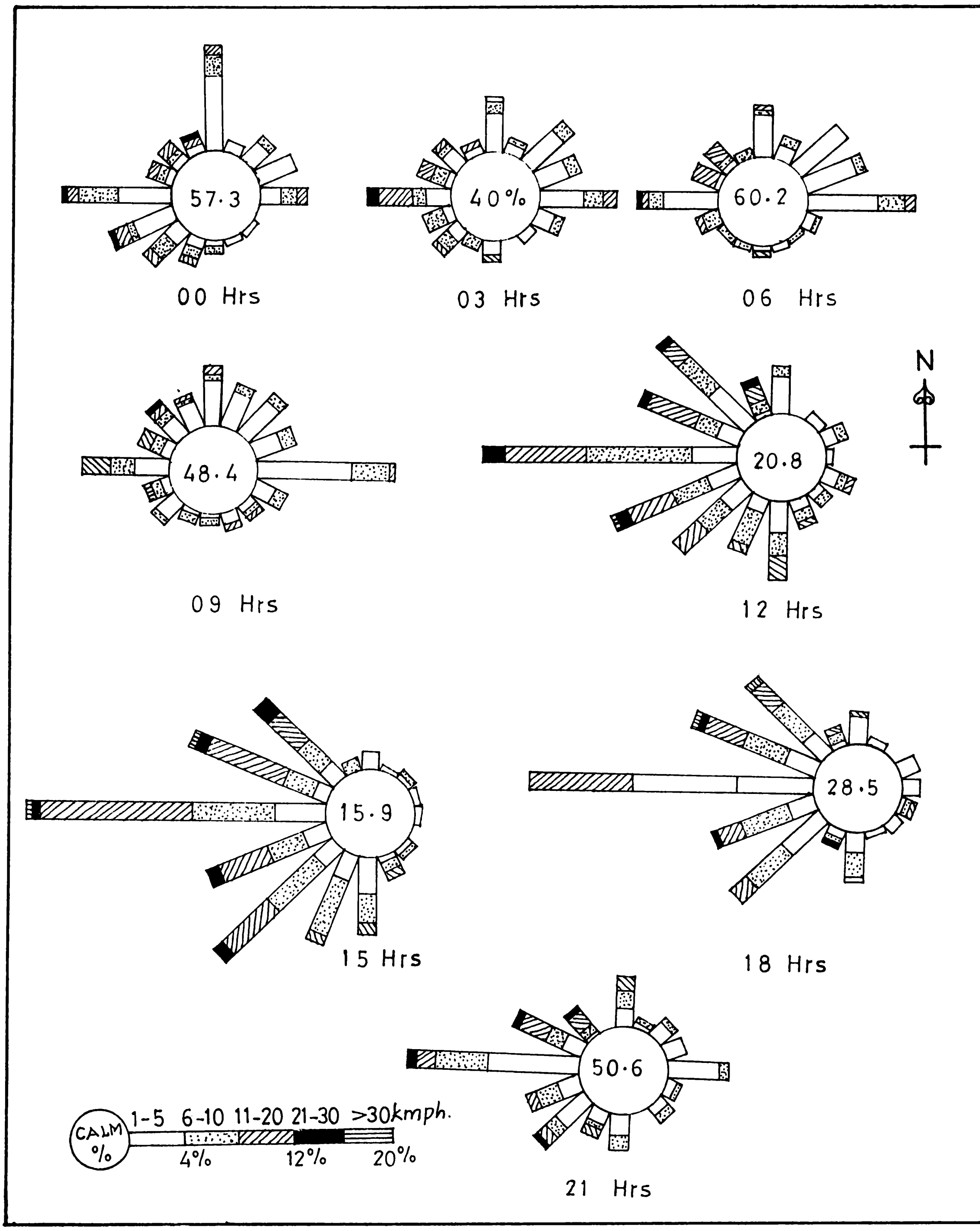


FIG. 3 . 24. WIND ROSES OVER COCHIN FOR JUNE.

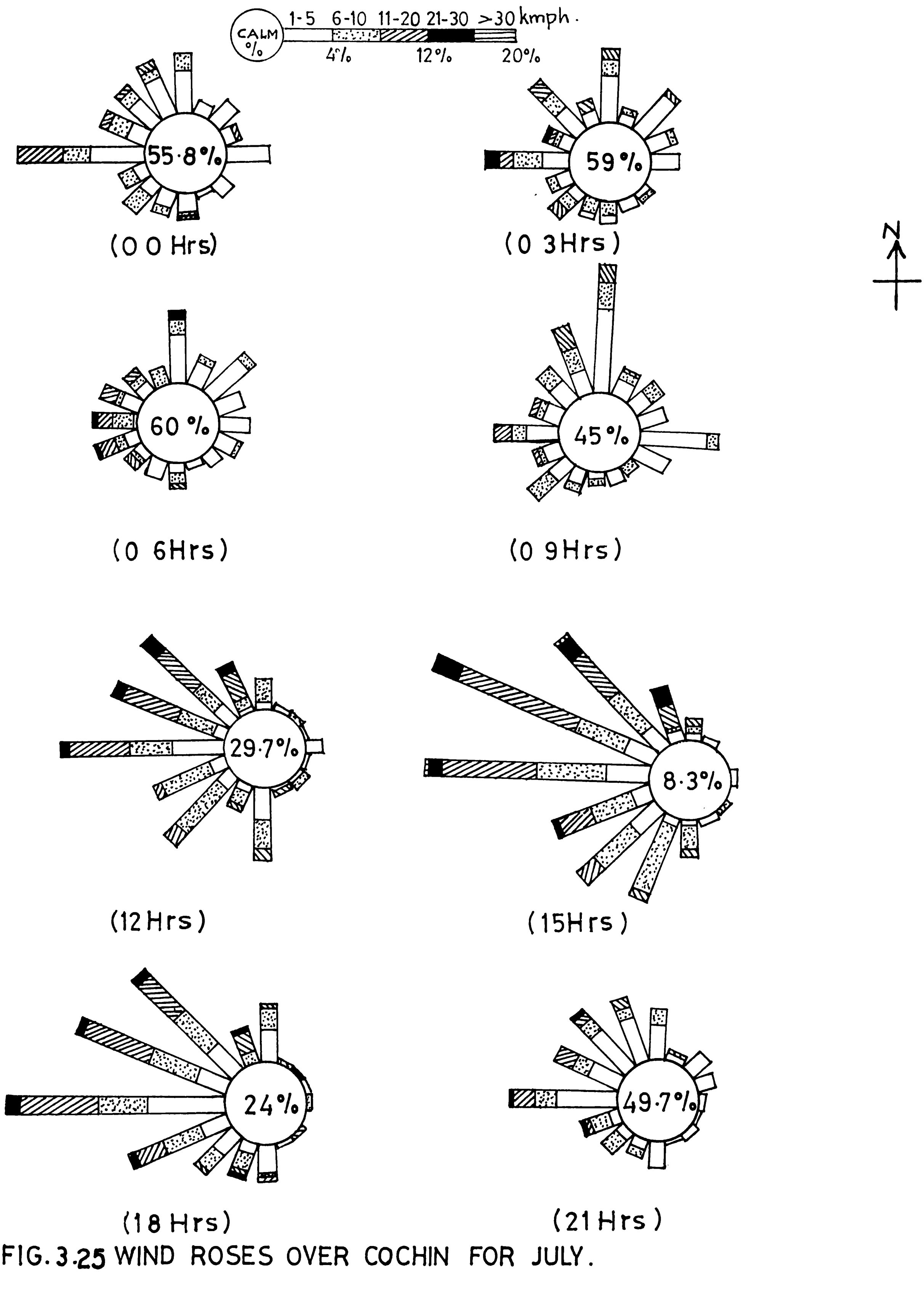


FIG. 3.25 WIND ROSES OVER COCHIN FOR JULY.

that the NW frequency is more compared to SW. The calm frequency is more or less same from 00 to 06 and decreases till 15 hrs and increases thereafter.

August (Fig. 3.26)

The W have dominated at almost all the hours in general, and more during day time. The winds are strong both during night and day time. As mentioned earlier, the W, whereever present, are stronger compared to those from other directions. The calm frequency is little over 50% from 00 to 06 hrs and decreased to 4% from 06 to 15 hrs and increased thereafter.

September (Fig. 27)

The W continue to dominate during the day time. The winds during night time are weak and distributed equally in all the directions except from SE sector. However, there is a slight predominance from SW at 00 hrs, from N at 03 hrs and from NE at 06 hrs. During day time however almost all the winds have got W components. The calm frequencies during night time have gone up compared to that in August. The same variation of calm frequency as in August is observed here also.

October (Fig. 3.28)

The winds are less strong compared to those in September. The W winds have the maximum frequency during

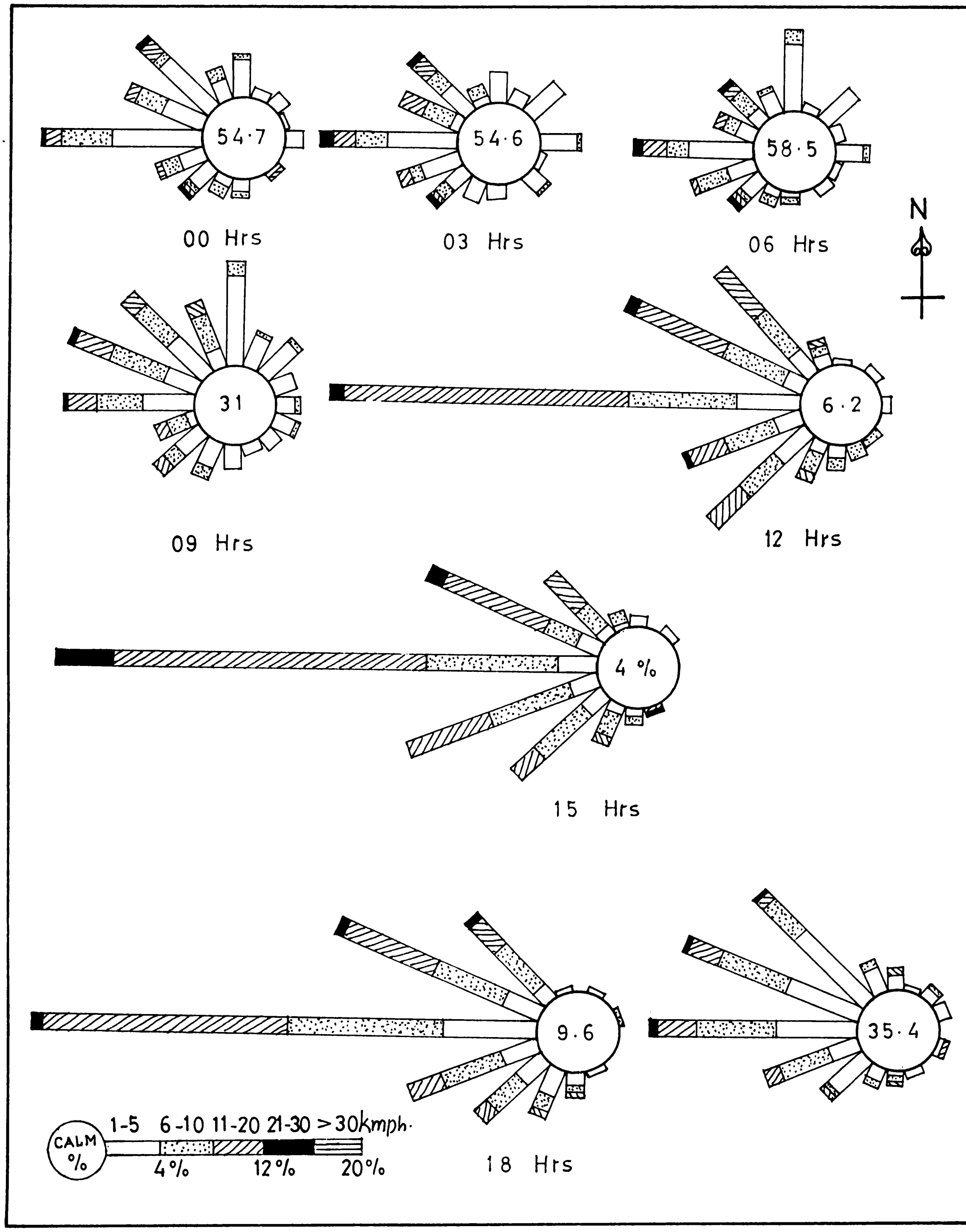


FIG. 3.26. WIND ROSES OVER COCHIN FOR AUGUST.

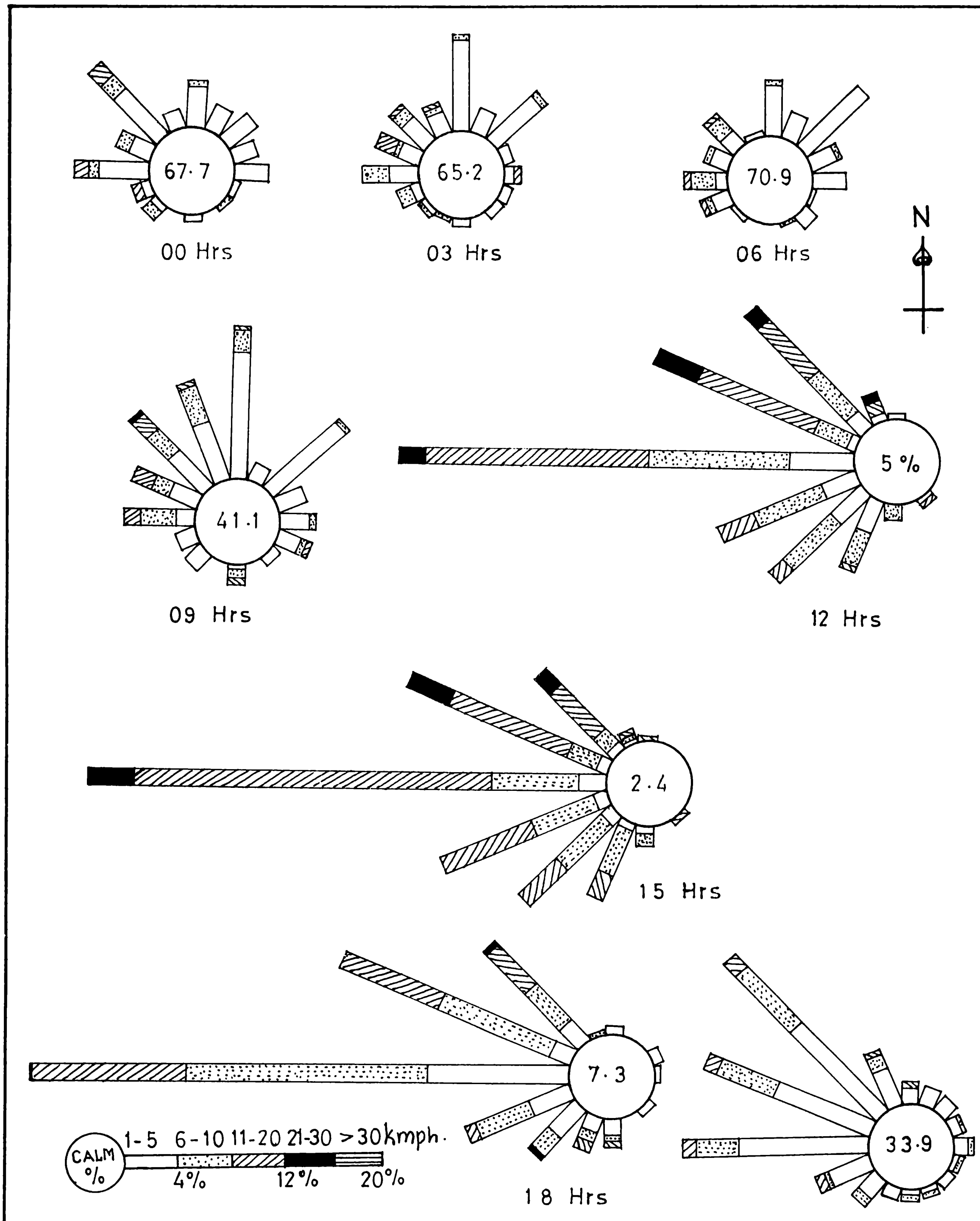


FIG. 3.27. WIND ROSES OVER COCHIN FOR SEPTEMBER.

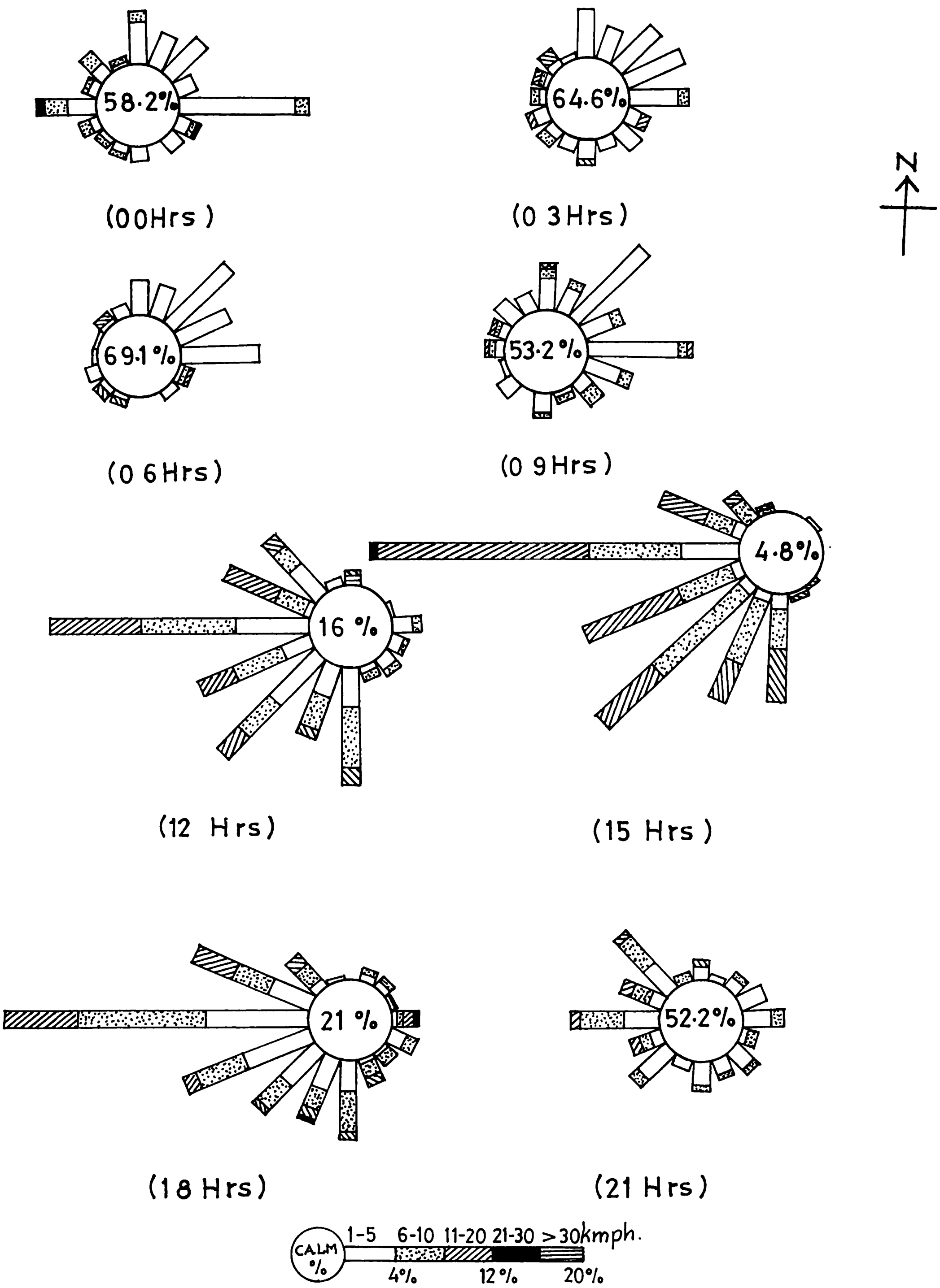


FIG3.28 WIND ROSES OVER COCHIN FOR OCTOBER.

day time. During night time the winds have some considerable frequency from the E but are weak. The calm frequency is more than 50% from 21 hrs to 09 hrs and considerably less during the rest of the period.

November (Fig. 3.29)

The winds during day time are more from the SW sector. During night time the winds are always from NE sector. This is observed right from 00 hrs to 09 hrs when the maximum NE and E wind are noticed. At 12 hrs there is still same frequency of winds coming from NE. From 21 hrs onwards the calm frequency has gone up more than 50% to 06 hrs. For the first time the E are seen to be relatively stronger at almost all the hours.

December (Fig. 3.30)

In this month once again winds are from NE sector during night time. However they are maximum at 09 hrs. The winds are equally distributed at 12 hrs and completely channelised from SW sector at 15 and 18 hrs. The winds are weak during night time and are strong during day time. The calm frequency is more than 50% from 21 hrs to 06 hrs.

In general,calm and weak winds are predominant during night time. During day time strong winds with less calm frequencies are noticed. The unstable conditions

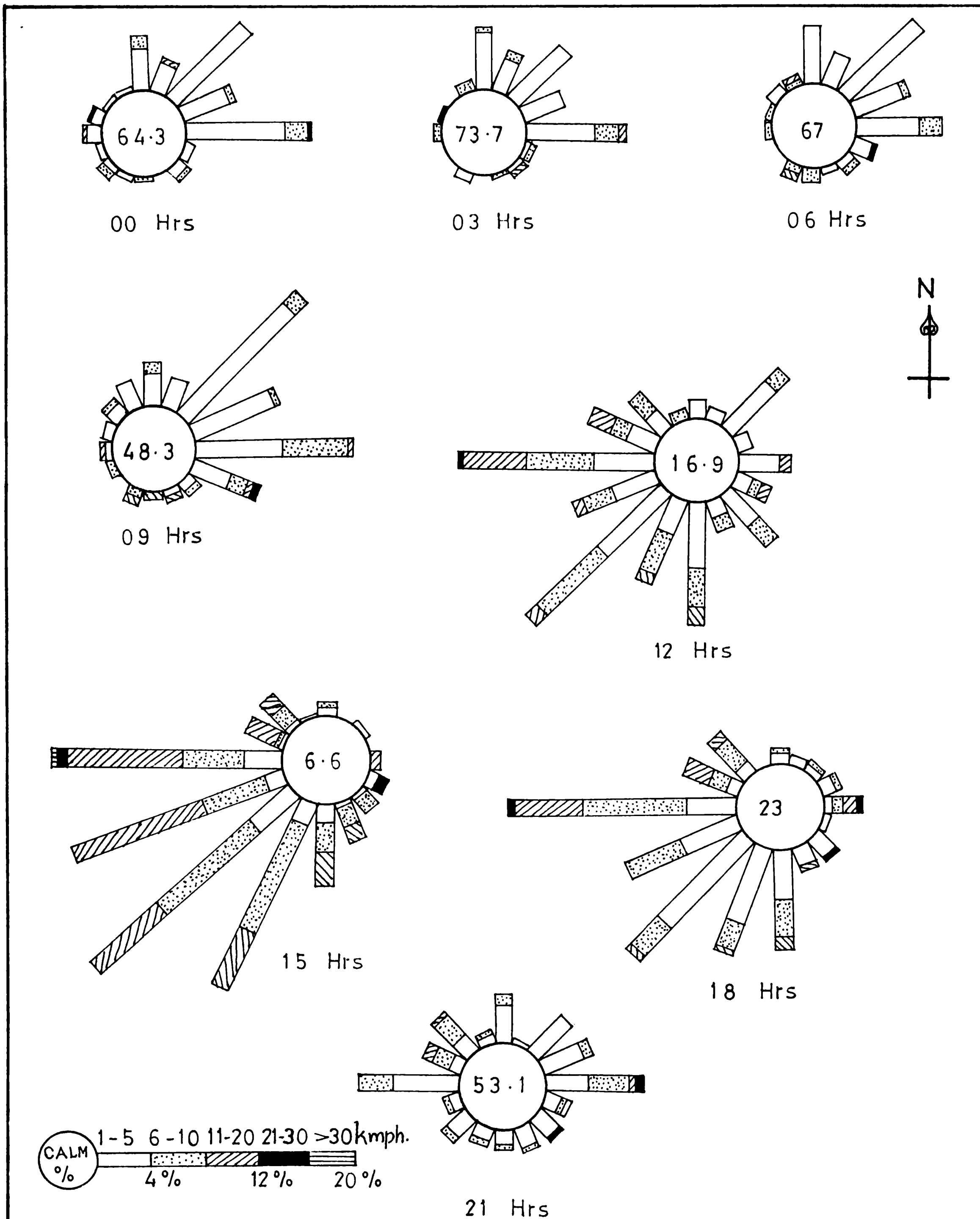


FIG. 3.29. WIND ROSES OVER COCHIN FOR NOVEMBER.

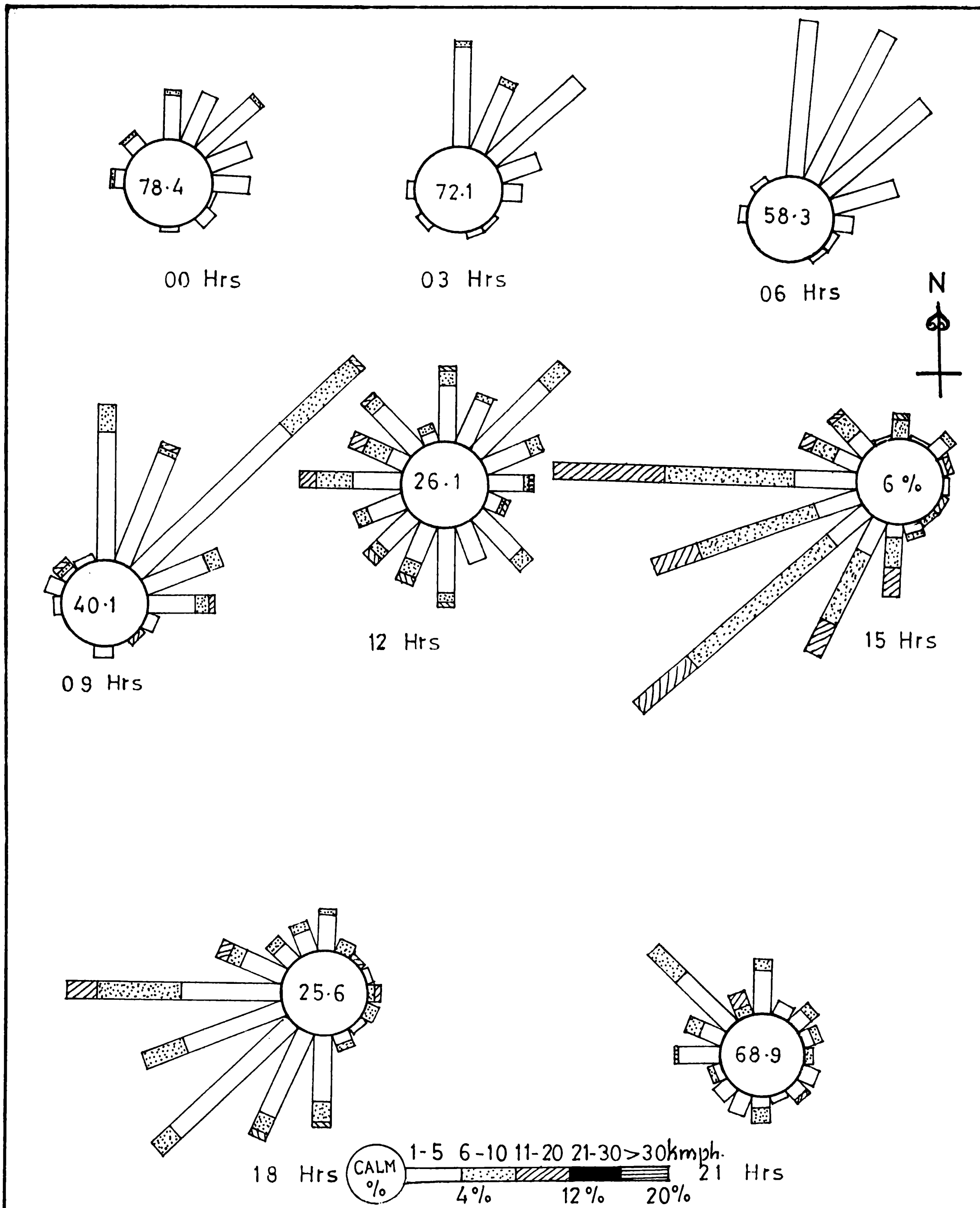


FIG. 3.30. WIND ROSES OVER COCHIN FOR DECEMBER.

during day time and the stable conditions during night time are responsible for strong winds during day time and weak winds during night times. In monsoon months however, the winds are not weak during night time. From January to March and from October to December the reversal of wind direction between night and day is very prominent. This can be attributed to the land and sea breeze phenomenon. The sea breeze is more effective than the land breeze. The W component of wind during the same month mentioned above during day time is because, the station is situated on the west coast and hence the sea breeze is to be from west. Whenever the winds are westerlies they are found to be stronger than compared to winds from other directions in almost all the months. In monsoon season the winds are more from the W and NW directions. The SW component is much less than the westerlies and northwesterlies combined.

The night time winds are very weak and as such cannot carry the pollutants for longer distances and hence result in the accumulation of pollutants. The extremely high calm frequencies during night time further corroborate the above fact. The general tendency is to carry the pollutants mostly towards E and towards NE. The pollutants from the far of sources are carried towards interior and the formation of smog is not uncommon in September or October in the recent past though the frequency of occurrence is very low.

3.2.4.2. Diurnal variation

The diurnal variation of the percent frequency of each of the 16 wind direction is depicted in Fig. 3.31 to 3.34 for the months of January, April, July and October respectively.

In January SW, WSW, W, NE and NW have shown considerable diurnal variation. The NE are observed only upto 12 hrs and the W, SW and WSW are from 12 hrs to 21 hrs.

In April many undulations were noticed in the case of winds from 00 hrs to about 08 hrs. However from 10 hrs onwards the W and the winds from SW sector start increasing till about 16 hrs and falling thereafter. The NW showed a maximum around 10 hrs. There are about two or more maxima observed in the other directions such as NE, WNW and SW.

The diurnal variation is minimum in the month of July. Only the W and WNW undergo the maximum diurnal variation followed by NW. There are only three directions viz., W, WNW and NW, whose frequencies are more than 10%.

In October, from midnight to about 10 hrs one finds a more or less uniform frequency of wind directions

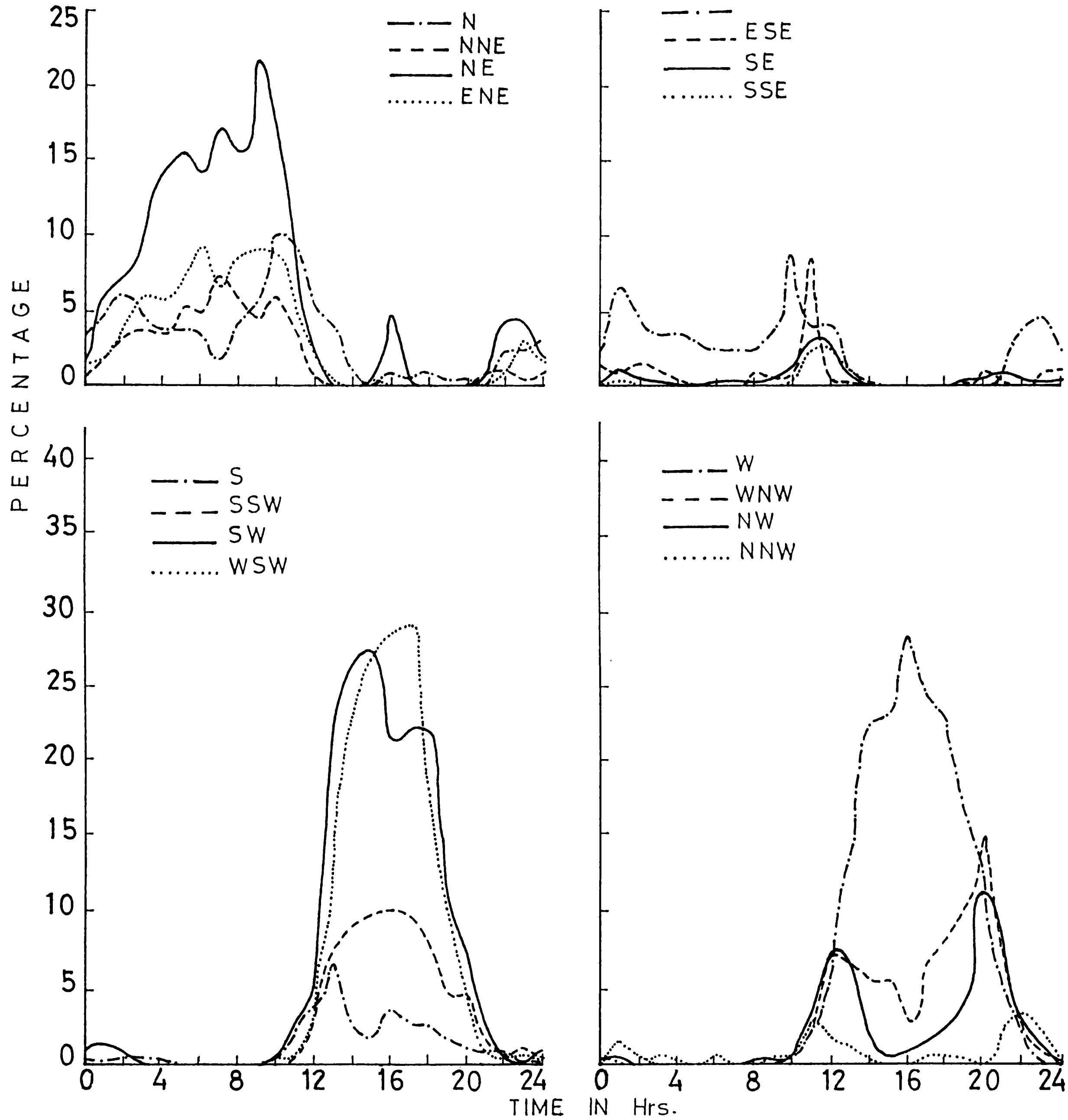


FIG.3.31. THE DIURNAL VARIATION OF THE PERCENTAGE FREQUENCY OF WINDS IN JANUARY.

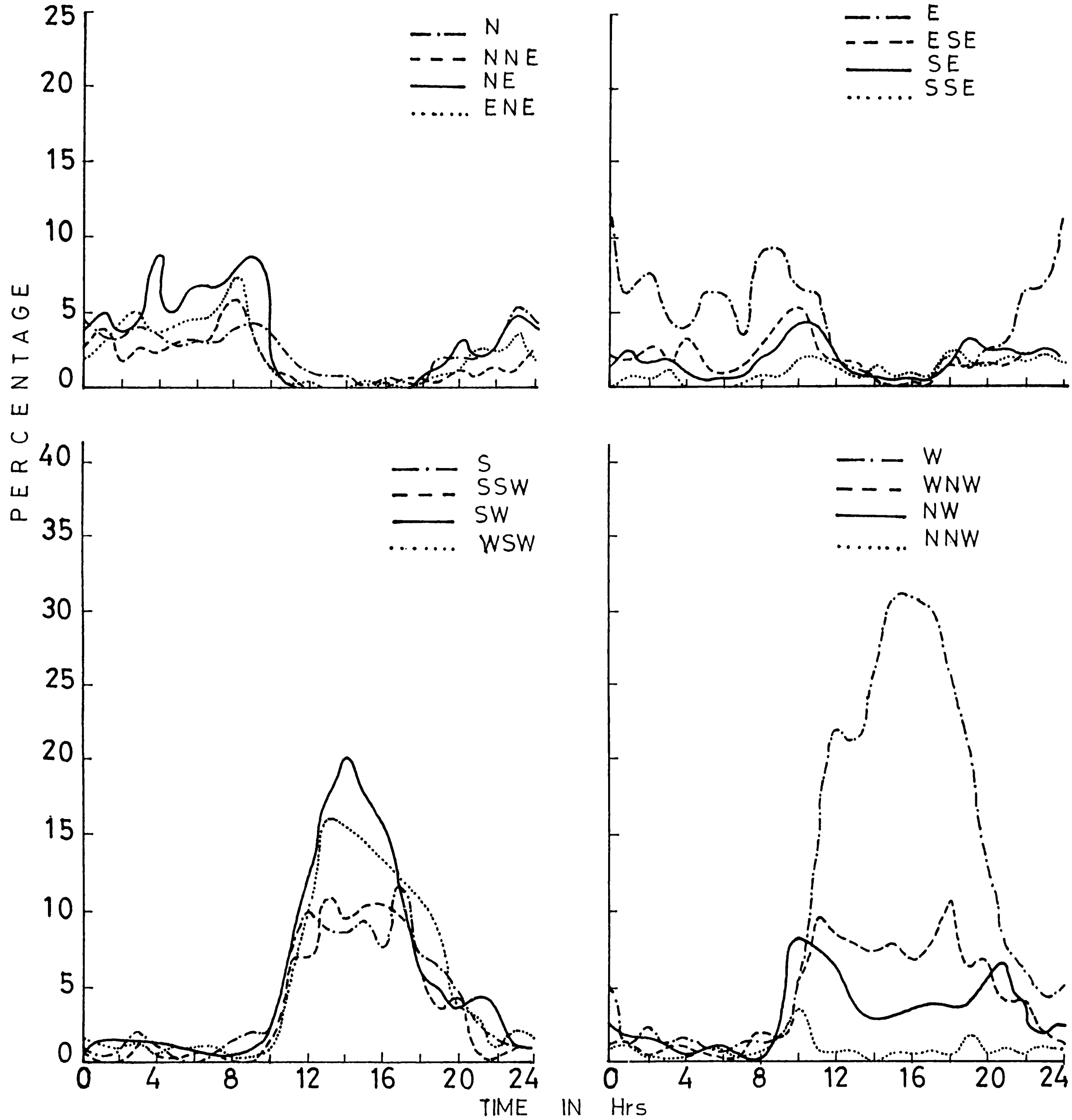


FIG.3.32. THE DIURNAL VARIATION OF THE PERCENTAGE FREQUENCY OF WINDS IN APRIL.

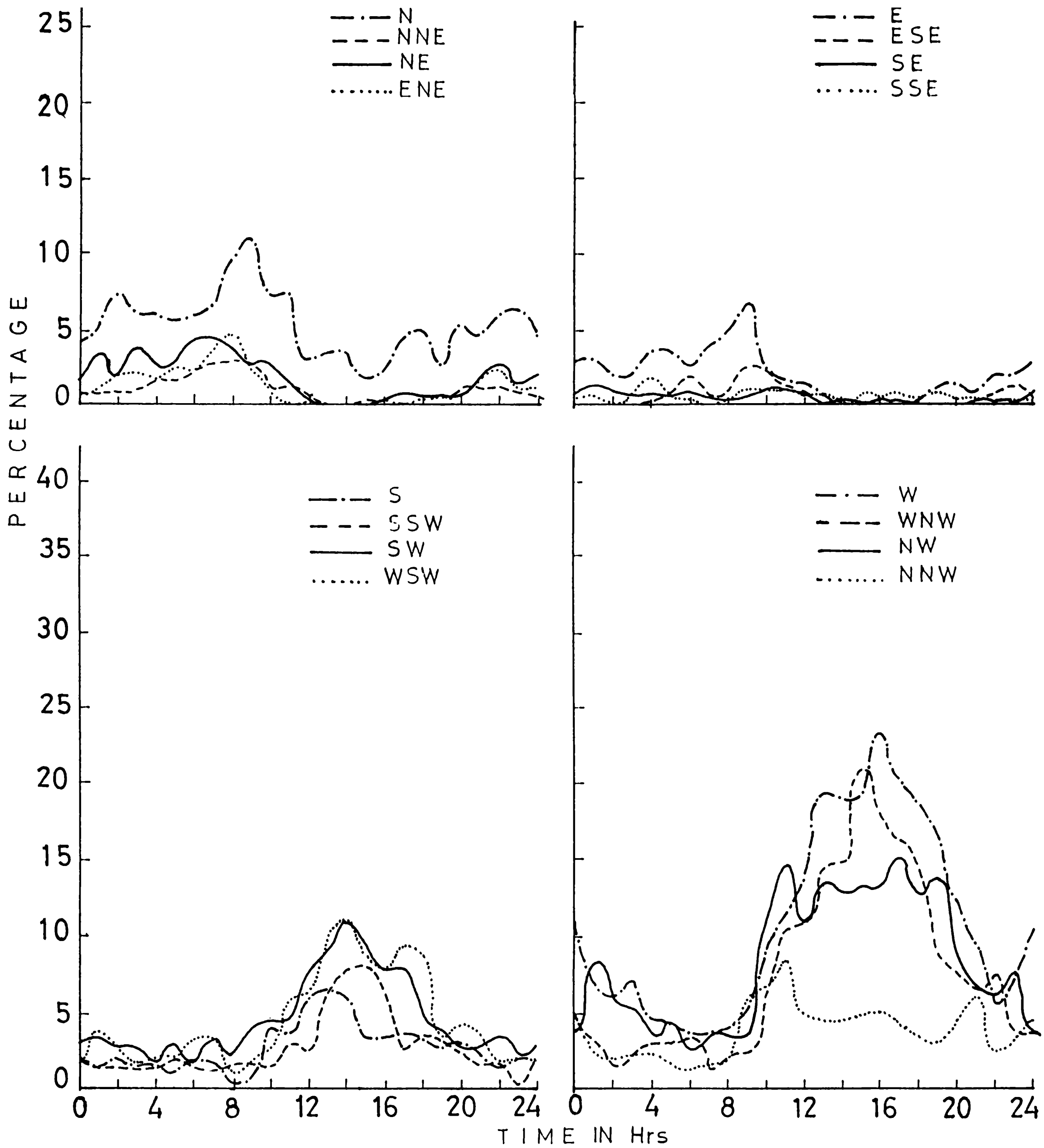


FIG.3.33. THE DIURNAL VARIATION OF THE PERCENTAGE FREQUENCY OF WINDS IN JULY.

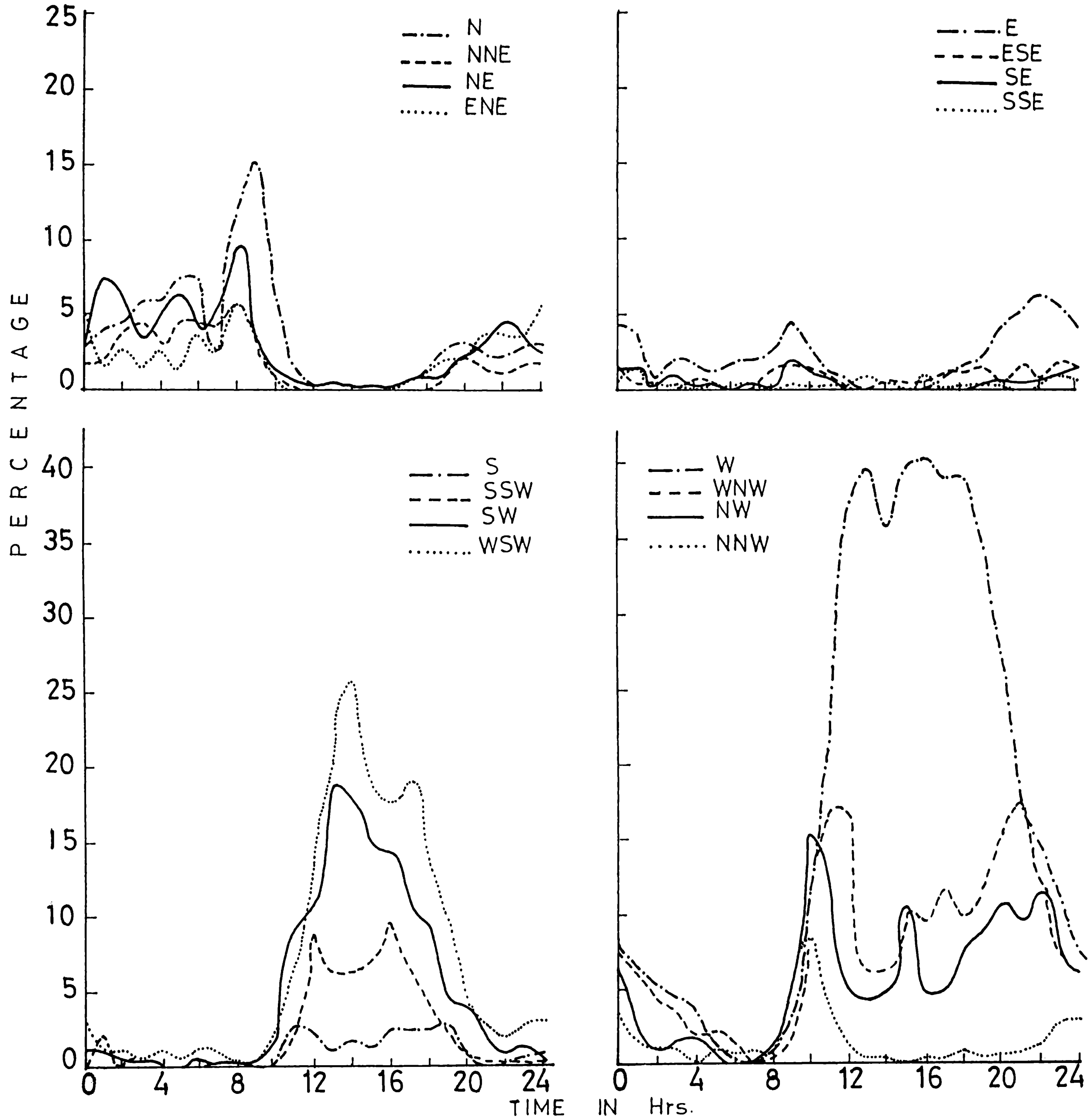


FIG.3.34. THE DIURNAL VARIATION OF THE PERCENTAGE FREQUENCY OF WINDS IN OCTOBER.

from the E sector. From 10 hrs onwards one finds the increase of the W components till about 16 hrs followed by a decrease upto about midnight. A single peak at 14 hrs in the SW and WSW is a noticeable feature as in the case of W. The other directions showed at least two or more maxima.

The diurnal variation also revealed the influence of land and sea breeze phenomenon. The diurnal variation is minimum in July followed by October, January and April. The winds are mostly from W continuously during day time. The continuous unidirectional wind is a matter of concern as far as air pollution is concerned. A distribution in the other directions would distribute pollutants, and as such the resulting ground concentration can also be brought to a lower value.

3.3. Summary

The percent frequency of occurrence of GI, EI and EIS is very low in all the months. IS is in considerable frequency, having values around 20 to 30%. The combined frequency of inversions and isothermals is shown to have a maximum of 35% in January, the minimum being in February.

The spatial variation of MH revealed that the southern portion of the city have the least MH in all the months and all the timings except at 12 hrs. The spatial range of MH is maximum at 12 hrs. It is shown that the MH at a given point cannot be taken to be representative for the whole city. The diurnal variation of MMH is studied for each month which showed a systematic variation, decreasing from January to July and increasing thereafter. The monthly variation of MMH is shown to be well marked at 12 and 18 hrs with a minimum in the monsoon season and maximum in December and January. The yearly variation of MMH also is well marked. The maximum MMH is observed between 1978 and 1980. The coefficient of variation is more at 15 hrs than that at 06 hrs. The comparison with MH for other cities revealed that the values of Cochin are comparable to that of Bombay. The diurnal range is almost comparable to that of inland stations.

The diurnal variation is well marked for VCs also with the daily means increasing from January to April and July to September and decreasing from April to July and September to November. The maximum VC always occurred at 15 hrs. It is also shown that the value did not exceed 6000 m^2/s and one of the reasons could be that the present values are under estimates, since only the surface wind instead of the vertically averaged wind, is used to compute VC. A comparison with other studies showed that VCs are lower than those for other cities. The reason of which is the relatively weak winds compared to those of other coastal stations like Madras, Bombay, Visakhapatnam and the under estimation of the present values.

The 3 hourly wind roses are depicted for every month which showed calm conditions during night time, strong winds during day time. The winds are mostly from W during day time and from NE during night time especially in the non monsoonal months. The diurnal variation is shown to be minimum in July because the winds are stronger during night time also. It is shown that during the SW monsoon season the winds are more from W and NW direction compared to that from SW. The continuous blowing of wind from one direction is pointed out to be a matter of concern. It is also shown that the build up of pollutants is likely during night time because of the very high calm frequency during night.

C H A P T E R - 4

4. ATMOSPHERIC STABILITY FOR POLLUTION STUDIES

Introduction

Atmospheric stability plays a very important role in air pollution studies. The various schemes of stability are presented in Chapter 2. In the present chapter the Pasquill's criterion of stability classification has been studied for Cochin. The diurnal variation of the climatology of stabilities, the monthly variation and the yearly variation of Pasquill's stability (PS) have been studied. The role of $\sigma\theta$ and the computational procedure of $\sigma\theta$ are presented in Chapter 2. It is pointed out that there is a necessity to have a validity of the factor used to get $\sigma\theta$ from the wind direction fluctuation range (WDFR) and the verification yielded that the factor should be 0.5 of the range instead of 1/6 of the range, the details of which are presented in Appendix I. However, the $\sigma\theta$ computed from Slade's method only is used in finding the relation between PS and $\sigma\theta$ and MH and $\sigma\theta$ to have an uniformity for comparing the relations obtained earlier by others. For studying the diurnal, monthly and yearly variation, the $\sigma\theta$ values are computed by taking 0.5 of the WDFR for 15 minutes.

4.2. PS for Cochin

4.2.1. Diurnal variation

The diurnal variation from January to June is presented in Fig. 4.1 and from July to December in Fig. 4.2. The diurnal variation is well marked in all the months. From 01 hrs to 06 hrs PS 'F' is cent percent in January. There is a small percentage of 'E' noticed from 19 to 24 hrs. At 07 hrs it is completely 'C'. At 08 hrs there is almost 25% of 'D' and the rest is 'B'. 'A' is noticed from 09 hrs to 13 hrs. Between the same timings there is some fraction of 'B' and 'C' also. From 14 hrs onwards it is a combination of 'A', 'B', 'C' and 'D' and from 16 hrs to 18 hrs it is 'C' and 'D' only. The highly stable conditions during night time gradually changed to slightly unstable in the morning hours and to highly unstable conditions in the afternoon. 'D' is not noticed during night time in this month.

In February more or less similar conditions as in January are observed, but for the slightly higher frequency of 'D'. A very small fraction of 'D' appeared during night time.

Once again, similar conditions are observed in March also. The 'A' frequency has come down than compared

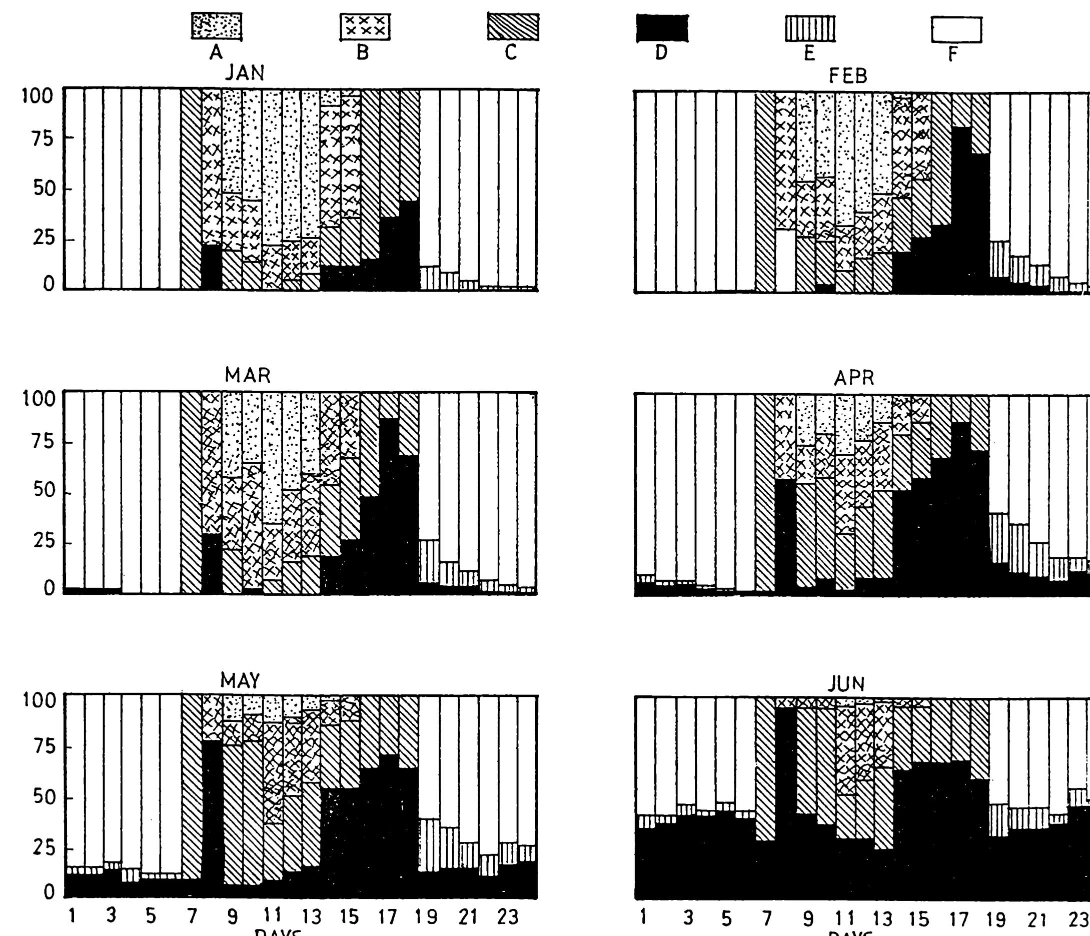


Fig.4.1.DIURNAL VARIATION OF PERCENT FREQUENCY OF PASQUILL'S STABILITY FOR COCHIN FROM JANUARY TO JUNE.

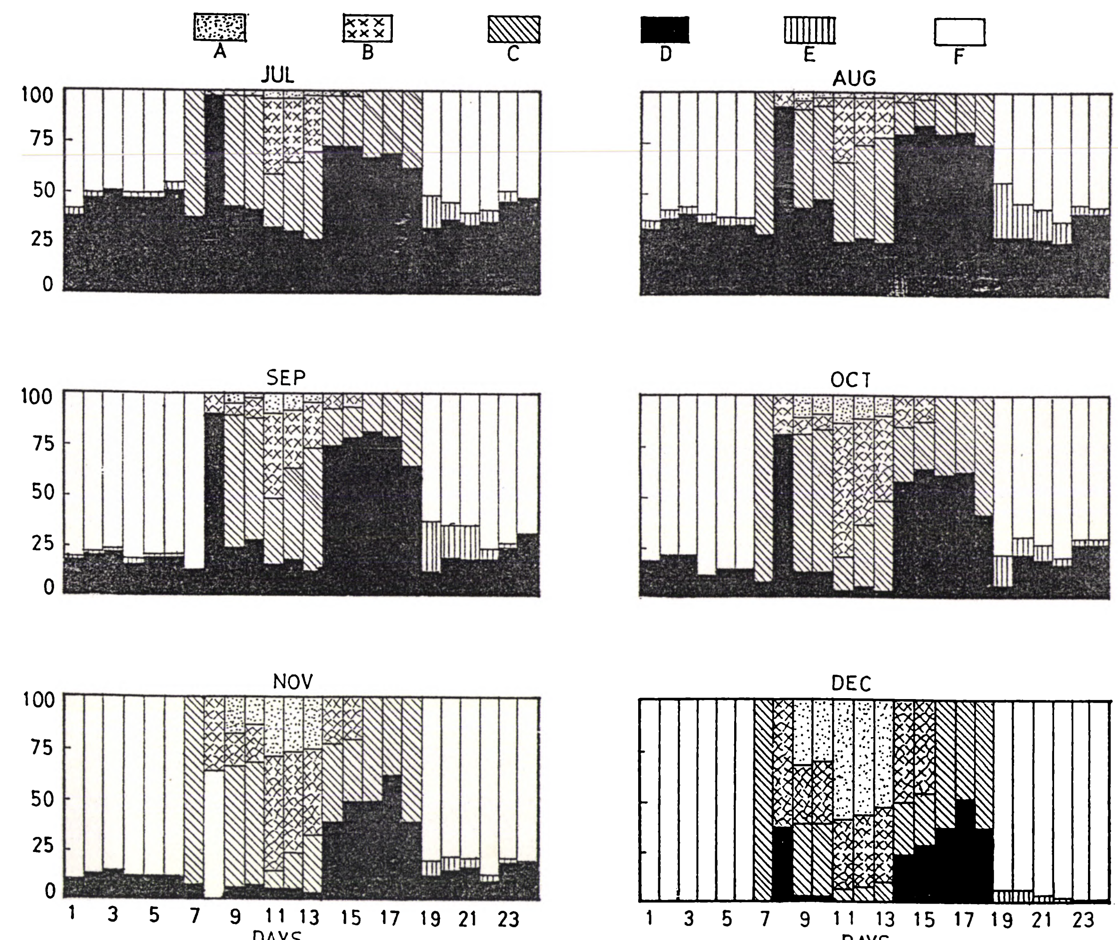


Fig. 4.2. DIURNAL VARIATION OF PERCENT FREQUENCY OF PASQUILL'S STABILITY FOR COCHIN FROM JULY TO DECEMBER.

to that in February. 'E' frequency has gone up slightly compared to that in January. A small fraction of 'D' has appeared for more time than compared to that in February.

In April 'A' has come down considerably and 'D' and 'C' have gone up than compared to that in March. Between 14 to 18 hrs it is mostly 'D' only. During both day and night time the 'D' is present at all the hours.

In May 'A' has further come down and 'C', 'B' and to some extent 'D' have increased in its place between 09 and 13 hrs. The 'D' frequency has gone up during night time and to some extent during day time also.

In June, 'D' has almost 50% frequency for all the hours put together. 'A' is in negligible quantity and 'B' has come down considerably excepting between 11 and 13 hrs. Next to 'D', it is 'F' followed by 'C' in so far as their frequency of occurrence is concerned.

In July once again, the 'D' frequency is more. The frequency is more than 50%. 'A' once again is in very small frequency. The percentage of occurrence is more for 'D' followed by 'F', 'C', 'B', 'E' and 'A'.

In August more or less similar conditions are observed as those in July. 'D' has gone up between

13 and 18 hrs slightly and decreased slightly during night time. Still it continues to dominate.

In September, however, the 'D' frequency has come down considerably during night time but remained the same between 13 and 18 hrs. 'A' has slightly gone up and so is 'F'.

In October 'D' has further come down during night time and slightly between 13 and 18 hrs. 'A' and 'B' are on the increase. The frequency of occurrence is more for 'F' followed by 'D', 'C', 'B', 'A' and 'E'.

In November 'A', 'B' and 'F' have gone up and 'D' has come down. 'F' continues to dominate followed by 'D', 'C', 'B', 'A' and 'E'.

In December there is only a very small fraction of 'D' during night time, the rest being completely dominated by 'F'. Between 09 and 13 hrs 'A' has gone up considerably. Between 14 and 18 hrs 'D' is at least 30% and the rest is 'C' and 'B' upto 15 hrs and 'C' alone upto 18 hrs.

Fig. 4.3 and 4.4 depict the occurrence of stability whose percentage is maximum at each hour for each month. In January 'A' is maximum during 09 and 13 hrs, 'B' at 08, 14 and 15 hrs, 'C' at 07, 16 and 18 hrs, 'D' at 17 hrs and 'F' for the rest of the period. In February, same

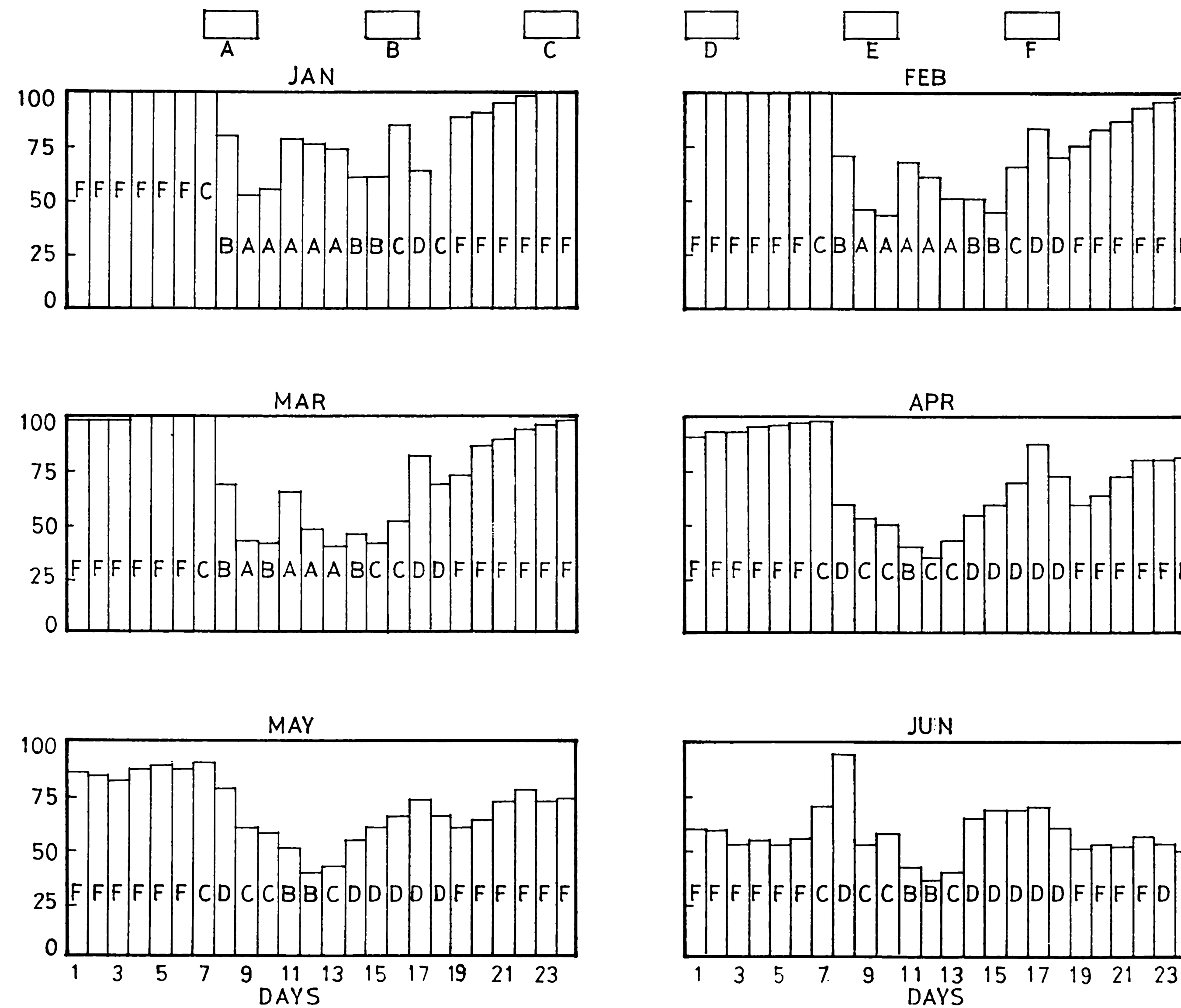


Fig. 4.3. MAXIMUM OCCURRING PASQUILL'S STABILITY AND ITS PERCENT FREQUENCY AT EACH HOUR FOR COCHIN FROM JANUARY TO JUNE.

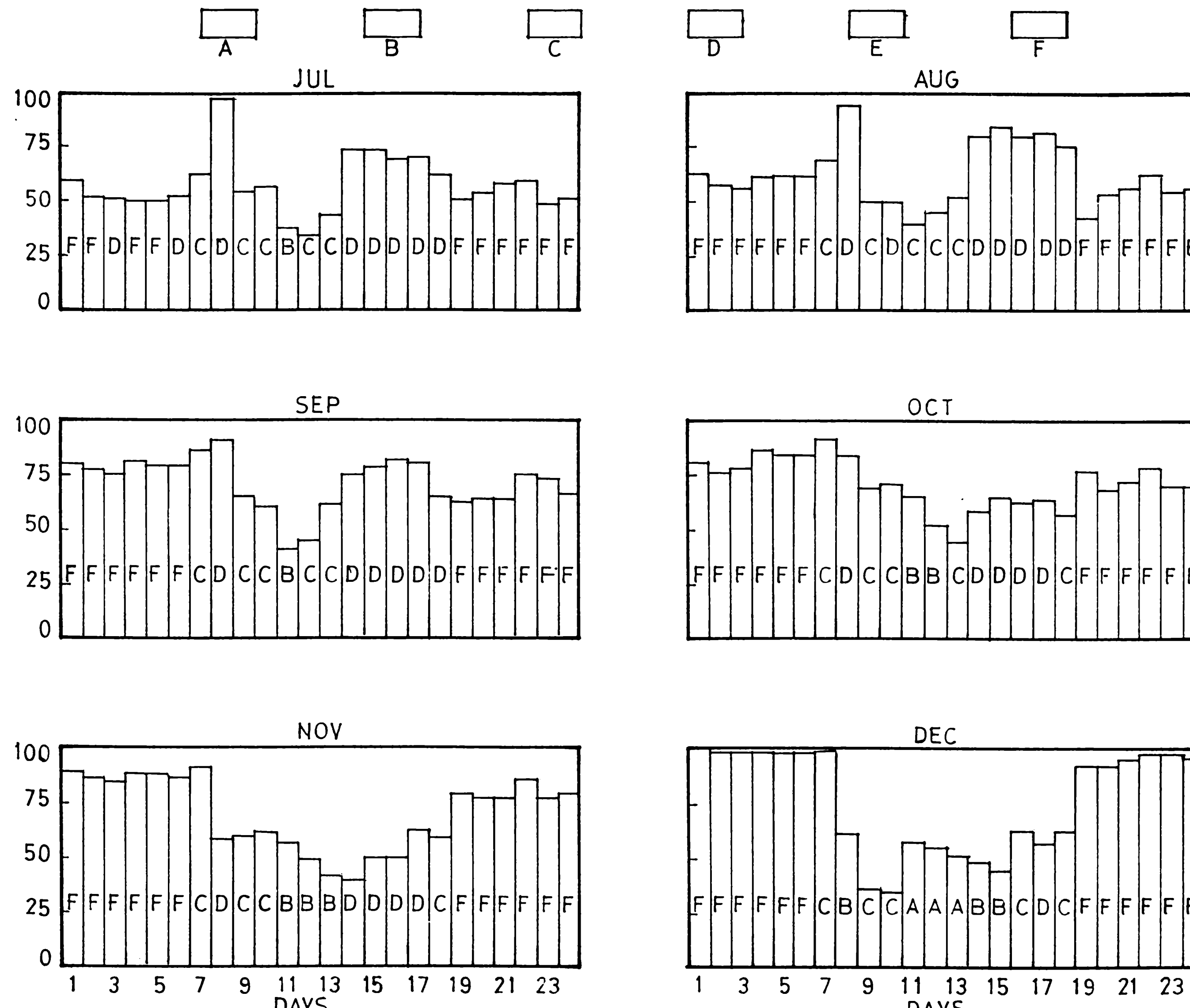


Fig. 4.4. MAXIMUM OCCURRING PASQUILL'S STABILITY AND ITS PERCENT FREQUENCY AT EACH HOUR FOR COCHIN FROM JULY TO DECEMBER.

conditions prevail except 'D' at 18 hrs instead of 'C'. In March also similar conditions but for 'C' at 15 hrs and 'B' at 10 hrs. However, the absolute values of the percentage are coming down between 9 and 16 hrs. In April 'F' during night time 'D' at 08, and 14 to 18 hrs, 'B' at 11 hrs and 'C' at the rest of the hours are noticed. The values are minimum at 12 hrs in this month. Similar conditions are noticed in May and June except for 'B' at 12 hrs in both the months and for 'D' at 23 hrs in June. The maximum values in general, have lower values in June compared to the other months. In July, 'D' is maximum at 03, 06, 08 and 14 to 18 hrs, 'F' during the rest of the night time, 'B' at 11 hrs and 'C' at rest of the hours. The variation is mostly between 'C' and 'F'. In August, 'D' is not maximum at any hour during night time but only 'F'. During day time, however, it is maximum at 08, 10 and 14 to 18 hrs. For the rest of the day time, 'C' is observed. The variation in this case is among 'C', 'D' and 'F'. More or less similar conditions in September and October but for a few cases in which 'B' is maximum at 11 hrs in September and at 11 and 12 hrs in October. In November 'B' is maximum at 13 hrs also, the rest being same as that in October. In December 'A' is maximum between 11 and 13 hrs, 'B' at 08, 14 and 16 hrs, 'C' at 07, 09, 10 and 16 and 18 hrs, 'D' at 17 hrs and 'F' at the rest of the period.

A systematic increase of 'D' from January onwards to August with a consequent decrease of 'A' and a systematic decrease from September onwards with a consequent increase of 'A' are the prominent features. The domination of 'F' during night time has decreased from January to July and increased from August to December. The relatively clear skies and the light winds during night time from December to March must be responsible for the domination of 'F'. Another interesting feature, in general, is the presence of 'D' from 13 to 18 hrs in all the months. Between 13 and 18 hrs the strongest winds of the day are observed (see Chapter 3). These strong winds are responsible for the neutral conditions between 13 and 18 hrs. The domination of 'D' from June to September is mainly due to overcast conditions which also make the atmosphere neutral. The relatively high frequency of 'D' in April and May compared to January, February and March is due to the relatively strong winds in these two months.

A comparison with the cities, Bombay, Madras, New Delhi and Calcutta showed a striking difference in the occurrence of 'D'. For example in Bombay, 'D' was noticed not even once in January and October, once in April and thrice in August (Viswanadham, 1980). According to him, same is the case in New Delhi, Madras and Calcutta. In Cochin, however, as already pointed out, 'D' is present in considerable frequency in all the months. In the monsoonal months, the decrease in range also is a prominent feature in the present case as well as in the studies made by Viswanadham, The diurnal variation has exactly followed the theory which states that the stable conditions during night time and unstable conditions during day time with transitions having slightly unstable or neutral conditions. If one is to discuss the pollutant dispersal with stability alone, it has to be stated that the night time emissions are of considerable concern because of no vertical mixing and light winds which would result in the stagnation of the pollutants and the consequent accumulation that may eventually be brought down to the ground level immediately after the stable conditions cease to exist i.e. in the late morning hours.

4.2.2. Monthly variation

The monthly variation of percent frequency of occurrence of 'A', 'B', 'C' and 'D' at 12 hrs is shown in Fig. 4.5. The reversal trend of variation of 'A' and 'D' is the most striking feature. While 'A' is maximum

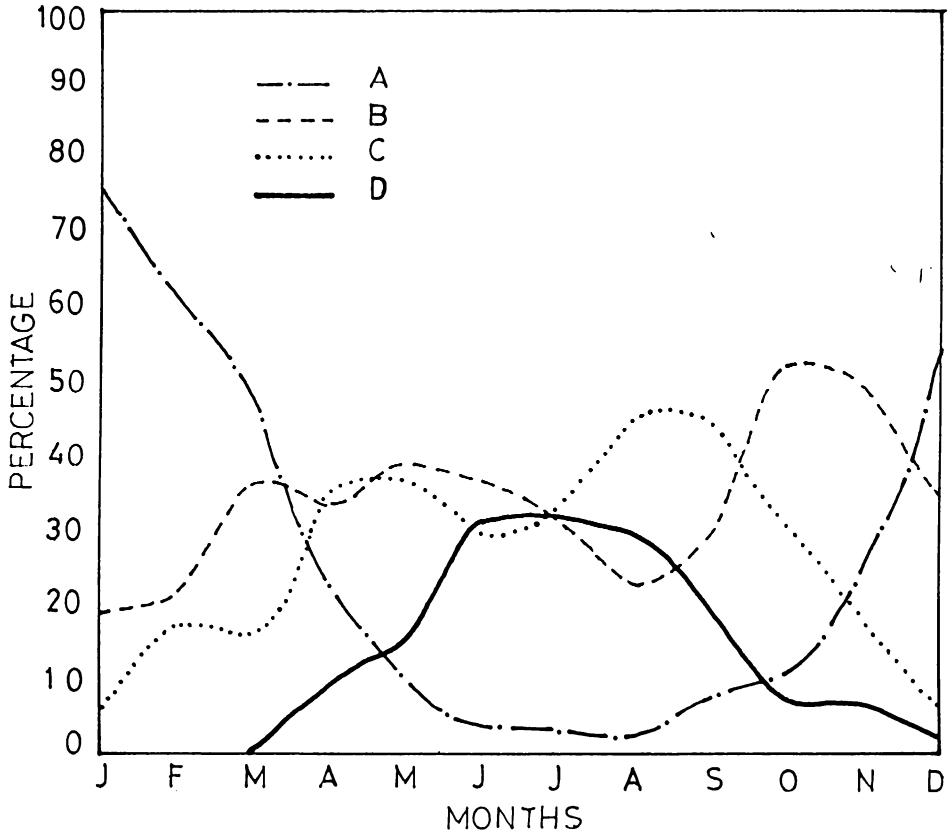


Fig.4.5. MONTHLY VARIATION OF PERCENT FREQUENCY OF PASQUILL'S STABILITY CLASSES 'A' 'B' 'C' AND 'D' FOR COCHIN AT 12 HOURS.

in January and decreasing upto August and increasing till December, 'D' is minimum in March increasing upto July and decreasing thereafter. As already explained, the overcast conditions and the strong winds are responsible for the maximum of 'D' from June to August and the minimum of 'A' during that period. The 'B' and 'C' have shown many undulations. 'C' is minimum in December and January and maximum in August while, 'B' is minimum in January and maximum in October.

4.2.3. Yearly variation

The yearly variation of the percent frequency of occurrence of stabilities at 12 hrs for all the months is depicted in Fig. 4.6. In January, 'A' is minimum in 1975 and maximum in 1979. While, it increased from 1975 to 1979 with a small kink in 1977, it decreased from 1979 onwards. The range of 'A' is almost 40%. 'B' exactly varied in the opposite direction. But the range is 30 to 35%. 'C' is almost negligible from 1976 onwards but has considerable percentage in 1974. The reversal trend between 'A' and 'B' is obvious because there are only these two categories in January except in 1974.

In February, the variation of 'A' is rather high, the range being 60%. To some extent one can see the reversal trend between 'A' and 'C' till 1980 and between 'A' and 'B'

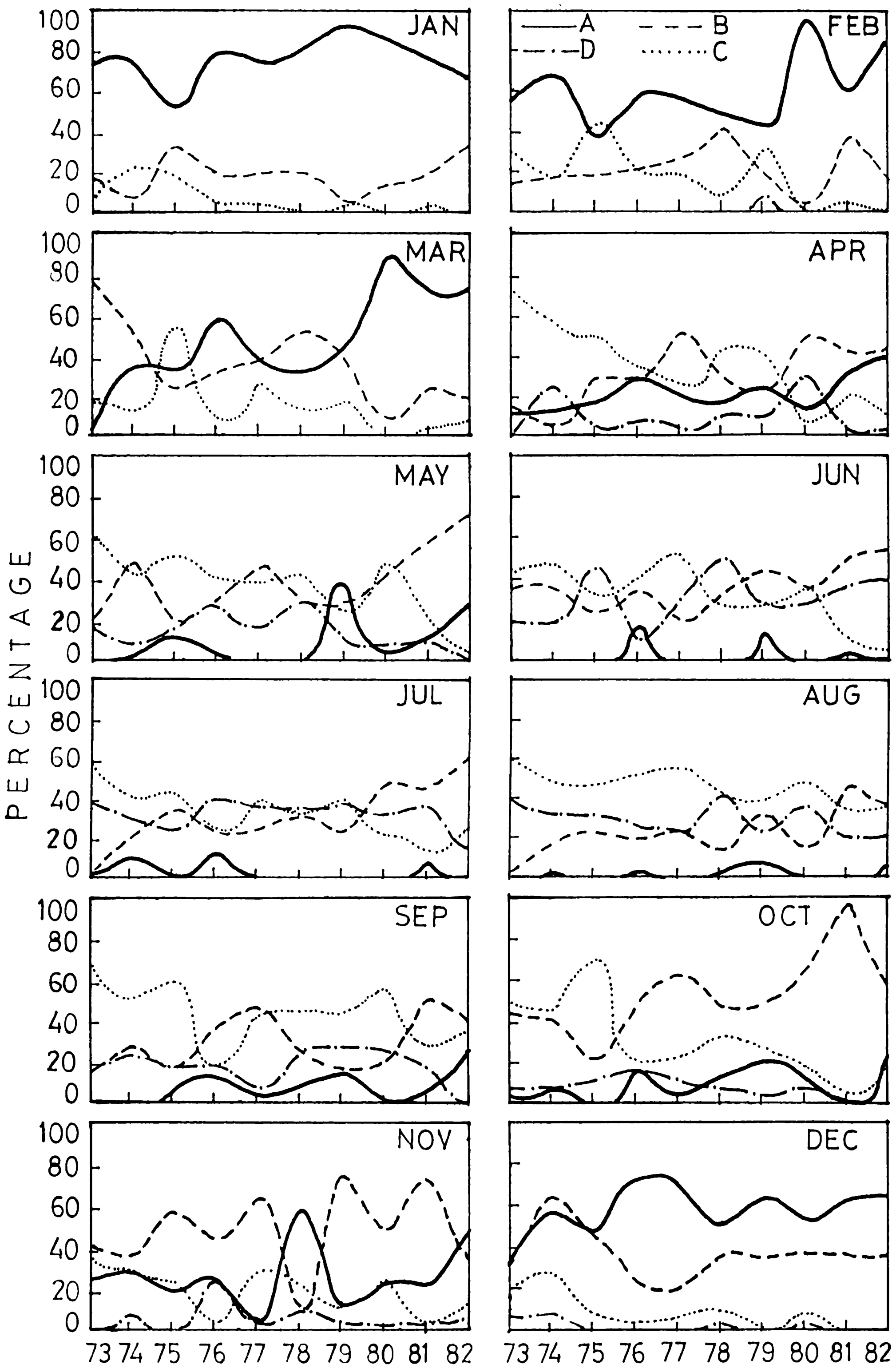


Fig.4.6. YEARLY VARIATION OF PERCENT FREQUENCY OF PASQUILL'S STABILITY CLASSES 'A' 'B' 'C' AND 'D' FOR COCHIN AT 12 Hrs.

from 1980 onwards. There is a decreasing trend of 'C', while 'B' remains almost the same with a slight increase till 1978 and sudden fall in 1980.

However, in the month of March, there is a clear cut increase in trend for 'A' and a consequent decrease in trend for 'B' and 'C'. The range of 'A' is almost 90%. The ranges for 'B' and 'C' are 70% and 60% respectively.

In April, a decreasing trend for 'C' and a slight increasing trend for 'B' are notable features. 'A' and 'D' do not have much range while, 'C' has 60% and 'B' has 50%. In this month all the 4 categories are seen.

In May, there are wide oscillations for all the 4 categories. 'A' is absent in 1977 and 1978 and the ranges are also relatively lower.

In June and July, the ranges of all the categories are minimum except for 'C'. 'A' is appearing only in few years.

In August, the ranges have slightly gone up and a reversal trend between 'B' and 'D' is observed.

In September, the ranges of each of these categories have gone up further. A reversal trend between 'A' and 'C' till 1980 and the same trend thereafter is a notable feature in this month. 'B' and 'D' are in reversal trend from 1975 to 1980 and in the same trend in the rest of the years.

In October and November there are wide fluctuations once again, especially for 'A' and 'B', both of which are in the same trend till 1978 and in the reversal trend thereafter. 'D' has considerably come down in all the years except in 1976.

In December 'D' is observed only in few years. 'A' and 'B' are in the same trend for few years and in the reversal trend for some other years.

In general, one can notice that there are reversal trends when two classes only are present and not when all the 4 categories are present. The specific reasons for the wide fluctuations are purely based on the local conditions in the individual years because, these are dependent mainly on cloud amount and wind speed.

4.3. σ_θ for Cochin

The σ_θ computed from the method outlined in Chapter 2 is used here to study the diurnal, monthly and the yearly variation.

4.3.1. Diurnal variation

The diurnal variation of $\sigma\theta$ from January to June is presented in Fig. 4.7 and from July to December in Fig. 4.8.

In January and February, $\sigma\theta$ varied from as low as 14 degrees at 00 hrs to as high as 55 degrees at 11 hrs. There is a gradual increase from 00 hrs to 09 hrs, a steep increase upto 11 hrs and a normal fall thereafter.

The diurnal variation is similar in March and April. The value decreased from 00 hrs to 05 hrs, increased thereafter to 11 hrs and decreased gradually. The diurnal range in March is around 33 degrees and in April around 29, both of which are less than those in January and February. The minimum in April is more than that in the preceeding months.

In May also, similar variation as that in April is observed, the only difference being, the diurnal range is further brought down to 26 degrees.

In June the value increased from 00 to 02 hrs and decreased from 05 to 11 hrs, from 02 to 05 hrs and from 11 hrs to 00 hrs. The diurnal range has attained a very low value of 17.5 degrees.

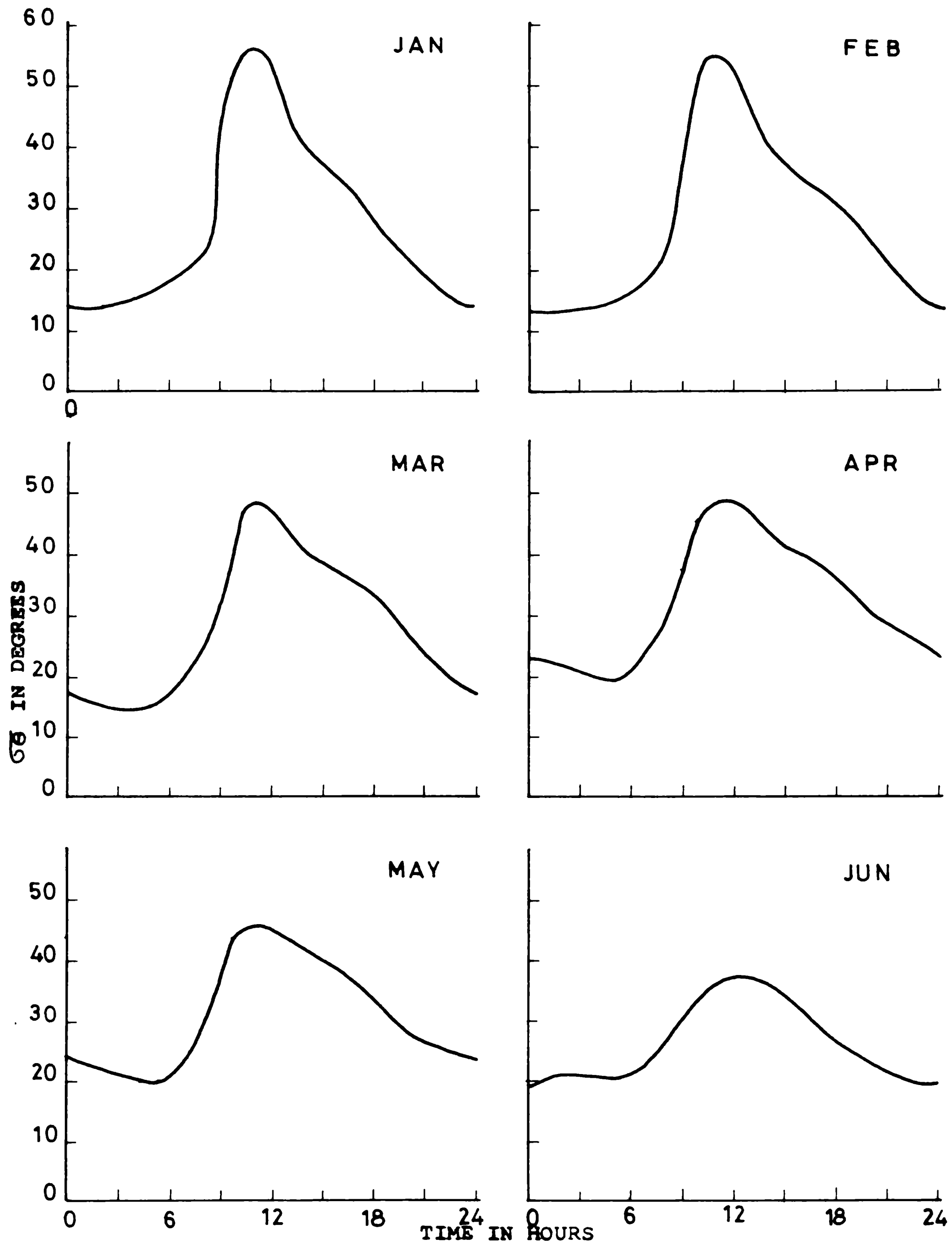


FIG. 4.7. DIURNAL VARIATION OF σ_θ FOR COCHIN FROM JANUARY TO JUNE

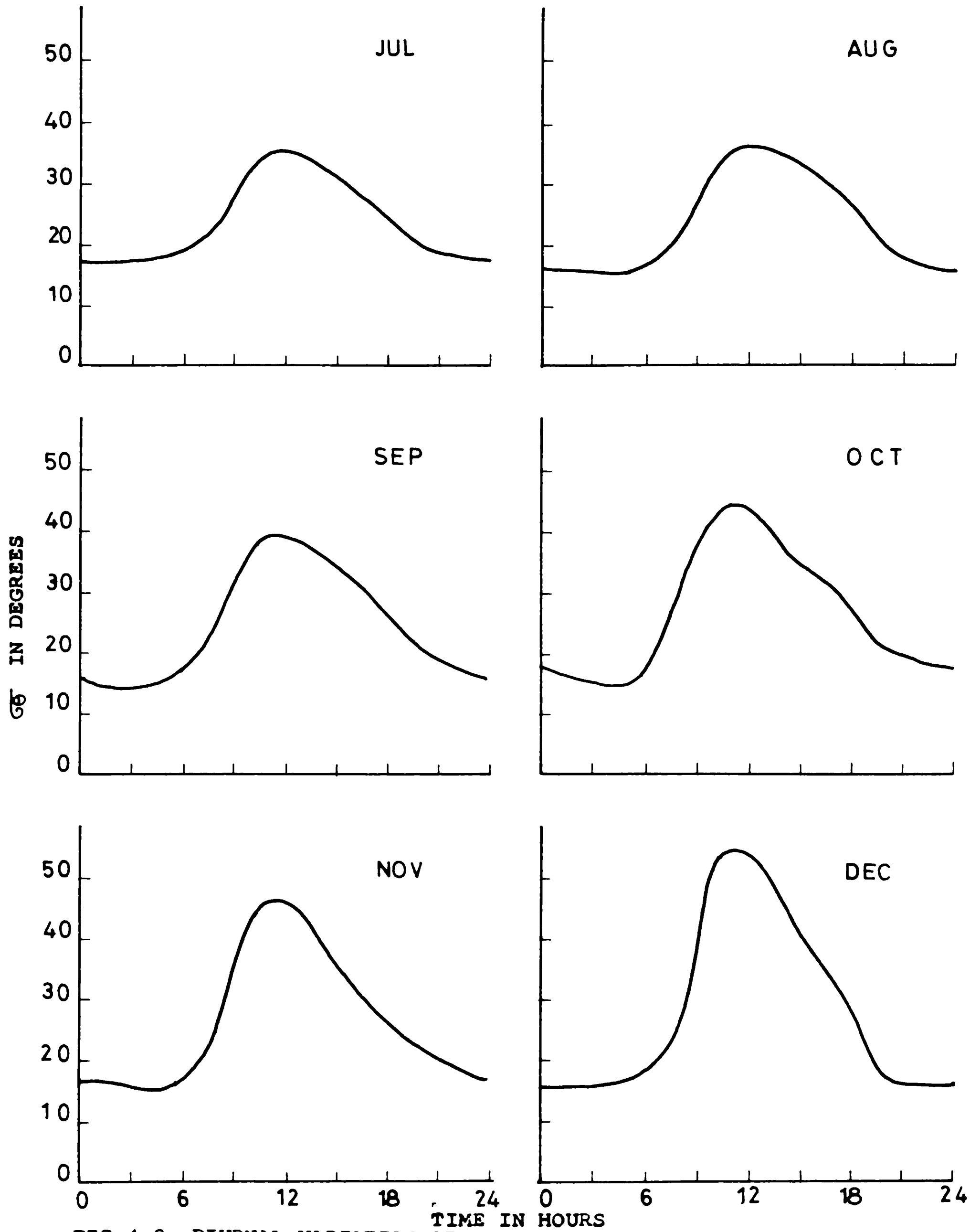


FIG.4.8. DIURNAL VARIATION OF $\bar{\sigma}$ FOR COCHIN FROM JULY TO DECEMBER

In July also, the diurnal range is 17.5 degrees with a minimum occurrence at 00 hrs and maximum at 11 hrs. It increased from 00 to 09 hrs at a very slow rate, increased steeply from then onwards till 11 hrs. There is a normal decrease from 11 hrs onwards.

In August and September, more or less similar variations are observed as in July excepting that the value decreased from 00 to 05 hrs and the diurnal range has gone up slightly. The minimum in August is observed at 05 hrs while, the same for September is observed at 02 hrs.

In October the range has further increased. The value decreased from 00 to 05 hrs and increased to 11 hrs followed by a more or less normal decrease.

In November, the minimum is once again observed at 05 hrs and maximum at 11 hrs. The range has gone up further to 31 degrees.

In December, the value remained the same till about 05 hrs and increased to a value of 54 degrees at 11 hrs followed by a smooth decrease till about 21 hrs.

In all the cases the maximum of $\delta\theta$ is observed at 11 hrs and the minimum at 05 hrs with a couple of exceptions. The variation is in excellent agreement with theory of turbulence which states that turbulence is minimum during night time because of stable conditions and the absence of insolation and gradually increases with insolation reaching a maximum in the afternoon because of the convective activity and decreasing thereafter. It shows that the WDFR can be taken as a good measure of surface turbulence though Sadhuram (1984) concludes that wind speed fluctuations be used instead of WDFR. The occurrence of maximum value at 11 hrs instead of at maximum temperature epoch is because of the three hourly interval chosen for this study which may have marked the maximum value. The diurnal range has decreased consistently from January to July and increased from July to December. As already discussed earlier the range of either the stability or turbulence should be minimum in the monsoonal months because of the continuous overcast and windy conditions which always tend to bring the extreme conditions to neutral. Same explanation can be offered for the $\sigma\theta$ range also. The relatively small diurnal ranges in April and May are because of the strong winds in those months. The winds in April and May are comparable to the monsoonal winds.

4.3.2. Monthly variation

The values for 00, 06, 12 and 18 hrs are picked from the diurnal charts and the monthly variations for those four timings are presented in Fig. 4.9. At 00 hrs the value slightly decreased from January to February and increased from then onwards to reach a maximum in April and May. From May onwards it decreased again till September and remained more or less same till December. At 06 hrs a similar variation is observed. The values between March and July are greater than for the other months. The monthly variation is well marked for σ_θ at 12 hrs. The minimum is observed in the monsoonal months and the maximum in December to February. At 18 hrs the variation resembled that at 00 hrs with the absolute values being higher in every month compared to those at 00 hrs. The higher values from December to May at 12 hrs and 18 hrs may be explained as due to the convective activity because of clear skies and high heat input. It may be noted here that the so called winter months December, January, February do not show the minimum temperatures compared to other seasons.

4.3.3. Yearly variation

The yearly variation of σ_θ for 05 and 11 hrs for each month from January to June is presented in Fig. 4.10 and from July to December in Fig. 4.11. In January σ_θ is minimum in 1973 and maximum in 1977 at 11 hrs. The

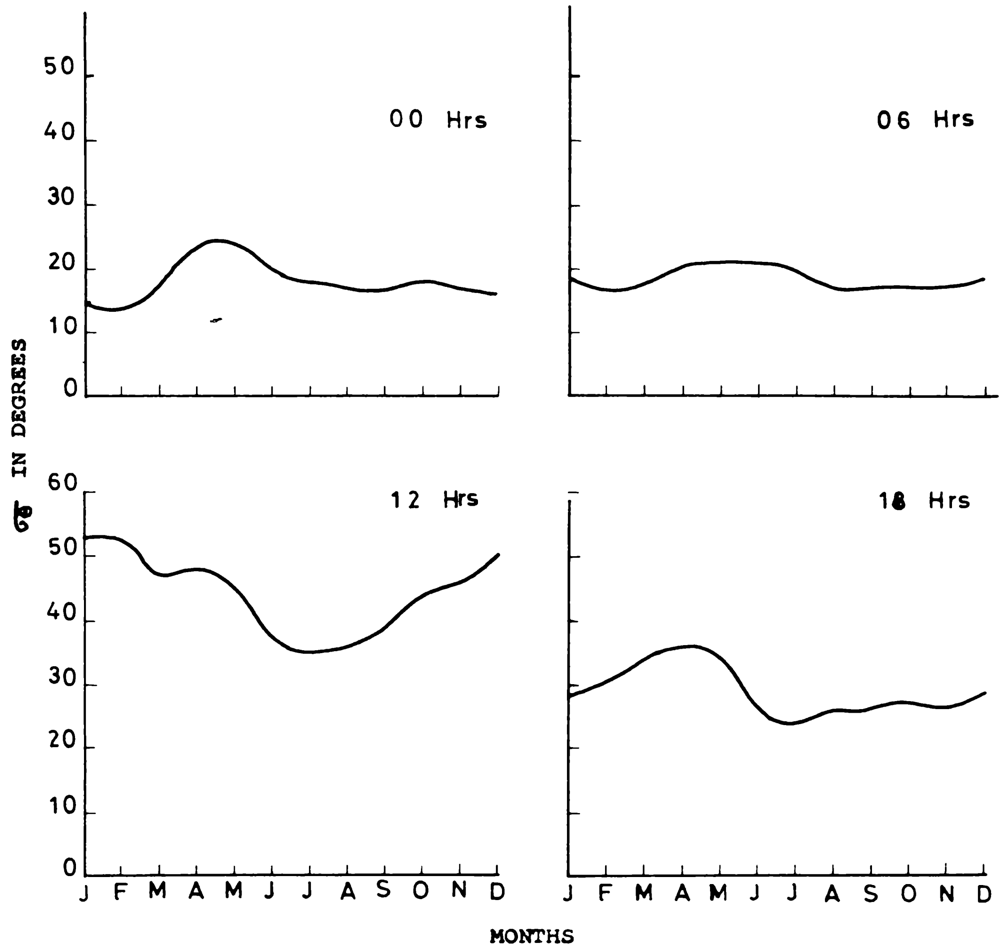


FIG. 4.9. MONTHLY VARIATION OF σθ FOR COCHIN AT 00, 06, 12 & 18 Hrs.

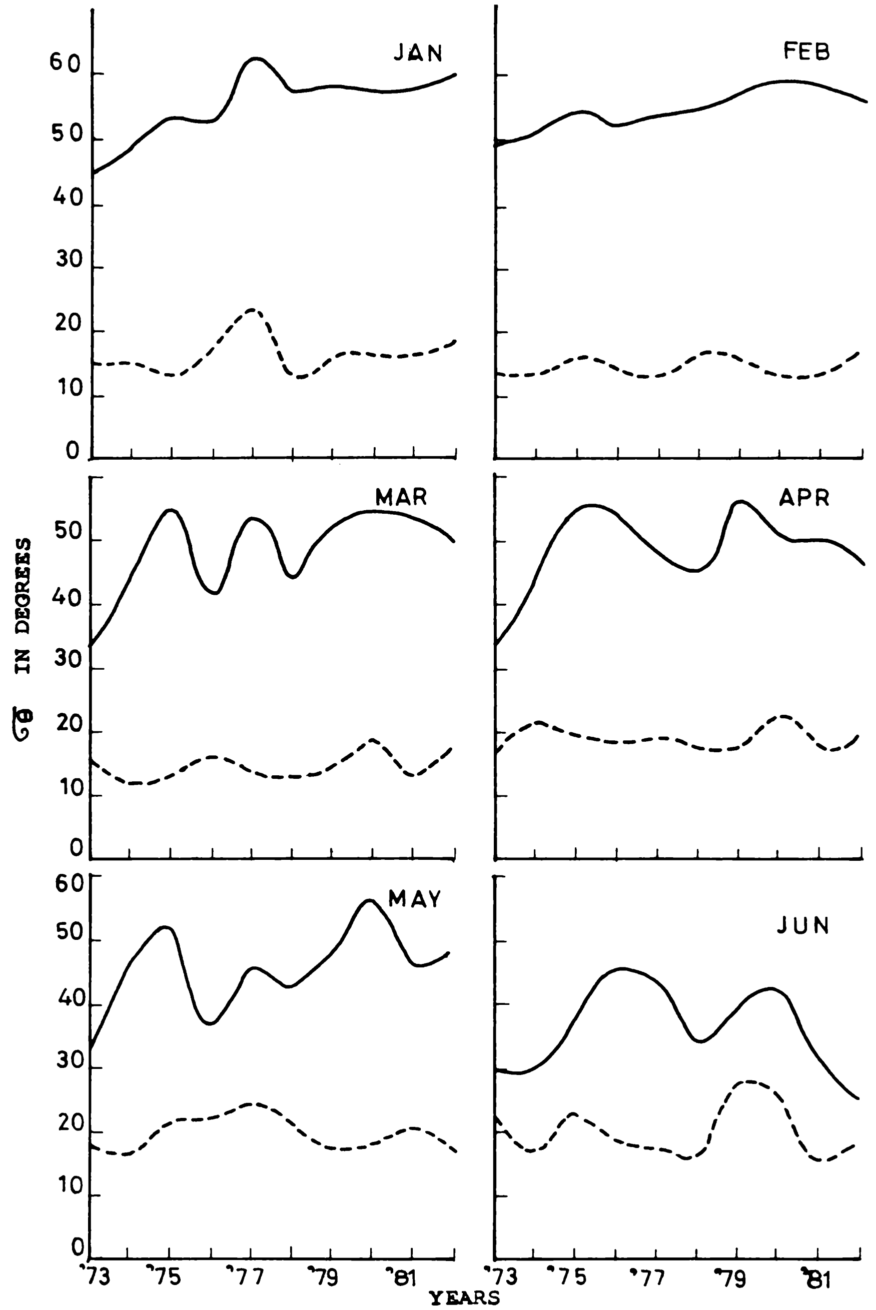


FIG. 4.10. YEARLY VARIATION OF σθ FOR COCHIN AT 05 (- - -) AND 11 (——) Hrs FROM JANUARY TO JUNE

maximum at 05 hrs is in 1977 and the minimum in 1978. The range at 11 hrs is 17.5 degrees and at 05 hrs, it is 11 degrees. The value at 11 hrs is increasing from 1973 to 1975, decreasing slightly from 1975 to 1976, sharply increasing from 1976 to 1977, again decreasing till 1978 and increasing slightly thereafter. The case for 05 hrs is different. It is decreasing from 1974 to 1975, increasing to 1977, decreasing till 1978, increasing from 1978 to 1979 and remaining the same till 1981 with a slight increase from 1981 to 1982.

In February at 11 hrs, $\sigma\theta$ is increasing from 1973 to 1980 except from 1975 to 1976. It is showing a decrease from 1980 onwards. The range at 11 hrs is 10 degrees. The variation at 05 hrs is resembling a sinusoidal oscillation. The crests are observed in 1975, 1978 and 1982 and the troughs in 1973, 1977 and 1981. The amplitude is 5 degrees.

In March and April the variation at 11 hrs is like a damping oscillation from 1973 to 1982. The maximum amplitude or range is 22 degrees in both the months. The variation at 05 hrs in March is once again like a sinusoidal oscillation, the amplitude being very small. The range is 7.5 degrees. The crests are occurring in 1973, 1976, 1980 and 1982. The range at 05 hrs in April is 5 degrees.
In May, an increase between 1973 and 1975, 1976 and 1977,

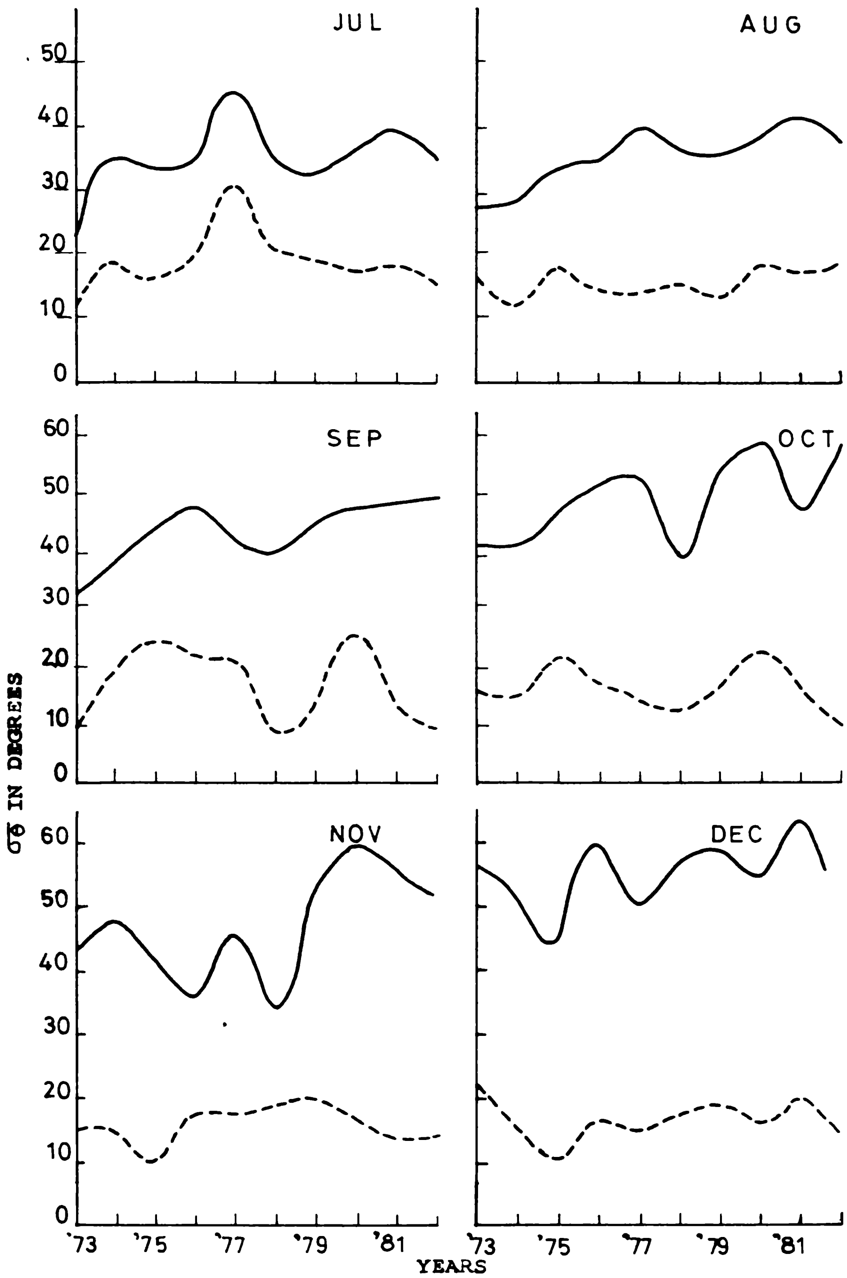


FIG. 4. 11. YEARLY VARIATION OF σ_θ FOR COCHIN AT 05(- - -) AND 11(——) Hrs FROM JULY TO DECEMBER

1978 and 1980 and again between 1981 and 1982 is observed at 11 hrs.

At 05 hrs in the same month, $\sigma\theta$ varied between 17 degrees and 25 degrees. The range at 11 hrs is 24 degrees. In June, $\sigma\theta$ increased from 1973 to 1976 and 1978 to 1980 and decreased from 1976 to 1978 and 1980 to 1982. The range at 11 hrs is 21 degrees. At 05 hrs the range is as high as 12 degrees, the value varying between 16 and 27.5 degrees. In July, the variation at 11 hrs and at 05 hrs are similar, having their peaks in 1977 and minimum in 1973. The range at 05 hrs is almost comparable to that at 11 hrs, the values being 20 and 22 degrees respectively. In August, the value at 11 hrs is on the increase from 1973 to 1982 with a few undulations. The range is only 14 degrees at this hour. At 05 hrs the range is 7 degrees with the value varying between 12 and 18 degrees respectively in 1974 and 1982. The range in September at both the hours are comparable, once again having almost the same value. The value at 11 hrs appears to be on the increase from 1973 to 1982 except between 1976 and 1978. The variation at 05 hrs in this month as well as in October showed once again a sinusoidal type of oscillation. In October at 11 hrs, an increasing trend is observed. The range is 17 degrees, the minimum occurring in 1978 and maximum in 1980. In November and December, the value at 11 hrs is having wide fluctuations though an increasing trend is observed. The range in November at 11 hrs is as high as 26 degrees, whereas, in December it is 19 degrees. At 05 hrs more or less similar variations are observed in both the months. The range in November is 10 degrees and the value varied between 10 degrees and 20 degrees while the range in December is 12 degrees with the value varying between 22 and 10 degrees.

Table 4.1 gives the Standard Deviation (SD) and the coefficient of variation of the yearly variation for every 3 hrs. From September to February the coefficient of variation is more during night time than compared to that of day time, the maximum variation being at 20 hrs in January and at 05 hrs in September. Between 11 and 17 hrs the coefficient of variation appears to be rather low in most of the cases. This is to be expected because the arithmatic mean is more in this period compared to that at other timings. Though the SD is also more during this period, proportionately the mean is much more, hence a small coefficient of variation. The interesting feature is that the coefficient of variation in most of the cases is below 20% which suggests that a lesser period, say 5 years, would suffice to establish the climatology of σ_θ, the wide fluctuations in some of the cases, notwithstanding. This fact is emphasized because,

Table 4.1

Standard deviation (in degrees) and Coefficient of variation of $\sigma\theta$ for every 3 hours

Month		Time in IST 2	5	8	11	14	17	20	23
January	SD	3.3	3.3	4.2	5.7	5.7	5.4	8.1	2.7
	CV	24.0	20.0	18.0	10.0	15.0	17.0	38.0	18.0
February	SD	2.7	1.6	2.7	3.3	6.6	6.6	4.8	3.9
	CV	20.0	12.0	12.0	6.0	17.0	20.0	20.0	28.0
March	SD	2.4	2.4	3.6	6.9	7.2	6.0	4.2	2.4
	CV	16.0	16.0	15.0	14.0	18.0	17.0	16.0	13.0
April	SD	3.6	1.8	4.8	6.3	7.5	9.6	4.2	3.9
	CV	17.0	9.0	16.0	13.0	18.0	25.0	16.0	16.0
May	SD	2.4	2.7	5.7	6.9	6.9	6.3	5.4	3.0
	CV	11.0	14.0	19.0	15.0	17.0	18.0	20.0	12.0
June	SD	3.6	4.2	5.1	6.9	5.1	4.8	4.2	3.0
	CV	17.0	21.0	19.0	19.0	14.0	17.0	19.0	16.0
July	SD	3.3	5.4	5.4	6.0	4.8	4.5	4.5	3.0
	CV	19.0	30.0	24.0	17.0	15.0	17.0	23.0	17.0
August	SD	1.8	2.4	3.6	4.5	4.8	3.9	3.9	2.7
	CV	11.0	16.0	17.0	13.0	14.0	13.0	20.0	17.0
September	SD	5.1	5.7	7.2	5.1	5.4	5.4	2.4	3.0
	CV	36.0	38.0	30.0	13.0	15.0	19.0	12.0	18.0
October	SD	4.8	3.6	4.8	6.6	4.8	6.3	3.9	4.2
	CV	31.0	25.0	19.0	15.0	13.0	21.0	20.0	24.0
November	SD	4.2	3.0	5.1	8.4	6.9	6.6	7.8	4.5
	CV	26.0	19.0	20.0	18.0	17.0	23.0	37.0	26.0
December	SD	3.3	3.6	4.2	6.6	5.1	3.6	4.8	3.3
	CV	21.0	22.0	16.0	12.0	11.0	11.0	29.0	21.0

SD = Standard deviation
CV = Coefficient of variation

analysing that many charts is rather laborious, especially when it does not result in much deviation.

4.4. Relation between PS, $\sigma\theta$ and MH

The stability, $\sigma\theta$ and MH are shown to exhibit a clear-cut diurnal variation and as such it is of interest to study the inter relationship between stability and $\sigma\theta$ and $\sigma\theta$ and MH. The relationship between PS and $\sigma\theta$ is presented for the 4 months January, April, July and October typical of the seasons winter, pre-monsoon, monsoon and post-monsoon respectively, in the form of Arithmatic Mean (AM), Median, Mode, Mean Deviation (MD), Standard Deviation (S.D.) and Coefficient of Variation (CV). Regression equations have been developed for finding out MH from $\sigma\theta$ for the 4 months mentioned above. It is to be noted here that the value of $\sigma\theta$ used in this section are obtained from the Slades method in order to compare the results of earlier studies by others.

4.4.1. PS vs $\sigma\theta$

Tables 4.2 to 4.5 represent the AM, Median, Mode, MD, SD and CV of $\sigma\theta$ for P.S. Classes A, B, C, D, E and F for the months January, April, July and October respectively. In January the AM, Median and Mode of $\sigma\theta$ are decreasing from 'A' to 'F' with the maximum for 'A' and minimum for 'F'. No distinction could be made between

Table 4.2

σ_θ in relation to Pasquill's stability classes for Cochin - January

Stability	AM	Median	Mode	Mean deviation	SD	Coefficient variation %
A	17.2	17.1	17.1	4.1	5.4	31.2
B	12.0	11.6	11.2	4.2	5.0	41.9
C	10.0	9.9	10.2	3.4	3.8	37.6
D	10.2	10.1	9.9	2.8	3.7	36.3
E	8.5	8.5	8.1	2.4	3.0	35.2
F	5.7	5.6	5.5	2.2	3.0	53.1

Table 4.3

$\sigma\theta$ in relation to Pasquill's stability classes for Cochin - April

Stability	AM	Median	Mode	Mean deviation	SD	Coefficient variation %
A	16.4	16.4	16.4	3.5	4.3	26.0
B	14.3	14.4	14.6	3.2	4.1	28.6
C	12.6	12.7	14.7	3.7	4.5	36.1
D	11.9	12.0	12.1	3.0	3.7	30.7
E	10.7	10.5	7.6	3.1	3.5	33.1
F	7.2	6.7	4.9	2.8	3.2	44.7

Table 4.4

σ_θ in relation to Pasquill's stability classes for Cochin - July

Stability	AM	Median	Mode	Mean deviation	SD	Coefficient variation %
A	11.9	11.2	9.0	3.9	4.7	39.4
B	12.6	12.1	11.3	3.8	4.5	36.0
C	10.0	9.6	9.0	3.4	4.1	41.0
D	8.8	8.5	7.9	2.8	3.6	41.1
E	7.0	6.6	6.1	2.2	2.6	37.6
F	5.1	4.8	3.8	2.6	3.4	66.6

Table 4.5

σ_θ in relation to Pasquill's stability classes for Cochin - October

Stability	AM	Median	Mode	Mean deviation	SD	Coefficient variation %
A	14.7	14.7	14.6	3.9	4.7	31.6
B	13.5	13.7	14.0	3.8	4.6	34.4
C	10.8	10.3	9.3	3.6	4.2	39.1
D	9.5	9.3	8.8	3.0	3.6	38.1
E	5.4	5.2	5.0	2.4	3.3	61.1
F	6.5	6.3	4.7	2.2	2.5	28.0

'C' and 'D'. MD and SD are also observed to be high for unstable conditions and low for stable conditions, while, CV is maximum for 'F' followed by 'B', 'C', 'D', 'E' and 'A'.

In April the mean values are once again observed to decrease from unstable to stable conditions. The values for 'F' have gone up in this month compared to those in January. The MD and SD are lower for unstable conditions in comparison with those in January and high for stable and neutral conditions with an exception for 'C'. The CV is once again maximum for 'F'. The CV, however, is comparatively low in all the cases compared to that in January. The mean σ_θ in April are higher than those in January except for 'A'.

In July, surprisingly the means of σ_θ for 'B' are more than that for 'A'. However from 'B' onwards the decreasing trend followed to 'F'. The means have come down considerably in this month and so is the range between 'A' and 'F'. With not much deviation in MD and SD from those in January and April and the means having come down, the CV have gone up considerably to a value of as high as 66.6% in 'F', the minimum being 36% in 'B'.

In October, the means have once again risen but still less than those in April. The trends are also maintained except for 'E' MD and SD have shown consistent fall from 'A' to 'F'. The CV is maximum for 'E' and minimum for 'A'.

The reversal trends between 'A' and 'B' in July and between 'E' and 'F' in October are mainly due to the extremely small frequencies of occurrence of 'A' in July and 'E' in October. Though the trends are maintained in the rest of the cases. The CV is very high for 'F'. It is often difficult to distinguish between 'C' and 'D' because of very narrow difference of the means between these two. If one considers the range in each of these categories it is always more than the difference between the mean representative σ_θ of any two successive PS categories. It is alarming to note that in some cases the ranges of σ_θ for individual PS categories is more than the total difference between σ_θ for 'A' and σ_θ for 'F'. With so much of deviation it is certainly not possible to pin-point the exact value of σ_θ for any of these stability categories. The seasonal variation is also well marked. The values are maximum in April and minimum in July and hence one set of values for all the months will lead to spurious results. They should be found out at least for each season if not for every month.

Table 4.6 gives the mean values of σ_θ for each of the PS categories by Sadhuram (1982), Padmanabha Murty and Gupta (1979), Shirvaikar (1965) and Slade (1968). Only Sadhuram (1982) has given the seasonal variation. The values computed by Sadhuram for Visakhapatnam are in very good agreement with the present computed values. The values presented by Padmanabha Murty and Gupta at 2.5 metres from the ground for a site which is located 150 km southeast of Delhi are comparable with the present values for July and those at 20.5 metres are lower than the lowest values of the present study. Slades values are undoubtedly high for unstable conditions and low for stable conditions.

The comparison brings out that the seasonal values of σ_θ are to be established for each of these stabilities. The question, however, remains whether an unique value can be suggested for a particular stability or with some range, which should be less than 0.5 of the difference between the means of σ_θ for that stability and for the following stability. This does not seem to be probable because of the wide deviation noticed.

4.4.2. σ_θ Vs MH

Linear regression equations have been obtained relating MH and σ_θ for the months of January, April, July and October (Fig. 4.12).

Table 4.6

Comparison of σ_θ values with those determined by others

Pasquill	Mean value of σ_θ by Sadhuram				Mean value of σ_θ Padmanabhamurthy and Gupta		Mean value of σ_θ given by	
	Jan.	Apr.	Aug.	Oct.	2.5 mts.	20 mts.	Slade	Shirvaikar
A	16.3	17.0	11.7	14.0	14.0	12.0	25.0	10.0
B	11.8	12.7	9.5	10.5	12.5	10.5	20.0	7.0
C	8.0	8.8	7.4	7.8	9.5	8.0	15.0	5.0
D	6.0	7.5	6.9	6.6	7.5	6.0	10.0	3.5
E	5.7	6.5	5.2	5.7	6.0	4.0	5.0	2.5
F	4.5	5.7	4.5	4.0	4.0	2.0	2.5	1.5

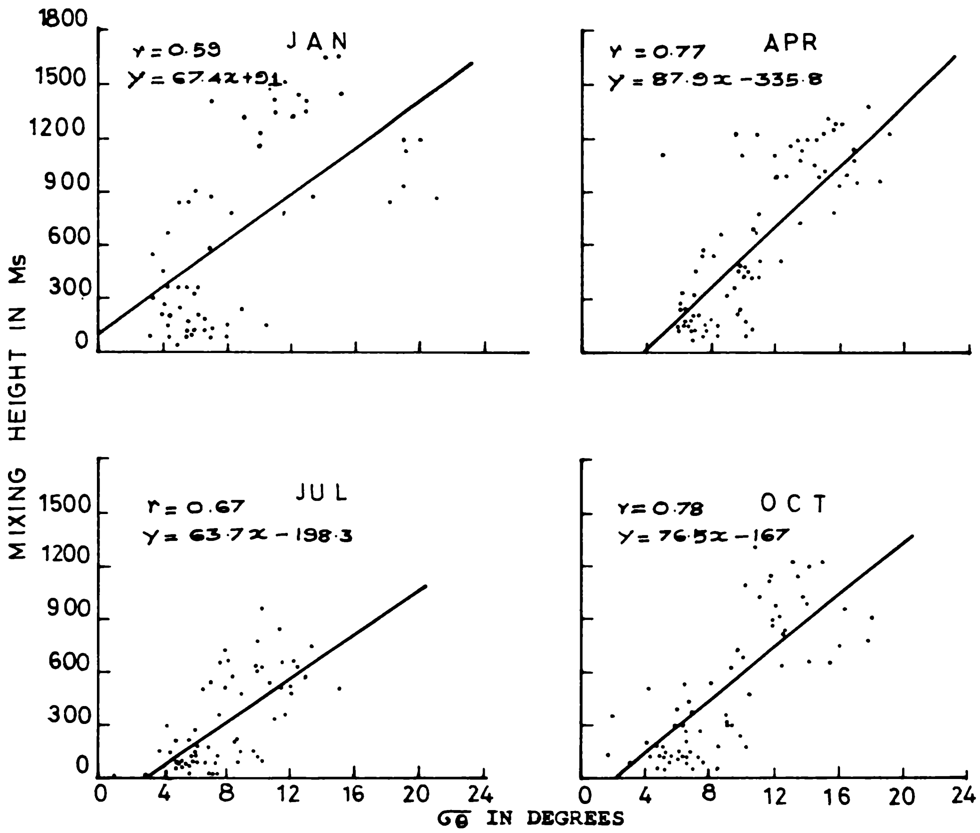


FIG. 4.12. RELATION BETWEEN σθ AND MIXING HEIGHT FOR COCHIN

The equations are

$$MH = 67.4\ \sigma\Theta + 91 \quad \text{(for January)}$$

$$MH = 87.9\ \sigma\Theta - 335.8 \quad \text{(for April)}$$

$$MH = 63.7\ \sigma\Theta - 198.3 \quad \text{(for July)}$$

and $$MH = 76.5\ \sigma\Theta - 167 \quad \text{(for October)}$$

The negative constants indicate that even if there is some value of $\sigma\Theta$, MH can be zero. This situation is observed in April, July and October while in January it has a positive intercept of Y axis which means that the vertical mixing can be there even if $\sigma\Theta$ is zero. The correlations between $\sigma\Theta$ and MH are 0.59 in January, 0.77 in April, 0.67 in July and 0.78 in October. The lowest correlation coefficient in January compared to that in other months, the positive intercept of Y axis and the wide scatter shows the relative non dependency of the relation between MH and $\sigma\Theta$, though the correlation is considerable otherwise. The negative intercept can be explained because MH in this case is computed purely based on the heat input at the surface and the vertical thermal structure of the atmosphere but does not take into consideration the mechanical mixing. $\sigma\Theta$ on the other hand, can be present even in the absence of thermal turbulence although the thermal turbulence enhances WDFR and consequently $\sigma\Theta$. In otherwards the MH is purely thermal while $\sigma\Theta$ is due to both thermal as well as mechanical turbulence. With the help of these regression equations, MH can be obtained from the values of $\sigma\theta$ with a fair degree of accuracy. $\sigma\theta$ is relatively easy to be computed from the anemograms. As MH requires the knowledge of the vertical thermal structure which may not be available at all the places, it can be computed from the values of $\sigma\theta$.

4.5. Summary

The diurnal, monthly and the yearly variation of PS and $\sigma\theta$ are studied, both of which have exhibited a clear-cut diurnal variation and monthly variation. Unstable conditions during day time and stable conditions during night time are the common features in all the months with neutral category having more frequency during the monsoonal months. Classes 'A' and 'D' are shown to have a reversal trend as far as monthly variations are concerned. The comparison with stabilities of other cities revealed that 'D' frequency is more in Cochin than in other cities. The yearly variation is shown to have reversal trends when only two categories are present and not a well marked variation when all the 4 categories are present. The range of the diurnal variation of $\sigma\theta$ is minimum in monsoonal month and maximum in winter months and showed a systematic variation in between. It is also shown that $\sigma\theta$ is a good measure of surface turbulence. $\sigma\theta$ is also shown to have considerable yearly variation and varying mostly in a sinusoidal oscillation. The CV and SD for the yearly variation are also presented for every month and the CV is considerably low. It is suggested that a 5 year period is enough to establish the climatology of σ_Θ. The relation between each of the PS and σ_Θ is found out for 4 typical months and the relationship is shown to have considerable monthly variation. It is also shown how difficult it is to give a unique value of σ_Θ for each PS category in view of the considerable deviations from mean of σ_Θ for individual stability. Finally the regression equations for computing MH from the values of σ_Θ alone are given because, a high degree of correlation is found to exist between σ_Θ and MH. Henceforth σ_Θ values can also be used for computing MH at any given location provided such regression equations are developed separately for individual places.

C H A P T E R - 5

5. GAUSSIAN PLUME MODEL FOR MULTIPLE SOURCES FOR COCHIN

5.1. Introduction

5.2. Results and discussion

5.2.1. Industrial sources and their emissions

5.2.2. Spatial distribution of SO_2 concentration

5.3. Summary

5.1. Introduction

The atmospheric dispersal capacity over Cochin, the frequency of occurrence of inversions and the stability of the atmosphere in relation to surface turbulence and mixing height have been discussed in detail in the preceeding chapters. The details of the Gaussian Plume Model (GPM) are given in chapter II. In the present chapter, the spatial distribution of the concentration of sulphur dioxide by means of GPM for multiple sources for Cochin, is studied. The results and discussion are given for each month. For the abatement of air pollution, some steps are suggested. The optimum locations for the industrial developments are also pointed out.

5.2. Results and discussion

5.2.1. Industrial sources and their emissions

Fig. 5.1. shows the 4 x 4 km grids over Cochin in which three major sources were identified, namely, source I, source II and source III. Source I comprises of Premier Tyres, Sree Chitra Mills, H.M.T., Carborandum Universal, Modern Bakery and Milma. All these factories have an overall emission of 866 kg/day of SO_2. Sources II

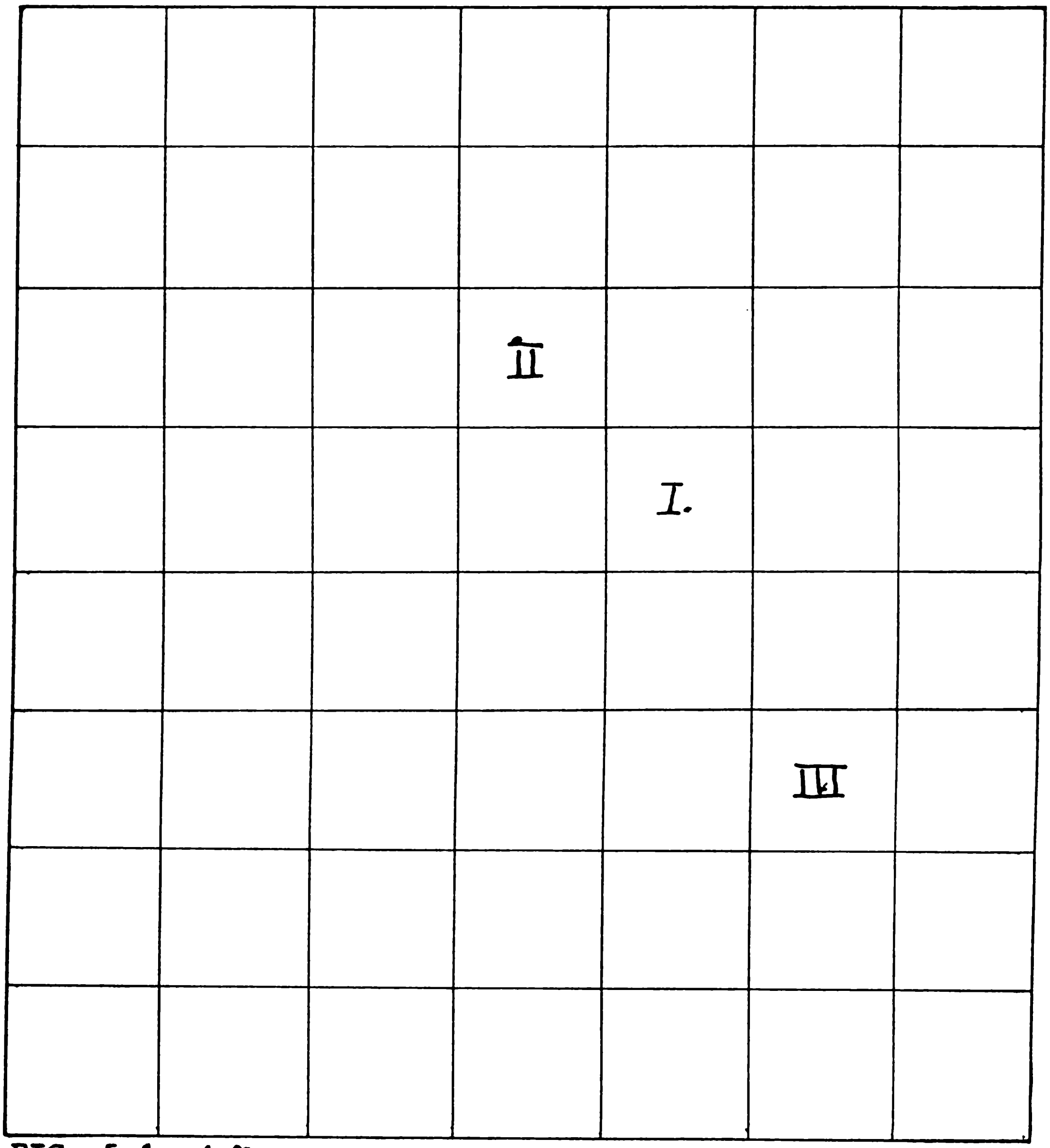


FIG. 5.1. 4 Km x 4 Km GRID OF COCHIN - LOCATIONS OF THE SOURCES

comprises of F.A.C.T., T.C.C., I.R.E., Cominco Binani Zinc, Periyar Chemicals, Kerala Acids and United Catalysts India Limited, amounting to an overall emission of 2.5 tons per day of SO_2. Source III comprises of Refinery, F.A.C.T. and Carbon Chemicals amounting to approximately 11.2 tons per day of SO_2. For the sake of convenience, all the physical stack heights falling in each source are averaged to have one representative stack height, from which the total emission from the corresponding source is assumed to occur. The representative plume rise is computed from the formula mentioned in chapter 2, by taking the average plume temperature within each source and the stack exit diameter.

5.2.2. Spatial distribution of SO_2 concentration

The SO_2 concentration from each source is computed for every hour at various distances from the source depending upon the stability, mixing height and wind roses as mentioned in chapter 2. In each grid, the contributions from all the three sources are added for every hour and the 24 hour cumulative value has been found out. The isolines in hundreds of $\mu g/m^3$ are drawn with two hundred $\mu g/m^3$ interval for each month.

Fig. 5.2 shows the spatial distribution of SO_2 concentration for January. The distribution is more or less uniform with slight intrusion towards west and South. As is to be expected, the maximum values occurred near the sources. The concentration between 400 and 600 $\mu g/m^3$ are recorded in the built up and thickly populated areas of Ernakulam. On the southeast sector, the extreme portion has shown a value of 200 $\mu g/m^3$. A value of 400 $\mu g/m^3$ is recorded beyond Alwaye in the Northeast sector.

Fig. 5.3 depicts the spatial distribution of SO_2 concentration for February. Most of the city and its suburbs have recorded a concentration of more than 600 $\mu g/m^3$ with maximum near Kalamassery. The distribution is more or less uniform with a slight spread towards Southeast. The values in this month are higher than those in January. The areas of dense population have recorded values ranging between 400 and 600 $\mu g/m^3$. There is a sharp fall of concentration towards North and a very gradual fall towards South.

The spatial distribution for March is represented in Fig. 5.4. The concentrations are further high in this month compared to previous months. The maximum is observed

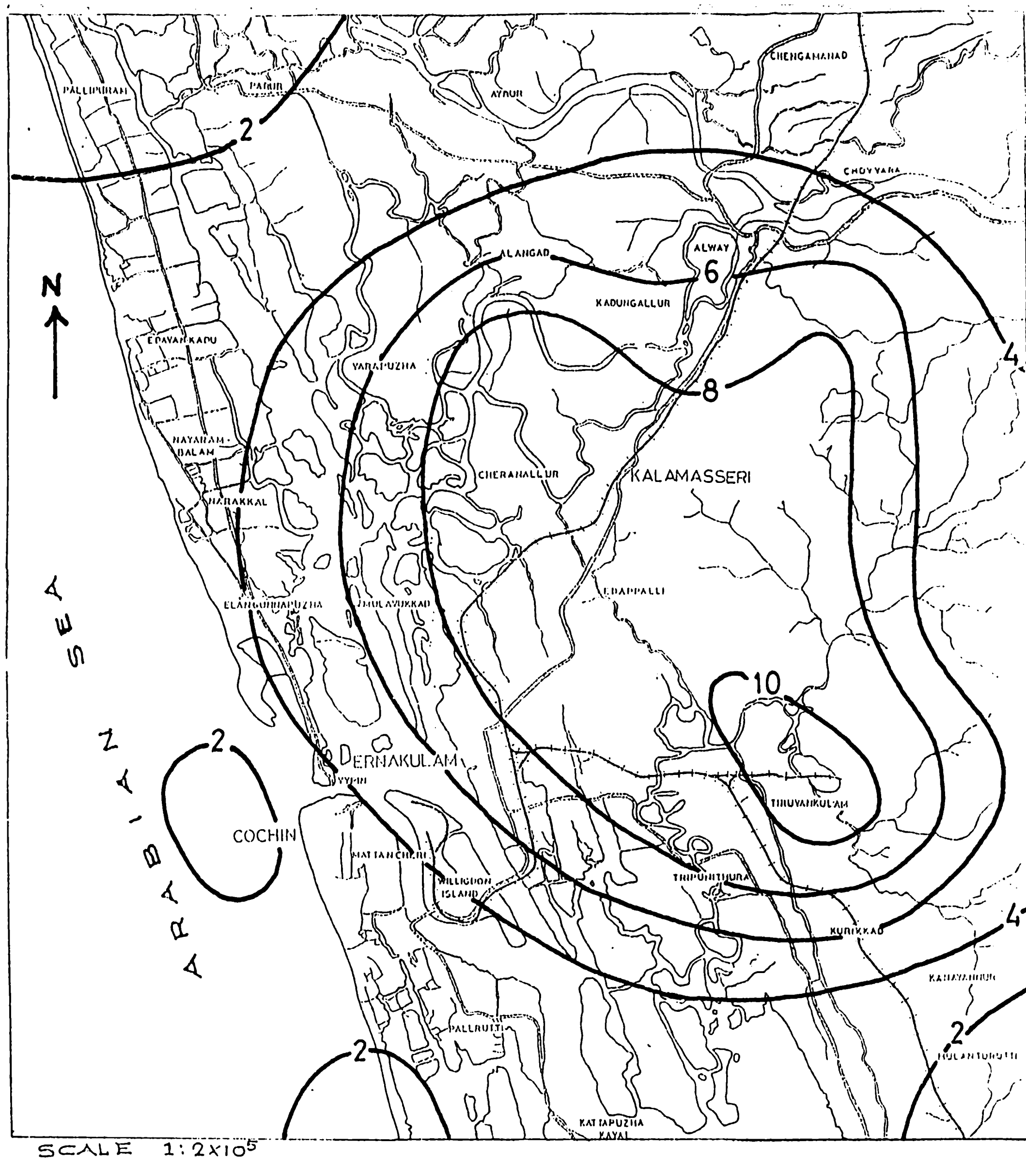


FIG.5.2. SPATIAL DISTRIBUTION OF 24Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN JANUARY

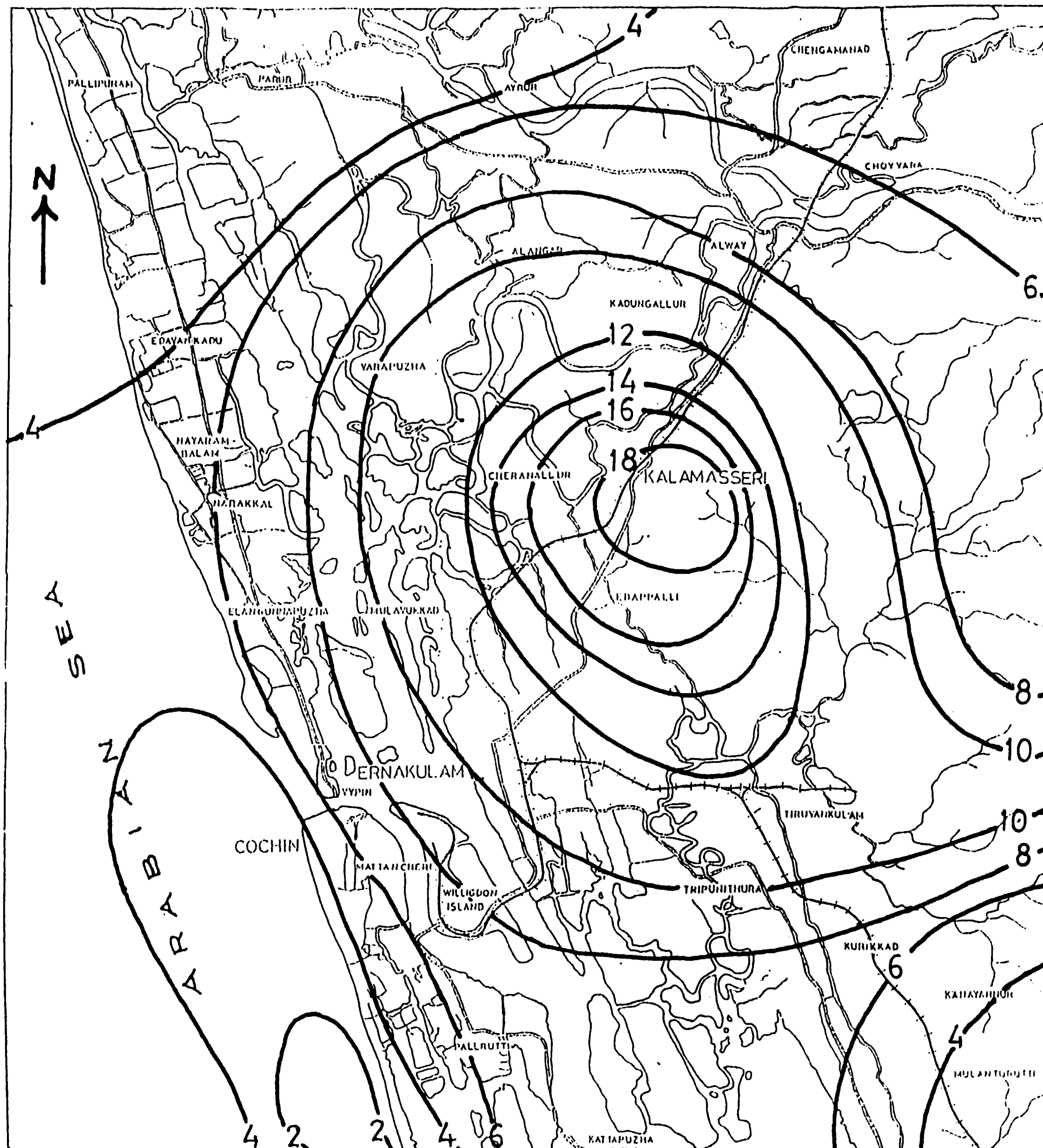


FIG.5.3. SPATIAL DISTRIBUTION OF 24 Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN FEBRUARY

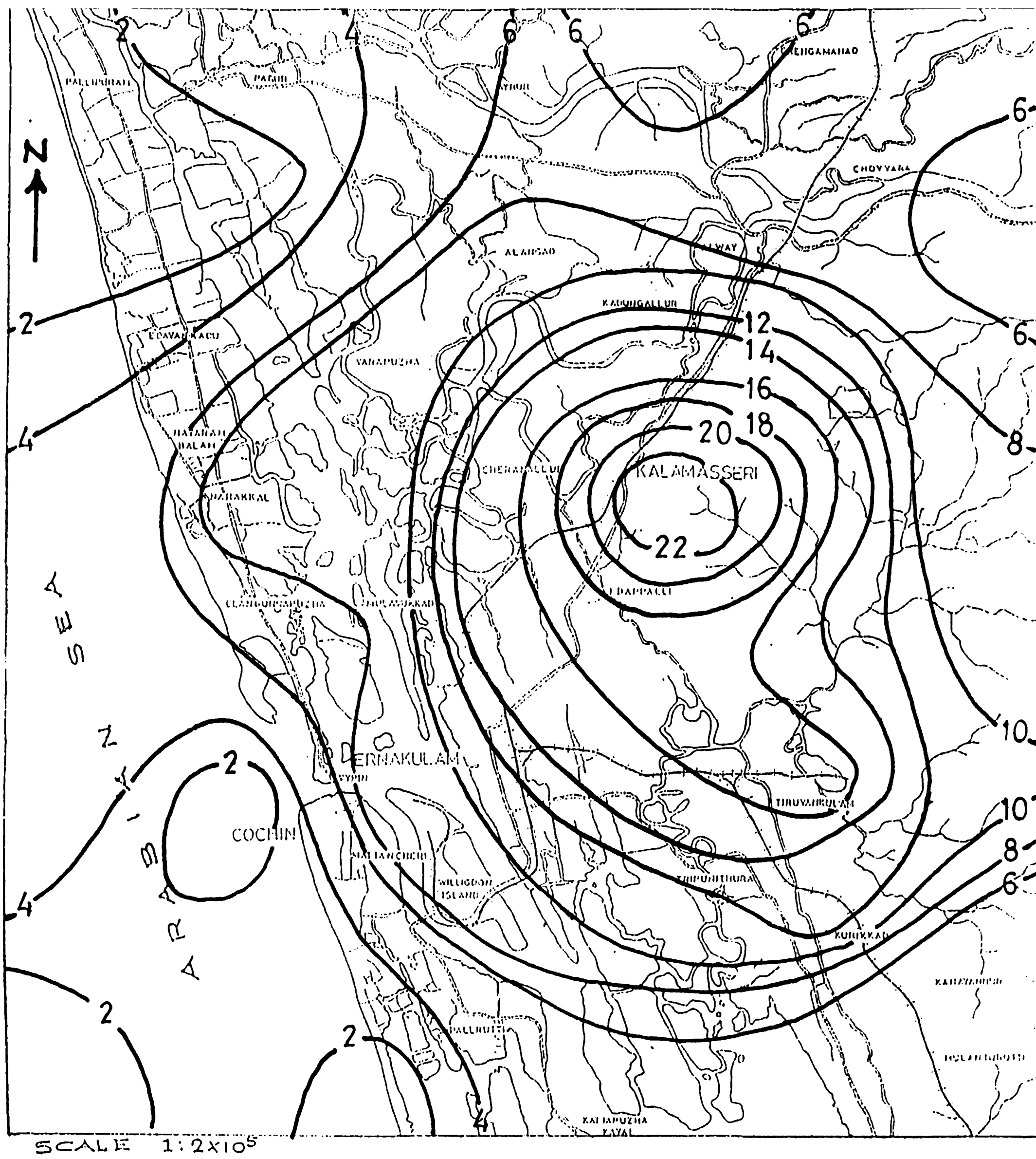


FIG.5.4. SPATIAL DISTRIBUTION OF 24 Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN MARCH

in Kalamassery region with a very sharp fall towards North. Once again the distribution is slightly towards South upto the Ambalamughal region and a sharp fall thereafter. Once again very high values are noticed in the densely populated areas.

Fig.5.5 shows the distribution in April. There is a sharp decrease of the concentration in this month compared to that in March and February, the maximum value recorded being 1400 $\mu g/m^3$. The spread is once again towards South with more or less uniform distribution in all directions except towards Westnorthwest, where a kink of 600 $\mu g/m^3$ isoline is noticed. Most of the built up areas and thickly populated areas have recorded values ranging between 400 and 600 $\mu g/m^3$.

Fig.5.6 depicts the distribution for May. The spread of the concentration is towards Southeast and Northeast and the values are relatively low in this month compared to that in April. Once again most of the urban region has shown the concentration between 400 and 600$\mu g/m^3$.

The concentration distribution for June is shown in Fig.5.7. One can notice a sharp increase from that of May, though spread is mostly towards Southeast, Southwest and Northeast directions. While there is a very sharp fall both along Southwest and Northeast, the fall is very gradual along Southeast from the source. In most of the built up areas, the recorded concentration shows a value of 600 $\mu g/m^3$. The area under the 600 $\mu g/m^3$ isopleth is more in this month compared to that in May.

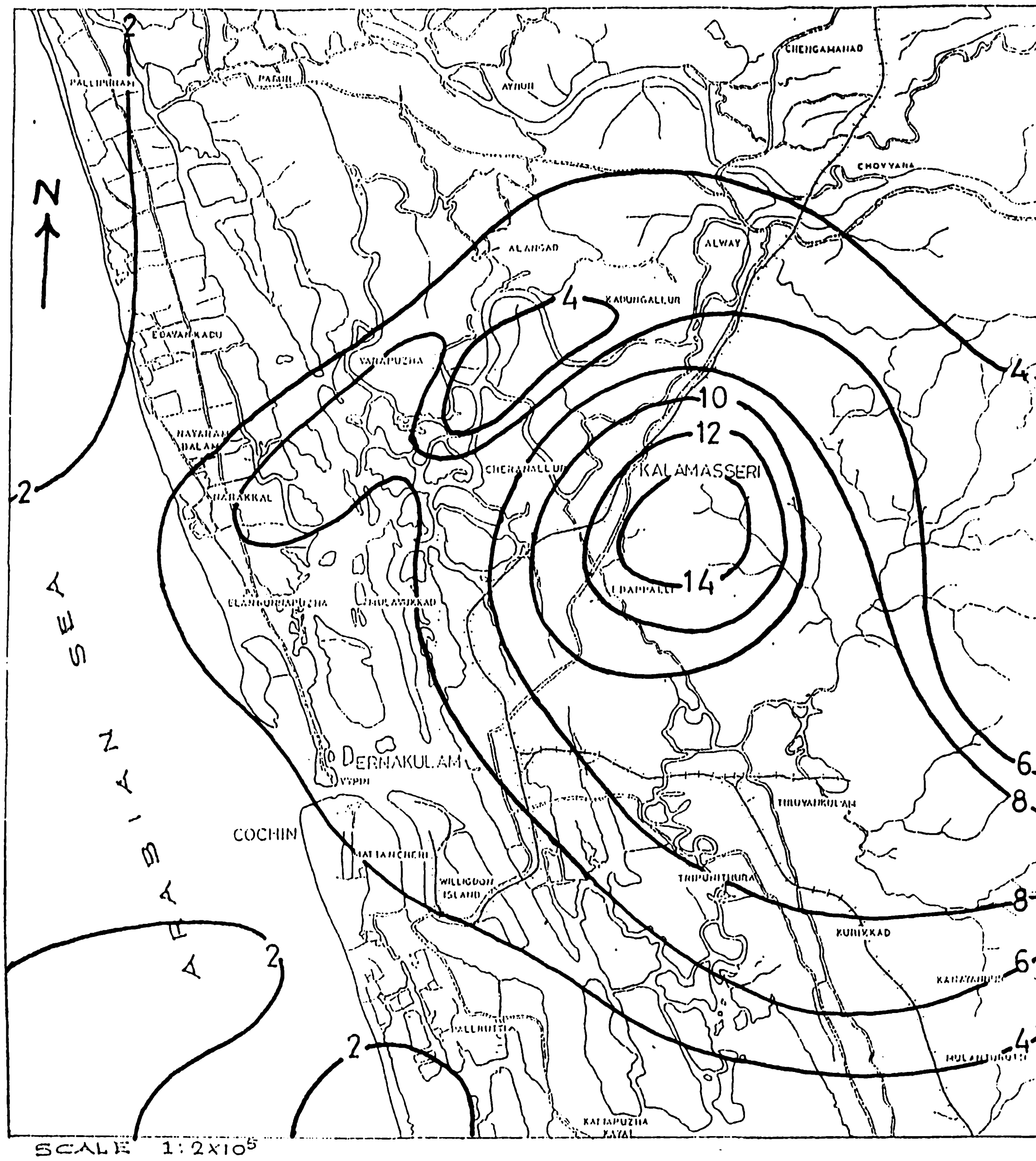


FIG. 5.5. SPATIAL DISTRIBUTION OF 24 Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN APRIL

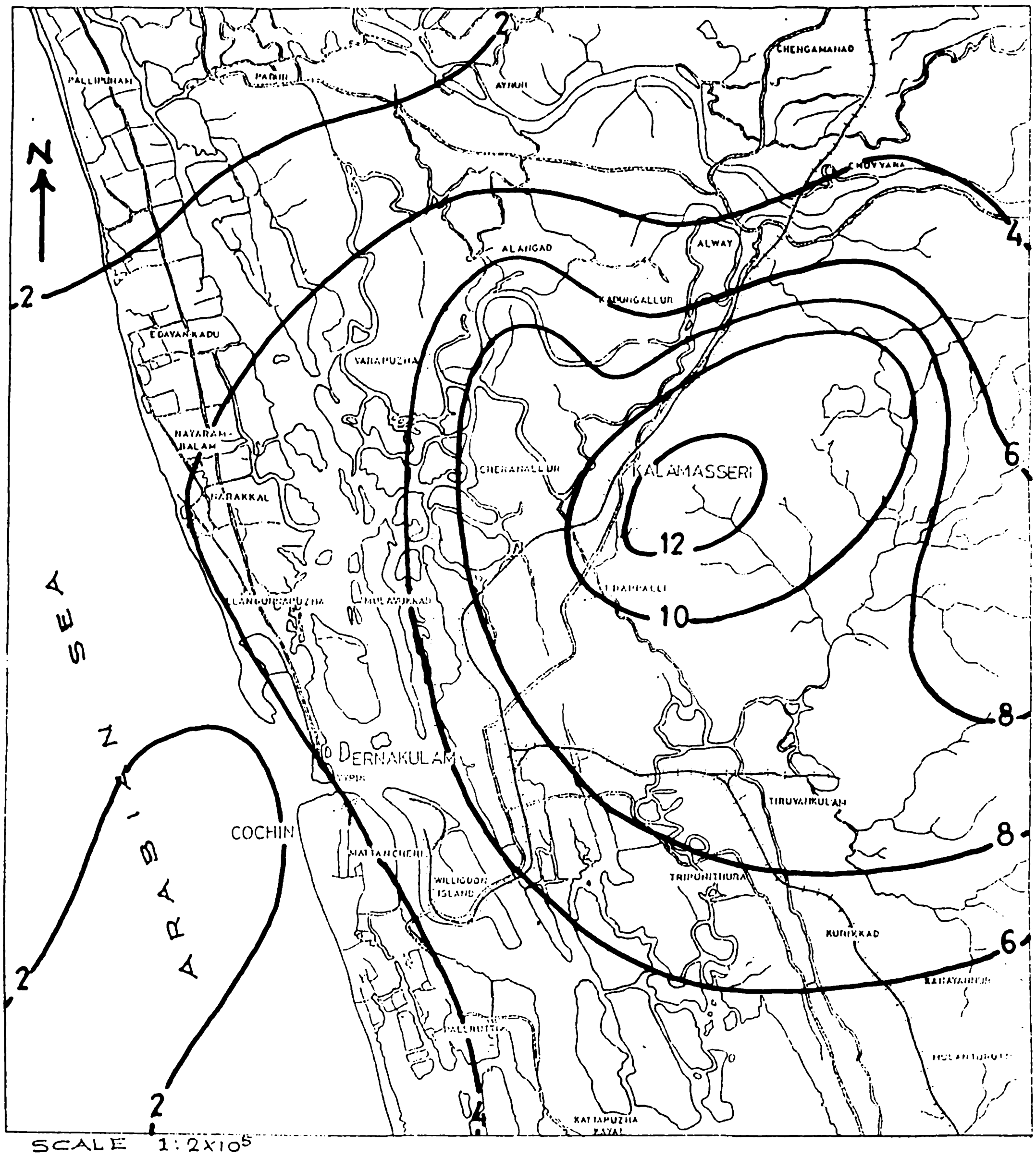


FIG.5.6. SPATIAL DISTRIBUTION OF 24 Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN MAY

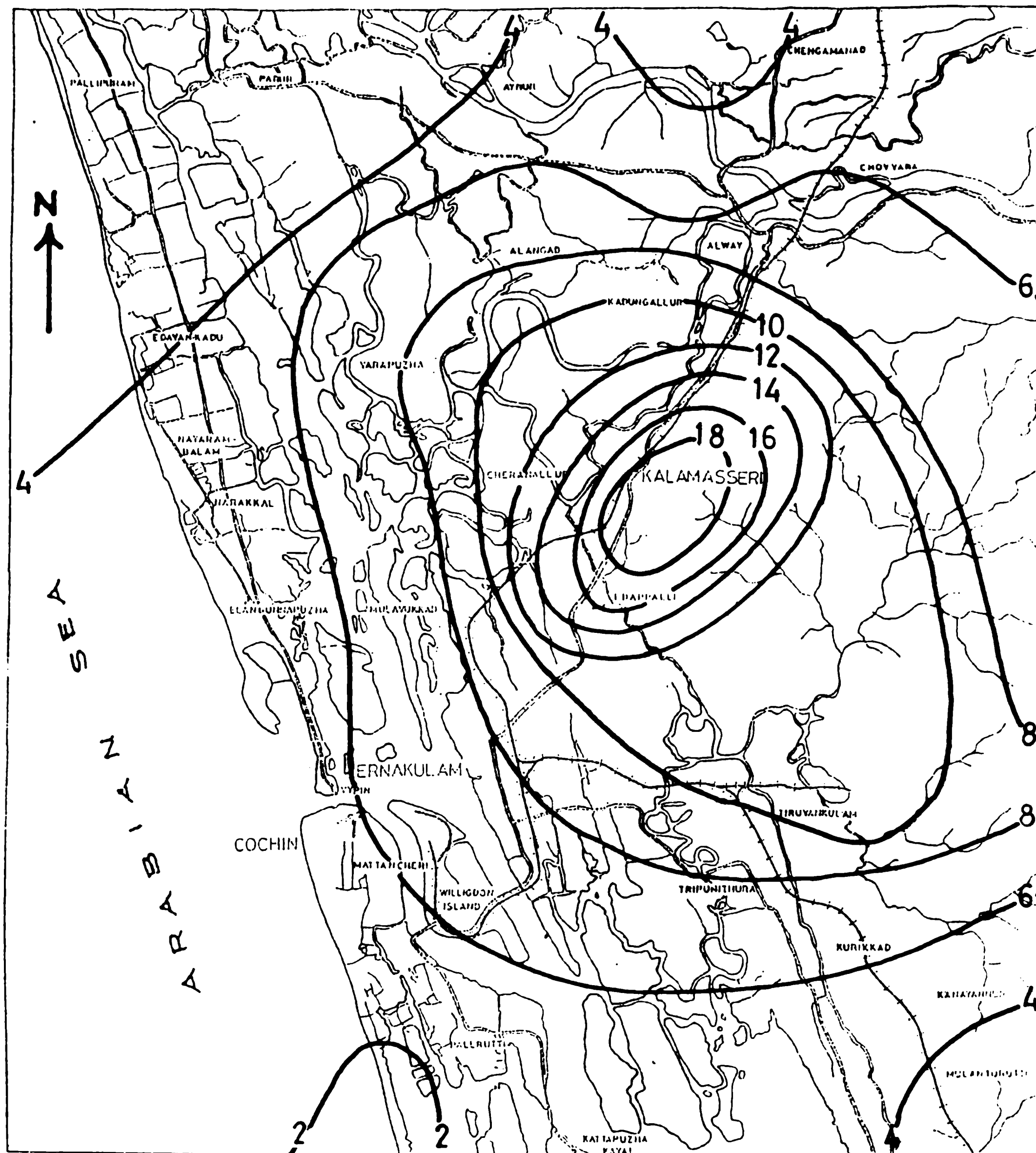


FIG.5.7. SPATIAL DISTRIBUTION OF 24 Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN JUNE

Fig. 5.8 shows the distribution for July. The pollutant is spread in the Northwest and Southeast directions with a sharp fall towards the former and a gradual fall towards the latter. The maximum value in this month is lower than that in June. The area under the 600 $\mu g/m^3$ isopleth is also lower in this month compared to that in June with the built up areas and densely populated areas showing a value of 400 $\mu g/m^3$.

The distribution for August is depicted in Fig. 5.9. There is a sudden increase of concentration in this month compared to that in July. The pollutant spread is once again towards Northwest and Southeast with a sharp fall towards the former and a gradual fall towards the latter. The area under the 600 $\mu g/m^3$ isopleth has further gone up than compared to that in July. The thickly populated areas have shown the values around 600 $\mu g/m^3$.

The spatial distribution in September is shown in Fig. 5.10. One can see a primary and a secondary maximum in this month in the vicinity of the respective sources, with values falling rapidly in all the directions from the centres of those maximum. For the first time most of the built up areas have shown the lowest value

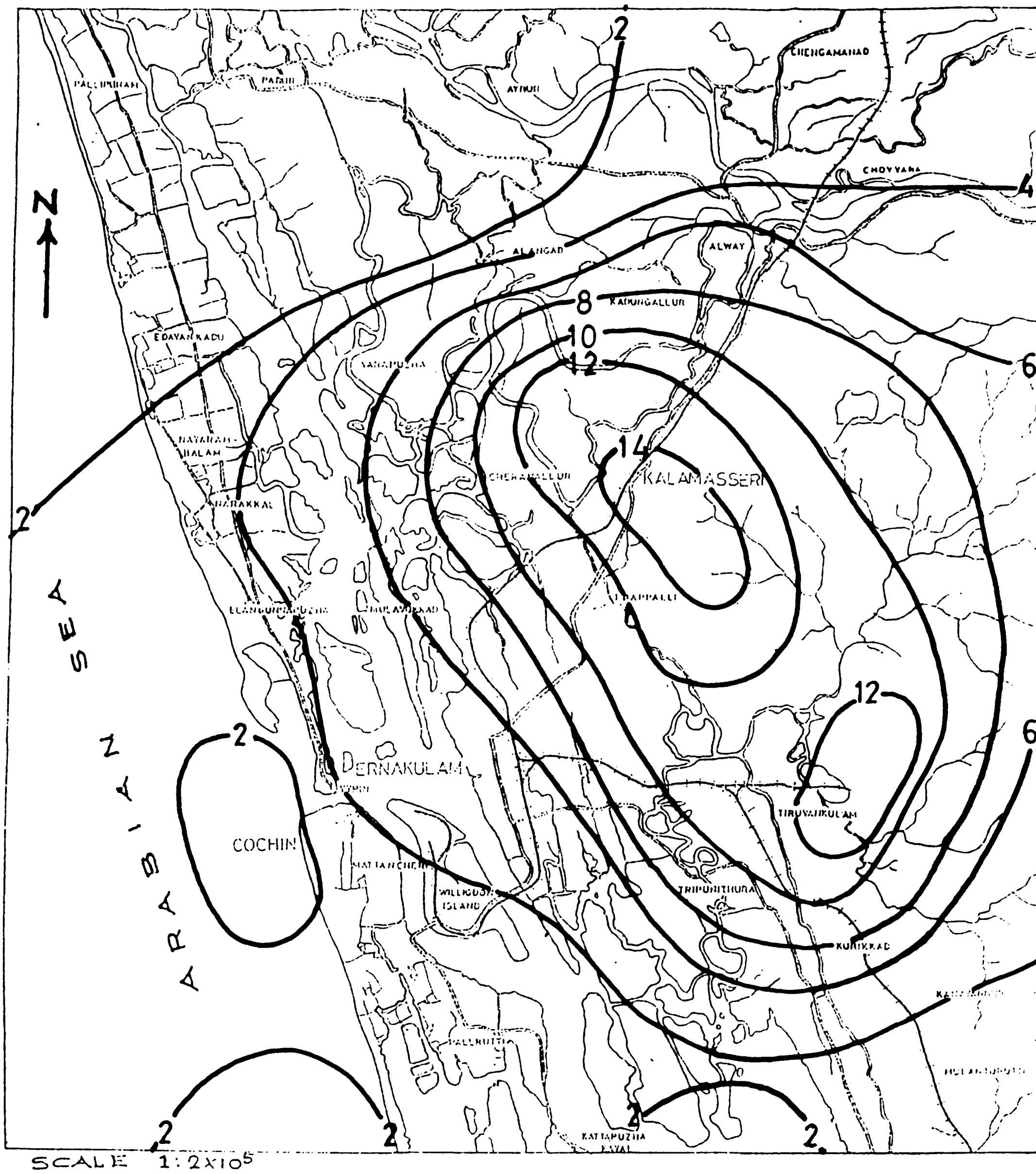


FIG.5.8. SPATIAL DISTRIBUTION OF 24 Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN JULY

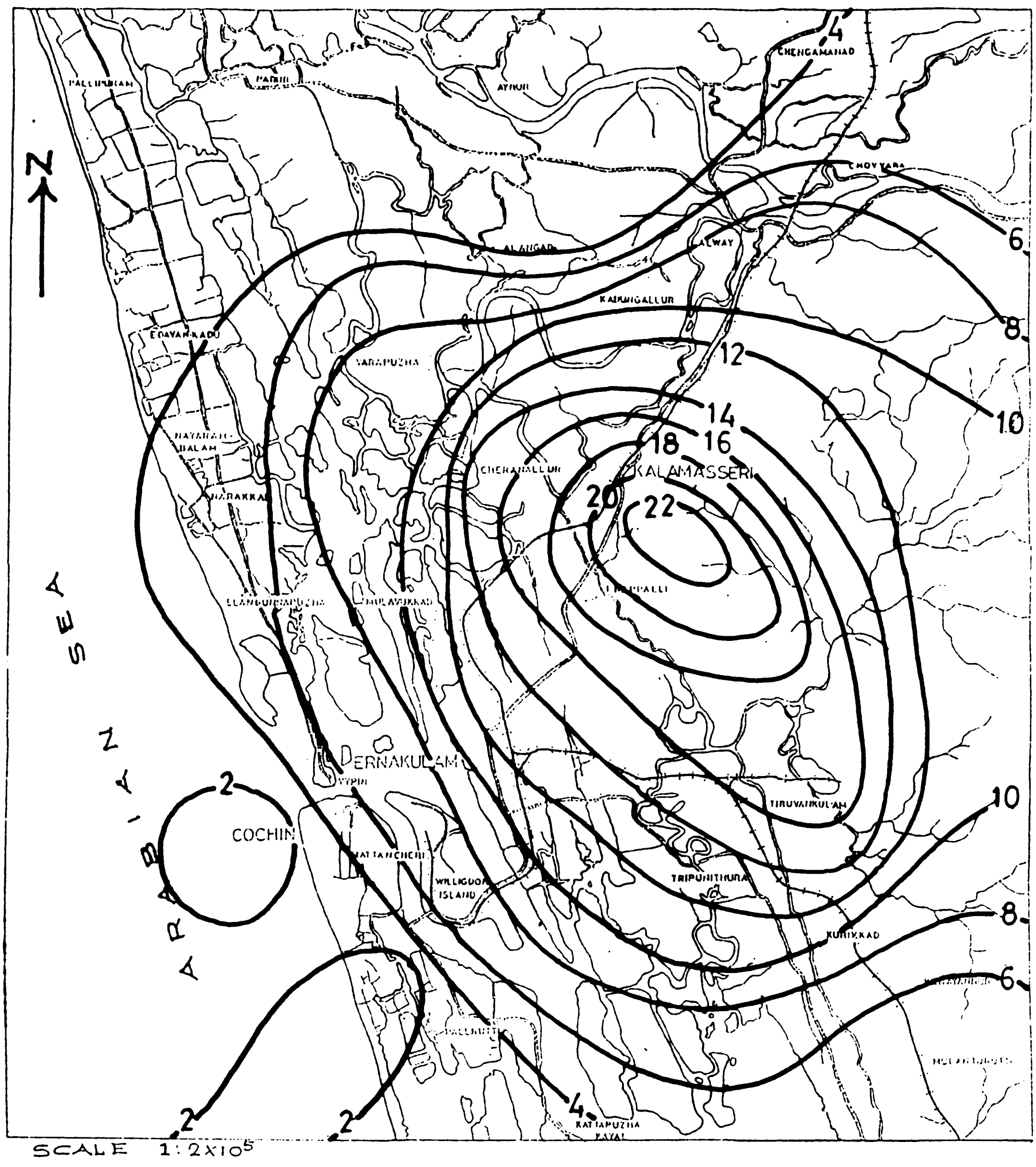


FIG.5.9. SPATIAL DISTRIBUTION OF 24 Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN AUGUST

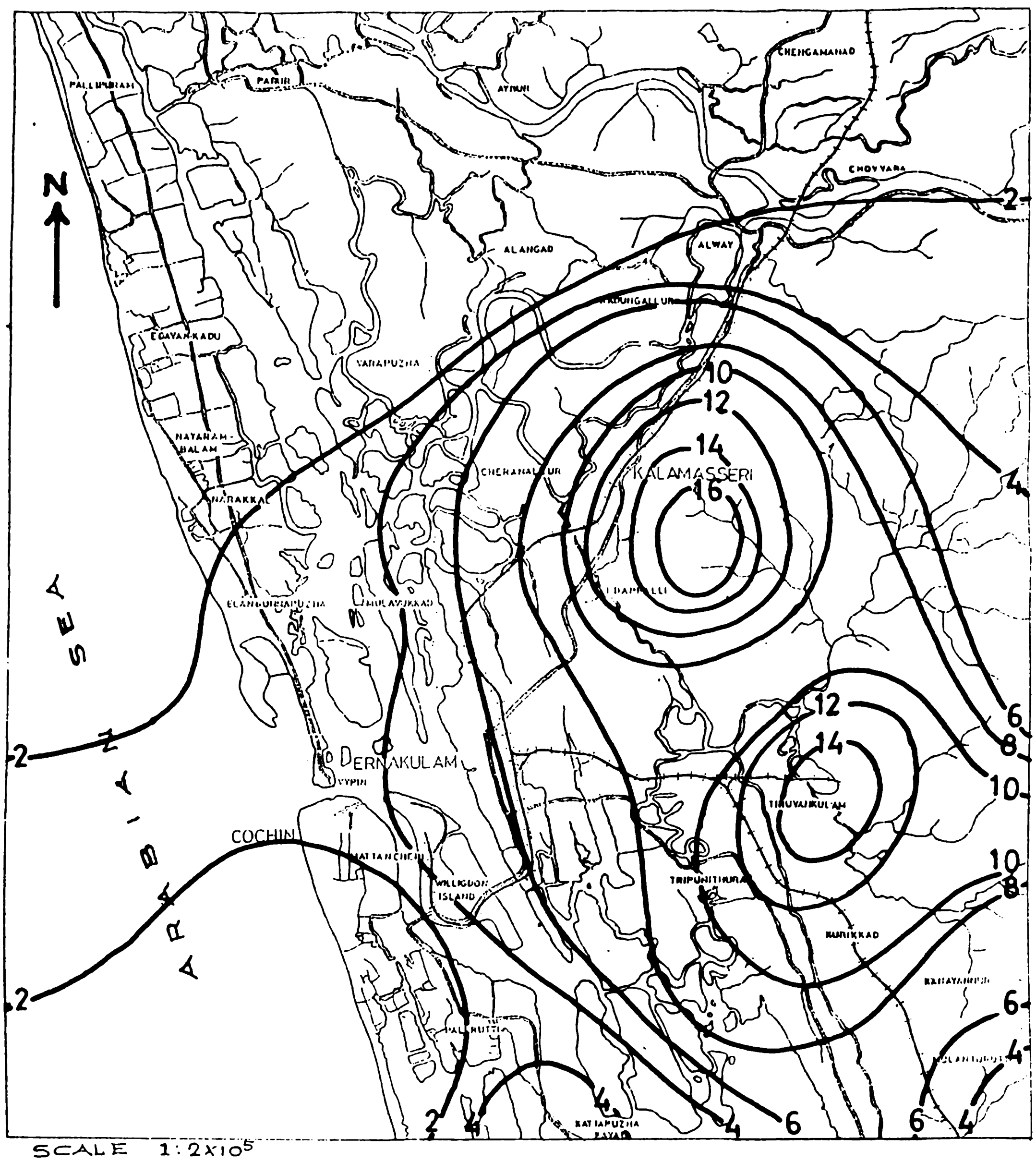


FIG.5.10. SPATIAL DISTRIBUTION OF 24 Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN SEPTEMBER

of 200 $\mu g/m^3$. Northwest portions have shown a concentration of less than 200 $\mu g/m^3$. The area under the 400 $\mu g/m^3$ isopleth in September is less than the area under the 600 $\mu g/m^3$ isopleth in August.

Fig. 5.11 shows the distribution for October. The values are very low near the sources compared to those in September, while the values distant from the sources are comparable to those in September. In fact, the area under the 400 $\mu g/m^3$ isopleth is more in this month than that in September, which shows a gradual fall in all the directions. Perhaps one can say that the distribution is spread towards West or Southwest in this month.

The distribution in November which is shown in Fig. 5.12 is more or less same as that in October excepting that there is only one maximum in this month compared to two in October. In this case also the spread is towards West and Southeast. Most of the built up areas have shown a value of 600 $\mu g/m^3$.

In December, the distribution for which is shown in Fig. 5.13, the maximum is the lowest than compared to that in all the other months. There are two maximum, one at Kalamassery and the other at Ambalamughal. Most

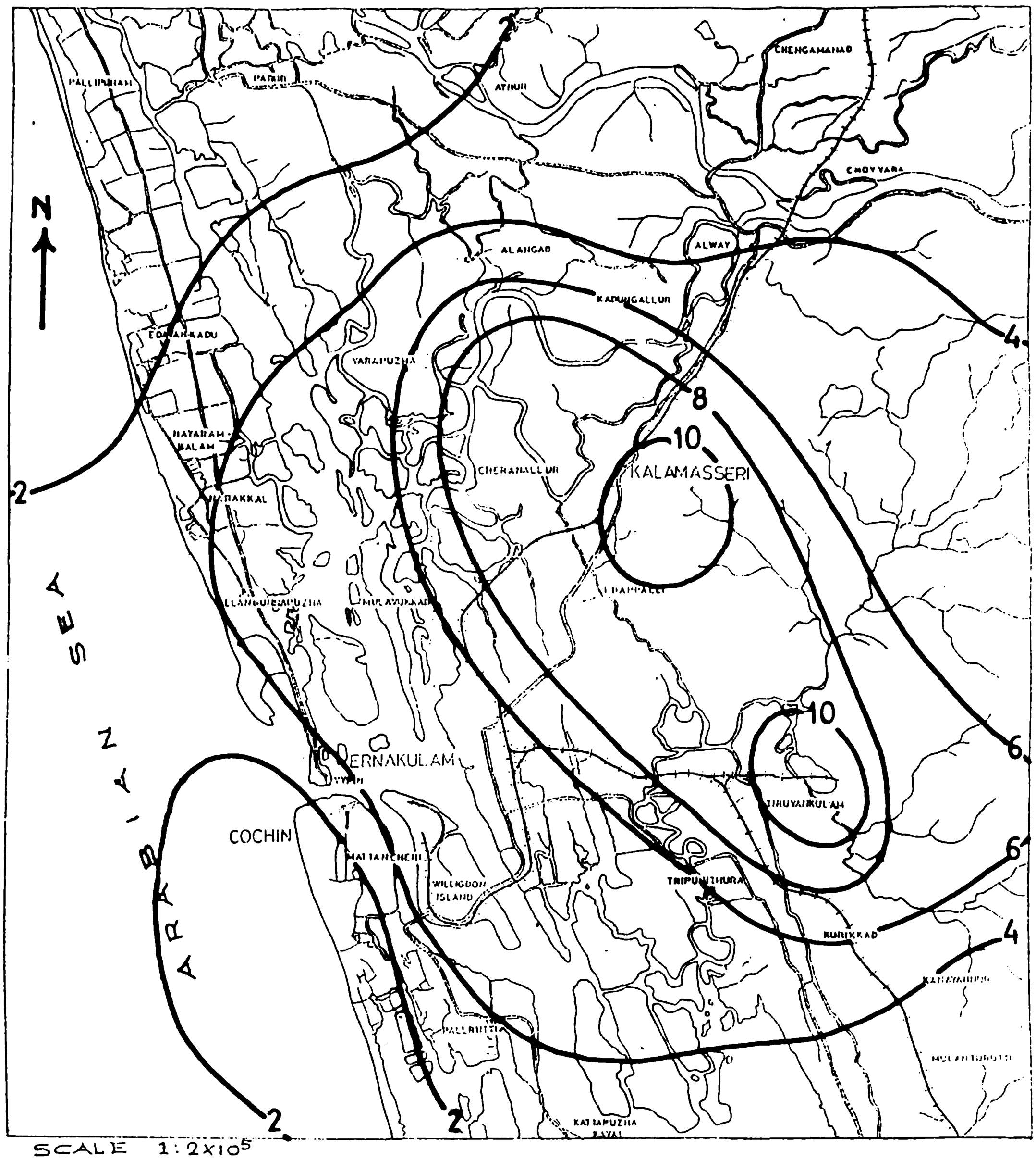
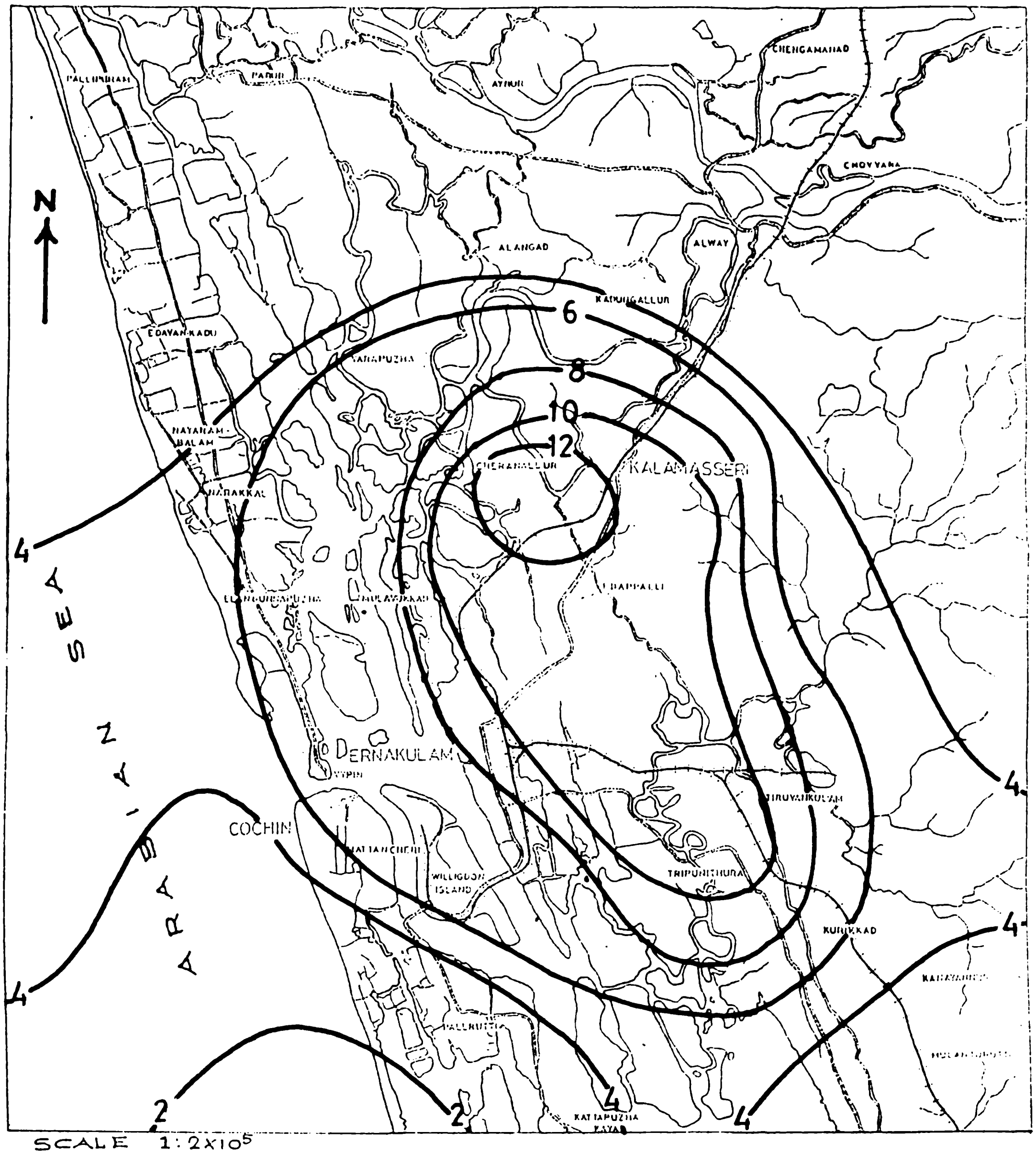


FIG.5.11. SPATIAL DISTRIBUTION OF 24 Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN OCTOBER



SCALE 1:2×10^5

FIG. 5.12. SPATIAL DISTRIBUTION OF 24 Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN NOVEMBER

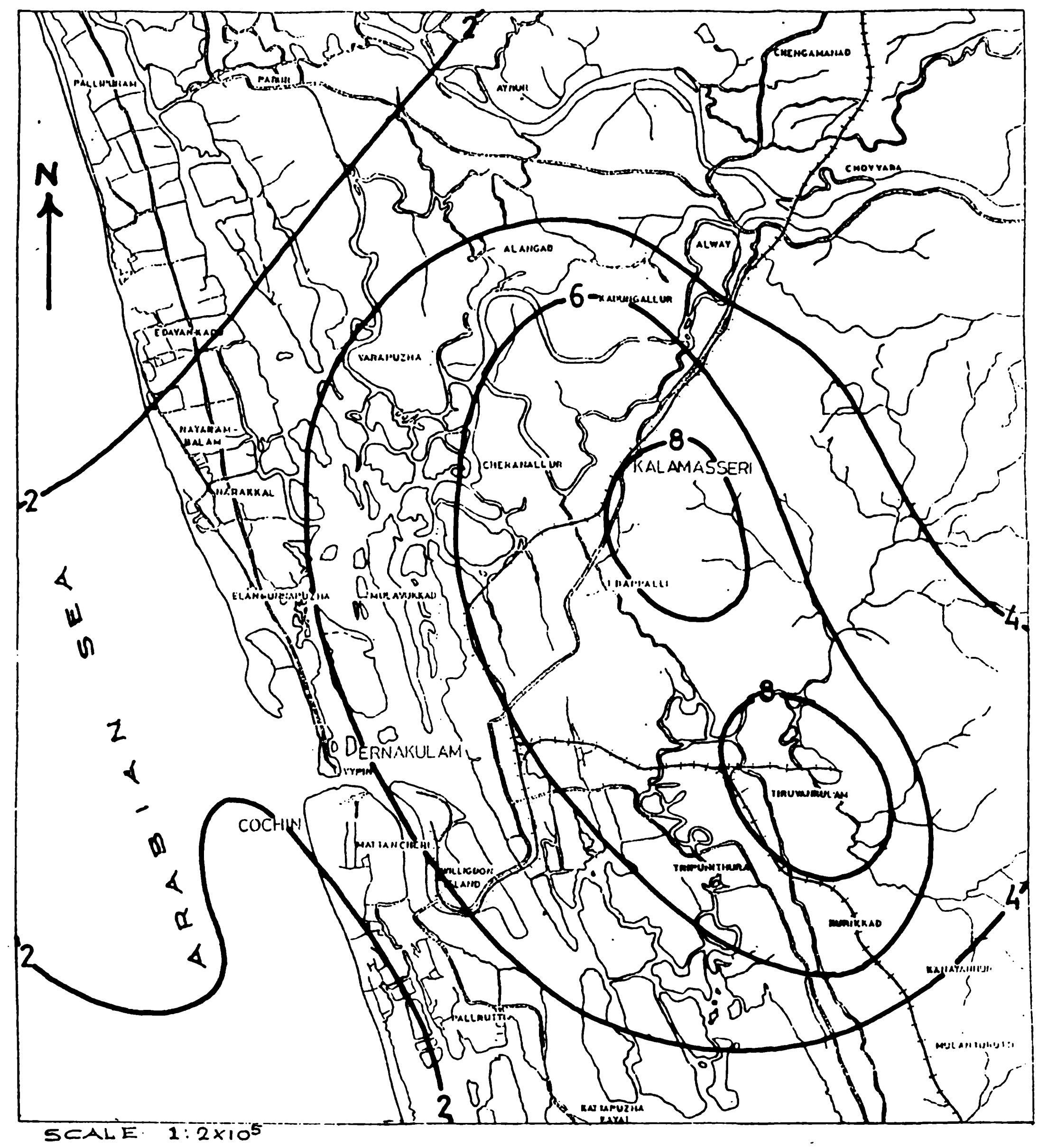


FIG.5.13. SPATIAL DISTRIBUTION OF 24 Hr SULPHUR DIOXIDE CONCENTRATION IN HUNDREDS OF $\mu g\text{-}m^{-3}$ OVER COCHIN IN DECEMBER

of the urban region have shown a concentration of 400 μg/m^3. The extreme Northern portions have very low values.

In general, it is observed that the maximum is always recorded near the sources with their magnitudes differing from month to month, showing highest values in August and March and the lowest in December. Based on these concentration distributions October, November, December and January can be grouped as one in so far as the uniformity in distribution is concerned. Incidently, this is the group of months which recorded the lowest values. February, March, June and August can be grouped as one with the maximum recorded values, while April, May, July and September as one which showed intermediate values.

The maximum concentrations recorded can be attributed to low effective stack height and/or low mixing height. For example in March, the effective stack height is extremely low though the mixing height is not low. August, on the other hand, has both low mixing as well as very low effective stack height. In fact, except in October, November, December and January, the effective stack heights are observed to be very low. The wind speed does not seem to be contributing more to the differences in concentration in various months mainly because the speed variation on an average from month to month is not really significant, with the values ranging between 7 and 11 kmph, although the diurnal variation is well marked. Hence the differences from month to month are to be attributed more towards the variation of mixing height and effective stack height, both of which have shown considerable variations, with the former dominating the latter.

Another striking feature of the distribution is the spread towards Southeast and a sudden fall from the centre of maximum towards North. This is mainly because, the source III is towards the Southeast of sources I and II which are very closeby and the maximum near the source III prevents any sudden fall from the centre of maximum of source I and II. Towards Northwest the contribution from source III is not very significant and obviously one can expect a steep fall.

There is no single direction in all the months in which the spread is very prominent. It should be noted here, that the concentrations are 24 hour values and hence the effect of the reversal of direction from day time to night time or vice versa is not felt. However, the day time wind speeds being more, calm percentage being less, there is a possibility of a slight domination of the wind directions during day time. At the same time it should be kept in mind that the day time concentrations are relatively low compared to the nocturnal concentrations. And hence, in spite of the presence of prominent wind directions, they may not make their dominance felt to the extent expected. On the other hand, the higher nocturnal concentrations cannot be spread to longer distances because of very high calm frequency and weak winds. These two facts together suggest that the wind direction dominance may not be felt to a large extent though there is a slight possibility for the day time direction to have a dominance. If one looks at a 12 hour distribution, though it is not conventional, one can perhaps see the complete dominance of the wind direction. In other words, the diurnal variation will be well marked.

Another interesting feature is that irrespective of the magnitude of the concentration at the source, the values in or near the densely populated areas in the city are more or less same with the value being mostly around 400 μgm^{-3} For example in October, November, December and January, one can see that through the densely populated areas, the value is around 400 $\mu g/m^3$, though the maximum at the source is only around 800 to 1000 $\mu g/m^3$.

In the case of higher values of maximum concentrations, the values in the thickly populated areas have never shown a proportionate increase, though there is a marginal difference. The observation is very interesting in view of the fact that even if the source strength goes up in the present sources identified, the increase of concentration will not be proportionate in the built up areas of Cochin.

The maximum concentration interestingly is well below 1 ppm in all the cases. But if one compares the standards of Environmental Protection Agency, U.S.A., the values exceeded the limit of 365 $\mu g/m^3$ in most of the places in Cochin. The concentrations, shown in these months are high compared to the computations made by Gupta and Padmanabhamurthy (1984) for Delhi where they have chosen a short term model to compute the concentration which are almost less than 400 $\mu g/m^3$. One reason as to why very high values are observed from the present model may be due to the inclusion of the calm conditions in the model and very low stack heights in Cochin. The present study is for a 10 year period from 1973 to 1982, whereas their model for Delhi is for 1976. Half kmph as the wind speed taken for most of the calm conditions would naturally lead to higher values than what it would be if the ordinary wind speeds are considered.

If all other conditions remain the same in the model, one can see that there could be a change of nearly 10 times or more of the concentrations because of the usage of wind speed as half kmph. However, just because of the fact that the values will be high, the calm conditions, whose nocturnal frequencies ranged from 50 to 80% cannot be left untouched, because only 20 to 50% of the concentration is to be divided among the various wind directions. Thus how one can account for the other 50 to 80% of the concentration which certainly cannot disappear but has to find its place somewhere. The scheme suggested in this, need not be fool-proof but certainly, an initiation towards this line is attempted mainly because, though the calm conditions prevail for sometime, the winds that would appear at a latter time would certainly carry the smoke of accumulated concentrations towards the appropriate directions depending upon their frequency and speed. In addition, the stack heights in some of the cases are as low as 25 m which would certainly result in a very high concentration.

It is in the interest of community, that the levels of SO_2 concentration should be reduced considerably. Without altering the structure and capacity of the sources, the physical stack heights should be raised in sources I and II. It is already seen that the emission from the sources I and II put together is roughly 1/3 of the emission at source III. But the concentration in the vicinity of I and II are higher than near the source III obviously because of the very high stack height both physical and effective, at source III compared to those in the other sources. An equivalent stack height in sources I and II as in source III would have made the distribution to be looking totally different from what it is now. Even if one feels that the concentration near the source III is more, from the health point of view, a slight reduction in emission could be effected which would certainly bring down the levels of pollution. The effect of the effective stack height, as is seen in this case, is very important and hence it is suggested that the average physical stack height in sources I and II could go up by at least five times the present heights. It should be noted that it is on an average only. For example the Premier Tyres in source I has already got a stack whose height is three to four times the value of that of Modern Bakery and that stack height need to go up by just three to four times of its present value, in which case the resulting concentration at the source would be 500 to 600 $\mu g/m^3$. If such a thing is effected, the values in the thickly populated region would be well below

200 μg/m^3. In source II some of the stacks should be risen by one and half to two times their present heights. For further bringing down the values of concentration, one can only suggest the devices to control at the source itself. Apart from rising the physical stack heights, the plume temperatures can also be made to be slightly higher to have further rise of the plume due to buoyancy or some devices should be installed that pump out the smoke through the stack exit, so as to have considerable vertical velocity of the plume.

The monsoonal months from June to September should be viewed with caution because of the enormous amount of rainfall and also very low vertical mixing. In fact,it is possible that much of the pollutant in the atmosphere may be washed out or rained out due to the showery precipitation in the form of rain in these months which is not taken care of in the model. As a result, the actual concentrations may be far lower than those presented here. However,one should not forget the extremely low mixing in this month which cannot dilute the pollutant in the vertical,resulting in higher concentration, notwithstanding the effect of precipitation. December and January which are supposed to be the winter months, have the lowest concentration. In fact, it is in these months that the mixing heights were shown to be maximum (see Chapter 3). This gives to a speculation as to whether these months can be considered as representative for winter season. The normal winter characteristics are not normally found here, partly because the station is coastal. The minimum temperature occurs in the monsoonal months if one looks at the annual march of the temperature. And it is clearly shown that because of the very low heat input in the surface in the monsoonal months, the vertical mixing is also limited resulting in a very high dose of pollutants. The values are high because, no absorption or deposition of the material is considered in the model. The thick vegetation within and around the region would also result in considerable reduction in levels, by means of obstruction, deposition and absorption too.

Since it was discussed earlier that the 12 hour concentrations during day time are lower than the nocturnal concentrations, while the capacity of the atmosphere to disperse them effectively is more during day time than during night time. Even the present levels can be brought down considerably if the emissions are increased during day time with a consequent decrease during night time. It is felt that an hour to hour emission schedule is not necessary at present.

As far as the locations of the existing industries are concerned, the ideal place would have been the extreme Southwest portions of the city so that the city interior and all the densely populated areas would be relatively free from pollution. In such a case, most of the spread of the pollutants is over the ocean. So mostly it is the marine environment which is affected. However, it is not worthwhile to think of hypothetical locations of the existing industries. In the present situation, the city can have few more industries towards the far East of the central portions, where it is mostly a rural locality. Since in most of the cases that were discussed earlier, the Northern portions of the city were having relatively low values, the probable places for the new industries could be the Southeast portions so that most of the spread will be away from the city.

5.3. Summary

The spatial distribution of the 24 hour SO_2 concentration for each month for a 10 year period has been studied in this chapter. In almost all the cases the distribution of pollutant concentration is uniform with a spread towards Southeast direction. It was shown that the concentration falls off rapidly towards North and very gradually towards Southeast which was attributed to the presence of a source on the Southeast of sources I and II together. In the thickly populated areas,the concentration is mostly around 400 $\mu g/m^3$. Irrespective of the source strength, the concentration in the thickly populated areas was found to be more or less uniform. The concentration is minimum in October, November, December and January, while higher values are observed in February, March, June and August. The extremely high values are attributed to the low effective stack height and/or low mixing height. It was also shown that the wind speed need not have much contribution to the variation of the pattern of distribution of pollutant concentration because of its low annual range. A comparison of the model made with that for Delhi has revealed that very high values were observed from the present model which was attributed to the inclusion of the calm conditions and extremely low effective stack height. It was shown again that near the sources I and II the concentration was higher compared to that in source III despite the fact that the emission at source III is almost three times, which was attributed only due to the enormous variation of effective stack heights at these three sources. Mere rising of stack heights would bring about considerable reduction in the concentrations. The wash out and rainout would also result in considerable reduction of concentration in the monsoonal months which was not taken care of in the model. It was speculated that whether December and January would represent the winter season since the lowest concentration is observed in this season. A reduction of emission from the industries during night time with a consequent increase during day time will also bring down the levels of pollution. The optimum locations for the new industries would be towards extreme Southeast portions of the city or extreme East of the central portion, so as to have the least possible environmental degradation.

C H A P T E R – 6

SUMMARY AND CONCLUSIONS

A proper and an effective environmental planning is necessary for any growing urban area, so as to reduce the levels of air pollution below their threshold limit values, caused mainly due to industries and vehicular traffic. Once the pollutants are emitted into the atmosphere, the dispersion of the pollutants is solely governed by the prevailing meteorological conditions. The present thesis deals with the comprehensive planning of a very rapidly developing industrial area, namely Cochin. The main objectives are to study the atmospheric dispersion capacity, wind climatology, atmospheric stability, pollutant distribution by means of a model and to suggest the optimum locations for industries. The definition, sources, types and effects of air pollution are dealt with very briefly. The influence of various meteorological parameters such as vector wind, temperature and its vertical structure and stability in relation to pollutant dispersal has also been dealt with for Cochin which is almost the second biggest city along the west coast of India after Bombay. Cochin has many industries that are polluting the atmosphere to a varying degree and hence this city has been chosen for the present study.

A review of the literature on the meteorological aspects of the air pollution and the modelling revealed that much of the work in the recent past is centred round the atmospheric dispersion capacity over a wide region and the application of the Gaussian Plume Model for pollutant dispersion despite the presence of a number of more complicated and complex models. Most of the model developments are mainly based on the basic Gaussian Plume Model. The spatial distribution of mixing heights on a micro scale serves to delineate the regions of good and poor dispersal within a given region. Such studies require a knowledge of the spatial distribution of temperature within a given city. Such studies were made earlier for few days in the winter months for Cochin which have been made use of for the present study in a manner explained in chapter 2, but not without limitations that were pointed out earlier. The importance of inversions, mixing heights, ventilation coefficients, wind climatology and atmospheric stability was brought out briefly. Their methods of computation and their merits and demerits were also pointed out clearly. A study of surface turbulence ($\sigma\theta$) in the form of range of wind direction fluctuation and its relation to stability and mixing height were shown to be of importance in air pollution studies. It was shown that there is a necessity to look into the method of computation of $\sigma\theta$. The development of the Gaussian Plume Model ab initio was presented alongwith the application of the model for multiple sources. The pollutant chosen for the present study is sulphur dioxide, in view of its deleterious effects even at low concentration. Industrial sources alone are considered.

The study of the inversions revealed that the percent frequency of occurrence of inversions and isothermals is low in all the months. The spatial variation of mixing heights within Cochin revealed that a single mixing height at the point of observation cannot be taken to be representative for the whole city in view of its very wide spatial variation. It also revealed that the Southern portions have low mixing heights. The diurnal, monthly and yearly variation of mixing height is well marked. The monsoonal months have shown the lowest mixing heights. It is suggested that some empirical formulae be developed for computing a representative mixing height for any city. The study of ventilation coefficients showed that the values did not exceed 6000 m^2/s, an optimum value suggested for good dispersal of pollutants by U.S., E.P.A. The low value may be due to the fact that only surface wind is used instead of the vertically averaged wind through the mixing layer.

Relatively more calm frequency and light winds during night and strong winds during day time are the salient features that the study of wind roses for Cochin has revealed. During most of the time of the year, westerlies during day time and northeasterlies during night time are the dominant winds.

Atmospheric stability and σ_θ have exhibited a pronounced diurnal and monthly variation. Unstable conditions with higher values of σ_θ during day time and stable conditions with lower values of σ_θ during night time are the prominent features. The monsoonal months have shown neutral category for most of the time. The diurnal variation of both stability and σ_θ has its minimum in monsoonal months and maximum in the winter months. The relation between Pasquill's stability and σ_θ has shown that there is considerable seasonal variation in their relationship. A study of the standard deviation and coefficient of variation of σ_θ for each Pasquill stability category has revealed the difficulty in giving a unique value of σ_θ for each category. For the first time, regression equations have been developed relating mixing height and σ_θ, in view of a high degree of correlation between these two. It is suggested that such regression equations be developed for individual places so that mixing height at any time can be computed from σ_θ alone. A closer examination of the computation of σ_θ revealed that half of the range of direction fluctuations is to be taken to compute σ_θ instead of 1/6 of the range.

The spatial distribution of 24 hour concentration of SO_2 has been studied for each month which showed a more or less uniform distribution with a slight intrusion towards South in almost all the cases. Interestingly the winter months have shown very low concentrations contrary to the expectations, mainly because the winter months recorded very high mixing heights, further corroborating the speculation that whether there is a winter season at all in Cochin. February, March, June and August have recorded higher concentrations which are attributed due to either low effective stack height and/or mixing height. The monthly variation of the concentration is influenced more by the mixing height and the effective stack height rather than the wind speed, because of the latter's negligible monthly variation. In the densely populated areas the concentration is mostly around 400 $\mu g/m^3$ which by itself, according to EPA standards, is more than the threshold limit value. However, the values that are reported here appear to be high in general, because no depletion of the material is assumed through dry or wet depositions and also because of the inclusion of calm conditions with a very light wind speed. At the same time the very low effective stack heights which certainly contribute more to the concentration, cannot be overlooked. Though the emission at source III is three times more than sources I and II put together the concentration at the former is less than that at the latter, obviously due to the very high effective stack heights in the source III. If stacks in sources I and II are of the same height as that in source III, the concentration near the sources I and II would be nearly three to four times less than what they are now, suggesting that the increase of the stack heights in sources I and II would be the foremost step to bring down the levels of pollution below their threshold limits.

A reduction of emission during night time with a consequent rise during day time would also bring down the levels of pollution because of the considerable diurnal variation of the concentration of the pollutants. The probable locations for the new industries could be the extreme Southeast parts because the concentration towards North from the source falls off very quickly resulting in lower concentrations, not very far from the source on the Northern side. In such a case most of the pollutant spread would be towards South and West, thus keeping the city interior relatively free from pollution, if the source is at the Southern end of the city.

A more detailed examination of the pollutant spread by means of models that would take the dry and wet deposition of the pollutants during their transport may be necessary to pinpoint the exact and absolute concentrations all over the city. Nevertheless the present model serves to give the trend of distribution of pollutant concentration with which also one can suggest the optimum locations for the new industries as was done in the present study.

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APPENDIX - I

ON THE RELATION BETWEEN σ_Θ AND WIND DIRECTION FLUCTUATION RANGE (WDFR)

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As mentioned in Chapter 2 that the relation between σ_Θ and WDFR, is found out for few typical cases for Cochin. The purpose of this study is to compute the SD of WDF (σ_Θ) from the conventional statistical methods and to relate the same to WDFR. Slade (1968) suggested a factor of 1/6 to be multiplied with WDFR to get σ_Θ. A verification of this value is made with the statistically computed σ_Θ ($\sigma_{\Theta s}$).

Three days each in January, April, July and October 1974 are chosen for computing $\sigma_{\Theta s}$ and WDFR for Cochin.

In each 10 minutes interval all the peak values are noted, the number of values thus noted varied from as low as 10 to 25 depending upon whether the variation is smooth or irregular. In a relatively smooth variation the peaks are not many. In the same 10 minutes interval the WDFR (difference between the extreme values in the 10 minutes interval) is also noted. The mean WDFR in each hour is obtained by adding all the 6 WDFRs and dividing that with 6.

This mean WDFR (R_{10}) is taken to be representative of the range in that particular hour. $\sigma\theta s$ is computed for each 10 minutes and the mean $\sigma\theta s$ for each hour is obtained by adding all the 6 $\sigma\theta s$ values in that hour and dividing that with 6. A linear regression equation of the form, y = mx is fitted for each month separately.

Figure (A 1) shows the scattered diagram of R_{10} and $\sigma\theta s$. The regression equations are $\sigma\theta s = 0.5\ R_{10}$ for January, $\sigma\theta s = 0.49\ R_{10}$ for April, $\sigma\theta s = 0.53\ R_{10}$ for July and $\sigma\theta s = 0.54\ R_{10}$ for October. On an average it can be taken as $\sigma\theta s = 1/2\ R_{10}$ which means that the range should be divided by 2 to get $\sigma\theta$. The correlations between $\sigma\theta s$ and R_{10} are very high varying from 0.7 to 0.9. The correlation is least in July and maximum in January. The diagram shows not many deviations from the line drawn except in a very few cases and that too, in July only. This suggests that 1/2 of the range of $\sigma\theta$ appears to be an appropriate value for the computation of $\sigma\theta$. For the purpose of comparison the relation $\sigma\theta = 1/6\ R_{10}$, suggested by Slade (Ibid), is also plotted in the same figure with a dashed line. Except in July, not even a single point has fallen on the line and all the points are lying on one side of the line. Hence it may be stated that $\sigma\theta$ computed by Slade is an under estimate of the actual $\sigma\theta$.

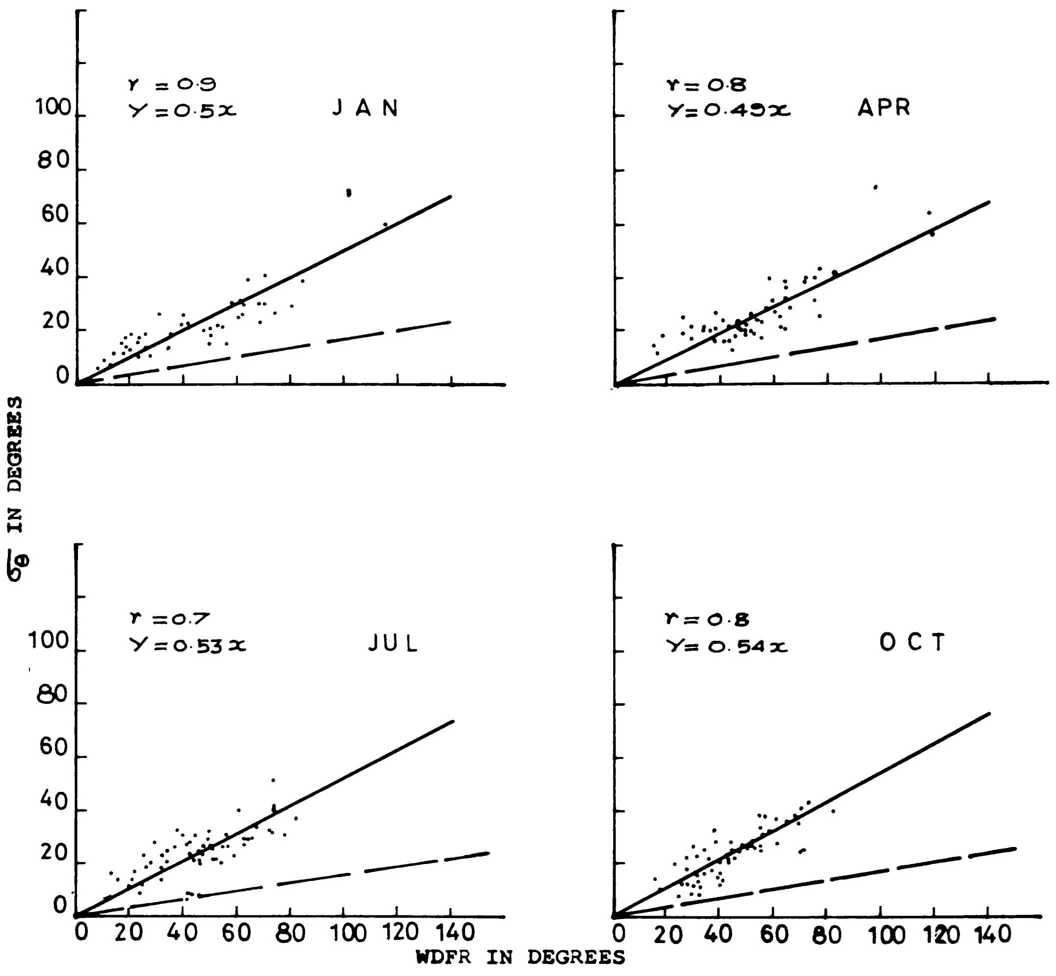

FIG. A.1. RELATION BETWEEN σ_θ AND WDFR FOR COCHIN - PRESENT STUDY (——)
SLADE'S STUDY (- - -)

Despite the proof presented above to take half the range as the real σ_Θ, one can not say for certain that the same holds good for other locations. A study of similar type for some other locations preferably an inland station can only substantiate the fact presented above. However, for Cochin this can be taken as unique value for computing σ_Θ at any time in any month because of the very high correlations.