STUDIES ON THE SPATIAL AND TEMPORAL DISTRIBUTION OF SURFACE METEOROLOGICAL PARAMETERS OVER INDIAN SUBCONTINENT

Thesis submitted to the
Cochin University of Science and Technology
in partial fulfilment of the requirements for the Degree of

DOCTOR OF PHILOSOPHY
in
METEOROLOGY

By

ANU SIMON

Department of Atmospheric Sciences
Cochin University of Science and Technology
Lake Side Campus, Fine Arts Avenue
Cochin - 682 016

MARCH 1996

To my beloved parents

CERTIFICATE

This is to certify that the thesis entitled *Studies on The Spatial and Temporal Distribution of Surface Meteorological Parameters over Indian Subcontinent* is a bonafide record of the research work done by **Smt. Anu Simon, M.Sc.**, in the Department of Atmospheric Sciences, Cochin University of Science and Technology. She carried out the study reported in this thesis, independently under our supervision. We also certify that the subject matter of the thesis has not formed the basis for the award of any Degree or Diploma of any University or Institution.

Certified that **Smt. Anu Simon** has passed the Ph.D qualifying examination conducted by the Cochin University of Science and Technology in January, 1994.

Cochin - 682 016
March 21, 1996.

(K. MOHANKUMAR)
Supervising Teacher

Cochin - 682 016
March 21, 1996

(C.K. RAJAN)
Supervising Teacher

DECLARATION

I hereby declare that this thesis entitled *Studies on The Spatial and Temporal Distribution of Surface Meteorological Parameters over Indian Subcontinent* is a genuine record of research work carried out by me and that no part of this thesis has been submitted to any University or Institution for the award of any degree or diploma.

Anu Simon

Kochi - 16
March 21, 1996

Anu Simon
Dept. of Atmospheric Sciences
Lake Side Campus,
Fine Arts Avenue
Cochin 682 016.

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ANU SIMON

CONTENTS

PREFACE

Studies of meteorological data collected throughout the world during the past century clearly demonstrate that climate is never strictly constant. Our knowledge of the fundamental nature of climatic fluctuations, its magnitude and direction are not adequate, due to enormously complex and subtle interactions between man and his environment. Even small climatic disturbances can have far-reaching impact on human welfare. Thus, studies on the spatial and temporal variations of different meteorological parameters over Indian subcontinent are of immense importance to the agriculture, economy and social development of the country.

Eventhough several studies on the time series of rainfall and temperature at different regions were reported, systematic studies on the spatial distribution of surface meteorological parameters based on long-term data over the entire Indian subcontinent have not been much documented. The intention of the present thesis work is to understand the physical processes responsible for climatic variability and predictability of the Indian subcontinent. The study is expected to delineate and emphasise the various boundaries and areas of transition and bring out the regional and temporal characteristics of the meteorological distribution of the country. The results obtained from the study is expected to provide a better understanding the physics of Indian climate, which can be incorporated for numerical weather prediction.

The thesis is divided into seven chapters. In Chapter 1, apart from the general introduction and the objectives of the study, the physiographic features and the general climatology of India are briefly discussed. Description of the data used for the study are also included in this chapter. Detailed literature review on the spatial and temporal studies of meteorological parameters conducted on India as well as on other parts of the globe have been carried out and presented in Chapter 2.

Chapter 3 deals with the results obtained from the harmonic analysis on the seasonal cycle in rainfall, surface temperature, and sea-level pressure over the country. Theoretical procedure of the harmonic analysis have been included in Chapter 3. It has been noted from the study that the semi-annual oscillation becomes significant in the region come under intense monsoon activity, but the annual oscillation is larger in the region of weak monsoon activity. Apart from the annual and semi-annual oscillations, the short-period oscillations are significant in the mountainous Western-Ghat region.

The interannual variability and trend in surface rainfall, temperature, pressure for a period of about 85 years are investigated and presented in Chapter 4. The technique of Fast Fourier Transform (FFT) is explained in detail. The presence of 11-year oscillation, the 5-year subharmonic, the 27-month, the 36-month oscillation and 14-month oscillations and the combination of tones are detected in all the three meteorological parameters used in the study and are discussed. It is found that the periodicity of QBO for rainfall is 27-28 months, whereas it is 24-months for rainfall and sea-level pressure.

In Chapter 5, detailed studies on the spatial and temporal distribution of the meteorological parameters over the Indian subcontinent have been carried out based on Principal Component Analysis (PCA). The study is extended for both the annual and monthly mean values and the results are discussed. The computation of the eigen vectors and principal components are also presented in detail. It is found that the first two eigen vectors are sufficient to explain the spatial pattern for the surface meteorological parameters.

An attempt has been made to find the predictability of meteorological parameters over the Indian subcontinent based on the computational techniques used in the former three chapters of the thesis. The results are presented and discussed in Chapter 6.

Chapter 7, abridges the results and conclusions of the thesis. References are cited in alphabetical order and furnished at the end of the thesis.

The computer programs in FORTRAN language for the Harmonic Analysis, FFT, PCA used in the thesis work are included as Appendix (A), (B) and (C).

Chapter 1

INTRODUCTION

1.1 RELEVANCE OF THE TOPIC

India is a land of contrasts, not only of religion and language but also of relief and climate. This is reflected on the variety of plants, animals, the people, their food habits and culture. Geographically, Indian subcontinent is an equatorward extension of the great Eurasian land mass. Physiography plays an important role on the climate of the country. The significant features are the very high mountains in the north, broad plains in the centre, desert zones in the northwest, tapering peninsula to the south, mountain ranges to the northeast and a lower range running along the west-coast of the peninsula. The vast expanse of the Indian Ocean lies to the south of the land mass with the Bay of Bengal and Arabian Sea pushing north engulfing the peninsula. This unique geographical configuration gives India her weather and climate system with two monsoon seasons and two cyclone seasons interspersed with hot and cold weather seasons.

Studies of the meteorological data collected throughout the world during the past years, decades and centuries clearly demonstrate that climate is never strictly constant. The magnitude of these climatic changes vary from place to place and time to time. Our knowledge of the fundamental nature, magnitude and direction of climatic fluctuations is not adequate due to enormously complex and subtle interactions between man and his environment. However, better understanding of physical systems based on increased number of parameters with better time resolutions and availability of long data series provide a new thrust to climate research.

The climate of a place is the sythensis of weather over a period long enough to establish its statistical properties. It exerts a profound influence on the civilisation and culture of the people, their way of life, environment and economical status. However, climate can act both as a benign influence on mankind and as an adversary affect. Although, long-term climatic changes have a more lasting effect, small climatic disturbances like floods, droughts, failure of monsoons etc., can have far-reaching impact on human welfare. In order to avert or reduce the magnitude of such disasters, a detailed knowledge of the spatial and temporal behavior of the meteorological parameters over a region is a prerequisite.

1.2 JUSTIFICATION OF THE STUDY

Climatologically, India covers tropical, temperate and polar climatic regimes. The altitude effect of mountains and high land areas cause polar weather conditions on one side, and the arid Rajasthan desert cause extreme high summer temperatures on the other side of the country. Northwest India presents a pronounced continental temperature regime with scorching hot summers and freezing cold winters, while the southern peninsula comes under direct maritime influence with very little annual variation in temperature. The year-to-year variations in temperature in tropical regions are quite small compared to middle latitudes. However, small changes in temperature affect the evaporation pattern and therefore are likely to be reflected in rainfall changes (Parthasarthy et al., 1981). Due to this large variability in temperature caused by geographical and topographical peculiarities, a study on the spatial and temporal distribution of surface temperature and oscillations in the seasonal cycle becomes necessary in understanding the climatological behaviour of the country.

The precipitable water or water vapour is the most important absorber of solar and terrestrial radiation in the atmosphere, and plays an important role in the general circulation pattern. Precipitation over the country is mainly governed by physical, spatial and temporal factors. The country as a whole, gets abundant rainfall, but the disparity in the distribution is so wide that some areas are ever arid, while some others experience heavy rainfall. The year-to-year variation is also so large that the same area may experience flood in one year and drought in the next. A detailed knowledge on the spatial and interannual variability of annual rainfall is hence important and has considerable impact on national activities, like agriculture, water-management, power generation, etc.

The general circulation pattern of the atmosphere of a particular region is characterised by the mean sea-level pressure distribution. The organisation of the atmospheric pressure on the surface is latitudinal, being a function of the insolation input, though modified by the distribution of land and water (Menon, 1979). The distribution of sea-level pressure and wind systems over the Indian subcontinent undergoes a complete reversal in the course of the year between the summer southwest and winter northeast monsoon. Anomalies in the seasonal pressure pattern can sometimes usher in climatic fluctuations on a global scale. Examination of these anomalies in the pressure field will provide useful insight into the evolving weather pattern and the climatological trend.

1.3 SCOPE OF THE STUDY

In the present thesis work, a detailed study on the spatial and temporal variability of surface meteorological parameters viz., rainfall, temperature and mean sea-level pressure of the Indian subcontinent has been carried out. The study is expected to delineate and emphasise the various boundaries and areas of transition and bring out the regional and temporal characteristics of the meteorological distribution of the country. The knowledge on the interannual variations of the surface meteorological parameters will also be helpful in forecasting calamities like droughts and floods. The results obtained from the present study is expected to provide a better understanding on the physics of Indian climate, which can be incorporated in numerical weather prediction models for medium as well as long range weather forecasting of the country.

1.4 PHYSIOGRAPHIC FEATURES OF INDIAN SUBCONTINENT

Physiography is the description of the physical features and the natural peculiarities of a region (Menon, 1989). Mountain barriers, altitude, latitude, distribution of land and water are all major factors in climatic control. Adequate knowledge of the topographical features of the country is therefore essential for any climatic study.

The Physiographic features of India and the natural divisions are illustrated in Fig. 1.1.

1.4.1 Natural Divisions

The Indian sub-continent falls into five natural divisions. They are:

(i) The great mountain wall,
(ii) The Indo-Gangetic plains,
(iii) The central highlands,
(iv) The peninsular plateau,
(v) The coastal plains.

(i) The Great Mountain Wall:

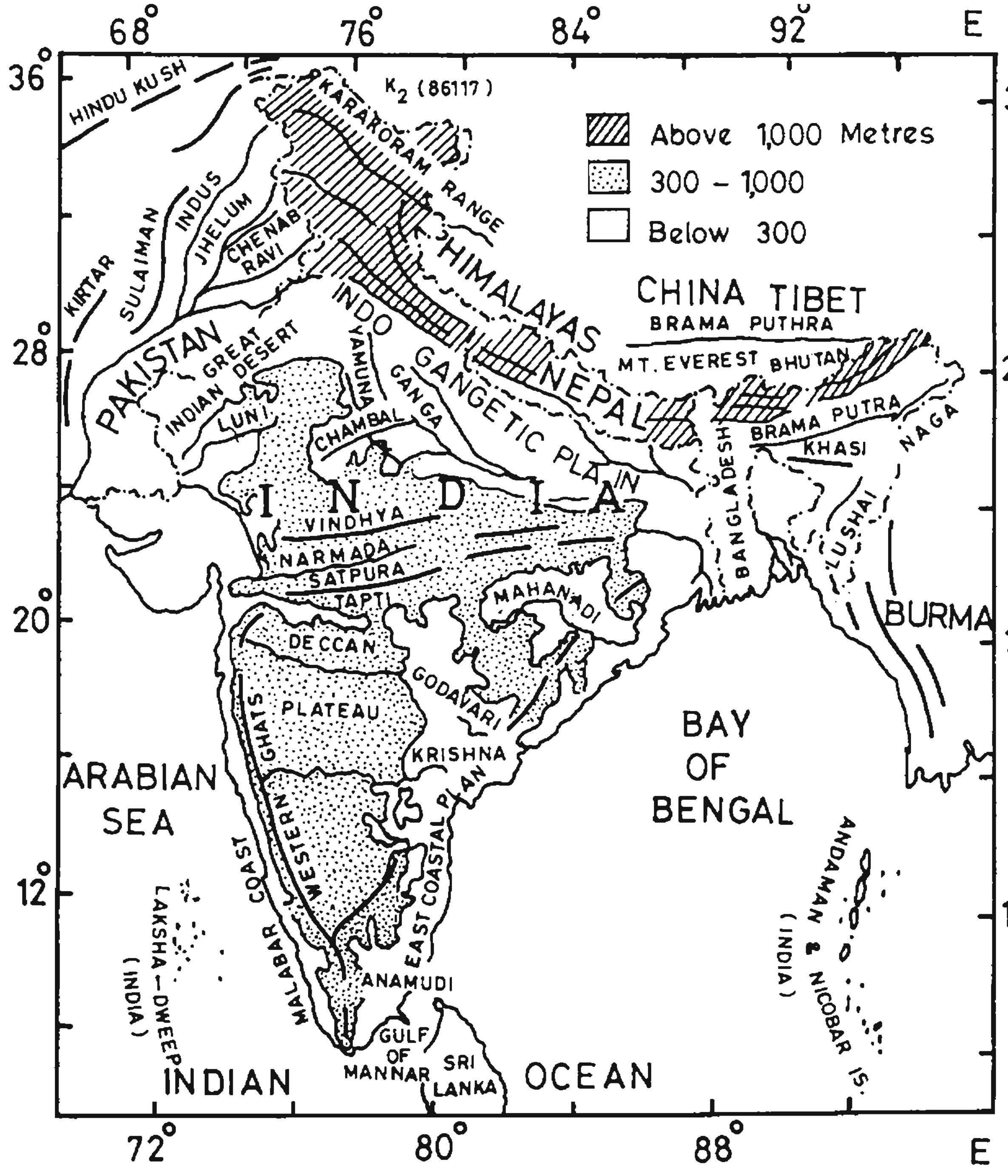


Fig. 1.1. Physiographic map of India

The Pamir Plateau, the highest and largest plateau in the world, in the extreme north is the focal point from which spreads out several mighty mountain systems. The Great Himalayan wall spreads southeastwards from the knot as an unbroken and continuous chain extending to Arunachal Pradesh. The Everest (8,848 m), Kanchanjunga (8,585 m), Makalu (8,470 m), Davalgiri (8,172 m), Nanga Parvat (8,126 m), Nanda Devi (7,817 m) are all snowclad peaks on the Himalayas. There are four distinct ranges in Kashmir, called the Pir Panjal, the Pangi, the Zaskar and the Ladhak ranges. To the eastern side, the chain is more simpler with two main ranges - the inner or Great Himalayas (Himadiri) and the outer or lesser Himalayas (Himachal). To the south of the Himalayas lies the Saiwalik frontal range, constituting the outermost foothills, extending from Kashmir to Assam.

To the north of the western end of the Himalayas lies the Karakoram mountain chain. Mount Godwin Austin (8,611 m), the second highest peak after Everest, is situated on the Karakoram mountain. To the east and northeast of the Pamir Knot are the Kunulun mountains and the Tien Shan ranges. The Hindu-Kush range runs in a westerly direction from the Pamir Knot and the Sulaiman ranges are seen to the south of the Knot.

The eastern end of the Himalayan chain extends as a complex system between India and Burma as the Namkai-Patkai-Naga-Barail-Lushai chain, and extends southwards as the Arakan Yomas in Burma. The Garo-Khasi-Jainta hills are westward extension of the

Barail range into Meghalaya, whose configuration plays a vital role in producing one of the rainiest spots of the World. Thus between 27°N and 43°N latitudes and 70°E and 105°E longitude, there is a mountain barrier, which prevents atmospheric exchange in the lower troposphere between the Indian sub-continent and the higher latitudes.

(ii) The Indo-Gangetic Plains:

To the south of the Great Mountain wall strecthes the Indo-Gangetic plains, extending between the Arabian Sea and Bay of Bengal. In the plains the alluvium is quite deep. The plains can be subdivided into:

(a) The northern fertile portion including the Punjab and Uttar Pradesh doabs;
(b) The western desert of Rajasthan;
(c) The eastern plains of Bihar and Bengal.

(iii) The Central Highlands:

The central Highlands are the northern extension of the peninsular plateau. However, between latitudes 21°N and 24°N, a series of mountain ranges are seen. The main range is the Satpuras, extending as the Mahadev Hills and Maikala ranges to the Chotanagpur plateau. To the north of the Satpuras are the Vindhyas, traversing the entire peninsula for about 1050 km, with an average elevation of 300 m above mean sea-level. Northeast of the Vindhyas is situated the Aravalli range, which is one of the oldest mountain system of the world. The central Highlands separate the Indo-Gangetic plains from the peninsular plateau.

(iv) The Peninsular Plateau:

The western boundary of the triangularly shaped plateau which slopes eastwards is the more or less continuous Western Ghats (Sahyadiri), which is aligned north-south for a length of nearly 1,600 km, from river Tapti in the north at about 20^{O}N latitude to Kanyakumari in the south. The peaks in the Western Ghats are : Kalsubai (1,646 m) near Igatpuri and Salher (1,567 m) near Nasik in the north, and Anamudi (2,695 m) and Vaval Mala (2,339 m) in the south. The eastern edge of the plateau is marked by a lower and broken range known as the Eastern Ghats (Purvadiri). Many rivers cut through these ranges. The particular shape of the peninsula allows maritime air to reach the northern plains.

(v) The Coastal Plains:

The narrow western coastal plain between the Arabian Sea and the Western Ghats, stretching between Kanyakumari and Surat and the broader eastern coastal plain between the Bay of Bengal and Eastern Ghats form the coastal Plains of the Indian subcontinent.

1.4.2 River systems:

There are three main watersheds, the Himalayas together with the Karakoram in the north, the central Highlands comprising the Vindhya-Satpura complex and the Western Ghats in the Peninsula. The Himalayan rivers are snowfed and are perennial, while the central Indian rivers are rainfed and the volume of water undergoes wide fluctuations. The peninsular rivers are small and are also rainfed and hence dry up in the non-rainy season (Menon, 1989).

1.5 GENERAL CLIMATOLOGY OF INDIA

1.5.1 Seasons of India:

The climate of India is dominated by the monsoon circulation. During one half of the year the wind blows from the cooler humid ocean to the warmer dry land, while during the other half there is a seasonal wind blowing from the cold dry Asiatic land mass to the warm Indian Ocean. There is a spectacular reversal of pressure and wind patterns between the two halves, the changeover taking place in gradual stages. The gradual rise in temperature through spring to summer does not happen, due to the onset of the south-west monsoon and temperatures drop sharply in June or July. The usual classification into spring, summer, autumn and winter is therefore not adopted. January-February is designated as the winter period and the hot weather period is from March to May. The four months of June to September is called the south-west monsoon period and October to December is the post-monsoon period. January, April, July and October are taken as the representative months of the four seasons.

1.5.2 Mean Pressure Distribution:

The distribution of sea-level pressure over the Indian subcontinent undergoes a complete reversal from January to July. During northeast monsoon or the post-monsoon period the pressure decreases to the south, whereas the it decreases to the north during the south-west monsoon season. In the transition months of April and October, the pressure gradient over the subcontinent is flat. The pressure distribution for the four seasons, viz., winter, spring, summer and autumn, represented by January, April, July and October, respectively are illustrated in Figs. 1.2 (a) - (d).

January:

In the month of January, the Indian subcontinent is at the periphery of the Siberian High centered at 45^{O}N and 105^{O}E. The Siberian High is the result of accumulation of cold continental air over the east central parts of Asia and the effect of the sub-tropical high pressure belt which becomes prominent over land. The Himalayas however obstruct the spreading of cold air from central Asia into northern India. The Siberian High is

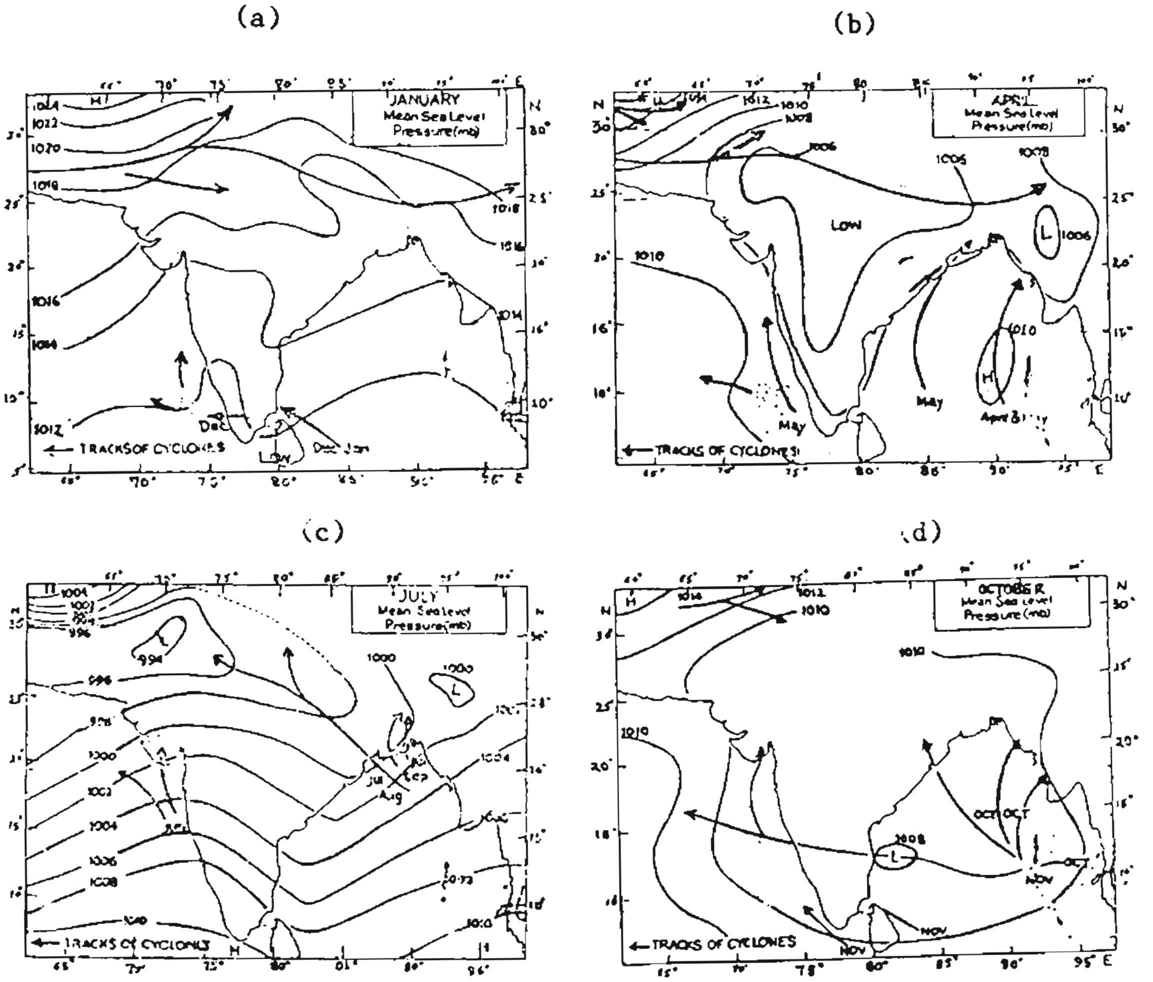


Fig. 1.2 Distribution of mean sea leavel pressure over India

marked in December, January and February. The pressure gradient around the Siberian High is strong to the north of the Himalayas but is weak over India. The position of the equatorial low pressure area in the Indian Ocean during this month is between 10^{O}S and 15^{O}S. In the northern region a weak ridge runs from north Pakistan to Bihar with a weak trough along the foot of the Himalayas. A marked trough extends from Kerala to Sind and a similar one is seen off the Tenasserim coast to central Burma. The ridge between these two troughs becomes prominent along the east coast of the peninsula. The pressure distribution is shown in Fig. 1.2(a).

April:

Fig. 1.2(b). gives the pressure distribution during the month of April. Development of low pressure due to increased heating over land starts over India in March, when the whole area has a flat pressure distribution with slightly higher pressures over the Arabian Sea and Bay of Bengal. By April, lows begin to develop along the Tropic of Cancer in the Indian region. Peninsular India, south of 20^{O}N, comes under considerable maritime influence, which makes the heating over land more marked to the north of 20^{O}N . There is a weak low over upper Sind and another over Bihar and east Uttar Pradesh. Over the peninsula a trough forms with the axis along longitude 78^{O}E. By May, the summer continental low pressure area completely dominates the scene, with the main central area over Sind and west Rajasthan and the low pressure extends as a trough to Orissa. In May the trough over the peninsula is along the Madras coast. During the hot weather period the Indian Ocean trough is seen along 3-5^{O}S latitude.

July:

During this season the low pressure area extending from north Africa to northeast Siberia is most intense. The lowest pressure is seen around upper Sind and surroundings. A trough lies over north India with its axis from Gandhinagar to the northern Bay of Bengal and is called the Monsoon Trough (Fig. 1.2(c). The position of this monsoon trough is an index of the activity of the monsoon over the subcontinent. The Indian Ocean high is strong and centered at 30^{O}S and about 60^{O}E. Pressure steadily decreases over the Indian Ocean northward of this high pressure belt except for a weak trough at 2^{O}S. Weak ridges are seen in the Arabian Sea off the west coast of India and in Bay of Bengal off the Tenasserim coast and also over Burma. This weak trough along the east coast of the south peninsula persist throughout the monsoon months and is more pronounced in September.

October:

Rather abruptly a trough develops over the bay of Bengal with its axis along 13^{O}N- 14^{O}N latitude and the pressure field is flat over the country. The trough along the east coast persists in November but disappears in December. By November-December, winter conditions set in and the winter pattern is fully established in January. Fig. 1.2(d) gives the pressure distribution during this season.

1.5.3 Mean Temperature Distribution

The main factors which affect the mean temperature of the air at any place are the altitude of the sun, latitude, elevation, distance from the sea, exposure and the type of prevailing air mass which in turn determines the pattern of cloudiness and weather. The annual changes in the thermal pattern would naturally show the highest temperature in summer and the lowest in winter. The incoming solar radiation is greater than the outgoing radiation from January to July and vice versa from July to December. However, due to the onset of the summer monsoon which gives rise to extensive cloudiness and rainfall, the pattern slightly changes in the Indian subcontinent. The distribution of temperature over the Indian sub-continent during the months of January, April, July and October are depicted in Figs. 1.3(a)-(d).

January:

The mean isotherms run more or less parallel to the latitudes except near the coasts during this season (Fig.1.3(a)). The temperature increases towards the south, markedly between 27°N latitude and 15°N latitude. The gradient is 0.9°C per

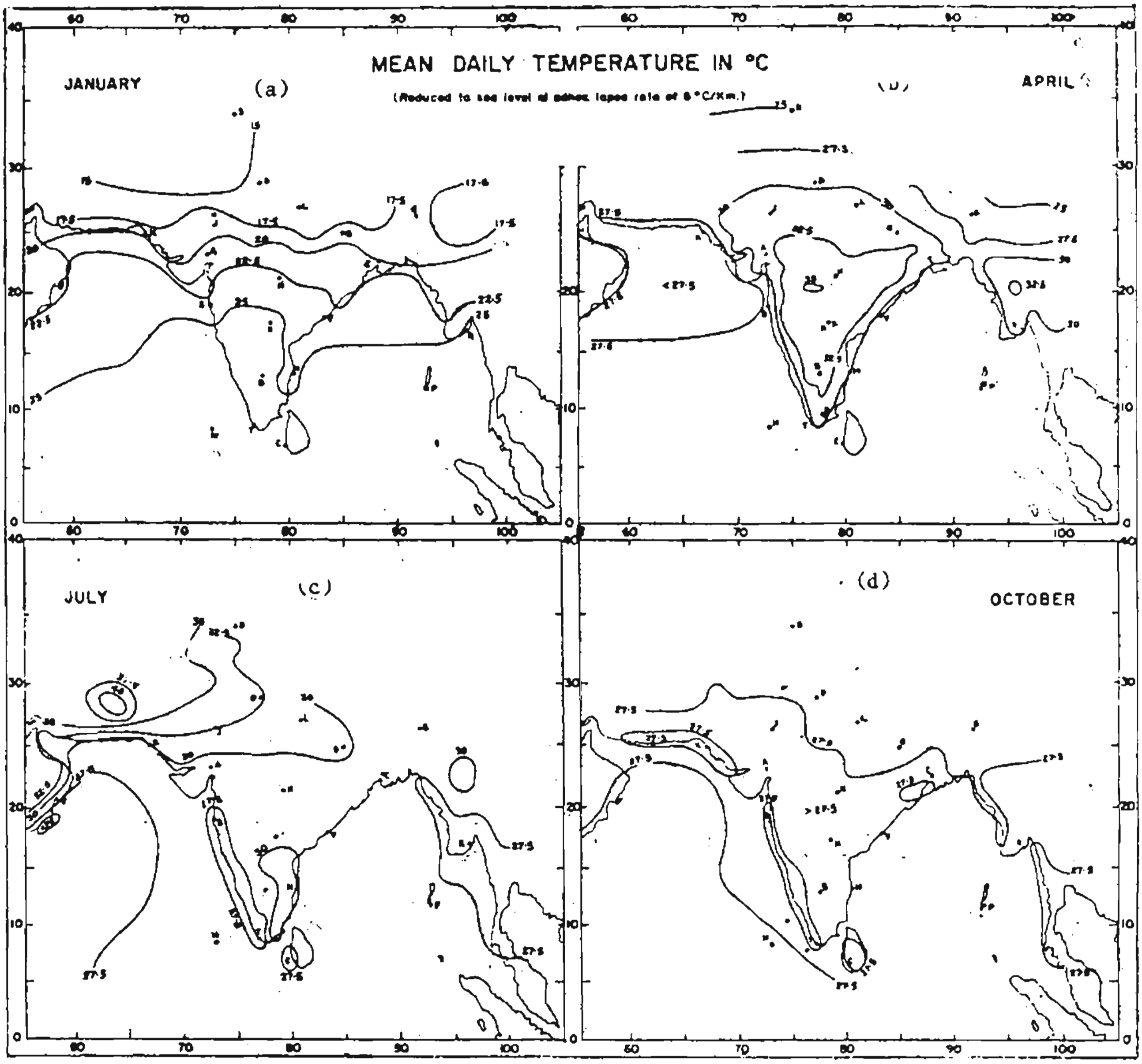


Fig. 1.3. Distribution of mean temperatures of Indian Subcontinent

latitude between 20^{o}N and 30^{o}N latitude and along 76^{o}E to 77^{o}E longitude. Temperatures are more even in the rest of the peninsula. Lower values occur on the east coast south of 17^{o}N. During winter, northern India experience higher temperatures compared to the places in the same latitude belt since the Himalayas obstruct the influx of cold air. However, in January and February abnormal low minimum temperatures occur over Jammu and Kashmir, Punjab, Himachal Pradesh, Haryana, Uttar Pradesh, Bihar, Rajasthan and Gujarat. These are referred to as 'Cold Waves'. The cold waves normally occur in the wake of intense Western Disturbances when there is a incursion of cold continental air. In such cases, the plains of north India experience sub-freezing temperatures and widespread frost damage may occur.

April:

Fig. 1.3(b) gives the temperature distribution during the hot weather season, April being the representative month. The land gets heated up, the sun now being in the Northern Hemisphere. This is the season of highest temperature because of clear skies and meager rainfall. May is the month of highest temperature. In Kerala and northeastern states, the temperature start decreasing as the intensity of pre-monsoon thundershowers increases. The mean maximum temperatures are of the order of 40^{o}C to 42^{o}C between latitudes 14^{o}N and 25^{o}N. The highest temperatures are noted in Rajasthan. The vast contrast between the land and ocean can be seen from the closely packed isotherms near the coasts. The temperatures are lower on the west-coast than on the east-coast due to to the prevailing westerly winds and pronounced sea-breeze effect along the western coast. In the hot months from March to May, the hottest region extends from west Pakistan to east Madhya Pradesh. The western and northwestern parts of the subcontinent have daily mean maximum temperature of the order of 35^{o}C to 45^{o}C. During summer, particularly in May and June, northwest India experience spells of abnormal high temperatures called 'Heat Waves'. Temperature over Rayalseema and Vidarbha are also abnormally high because of their remoteness from the sea, absence of marine influence and probably by the influence of black soil.

July:

The summer temperature pattern of the subcontinent is modified by the onset of the south-west monsoon. The associated hydrometeors affect the temperature which initially drop and then remain more or less uniform. The monsoon air mass temperature are nearly uniform along the west-coast, and the highest temperatures occur over northwest India where continental air mass still persists and very little clouding is experienced. The rainshadow regions to the east of the Western Ghats are also warmer than the surrounding regions. After June, the temperature starts decreasing thereby modifying the summer maximum. There is a secondary maximum in September after the cessation of the rains and hence September is often referred as the 'Little Summer'. The temperature distribution during this season is represented in Fig. 1.3(c).

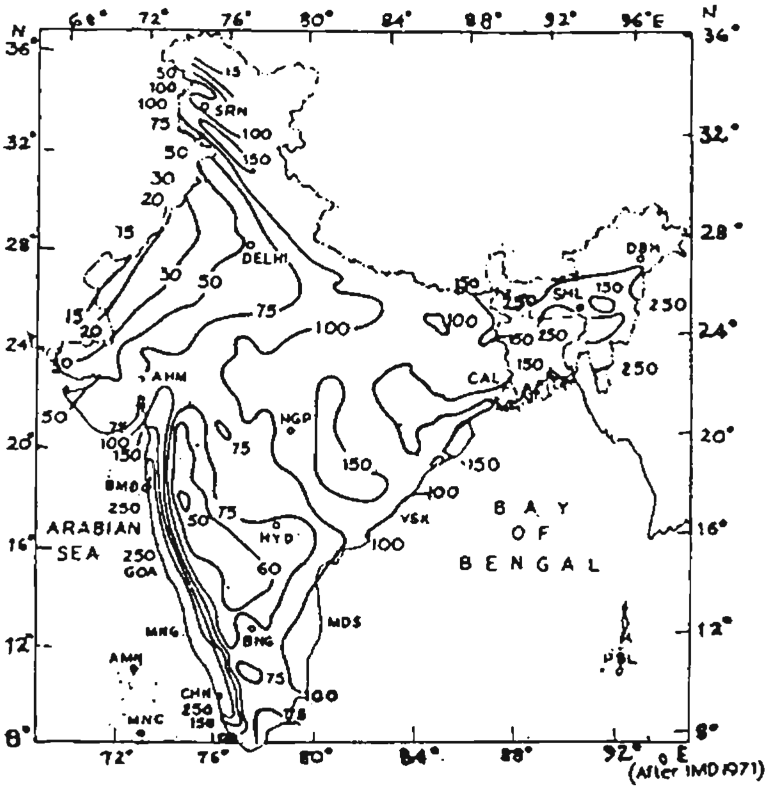
October:

Practically, throughout the subcontinent temperature in October are generally within the range of 27^{o}-29^{o}C. This is the month of the most equable distribution of temperature in India. Northern India cooled by the south-west monsoon is nearing winter and the south is experiencing the northeast monsoon rains. The temperature along the west-coast is still lower than the sea and it is seen that along the north Orissa coast and Sind-Mekran coasts, air temperature is lower than the neighboring sea (Fig. 1.3(d)).

1.5.3 **Mean Rainfall Distribution:**

Annual Rainfall:

Fig. 1.4 shows the annual rainfall over the Indian subcontinent. Hills and mountain ranges cause a striking variations in rainfall. On the southern slopes of Khasi-Jainta hills, rainfall is over 1000 cm in Cherrapunji, while to the north in Brahmaputra valley it decreases to about 200 cm. Similarly, from the west-coast, along the slopes of the Western Ghats, rainfall increases and it decreases rapidly to the eastern side.



(After IMD 1971)

Fig. 1.4. Annual Rainfall over Indian subcontinent

Rainfall decreases inland from the east coast in the peninsula south of $17^{O}N$. This decrease in trend continues up to the eastern side of the Western Ghats, while there is some increase along the Eastern Ghats. Between $17^{O}N$ and $20^{O}N$, the Eastern Ghats is closer to the coast and higher than further south, and hence the rainfall increases from the coast to the hill ranges. Behind the first range in the Eastern Ghat, there is a slight decrease and then increases over the next range. From $80^{O}E$ rainfall decreases continuously upto the east of the Western Ghats. From the coast of West Bengal and the hills of Orissa rainfall decreases inland. Further westwards, the Chota Nagpur hills, the Maikala range and the Mahadeo hills cause increase of rainfall with lesser amounts in the valleys in between them.

Across northern India a line of minimum rainfall runs from the region $28.5^{O}N$ and $75^{O}E$ to $25^{O}N$ and $85^{O}E$ which is paradoxically close to the monsoon trough. Areas to the south of this line falls in the track of monsoon trough where monsoon depressions are responsible for the increase in rainfall and in areas north of this track there is some effect of the Himalayas in increasing the rainfall.

Rainfall in Andaman and Nicobar islands in the Bay of Bengal about 300 cm while in Laccadives and Maladives in the Arabian Sea it is only 150 cm, though both island groups are in the same latitude belt.

Seasonal Rain:

January-February:

The winter precipitation over the Indian subcontinent is a small percentage of the annual rainfall, except in Kashmir and surroundings. However, this rainfall is very important for the winter crops in the northern parts of the country. Fig. 1.5(a) shows the rainfall distribution during this season. Rainfall is more than 40 cm in Kashmir and in some places in the Nicobar islands. northeast India, east of 90^{O}E longitude, Bihar plateau and the adjoining parts of Madhya Pradesh and Orissa, the peninsula south of 10^{O}N, the east coast strip south of 15^{O}N and the two island groups receives over 5 cm of rainfall during this season.

March-May:

In the hot weather period (March-May), the major areas of rainfall are Assam, Jammu and Kashmir and Kerala. The northeastern parts of the country also receives rainfall during this season mainly from thunder showers. Southwest Rajasthan and Sind are the driest areas during this period (Fig. 1.5(b)).

June-September:

The rainfall distribution during the principal rainy season of India, the southwest monsoon period lasting from June to September, is shown in Fig. 1.5(c). With the exception of

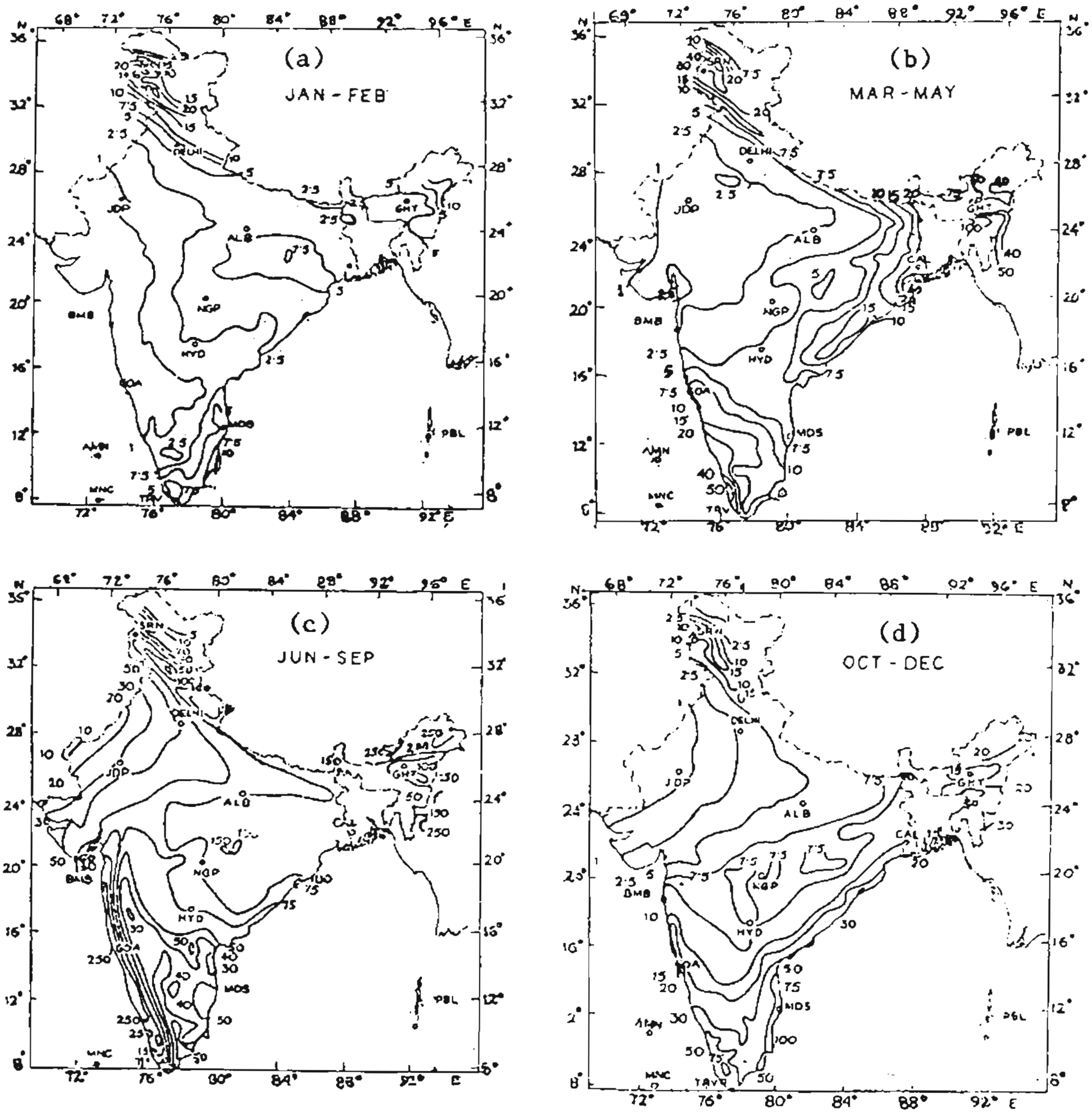


Fig. 1.5. Seasonal rainfall distribution over India

Kashmir and surroundings, and the extreme south peninsula (other than the west-coast), the annual rainfall is mainly accounted by the falls in this season and hence the annual as well as the monsoon seasonal rainfall are similar in distribution. Orographic influence is dominant in the distribution of rainfall in this season, as the prevailing winds blow almost at right-angles to the Western Ghats and the Khasi-Jainta hills.

Rainfall decreases very rapidly southwards along the west-coast from 9.5^{O}N to Kanyakumari. To the east of the Western Ghats, between 8^{O}N and 10^{O}N latitude, rainfall decreases considerably and in the coastal strip rainfall is only 2 cm. In the northwestern parts of the subcontinent, the rainfall progressively decreases westwards.

October-December:

In the post-monsoon period, the south peninsula, the east-coast, Assam and parts of Kashmir are the major areas of precipitaion, as seen from Fig. 1.5(d). From the east-coast, the rainfall decreases inland, markedly so in Tamil Nadu and Andhra Pradesh. South of 15^{O}N, rainfall again increase over and near the Western Ghats but decreases towards the west-coast. The increase in rainfall near Eastern Ghats, however, is not quite marked.

1.6 MONSOONS OVER INDIA

South-West Monsoon:

During the Northern Hemisphere summer, the Asian land mass gets heated while the surrounding oceans remain relatively cool. A deep low pressure system (994 mb) develops over north Pakistan and high pressure cells build up over south Indian Ocean. These quasi-permanent systems control the low-level circulation. The sub-tropical high's of the Southern Hemisphere shift northwards by April when the south-east trade winds start crossing the equator. During this period the temperatures progressively rise and the pressure decreases over the Indian subcontinent with increasing insolation. By June, the low over Pakistan gets fully established and extends to the head Bay of Bengal across the Indo-Gangetic plains. This trough of low is called the 'monsoon-trough'.

The south-east trades gets deflected on crossing the equator due to the earth's rotation, advance northwards and becomes south-west trades. The south-west trades strike the Kerala coast towards the end of May or beginning of June and constitute the 'Southwest Monsoon'. The monsoon current further advances northward in stages, reaches northwestern India by mid-July. It starts withdrawing from this region by early September and gradually recedes southwards and leaves the country by October. The period June to September is referred to as the 'South-West Monsoon' season.

The country receives most of its rainfall during this season. Heaviest rainfall occurs on the western coastal uplands on the windward slopes of the Western Ghats, particularly between 10°N and 20°N latitude the southern slopes of Khasi-Jainta hills and the southern slopes of Eastern Himalayas. The location and orientation of the monsoon trough and the monsoon depressions forming in Bay of Bengal influences the precipitation pattern of the country during this season.

Northeast Monsoon:

The southwest monsoon starts withdrawing from the extreme northwestern portions of India by the beginning of September. The withdrawal takes place in spurts and stages, southwards and eastwards. The intermediate transitional period when the summer pattern of pressure and winds undergoes slow modification for the establishment of the winter period is called the 'post-monsoon' season. Tamilnadu gets its maximum rainfall and Kerala experience a secondary rainfall spell during this season.

1.7 TROPICAL CYCLONES IN THE INDIAN SEAS

Tropical revolving storms (TRS) from in the vast expenses of the warm tropical oceans. They are violent whirls spiraling upward from the ocean surface to great heights, sometimes upto the tropopause and moves across the ocean from east to west.

They are characterised by huge pressure deficit at the centre, cyclonic circulation, violent winds and severe weather. Tropical revolving storms are called tropical cyclones in the Indian Seas.

Tropical cyclones are mostly formed during the post-monsoon period of October-December. Tropical systems originate in the latitude belt of 8°N to 14°N during this season. Initially they move west or northwest, but subsequently many of them recurve and move northeast. The most vulnerable areas of land fall are the coastal belts of Tamil Nadu, Andhra Pradesh and Bangladesh. Many of the cyclones which strike the coast south of 15°N move across the peninsula and emerge into the Arabian Sea. They sometimes reintensify into severe cyclonic storms. These systems initially move north westwards but later recurve northeast and strike the Konkon, Maharashtra and the Gujarat coast. The Bay of Bengal is more prone for the formation of tropical cyclones than the Arabian Sea.

During March-May a few cyclones form in the Arabian Sea but generally does not affect the Indian area. The number of cyclones forming in the Bay of Bengal is much more than in the Arabian Sea during this season. The south-west monsoon period and winter season are periods of least cyclone activity in the Indian Seas.

1.8 OTHER WEATHER SYSTEMS

1.8.1 Western Disturbances

During October to June middle latitude cyclones pass across the northern portions of the Indian subcontinent. These cyclones originating in West Asia, the Mediterranean sea and in Atlantic Ocean reach the Indian area in the course of their eastward passage. Most of these disturbances are in the occluded stage when they reach India. These extratropical cyclones reaching India from the west are called 'Western Disturbances'.

The term 'Western Disturbances' is applied generally to all perturbations which come from the west. When these disturbances reach Rajasthan, Haryana and Punjab they slow down and stagnate due to the nearly closed-in nature of the region with high hills to the north-west, north and east and open terrain to the south. After intaking moisture from the Arabian Sea, the disturbances intensify and move northeast. These disturbances give precipitation in the form of snowfall over Kashmir, Himachal Pradesh and Kumaon hills during October to December. The 'Western Disturbances' affect the weather of Arunachal Pradesh, sub-Himalayan West Bengal and Assam during the winter period.

1.8.2 Norwesters

The convectional activity increases all over the country as the insolation increases during the hot weather period of March to May. Northeastern states of Mizoram, Tripura, Manipur, Nagaland, Meghalaya, Arunachal Pradesh, Assam, Bengal and adjoining areas of Orissa and Bihar and Kerala experience an increase in thunderstorm activity during this season. The thunderstorms of Bengal and the adjoining areas of Bihar, Orissa, and Assam are known as 'Norwesters' or 'Kalbaisakhis'. The squalls come predominantly from the northwest and hence are termed as 'Norwester'. They commence mainly in the month of Vaisakha (mid-March to mid-April) and are extremely destructive and hence the name 'Kalbaisakhis'. They are in the nature of line squalls and fresh ones come up repeatedly by a process of regeneration through the downdrafts of the decaying cells, producing new cells. The most susceptible regions of formation are the Chota Nagpur plateau and the chain of hills to the east of it. Squall speeds reach 60 to 80 Kt and the preferred time of occurrence is late afternoon or evening. Heavy showers and hail with 80 Kt squalls are responsible for immense damage in life and property.

1.8.3 Andhis

The dust storms of western India are locally known 'Andhis'. The dust storms are essentially thunderstorms, the downdrafts from which scoop up large quantities of dust or sand and move as a solid dust wall. Since the moisture content is small, precipitation is negligible. The squall speeds usually reach 30-40 Kt but in severe storms can go upto 40-60 Kt. The direction of the squall is generally NW/W, but can vary according to the direction of cumulonimbus cells. Dust storms are common over Jammu, Haryana, Punjab, Rajasthan, Delhi, Uttar Pradesh, Madhya Pradesh and Bihar.

1.9 DETAILS OF THE DATA USED FOR THE STUDY

In response to the rapid growth in data utility of the global data, the Carbon-dioxide Information Analysis Center (CDIAC) and the National Climatic Data Center (NCDC) commenced the Global Historical Climatology Network (GHCN) project. The purpose of this project was to construct an improved global baseline data set of monthly mean temperature, precipitation, sea-level pressure and station-level pressure for a dense network of worldwide meteorological stations. The spatial and temporal resolution of the GHCN data base makes it well suited for use in long-term local, regional and global-scale climatological analysis (Russell et al. 1992).

Compilation of the GHCN data:

The compilation of the Global Historical Climatology Network (GHCN) data base took place in several stages, beginning with data base acquisition. The GHCN data base was assembled from the various national, continental and global data scale bases obtained through the World Monthly Surface Station Climatology. The second step of compilation of the GHCN data base entitled scrutinising and revising all station inventory parameters (country codes, station numbers, station names, latitudes, longitudes and elevations). Whenever possible all such parameters were updated with the most recent information available from World Meteorological Organisation (WMO).

In the third step all data sets were merged and subjected to a process that removed the numerous duplicate stations. In the final compilation step all stations in the data base were subjected to a two-part quality control analysis. In the first part, all observations exceeding certain thresholds (obtained from world record values) were set to be missing. In second part, each time series was plotted and inspected for gross errors (errors visible to the naked eye). Some erroneous values were readily corrected (i.e., observations with missing negative signs etc.). Uncorrectable mistakes were set to missing.

The GHCN data base contains mean monthly temperature data in tenths of degree Celsius. Total monthly precipitation data (in tenths of millimeters) and mean monthly sea-level pressure data in tenths of millibars are also available in the GHCN data base.

Limitations and Restrictions of the GHCN data base:

(i) **Station Homogeneity:** A time series representing the variations of a climatological element is called homogeneous if the variations are caused only by effects of weather and climate. A variety of anthropogenic factors may create an inhomogeneous time series including sysematic changes in the environment of the station, station relocations, instrumentation or exposure changes, changes in observers or observation times and changes in the methods used to calculate daily or monthly averages. No quantitative assessments of homogeneity have been made for stations in the GHCN data. However, each time series was plotted and visually inspected for gross discontinuities and were accordingly.

(ii) **Metadata Quality:** The GHCN data base was compiled from a number of different data sets that included various quantities of metadata. A few data sets documented station relocations and instrumentation changes while most others provided only station names and co-ordinates. For this reason the GHCN data base contains only the most elementary metadata parameters (e.g., station number, name, latitude, longitude and elevation). Moreover, errors may occur due to the fact that latitudes and longitudes are rounded to nearest of a degree and also differences in computation of elevations. Detailed station history are not currently available with the GHCN data base.

(iii) Data Precision: In the ghcn data base, temperature data are archived to the nearest tenth of a degree, precipitation to the nearest tenth of a millimeter, and pressure to the nearest tenth of a millibar. In numerous cases, however, the values in the source data sets were specified to the nearest whole unit (e.g., whole millimeters rather than tenths of millimeters). For some stations, the rounding was internally consistent but for many others, the rounding was not consistent. Another potential precision error might have been introduced if the data values had been previously converted from English to Metric units. Detailed documentation on changes in precision and data conversions are not currently available with the GHCN data base.

(iv) **Computational practices:** The GHCN data base contains monthly mean temperature, sea-level pressure, station-level pressure and precipitation data. Unfortunately, the method used to compute the monthly mean values can vary for different times and different types of weather stations and no detailed documentation on computational methods is available in the GHCN data base.

(v) **Recording practices:** Recording practices (e.g., time of observation, type and exposure of instrumentation) vary from time to time and from place to place and no detailed documentation on these recording practices are available in the GHCN data base.

Extended description about the collection, compilation, and correction of the data are mentioned elsewhere (Russel, et al., 1992).

Interpolation techniques and period of data used:

Monthly mean surface mean sea-level pressure, temperature and rainfall data from stations located all over India obtained through the Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, Oak Ridge , USA is utilised for the study. Details about the stations selected, their location, elevation from the mean sea-level and number of years of data available are illustrated in Tables 1.1, 1.2 and 1.3 and the position of the stations are marked in Figs. 1.6, 1.7 and 1.8, respectively for rainfall, temperature and sea level pressure.

Eventhough, surface data is available for more than 75 stations located all over the country, stations with data length less than 30 years of continuous observations are not included for the present study. Missing data are interpolated by replacing the long-period (climatological) monthly mean values for the corresponding month. However, if the interpolation of data exceeds 10% of the total data length that particular station is also omitted. Thus 48 stations having continuous temperature data, 47 rainfall stations and 35 stations of continuous mean sea-level pressure data distributed all over the Indian subcontinent is utilised for the thesis work.

Table 1.1 Details of the stations, their location and data length for temperature measurement over India.

No.	Station Name		Latitude ($^{\circ}$N)	Longitude ($^{\circ}$E)	Altitude from msl (gpm)	Data length
1	SRINAGAR	(SRN)	$34^{\circ}51'$	$74^{\circ}50'$	1585	1893-1990
2	AMRITSAR	(AMR)	$31^{\circ}38'$	$74^{\circ}52'$	229	1948-1990
3	SHIMLA	(SML)	$31^{\circ}06'$	$77^{\circ}10'$	2205	1863-1960
4	LUDHIANA	(LDN)	$30^{\circ}52'$	$75^{\circ}56'$	255	1893-1990
5	MUKTESHWAR	(MKS)	$29^{\circ}28'$	$79^{\circ}39'$	2310	1897-1989
6	BIKANER	(BKR)	$28^{\circ}00'$	$73^{\circ}18'$	223	1878-1990
7	NEW DELHI	(DLH)	$28^{\circ}35'$	$77^{\circ}12'$	211	1875-1990
8	AGRA	(AGR)	$27^{\circ}10'$	$78^{\circ}02'$	168	1862-1989
9	DARJEELING	(DJG)	$27^{\circ}03'$	$88^{\circ}16'$	2127	1867-1991
10	DIBRUGARH	(DBG)	$27^{\circ}29'$	$95^{\circ}01'$	110	1901-1991
11	JODHPUR	(JDP)	$26^{\circ}18'$	$73^{\circ}01'$	217	1901-1990
12	JAIPUR	(JPR)	$26^{\circ}49'$	$75^{\circ}48'$	385	1898-1990
13	DARBHANGA	(DBG)	$26^{\circ}10'$	$85^{\circ}54'$	47	1868-1990
14	DHUBRI	(DHB)	$26^{\circ}01$	$89^{\circ}59'$	35	1875-1971
15	GAUHATI	(GHT)	$26^{\circ}06'$	$91^{\circ}35'$	47	1850-1990
16	KOTA	(KTA)	$25^{\circ}09'$	$75^{\circ}51'$	273	1898-1988
17	ALLAHABAD	(ALB)	$25^{\circ}37'$	$81^{\circ}44'$	97	1861-1990
18	PATNA	(PTN)	$25^{\circ}36'$	$85^{\circ}12'$	53	1868-1960
19	SHILLONG	(SHL)	$25^{\circ}34'$	$91^{\circ}53'$	1598	1867-1967
20	DALTONGANJ	(DTG)	$24^{\circ}03'$	$84^{\circ}4'$	221	1893-1989
21	DUMKA	(DMK)	$24^{\circ}16'$	$87^{\circ}15'$	149	1883-1973
22	SILCHAR	(SLC)	$24^{\circ}49'$	$92^{\circ}48'$	28	1869-1974
23	AHMADABAD	(AHM)	$23^{\circ}04'$	$72^{\circ}38'$	55	1869-1990
24	DWARKA	(DWR)	$22^{\circ}22'$	$69^{\circ}05'$	10	1901-1989
25	INDORE	(IND)	$22^{\circ}43'$	$75^{\circ}48'$	561	1893-1990
26	CALCUTTA	(CAL)	$22^{\circ}32'$	$88^{\circ}33'$	5	1829-1989
27	NAGPUR	(NGP)	$21^{\circ}06'$	$79^{\circ}03'$	308	1855-1990
28	VERAVAL	(VVL)	$20^{\circ}54'$	$70^{\circ}22'$	6	1893-1990
29	AKOLA	(AKL)	$20^{\circ}42'$	$77^{\circ}2'$	280	1870-1989
30	CUTTACK	(CTK)	$20^{\circ}28'$	$85^{\circ}56'$	27	1867-1973
31	JAGDALPUR	(JGD)	$19^{\circ}05'$	$82^{\circ}02'$	552	1901-1980
32	BOMBAY	(BMB)	$18^{\circ}54'$	$72^{\circ}49'$	10	1847-1989
33	POONA	(PNA)	$18^{\circ}32'$	$73^{\circ}51'$	555	1826-1990
34	HYDERABAD	(HYD)	$17^{\circ}27'$	$78^{\circ}28'$	530	1893-1990
35	VISHAKHAPATNAM	(VSK)	$17^{\circ}43'$	$83^{\circ}14'$	3	1866-1989
36	MACHILIPATNAM	(MAC)	$16^{\circ}12'$	$81^{\circ}09'$	3	1863-1990
37	GOA	(GOA)	$15^{\circ}29'$	$73^{\circ}49'$	58	1961-1990
38	BELGAUM	(BLG)	$15^{\circ}51'$	$74^{\circ}32'$	758	1890-1990
39	MADRAS	(MDS)	$13^{\circ}00'$	$80^{\circ}11'$	10	1813-1990
40	MANGALORE	(MNG)	$12^{\circ}55'$	$74^{\circ}53'$	22	1864-1981
41	BANGALORE	(BNG)	$12^{\circ}58'$	$77^{\circ}35'$	920	1837-1990
42	AMINI DIVI	(AMN)	$11^{\circ}07'$	$72^{\circ}44'$	3	1901-1963
43	PORT BLAIR	(PBL)	$11^{\circ}40'$	$92^{\circ}43'$	73	1868-1990
44	KODAIKANAL	(KDK)	$10^{\circ}14'$	$77^{\circ}28'$	2339	1900-1961
45	COCHIN	(CHN)	$9^{\circ}57'$	$76^{\circ}16'$	1	1842-1973
46	PAMBAN	(PBN)	$9^{\circ}16'$	$79^{\circ}18'$	10	1893-1989
47	MINICOY	(MNC)	$8^{\circ}18'$	$73^{\circ}09'$	1	1891-1989

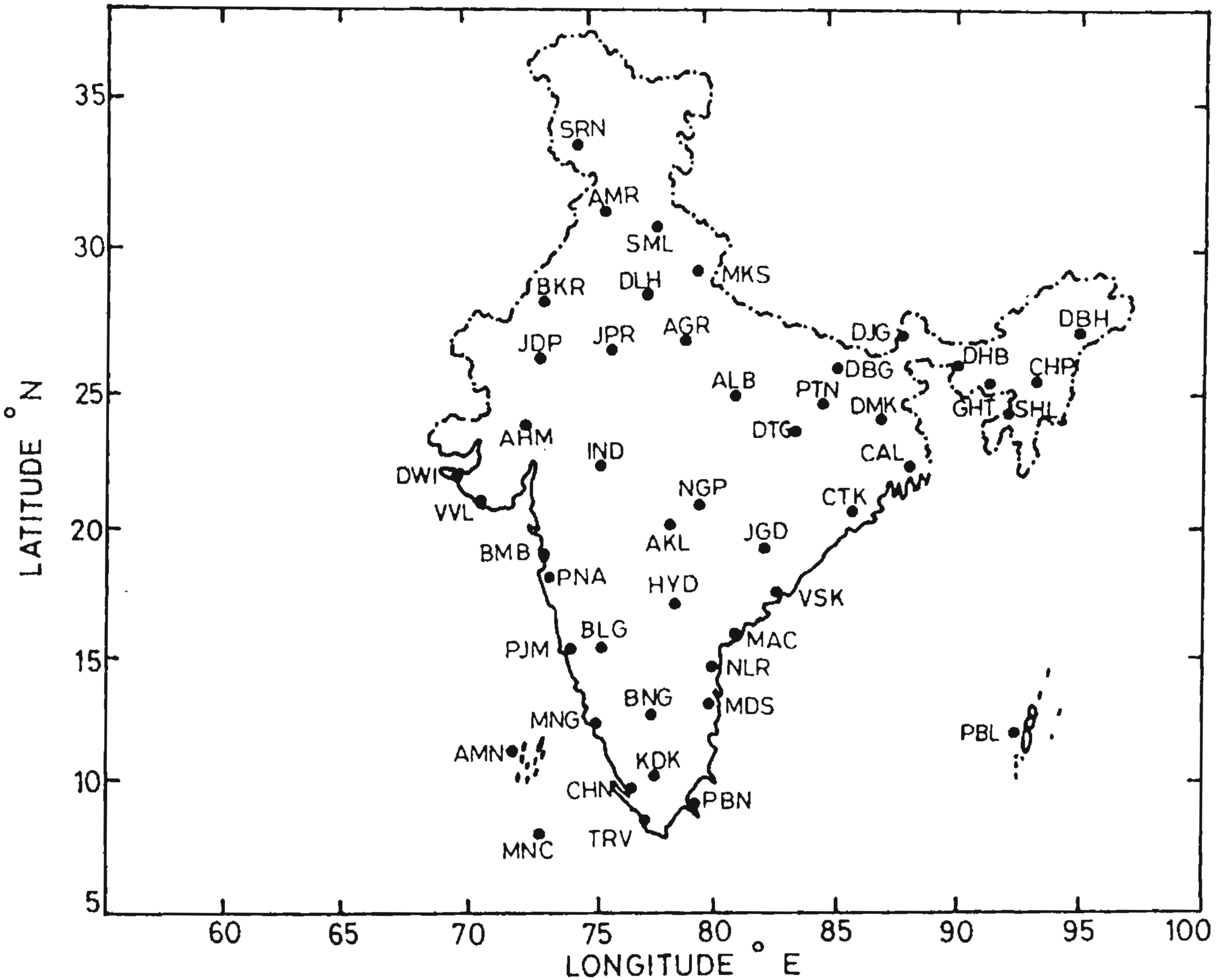


Fig.1.6. Map of India showing rainfall stations.

Table 1.2 Details of the stations, their location and data length for rainfall measurement over India.

No.	Station Name		Latitude (°N)	Longitude (°E)	Altitude from msl (gpm)	Data length
1	SRINAGAR	(SRN)	34°51'	74°50'	1585	1893-1990
2	AMRITSAR	(AMR)	31°38'	74°52'	229	1948-1990
3	SHIMLA	(SML)	31°06'	77°10'	2205	1863-1960
4	LUDHIANA	(LDN)	30°52'	75°56'	255	1893-1990
5	MUKTESHWAR	(MKS)	29°28'	79°39'	2310	1897-1989
6	BIKANER	(BKR)	28°00'	73°18'	223	1878-1990
7	NEW DELHI	(DLH)	28°35'	77°12'	211	1875-1990
8	AGRA	(AGR)	27°10'	78°02'	168	1862-1989
9	DARJEELING	(DJG)	27°03'	88°16'	2127	1867-1991
10	DIBRUGARH	(DBG)	27°29'	95°01'	110	1901-1991
11	JODHPUR	(JDP)	26°18'	73°01'	217	1901-1990
12	JAIPUR	(JPR)	26°49'	75°48'	385	1898-1990
13	DARBHANGA	(DBG)	26°10'	85°54'	47	1868-1990
14	DHUBRI	(DHB)	26°01	89°59'	35	1875-1971
15	GAUHATI	(GHT)	26°06'	91°35'	47	1850-1990
16	ALLAHABAD	(ALB)	25°37'	81°44'	97	1861-1990
17	PATNA	(PTN)	25°36'	85°12'	53	1868-1960
18	SHILLONG	(SHL)	25°34'	91°53'	1598	1867-1967
19	DALTONGANJ	(DTG)	24°03'	84°4'	221	1893-1989
20	DUMKA	(DMK)	24°16'	87°15'	149	1883-1973
21	SILCHAR	(SLC)	24°49'	92°48'	28	1869-1974
22	AHMADABAD	(AHM)	23°04'	72°38'	55	1869-1990
23	DWARKA	(DWR)	22°22'	69°05'	10	1901-1989
24	INDORE	(IND)	22°43'	75°48'	561	1893-1990
25	CALCUTTA	(CAL)	22°32'	88°33'	5	1829-1989
26	NAGPUR	(NGP)	21°06'	79°03'	308	1855-1990
27	VERAVAL	(VVL)	20°54'	70°22'	6	1893-1990
28	AKOLA	(AKL)	20°42'	77°2'	280	1870-1989
29	CUTTACK	(CTK)	20°28'	85°56'	27	1867-1973
30	JAGDALPUR	(JGD)	19°05'	82°02'	552	1901-1980
31	BOMBAY	(BMB)	18°54'	72°49'	10	1847-1989
32	POONA	(PNA)	18°32'	73°51'	555	1826-1990
33	HYDERABAD	(HYD)	17°27'	78°28'	530	1893-1990
34	VISHAKHAPATNAM	(VSK)	17°43'	83°14'	3	1866-1989
35	MACHILIPATNAM	(MAC)	16°12'	81°09'	3	1863-1990
36	GOA	(GOA)	15°29'	73°49'	58	1961-1990
37	BELGAUM	(BLG)	15°51'	74°32'	758	1890-1990
38	MADRAS	(MDS)	13°00'	80°11'	10	1813-1990
39	MANGALORE	(MNG)	12°55'	74°53'	22	1864-1981
40	BANGALORE	(BNG)	12°58'	77°35'	920	1837-1990
41	AMINI DIVI	(AMN)	11°07'	72°44'	3	1901-1963
42	PORT BLAIR	(PBL)	11°40'	92°43'	73	1868-1990
43	KODAIKANAL	(KDK)	10°14'	77°28'	2339	1900-1961
44	COCHIN	(CHN)	9°57'	76°16'	1	1842-1973
45	PAMBAN	(PBN)	9°16'	79°18'	10	1893-1989
46	MINICOY	(MNC)	8°18'	73°09'	1	1891-1989
47	TRIVANDRUM	(TRV)	8°29'	76°57'	60	1901-1989

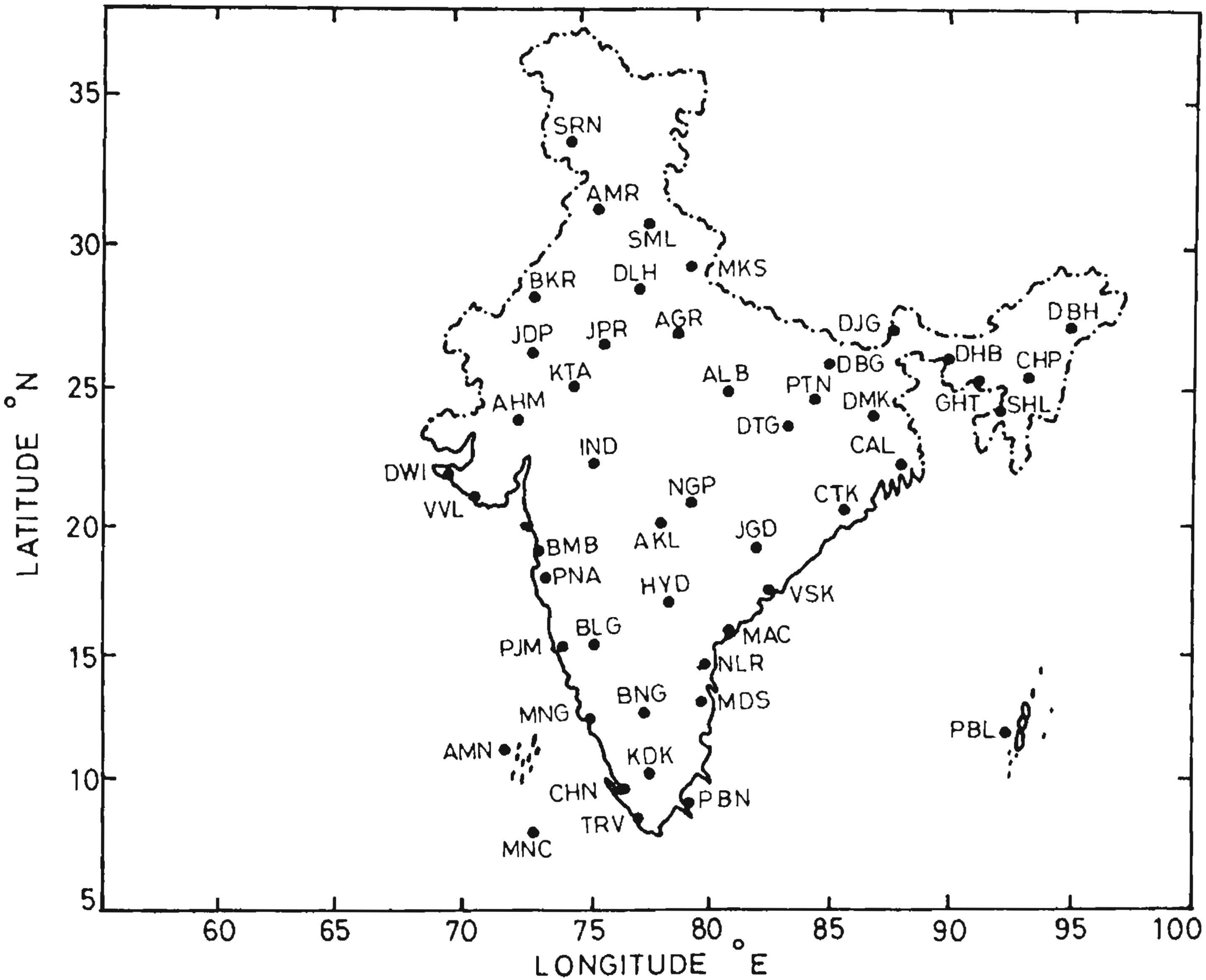


Fig.1.7. Map of India showing temperature stations.

Table 1.3 Details of the stations, their location and data length for sea-level pressure measurement over India.

No.	Station Name		Latitude (°N)	Longitude (°E)	Altitude from msl (gpm)	Data length
1	AMRITSAR	(AMR)	31°38'	74°52'	229	1948-1988
2	LUDHIANA	(LDN)	30°52'	75°56'	255	1893-1990
3	BIKANER	(BKR)	28°00'	73°18'	223	1893-1973
4	NEW DELHI	(DLH)	28°35'	77°12'	211	1941-1988
5	AGRA	(AGR)	27°10'	78°02'	168	1893-1988
6	JODHPUR	(JDP)	26°18'	73°01'	217	1897-1988
7	JAIPUR	(JPR)	26°49'	75°48'	385	1941-1988
8	GAUHATI	(GHT)	26°06'	91°35'	47	1901-1976
9	KOTA	(KTA)	25°09'	75°51'	273	1941-1988
10	ALLAHABAD	(ALB)	25°37'	81°44'	97	1941-1960
11	PATNA	(PTN)	25°36'	85°12'	53	1893-1974
12	SILCHAR	(SLC)	24°49'	92°48'	28	1941-1988
13	AHMADABAD	(AHM)	23°04'	72°38'	55	1901-1979
14	DWARKA	(DWR)	22°22'	69°05'	10	1893-1949
15	INDORE	(IND)	22°43'	75°48'	561	1931-1988
16	CALCUTTA	(CAL)	22°32'	88°33'	5	1941-1988
17	NAGPUR	(NGP)	21°06'	79°03'	308	1893-1988
18	VERAVAL	(VVL)	20°54'	70°22'	6	1893-1988
19	AKOLA	(AKL)	20°42'	77°2'	280	1893-1973
20	CUTTACK	(CTK)	20°28'	85°56'	27	1909-1949
21	JAGDALPUR	(JGD)	19°05'	82°02'	552	1921-1988
22	BOMBAY	(BMB)	18°54'	72°49'	10	1893-1949
23	POONA	(PNA)	18°32'	73°51'	555	1961-1970
24	HYDERABAD	(HYD)	17°27'	78°28'	530	1941-1988
25	VISHAKHAPATNAM	(VSK)	17°43'	83°14'	3	1941-1988
26	MACHILIPATNAM	(MAC)	16°12'	81°09'	3	1956-1975
27	BELGAUM	(BLG)	15°51'	74°32'	758	1941-1988
28	MADRAS	(MDS)	13°00'	80°11'	10	1941-1988
29	MANGALORE	(MNG)	12°55'	74°53'	22	1941-1981
30	AMINI DIVI	(AMN)	11°07'	72°44'	3	1921-1960
31	PORT BLAIR	(PBL)	11°40'	92°43'	73	1946-1988
32	COCHIN	(CHN)	9°57'	76°16'	1	1941-1973
33	PAMBAN	(PBN)	9°16'	79°18'	10	1893-1988
34	MINICOY	(MNC)	8°18'	73°09'	1	1941-1988
35	TRIVANDRUM	(TRV)	8°29'	76°57'	60	1893-1988

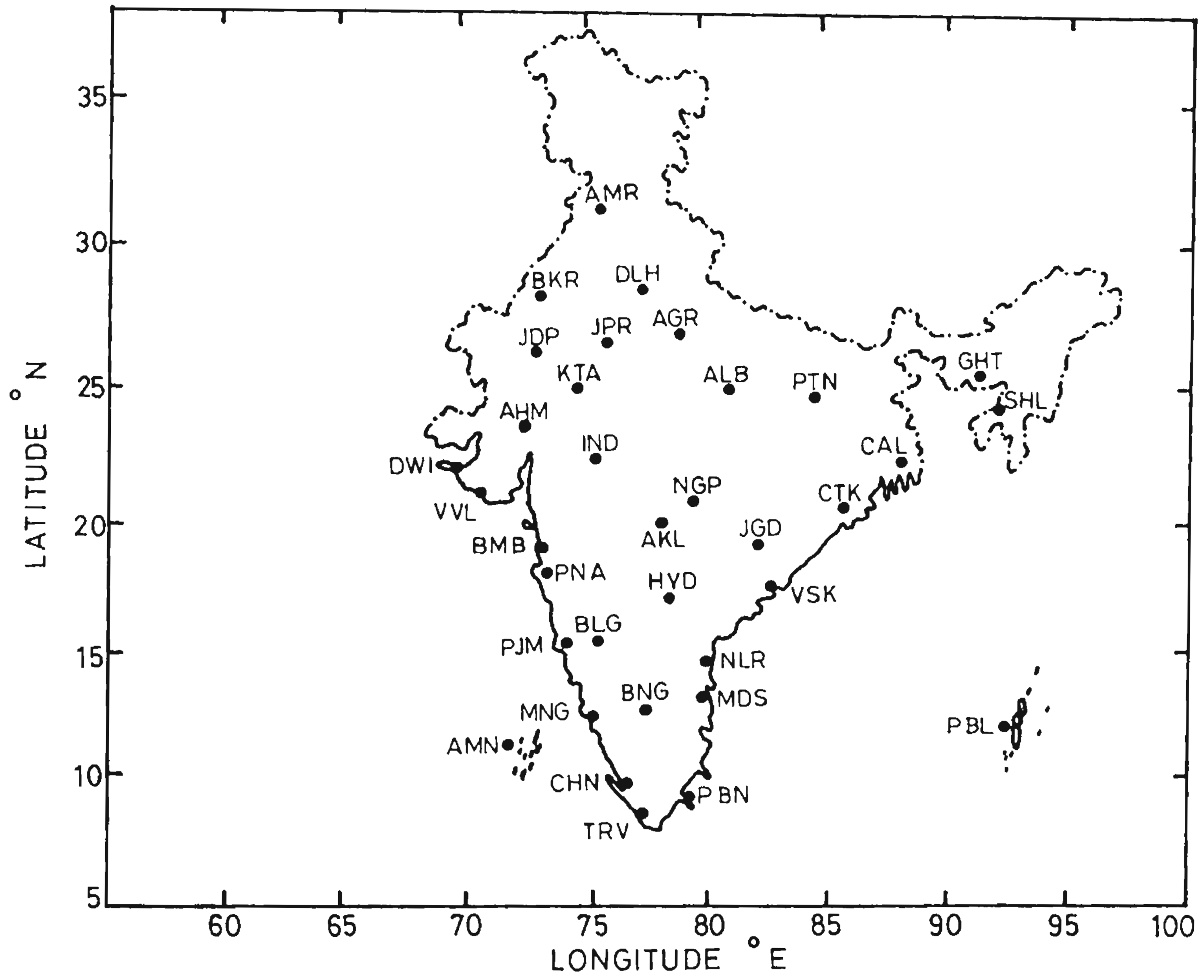


Fig. 1.8 . Map of India showing sea - level pressure stations.

Chapter 2

LITERATURE REVIEW

2.1 GENERAL

Nature has bestowed India with a unique geography. India is a tropical country of subcontinental size, peninsular in shape with vast areas of sea on the three sides and only Antartica in the far south as a land mass. The Tibetan plateau, which is the highest plateau in the world, is situated in the northern boundary of the country and acts as a massive heat source in the mid-troposphere. The Himalayas in the north, the Western Ghats and the Khasi-Jainita hills all play an important role in enhancing the monsoon rainfall and hence important in influencing the climate of the subcontinent. The unique geographical configuration gives India her weather and climate.

Success of agriculture depends on weather conditions to a considerable extent. A through and careful study on weather is inevitable in assessing the reliability of agricultural production and is also an important ingredient in making decisions in different fields of our national economy. Both weather and climate are characterised by certain physical elements. Among these, rainfall, surface air temperature and sea-level pressure are important. All these parameters vary both spatially and temporally especially in the Indian subcontinent. A detailed analysis of the spatial and temporal behaviour of surface meteorological parameters can reveal the climatological behaviour of our country which will help in future planning and production purposes.

2.2 RAINFALL STUDIES

The study of precipitation patterns over India is of particular significance, especially for agricultural purposes. Precipitation over the Indian subcontinent is governed by a number of physical, spatial and temporal factors. There is great diversity in the spatial distribution of rainfall over the country. The interannual variability of the yearly and monsoon rainfall is also very important. Several researchers have studied the spatial and temporal changes of precipitation distribution on a regional scale and for different time periods.

Blanford (1886) was the first meteorologist to make extensive studies of Indian rainfall. The analysis of 19 years (1867-1885) of annual rainfall data for India as a whole did not reveal any systematic trend. Pramanik and Jagannathan (1953) and Rao and Jagannathan (1963) analysed the south-west monsoon rainfall of India and found that there was no systematic change in Indian rainfall during the period of study. The time series of continuous Indian rainfall for the period 1901-1960 has been studied by Parthasarathy and Dhar (1976) and found that the increase in rainfall from 1901-30 to 1931-60 was significant. (Mooley (1975) examined the area of the country under deficient rainfall for the period 1947-1974 and showed that 1951, 1965, 1966, 1968, 1972 and 1974 were bad monsoon years when 33-35% of the country's area experienced deficient monsoon rainfall. Parthasarathy and Mooley (1978) studied the features of Indian summer monsoon rainfall for the 33 meteorological subdivisions of India. Parthasarathy and Dhar (1974) examined the secular variations of regional annual rainfall over India and noticed a positive trend in rainfall over Central India and the adjoining parts of the peninsula and also over two smaller areas in north-west and north-east part of the country.

Sarker and Thapliyal (1988) used the past records of rainfall to study the climatic variability. Their study showed that there is no increase or decrease in rainfall and similar variations had also occurred in the past. Thapliyal (1990) showed that rainfall is not increasing or decreasing over the country during the period 1875-1989. Thapliyal et al. (1991) summarised the climate changes and trends over India and indicated that, even though the long-period annual rainfall exhibits year-to-year fluctuations, there seems to be no systematic long-term climatic change or trend.

Harmonic analysis permits a detailed investigation of the seasonal cycle by decomposing the annual precipitation regime into independent variations. The method of harmonic analysis was employed by Kirkyla et al. (1989) to study the seasonal cycle in precipitation over the United States. The global precipitation pattern was discussed by Hsu et al. (1976) using the method of harmonic analysis. Chowdhury et al. (1988) used the technique of harmonic analysis to study the low frequency oscillations in summer monsoon rainfall. Their study indicated the presence of a 30-60 day periodicity in monsoon rainfall over India. A harmonic analysis study of the normal pentad rainfall of Indian stations by Ananthakrishnan et al. (1988) showed that most of the rainfall variability is accounted by the first two harmonics. Harmonic analysis of the area weighted monsoon rainfall over the country as a whole and for areas of normal or excess and deficient rainfall for a period of 85 years showed the triennial, seven and seventeen year cycles in rainfall variation to be significant (Biswas et al. 1989).

Analysis of time series by spectrum analysis is useful to obtain the contribution of oscillations with various frequencies to the variance of the time series. Spectral analysis of seasonal precipitation in low-land California indicated significant oscillations in winter-spring precipitation with a period of 25-26 years in most of the stations selected (Granger et al. 1977). Bhargava and Bansal (1969) used the method of spectral analysis to investigate the presence of Quasi-biennial oscillation in precipitation for a few Indian stations and found significant QBO at Bombay. Ragavendra (1974) used power spectrum analysis to bring out the periodicities in daily rainfall data for Maharashtra state.

The south-west monsoon is a repetitive annual phenomena, hence the agricultural production depends upon the spatial and temporal distribution of the monsoon rainfall. However, the Indian monsoon is synonymous with vagaries. A study on the interannual and intraseasonal variability of monsoon rainfall is necessary for any future prediction purposes. Several authors have studied the fluctuations in the monsoon rainfall over India.

Vagaries of Indian monsoon rainfall and its relationship with regional and global circulations were studied by Parthasarathy et al. (1990). The interannual variability of the monthly mean upper layer thickness for the central Arabian Sea was investigated in relation to Indian summer monsoon rainfall variability (Dube et al. 1990). Similar studies on the various aspects of the interannual variability of monsoon rainfall over the Indian subcontinent was studied by Jagannathan and Parthasarathy (1973), Parthasarathy and Mooley (1978), Bhalme and Mooley (1980) and Mooley et al. (1981). During the summer monsoon, there are fluctuations between active spells with well distributed monsoon rainfall and weak spells or breaks without any rain on a large scale with a time scale of about two weeks (Ramamurthy, 1969 ; Murakami, 1976 ; Krishnamurthi and Bhalme, 1976 ; Gadgil and Asha, 1992). Active spells of the Indian monsoon are associated with an intense intertropical convergence zone (ITCZ) across the monsoon zone over the heated subcontinent. Sikka and Gadgil (1980) showed that the warm equatorial Indian ocean is a favourable zone for the occurrence of the ITCZ. They found that active spells of the continental ITCZ with large scale monsoon rainfall is associated with weak spells of oceanic ITCZ.

The maximum entropy method (MEM) was used by Ahlquist et al. (1990) to study the intraseasonal fluctuations in monsoon rainfall over India. Their study showed that most of the variance in monsoon weather comes from intraseasonal activity with periods longer than 10 days, and not from 10-20 or 30-50 day time scales. However, the intraseasonal fluctuations of the Asiatic summer monsoon investigated by Chandrasekhara (1990) and noted the presence of 30-60, 10-20 and less than 10-days oscillations in the monsoon rainfall. Similar studies carried by Rao et al. (1990) also confirmed the presence of 30-40 day oscillations. The intra-annual periodicities in Indian rainfall has been brought out by Krishnamurthi and Bhalme (1976)) and Keshavamurthy (1973). The search for quasi-biweekly periodicities in Indian rainfall confirm peaks at 9-12 days, 12 to 18 days and 20-25 days (Raj et al. 1989).

Rainfall is a unique phenomena varying in space and time due to several factors like topography, nature of weather systems, geogrpahy, aerosol content in the atmosphere and drop size distribution in clouds etc. The amount of rainfall varies from place to place and is affected by wind fluctuations, wind flow etc. Regional studies on the distribution of precipitation has been discussed in detail by many authors. On the basis of the annual absolute rainfall totals for a period of 100 years (1881-1980), the interannual rainfall variability of 14 meteorological stations in Srilanka was discussed by Naumann (1990). The study showed that higher interannual variability is present in stations in the dry zone than in the wet zone. Parthasarathy et al. (1987) studied the droughts and floods during summer monsoon for 29 meteorological subdivisions using data for a period of 1871-1985. This was done by taking the area weighted station values of the respective districts, and computing the subdivision values by summing the area weighted station values and dividing by the area of the subdivision. The same procedure has been used for many earlier studies of Indian summer monsoon rainfall (Mooley et al., 1981; Parthasarathy et al., 1985). However, the overall generalisation of rainfall occurring over India as a whole, does not satisfactorily reflect year-to-year fluctuations for entire India. Realising this fact Gregory (1989) defined macro-regional units and clearly brought out the temporal variations of summer monsoon rainfall for these regions.

Average rainfall of the contiguous Indian area consisting of 31 homogeneous meteorological subdivisions outside Bay of Bengal and Arabian Sea Island subdivision was studied by Dhar et al. (1974) using 60 year of data from 1901-1960. Dhar et al. (1978) also discussed the monthly, seasonal and annual rainfall of heavy rainfall stations in detail. Long-term variations of the rainfall at Jalpaiguri in North Bengal was investigated by Prasad et al. (1989). Manikiam et al. (1988) studied the synoptic systems causing significant rainfall over Tamil Nadu during south-west monsoon season. Kavi (1990) using the monthly mean rainfall for a period of 50 years (1938-1987) at

Bangalore showed that there is no regular trend of either increase or decrease in the annual rainfall during the past fifty years at Bangalore.

The climate system undergoes variations on all time scales ranging from the longest observable climatic changes (10^4-10^8 years), to climatic fluctuations (10-10^4 year) and to climatic variability of interannual (1 year) or intra-annual (10^{-1} year). The complexity of the behaviour of the climate system has urged many authors to study these climatic oscillations and to bring out the major periodicities in meteorological parameters especially rainfall.

Evidence for the solar-cycle signal in drought-flood proxy records has been reported for Western North America (Currie, 1984), Argentina (Currie, 1983) and China (Currie et al., 1985). Significant correlations has been brought out by Berger (1981) with changes in the pattern of South West monsoon rainfall over India and solar activity. It was shown that significant correlation does not exist between solar activity and Indian monsoon rainfall (Parthasarathy et al., 1978). However, Parthasarathy and Dhar (1974) had detected significant cycles with the range of 8.5 to 12 years, in rainfall for arid and semi-arid regions of Rajastahan, central parts of India and extreme south Indian Peninsula. The variation of cyclonic disturbances with solar activity was studied by Chakraborthy et al. (1989). The study revealed that there is a negative correlation between sunspot number and cyclonic disturbances. Recently, Bhukan Lal (1992) found significant cycles of range of 5.5 to 8.6 years for rainfall mainly in eastern and southwestern districts of Haryana and Delhi. The 5.5 year cycle can be considered as the subharmonic of the 11-year solar cycle.

The quasi-biennial oscillation with a periodicity of 26-28 months has been detected in summer monsoon rainfall along the west coast of India (Koteswaram and Alvi, 1969) and in annual rainfall over India as a whole .and also subdivision-wise (Parthasarathy and Dhar, 1974).

Significant quasi-biennial oscillation was observed in rainfall at Bangalore, Madras, Bombay, Jagadalpur, Jaipur, Agra and Srinagar (Jagannathan and Parthasarathy, 1973). QBO is often considered as a part of the solar cycle which is related to ultra-violet radiation. Jagannathan and Parthasarathy (1973) could not establish a relationship between QBO and the 11 year solar cycle, since all the stations with QBO did not exhibit the 11-year cycle. Studies of Bhalme and Jadhav (1984) indicated a spectral peak associated with the QBO and Indian summer monsoon rainfall and the number of monsoon depressions.

Chowdhury et al. (1991) used the rainfall data of 31 meteorological sub-divisions in India for around 113 years (1875-1987) to develop a flood index. Their study revealed that during

1971-1980 there were more number of flood years than drought years, but could not associate a particular phase of the QBO with the occurrence of floods and droughts or depression activity during the monsoon season. However, Mohankumar (1996) related excess/normal rainfall (frequent floods) with the westerly phase of QBO and deficient/normal rainfall (frequent droughts) to the easterly phase during periods of low solar activity. His study also showed that during periods of high solar activity normal rainfall is observed during the westerly phase of QBO.

Quasi-biennial oscillation at the 95% significance level in rainfall series was detected by Bhukan Lal et al. (1992) in Ambala, Kurukshetra, Faridabad and Karnal. The study by Ragavendra (1973) had earlier confirmed the presence of QBO in the northwest Indian region. Periodicities of 2.1 to 3.6 years which correspond to the frequency range of the QBO, 5.1 to 10 years and 19.3 years was observed by Subramanian (1992) in monthly rainfall data for many Indian meteorological subdivisions. Yasunari (1989) investigated the possible link of QBO between stratosphere, troposphere and sea surface temperature.

EL-Nino Southern Oscillation (ENSO) is a quasi-periodic disturbance to the climate system which occurs every few years and lasts for approximately one year. It can exist in either a warm or a cold phase, but the warm phase tends to have more impact than the cold phase. Eventhough the center of action of

ENSO is in the tropical Pacific, its influence can be felt well beyond the Pacific.

Many processes in the tropics relevant to ENSO have been studied in detail. Eventhough the theoretical basis for seasonal predictability of large scale circulation is the tropics is well documented, the predictability of meteorological variables like rainfall is not yet well established. Much work has been carried out is this direction (Matsuno,1966; Webster, 1972; Gill, 1980; Charney and Shukla, 1984).

An index of the ENSO is a very important input to seasonal prediction models for many tropical areas. This is provided by the Southern Oscillation Index (SOI), which is a measure of the strength of the Walker circulation across the Pacific. In particular SOI is defined as the normalised pressure difference between Tahiti and Darwin.

Considerable interest in using ENSO as predictors exists in Southern Hemisphere extratropics. Strong influences of ENSO are well documented throughout Australia (Nicholls, 1988; McBride and Nicholls, 1993) and New Zealand (Trenberth, 1976). Ramusson and Carpentor (1983) showed that there is an apparent connection between ENSO and Asian summer monsoon. Drought years over India are associated with the warm phase of ENSO and flood years with the cold phase (Shukla, 1991). Bhalme et al. (1983) found significant negative relationship between SOI and drought and positive relationship between SOI and floods over India.

Positive correlation between monsoon rainfall and southern oscillation Index was also investigated by Mooley and Parthasarathy (1983). EL-Nino modulates the monsoon atmosphere by suppressing formation of the monsoon depressions in some years, but the influences of the El-Nino on these systems are present only in a limited degree (Chowdhury et al. 1991). However, no significant correlation was found out between SOI and post-monsoon cyclone activity (Rajeevan, 1989)

The primary use of Empirical Orthogonal Function (EOF) analysis is its ability to reduce the dimensionality of the data set and to efficiently describe coherent variability in the data sets (Chen et al. 1993). The utility of eigen vector analysis to describe the important modes of variance has been demonstrated by various authors in climatic studies of surface observations.

Kutzbach (1967) used eigen vector analysis to study the large scale features of monthly pressure, temperature and precipitation patterns over North America. In a related paper Kutzbach (1970) also examined sea-level pressure patterns over Northern Hemisphere. A study of monthly means of surface pressure, temperature and rainfall for both hemisphere and the tropical belt was made by Kidson (1975). His approach was different from that of Kutzbach (1970) in that continuous time series was used for a period of 10 years, whereas Kutzbach (1970) utilised long-term series of specific time or month of the year. Eigen vector analysis of the daily 500 mb geopotential topography over the Northern Hemisphere was made by Craddock and Flood (1969). Stidd (1967) employed the eigen vectors to study the climate estimates and was used for prediction purposes. Heddingaus et al.(1980) employed the EOF analysis to study the Northern hemisphere monthly values of temperature and kinetic energy.

Complex principal components analysis was used by Horel (1984) and Barnett (1977) used the same technique to study the time and space scales of the pacific trade wind fields. Earlier White et al. (1958) used this methodology for the prediction of sea-level pressure. Unrotated PCA often directs vectors between clusters of interrelated data points, thereby failing to capture the mode of variability. This drawback is removed by rotating the PC scores (Alexander et al., 1993)

Indian rainfall was studied using Principal Component Analysis by many workers. Identification of coherent zones (Gadgil et al., 1988) and clustering of stations into groups (Gadgil and Iyengar, 1978) are examples of such studies. Singh and Kripalani (1986), Bedi and Bindra (1980), Rakecha an Mandal (1977), Iyengar (1991) have also employed this technique to study the spatial and temporal patterns of rainfall distribution over the country.

2.3 TEMPERATURE STUDIES

For a tropical country like India, the temperature of the air near the surface of the ground is an important climatic parameter. Eventhough, the year-to-year fluctuations in air temperature is small, there is large spatial variability in the distribution of surface air temperature over our subcontinent. Realising the importance of the long-term climatic change in surface temperature of India, several studies were carried out using long-term temperature data from the middle of this country.

The annual maximum and minimum temperatures of 20 meteorological observatories situated in India and neighborhood were studied by Pramanik and Jagannathan (1954). The study revealed that there is no general tendency of systematic increase or decrease of temperature over these stations. Jagannathan (1963) and Jagannathan and Parthasarathy (1972) have analysed the trends in the characteristics of seasonal variation of temperature in the arid and semi-arid regions of the globe including 8 Indian stations, based on 55 to 100 years of data. No systematic increase or decrease were observed by them in the mean annual temperature of Indian stations were observed. Recently, Hignane et al. (1985), Sarker and Thapliyal (1988) and Thapliyal (1990) studied the trends in temperature from about 70 well distributed stations over India. These studies indicated the presence of a slight warming trend of the order of $0.4^{O}C/100$ years. While certain regions of the country such as the west coast, interior peninsula, north central India and northeast India have shown warming since 1901, other regions have shown slight cooling or no noticeable trend (Thapliyal et al., 1991). For determining the decadal trend in temperature, Thapliyal (1990) studied the 10-year running means of Indian surface temperature for 89 years (1901-1989) and found that the temperature variation exhibits epochal trends on a decadal basis. The study of Thapliyal et al. (1991) indicated that the Indian mean annual temperature does not show the post - 1940 cooling as observed in Northern Hemisphere data. A study on the decadal trends in climate over India by Srivastava et al. (1992) showed that the temperatures exhibit a decreasing trend in all the northern parts of the country (north of 23^{O}N) and a rising trend in southern parts (south of 23^{O}N). However, it was observed that for the country as a whole there is a small warming trend.

The method of harmonic analysis is employed by many workers to determine the seasonal variations in air-temperature both in India and abroad. Sankar Rao and Saltzman (1969) performed the spherical harmonics analysis of ground temperatures for the whole of the earth in order to study the global monsoon pattern. Significant semi-annual wave in temperature in the tropical stratosphere was discovered by Reed (1965). The salient features of the tropospheric annual and semi-annual temperature oscillations for the whole of the Northern Hemisphere were studied in relation to the spectacular annual monsoon cycle of southeast Asia (Asnani and Verma, 1977). Appa Rao and Brahmananda Rao (1971) studied the harmonic analysis of the mean surface temperature of the Northern Hemisphere in order to investigate the influence of heat sources and sinks in general circulation over the tropics and middle latitudes. Harmonic analysis study was also carried out by Walker (1975) of the zonal winds in the tropics. Verma et al. (1985) studied the interannual and long-term variability of the summer monsoon and its possible link with the Northern Hemispheric surface air temperatures. Harmonic analysis study of the upper air temperatures over India by Banerjee et al. (1967) indicated the presence of two maxima in temperature amplitudes, one from the ground upto 850 mb and the other higher up in the troposphere between 600-150 mb. The seasonal oscillation of the diurnal range of temperature in India and neighborhood was studied by Jagannathan et al. (1963) employing the method of harmonic analysis.

The fluctuations in the seasonal oscillations of temperature in India was studied by Jagannathan and Parthasarathy (1972). Their study included 8 stations with data from 1875-1968. It was shown that for these stations the first three harmonics are important and the seasonal variation of temperature which is largely a measure of the continentality experiences considerable variations from year-to-year. Earlier Jagannathan (1957) had observed that the first two harmonics account for nearly 90% of the seasonal variation in temperature. A study on the spatial distribution of temperature by Doraiswamy Iyer (1958) have indicated that there are two peaks in maximum temperature over North Konkan coast, while only one peak in maximum temperature over north coastal Andhara Pradesh in May-June. This was attributed to the hot westerly winds that blow across the north of peninsula. The continuation of rains in October-November prevents any rise in temperature. However, Rao (1981) had indicated the absence of semi-annual oscillation in temperature south of Mangalore along the west-coast.

Spectral analysis is an important tool in detecting periodicities in data sets. The technique of power spectrum analysis for meteorological application was discussed in detail by Panofsky et al . (1955). Madden (1977) used the technique to estimate the spectra of seasonal mean temperatures over North America and found that predictability is greater for summer temperature than for winter temperatures. Olapipo (1989) used the technique to investigate periodicities in the drought indices for the interior plains of North-America. Appa Rao and Pishal (1983) employed the spectral method to study the performance of different evapo-transpirometers.

The presence of the 11-year solar cycle in meteorological parameters have been investigated by many workers. Pittock (1978) critically analysed the relationship of solar activity and temperature and rainfall and found that there is no significant correlations between solar activity and these climatic parameters. Schuurmans (1981) found that climatic responses to the 11- year solar cycle, although relatively weak are in evidence. Significant correlations with air temperature and solar activity was investigated by Currie (1984). Bhargava et al. (1970) studied the possible relationship of long-period temperature data and solar activity and found that almost all the stations in the interior peninsula exhibit variations with a period of 130 months close to one solar activity in temperature. Jagannathan (1963) also showed that the mean annual temperature experienced a slight decrease at practically all Indian stations during periods of maximum solar activity over those of minimum solar activity and also the annual range of temperature and the seasonal and semi-annual waves of temperature showed fluctuations in accordance with the solar cycle.

Using a worldwide network of surface station records Landsberg (1963) established QBO in surface temperature all over the world, with opposite phases in tropical and extra-tropical latitudes similar to that in stratosphere temperature. Significant quasi-biennial oscillation was investigated by Berger (1981) in all the climatic variables. Statistical analysis of the time series of the mean annual temperature indicated the presence of significant quasi-biennial oscillation in mean annual temperature and also in the seasonal variation in temperature for different parts of the country (Jagannathan and Parthasarathy, 1972). The presence of variability in surface air temperature in the Northern Hemisphere was investigated by Barnett (1978).

2.4 SEA-LEVEL PRESSURE STUDIES

The work on long term pressure changes over India and the world as a whole is meager as available in the published literature. The day-to-day variation in the pressure gradient over India for the south-west monsoon seasons of 1961-1970 were examined by Bhalme and Parasnis (1975). The spectra indicated a spectral peak with a period 5-6 days associated with the pulsatory behaviour of the south-west monsoon. Asnani and Verma (1975) studied the annual and semi-annual pressure oscillations at different levels and found that the amplitude of the semi-annual wave are smallest in the equational latitudes and largest in sub-tropical or higher latitudes. Misra (1973) had earlier confirmed the presence of 4-5 day oscillations in pressure.

The presence of the 11-year solar cycle in atmospheric pressure was found by Currie (1984). Wagner (1971) analysed seasonal pressure patterns and found significant QBO in pressure systems. Study of air pressure variations simulated in two general circulation models led to reports of several atmospheric oscillations (Currie and Hameed, 1988 and Hameed and Currie, 1989). The quasi-biennial oscillation with a period of 26 months and a Chandler - Wobble oscillation with a period of 14.7 months were identified as spectral peaks in their study. Spectral peaks near 10 months and 6-7 months were also detected as peaks in their study, which were explained as the interaction of the Chandler - Signal with the annual term and its 6-month harmonic.

Detailed analyses of long period (80-100 years) pressure data (Pramanik and Jagannathan, 1955, Sarker and Thapliyal, 1988) have not revealed any systematic increasing or decreasing trend of the surface atmospheric pressure over the country, though considerable year-to-year fluctuations have been noted. Srivastava et al. (1992) analysed the station-level pressure for 475 meteorological stations spread all over the country for a period of 1901-1986. His study revealed the presence of a general decreasing trend in pressure at the rate of 0.7h Pa/100 year.

Chapter 3

SPATIAL VARIABILITY IN THE SEASONAL CYCLE IN SURFACE METEOROLOGICAL PARAMETERS OVER INDIAN SUBCONTINENT

3.1 GENERAL

Climatologically, India covers tropical, temperate and polar climatic regimes. The altitude effect of mountains and high land areas cause polar weather conditions on one side, and the arid Rajasthan desert causes extreme high summer temperatures on the other side of the country. Northwest India presents a pronounced continental temperature regime with scorching hot summers and freezing cold winters, while the southern peninsula comes under direct maritime influence with very little annual variation in temperature. The mean annual rainfall is as high as 1,000 cm over the Khasi hills and as low as 10 cm in western Rajasthan. Devastating floods in one part of the country and parching droughts in another part is a common phenomena. A complete reversal of the pressure and wind systems takes place in the course of the year between the summer southwest and winter northeast monsoon. Due to this large variability caused by geographical and topographical peculiarities, a study on the spatial distribution of surface meteorological parameters in seasonal cycle becomes necessary in understanding the climatological behaviour of the country as a whole, and is of immense economic and agricultural importance.

The aim of the study in this Chapter is to find the spatial changes in the temperature, precipitation and pressure patterns at different parts of the country, based on monthly data obtained from various stations located all over India. The method of harmonic analysis is employed for the purpose of the investigation.

3.2 METHOD OF ANALYSIS

One of the important tools used in the analysis of meteorological and climatological time series is the harmonic analysis, in which periodic terms or waves are related to whole numbers. The analysis is a convenient technique if periodic phenomena are studied, especially for known periodicities such as the annual, semi-annual or daily cycles of meteorological elements.

Harmonic analysis is based on the fourier theorem which states that any periodic function can be regarded as a combination of simple harmonic vibrations whose frequencies are an integral multiple of the given function (Mathur, 1981). This finite, single valued continuous periodic function X(t), can be expanded into a summation series of sine and cosine terms by the equation

$$X(t) = A_o + \sum_{1}^{n} A_n \sin nwt + \sum_{1}^{n} B_n \cos nwt \qquad \ldots(3.1)$$

where A_o represents the mean value of the function and the sine and cosine terms represent the component sinusoidal vibrations of frequencies which are integral multiples of frequency $w/2\pi$ of the periodic function and A_n and B_n are the amplitudes of these vibrations and are known as fourier coefficients. For the present study the general mathematical formula given by Kirkyla and Hameed (1989) is used for the computation

$$X_t = \langle X \rangle + \sum_{i=1}^{N/2} A_i \cos ((360 \; it/p) + \Phi_i) \qquad \ldots(3.2)$$

where, $\langle X \rangle$ is the arithmetic mean of the element X, A_i and Φ_i are the amplitude and phase angle of the i th harmonic, N is the number of observations, p is the period of observations and X_t is the value of the element at time t. Usually p is identical with the number of observations and in the present analysis we use the monthly mean values and p is therefore, 12 months.

The computations of arithmetic mean, the coefficients A_i, the amplitudes and the phase angles Φ_i are carried out using the formula

$$\langle X \rangle = 1/N \sum_{i=1}^{p} X_i \qquad \ldots(3.3)$$

$$a_i = 2/p \sum_{i=1}^{p} X_i \cos it_i \qquad \ldots(3.4)$$

$$b_i = 2/p \sum_{i=1}^{p} X_i \ \mathrm{sinit}_i \qquad \ldots(3.5)$$

$$A_i^2 = (a_i^2 + b_i^2)^{o} \qquad \ldots(3.6)$$

$$\Phi_i = \tan b_i/a_i \qquad \ldots(3.7)$$

The quantity i in the harmonic analysis is called the number of harmonic or the wave number and it measures the complete cycles in the basic period. In the present analysis, six harmonics are calculated with periods 12, 6, 4, 3, 2.4 and 2 months.

The nature of the seasonal variations demonstrating the curve can be understood by a comparison of the size of the amplitudes, A_i. A large first harmonic amplitude shows strong annual variation, while a relatively large second harmonic amplitude points to strong semi-annual variation. The phase angle gives the time of the year for maximum of a given harmonic. In general, long period harmonics represent large scale features of atmospheric circulation while short period harmonics indicate influences of other local phenomena. The method of harmonic analysis, therefore, helps to delineate and emphasise various boundaries and bring out the regional characteristics that may otherwise be undetected (Kirkyla and Hameed, 1989).

Monthly mean surface temperature, rainfall and sea-level pressure data from stations located all over India obtained through the Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, Oak Ridge, USA, is utilised for the study. Details about the stations selected, their location, elevation from the mean sea level and number of years of data available for rainfall, temperature and sea-level pressure are illustrated in Tables 3.1, 3.2 and 3.3, respectively and the position of the stations are marked in Figs. 3.1, 3.2, and 3.3.

3.3 RESULTS AND DISCUSSION

3.3.1 SEASONAL CYCLE IN RAINFALL

The largest amount of rain for the major portion of the country is received during the southwest monsoon period, extending from June to September. The rainfall distribution depends on the strength of the monsoon, the depth and orientation of the monsoon trough over the Indo-Gangetic plain and the number, intensity and tracks of the tropical depressions moving inland from the Bay of Bengal. The rainfall decreases considerably towards the east of the Western Ghats, where there is a rain shadow region. The rainiest season in most part of the country outside Tamil Nadu is the southwest monsoon season. The rainfall however, exhibits wide variations in both time and space due to irregular distribution, abnormal dates of onset,

Table 3.1. Details of the stations, their location and data length for rainfall measurement over India.

No.	Station Name		Latitude (°N)	Longitude (°E)	Altitude from msl (gpm)	Data length
1	SRINAGAR	(SRN)	34°51'	74°50'	1585	1893-1990
2	AMRITSAR	(AMR)	31°38'	74°52'	229	1948-1990
3	SHIMLA	(SML)	31°06'	77°10'	2205	1863-1960
4	LUDHIANA	(LDN)	30°52'	75°56'	255	1893-1990
5	MUKTESHWAR	(MKS)	29°28'	79°39'	2310	1897-1989
6	BIKANER	(BKR)	28°00'	73°18'	223	1878-1990
7	NEW DELHI	(DLH)	28°35'	77°12'	211	1875-1990
8	AGRA	(AGR)	27°10'	78°02'	168	1862-1989
9	DARJEELING	(DJG)	27°03'	88°16'	2127	1867-1991
10	DIBRUGARH	(DBG)	27°29'	95°01'	110	1901-1991
11	JODHPUR	(JDP)	26°18'	73°01'	217	1901-1990
12	JAIPUR	(JPR)	26°49'	75°48'	385	1898-1990
13	DARBHANGA	(DBG)	26°10'	85°54'	47	1868-1990
14	DHUBRI	(DHB)	26°01	89°59'	35	1875-1971
15	GAUHATI	(GHT)	26°06'	91°35'	47	1850-1990
16	ALLAHABAD	(ALB)	25°37'	81°44'	97	1861-1990
17	PATNA	(PTN)	25°36'	85°12'	53	1868-1960
18	SHILLONG	(SHL)	25°34'	91°53'	1598	1867-1967
19	DALTONGANJ	(DTG)	24°03'	84°4'	221	1893-1989
20	DUMKA	(DMK)	24°16'	87°15'	149	1883-1973
21	SILCHAR	(SLC)	24°49'	92°48'	28	1869-1974
22	AHMADABAD	(AHM)	23°04'	72°38'	55	1869-1990
23	DWARKA	(DWR)	22°22'	69°05'	10	1901-1989
24	INDORE	(IND)	22°43'	75°48'	561	1893-1990
25	CALCUTTA	(CAL)	22°32'	88°33'	5	1829-1989
26	NAGPUR	(NGP)	21°06'	79°03'	308	1855-1990
27	VERAVAL	(VVL)	20°54'	70°22'	6	1893-1990
28	AKOLA	(AKL)	20°42'	77°2'	280	1870-1989
29	CUTTACK	(CTK)	20°28'	85°56'	27	1867-1973
30	JAGDALPUR	(JGD)	19°05'	82°02'	552	1901-1980
31	BOMBAY	(BMB)	18°54'	72°49'	10	1847-1989
32	POONA	(PNA)	18°32'	73°51'	555	1826-1990
33	HYDERABAD	(HYD)	17°27'	78°28'	530	1893-1990
34	VISHAKHAPATNAM	(VSK)	17°43'	83°14'	3	1866-1989
35	MACHILIPATNAM	(MAC)	16°12'	81°09'	3	1863-1990
36	GOA	(GOA)	15°29'	73°49'	58	1961-1990
37	BELGAUM	(BLG)	15°51'	74°32'	758	1890-1990
38	MADRAS	(MDS)	13°00'	80°11'	10	1813-1990
39	MANGALORE	(MNG)	12°55'	74°53'	22	1864-1981
40	BANGALORE	(BNG)	12°58'	77°35'	920	1837-1990
41	AMINI DIVI	(AMN)	11°07'	72°44'	3	1901-1963
42	PORT BLAIR	(PBL)	11°40'	92°43'	73	1868-1990
43	KODAIKANAL	(KDK)	10°14'	77°28'	2339	1900-1961
44	COCHIN	(CHN)	9°57'	76°16'	1	1842-1973
45	PAMBAN	(PBN)	9°16'	79°18'	10	1893-1989
46	MINICOY	(MNC)	8°18'	73°09'	1	1891-1989
47	TRIVANDRUM	(TRV)	8°29'	76°57'	60	1901-1989

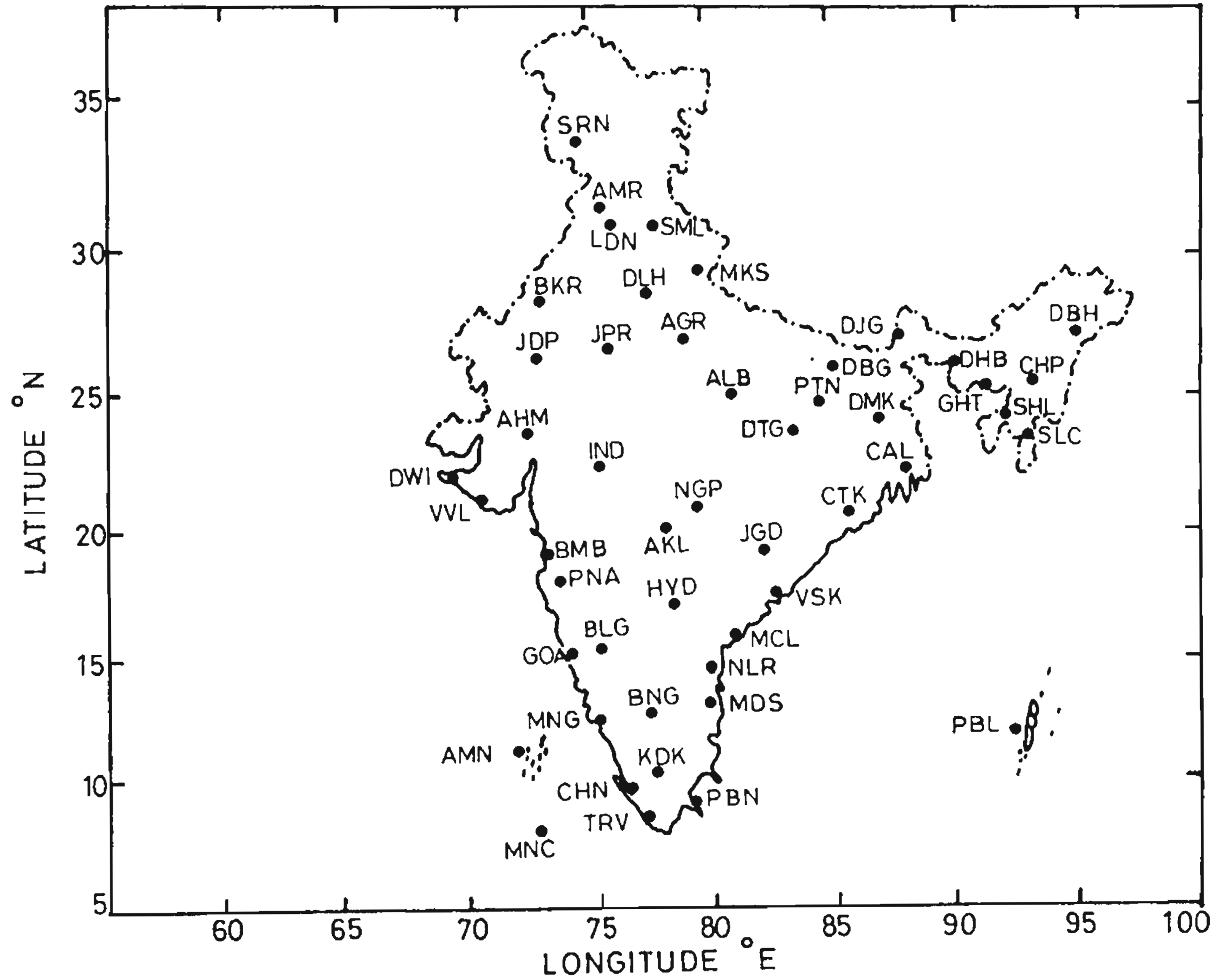


Fig. 3.1. Map of India showing rainfall stations.

Table 3.2. Details of the stations, their location and data length for temperature measurement over India.

No.	Station Name		Latitude (°N)	Longitude (°E)	Altitude from msl (gpm)	Data length
1	SRINAGAR	(SRN)	34°51'	74°50'	1585	1893-1990
2	AMRITSAR	(AMR)	31°38'	74°52'	229	1948-1990
3	SHIMLA	(SML)	31°06'	77°10'	2205	1863-1960
4	LUDHIANA	(LDN)	30°52'	75°56'	255	1893-1990
5	MUKTESHWAR	(MKS)	29°28'	79°39'	2310	1897-1989
6	BIKANER	(BKR)	28°00'	73°18'	223	1878-1990
7	NEW DELHI	(DLH)	28°35'	77°12'	211	1875-1990
8	AGRA	(AGR)	27°10'	78°02'	168	1862-1989
9	DARJEELING	(DJG)	27°03'	88°16'	2127	1867-1991
10	DIBRUGARH	(DBG)	27°29'	95°01'	110	1901-1991
11	JODHPUR	(JDP)	26°18'	73°01'	217	1901-1990
12	JAIPUR	(JPR)	26°49'	75°48'	385	1898-1990
13	DARBHANGA	(DBG)	26°10'	85°54'	47	1868-1990
14	DHUBRI	(DHB)	26°01	89°59'	35	1875-1971
15	GAUHATI	(GHT)	26°06'	91°35'	47	1850-1990
16	KOTA	(KTA)	25°09'	75°51'	273	1898-1988
17	ALLAHABAD	(ALB)	25°37'	81°44'	97	1861-1990
18	PATNA	(PTN)	25°36'	85°12'	53	1868-1960
19	SHILLONG	(SHL)	25°34'	91°53'	1598	1867-1967
20	DALTONGANJ	(DTG)	24°03'	84°4'	221	1893-1989
21	DUMKA	(DMK)	24°16'	87°15'	149	1883-1973
22	SILCHAR	(SLC)	24°49'	92°48'	28	1869-1974
23	AHMADABAD	(AHM)	23°04'	72°38'	55	1869-1990
24	DWARKA	(DWR)	22°22'	69°05'	10	1901-1989
25	INDORE	(IND)	22°43'	75°48'	561	1893-1990
26	CALCUTTA	(CAL)	22°32'	88°33'	5	1829-1989
27	NAGPUR	(NGP)	21°06'	79°03'	308	1855-1990
28	VERAVAL	(VVL)	20°54'	70°22'	6	1893-1990
29	AKOLA	(AKL)	20°42'	77°2'	280	1870-1989
30	CUTTACK	(CTK)	20°28'	85°56'	27	1867-1973
31	JAGDALPUR	(JGD)	19°05'	82°02'	552	1901-1980
32	BOMBAY	(BMB)	18°54'	72°49'	10	1847-1989
33	POONA	(PNA)	18°32'	73°51'	555	1826-1990
34	HYDERABAD	(HYD)	17°27'	78°28'	530	1893-1990
35	VISHAKHAPATNAM	(VSK)	17°43'	83°14'	3	1866-1989
36	MACHILIPATNAM	(MAC)	16°12'	81°09'	3	1863-1990
37	GOA	(GOA)	15°29'	73°49'	58	1961-1990
38	BELGAUM	(BLG)	15°51'	74°32'	758	1890-1990
39	MADRAS	(MDS)	13°00'	80°11'	10	1813-1990
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41	BANGALORE	(BNG)	12°58'	77°35'	920	1837-1990
42	AMINI DIVI	(AMN)	11°07'	72°44'	3	1901-1963
43	PORT BLAIR	(PBL)	11°40'	92°43'	73	1868-1990
44	KODAIKANAL	(KDK)	10°14'	77°28'	2339	1900-1961
45	COCHIN	(CHN)	9°57'	76°16'	1	1842-1973
46	PAMBAN	(PBN)	9°16'	79°18'	10	1893-1989

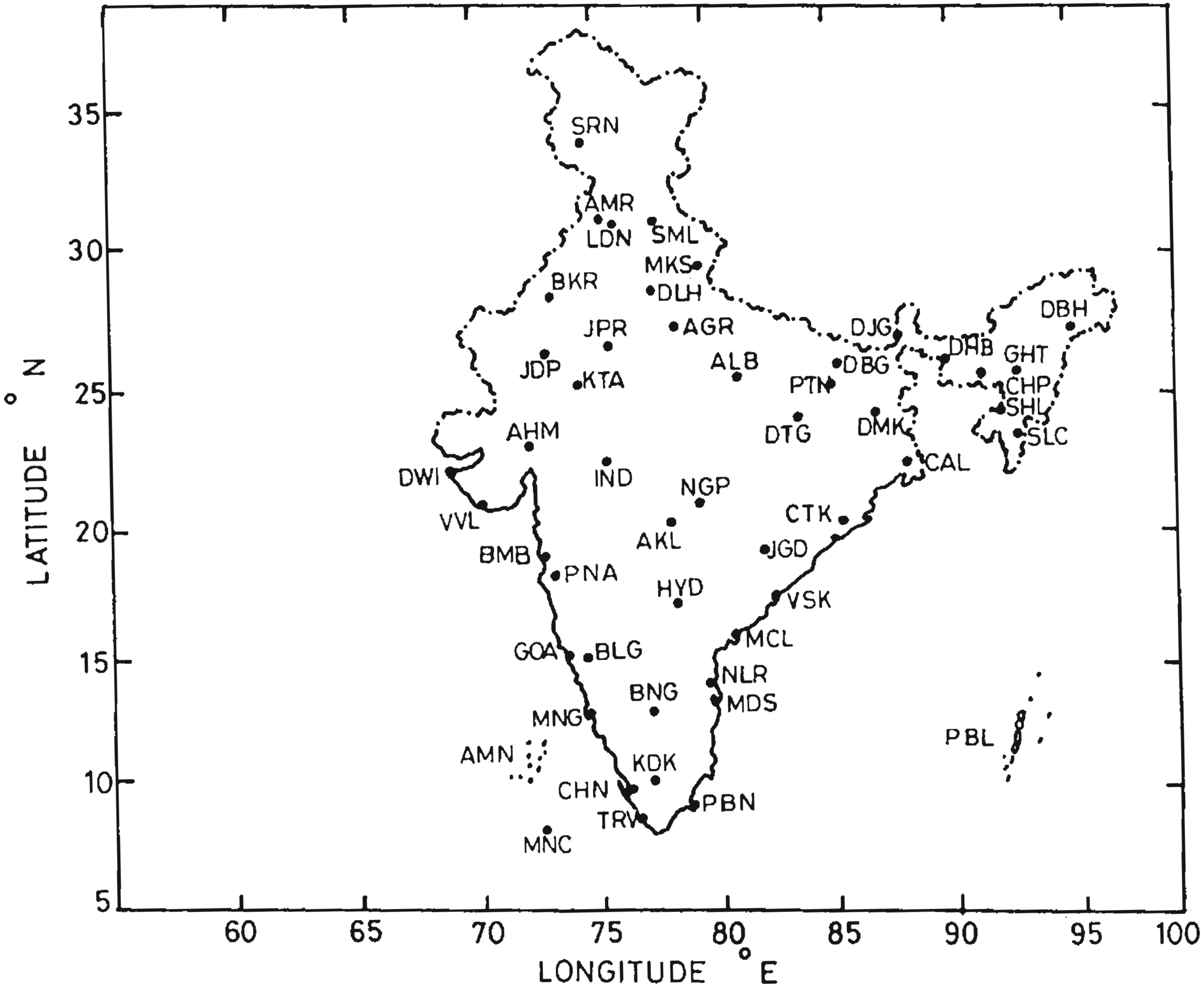


Fig. 3.2 Map of India showing the temperature stations

Table 3.3. Details of the stations, their location and data length for sea-level pressure measurement over India.

No.	Station Name	Latitude (°N)	Longitude (°E)	Altitude from msl (gpm)	Data length
1	AMRITSAR (AMR)	31°38'	74°52'	229	1948-1988
2	LUDHIANA (LDN)	30°52'	75°56'	255	1893-1990
3	BIKANER (BKR)	28°00'	73°18'	223	1893-1973
4	NEW DELHI (DLH)	28°35'	77°12'	211	1941-1988
5	AGRA (AGR)	27°10'	78°02'	168	1893-1988
6	JODHPUR (JDP)	26°18'	73°01'	217	1897-1988
7	JAIPUR (JPR)	26°49'	75°48'	385	1941-1988
8	GAUHATI (GHT)	26°06'	91°35'	47	1901-1976
9	KOTA (KTA)	25°09'	75°51'	273	1941-1988
10	ALLAHABAD (ALB)	25°37'	81°44'	97	1941-1960
11	PATNA (PTN)	25°36'	85°12'	53	1893-1974
12	SILCHAR (SLC)	24°49'	92°48'	28	1941-1988
13	AHMADABAD (AHM)	23°04'	72°38'	55	1901-1979
14	DWARKA (DWR)	22°22'	69°05'	10	1893-1949
15	INDORE (IND)	22°43'	75°48'	561	1931-1988
16	CALCUTTA (CAL)	22°32'	88°33'	5	1941-1988
17	NAGPUR (NGP)	21°06'	79°03'	308	1893-1988
18	VERAVAL (VVL)	20°54'	70°22'	6	1893-1988
19	AKOLA (AKL)	20°42'	77°2'	280	1893-1973
20	CUTTACK (CTK)	20°28'	85°56'	27	1909-1949
21	JAGDALPUR (JGD)	19°05'	82°02'	552	1921-1988
22	BOMBAY (BMB)	18°54'	72°49'	10	1893-1949
23	POONA (PNA)	18°32'	73°51'	555	1961-1970
24	HYDERABAD (HYD)	17°27'	78°28'	530	1941-1988
25	VISHAKHAPATNAM (VSK)	17°43'	83°14'	3	1941-1988
26	MACHILIPATNAM (MAC)	16°12'	81°09'	3	1956-1975
27	BELGAUM (BLG)	15°51'	74°32'	758	1941-1988
28	MADRAS (MDS)	13°00'	80°11'	10	1941-1988
29	MANGALORE (MNG)	12°55'	74°53'	22	1941-1981
30	AMINI DIVI (AMN)	11°07'	72°44'	3	1921-1960
31	PORT BLAIR (PBL)	11°40'	92°43'	73	1946-1988
32	COCHIN (CHN)	9°57'	76°16'	1	1941-1973
33	PAMBAN (PBN)	9°16'	79°18'	10	1893-1988
34	MINICOY (MNC)	8°18'	73°09'	1	1941-1988
35	TRIVANDRUM (TRV)	8°29'	76°57'	60	1893-1988

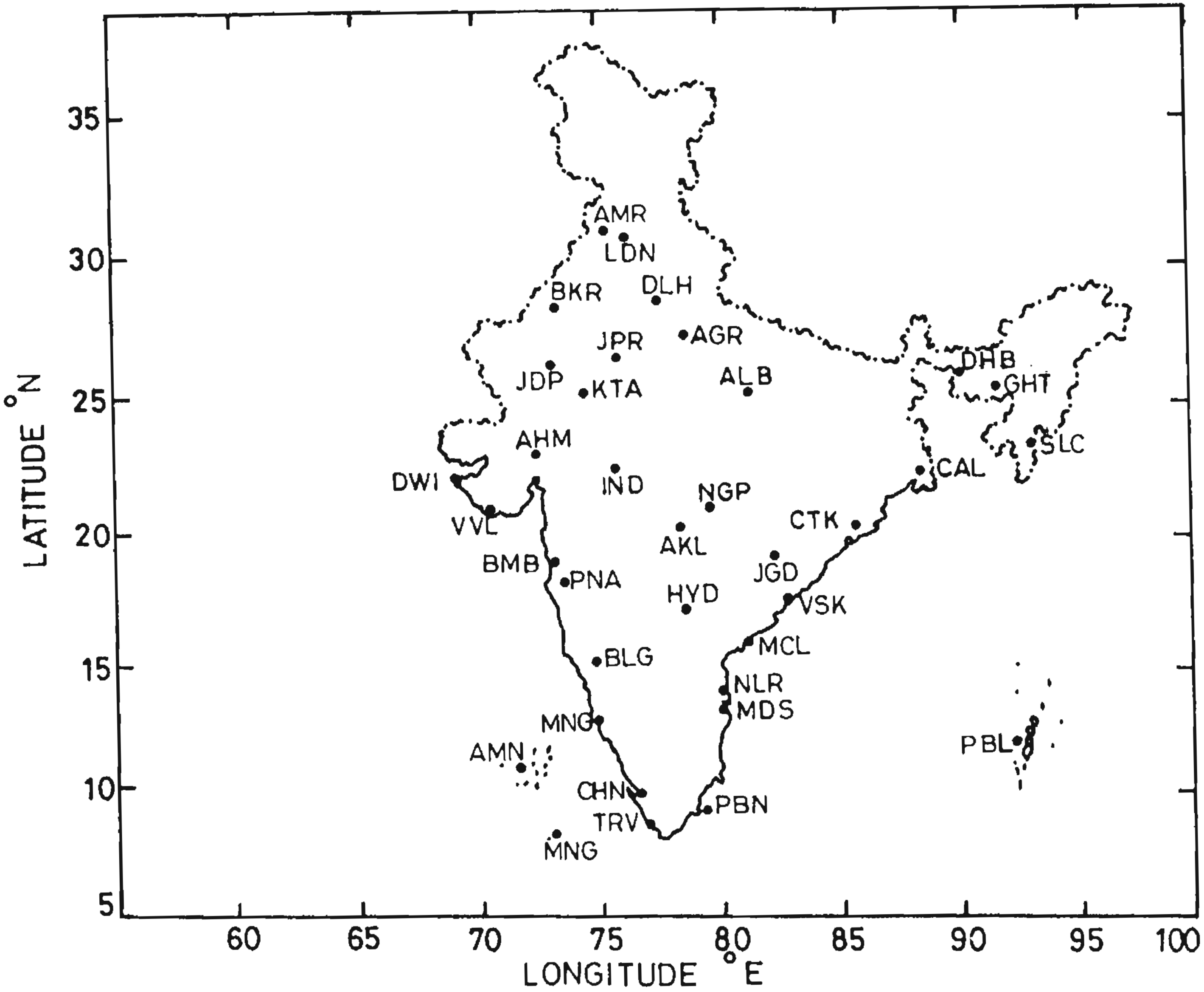


Fig. 3.3 Map of India showing the pressure stations

withdrawal and breaks in the monsoon, the frequency and tracks of the monsoon depression, etc., giving rise to the extreme events such as floods and droughts.

Generally, the winter northeast monsoon season is the dry period over the country outside northwest and southeast part of India. The southeastern peninsular region receives maximum rainfall during the retreating summer monsoon season, under the influence of tropical cyclones or easterly waves. In northwest India, the dry spell is often broken when western disturbances or westerly waves move across the country from west to east.

3.3.1.1 Annual precipitation pattern

Annual precipitation values at different parts of the country are plotted on a map of India and the isohytes are drawn as shown in Fig. 3.4. Heavy rainfall is noted on the western coastal plains to the west of the Western Ghats, between latitudes 10^{O}N to 17^{O}N and over the northeastern hilly region of the country. The rainfall decreases sharply on the eastern part of the Western Ghats, due to the desiccation of the moist air mass and descent.

The rainfall is found to be progressively decreasing westwards from northeastern hilly regions to the south of the Himalayas. The lowest annual rainfall is found over Leh area, which is a high altitude station and also a rainshadow region. The rainfall is found to be uniform in the plain lands of central

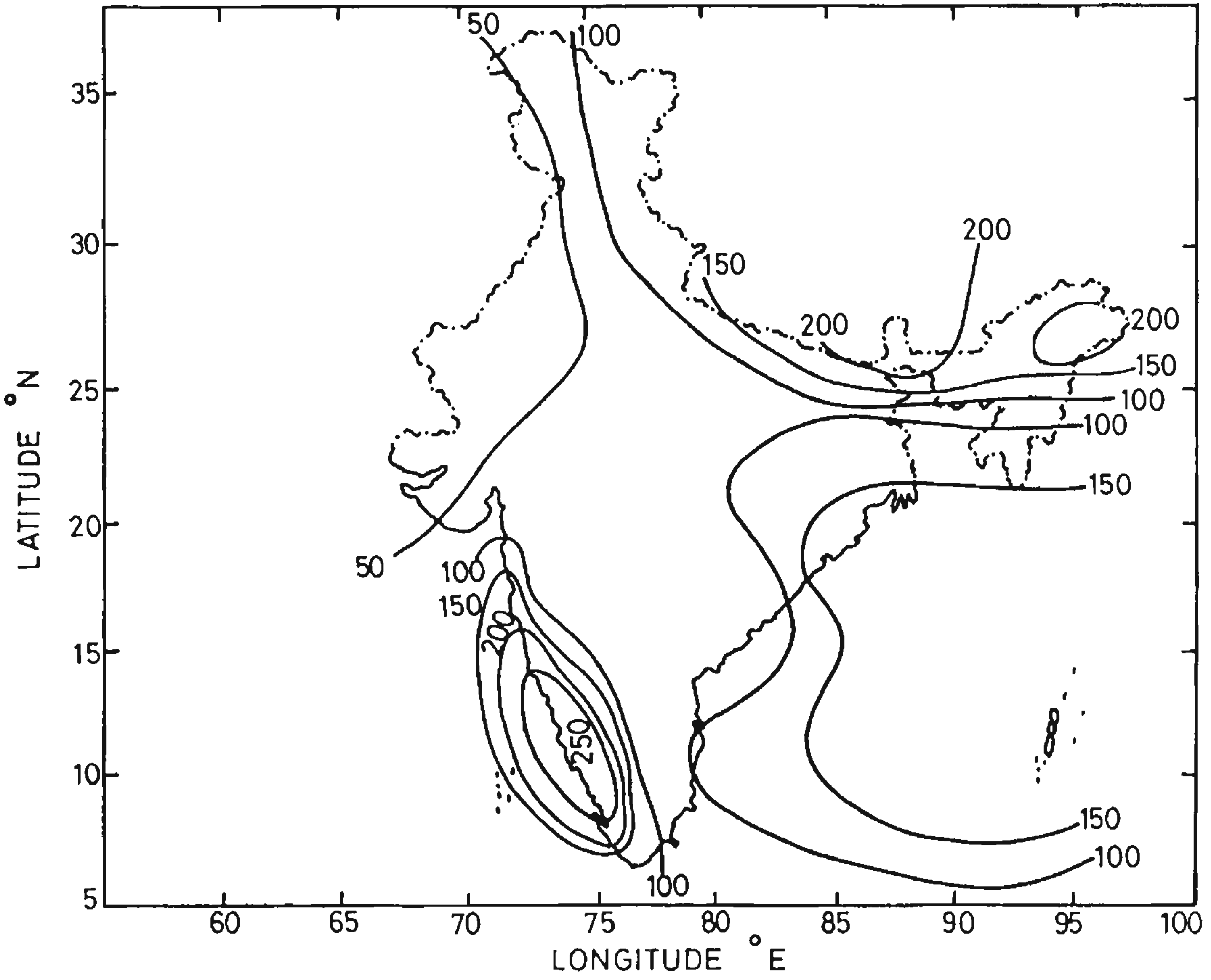


Fig. 3 .4. Annual rainfall of India (mm.)

India, extending from south to north and also in the east-west direction.

The northwest part of the country experiences scanty rainfall. Eventhough, this region comes under the moist regime of southwesterlies during the monsoon season, due to the absence of the orography the precipitation becomes scanty. In this region convectional type of precipitation is also quite unusual.

3.3.1.2 Variation in the amplitude of annual oscillation

The distribution of the square of amplitudes of annual oscillation (AO) in precipitation over Indian subcontinent is depicted in Fig. 3.5. The highest amplitude of AO is noted at the central part of the western peninsular region. Maximum amplitude is observed at Goa, around 15^{O}N latitude, situated north of the annual rainfall maximum located at Mangalore. A secondary maximum in amplitude of the annual cycle is observed in the northeastern part of India which receives abundant rainfall. Highest amplitude in AO in this region is seen noted at Darjeeling in Assam. The amplitude of the AO is found to be decreasing towards the west.

Lowest amplitude in AO is found in the extreme northwestern part of the country. In the longitudinal belt, between 78^{O}E and 85^{O}E, the entire Indian subcontinent extending from north to south experiences uniform amplitude in AO. Above 20^{O}N,

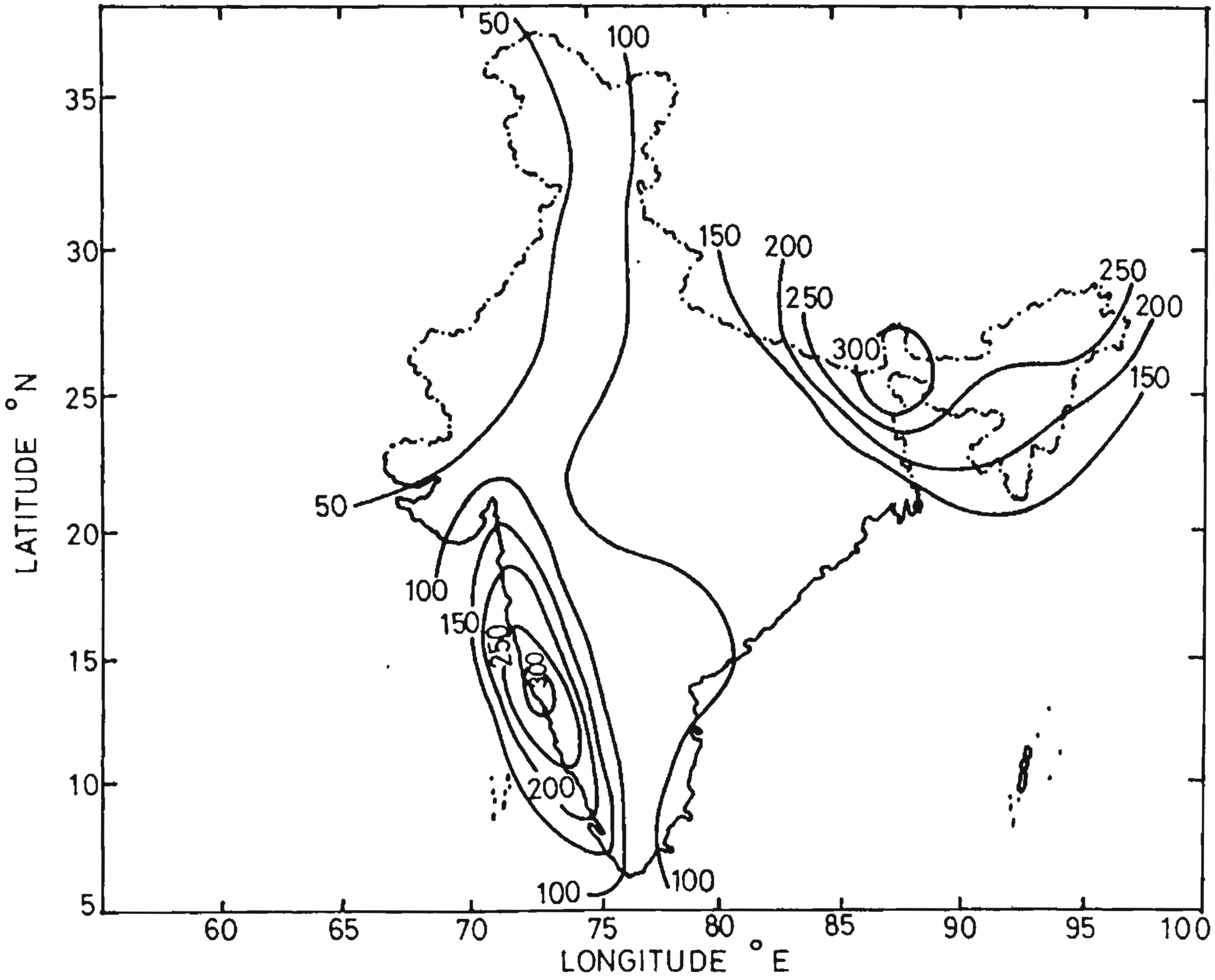


Fig. 3.5. The amplitude of annual cycle in precipitation (mm.)

latitude the gradient in the amplitude of annual precipitation increases from west to east. South of 20°N latitude, on the other hand, the gradient increases from east to west. The amplitude gradient vanishes in the meridional direction of the central part of India.

The amplitude of the AO is found to be directly connected with the annual mean precipitation pattern, with large amplitudes in regions of high rainfall and vice versa.

3.3.1.3 Variation in the amplitude of semi-annual oscillation

The semi-annual amplitudes are plotted at various stations over India and the isolines are drawn as indicated in Fig. 3.6. Large amplitude in semi-annual oscillations (SAO) are noted in the Western Ghat region, with the highest value of SAO at Mangalore (13°N), the region of highest annual rainfall. In the western peninsular region, the annual rainfall pattern is bimodal with the main rains in the south-west monsoon season and the subsidiary rains during the post-monsoon season (Menon, 1979). There are three distinct regions in the country, where the amplitude of SAO becomes smaller. They are the northwest, northeast and the central peninsular regions of the country. It is interesting to note that while, northeastern region experiences high amplitude in annual oscillation the amplitude of semi-annual oscillation is quite small. Eventhough, this part of the country receives abundant rainfall, the contribution from

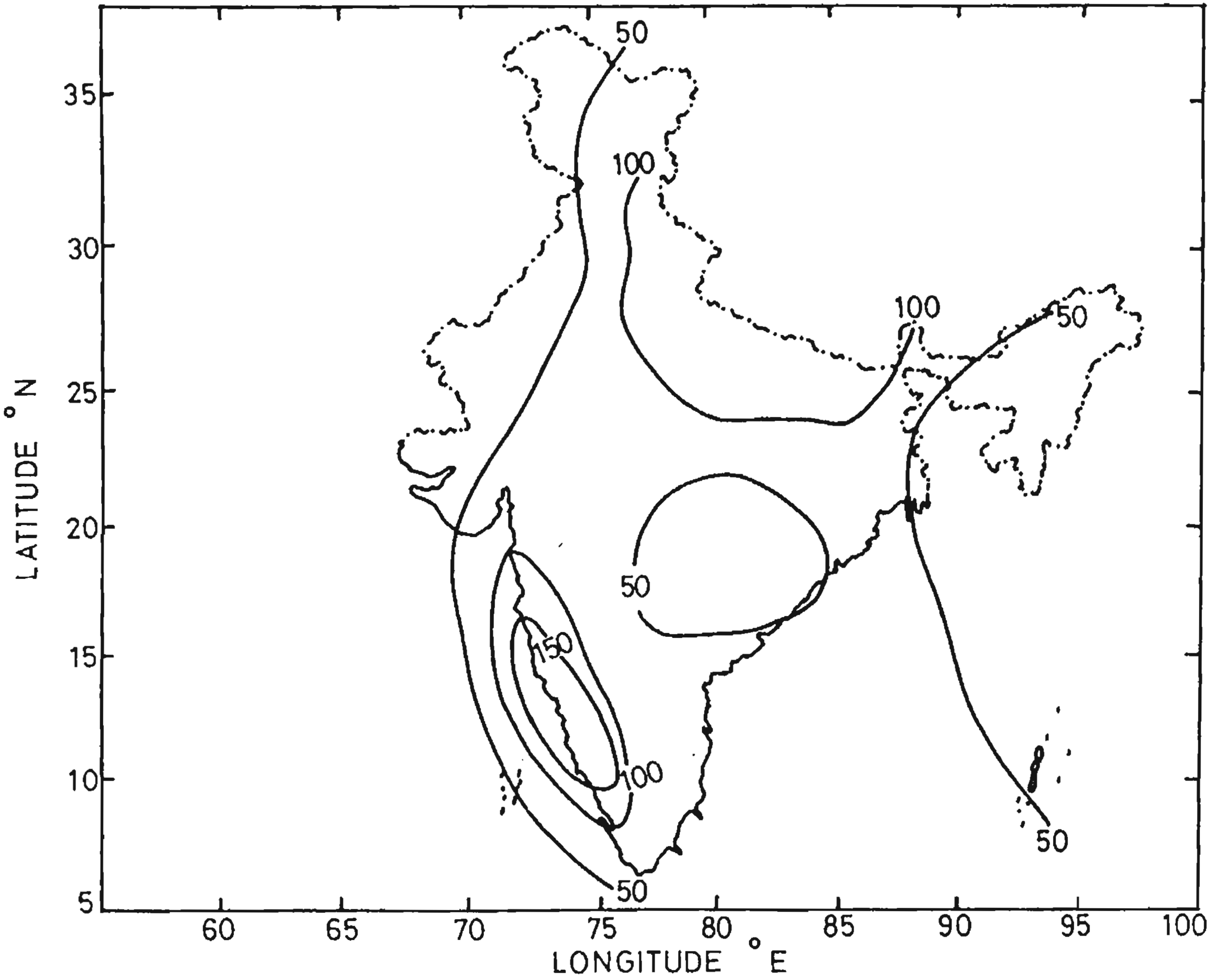


Fig. 3.6 . The amplitude of semi - annual cycle in rainfall (mm.)

the post-monsoon rains are comparatively lower. The northeastern states receive rainfall during post-monsoon season due to the cyclonic storms, whose number and tracks vary from year-to-year (Menon, 1989). It is evident from Fig. 3.6 that the semi-annual oscillation in rainfall is quite weak over the entire country except the Western Ghat region.

3.3.1.4 Ratio of the amplitudes of annual to semi-annual oscillations

The ratio of the amplitude of the first and second harmonics is a convenient way of determining the relative importance of these two harmonic components. Fig. 3.7. illustrates the distribution of the ratio of annual to semi-annual amplitudes in precipitation over India. On the leeward side of the Western Ghats, higher ratio indicate that the annual cycles are quite strong compared to that of the semi-annual cycles. The amplitudes of AO are found to be very high compared to that of SAO over the northeastern hilly region, especially in Assam and Meghalaya. In the northern part of India, the ratio lies between 1 and 2, indicating that both these oscillations have more or less same order of amplitudes. In general, it can be seen that the annual oscillation is the most dominant oscillation in precipitation.

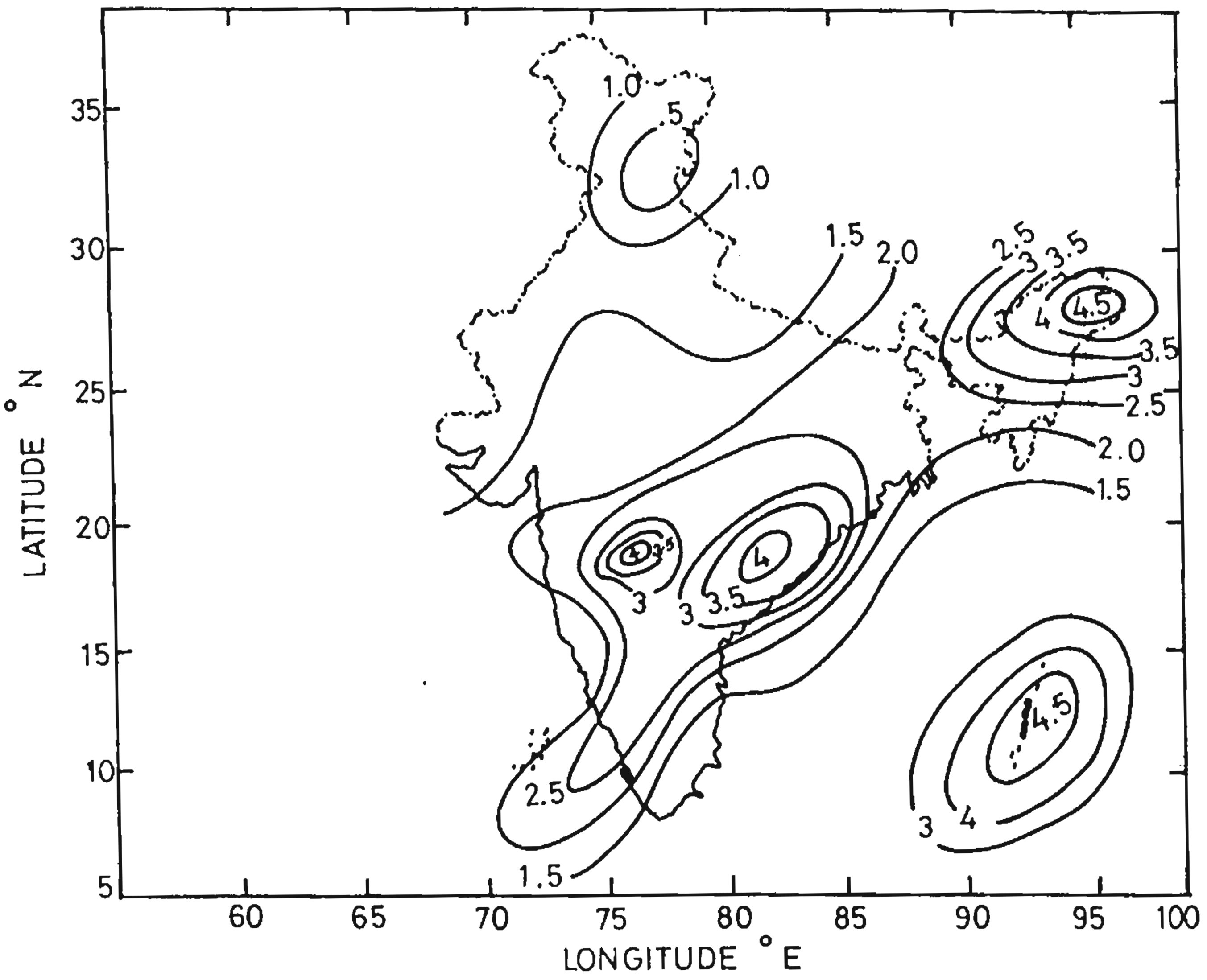


Fig. 3 .7. Ratio of annual to semi - annual amplitude in rainfall.

3.3.1.5 Contribution of the annual, semi-annual and tri-annual oscillations

The relative contribution from the first three harmonics to the seasonal variations is given by the ratio of the sum of the squares of the first three amplitudes to the sum of squares of all the six amplitudes. The ratio close to unity suggests that the first three harmonics account for most of the seasonal variations in the curve; on the other hand, a smaller fraction implies a more complex annual curve with a greater amount of variability contained in the high frequency harmonics. Fig. 3.8. illustrates the contribution of the first three harmonics to the sum of all the harmonics of the seasonal cycle in precipitation. More than 90% of the total variability in rainfall in the eastern part of the India, especially in Bihar and Assam, is due to the contribution from the first three harmonics. Short period oscillations are not found to be significant in this zone of the country. The localised short period cycles seem to have some influence on the central peninsular and northwest part of the country, where the ratio falls below 0.8. The contributions of the annual, semi-annual and tri-annual oscillations in precipitation contributes 80-90% of the total variability in the rest of the country.

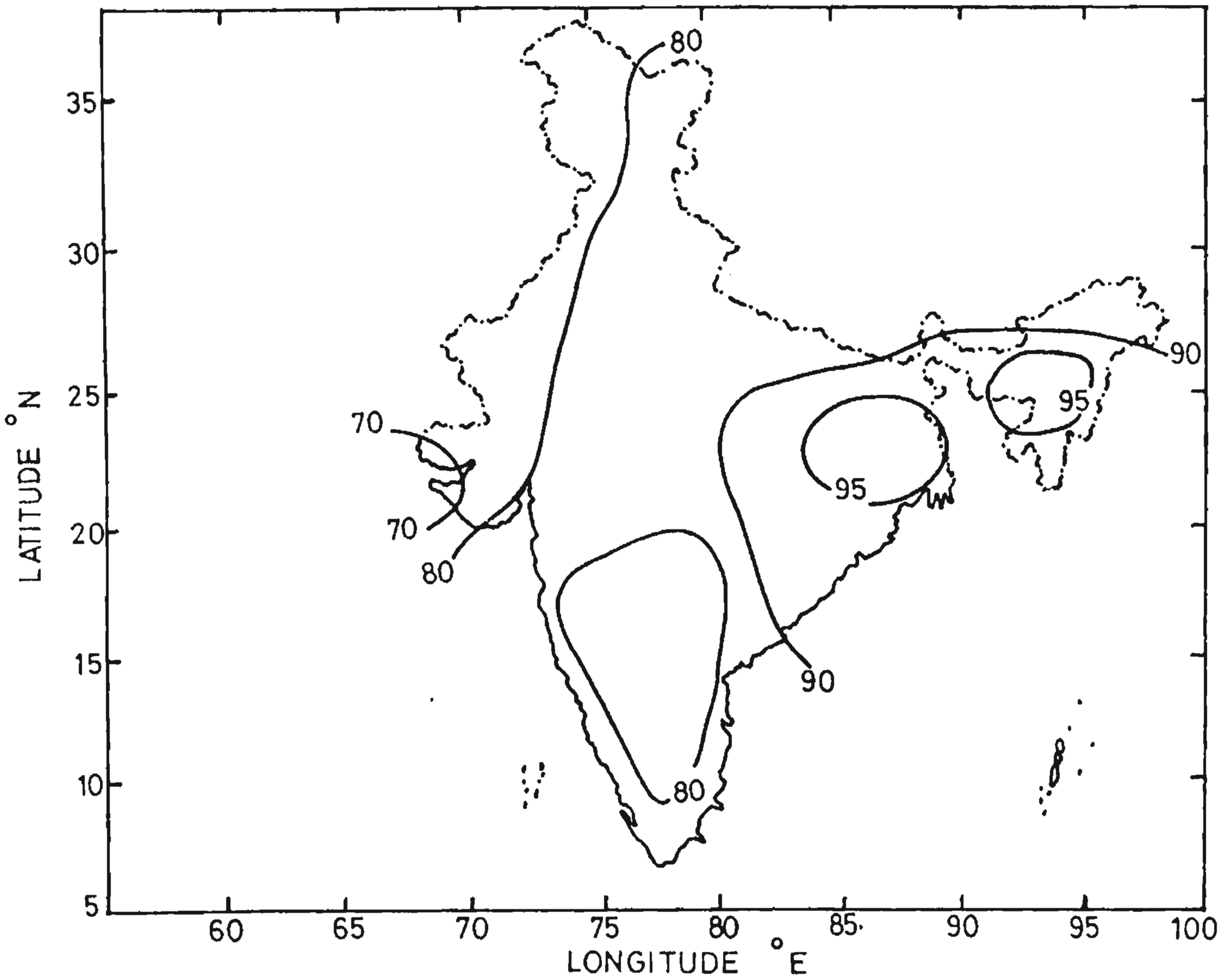


Fig. 3.8. Contribution of annual, semi-annual and tri annual oscillation in rainfall (%).

3.3.1.6 Phase of annual cycle

Fig.3.9 is a plot of the phase of annual cycle in various parts of the country. The highest rainfall is in the months of July and August in the entire country except in southeastern part of India. The southeastern part gets abundant rainfall only during the northeast monsoon season (Oct-Dec), and therefore the maximum annual phase is noted after August. The phase of the annual oscillation reduces to 6 in the extreme north-eastern part of the country, which experiences intense pre-monsoon thundershowers.

3.3.1.7 Phase of semi-annual cycle

The phase of the semi-annual oscillation at different parts of India are illustrated in Fig. 3.10. The phase of SAO is maximum during January in most parts of the country excluding the southeastern peninsular region. October and November are periods of significant phase of SAO in the southeastern part of the country. It can be seen that the region which comes under the sway of summer monsoon experiences a secondary maximum in rainfall during the month of January, while, in regions of winter rainfall the phase of SAO during the month of January and the region of winter month rainfall indicate the phase maximum is during the month of October and November.

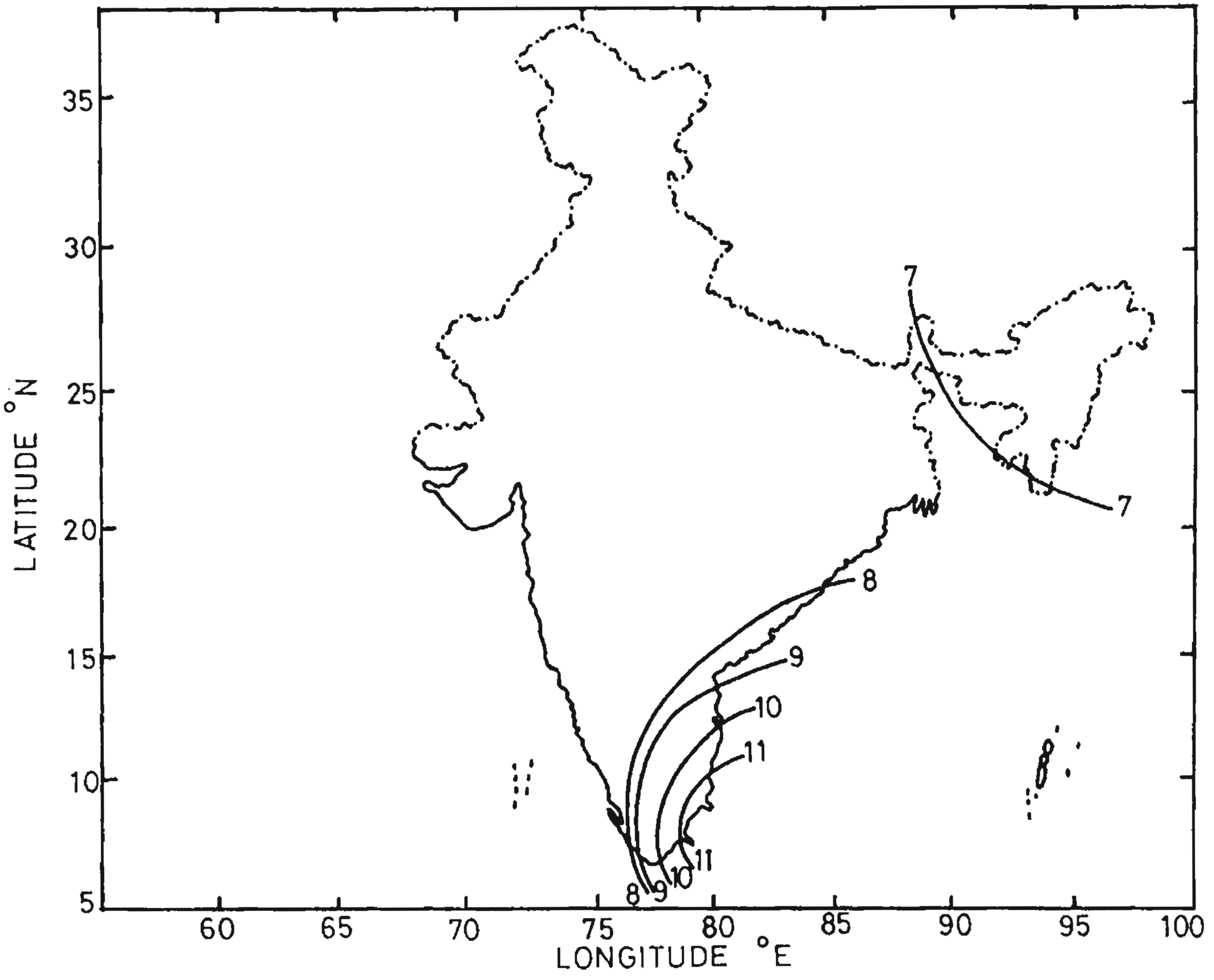


Fig. 3.9. Phase of annual cycle (months).

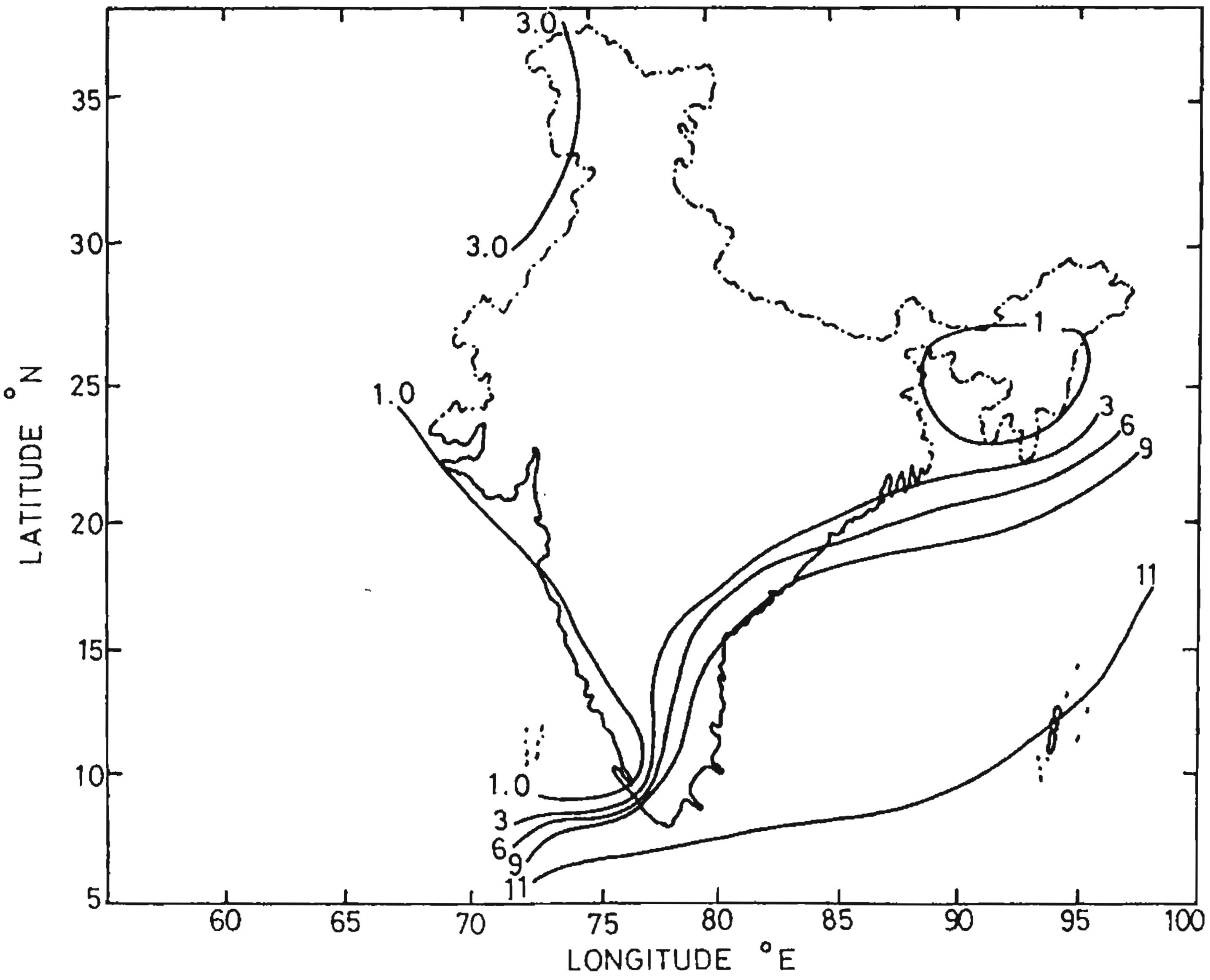


Fig. 3.10 . Phase of semi-annual cycle (months).

3.3.2 SEASONAL CYCLE IN TEMPERATURE

3.3.2.1 Spatial distribution of annual mean temperature .

The mean temperature of the air at any place depends on many factors, of which latitude, altitude, proximity to the sea, exposure and the type of prevailing air mass are important (Verma and Sikka, 1981). The altitude effect of mountain regions and high altitude places are removed by reducing the station level temperatures to mean sea level temperatures by assuming a constant environmental lapse rate of $6.5^{\circ}C/km$ in the lower troposphere (Fredrick and Tarbruk, 1974). However, assumption of constant lapse rate at all high altitude stations will lead to errors at these stations. The temperature thus reduced to mean sea level at different stations are plotted on a map and the isotherms are drawn as illustrated in Fig 3.11.

The annual mean temperatures are the highest in the central peninsular region being about $29^{\circ}C$ - $30^{\circ}C$. Temperature in this region is high due to the remoteness from the sea, the absence of marine influence and also the presence of black soil (Rao, 1981). Lowest mean temperature over the Indian subcontinent is noted in the northeastern part of India, that is in Assam and adjoining areas with temperatures of the order of $24^{\circ}C$ - $25^{\circ}C$. During the earlier part of summer season, from March to June, the northeastern part of the country including Assam, Bengal and adjoining areas experience large amount of

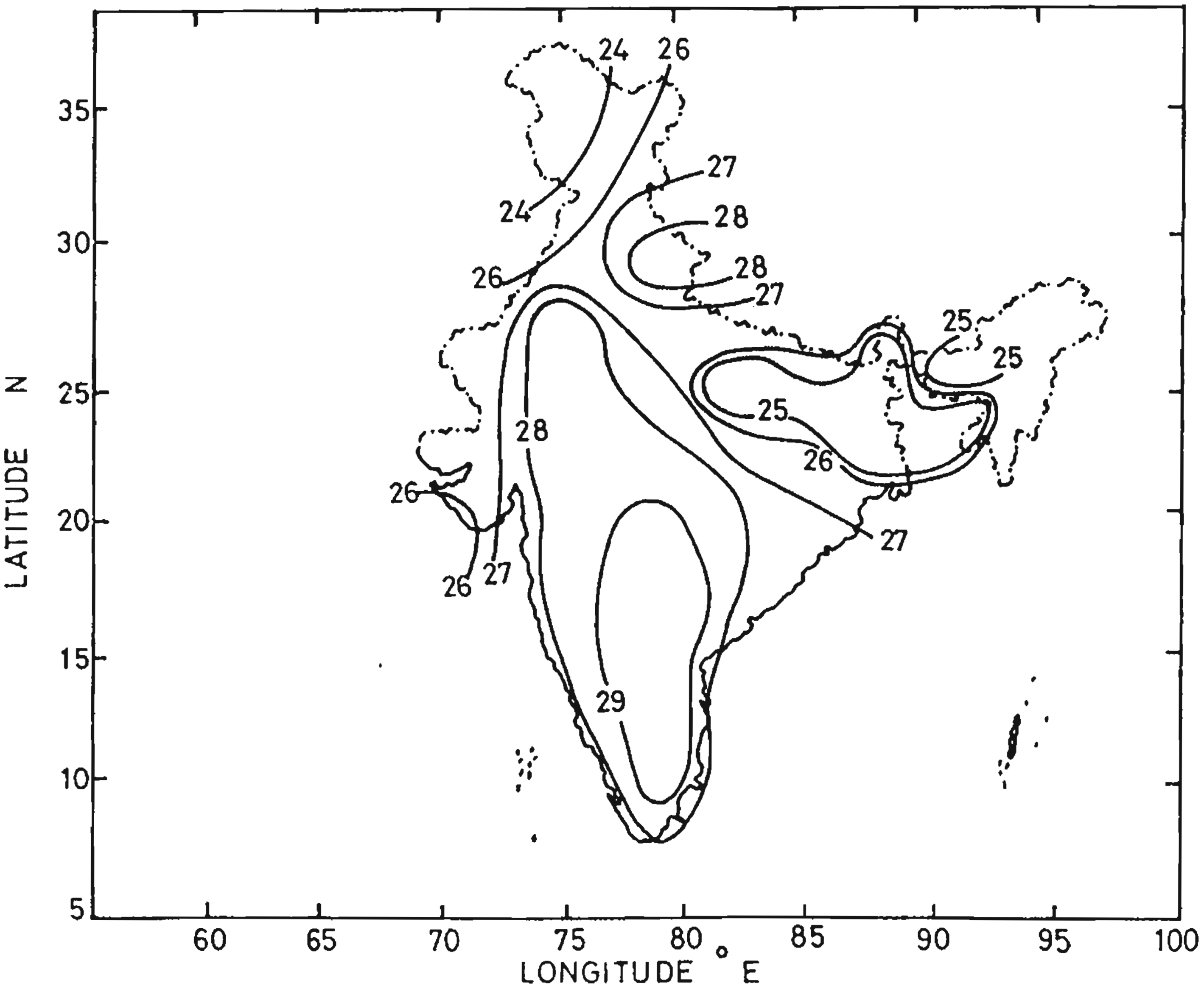


Fig. 3.11 Mean sea level temperature (°c) distribution at various places over India

cloudiness due to thundershowers, squalls and other local phenomena. The effect of the southwest monsoon give rise to extensive cloudiness and rainfall and therefore lowering the surface mean temperature from June to September. The specific topographical nature of the northeastern part of the country is also responsible for lowering the mean surface temperature (Asnani, 1993).

The Western Ghats, which are oriented in the north-south direction along the western part of the Indian peninsula, produce pronounced cloudiness due to orographical effect during the monsoon season and the pre-monsoon thundershower period which, in turn reduces the mean temperature in the west coast. Due to the absence of the summer monsoon effect, the eastern part of the peninsula experiences higher mean temperature than the western side. The Western Ghats also obstruct the spreading of the sea breeze much beyond to the eastern part. The isotherms are therefore noted parallel to the north-south oriented Western Ghats on the western peninsular region.

3.3.2.2 Spatial changes in seasonal mean temperature

The climate of India is dominated by the monsoon circulation. During one half of the year the wind blows from the cooler humid ocean to the warmer dry land, while during the other half there is a seasonal wind blowing from the cold dry Asiatic land mass to the warm Indian Ocean. The temperature variations due to the influence of the wet southwest monsoon is such that the highest temperatures are experienced in spring rather than in summer (Menon, 1979). Therefore, the present study is extended to look for a spatial variations in seasonal temperature distribution.

The mean sea level temperatures for the four seasons, viz., winter (Dec-Feb), spring (Mar-May), summer (June-Aug) and autumn (Sept-Nov) are represented in Figs. 3.12(a), 3.12(b), 3.12(c) and 3.12(d) respectively. The winter temperature pattern, Fig. 3.12(a) shows that the isotherms are nearly parallel to the latitudes except near the coasts. The temperatures are higher in the central peninsular region and decreases towards the north with the lowest temperatures around Srinagar. Spring is the season when the land gets progressively heated after January and highest temperatures are noted with clear skies and meager rainfall. The highest temperatures are found around 20°N, the position of the sun now being in the tropic of cancer (Fig. 3. 12(b)). The summer temperature (Fig. 3. 12(c)) pattern gets modified with the onset of the southwest monsoon and the associated cloudiness and rainfall. The highest temperature occur over northwest India where the continental air still persists and there is very little cloudiness. During autumn (Fig. 3.12(d)) the temperatures are generally within 26-29°C throughout the subcontinent. This is the season of the most equable distribution of temperature in India.

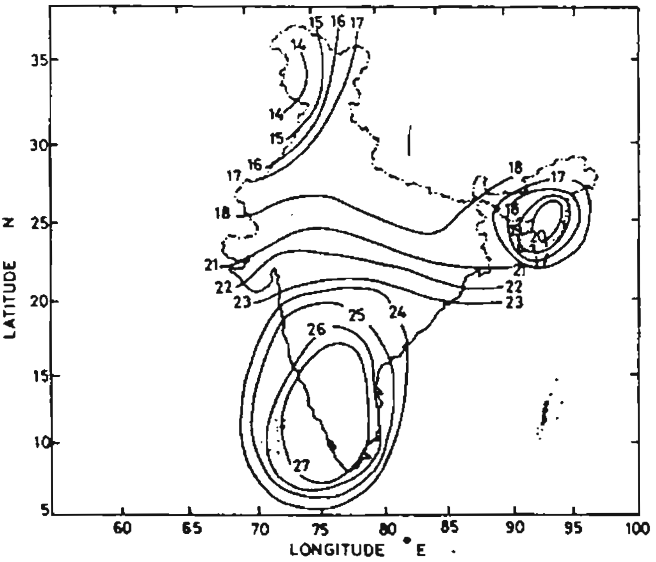


Fig. 3.12a Seasonal mean temperature (°C) for winter

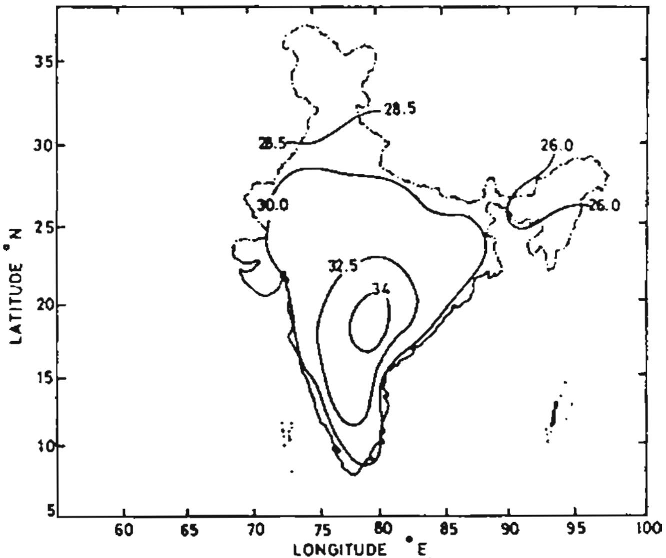


Fig. 3.12 b Seasonal mean temperature (°C) for spring

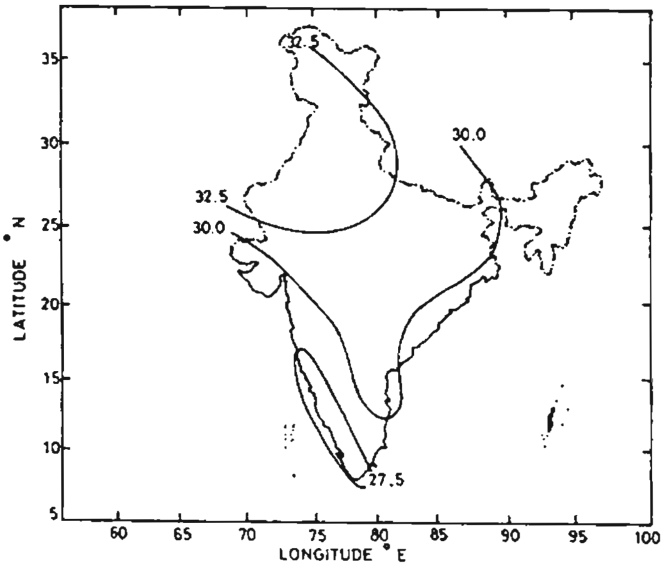


Fig. 3.12c Seasonal mean temperature (°C) for summer

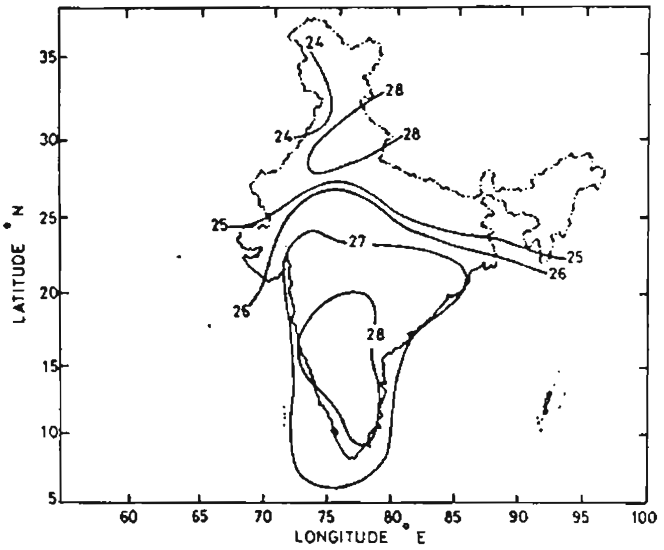


Fig. 3.12d Seasonal mean temperature (°C) for autumn

3.3.2.3 Variance in temperature

The variance in mean annual temperature for the entire country is illustrated in Fig. 3.13. It can be seen that the variance is least in the west coast region south of 20^{o}N and decreasing southwards. Temperature variations in these regions are small, possibly due to the marine influence and proximity to the equator. The variance increases northwards with the isolines running almost east-west oriented upto around 25^{o}N and 80^{o}E and then takes a sharp turn to the northwest. Very high values are noted in this region which has a purely continental type of climate characterised by extreme temperature, low humidity and comparatively clear sky, while the rest of the country possesses sub-continental characteristics (Subrahmanyam, 1963).

3.3.2.4 Distribution of the amplitude of annual oscillation (AO)

The amplitude of annual oscillation (AO) observed from harmonic analysis study at different stations over the entire country is illustrated in Fig 3.14. The amplitudes of annual cycle in temperature are low in the central part of the western peninsula (centered near Goa) and all the island stations in Arabian Sea and Bay of Bengal. The increase in amplitude of annual oscillation with latitude slow in the western peninsular region than in the eastern side, where there is a steady increase with latitude. The highest annual oscillation in temperature is seen in the northwest part of the country, with scorching summers and freezing winters.

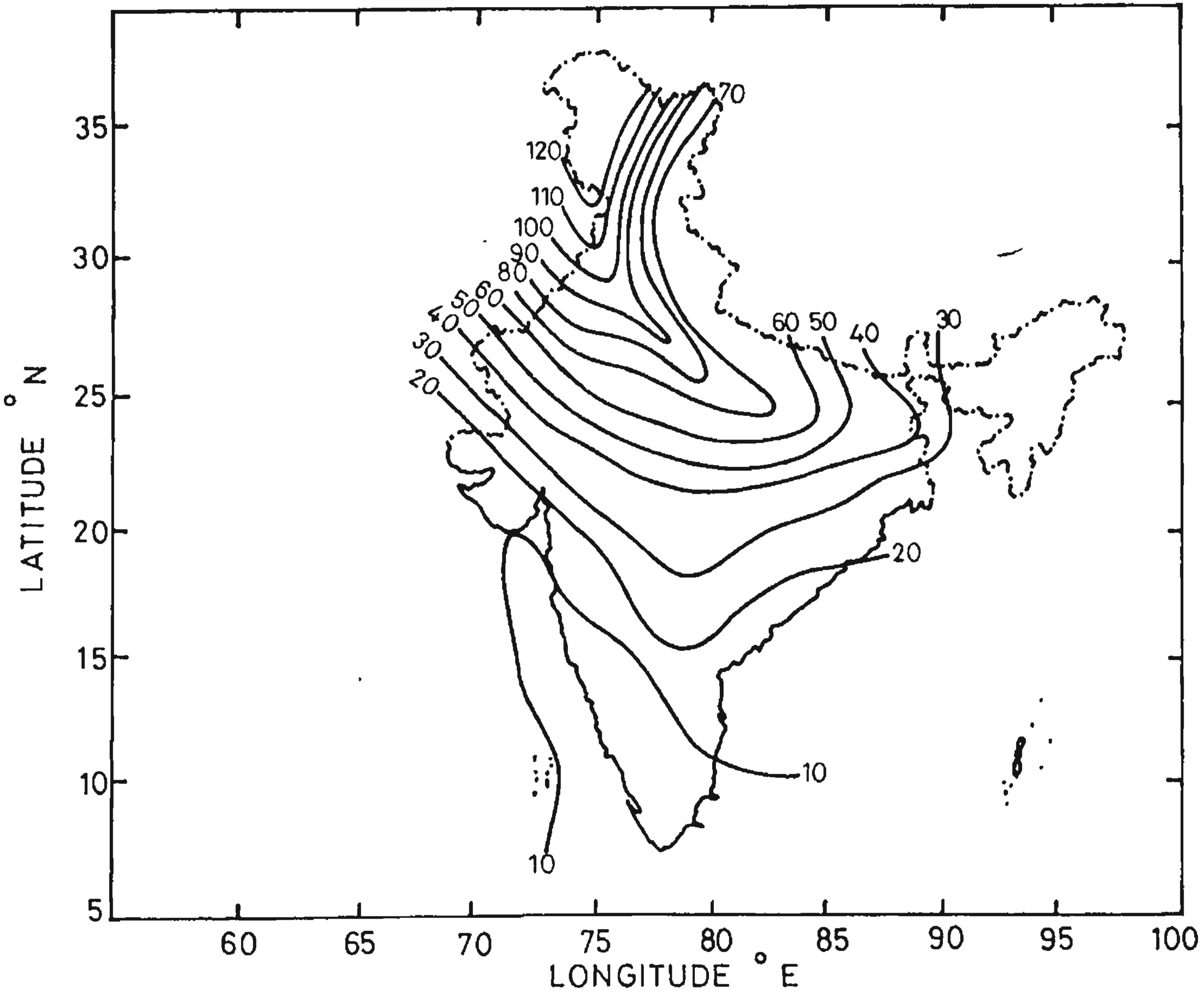


Fig. 3 .13 Variance of temperature over India

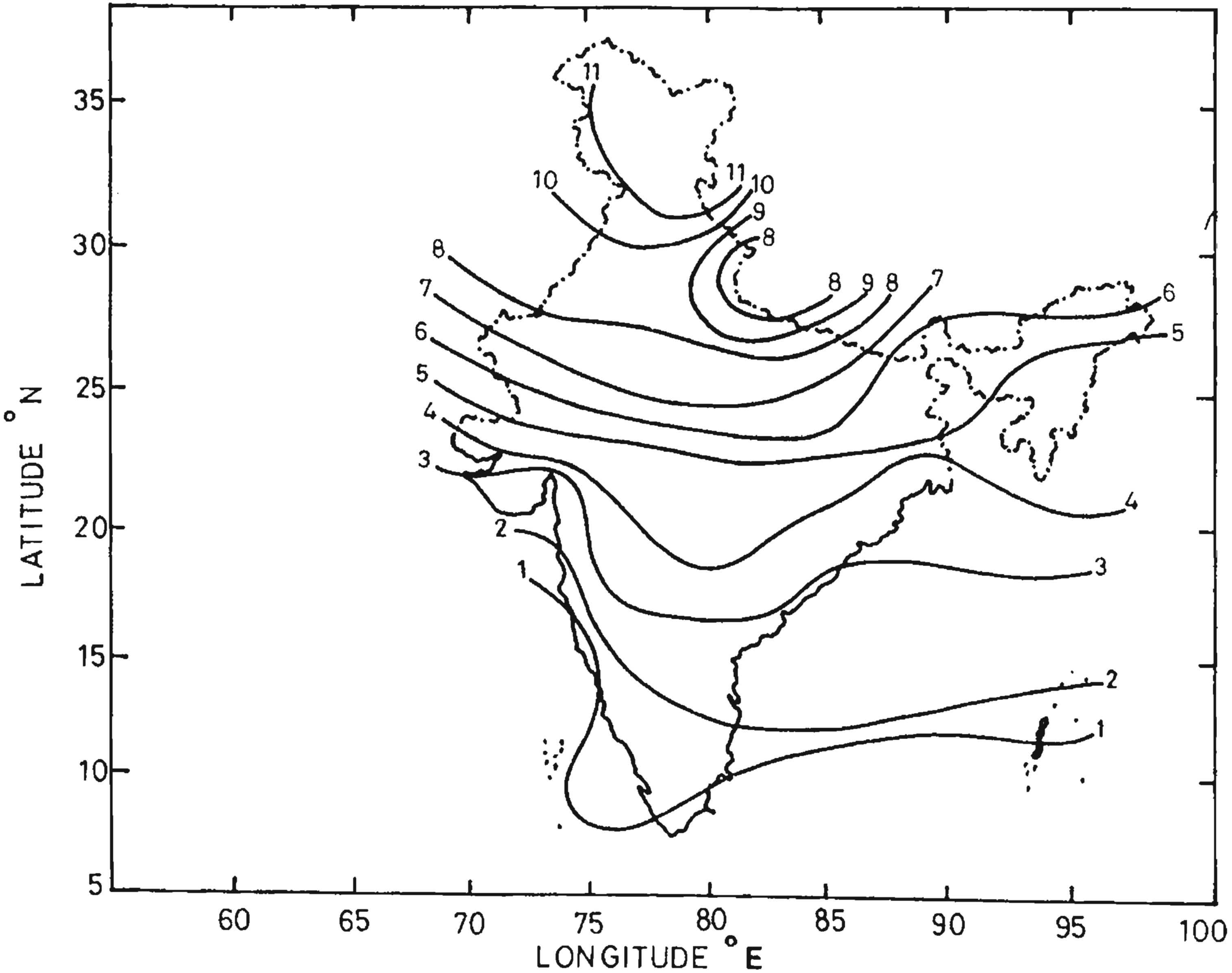


Fig. 3.14 The amplitude of annual cycle in temparature oscillation (°C)

3.3.2.5 Distribution of amplitude semi-annual oscillation (SAO)

Fig. 3.15 gives the amplitude of the semi-annual oscillation. It can be seen that the amplitude of the semi-annual oscillation is much smaller in magnitude than the annual oscillation. The highest values of the order of 2-3°C are obtained in the central parts of the country, between 18°N and 28°N. In the extreme south of the peninsula, the maximum amplitude of SAO is of the order of 1°C. It can be seen from Fig. 3.15 that the values are smaller near the coastal regions.

3.3.2.6 Ratio of the amplitudes of annual to semi-annual amplitudes

The summer temperature is modified by the southwest monsoon. The associated hydrometeors affect the temperature which initially drop and then remain uniform. The cloudiness is intense in the regions, (1) between 17°N and 24°N in the central region; (2) west of 77°E and south of 17°N in the peninsula; and (3) east of approximately 85°E in the northeast. There is a secondary maximum in temperature after the cessation of the rains in these regions. The relative importance between the annual and semi-annual oscillation (SAO) in temperature is determined by taking the ratio of the square of the amplitudes of SAO to AO. Fig 3.16. illustrates the ratios of the amplitudes of the semi-annual to the annual oscillations in temperature at different parts of the country and are represented

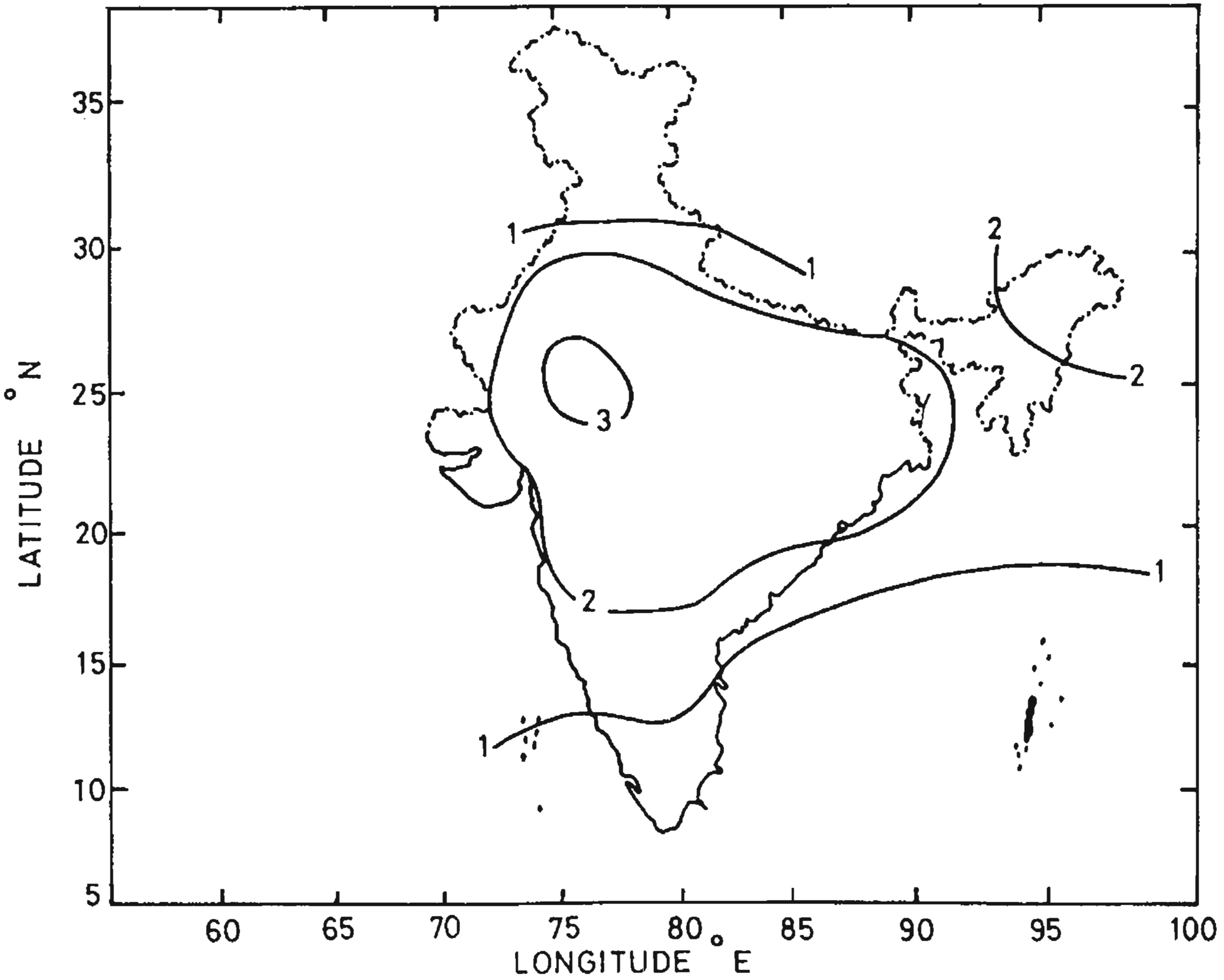


Fig. 3.15 The amplitude of semi-annual cycle in temperature oscillation (°C)

in percentage. The annual oscillation is quite dominant than the semi-annual oscillation in all parts of the country, except Goa in the western part of the peninsular region where the ratio is unity (100%) indicating that the annual and semi-annual oscillations are equally prominent. The semi-annual oscillation is equally strong to that of AO in the western peninsular region, where the temperature increases immediately after the south-west monsoon, but again starts decreasing with the onset of the north-east monsoon. The southeastern part of the peninsula is more pronounced by the AO, where the summer monsoon is practically absent. Madras region experiences 80% of the amplitude of annual cycle in temperature which is the highest contribution of AO in the southern half of the country. In the northern part of India the annual oscillation is significant, where the monsoon activity is weak and only for shorter durations compared to that of southwest peninsular India. In Assam and adjoining areas, since the north-east monsoon is comparatively weaker than the southwest monsoon the contribution of annual component is more prominent.

3.3.2.7 Contribution of major oscillations in seasonal cycle

In order to make a comparison between the long period seasonal cycle such as the annual and semi-annual oscillations, and the short period oscillations, the ratio of the sum of square of the first two harmonics to the variance in temperature cycle is computed and the results are shown in Fig 3.17. In the

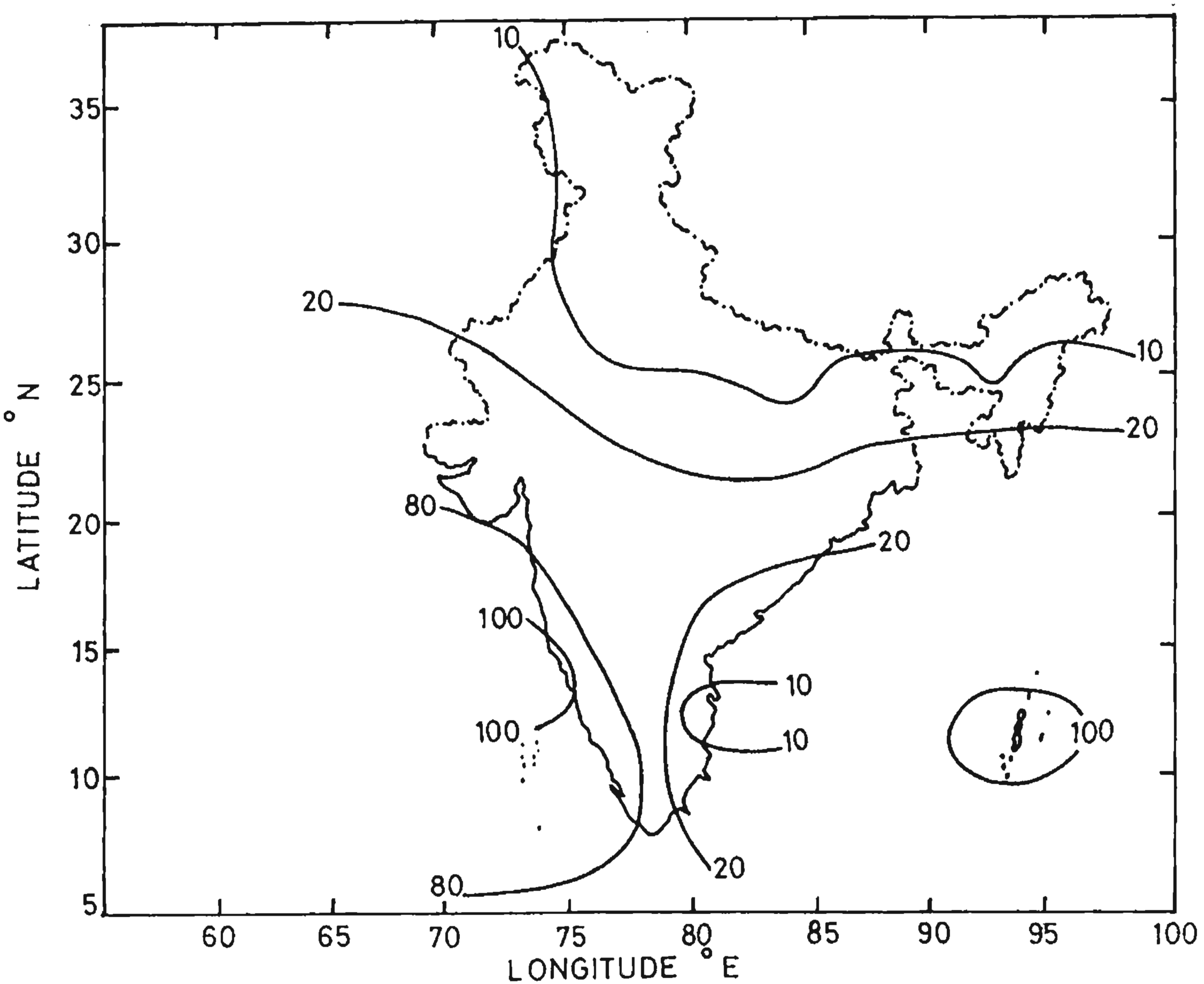


Fig.3 .16 Ratio of the semi-annual amplitude to the annual amplitude in temperature in (%)

western part of the peninsular region, parallel to the Western Ghats, the shorter period oscillations contribute to the variance in temperature. Orography coupled with the plentiful supply of moisture from the sea and the effect of sea breeze cause high thunderstorm activity and associated rainfall in this region during summer (Srinivasan, et al. 1973). The effect due to shorter period temperature oscillations gradually diminishes towards to the eastern peninsular region and becomes least significant above the Madras coast. Long period oscillations are very strong in the northwestern parts of the country.

3.3.2.8 Phase of annual cycle

Phase of the harmonic gives the time of the maximum of oscillations in a given harmonic. Fig. 3.18 represent the phase of annual oscillation. Over most part of India, day time temperatures are highest in May, after which the temperatures decreases with the effect of southwest monsoon. In some parts of the country the prevailing circulation brings down the maritime influence much earlier putting an end to the temperature rise. In the western half of the peninsula (south of 15^{O}N) maximum temperature is noted during March-April. During this period, the overhead sun produces the maximum temperature in this region. North of 15^{O}N along the west coast, May records the maximum temperature. In the coastal stations of Mangalore, Cochin and Trivandrum on the west coast, March-April is the hottest month while June is the hottest month in the east coast.

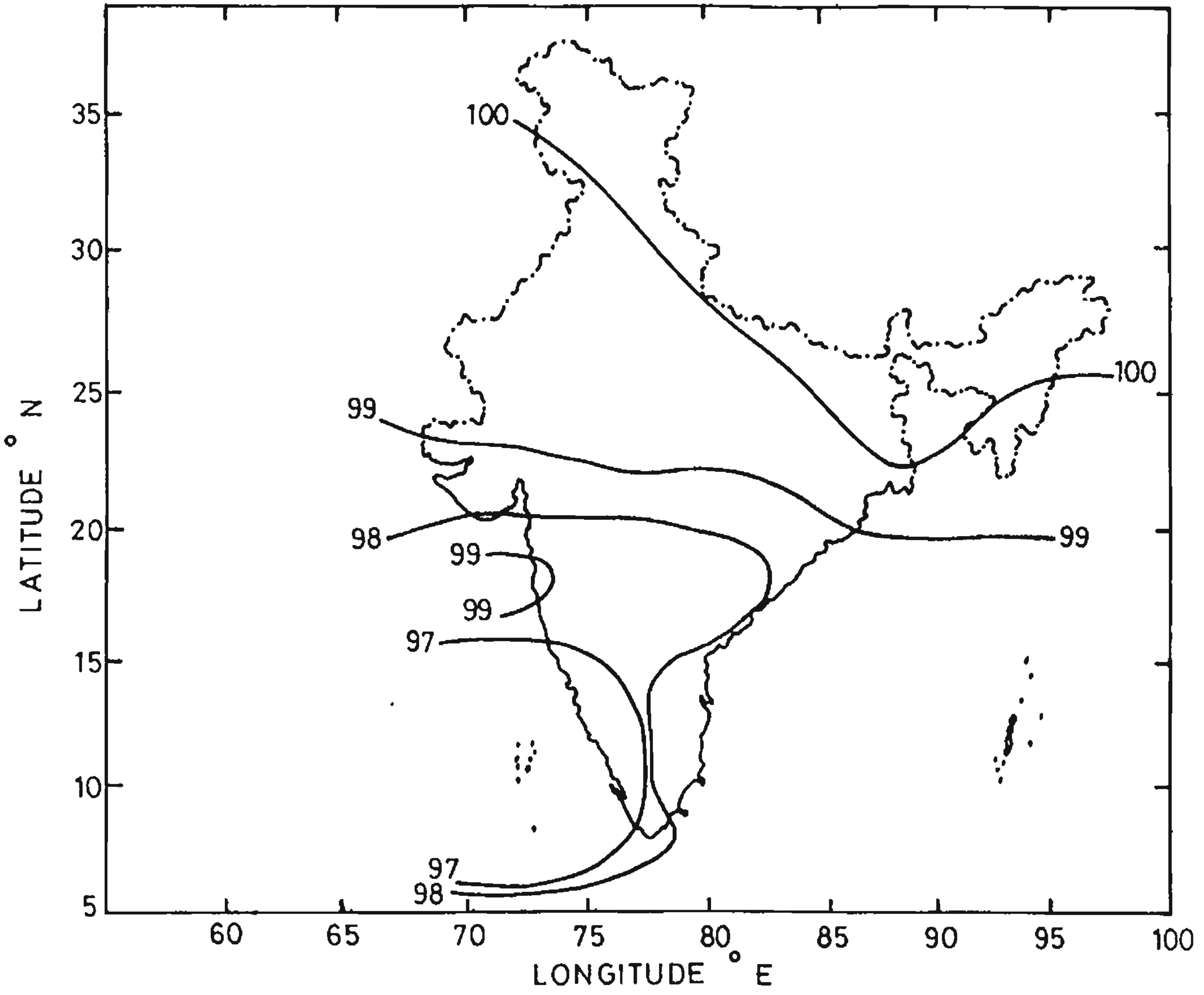


Fig. 3.17 Ratio of the first two harmonics to the variance in temperature (in %)

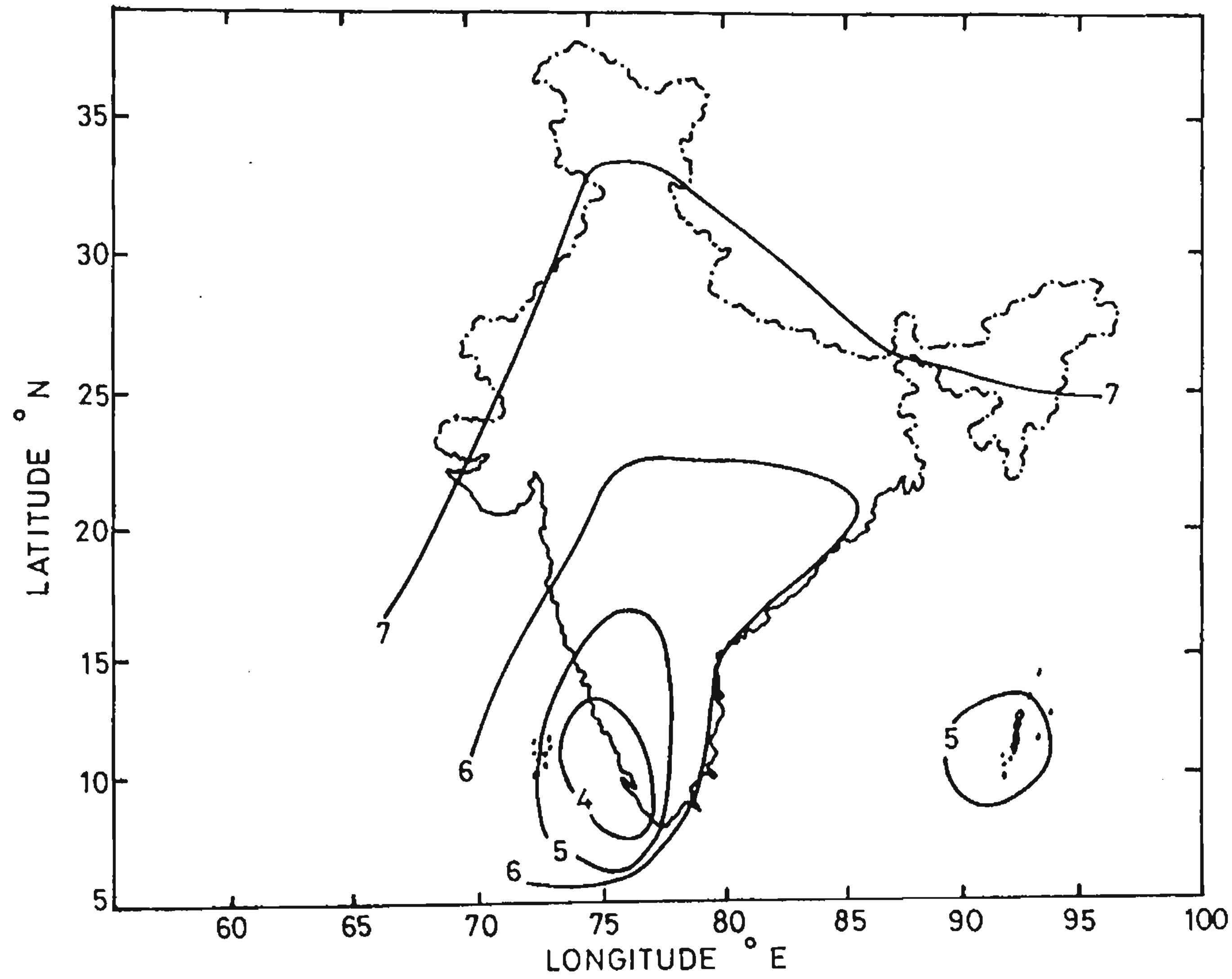


Fig. 3.18 Distribution of the phases of annual cycle in temperature over the entire subcontinent (months)

In the northern parts, the highest temperature is reached in July. The Sun reaches its highest altitude in late June in these latitudes and the temperature usually has a lag of one month. The onset of monsoon in the northern part of India normally occurs during July. Stations located north of 34°N, highest temperature is found in July, which are not influenced by the monsoon clouding and rainfall. In the Andaman Islands the day temperatures are highest in April.

3.3.2.9 Phase of semi-annual cycle

The phase of the semi-annual oscillation in temperature show that there is a secondary maximum in temperature after the cessation of the rains. In most parts of the country it is in October except in the northeastern regions where it is in September (Fig.3.19).

3.3.3 SEASONAL VARIATION IN SEA-LEVEL PRESSURE

3.3.3.1 Variance in sea-level pressure

The distribution of sea-level pressure undergoes a complete reversal from January to July. The pressure gradient is directed towards north in July and is directed towards south in the month of January. High pressure is observed in the northwest part of the country during January, when the subcontinent is at the periphery of the Siberian High. However, in April a heat low

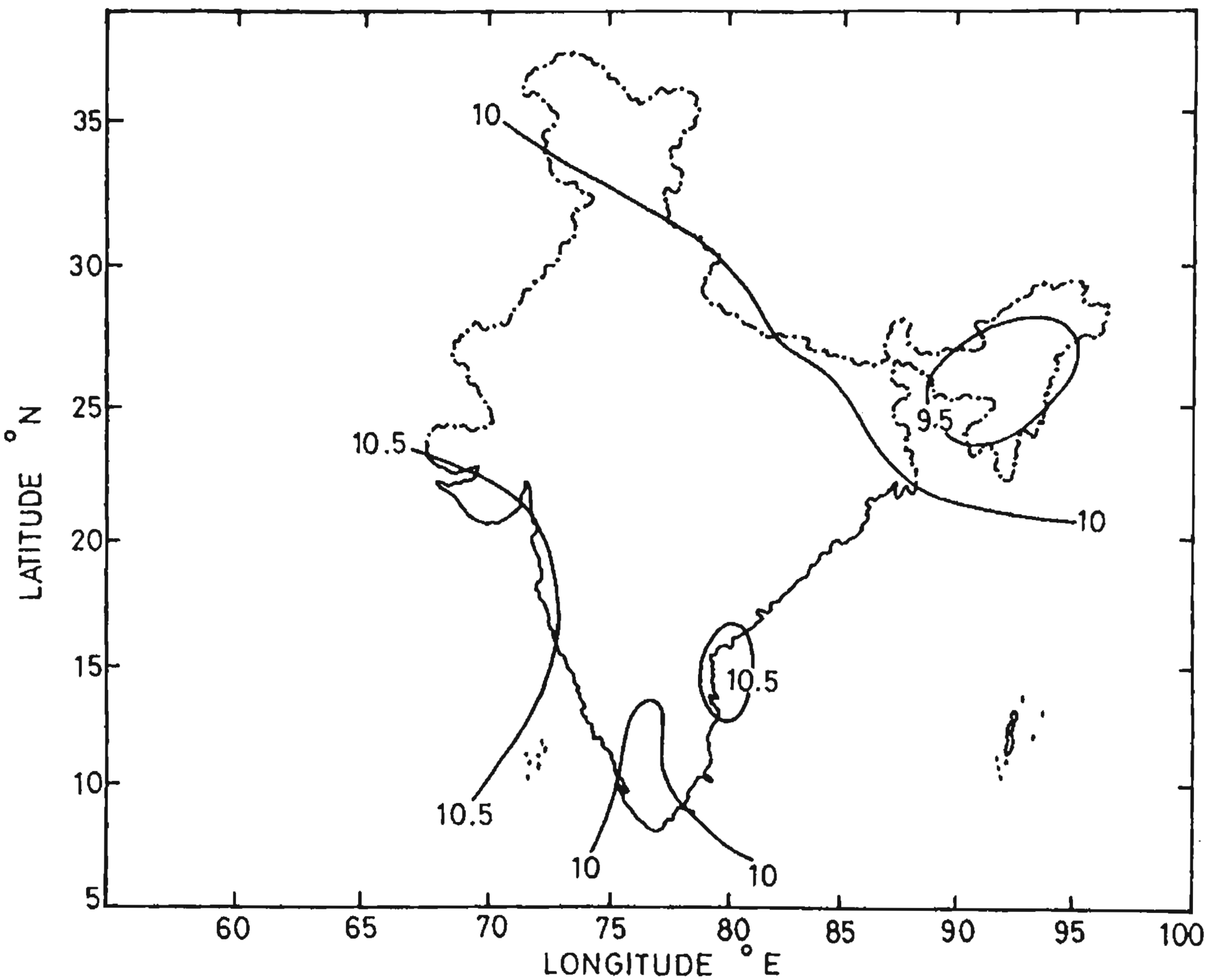


Fig. 3.19 Distribution of the phases of semi-annual cycle in temperature over the entire sub-continent (months)

develops in this region making the variance in pressure very high in this area. Fig. 3.20. illustrates the variance in pressure. The variance decreases southwards and is least in the west-coast south of 15^{o}N, possibly due to the proximity to the equator and also the maritime influence.

3.3.3.2 Variation in annual oscillation

The amplitude of annual oscillation in pressure is illustrated in Fig. 3.21. Low amplitude annual cycle is observed along the west-coast, south of Mangalore and in the Arabian sea and Bay island stations. Two nearby stations Bombay and Poona shows remarkable variation in the annual amplitude, which indicates the role of orography in the distribution of annual cycle. Bombay lies to the windward side of Western Ghats while, Poona is to the leeward side. The highest annual oscillation is seen in the northwest part of the country, which comes at the periphery of the Siberian High in January and develops a low pressure in April.

3.3.3.3 Variation in the semi-annual oscillation

The spatial distribution in the semi-annual amplitude in sea-level pressure are plotted at various stations and the isolines drawn as indicated in Fig. 3.22. Semi-annual amplitudes are generally weak compared with the magnitude of annual oscillation. Lowest amplitude in SAO is seen in central parts of

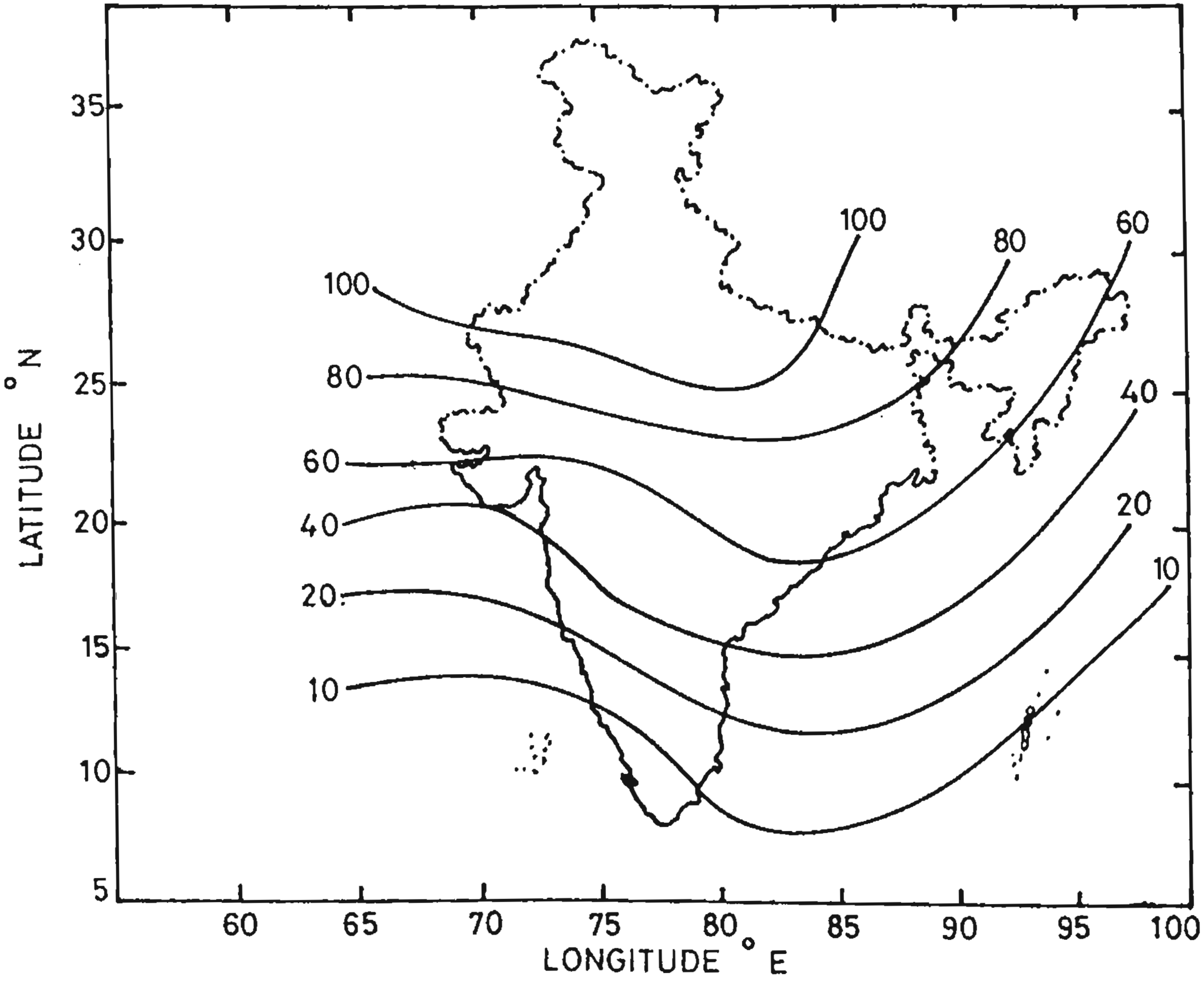


Fig. 3.20 Variance of pressure over India

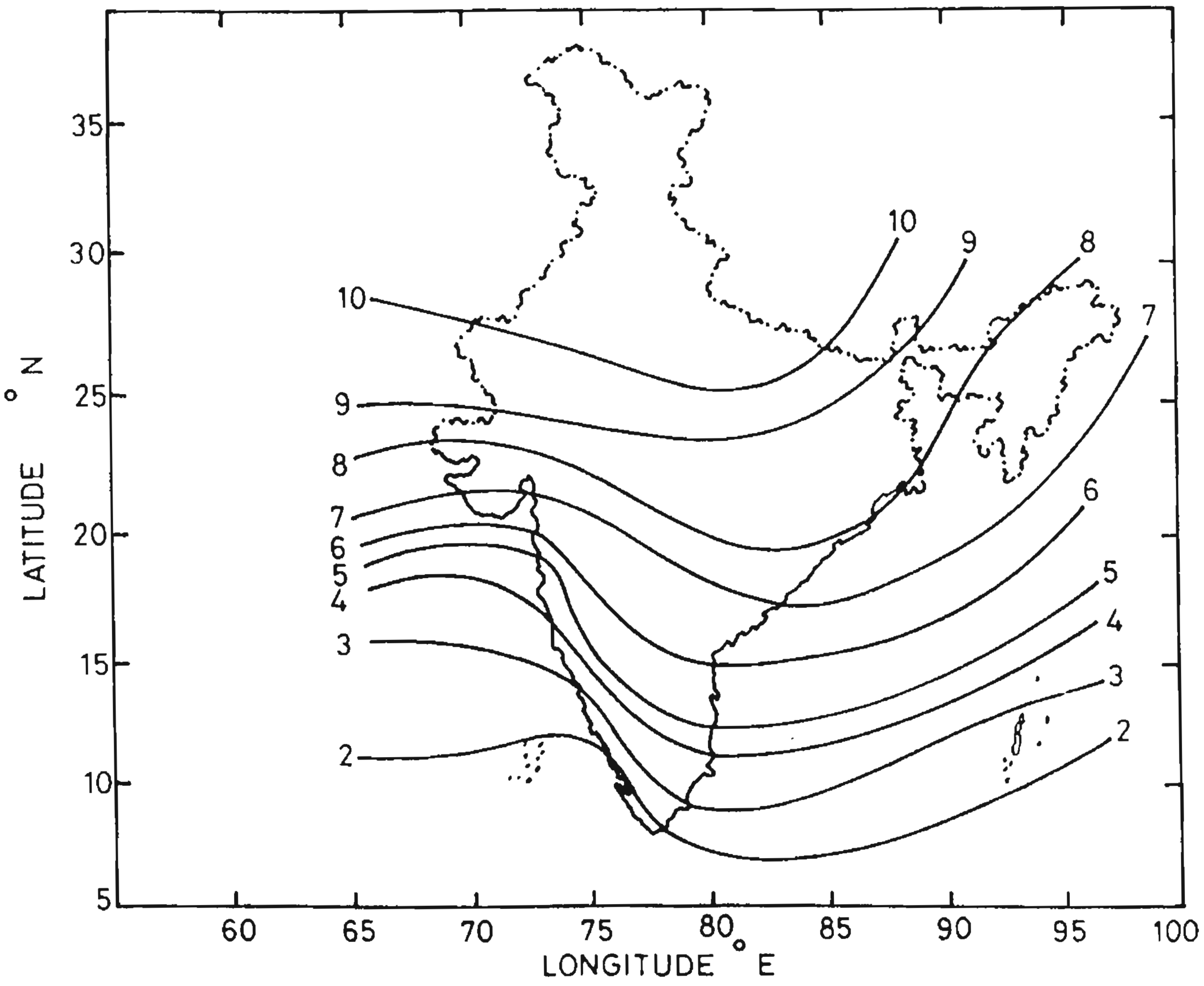


Fig. 3.21 The amplitude of annual cycle in pressure (mb)

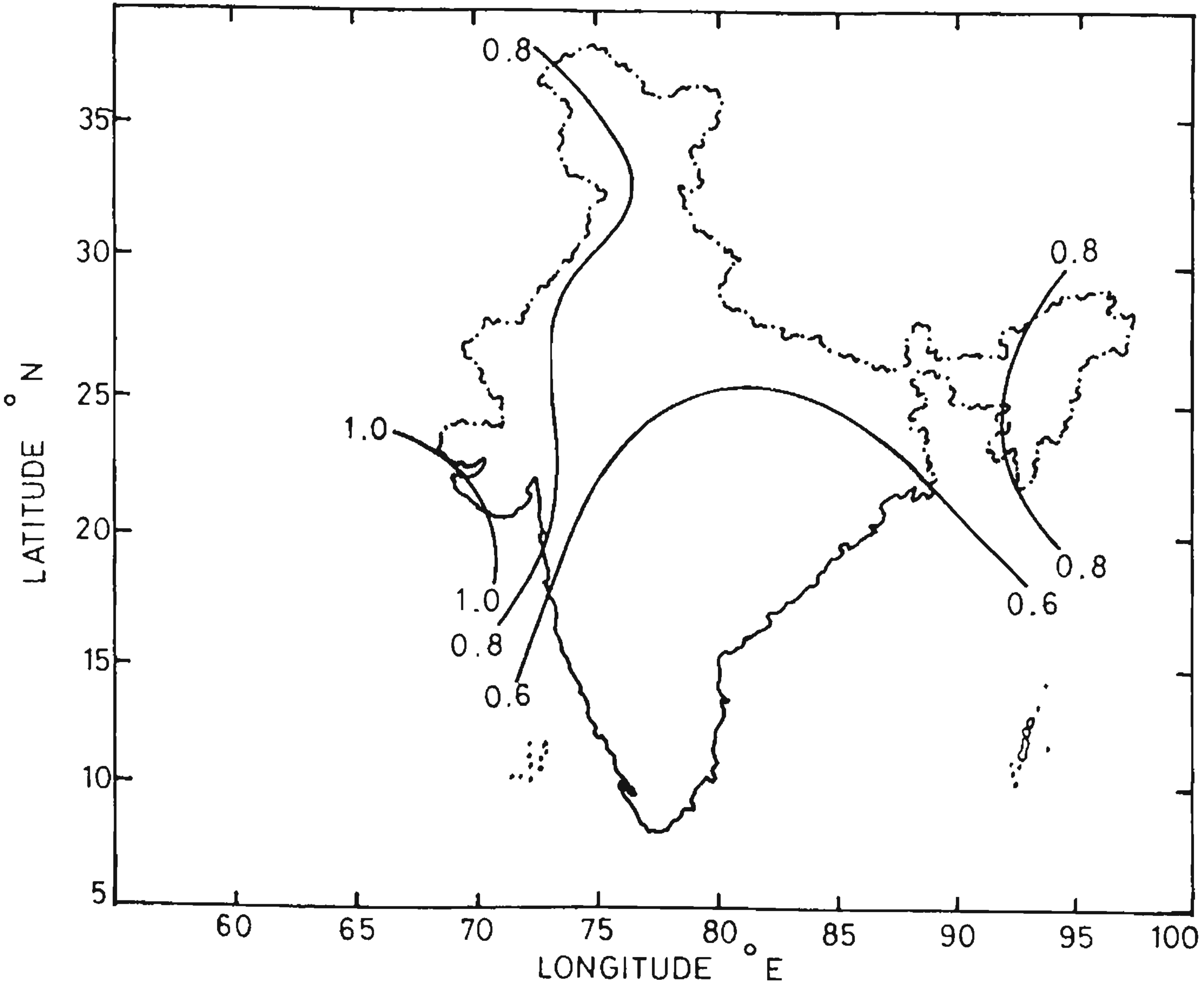


Fig. 3.22 The amplitude of semi-annual cycle in pressure (mb)

peninsular India between 14^{O}N and 20^{O}N. The highest amplitude of the order of 1-1.5 mb is seen along Gujarat coast which is influenced by the monsoon trough.

3.3.3.4 Ratio of the annual and semi-annual amplitudes

The ratio of the square of the amplitudes of the first and second harmonics is a convenient way of determining the relative importance of these two components. Fig. 3.23. illustrates the percentage distribution of the ratio of the square of the annual and semi-annual amplitudes over India. The annual oscillation is quite dominant than the semi-annual oscillation on all parts of the country except the western peninsular region, which comes under the sway of the summer monsoon. Gujarat coast is also influenced by the semi-annual oscillation. Lowest ratio is seen in the central parts of the country. Short period oscillations in pressure are not significant over India (Fig.3.24).

3.3.3.5 Phases of the annual and semi-annual oscillations

Phase of the given harmonic gives the time of the year when the maximum of the given harmonic takes place. Figs. 3.25 and 3.26 gives the phases of annual and semi-annual oscillations. Over most of the country the highest pressure is observed in mid-January when the country is at the periphery of the Siberian High. With the advance of the south-west monsoon, pressure starts decreasing and there is a secondary maximum is seen in

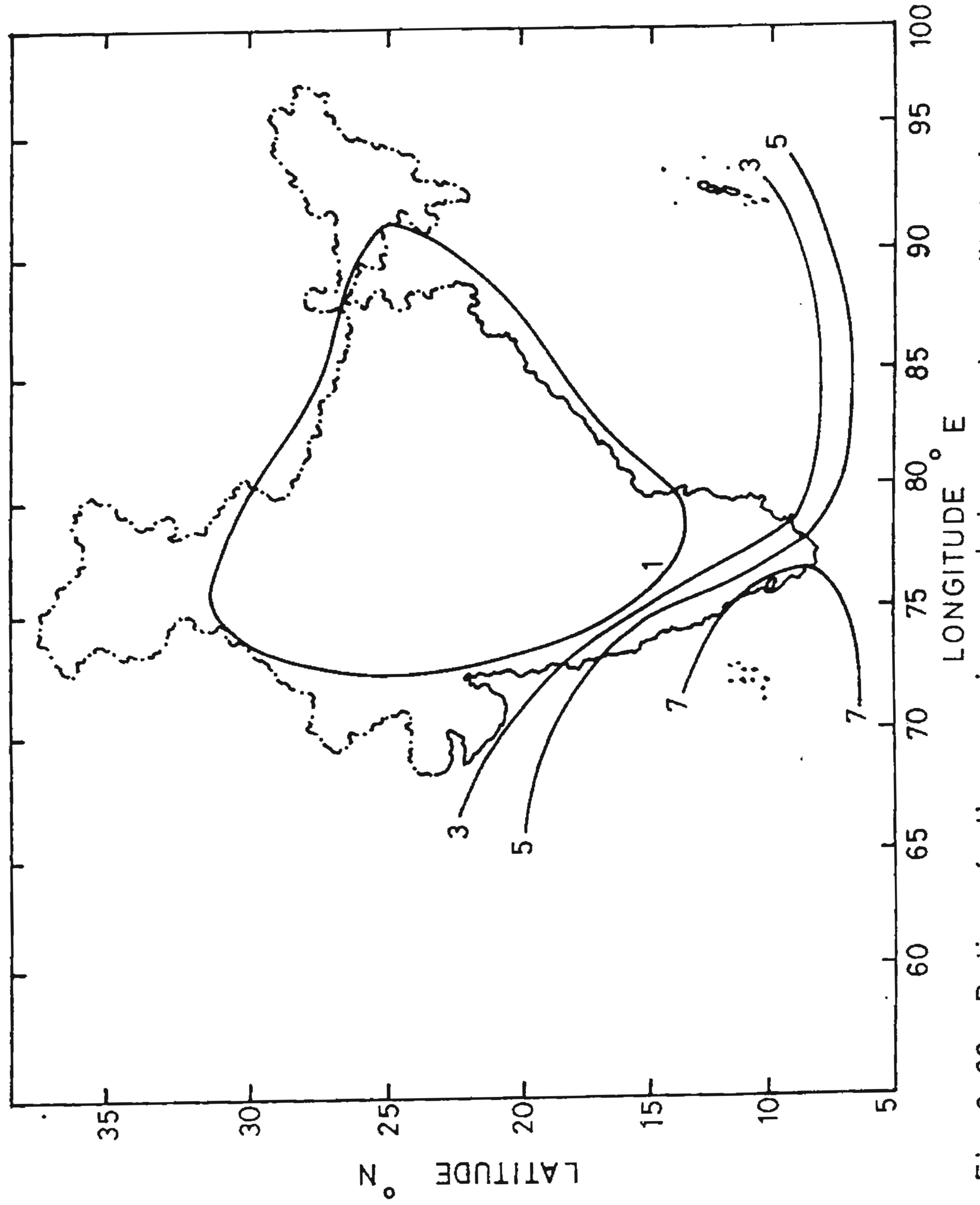


Fig. 3.23 Ratio of the semi-annual to annual amplitude in pressure (%)

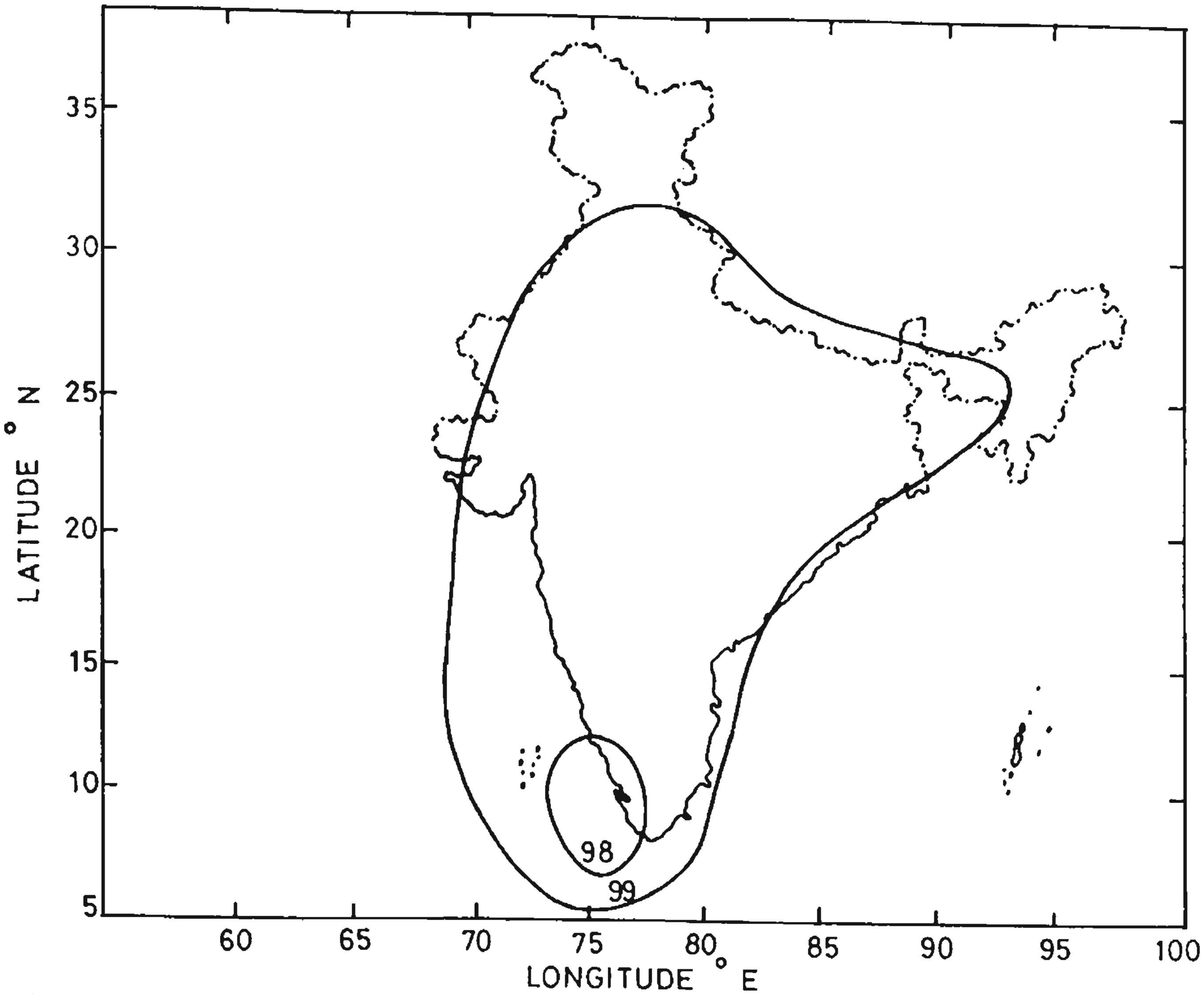


Fig. 3.24 Contribution of major oscillations in pressure (%)

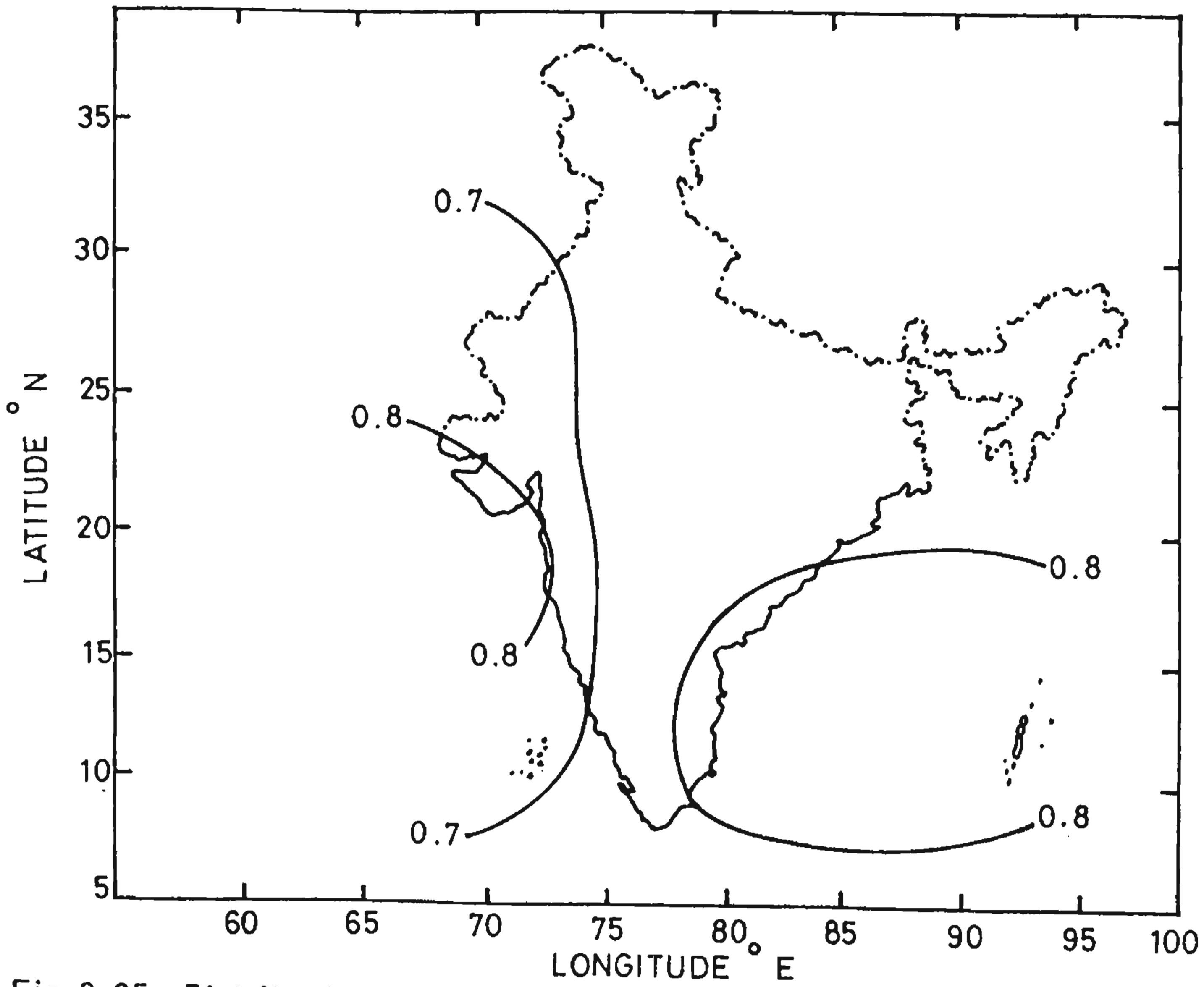


Fig. 3.25 Distribution of the phases of annual cycle in pressure over India (months)

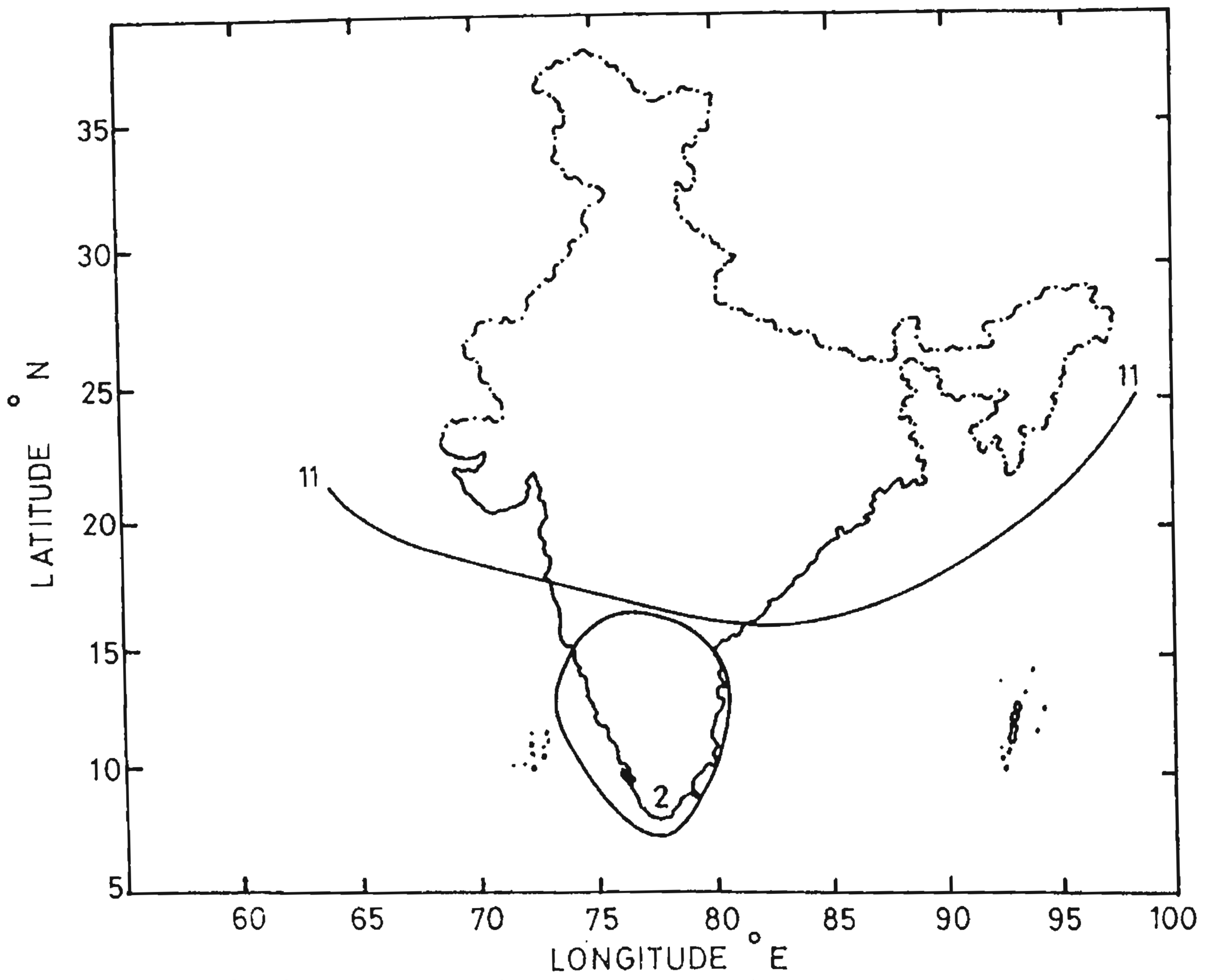


Fig. 3. 26 Distribution of the phases of semi-annual cycle in pressure (months)

February south of $15^{O}N$ in the peninsula due to the influence of the cyclonic circulation in the Bay of Bengal.

3.4 SUMMARY

The harmonic analysis on the seasonal cycle in annual rainfall pattern indicate that the highest amplitude in annual cycle in precipitation lies over the Western Ghat region, centered around $15^{O}N$ latitude. Northeastern part of the country also experiences the large annual amplitudes. In general, the semi-annual oscillation in precipitation is found to be quite weak over the entire country except over the Western Ghat region. The annual cycles are strong on the leeward side of the Western Ghats and the northeastern hilly region. Large period oscillation are found to be significant in most part of the country. The localised short period cycles seem to have some influence on the central peninsular and northwest part of the country. The phase of the annual cycle shows the highest value in most part of the country during the month of July, which is connected with the active southwest monsoon season. The spatial distribution of the thermal regimes over the Indian subcontinent is caused due to the topographical and atmospheric variations, which in turn influence local and regional thermal regimes. The highest peak in the mean sea level temperature over the Indian subcontinent is noted in the central peninsular region centered at Hyderabad and the lowest mean temperature is recorded in the northeastern part of the country. The temperature remains more or less constant in the Western Ghat region. Amplitude of annual oscillations are lower in the western part of the peninsula and they are quite strong in the eastern part. A comparative evaluation between the amplitude of the annual and semi-annual oscillation in temperature reveals that in the regions coming under intense monsoon activity, the semi-annual oscillation is equally strong. The shorter period oscillations are significant only in the Western Ghat region. The phase of the semi-annual oscillation reaches its maximum during September-middle to November-middle and the phase of annual oscillation peak from April to June. The sea-level pressure distribution over India is influenced by the annual amplitude and the semi-annual dominance is found only in the western peninsular region and the Gujarat coast which comes under the sway of the summer monsoon.

Chapter 4

INTERANNUAL VARIABILITY AND TRENDS IN RAINFALL, SURFACE TEMPERATURE AND SEA LEVEL PRESSURE OVER INDIA

4.1 GENERAL

Climate is the 'sum total' of the weather experienced at a place over a period of time and it includes the 'normal', the 'extremes' and 'long-term' variations. The earth's climate fluctuates quite noticeably from year-to-year, and these fluctuations and long-term changes are the result of natural internal processes or external causes influencing the complex climate system. The study of the past climate over a region helps in understanding the behaviour of the atmosphere and its vagaries. This will be extremely useful to construct a comparable and comprehensive climatic time series. Among the various climatic parameters, the temperature of the air near the surface, rainfall and sea-level pressure are of greatest concern to the agriculture and economy of a developing country like India. Rainfall and other hydrological parameters are characterised by variability and oscillatory behaviour. This includes the long-term and interannual variations which are of great significance in national activities like agriculture, water-management and energy generation. The year-to-year variations in temperature in tropical regions are quite small compared to middle latitutdes. However, small changes in temperature affect the evaporation pattern and are likely to be reflected in rainfall changes (Parthasarathy et al. 1978). Oscillations in sea-level pressure will cause changes in climate on a global scale and will eventually affect the climate system. A study on the interannual fluctuations of surface meteorological parameters will help in understanding the physical processes responsible for climatic variability and will be useful for predicting the climate system.

The aim of the study in this Chapter is to bring out the interannual variability and trend in surface temperature, rainfall and sea-level pressure and will provide a better understanding on the regional and temporal characteristics of their distribution.

4.2 METHODOLOGY

4.2.1. FAST FOURIER TRANSFORM

Discrete fourier series is based on the principle that any continuous function can be described by the sum of an infinite number of sine and cosine terms. Using Euler's notation, the Fourier series representation of any time series A(K) is written as

$$A(K) = \sum_{n=1}^{N-1} F_A(n)\, e^{i2\pi nk/N} \qquad \ldots(4.1)$$

where A(K) is the time series of K, $F_A(n)$ is the Fourier Transform, n is the frequency (cycles per month), N is the total number of data points and k varies from 0 to N-1 (Stull, 1988). In the present study N is taken as 1020.

$F_A(n)$ is a complex number, where the real part represents the amplitude of the cosine wave and the imaginary part is the sine wave amplitude. It is a function of frequency because the waves of different frequencies must be multiplied by different amplitudes to reconstruct the original time series. If the original time series is A(K) then,

$$F_A(n) = \sum_{k=0}^{N-1} A(k)/N \ e^{i2\pi nk/N} \qquad \ldots(4.2)$$

Equation (4.1) and (4.2) are called Fourier Transform pairs.

The total variance of the original time series is given by the equation

$$\sigma^2 A = 1/N \sum_{n=1}^{N-1} F_A \ (n)^2 \qquad \ldots(4.3)$$

where, $F_A(n)^2$ explains the portion of variance by waves of frequency n. The discrete spectral intensity (or energy), $E_A(n)$ is defined as $E_A\ (n) = 2\ E_A(n)^2$, for $n = 1$ to $n = n_f$, when N is odd, where n_f is called the Nyquist frequency and is the highest frequency that can be resolved using this technique. For N is even, $E_A(n) = 2\ F_A(N)^2$ for frequencies $n = 1$ to

$n = (n_f - 1)$ and $E_a(n) = F_a(n) = F_a(n)^2$ at the Nyquist frequency. This representation is called the discrete variance spectrum

The Fast Fourier Transform (FFT) is nothing but a discrete fourier transform that is factored and restructered for computations on a digital computer. While, the discrete fourier transform requires N^2 operations, the FFT requires only $(3N/2)\log_2 N$ operations. Hence, for large data sets the FFT computations takes only 0.5% of the time of a discrete fourier transform computation.

However, the FFT technique is not free from limitations. Fourier series applies only to infinite duration periodic data sets. Since we examine only finite size record data, the fourier analysis assume that the data is periodic and repeats itself both before and after the limited period of observation and thus create spurious frequencies called the red noise and are removed by detrending the data series. Any low frequency oscillations having periods longer than the sampling period will also generate noise. If the period of these oscillations are known they must also be removed from the data before performing the FFT. Similarly, any high frequency signal in the data will get folded back or aliased into a lower frequency creating an erroneous fourier spectrum. Moreover, the FFT technique requires equally spaced input data points with no missing data.

Analysis of time series by FFT is extremely useful to obtain the contribution of oscillations with various frequencies to the total variance of the time series. It also helps to understand the underlying physics of the variations and points out the significant maxima and minima in the series (Panofsky and Brier, 1968).

The computer program given by Gouvia et al. (1983) is used to compute the fourier spectra. The program obtains the spectral estimates by using the Fast Fourier Transform algorithm of Cooley and Tukey (1965). The algorithm requires that the number of data points in the time series should be expressible as a power of 2. This is achieved by adding the required number of zeroes or truncating the data series. In the present study monthly values of 85 years are used, which gives a total of 1020 values. It should be noted that 2^{10} is 1024 and hence it is required to add only 4 zeroes which will not affect the statistical reliability of the estimates, as far as temperature and rainfall are considered. For sea-level pressure, non-availability of continuous data for 85 years required the addition of more number of zeroes.

The linear-trend is removed from the raw data, and the data is also subjected to 'Hanning Windowing' to minimise the distortions of the spectrum. In order to improve the reliability of the estimates ensemble averaging is also performed.

4.2.2 METHOD OF LEAST SQUARES

This is a mathematical method of measuring trend, in such a manner that the following two conditions are satisfied.

$$(1) \quad (Y-Y_C) = 0.0 \qquad \ldots(4.4)$$

i.e., the sum of deviations of the actual values of Y and computed values of Y_C is zero and

$$(2) \quad (Y-Y_C)^2 \text{ is least} \qquad \ldots(4.5)$$

i.e., the sum of squares of the deviations of the actual and computed values is least from the trend line. The line obtained by this method is known as the 'line of best fit.'

The straight line trend is represented by the equation

$$Y_C = a + bX \qquad \ldots(4.6)$$

where Y_C is the trend value, a is the y-intercept or the computed trend figure of the Y-variable when X = 0 and b represents the slope of the trend line or the amount of change in Y-variable that is associated with a change of one unit in X-variable. The X-variable usually represents time (Gupta, 1981).

4.2.3 THE MANN-KENDALL RANK STATISTIC

The Mann-Kendall rank statistic has been suggested as a powerful test (Kendall and Stuart, 1961) when the most likely alternative to randomness is linear or non-linear trend. The statistic (τ) is computed from the equation

$$(\tau) = \left(\sum n_i / N(N-1) \right) - 1 \qquad \ldots(4.7)$$

where n_i is the number of values larger than the Ist value in the series subsequent to its position in the time series. The test statistic $(t)_t$ is

$$(\tau)_t = t_g \left((4N + 10/9N\,(N-1)) \right)^{\circ} \qquad \ldots(4.8)$$

t_g is the value of t at the probability percentage in the Gaussian distribution appropriate to the two-tailed test usually taken at the 95% level.

4.3 DATA USED FOR THE STUDY

The monthly rainfall values from 23 stations and monthly temperature records from 22 well distributed meteorological stations, all over India for a period of 85 years (1901-1985) is considered for the study. Details about the stations selected, their location and elevation from the mean sea-level are illustrated in Table 4.1 and 4.2. In the case of sea-level pressure the number of stations with 85 years of continuous data are small and therefore 12 stations having more than 70 years of continuous record are considered for the study. Details of the stations selected, their location, elevation from the mean sea-level and the period of data length are illustrated in Table 4.3.

4.4 RESULTS AND DISCUSSION

4.4.1 The Fourier Spectrum

The climatic variability, in which the average remains the same, but there are oscillations about this average is calculated using the fourier spectrum. After substracting the mean value from the time series and dividing by the standard deviation, the fourier spectrum is calculated for the normalised values. Estimates of the amplitudes of the climatic variations show spectral peaks at the annual, semi-annual, tri-annual oscillations of the seasonal cycle at 3, 2.4 and 2 months. The other major quasi-periodicitics appearing as peaks in the spectrum are the 11-year solar cycle, its 5-year sub-harmonic, the Quasi-triennial oscillation (QTO) with a period of 36-months, the 28-month periodicity or the Quasi-Biennial

Table 4.1 Details of the stations and their location utilised for rainfall study.

No.	Station Name		Latitude (°N)	Longitude (°E)	Altitude from msl (gpm)
1	SRINAGAR	(SRN)	34°51'	74°50'	1585
2	MUKTESHWAR	(MKS)	29°28'	79°39'	2310
3	BIKANER	(BKR)	28°00'	73°18'	223
4	NEW DELHI	(DLH)	28°35'	77°12'	211
5	DIBRUGARH	(DBG)	27°29'	95°01'	110
6	JODHPUR	(JDP)	26°18'	73°01'	217
7	GAUHATI	(GHT)	26°06'	91°35'	47
8	ALLAHABAD	(ALB)	25°37'	81°44'	97
9	AHMADABAD	(AHM)	23°04'	72°38'	55
10	CALCUTTA	(CAL)	22°32'	88°33'	5
11	NAGPUR	(NGP)	21°06'	79°03'	308
12	VERAVAL	(VVL)	20°54'	70°22'	6
13	AKOLA	(AKL)	20°42'	77°2'	280
14	BOMBAY	(BMB)	18°54'	72°49'	10
15	POONA	(PNA)	18°32'	73°51'	555
16	HYDERABAD	(HYD)	17°27'	78°28'	530
17	VISHAKHAPATNAM	(VSK)	17°43'	83°14'	3
18	MACHILIPATNAM	(MAC)	16°12'	81°09'	3
19	MADRAS	(MDS)	13°00'	80°11'	10
20	BANGALORE	(BNG)	12°58'	77°35'	920
21	PAMBAN	(PBN)	9°16'	79°18'	10
22	MINICOY	(MNC)	8°18'	73°09'	1
23	TRIVANDRUM	(TRV)	8°29'	76°57'	60

Table 4.2 **Details of the stations and their location utilised for temperature study.**

No.	Station Name		Latitude (°N)	Longitude (°E)	Altitude from msl (gpm)
1	MUKTESHWAR	(MKS)	29°28'	79°39'	2310
2	BIKANER	(BKR)	28°00'	73°18'	223
3	AGRA	(AGR)	27°10'	78°02'	168
4	DIBRUGARH	(DBG)	27°29'	95°01'	110
5	JODHPUR	(JDP)	26°18'	73°01'	217
6	GAUHATI	(GHT)	26°06'	91°35'	47
7	ALLAHABAD	(ALB)	25°37'	81°44'	97
8	DWARKA	(DWR)	22°22'	69°05'	10
9	INDORE	(IND)	22°43'	75°48'	561
10	CALCUTTA	(CAL)	22°32'	88°33'	5
11	NAGPUR	(NGP)	21°06'	79°03'	308
12	VERAVAL	(VVL)	20°54'	70°22'	6
13	AKOLA	(AKL)	20°42'	77°2'	280
14	BOMBAY	(BMB)	18°54'	72°49'	10
15	POONA	(PNA)	18°32'	73°51'	555
16	HYDERABAD	(HYD)	17°27'	78°28'	530
17	VISHAKHAPATNAM	(VSK)	17°43'	83°14'	3
18	MADRAS	(MDS)	13°00'	80°11'	10
19	BANGALORE	(BNG)	12°58'	77°35'	920
20	PORT BLAIR	(PBL)	11°40'	92°43'	73
21	PAMBAN	(PBN)	9°16'	79°18'	10
22	TRIVANDRUM	(TRV)	8°29'	76°57'	60

Table 4.3 **Details of the stations, their location and data periodicity utilised for pressure study.**

No.	Station Name		Latitude (°N)	Longitude (°E)	Altitude from msl (gpm)	Data length
1	LUDHIANA	(LDN)	30°52'	75°56'	255	1901-1985
2	BIKANER	(BKR)	28°00'	73°18'	223	1901-1973
3	AGRA	(AGR)	27°10'	78°02'	168	1901-1985
4	JODHPUR	(JDP)	26°18'	73°01'	217	1901-1985
5	GAUHATI	(GHT)	26°06'	91°35'	47	1901-1976
6	AHMADABAD	(AHM)	23°04'	72°38'	55	1901-1979
7	NAGPUR	(NGP)	21°06'	79°03'	308	1901-1985
8	VERAVAL	(VVL)	20°54'	70°22'	6	1901-1985
9	AKOLA	(AKL)	20°42'	77°2'	280	1901-1973
11	PAMBAN	(PBN)	9°16'	79°18'	10	1893-1988
12	TRIVANDRUM	(TRV)	8°29'	76°57'	60	1901-1985

Oscillation (QBO) and the Chandler-Wobble Oscillation (CW) with an average period of 14.43 months. However, these oscillations show great spatial variability. The seasonal oscillation have already studied and presented in Chapter 3 of this thesis.

Omitting the annual term and its sub-harmonics the average ratio of each spectral estimate to the background spectrum is calculated and are plotted in Fig. 4.1(a-c) for rainfall, Fig.4.2(a-c) for temperature and Fig. 4.3(a-b) for sea-level pressure. The peaks above unity are only considered as signals.

4.4.1.1 The 11-year cycle and 5- year cycle

The 11-year cycle and its 5-year subharmonic is observed in all the stations for rainfall (Fig. 4.1(a-c)). Two coastal stations in the south, Madras and Pamban, are more influenced by the 5 year periodicity than the 11-year cycle (see Fig. 4.1(c). The physical cause for this behaviour is to be further investigated. Fig. 4.2 (a-c) gives the ratio of the spectral estimates for temperature. While the 11-year cycle is observed in temperature for all the stations except Trivandrum and Port Blair, the 5 year periodicity is more prominent in the three inland stations, viz., Hyderabad, Poona and Bangalore (see Fig. 4.2(b) and 4.2(c)). The pressure pattern of the country is influenced by the 11-year solar cycle and its sub-harmonic at all the stations. The period of this oscillation is found to be around 12-years and could be due to the fact that the FFT technique will not resolve exact periodicitics.

It is illustrated that the number of sunspots and the solar radio flux show a cycle of nearly 11- years and since the total radiation as well as nature of radiation would affect the terrestrial climate, sunspot cycle influences the meteorological conditions to some extent (Menon, 1989). Anathakrishnan et al. (1984) studied the relation of Indian rainfall and solar activity using a wide number of stations. The studies of Parthasarathy and Mooley (1978) did not show any significant correlation with Indian monsoon rainfall and solar activity. However, it is shown that significant correlations exist with changes in the pattern of south-west monsoon rainfall over India (Berger, 1981) and air temperature and air pressure world wide (Currie, 1984) with solar activity. As long as there is no clear understanding on the influence of the solar variability on meteorological parameters, it is difficult to assess the magnitude of climatic changes due to changes in solar activity. Since the presence of 11-year cycle is observed in all the three parameters over India, it should be considered that the 11-year quasi-periodicity and its sub-harmonic related to solar activity is a transient phenomena.

4.4.1.2 The Quasi - Triennial Oscillation (QTO)

An important spectral peak observed for Indian region in the sub-annual time scale is a periodicity with a period of around 36 months, which is called the Quasi Triennial Oscillation (QTO) and is considered as one signature of the EL-Nino Southern Oscillation (ENSO).

The presence of the 36-month periodicity in rainfall is observed in Allahabad, Srinagar and New Delhi in north India and Ahmedabad, Veraval, Bombay and Poona on the western side (fig. 4.1(a-b)). The southern stations of Madras, Bangalore, Pamban and Minicoy also exhibit QTO (Fig. 4.1(c)). The inland stations of Akola, Nagpur and Hyderabad are not much influenced by the QTO (Fig. 4.1(b)), while the precipitation pattern of Vishakhapatnam and Machilpatnam are slightly influenced by the 36-month periodicity (Fig. 4.1(c)). The eastern region of the country, which receives abundant rainfall throughout the year is not influenced by QTO. It is interesting to note that the QTO influences the rainfall distribution of south Indian stations except that of Trivandrum.

The presence of QTO in surface air temperature was detected only in 6 of the 22 stations selected for the study (Fig. 4.2(a-c)). It is interesting to find that all these 6 stations (viz., Nagpur, Indore, Jodhpur, Bikaner, Agra and Mukteshwar) are inland stations. The coastal stations are not

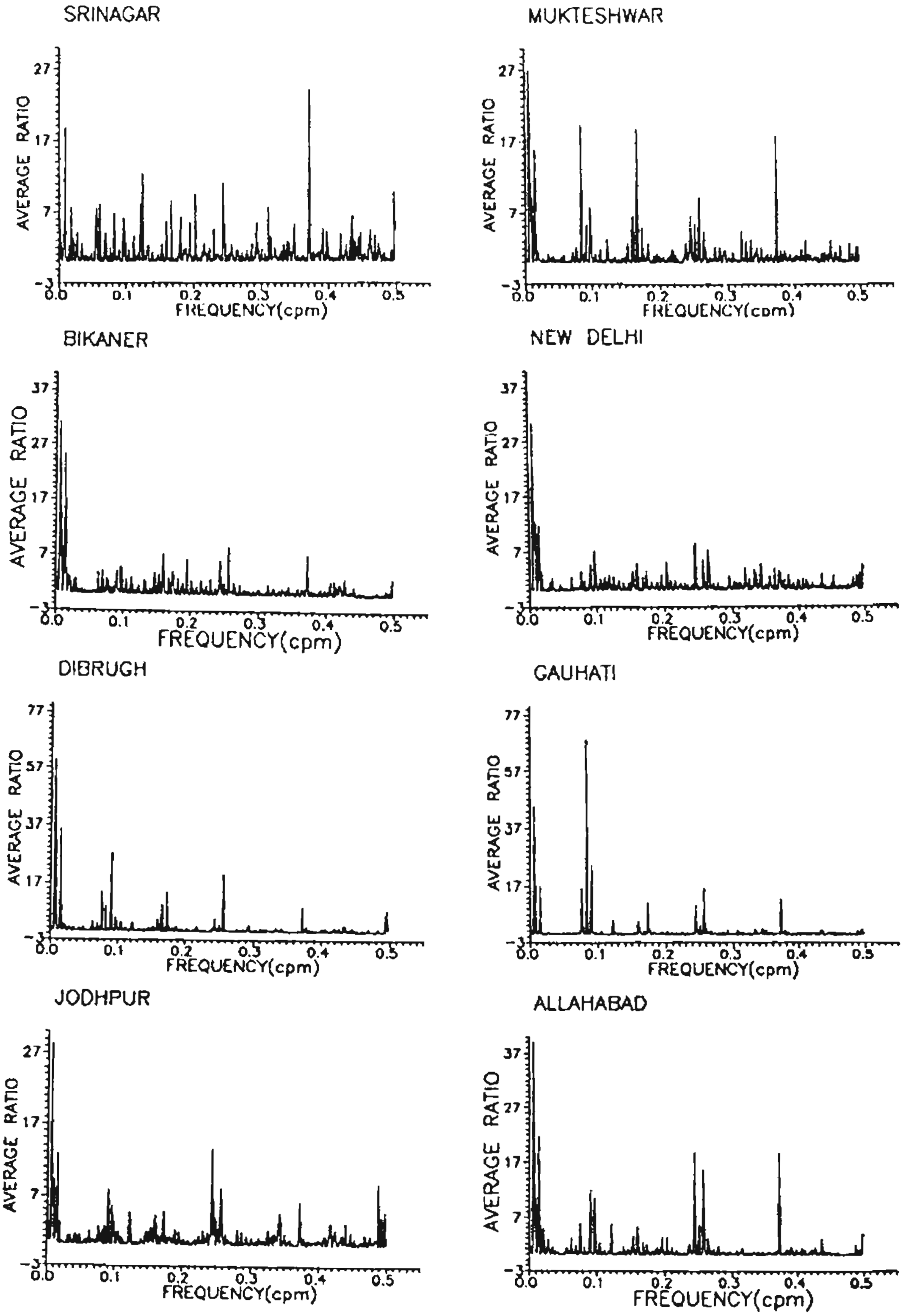


Fig. 4.1 (a) Spectral Estimate of Rainfall

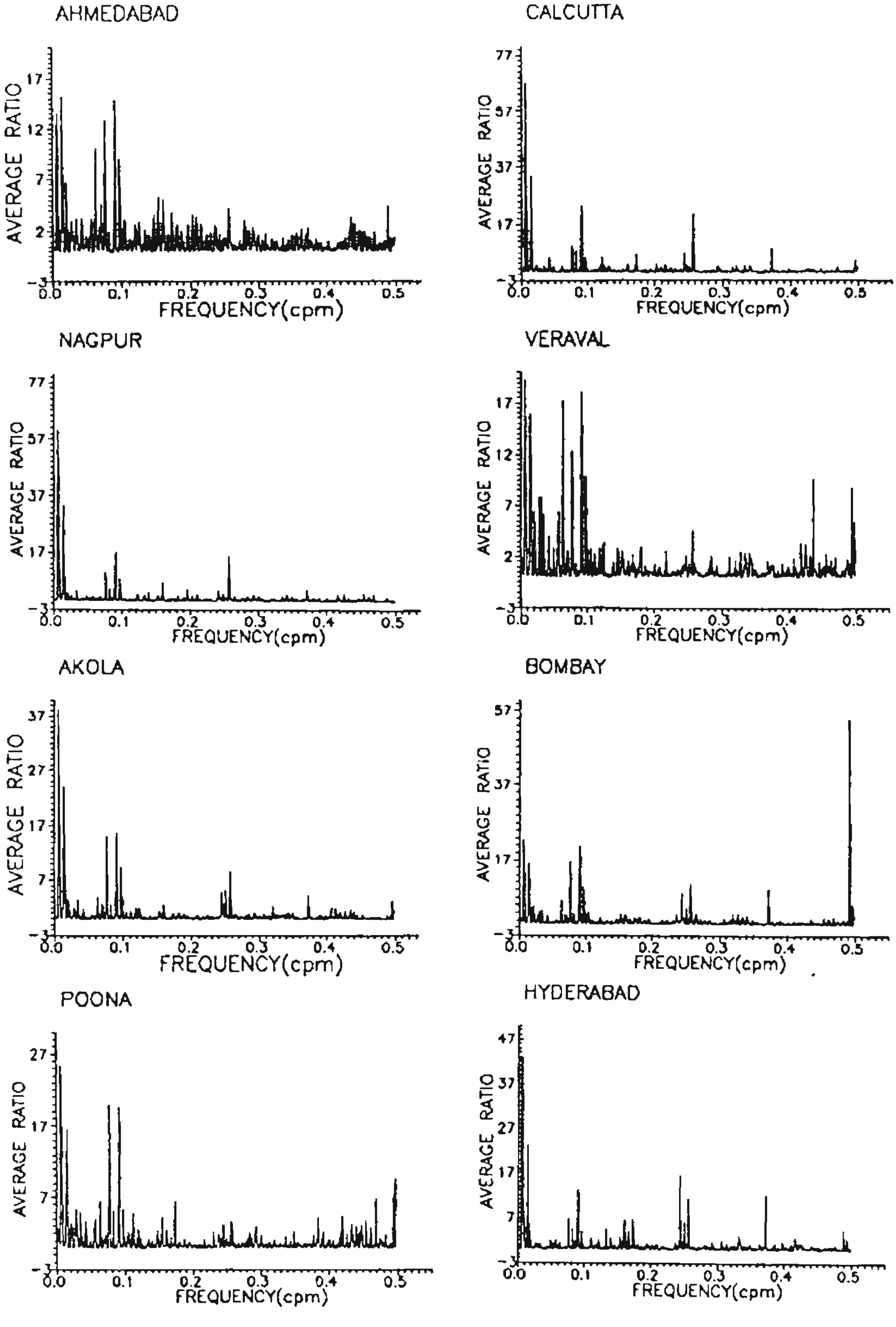


Fig. 4.1 (b) Spectral Estimate of Rainfall

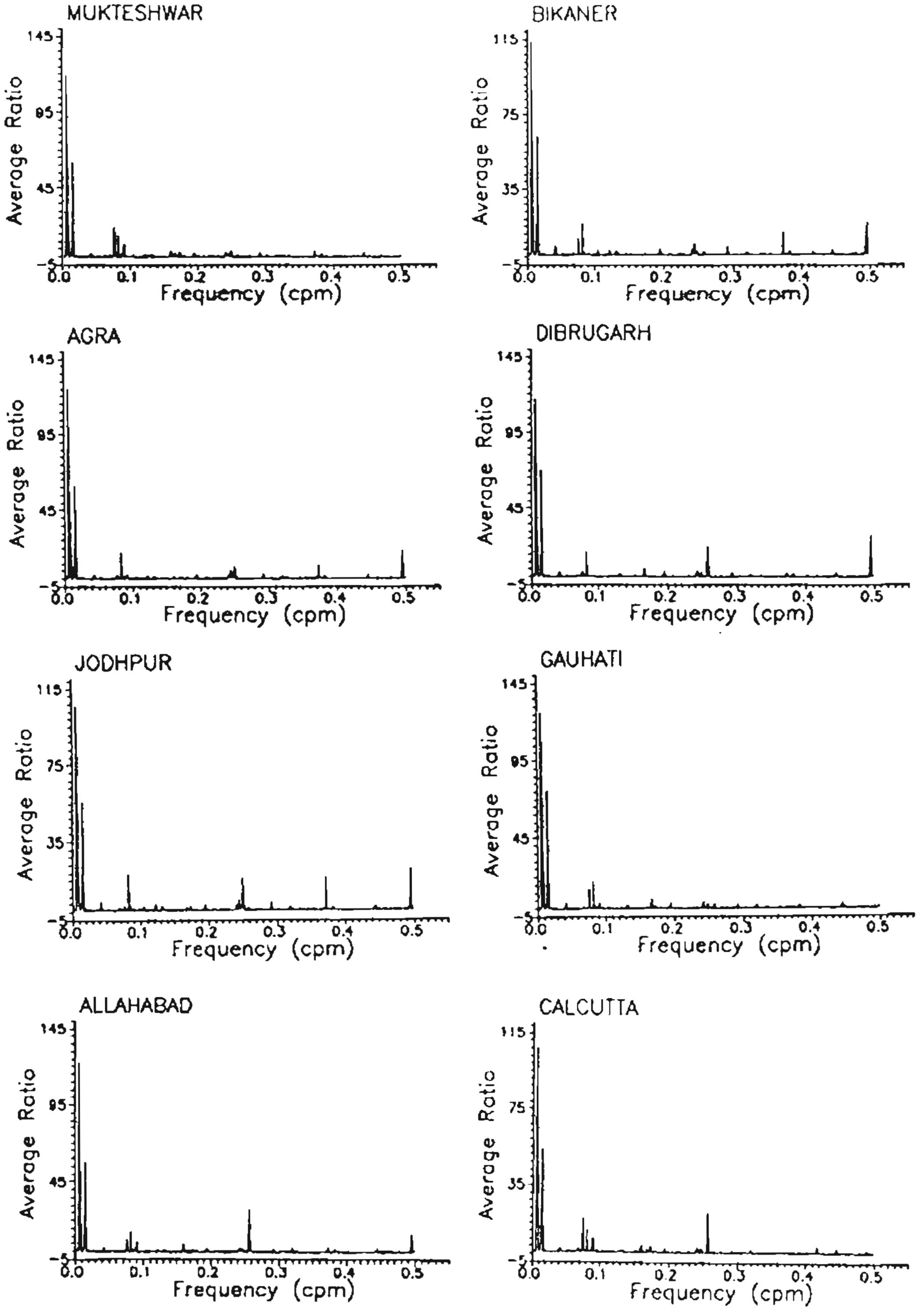


Fig. 4.2 (a) Spectral Estimate of Temperature

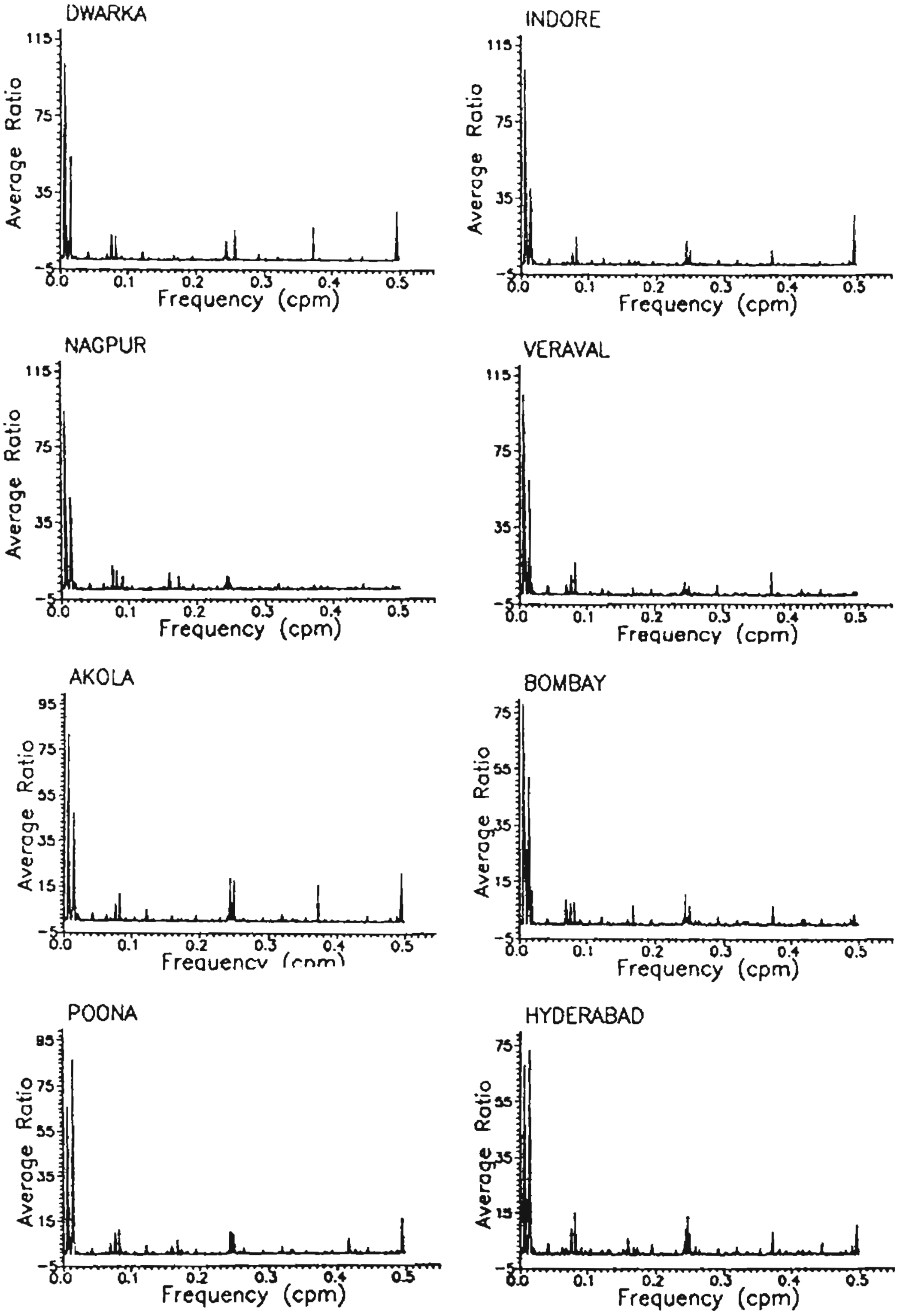


Fig. 4.2 (b) Spectral Estimate of Temperature

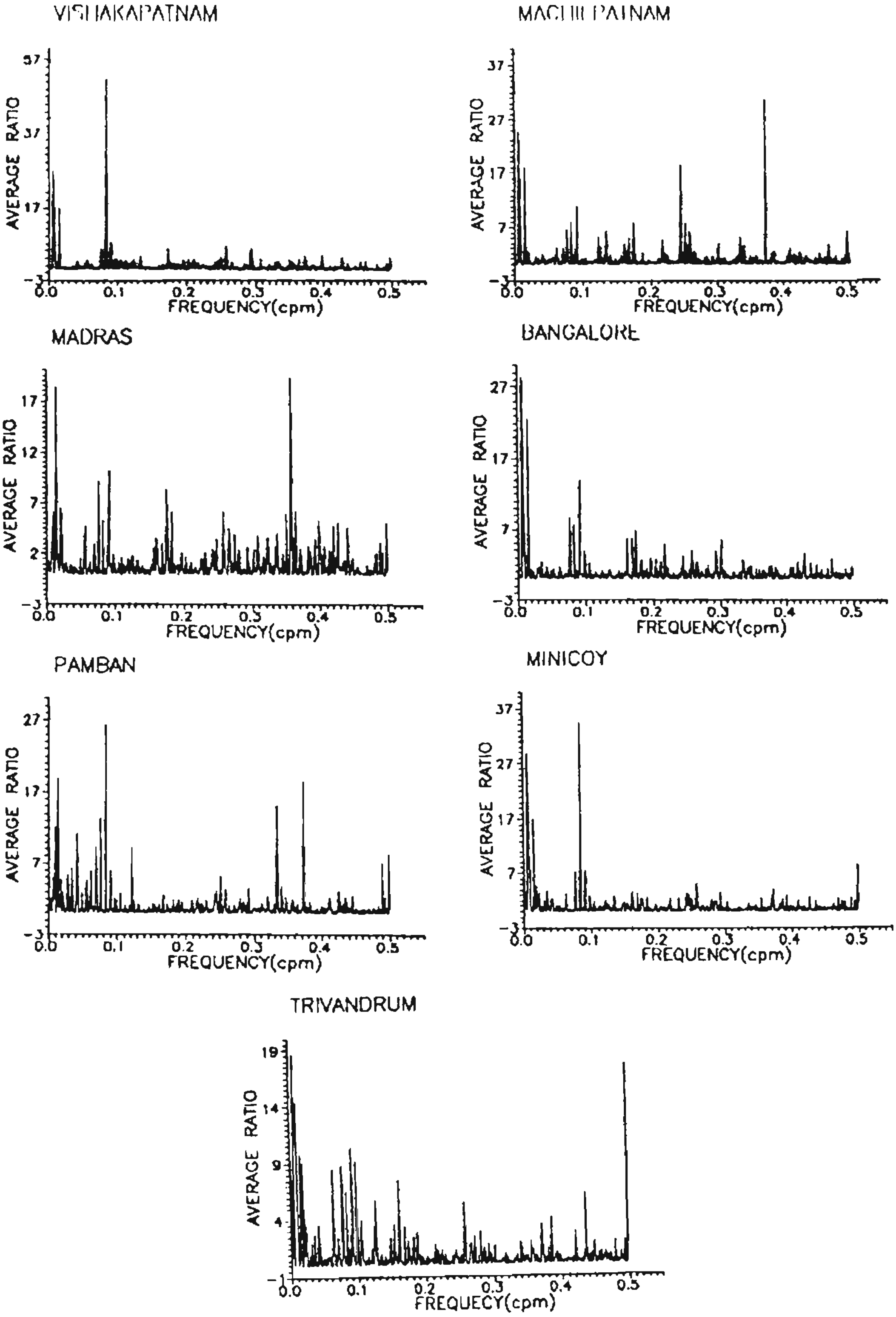


Fig. 4.1 (c) Spectral Estimate of Rainfall

well dominated by the quasi triennial oscillation. This is in contrast to the rainfall pattern, which exhibits QTO in coastal stations and not in the inland stations. The 36-months periodicity is not well dominating for sea-level pressure over India (see Figs. 4.3(a-b)).

The Southern Oscillation (SO) is the see saw type pressure oscillation between the tropical Indian Ocean and the tropical Pacific Ocean (Asnani, 1993). The amplitudes of these oscillations undergo quasi-periodic oscillations and for Indian rainfall and temperature the QTO exhibits a periodicity of 33 to 40 months. During EL-Nino situation, the Pacific Walker cell is displaced eastward with the ascending branch in phase with the areas of maximum SST and descent in motion occurs over central and West Pacific and the south east Asian region. Such an event would in turn suppress the formation of monsoon disturbances and affect the overall rainfall activity (Chowdhury et al, 1991). These changes will be reflected in surface temperature also. The quasi-triennial oscillation in rainfall is detected in almost all the coastal stations and for temperature the QTO is dominant only in the inland stations. The QTO, however is not detected in sea level pressure.

4.4.1.3 The Quasi-Biennial Oscillation (QBO)

The Quasi-Biennial Oscillation (QBO) which corresponds to the transition between easterlies and westerlies in the lower stratosphere, with a periodicity of about 28 months is one of the major climatic oscillation. Significant quasi-biennial oscillation in rainfall with a period of 28-29 months is observed in Allahabad, Srinagar, New Delhi, Bikaner, Ahmedabad, Bombay, Veraval, Poona, Bangalore, Madras, Pamban and Trivandrum (Fig. 4.1(a-c)). The QBO is relatively weak and not well marked in the eastern coastal stations of Calcutta, Vishakhapatnam and Machilipatnam.

Analysis of the spectrum of temperature and pressure indicates that there is a spectral peak at around 24 months for both temperature and pressure, observed almost all the stations. This spectral peak is associated with the QBO. In a strictly biennial oscillation, there is a phase difference in the same months in successive years. In a 26-month oscillation, 180| phase difference would occur after 13 months. Even and odd Januaries have, however indicated some contrast. If this contrast is permanent, then the period of oscillation is 24-months and not 26-months (Asnani, 1993).

Using the worldwide network of surface station records, Landsberg (1963) established QBO in surface temperature all over the world, with opposite phases in tropical and extra tropical latitudes. Wagner (1971) analysed seasonal pressure patterns and found significant QBO in pressure systems. Eventhough, much work has been carried out to relate rainfall and QBO (Chowdhury et al. 1991; Bhukan Lal et al. 1992), there is no reliable theory on why

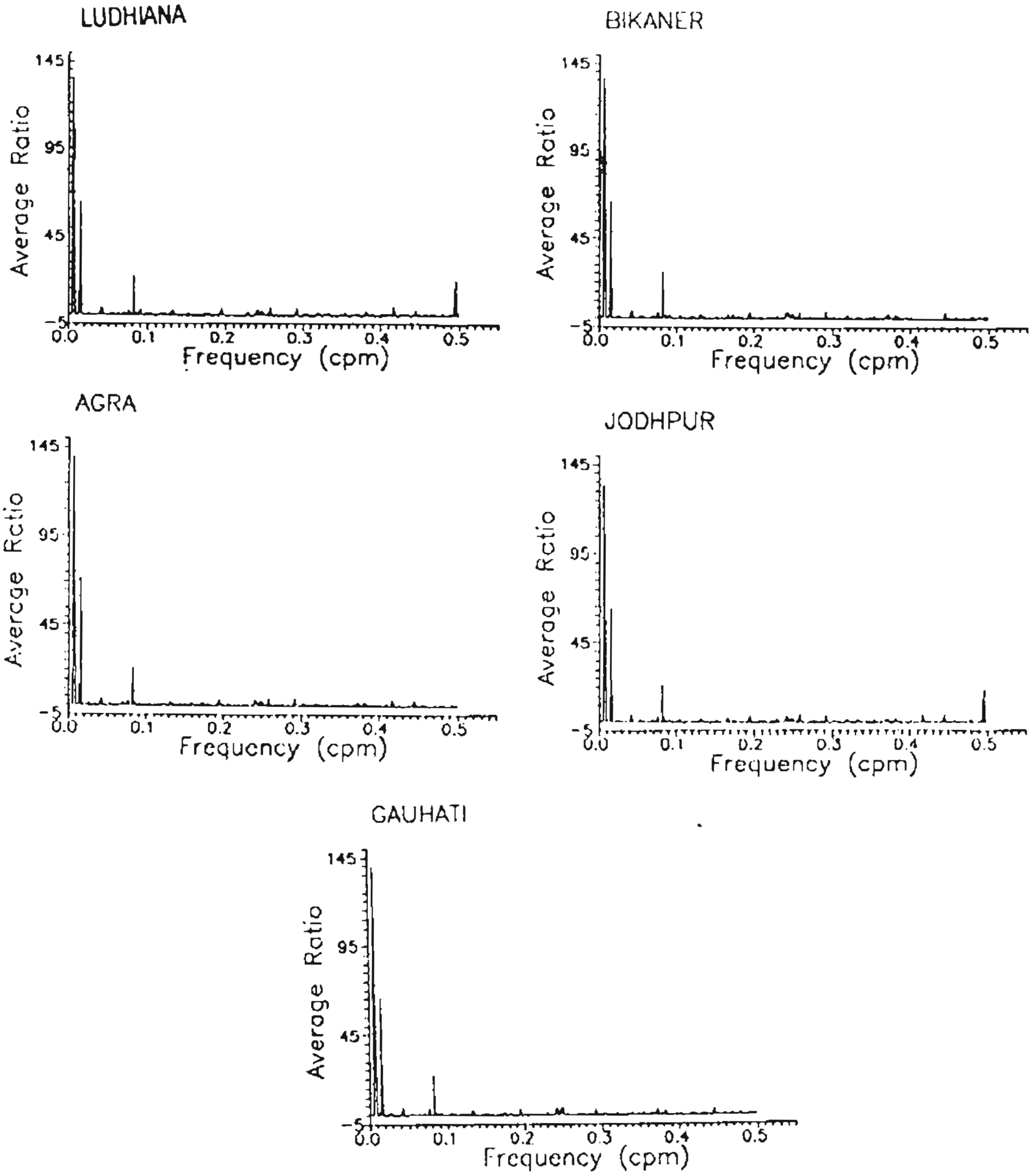


Fig. 4.3 (a) Spectral Estimate of Pressure

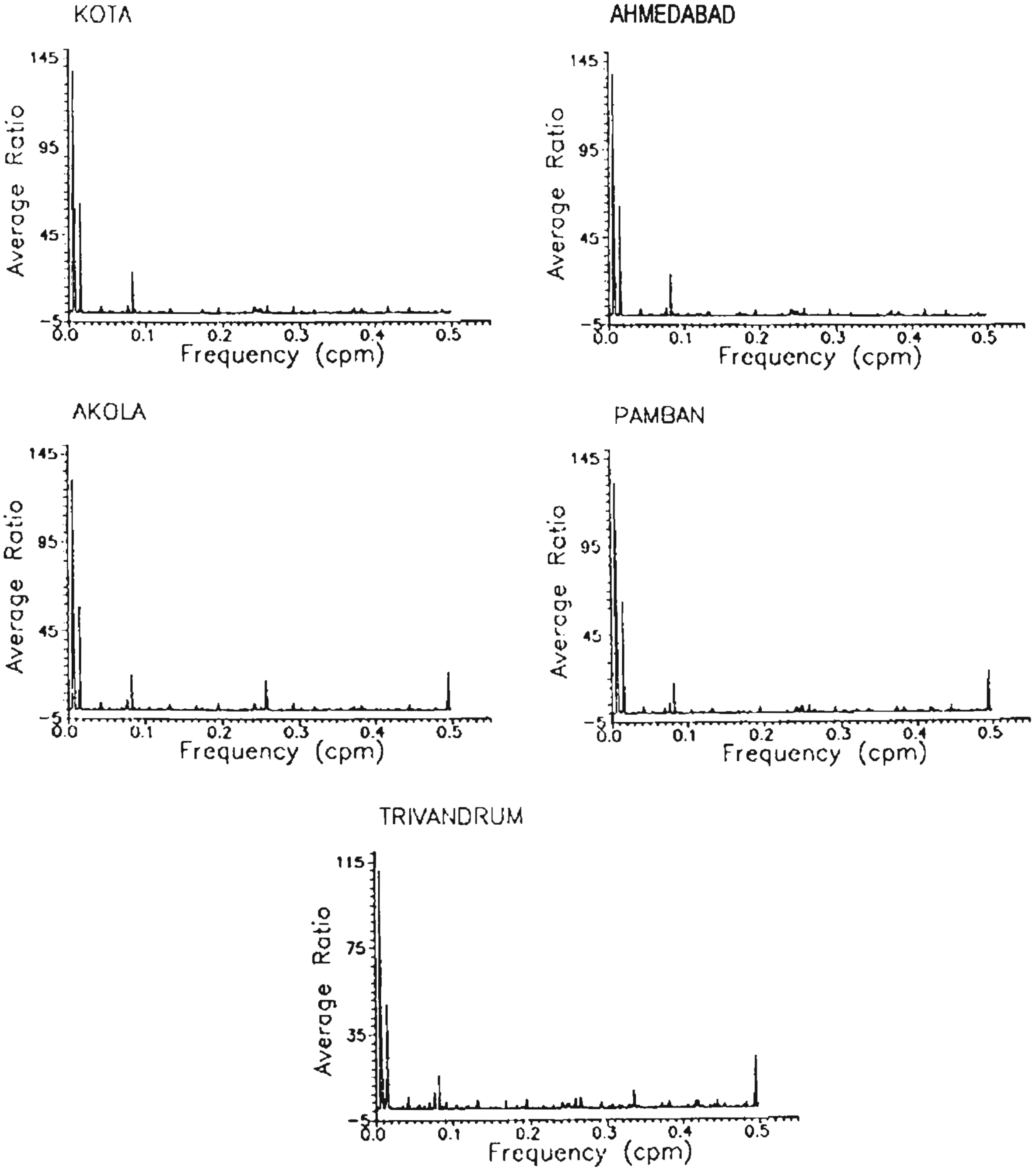


Fig. 4.3 (b) Spectral estimate of Pressure

QBO is observed in all meteorological parameters over the whole globe. While, QBO in rainfall exhibits a periodicity of 28-29 months, its period for temperature and pressure is slightly less than 24 months. This is an important feature that is to be seriously considered when any future long term prediction is attempted.

4.4.1.4 The Chandler-Wobble Oscillation (CW)

The fourier spectra calculated for rainfall, temperature and sea-level pressure indicates a peak at 14.43 months. This quasi-periodicity is associated with the Chandler-Wobble (CW) oscillation, after its discoverer, Sir, S.C.Chandler. A fixed point on the earth's surface wobbles about the axis of rotation axis at two discrete periods of 12-months and 14-months. The annual term is recognised as the forced wobble caused by seasonal shifts in air mass, and the 14-month Oscillation is called the Chandler Wobble Oscillation (Hameed et al. 1989). This periodicity is observed in sea-level (Miller et al, 1973) and in surface air pressure in northern latitudes (Currie et al. 1990).

The CW Oscillation is detected for Indian rainfall with an average period of 14.43 months. The oscillation is well pronounced in Ahmedabad, Poona, Veraval, Bombay, Srinagar, Allahabad, Pamban and Trivandrum (Fig. 4.1(a-c)). It is interesting to note that while CW is absent for interior stations as far as rainfall is concerned, it is detected in temperature in inland stations such as Agra, Bikaner, Gauhati, Hyderabad, Indore, Jodhpur and Nagpur (Fig. 4.2(a-b)). Eventhough, CW is a pressure oscillation, it is not clearly detectable for sea- level pressure over India, for all the stations. The 14.43- month oscillation in surface pressure is found only in Agra, Bikaner, Pamban and Trivandrum (fig. 4.3(a-b)). The influence of this oscillation in the climate of the country is yet to be studied in detail. It is to be noted that the number of stations with continuous data for 85 years is small. A better resolution of long period data in sea level pressure would resolve the presence of CW in pressure.

The spectrum of the meteorological parameters over India is of particular interest because of the large interannual variability displayed by these parameters. The overall spectrum suggests that most of the variability is contained in bands of known physical origin and hence predictable. However, non systematic variability should also be taken into account before any prediction is to be carried out.

4.4.2 TREND

The method of least square is employed to calculate the trend and is tested with the Mann-Kendall rank statistic. The stations having significant trend at the 95% level is illustrated in this Chapter.

4.4.2.1 Trend in rainfall

Sarker and Thapliyal (1988) and Thapliyal (1990) studied the long period (1875 - 1989) annual rainfall of India using the data of large number of rainguages well distributed over the country. Later study of Soman et al.(1988) revealed a decreasing trend in rainfall for Kerala. Fig 4.4 gives the trend for stations showing significant trend in rainfall. It is seen that Jodhpur, New Delhi, Veraval and Bombay show an increasing trend in rainfall, while rainfall is decreasing at the rate of 0.2376 mm/year at Dibrugarh in the eastern part of the country.

4.4.2.2 Trend in temperature

Fig. 4.5(a-b) gives the trend in temperature for the different stations. Trend analysis in temperature reveal a significant warming in Agra, Akola, Bombay, Calcutta, Dibrugarh, Dwarka, Veraval and Vishakhapatnam and a cooling trend in Port Blair, Hyderabad and Bikaner during the last century. The results are similar to that found by Srivastava et al, (1992) who found a warming trend south of 23^{O}N and cooling trend in northwest and northeast India, the only exception being the cooling trend in Hyderabad and Port Blair. Considering the country as a whole, the temperatures are found to be increasing at the rate of 0.24^{O}C/100 years. Based on the available data, it should be considered as there is a definite warming trend in the country.

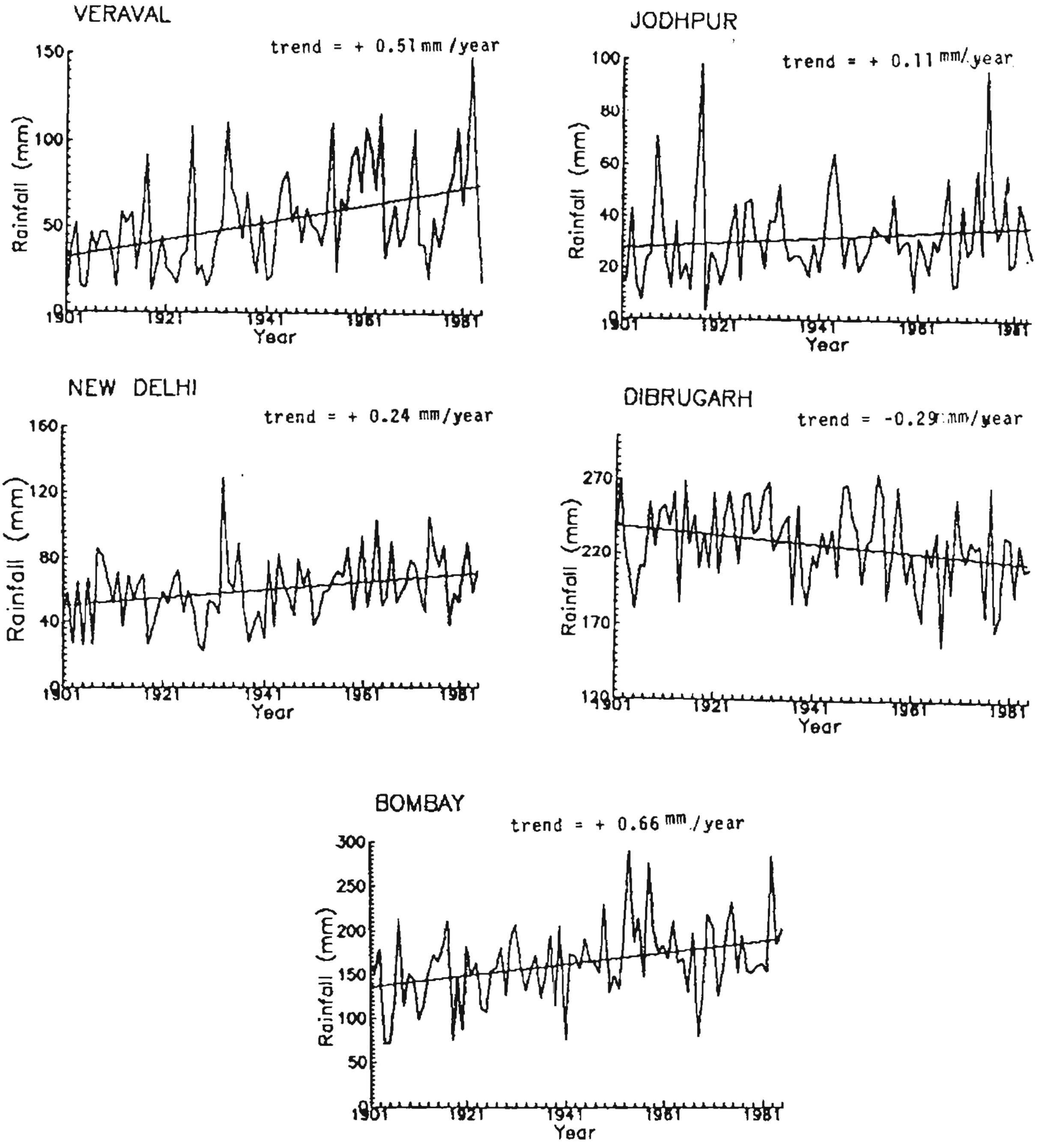


Fig. 4.4 Trend in Rainfall for different stations

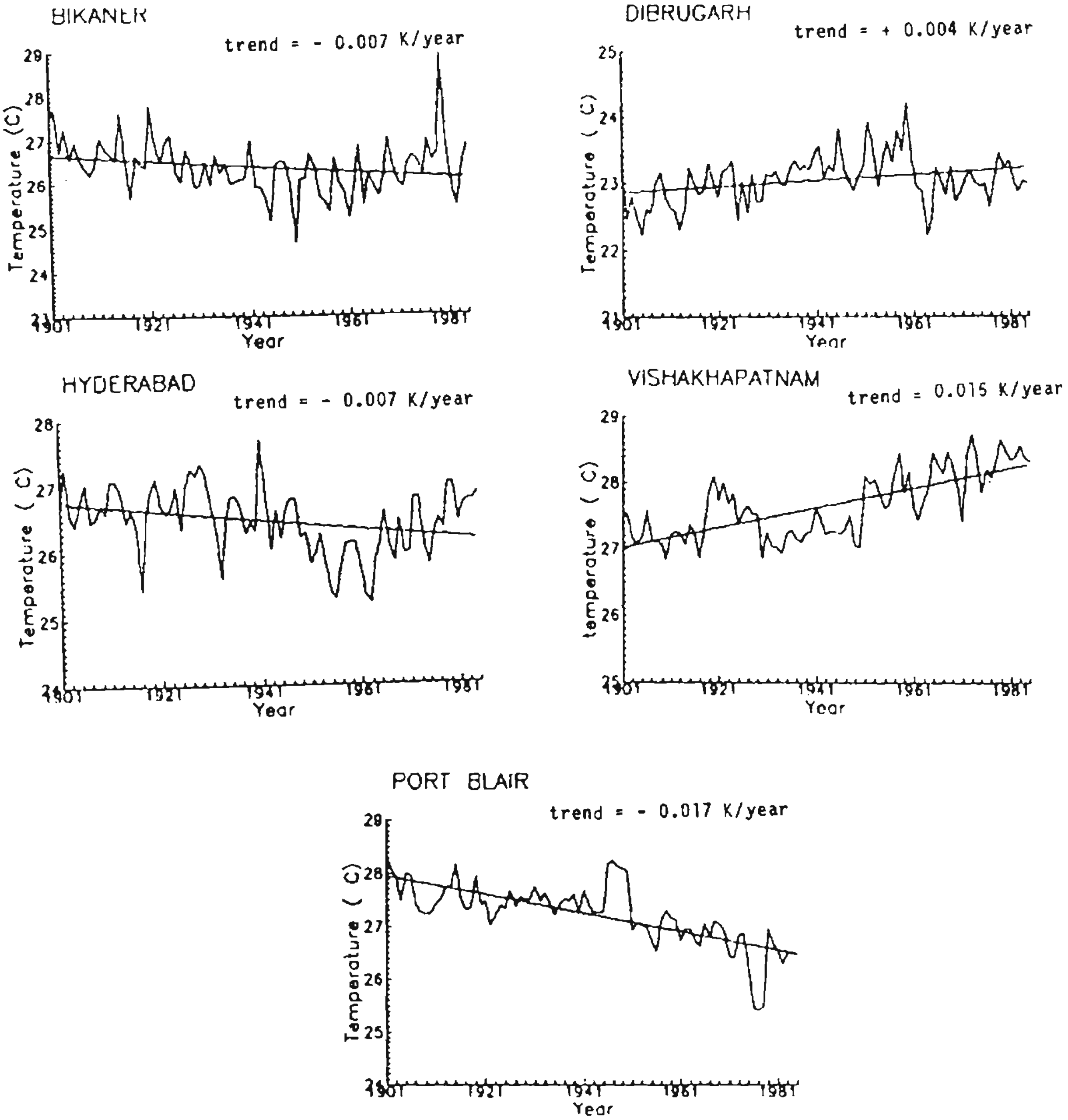


Fig. 4.5 (a) Trend in temperature for different stations

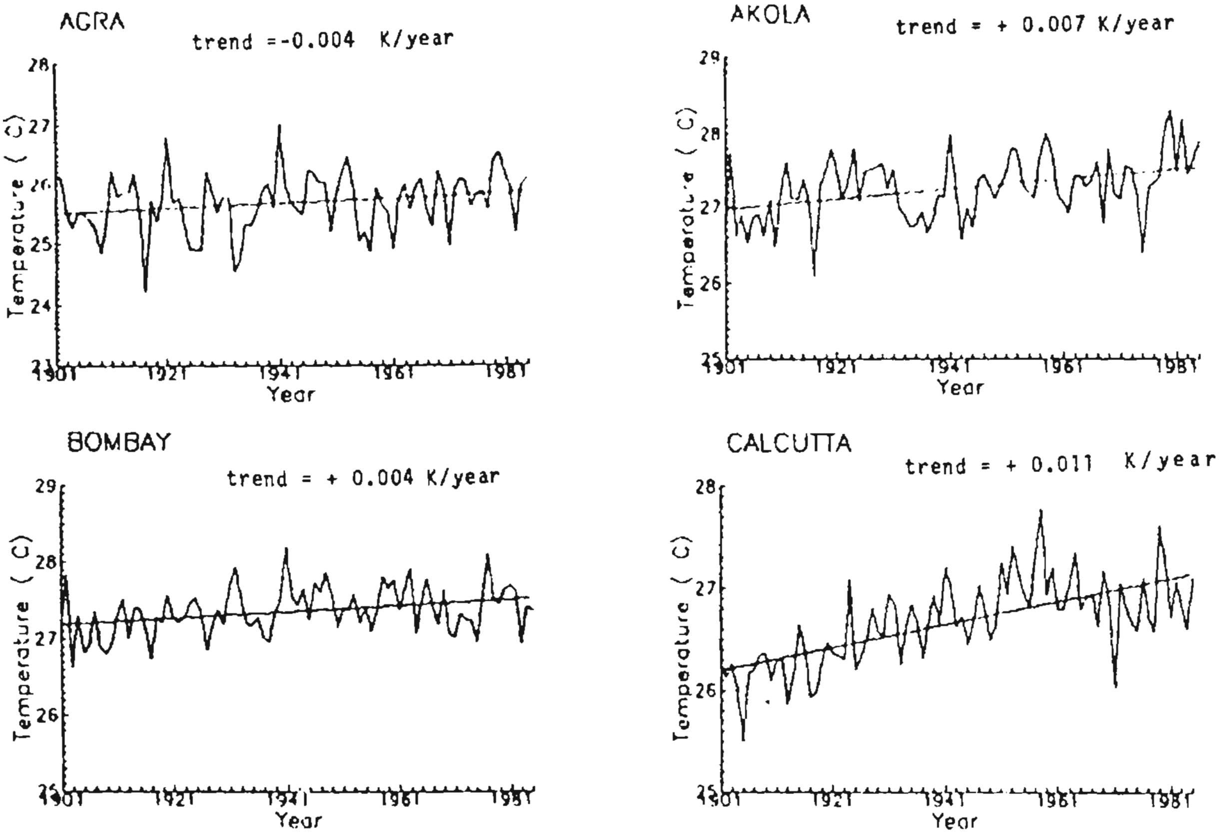


Fig. 4.5 (b) Trend in temperature for different stations

4.4.2.3 Trend in pressure

Systematic studies on long term pressure changes over India have not yet been attempted. Srinivasan et al. (1992) studied the mean station level pressure and found a decreasing trend of 0.7hpa/100 years. Our study also gives a general decreasing trend at the 95% significance level at all the stations considered in the study.

It appears that although the long period annual rainfall data exhibits year-to-year fluctuations it does not indicate any long-term climatic change or trend. However, temperature over our Indian region shows a small warming trend and sea level pressure a gradual decreasing trend.

4.5 SUMMARY

The interannual variability in meteorological parameters over the Indian Subcontinent is caused due to signals of known physical origin. Apart from the annual cycle and its sub-harmonics the major periodicitics detected are the 11-year solar cycle, the 5-year sub-harmonic, the quasi-biennial oscillation (QBO) quasi-triennial oscillation (QTO) and Chandler-Wobble Oscillation (CW). The period of QTO for surface meteorological parameters over Indian region is 33-40 months, while the QBO exhibits a periodicity of 28-29 months in rainfall and 24 months in temperature and sea-level pressure over India. The QTO, QBO and CW are well pronounced in coastal stations for rainfall and in interior stations for temperature. Rainfall over Indian stations does not show any significant trend, however temperature is increasing and pressure is decreasing as a whole of India.

Chapter 5

PRINCIPAL COMPONENT ANALYSIS OF THE SPATIAL AND TEMPORAL VARIABILITY OF SURFACE METEOROLOGICAL PARAMETERS

5.1 GENERAL

In a tropical country like India, the economy essentially depends on agriculture, which in turn depends mostly on the seasonal rains. The amount of rainfall however, undergoes variations from place to place and also from time to time. Variability can be defined as a tendency of a parameter to fluctuate around a long-term average value (Iyengar, 1991). It will be of great importance to know whether this variability exhibits any identifiable pattern or whether the variation is purely random. As the monsoon is known to be organised spatially on a large scale and is persistent in time for several months, it will be useful to study the rainfall variability on a few optimal scales. However, since the optimal time and space scales of rainfall is not yet defined, the existence of rainfall patterns are to be investigated in a empirical manner. Eventhough, the south-west monsoon (June-September) is the major rainfall season of India, the post-monsoon season or north-east monsoon (October 0 to December) is equally important for the southern peninsula. A study on the spatial and temporal patterns of the annual, monthly, south-west and post-monsoon rainfall is of importance. The existence of spatial and temporal patterns in surface air temperature and sea-level pressure is also investigated, since these parameters exhibit spatial and temporal variations over the country.

The present chapter is concerned with both spatial and temporal variation of the surface meteorological parameters by composing the large scale data into empirical orthogonal functions (EOF) in space and principal components (PC) in time. The main emphasis of the study is to explain the spatial structure of the meteorological elements considered and to bring out information about the seasonal, interseasonal and interannual variability.

5.2 METHOD OF ANALYSIS

5.2.1 Principal Component Analysis (PCA)

The primary objective of principal component analysis is to synthesise a large quantity of data into much smaller number of components that can still convey all the essential information contained in the original data (Rakecha and Mandal, 1981). The eigen vectors are linear combinations of the individual station data with weights chosen so that the sums are uncorrelated with each other. The eigen vectors replaces the large number of highly intercorrelated grid-point values by a much smaller number of mutually uncorrelated coefficients (Craddock and Flood, 1969). Principal components are linear combinations of random or statistical variables having special properties in terms of variance (Anderson, 1984). The number of eigen vectors are the same as the number of data points on the analysis grid, and the eigen vector matrix contains components in the order of decreasing amount of variance explained.

The relative magnitudes of the eigen values are used to rank-order the eigen vectors in terms of decreasing significance in representing the data. The most important eigen vectors are identified with physically important patterns in the original data set and the temporal expansions are given by the principal components. The eigen vectors can be derived from either a correlation matrix or a covariance matrix. Since a correlation matrix equally weighs all variables and a covariance matrix does not do so, a covariance matrix more accurately represents the actual deviations of the data.

In the present analysis, the equations given by Iyengar (1991) are used for the computation of the eigen vectors and principal components. The eigen vector is the characteristic vector of the covariance matrix and principal components are the characteristic roots. If R_{it} is the actual rainfall at station i (i = 1,2 .. M) in the year t (t=1,2 .. N) the mean value (m_i) is

$$m_i = (1/N) \sum_{i=1}^{N} R_{it} \qquad \ldots (5.1)$$

and the centered data (r_{it}) is given by the equation

$$r_{it} = (R_{it} - m_i) \qquad \ldots (5.2)$$

The covariance matrix (C_{ij}) is then

$$C_{ij} = (1/N) \sum_{t=1}^{N} r_{it}\, r_{tj} \qquad \ldots (5.3)$$

The eigen values $_j$ and eigen vectors Φ_{ij} of this symmetric matrix are extracted by the Jaccobi's iteration method.

The principal components are calculated from the equation,

$$p_{jt} = \sum_{i=1}^{M} r_{it}\, \Phi_{ij}; \; (j = 1, \ldots M) \qquad \ldots (5.4)$$

This procedure transforms the original time series r_{jt} into the new time series p_{jt}. The first few p_{jt}'s are generally sufficient to account for a large percentage of the spatial variation of the original data. The eigen vectors Φ_{ij} represents spatial patterns and p_{jt} contains useful information about the temporal variability.

From the orthogonal representation,

$$r_{it} = \sum_{j=1}^{M} p_{jt}\, \Phi_{ij} \qquad \ldots (5.5)$$

There are different rules that can test the significance of the principal components and eigen values. The eigen values should be tested to verify how significantly the data deviate from purely random noise. If the basic data are spatially uncorrelated with zero mean and unit variance, the eigen values will be equal to unity, and each value will represent 100/M percent of the total variance. To test the significance of the eigen values they are normalised by the equation

$$\lambda_j = M \lambda_j \Big/ \sum_{j=i}^{M} \lambda_j \qquad \ldots (5.6)$$

It is found that in our study the first four eigen vectors are important, with the first two eigen vectors accounting for most of the variance.

One of the limitations of conventional principal components (PC) is that spatial orthogonality of spatial patterns is assumed and there will be difficulty in interpreting the solution when the number of variables are large. Moreover, PC analysis detects only standing oscillations and not travelling waves, and therefore cannot be used to detect and test non-linear relationships. Another important requirement of the PC analysis is that the data must be of equal dimension. Because of this constraint we could use only 23 rainfall stations, 22 temperature stations and 7 sea-level pressure stations, having 85 years

(1901-1985) of continuous data. The details of the stations selected for the study are given in Tables. 5.1, 5.2 and 5.3, respectively for rainfall, temperature and sea-level pressure. The stations selected are also given in Figs. 5.1, 5.2 and 5.3. How far the principal component analysis can detect the spatial and temporal patterns of a large country like India is of argument, and better resolution of long-term data sets would yield better results.

5.2.2 The χ^2 test

The χ^2 test is one of the simplest and most widely used non-parametric test in statistical work. The quantity χ^2 describes the magnitude of the discrepancy between theory and observation. It is defined as,

$$\chi^2 = \sum \frac{(OBS - EXP)^2}{EXP} \qquad \ldots (5.7)$$

where 'OBS' refers to the observed frequencies and 'EXP' are the expected frequencies. The value of χ^2 can vary from zero to infinity. If χ^2 is zero it means that the observed and expected frequencies completely coincide. The greater the discrepancy between the observed and expected frequencies, the greater is the value of χ^2. The calculated value of χ^2 is compared with the table value of χ^2 at given degrees of freedom at a certain level

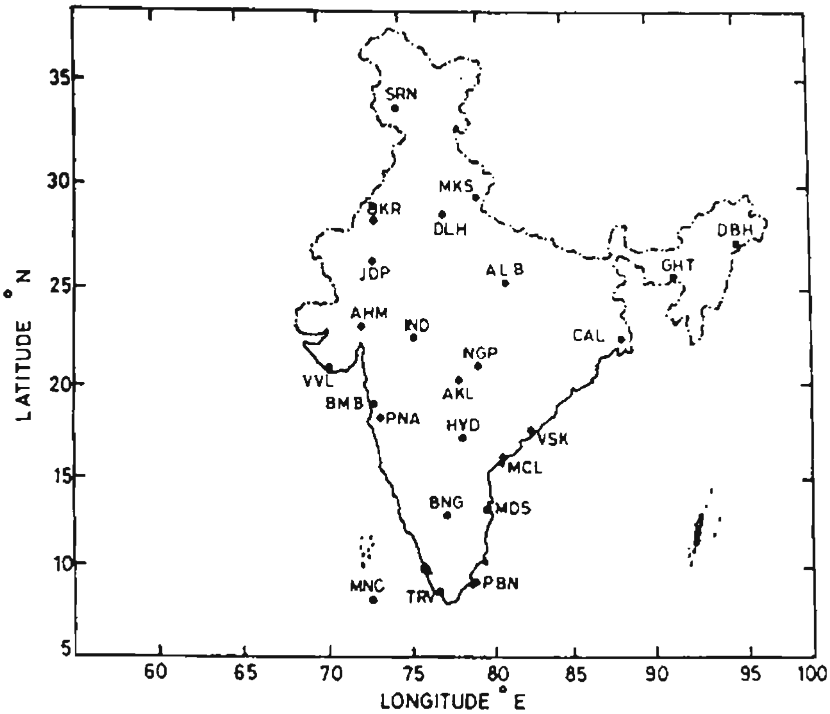


Fig. 5.1. Stations used for rainfall study

Table 5.1 Details of the stations chosen for rainfall study.

No.	Station Name		Latitude (°N)	Longitude (°E)	Altitude from msl (gpm)
1	SRINAGAR	(SRN)	34°51'	74°50'	1585
2	MUKTESHWAR	(MKS)	29°28'	79°39'	2310
3	BIKANER	(BKR)	28°00'	73°18'	223
4	NEW DELHI	(DLH)	28°35'	77°12'	211
5	DIBRUGARH	(DBG)	27°29'	95°01'	110
6	JODHPUR	(JDP)	26°18'	73°01'	217
7	GAUHATI	(GHT)	26°06'	91°35'	47
8	ALLAHABAD	(ALB)	25°37'	81°44'	97
9	AHMADABAD	(AHM)	23°04'	72°38'	55
10	CALCUTTA	(CAL)	22°32'	88°33'	5
11	NAGPUR	(NGP)	21°06'	79°03'	308
12	VERAVAL	(VVL)	20°54'	70°22'	6
13	AKOLA	(AKL)	20°42'	77°2'	280
14	BOMBAY	(BMB)	18°54'	72°49'	10
15	POONA	(PNA)	18°32'	73°51'	555
16	HYDERABAD	(HYD)	17°27'	78°28'	530
17	VISHAKHAPATNAM	(VSK)	17°43'	83°14'	3
18	MACHILIPATNAM	(MAC)	16°12'	81°09'	3
19	MADRAS	(MDS)	13°00'	80°11'	10
20	BANGALORE	(BNG)	12°58'	77°35'	920
21	PAMBAN	(PBN)	9°16'	79°18'	10
22	MINICOY	(MNC)	8°18'	73°09'	1
23	TRIVANDRUM	(TRV)	8°29'	76°57'	60

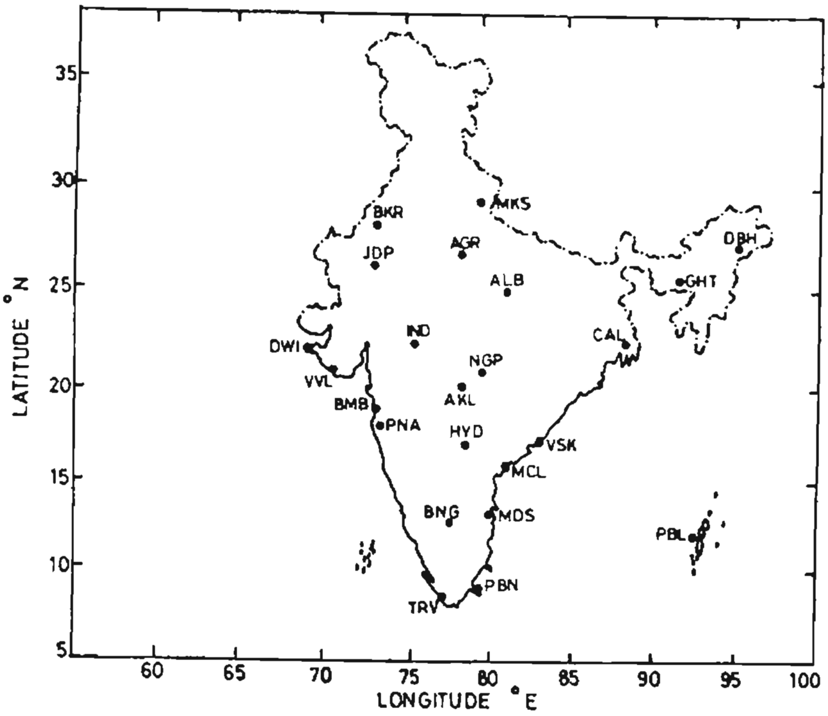


Fig. 5.2 . Stations used for temperature study.

Table 5.2 Details of the stations selected for temperature study.

No.	Station Name		Latitude (^{o}N)	Longitude (^{o}E)	Altitude from msl (gpm)
1	MUKTESHWAR	(MKS)	$29^{o}28'$	$79^{o}39'$	2310
2	BIKANER	(BKR)	$28^{o}00'$	$73^{o}18'$	223
3	AGRA	(AGR)	$27^{o}10'$	$78^{o}02'$	168
4	DIBRUGARH	(DBG)	$27^{o}29'$	$95^{o}01'$	110
5	JODHPUR	(JDP)	$26^{o}18'$	$73^{o}01'$	217
6	GAUHATI	(GHT)	$26^{o}06'$	$91^{o}35'$	47
7	ALLAHABAD	(ALB)	$25^{o}37'$	$81^{o}44'$	97
8	DWARKA	(DWR)	$22^{o}22'$	$69^{o}05'$	10
9	INDORE	(IND)	$22^{o}43'$	$75^{o}48'$	561
10	CALCUTTA	(CAL)	$22^{o}32'$	$88^{o}33'$	5
11	NAGPUR	(NGP)	$21^{o}06'$	$79^{o}03'$	308
12	VERAVAL	(VVL)	$20^{o}54'$	$70^{o}22'$	6
13	AKOLA	(AKL)	$20^{o}42'$	$77^{o}2'$	280
14	BOMBAY	(BMB)	$18^{o}54'$	$72^{o}49'$	10
15	POONA	(PNA)	$18^{o}32'$	$73^{o}51'$	555
16	HYDERABAD	(HYD)	$17^{o}27'$	$78^{o}28'$	530
17	VISHAKHAPATNAM	(VSK)	$17^{o}43'$	$83^{o}14'$	3
18	MADRAS	(MDS)	$13^{o}00'$	$80^{o}11'$	10
19	BANGALORE	(BNG)	$12^{o}58'$	$77^{o}35'$	920
20	PORT BLAIR	(PBL)	$11^{o}40'$	$92^{o}43'$	73
21	PAMBAN	(PBN)	$9^{o}16'$	$79^{o}18'$	10
22	TRIVANDRUM	(TRV)	$8^{o}29'$	$76^{o}57'$	60

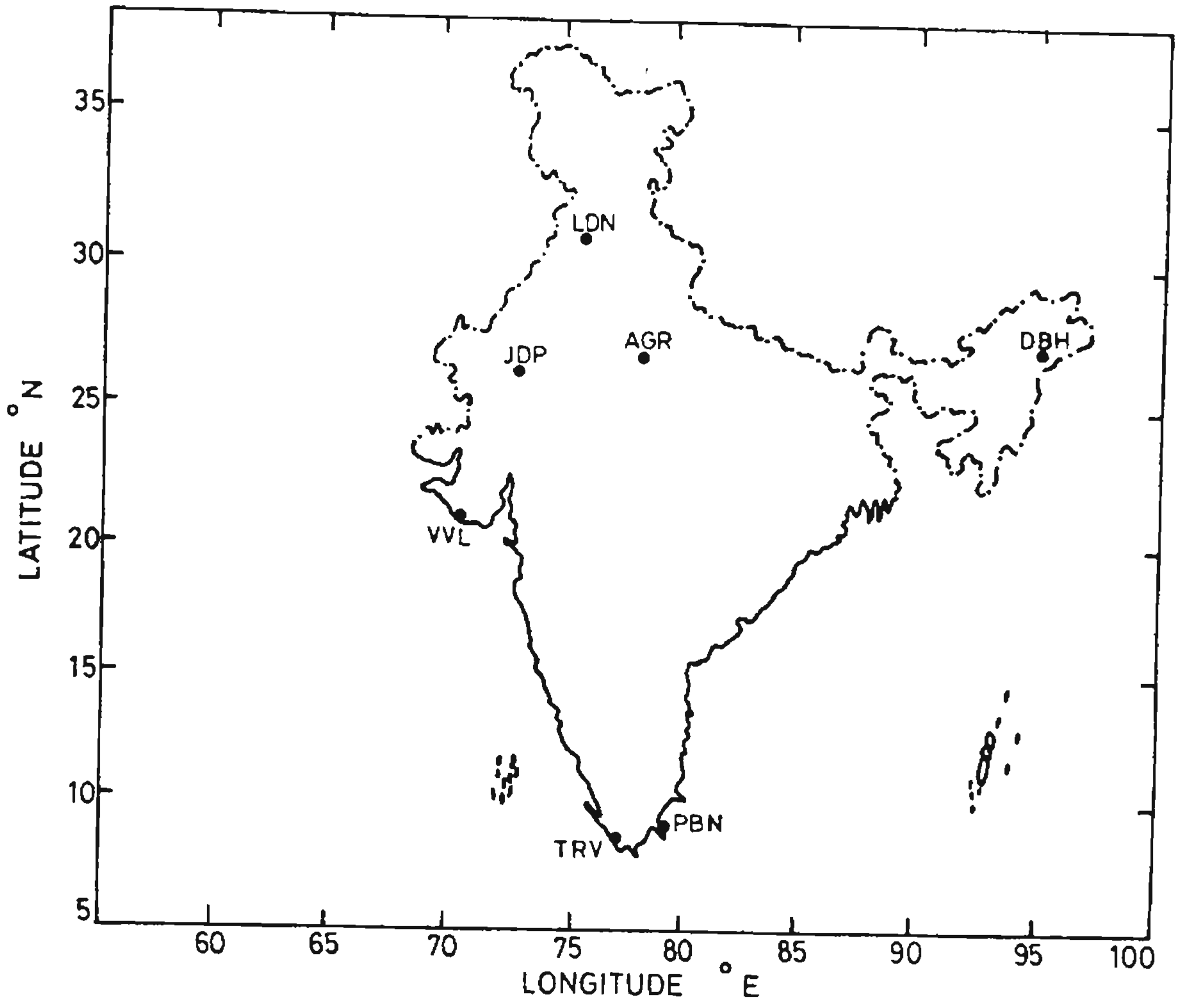


Fig. 5.3. Station used for pressure study.

Table 5.3 **Details of the stations considered for the pressure analysis.**

No.	Station Name		Latitude (°N)	Longitude (°E)	Altitude from msl (gpm)
1	LUDHIANA	(LDN)	30°52'	75°56'	255
2	AGRA	(AGR)	27°10'	78°02'	168
3	JODHPUR	(JDP)	26°18'	73°01'	217
4	NAGPUR	(NGP)	21°06'	79°03'	308
5	VERAVAL	(VVL)	20°54'	70°22'	6
6	PAMBAN	(PBN)	9°16'	79°18'	10
7	TRIVANDRUM	(TRV)	8°29'	76°57'	60

of significance. If at the stated level the calculated value of χ^2 is more than the table value of χ^2 the difference between theory and observation is considered to be significant (Gupta, 1981).

5.3 RESULTS AND DISCUSSION

5.3.1 Annual Rainfall

The spatial patterns in annual rainfall distribution are determined from eigen vectors and the temporal variation from the amplitudes of the principal components. The first four eigen vectors account for 70% of the total variance in the rainfall distribution. However, the first two eigen vectors themselves account for 58% of this variance.

The similarity between the western and central parts of India appears to be the most dominant feature of the annual precipitation regime. The rest of the country does not show any significant spatial relationship. This accounts for 50% of the total variance (Fig. 5.4(a)). During active monsoon epochs, which is the major contributor of the annual rainfall, disturbances form in the mid-tropospheric east-west shear zone over western India. These disturbances coupled with the depressions forming over the north Bay of Bengal result in well distributed rainfall over central and western India (Goswami et al. 1981).

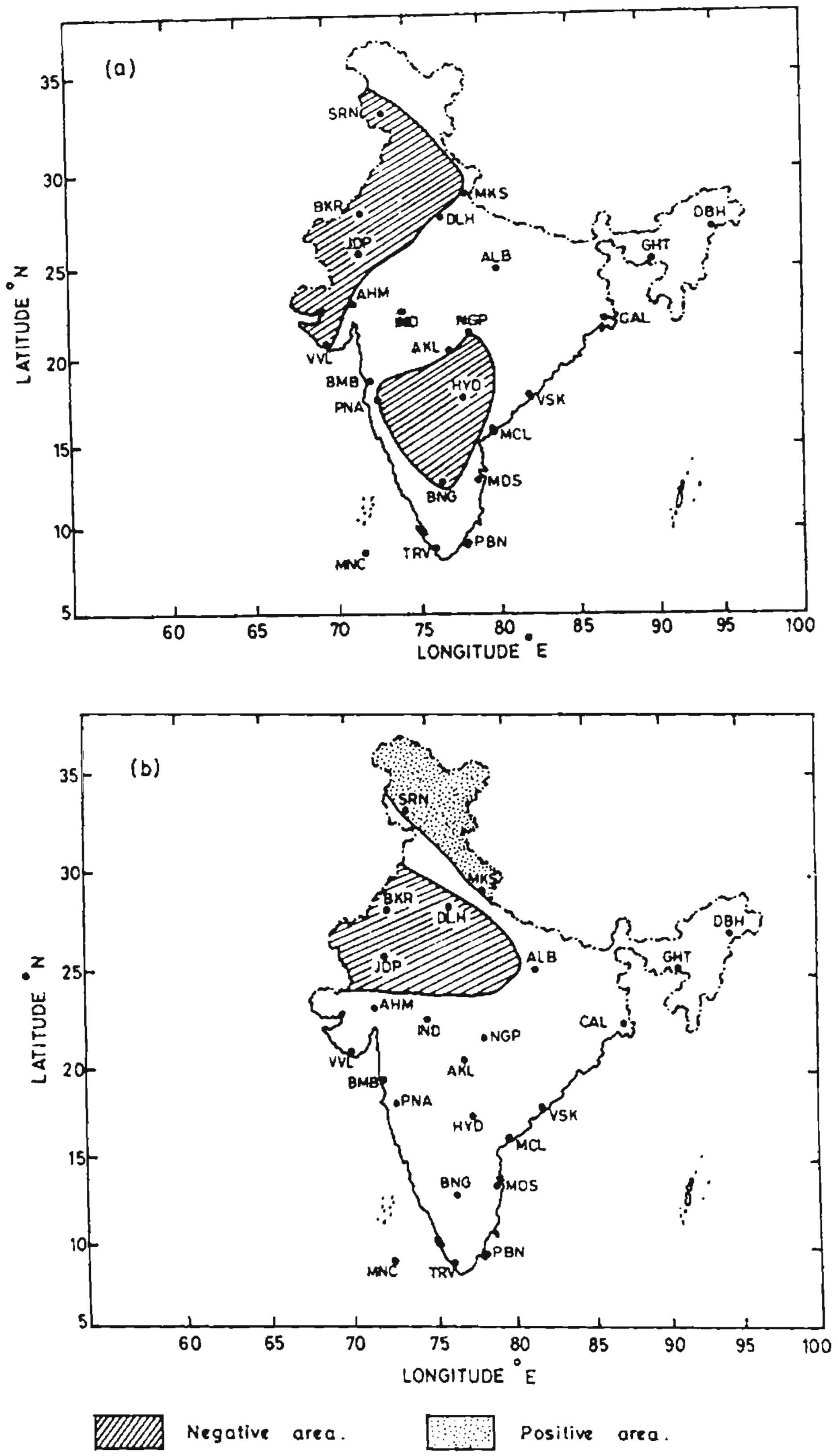


Fig. 5.4 (a). Distribution of first eigen vector of annual rainfall
(b). Distribution of second eigen vector of annual rainfall

The second eigen vector which contributes 8% of the variance in rainfall is shown in Fig. 5.4(b). It is seen that the region covering the western Himalayas shows an opposite behaviour with the plains of northwest India and no prominent relationship could be noticed with the rest of the country. This is again a well recognised feature of the monsoon rainfall. The northward shift of the western end of the monsoon trough occurs in association with the movement of a 'Western Disturbance' across the Western Himalayas. This is often associated with excessive rainfall over Western Himalayas and deficient rainfall over the plains of north-west India (Desai, 1990).

The amplitudes of the first and second principal components are shown in Figs. 5.5(a) and 5.5(b), respectively. The positive and negative amplitudes of the first component are almost evenly distributed with more rapid oscillations after 1950. However, no significant trend could be detected (Fig. 5.5(a)). Compared to the first component, the amplitudes of the second component is relatively smaller in magnitude, but is evenly distributed on the positive and negative side, without any systematic trend (Fig. 5.5(b)).

Unrotated principal component analysis often directs vectors between clusters of interrelated data points, thereby failing to capture the exact mode of variability. Applying a rotation to the principal components, tends to represent clusters of interrelated data points more accurately (Alexander et al. 1993). Varimax rotation is used to rotate the principal components of annual rainfall. After rotation there are only a few peaks left in the series, and it is interesting to note that all these peaks are associated with El-Nino years. However, all the El-Nino years are not detected in the series as peaks (Fig. 5.6. Eventhough, influence of El-Nino on Indian rainfall has been reported by many workers (Ramusson and Carpentor, 1983; Chowdhury, 1991; Gadgil and Asha, 1992; Sikka and Gadgil 1980), more work is needed in this direction to quantify the influence of this oscillation on Indian rainfall.

5.3.2 Monthly Rainfall Pattern

An examination of the eigen vectors of the monthly rainfall gives a picture of how rainfall gets organised in a particular month. Since the first two eigen vectors account for most of the variance, these two eigen vectors are plotted and the isolines drawn. Figs. 5.7(a) to 5.7(b) give the first eigen vectors for the winter period (January-February). It is seen from the Figs. 5.7(a) and 5.7(b) that the entire country remains spatially correlated during this season. The Himalayan belt and the northern parts of India receive some rain due to 'Western Disturbances' and the peninsula gets a few isolated rain falls from eastward moving perturbations. Troughs and vortices off the Kerala coast cause some rain in south Kerala and Tamil Nadu during this season. However, taking the country as a whole, this season is the driest period of the country.

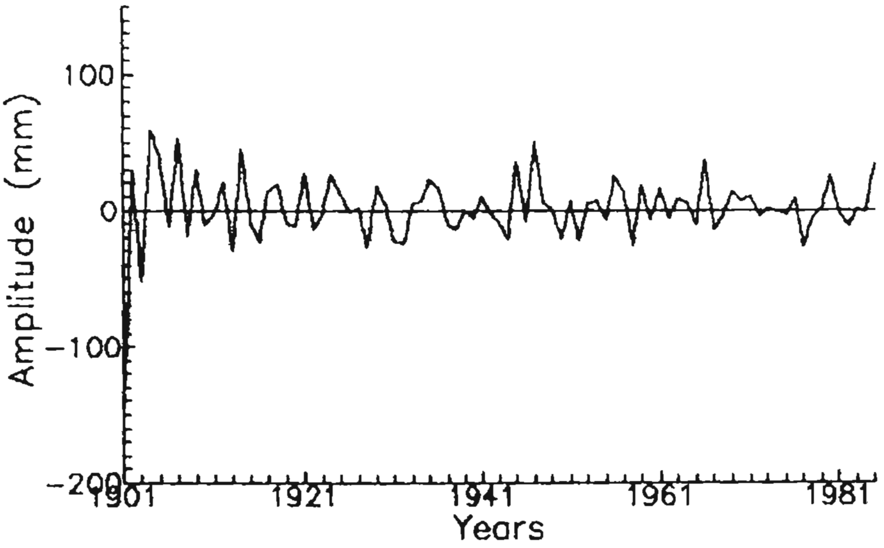


Fig. 5.5 (a) Amplitudes of Ist principal component of annual rainfall

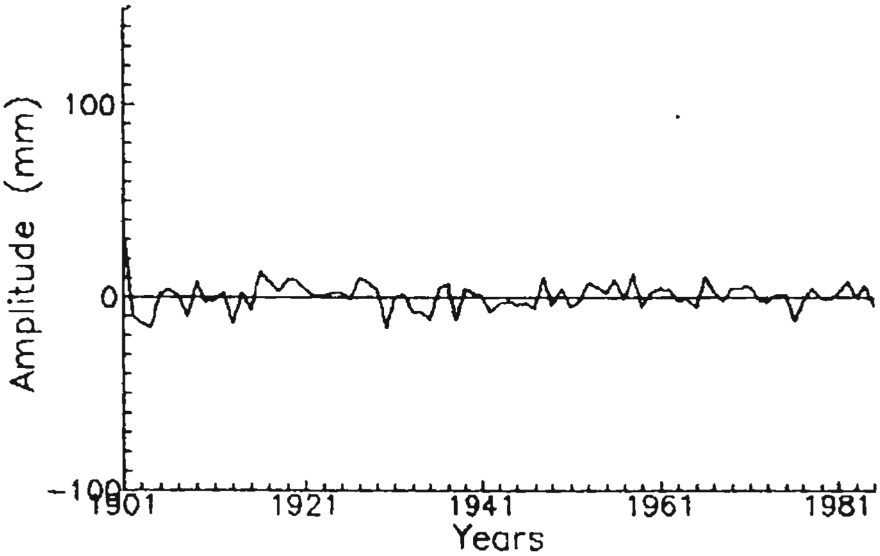


Fig. 5.5 (b) Amplitudes of IInd principal component of annual rainfall

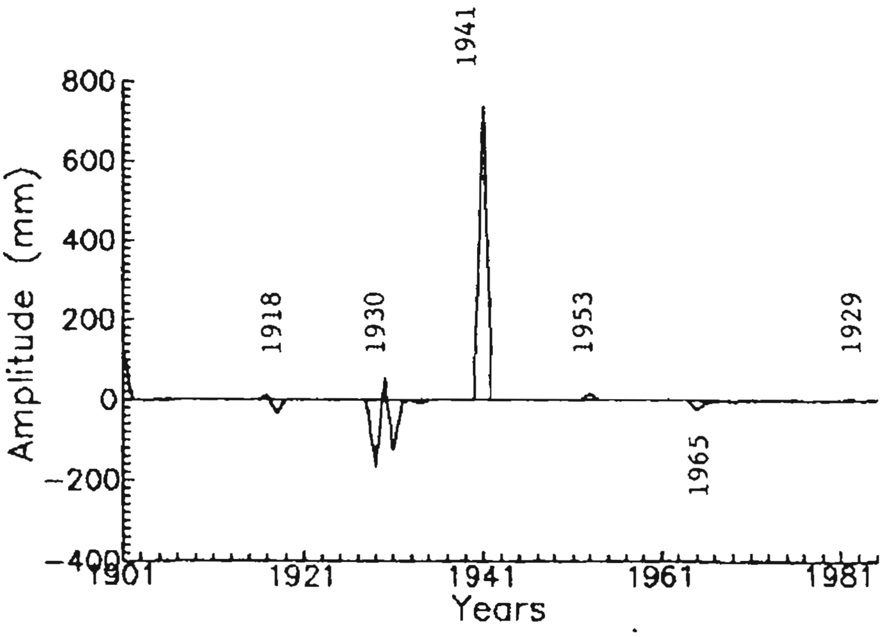
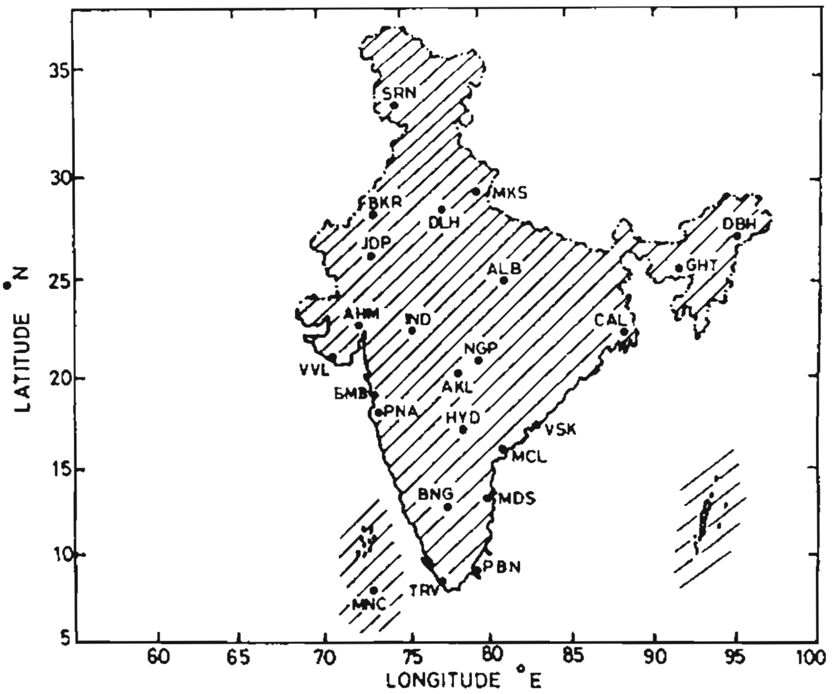
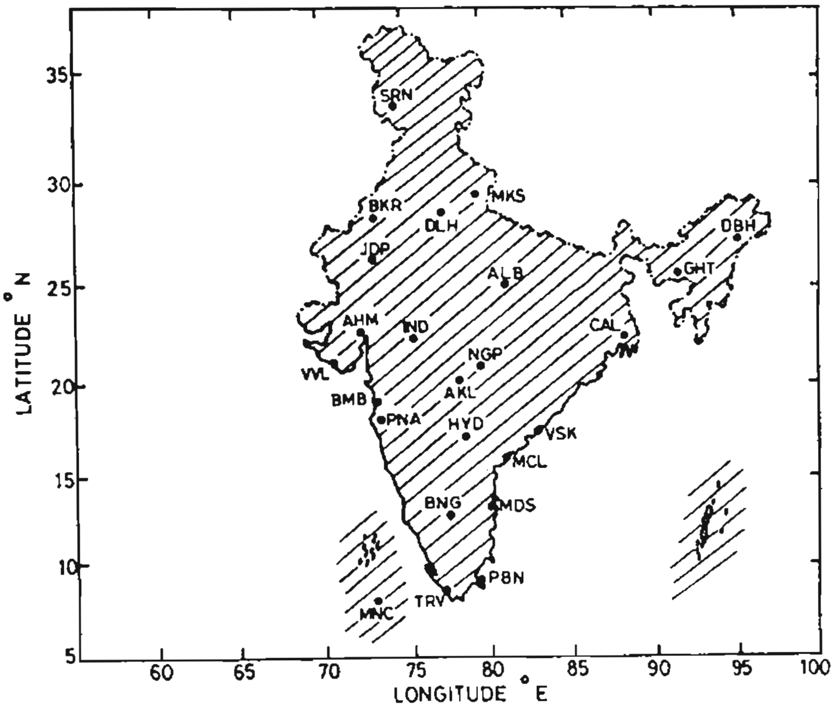


Fig. 5.6 First principal component after rotation



▨ Negative area.

Fig. 5.7a. Distribution of Ist eigen vector for January rainfall.



▨ Negative area.

Fig. 5.7b. Distribution of Ist eigen vector for February rainfall.

The hot season period covering March, April and May is a transitional period when the winter monsoon pressure and wind systems gradually gets disrupted prior to the setting in of the summer monsoon features. Figs. 5.8(a), 5.8(b) and 5.8(c) give the distribution of the first eigen vectors for these three months, respectively. During March, there is a spatial contrast between the extreme south of the country and rest of India. Above/below normal rainfall in the south is associated with below/above normal rainfall in the rest of the subcontinent. In April, however, rainfall can be grouped into three regions, the extreme northeast, the western coastal region and the rest of the country. Above normal rainfall in the extreme northeast and western peninsula is associated with below normal rainfall elsewhere. In May, positive relationships are restored for the entire country with only northeastern part having the opposite sign.

The first eigen vectors for the south-west monsoon period (June-September) are illustrated in Figs. 5.9(a) - 5.9(d). During June (Fig. 5.9(a)) when south-west monsoon sets in, there is a spatial contrast between the southern tip and rest of India. The possible reason for this contrast could be fluctuations in the onset of the seasonal rains. Normal or delayed monsoon over Kerala is associated with weakening of upper tropospheric westerlies over north India at the time of onset and early monsoon is often associated with persistence of upper tropospheric westerlies (Anathakrishnan et al., 1968). Fig. 5.9(b) gives the eigen vector for the month of July. In July, the pattern changes and there is a positive relationship between northeast and the southern peninsula and negative relationship with the rest of the country. When a monsoon depression forms over the head Bay and is still in the sea, the monsoon activity in terms of rainfall is weak on the southern tip of the subcontinent and northeastern part and high over Konkan coast (Asnani, 1993). Positive spatial relationship is observed during August (Fig. 5.9(c)) between northeast India and foot hills of the Himalayas. It is observed that when the monsoon trough bends northwards with height in the lower troposphere, rainfall decreases along the westcoast, central India, Gujarat, Rajasthan and Uttar Pradesh and increases over the foot hills of Himalayas and northeast (Asnani, 1993). During September, retreating month of the south-west monsoon the spatial contrast in rainfall distribution decreases only in the extreme northeastern part of India having a negative relationship with the rest of the country (Fig. 5.9(d)), the pattern similar to that in May.

The first eigen vector for the month of October which accounts for 22% of the total variance is shown in Fig. 5.10(a). This figure indicates a spatial similarity between the extreme southern tip and the western Himalayan regions. Sharma and Subramaniam (1983) have shown a linkage between the passage of a 'Western Disturbance' and lows in the lower tropospheric

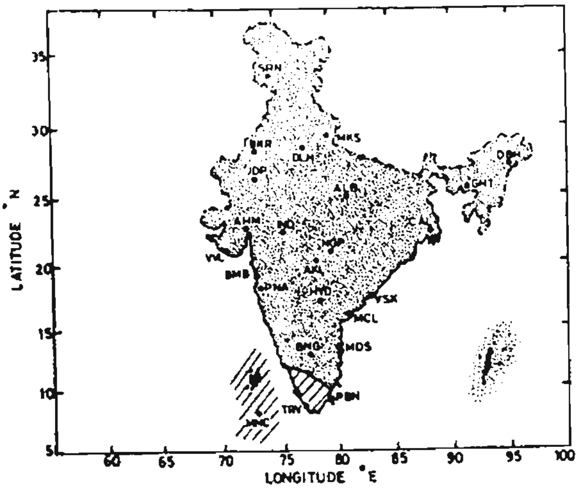


Fig. 5.8 a.Distribution of 1st eigen vector for March rainfall.

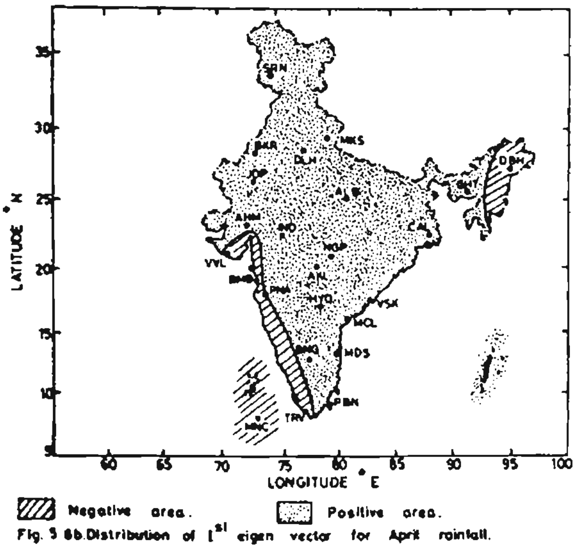


Fig. 5 8b.Distribution of 1st eigen vector for April rainfall.

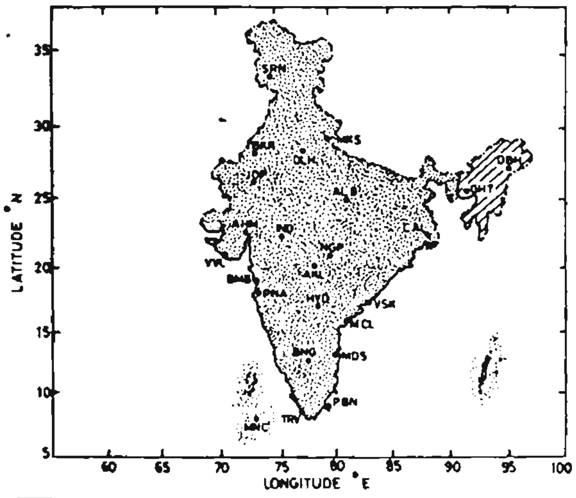


Fig.5.8c. Distribution of 1st eigen vector for May rainfall.

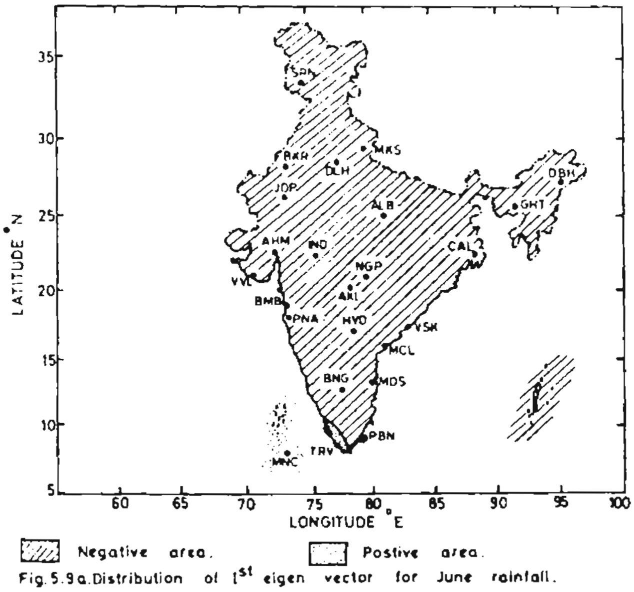


Fig. 5.9a. Distribution of 1st eigen vector for June rainfall.

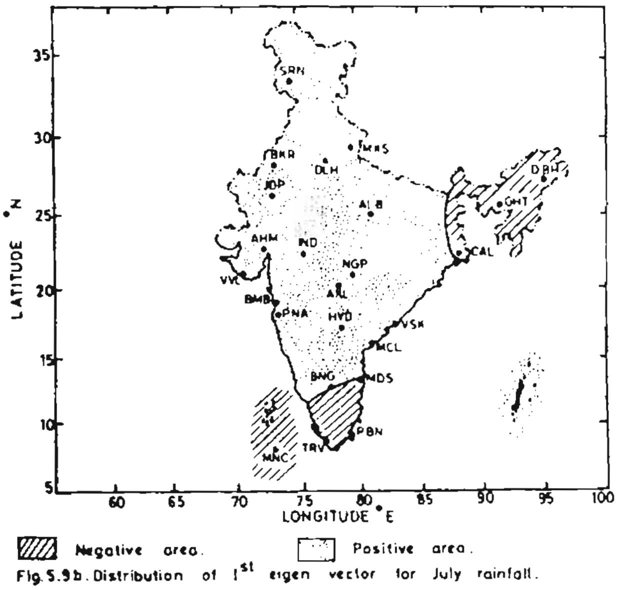


Fig. 5.9b. Distribution of 1st eigen vector for July rainfall.

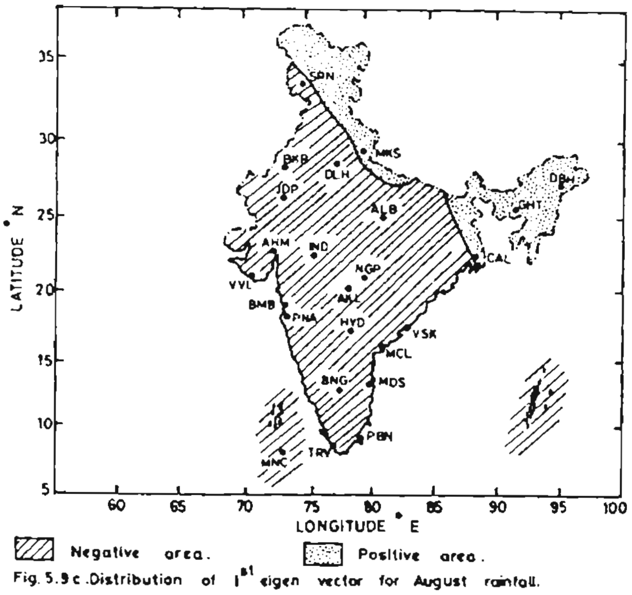


Fig. 5.9c. Distribution of 1st eigen vector for August rainfall.

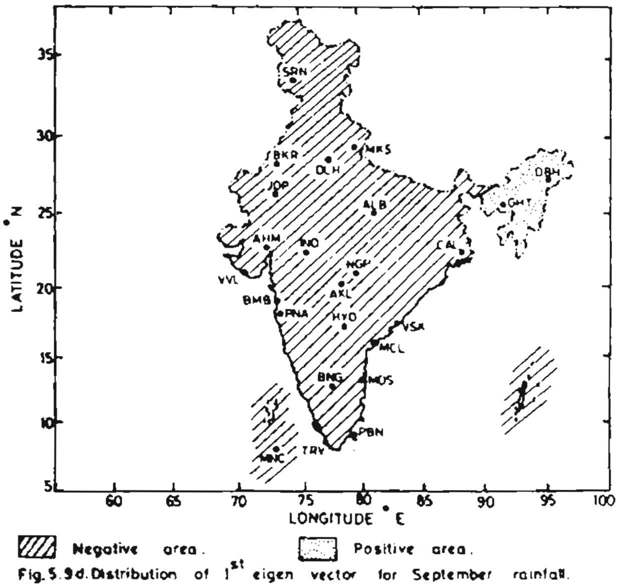


Fig. 5.9d. Distribution of 1st eigen vector for September rainfall.

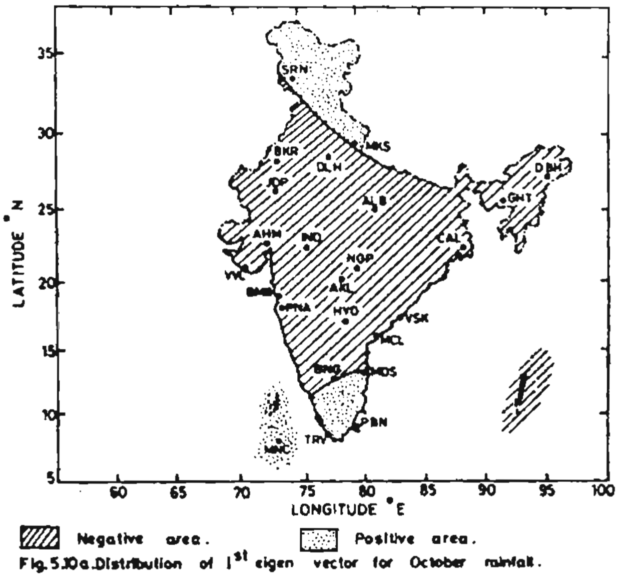


Fig. 5.10a. Distribution of 1st eigen vector for October rainfall.

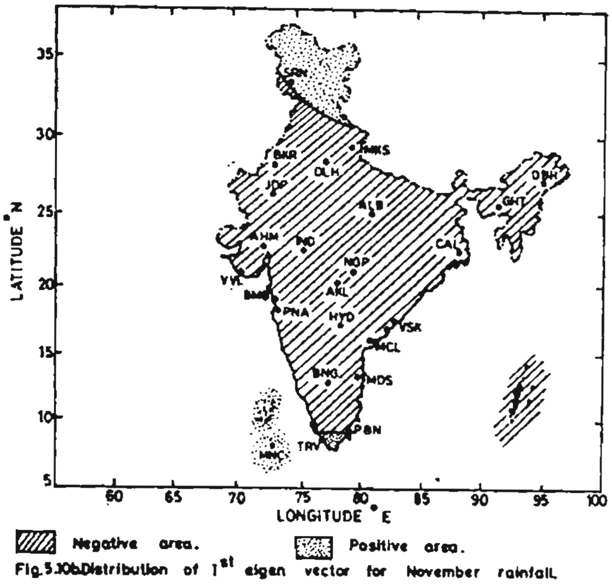


Fig. 5.10b. Distribution of 1st eigen vector for November rainfall.

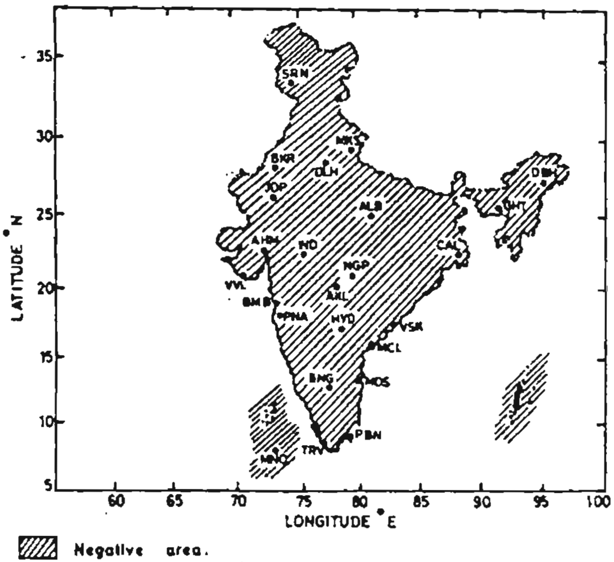


Fig. 5.10c. Distribution of 1st eigen vector for December rainfall.

easterlies in the Arabian sea off the west coast. This linkage is responsible for the intensification of a 'Western Disturbance' and the associated precipitation in northern India and extension of precipitation to the far south. In November, the spatial contrast decreases (see Fig. 5.10(b)) and by December the country is spatially correlated as far as rainfall is concerned (Fig. 5.10(c)). The second eigen vectors of the monthly rainfall which accounts for 10% of the total variance is associated with local features and is not related to large-scale atmospheric circulation.

The total rainfall for the south-west monsoon season (June-September) and north-east monsoon (October-November) are considered separately and analysed in a similar manner. The first eigen vector of the south-west monsoon rainfall is shown in Fig. 5.11(a) and this vector accounts for 20% of the total variance in monsoon rainfall. The first eigen vector is associated with large scale monsoon circulation and the country remains spatially correlated. The second eigen vector which contributes 8% of the variance indicates that above/below normal rainfall in the western India and eastern coastal zone is associated with below/above normal rainfall elsewhere (Fig. 5.11(b)). The spatial contrast between stations that receive rainfall during the post-monsoon season and stations that does not recive rainfall are shown by the first eigen vector of the north-east monsoon (Fig. 5.12(a)). This vector accounts for 16% of the total variance in rainfall during this season. The second eigen vector

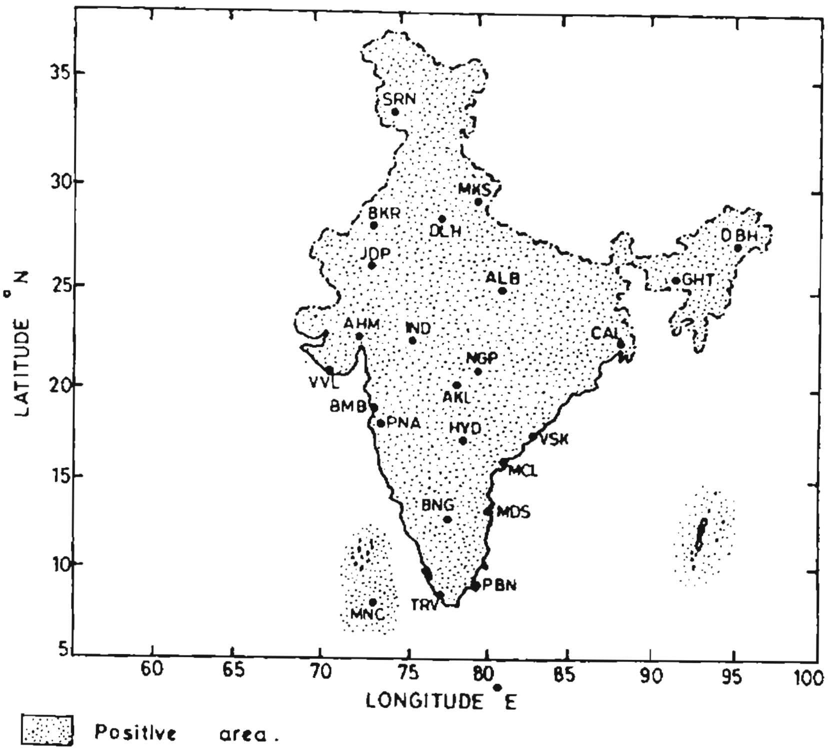


Fig.5.11a.Distribution of Ist eigen vector for south-west monsoon rainfall.

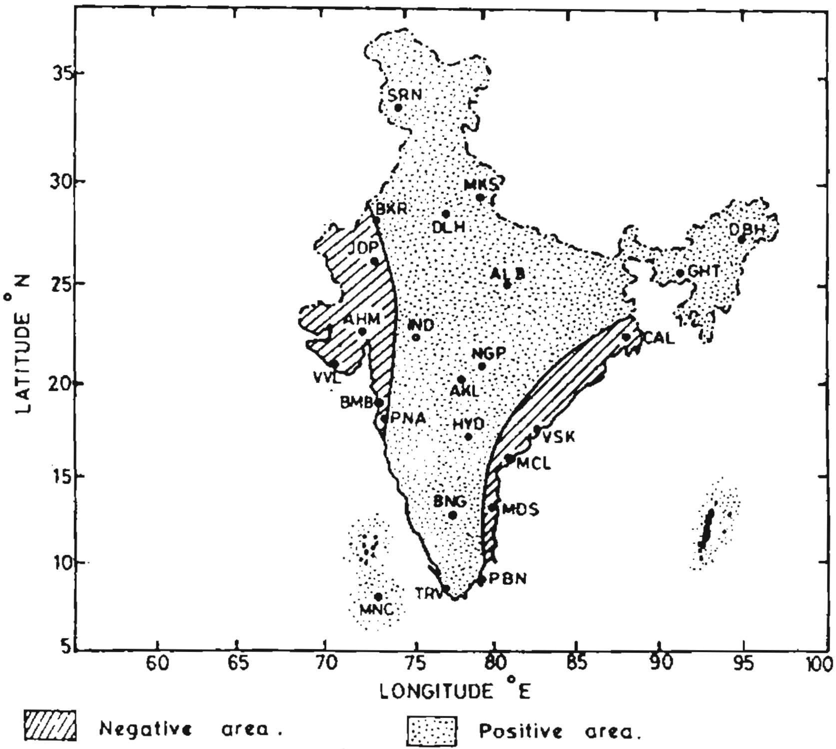


Fig.5.11b.Distribution of IInd eigen vector for south-west monsoon rainfall.

of this season (Fig. 5.12(b)) also establishes the contrast between stations receiving rainfall during October-December, but the pattern is slightly extended to the north and central parts of the country. The influence of tropical cyclones on the rainfall pattern of this region could be the possible reason for this behaviour of rainfall during the post-monsoon period.

5.3.3 Monthly Transitions

The principal components are area-rainfall time series and there is a possibility of a correlation existing in area rainfall time series. If monthly associations are present in the basic data they will be reflected in the way the principal components evolve from month to month. The principal components will be zero, if at a particular month the rainfall is normal at all the sampling stations. However, the intraseasonal variability of rainfall can be brought out by the examination of the sign of the principal components. Since June-September is the primary rainfall season of the entire country as a whole it will be of interest to examine the presence of dependence of monthly rainfall during this season. The persistence or change in the sign is collected in a 2x2 contingency table, and the association between sign changes are tested. The null hypothesis adopted is that there is no dependence in the month to month sign changes. The calculated χ^2 value is tested against the tabulated value of χ^2 of 3.84 at one degree of freedom at the 95% significance level.

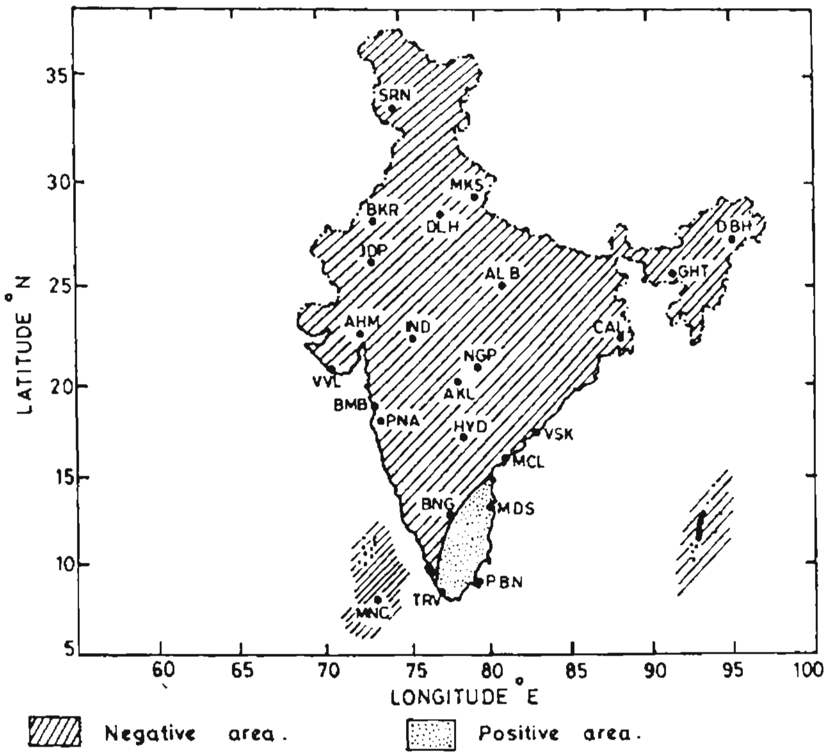


Fig. 5.12a. Distribution of first eigen vector for north-east monsoon rainfall

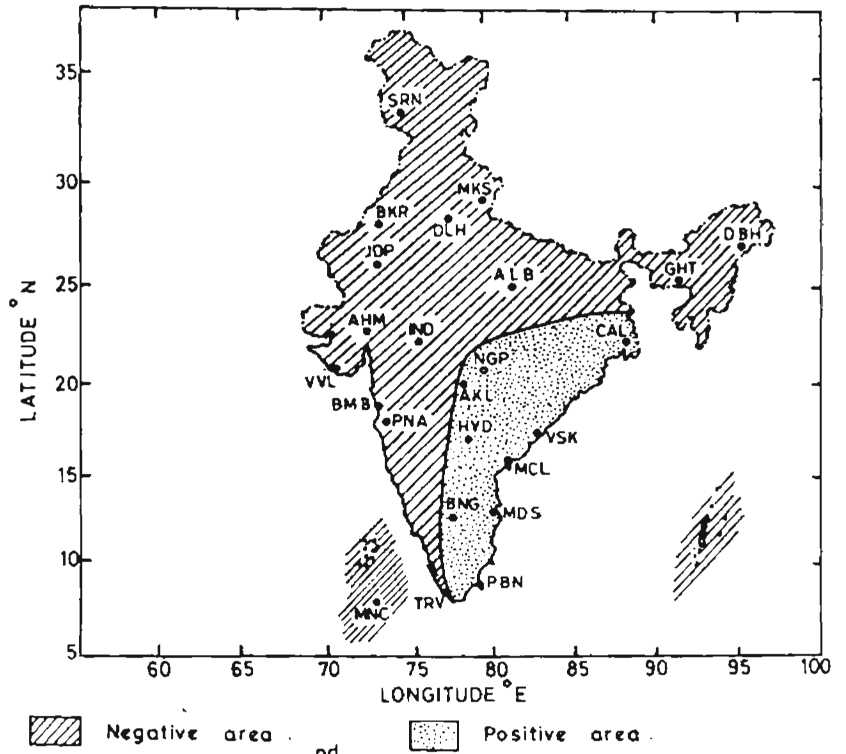


Fig. 5.12b. Distribution of IInd eigen vector for north-east monsoon rainfall

Table 5.4(a) gives the sign sequences in the Ist PC for monthly rainfall. It is seen from the table that the transition between June-July, August to September and September to October exhibit a definite pattern, whereas the transition from July to August and May to June rainfall is purely due to chance. The persistence in sign change for the IInd PC is also examined (Table 5.4(b)) and it is observed that there is a definite pattern in the transition of rainfall from September to October. In other words, the rainfall of September which is last month of south-west monsoon season is an indicator of how rainfall will be organised in the first month of the north-east monsoon season. However, the rainfall in May, the preceding month of the south-west monsoon season is not an indicator of how rainfall will be organised during June-September. Earlier Iyengar (1991) had shown similar results for Karnataka rainfall.

5.3.4 Interannual variability:

The interannual variation of summer monsoon rainfall has a profound influence on socio-economic activities in India. The interannual variability of the monsoon is related to interaction between the land, ocean and the atmosphere. An attempt is made to study the interannual variability of monthly rainfall of June to September and the total rainfall during south-west monsoon and north-east monsoon seasons as a whole.

Table 5.4(a) Frequency of sign sequences in the I PC of monthly rainfa
(N = 85 years)

MONTH	OBS (+)	EXP (+)	OBS (+)	EXP (-)	OBS (-)	EXP (+)	OBS (-)	EXP (-)	χ^2
May - Jun	21	22.76	24	22.24	22	20.24	18	19.76	0.59
Jun - Jul	15	19.78	28	23.27	24	19.27	18	22.27	4.24
Jul - Aug	22	18.81	17	20.18	19	22.19	27	23.81	1.93
Aug - Sep	25	18.88	16	22.19	14	20.19	30	23.81	7.64
Sep - Oct	23	15.6	16	23.40	11	18.40	35	27.6	10.80

Table 5.4(b) Frequency of sign sequences in the II PC of monthly rainfa
(N = 85 years)

MONTH	OBS (+)	EXP (+)	OBS (+)	EXP (-)	OBS (-)	EXP (+)	OBS (-)	EXP (-)	χ^2
May - Jun	19	18.82	21	21.76	21	21.76	24	23.82	0.006
Jun - Jul	20	18.82	20	21.18	20	21.18	25	21.18	4.271
Jul - Aug	17	18.35	22	20.65	23	21.65	23	24.35	1.347
Aug - Sep	21	17.88	19	22.12	17	20.12	28	24.88	1.86
Sep - Oct	27	20.12	11	17.88	18	24.88	29	22.12	9.04

The dependence of the PC signs for June-September (Table 5.5(a)) show that the interannual variability in monthly rainfall is due to chance and there is no definite pattern. The variability in south-west monsoon rainfall and north-east rainfall also shows there is no definite pattern in the sign change (Tables 5.5(b) and 5.5(c)). How far the PC analysis is capable of analysing the temporal pattern of a large country like India is questionable. Better network of continuous rainfall stations will give better results. Iyengar (1991) had indicated that the second principal component of south-west monsoon rainfall for Karnataka state exhibits interannual variability.

5.3.5 ANNUAL TEMPERATURE

The surface air temperature undergoes spatial variation over India country, but the temporal variation in temperature is not very significant. The spatial patterns are resolved by an analysis of the eigen vectors and the temporal variability from the principal components. The first eigen vector which accounts for 34% of the total variance in annual temperature, is plotted in Fig. 5.13(a). It is seen that the whole of the country is spatially correlated, with only sign change in Port Blair which is an island station. The second eigen vector which account for 10-15% of the variance is illustrated in Fig. 5.13(b). The second eigen vector indicates a interior-coastal spatial contrast and the northeastern part of the country. The interannual variability in annual temperature pattern is checked by the examination of PC

Table 5.5(a) Frequency of annual sign sequences for monthly rainfall

COMP	OBS (+)	EXP (+)	OBS (+)	EXP (-)	OBS (-)	EXP (+)	OBS (-)	EXP (-)	χ^2
June									
PC I	21	21.50	21	20.50	22	21.50	20	20.50	0.048
PC II	18	18.57	22	21.46	21	20.45	23	23.57	0.062
July									
PC I	17	18.11	22	20.89	22	20.89	23	24.11	0.232
PC II	18	17.64	20	20.36	21	21.36	25	24.64	0.025
August									
PC I	22	20.01	19	20.99	19	20.99	24	20.01	0.77
PC II	19	18.57	21	21.43	20	20.43	24	23.57	0.04
September									
PC I	19	18.11	20	20.99	20	20.89	25	24.11	0.15
PC II	14	16.29	23	20.70	23	20.70	24	26.29	1.04

Table 5.5(b) Frequency of annual sign sequences for south-west monsoon season

COMP	OBS (+)	EXP (+)	OBS (+)	EXP (-)	OBS (-)	EXP (+)	OBS (-)	EXP (-)	χ^2
PC I	17	16.29	20	20.70	20	20.70	27	26.29	0.097
PC II	16	18.57	23	20.43	24	21.43	21	23.57	1.26
PC III	26	24.64	20	21.34	19	20.34	19	24.11	0.36
PC IV	21	22.52	22	20.48	23	21.48	18	20.01	0.44

Table 5.5(c) Frequency of annual sign sequences for north-east monsoon season

COMP	OBS (+)	EXP (+)	OBS (+)	EXP (-)	OBS (-)	EXP (+)	OBS (-)	EXP (-)	χ^2
PC I	12	13.36	21	19.64	22	20.64	29	30.34	0.381
PC II	16	18.11	23	20.89	23	20.89	22	24.11	0.854
PC III	26	24.64	20	21.34	19	20.34	19	17.64	0.404
PC IV	23	25.74	23	20.26	24	21.26	14	16.70	1.232

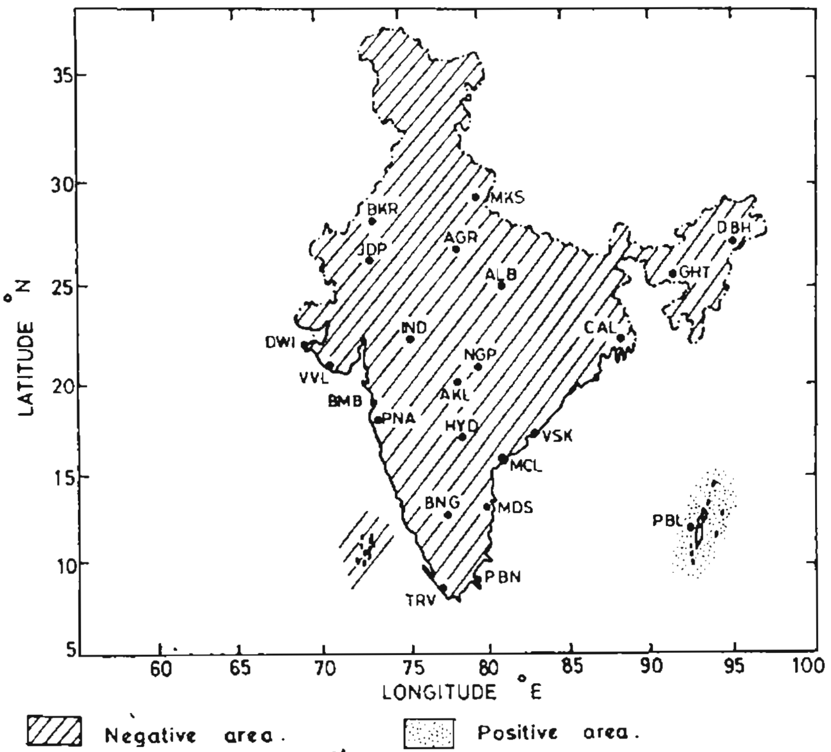


Fig. 5.13 a. Distribation of Ist eigen vector of annual temperature.

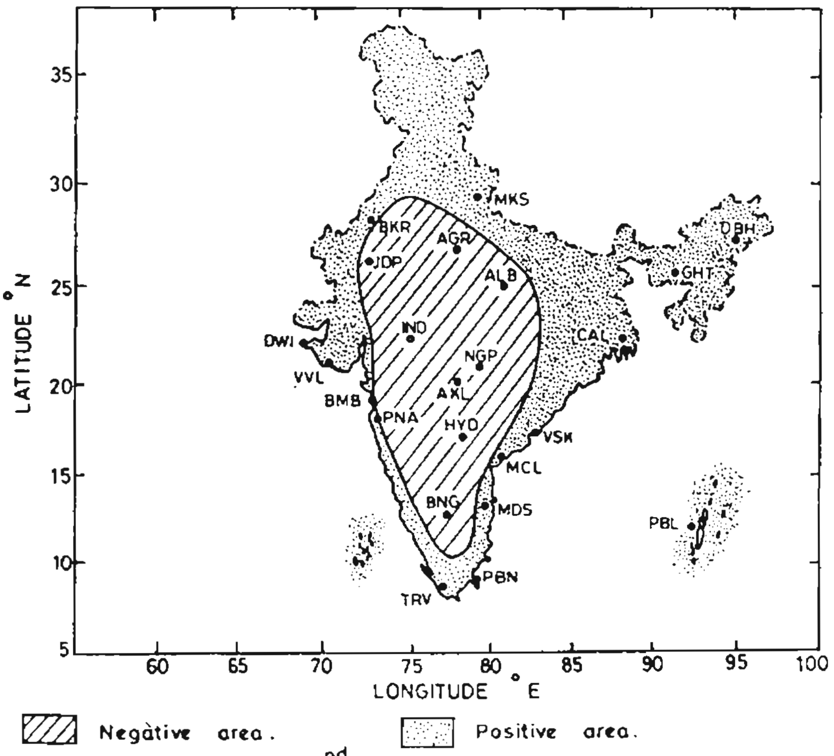


Fig. 5.13b. Distribution of IInd eigen vector of annual temperature.

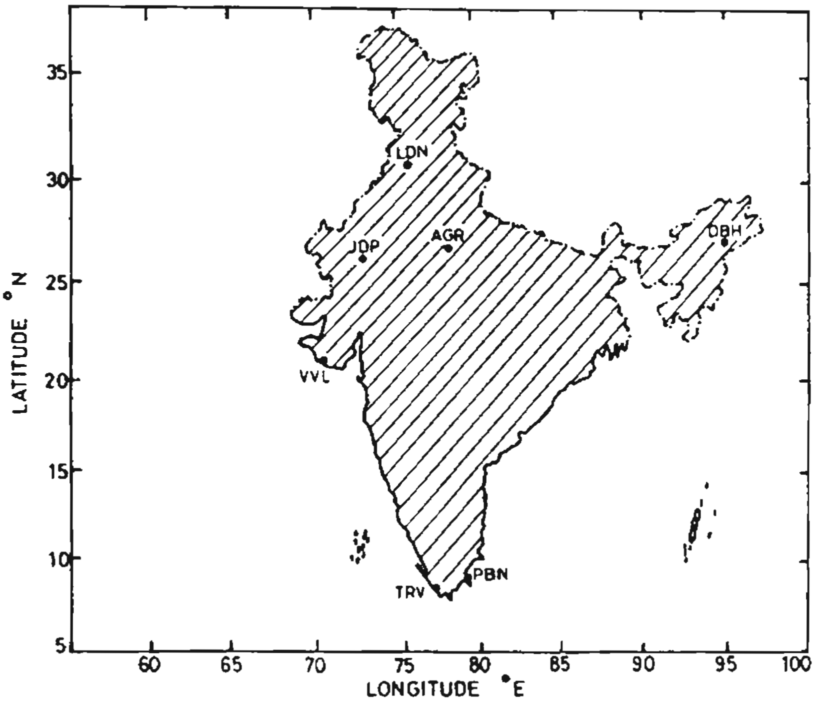
igns. It is seen that the second principal component is ignificant at the 95% level. This indicates that the emperature contrast between the coastal and interior stations xhibits interannual variations. The dependence of the PC signs or temperature is indicated in Table 5.6.

Table 5.6 Frequency of annual sign sequences for temperature

COMP	OBS (+)	EXP (+)	OBS (+)	EXP (-)	OBS (-)	EXP (+)	OBS (-)	EXP (-)	χ^2
PC I	11	10.01	18	18.98	18	18.98	37	36.01	0.224
PC II	30	36.01	25	18.99	25	18.99	4	34.07	8.42
PC III	8	11.07	22	18.92	23	19.93	31	10.02	2.09
PC IV	29	25.19	17	20.81	17	20.81	21	17.19	2.81

5.3.6 SEA-LEVEL PRESSURE

Non-availability of sea-level pressure data for 85 years in well distributed stations over India restricted the study on the sea-level pressure patterns. Only 7 Indian stations with sea-level pressure data for 85 years (1901-1985) are used in the study. It is interesting to note that 93% of the total variance in sea level pressure distribution is accounted by the first eigen vector (Fig. 5.14). The eigen vector distribution does not



▨ Negative area.

Fig. 5.14. Distribution of 1st eigen vector of sea level pressure.

show any spatial contrast in pressure distribution. The dependence of the PC signs indicate that there is a definite pattern in the spatial distribution. The statistical significance of this pattern is questionable due to the poor network of stations.

5.4 SUMMARY

Principal component analysis produces a decomposition of the data field into spatial eigen vectors and temporal principal components. The rainfall and temperature data for the country spread over 22 stations for a period 85 years show that PCA is a valuable aid in gaining insight into the spatial and temporal behaviour of meteorological parameters. The similarity between western and central parts of the country as far as annual rainfall distribution is concerned is brought out by the study. Rotation of principal components reveal the influence of El-Nino oscillation on rainfall pattern. Monthly transitions of rainfall shows that the September rainfall is an indicator for the rainfall during the first month of the northeast monsoon. While interannual variability in monthly rainfall is not clearly captured by the study the second principal component of annual temperature indicates a definite pattern. However, further detailed analysis in the use of PC analysis is required to quantify the spatial and temporal patterns.

Chapter 6

PREDICTABILITY OF SURFACE METEOROLOGICAL PARAMETERS OVER INDIAN SUBCONTINENT

6.1 GENERAL

Earlier studies clearly indicate that there are fluctuations in the climate system on all time scales, with large amplitudes on the very long time scales and small amplitudes on shorter time scales. Climate variability can be defined as the deviation of a parameter about its long-term average value. This deviation need not be a random change, and one expects a definite pattern in this variability. The ultimate aim of any climatic study is to predict these variations. There are several models that are used to predict the climate system like the general circulation models, statistical-dynamical models, energy balance models, stochastic models and statistical models. The statistical modelling is the most simplest approach in modelling purposes, which are used to show relations between certain aspects of the climate without knowledge of the physical mechanisms involved (Opstecgh, 1981).

The present chapter is concerned with the prediction of meteorological parameters over the Indian subcontinent using the methods of harmonic analysis, fast fourier transform and the principal component analysis (PCA).

6.2 METHOD OF ANALYSIS

6.2.1 Harmonic Analysis:

The technique of harmonic analysis used in Chapter 3 is utilised to predict the seasonal variation of meteorological parameters over the Indian subcontinent. Since the first three harmonics account for 90% of the variance in the seasonal variation, the first, second and the third harmonics are used to reconstruct the original time series. The equation used by Kirkyla and Hameed (1989) is used for the computation.

$$X_t = \langle X \rangle + \sum_{i=1}^{N/2} A_i \mathrm{Cos}\ (360it/p) + \Phi_i] \qquad \ldots(6.1)$$

where $\langle X \rangle$ is the arithmetic mean of the element X, A_i and Φ_i are the amplitudes and phase angles of the first three harmonics, N is the number of observations and X_t is the value of element at time t. The basic period is 12 months.

6.2.2 Combination of Tones:

The study on the interannual variability carried on the surface parameters show that the major periodicities apart from the annual term and its subharmonics are the 11-year cycle, the

5-year periodicity, the 36-month oscillation, the 28-month and 14.43-month oscillations. These sub-annual periods at 11- years, 5-years, 36-months, 28-months and 14.43-months are considered as "parent" oscillations and the "combination of tones" with the seasonal cycle are predicted from the equation

$$1/T_1 + 1/T_2 = 1/T_3 \qquad \ldots\ldots(6.2)$$

$$1/T_1 - 1/T_2 = 1/T_4 \qquad \ldots\ldots(6.3)$$

where T_1 is the "parent oscillation" and T_2 is the seasonal cycle with periods of 12, 6, 4, 3, 2.4 and 2 months. T_3 is called a "summation tone and T_4 is the "difference tone" of these oscillations. This is suggested since "combination of tones" are generated in non-linear systems (Currie and Hameed, 1990).

6.2.3 Principal component regression:

Multiple regression model based on the principal components (PC) is performed to predict rainfall at a particular station. We assume that rainfall at the station i is correlated with other stations at the 90% significance level. The principal component analysis on these independent variables $W_1, W_2, \ldots\ldots W_q$ is performed and the eigen values and eigen vectors extracted. To reduce the dimensionality of the principal components, the variables are standardised by substracting the mean and dividing by the standard deviation. The jth principal score for the uth sample observation, Y_{ju} will be

$$Y_{ju} = a_{ji} W_1 + a_{j2} W_2 + \dots + a_{jq} W_q \qquad \dots(6.4)$$

The number of PC scores are selected in such a manner that the total variance accounted by these scores are about 80% of the total variance. The final rainfall Y_i at station i is predicted from the equation.

$$Y_i = \text{Constant} + a\ PC\ (1) + b\ PC\ (2) + c\ PC\ (3) + \dots n\ PC(n) \qquad \dots(6.5)$$

where PC (1), PC (2) ..... PC (n) are the PC scores that account for 80% of the variance and a, b, c,...,n are the coefficients obtained from the regression model. The standard error of estimate is calculated from the equation.

$$S.E.E. = S_y\ (1 - r^2)^{\circ} \qquad \dots(6.6)$$

where S_y, is the standard deviation. The standard error of estimate (S.E.E.) gives the prediction error and r^2 is the percentage variance of the predicted variables that is explained by the combined predictor variables (Best and Kahn, 1992).

6.3 RESULTS AND DISCUSSION

The results of the prediction of seasonal variation by the harmonic analysis suggest that, this technique is not statistically significant to reconstruct the original time series. The results of a sample station Bombay (Fig. 6.1) is presented here. Although, the predicted temperature for Bombay, indicates two peaks in temperature, the two maxima are in April and September rather than in May and October. The rainfall pattern in Bombay indicates a clear maximum in the month of July, whereas the predicted values show two peaks one in April and the other in September. Even though predicted pressure values of this station show a discrepancy with the observed values, it is interesting to note that the minimum pressure value almost coincides with that of the observed value and is also in the same month. Harmonic analysis resolves the time series into waves, and this could be the reason for the discrepancy in the predicted and observed values. It can be noted that the harmonic analysis is not a suitable method to reconstruct the original time series, but it could be adopted to understand the seasonal variation of the parameter considered.

Table 6.1(a) gives the observed and predicted periods in months in rainfall for northern stations. In Jodhpur and Allahabad all the 27 of the predicted tones are observed in the rainfall series at 95% significance level. However, in other

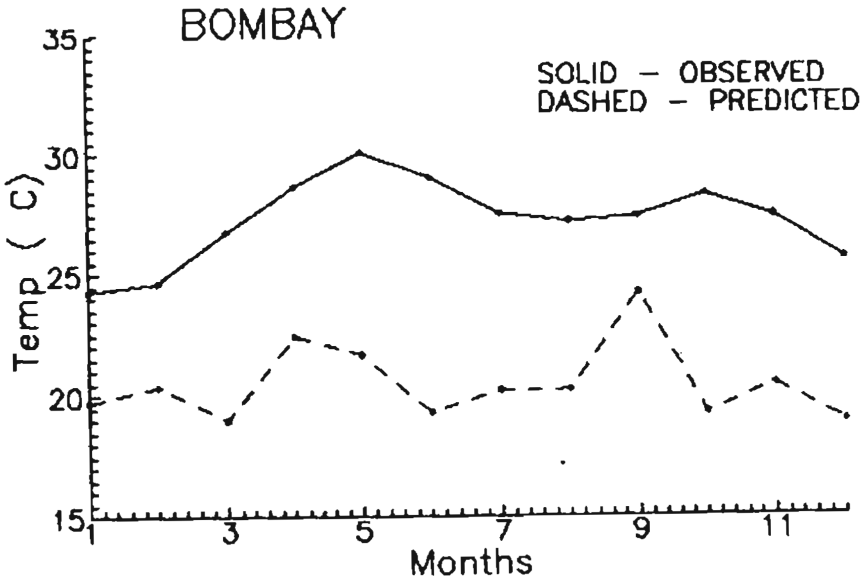


Fig. 6.1 Prediction of seasonal variation in Temperature by harmonic analyis

Table 6.1(a) Observed and predicted periods in rainfall series (months)

TONES	ALLABAHAD		MUKTESHWAR		NEW-DELHI		SRINAGAR		BIKANER		JODHPUR	
	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED
1	11.01	11.13	11.01	11.13	11.14	11.13	10.24	10.78	11.01	11.13	11.01	11.13
2	13.12	13.12	13.12	13.12	12.97	13.12	-	13.66	13.12	13.12	13.12	13.12
3	10.24	10.14	10.24	10.14	10.24	10.14	-	9.87	10.24	10.34	10.34	10.14
4	16.00	14.84	-	14.84	16.00	14.84	16.53	15.52	-	-	16.00	14.84
5	9.56	8.98	8.91	9.14	8.91	8.82	-	9.07	8.90	9.07	9.22	8.82
6	17.95	18.27	17.36	17.67	-	18.97	17.95	-	17.95	17.95	17.95	18.97
7	8.19	8.46	8.19	8.53	8.46	8.53	-	8.46	8.19	8.26	9.47	8.53
8	25.00	20.92	23.80	20.49	21.79	20.49	-	20.92	-	22.26	20.49	20.49
9	6.52	6.57	6.57	6.52	6.52	6.52	-	6.57	6.83	6.57	6.44	6.49
10	5.75	5.75	5.75	5.75	5.75	5.75	-	5.65	5.72	5.75	5.75	5.75
11	6.28	6.24	6.24	6.24	6.28	6.24	-	6.34	6.24	6.24	6.24	6.28
12	5.50	5.48	5.48	5.48	5.53	5.48	-	5.38	5.51	5.53	5.28	5.48
13	5.09	5.12	5.15	5.17	5.09	5.07	4.92	5.15	5.12	5.15	5.12	5.07
14	7.16	7.21	-	7.11	7.16	7.32	-	7.16	-	7.16	6.83	7.16
15	4.92	4.95	-	4.97	4.92	4.97	4.92	4.95	4.61	4.88	4.95	4.97
16	7.58	7.59	-	7.53	7.53	7.53	8.00	7.59	7.59	7.75	8.19	7.53
17	4.23	4.23	4.21	4.21	4.06	4.21	-	4.23	4.34	4.23	4.32	4.25
18	3.89	3.89	3.89	3.89	3.89	3.91	-	3.84	3.89	3.79	3.89	3.89
19	3.58	3.59	3.78	3.62	3.78	3.77	-	3.72	3.67	3.61	3.57	3.57
20	4.59	4.51	4.59	4.47	4.47	4.28	-	4.49	4.34	4.49	4.45	4.55
21	3.17	3.13	3.13	3.12	3.13	3.18	3.21	3.13	3.18	3.13	3.07	3.14
22	2.93	2.94	2.92	2.94	2.92	2.94	-	2.91	2.91	2.94	2.92	2.94
23	2.88	2.86	2.86	2.86	2.75	2.86	-	2.84	-	2.88	2.85	2.86
24	3.25	3.28	3.25	3.26	3.29	3.30	3.21	3.26	-	3.26	3.40	3.29
25	2.46	2.48	2.44	2.47	2.50	2.49	-	2.48	2.46	2.48	2.44	2.48
26	2.29	2.26	2.25	2.25	2.30	2.26	-	2.25	2.27	2.25	2.27	2.28
27	2.69	2.60	2.60	2.56	2.70	2.61	2.68	2.57	2.69	2.57	2.69	2.60

stations like Muktheshwar, Srinagar, New Delhi and Bikaner while all the 27 tones are absent, however, certain "combination of tones" are well established. In the eastern part and the central region of the country the "combination of tones" are not well dominated (see Table 6.1(b) and 6.1(c)). On the other hand, all the stations in the western side are influenced by the "summation" and "difference" tones. The predicted and observed periods for Bombay, Ahmedabad, Veraval and Pune are shown in Table 6.1(d). In Madras, the "combination of tones" due to the 11-year cycle is not observed. However, in Pamban, a station which is more pronounced by the 5-year cycle the "combination of of tones" due to the 11-year cycle is observed and could be possibly due to the strong seasonal variation (Table 6.1(e)). The "summation" tones of the 11-year cycle and the CW oscillation with the 12-month annual term, estimated a periodicity with a period of 11.13 and 6.6 months and a "difference" tone of these oscillations with the semi-annual term having a periodicity of 13.12 month and nearly 10-months are quite significant to that of the observed periodicities in almost all the stations for rainfall.

The observed and predicted periods in temperature series for the northern stations of Allahabad, Agra, Bikaner, Jodhpur and Muktheshwar are illustrated in Table 6.2(a). Although, all the predicted tones are not detected in the series, the "summation tone" of the 11-year oscillation with the annual cycle and the difference tone" of this oscillation with the semi-annual

Table 6.1(b) Observed and predicted periods in rainfall (months)

TONES	CALCUTTA		GAUHATI		DIBRUGARH	
	OBS	PRED	OBS	PRED	OBS	PRED
1	11.13	11.13	11.13	11.13	11.01	11.13
2	13.12	13.12	13.12	13.12	12.97	13.12
3	10.34	10.14	10.34	10.14	10.23	10.14
4	16.26	14.84	15.29	14.84	16.00	14.84
5	8.9	8.98	9.57	9.14	8.99	8.98
6	-	18.27	-	17.67	-	18.27
7	8.19	8.53	8.19	8.53	8.40	8.46
8	20.49	20.49	-	20.49	20.49	20.92
9	6.52	6.6	6.48	6.57	6.61	6.57
10	5.75	5.75	5.75	5.75	5.75	5.75
11	6.21	6.24	6.28	6.24	6.28	6.24
12	5.75	5.48	5.45	5.48	5.33	5.48
13	5.15	5.12	5.15	5.17	-	5.12
14	7.11	7.21	-	7.11	7.16	7.21
15	4.92	4.97	4.95	4.97	4.92	4.95
16	7.59	7.53	-	7.53	8.19	7.59
17	4.10	4.25	4.10	4.23	4.15	4.23
18	3.90	3.89	3.89	3.89	3.89	3.89
19	-	3.59	3.58	3.62	3.62	3.59
20	4.61	4.51	4.47	4.47	4.59	4.51
21	3.11	3.14	3.18	3.13	3.21	3.13
22	2.93	2.94	2.91	2.94	2.93	2.94
23	-	2.86	2.86	2.86	-	2.86
24	3.18	3.28	3.25	3.26	3.40	3.28
25	-	2.49	2.46	2.48	2.49	2.48
26	-	2.26	2.25	2.25	2.25	2.23
27	2.69	2.60	2.62	2.56	-	2.55

Table 6.1(c) Observed and predicted periods in rainfall (months)

TONES	MAGPUR		AKOLA		HYDERABAD		MACHILPATNAM		VISHAKPATNAM	
	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED
1	11.01	11.13	11.01	11.13	11.13	11.13	11.14	11.13	11.13	11.13
2	13.12	13.12	13.12	13.12	12.97	13.12	13.12	13.12	13.12	13.12
3	10.34	10.14	10.24	10.14	10.34	10.14	10.14	10.14	10.24	10.14
4	16.00	14.84	16.00	14.84	16.00	14.84	16.53	14.84	16.00	14.84
5	8.99	9.14	8.99	8.98	8.99	9.07	8.19	8.75	-	8.75
6	17.36	17.67	17.67	18.27	17.67	17.95	19.31	19.34	-	19.34
7	8.13	8.53	8.46	8.53	8.46	8.53	-	8.46	-	8.46
8	20.49	20.49	-	20.49	20.49	20.49	-	20.92	-	20.92
9	6.61	6.6	6.52	6.57	6.48	6.57	6.44	6.52	-	6.57
10	-	-	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75
11	6.28	6.24	6.28	6.24	6.21	6.24	6.24	6.24	-	6.24
12	5.48	5.48	5.48	5.48	5.72	5.48	5.33	5.48	-	5.48
13	5.12	5.17	-	5.12	5.15	5.15	-	5.04	-	5.12
14	7.16	7.11	-	7.21	7.11	7.16	-	7.37	-	7.21
15	4.92	4.97	-	4.97	4.92	4.97	-	4.95	-	4.95
16	7.53	7.53	8.13	7.53	7.53	7.53	7.53	7.59	-	7.59
17	4.14	4.25	4.10	4.23	4.21	4.23	-	4.23	-	4.23
18	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89
19	3.77	3.62	3.43	3.59	-	3.61	-	3.55	-	3.59
20	-	4.47	-	4.51	-	4.49	4.61	4.57	-	4.51
21	-	3.14	3.13	3.13	3.18	3.13	-	3.13	-	3.13
22	2.92	2.92	2.92	2.94	-	2.94	2.93	2.94	2.86	2.94
23	2.86	2.84	2.86	2.86	2.86	2.86	2.86	2.86	-	2.86
24	-	3.23	3.25	3.28	3.25	3.26	3.33	3.31	-	3.28
25	2.44	2.47	2.46	2.48	2.51	2.48	2.44	2.48	-	2.48
26	2.69	2.76	2.30	2.24	-	2.24	-	2.23	-	2.26
27	2.35	2.26	2.57	2.56	-	2.55	2.60	2.59	-	2.60

Table 6.1(d) Observed and predicted periods in rainfall (months)

TONES	BOMBAY		AHMEDABAD		VERAVAL		PUNE	
	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED
1	11.13	11.13	11.13	11.13	11.14	11.13	11.13	11.13
2	13.12	13.12	13.12	13.12	13.12	13.12	13.12	13.12
3	10.34	10.34	10.34	10.14	10.34	10.14	10.34	10.14
4	16.00	14.84	16.00	14.84	16.00	14.84	16.00	14.84
5	9.57	8.98	8.91	9.07	9.05	9.07	8.99	8.98
6	17.95	18.27	17.95	17.95	17.95	17.95	17.95	18.27
7	8.53	8.19	8.40	8.53	8.46	8.53	8.46	8.53
8	20.49	23.80	20.08	20.49	20.49	20.49	20.49	20.49
9	6.57	6.52	6.52	6.52	6.57	6.57	6.48	6.52
10	5.69	5.53	5.75	5.75	5.75	5.75	5.75	5.78
11	6.17	6.24	6.24	6.24	6.21	6.24	6.24	6.27
12	5.42	5.48	5.53	5.48	5.53	5.48	5.33	5.50
13	5.07	5.12	5.09	5.15	5.33	5.15	5.15	5.14
14	7.11	7.16	7.21	7.16	7.21	7.16	7.21	7.25
15	4.92	4.92	4.92	4.97	4.97	4.97	4.92	4.99
16	7.42	7.53	7.53	7.53	8.00	7.53	7.47	7.58
17	4.19	4.10	4.23	4.19	4.27	4.23	4.34	4.23
18	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89
19	3.59	3.68	3.58	3.61	3.57	3.61	3.52	3.59
20	4.51	4.49	4.47	4.49	4.59	4.49	4.61	4.51
21	3.13	3.13	3.12	3.12	3.13	3.13	3.11	3.12
22	2.94	2.94	2.93	2.94	2.94	2.94	2.91	2.94
23	2.86	2.87	2.86	2.86	2.86	2.86	2.86	2.86
24	3.28	3.25	3.26	3.26	3.25	3.26	3.32	3.28
25	2.48	2.44	2.48	2.47	2.51	2.48	2.50	2.47
26	2.26	2.25	2.27	2.25	2.29	2.25	2.27	2.26
27	2.60	2.64	2.57	2.57	2.67	2.60	2.60	2.60

Table 6.1(e) Observed and predicted periods in rainfall (months)

TONES	MADRAS		BANGALORE		TRIVANDRUM		PAMBAN		MINICOY	
	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED
1	-	11.13	11.01	11.13	11.13	11.13	11.13	11.13	11.13	11.13
2	-	13.12	13.12	13.12	13.12	13.12	13.12	13.12	13.12	13.12
3	10.24	10.34	10.24	10.24	10.23	10.14	10.14	10.14	10.14	10.14
4	16.00	14.84	16.00	14.84	16.00	14.84	16.00	14.84	16.00	14.84
5	-	8.98	-	8.98	-	8.82	9.56	8.98	-	8.82
6	-	18.27	19.31	18.27	-	18.97	17.95	18.27	-	18.97
7	-	8.46	-	8.46	8.00	8.46	8.19	8.46	8.32	8.46
8	-	20.92	19.31	20.92	24.39	20.92	20.49	20.92	-	20.92
9	-	6.57	-	6.57	6.57	6.57	-	6.57	-	6.57
10	-	5.75	5.75	5.75	5.75	5.78	5.51	5.75	5.72	5.78
11	-	6.24	6.24	6.24	6.24	6.28	6.21	6.24	6.24	6.28
12	-	5.48	5.51	5.48	5.51	5.50	-	5.48	5.48	5.5
13	-	5.12	5.12	5.12	-	5.09	5.15	5.12	-	5.09
14	-	7.21	-	7.21	-	7.36	-	7.21	7.53	7.36
15	-	4.95	4.92	4.95	-	4.96	-	4.95	-	4.97
16	-	7.59	-	7.59	-	7.63	7.59	7.59	7.59	7.64
17	-	4.23	4.10	4.23	-	4.25	4.34	4.23	4.33	4.25
18	-	3.89	3.89	3.89	-	3.89	3.88	3.89	3.89	3.89
19	-	3.59	3.41	3.59	-	3.57	3.58	3.59	3.42	3.57
20	-	4.51	4.61	4.51	-	4.55	4.59	4.51	-	4.55
21	-	3.13	3.23	3.13	-	3.13	3.07	3.13	-	3.13
22	-	2.94	2.93	2.93	2.96	2.94	2.94	2.94	2.82	2.94
23	2.86	2.86	2.88	2.86	2.82	2.86	2.88	2.86	-	2.86
24	-	3.28	-	3.27	-	3.29	3.22	3.28	-	3.30
25	-	2.48	-	2.47	-	2.48	2.44	2.48	2.55	2.48
26	-	2.26	2.25	2.25	2.23	2.24	2.25	2.26	-	2.23
27	-	2.60	2.65	2.57	2.60	2.59	2.69	2.60	2.59	2.59

term with periods of 11.13-months and 13.12-months are well pronounced. The sub-harmonic of the 11-year cycle with a period of 5-years interacts with the 4 month oscillation to produce a strong signal at 4.1 to 4.2 months in these stations. The eastern stations of Dibrugarh, Calcutta and Gauhati are well influenced by the 11.13-month and 13.12-month oscillation in temperature (Table 6.2(b)). Another prominent "combination of tone" that influences the thermal regime is the 4.1-4.2 month oscillations. It is quite interesting to note that the 11.13-month oscillation is absent in Veraval, Bombay and Poona (Table 6.2(c)). However, all these stations are influenced by the 11-year solar oscillation. While the "summation" period of the 11-year oscillation and the annual term are detected in Akola, Hyderabad, Indore and Nagpur, they are not clearly seen in Vishakhapatnam, Pamban and Port Blair (Table 6.2(c) and 6.2(d)). The 13.12-month oscillation is not observed in the coastal stations, such as Trivandrum, Pamban and Port Blair. Port Blair, an island station considered for the study is only influenced by the 4.2-month oscillation (Table 6.2(e)).

Table 6.3 gives the observed and predicted tones for sea-level pressure. Stations having continuous data for 85-years are chosen to predict the combination of tones. As in the case of temperature all the tones are not observed in the series for Agra, Akola, Jodhpur, Veraval, Port Blair, Pamban and Trivandrum. The "difference tone" of 11-year cycle and the semi-annual

Table 6.2(a) Observed and predicted periods for temperature (months)

TONES	ALLABAHAD		AGRA		BIKANER		JODHPUR		MUKTESHWAR	
	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED
1	11.14	11.13	11.14	11.13	11.01	11.13	-	11.13	11.01	11.13
2	13.13	13.12	13.12	13.12	13.12	13.12	13.12	13.12	13.12	13.12
3	5.75	5.76	5.75	5.72	5.56	5.48	5.76	5.75	5.75	5.75
4	6.24	6.24	6.24	6.24	6.24	6.24	-	6.24	6.24	6.24
5	-	10.13	9.57	10.14	9.57	10.14	9.16	10.14	9.57	10.14
6	-	5.3	5.34	5.34	-	5.5	-	5.48	-	5.48
7	3.7	3.53	3.7	3.78	3.69	3.78	3.42	3.53	-	3.53
8	4.10	4.24	4.09	4.23	-	4.09	4.09	4.14	4.15	4.14
9	3.13	3.34	3.42	3.34	3.42	3.34	-	3.3	3.42	3.3
10	2.25	2.25	2.25	2.26	2.25	2.26	-	2.25	-	2.25
11	2.02	2.1	2.02	2.1	2.02	2.1	2.02	2.1	2.02	2.1
12	16.00	17.60	18.6	17.67	-	17.67	-	17.67	-	17.67
13	6.87	7.11	7.57	7.11	7.11	-	-	7.11	7.58	7.11
14	-	5.30	-	5.30	5.34	5.30	5.17	5.15	5.15	5.17
15	-	3.6	-	3.6	-	3.6	-	3.6	-	3.6
16	2.69	2.67	2.69	2.6	2.69	2.56	2.62	2.6	2.62	2.6
17	-	8.00	-	8.0	8.19	7.99	8.19	8.00	8.19	8.00
18	2.82	2.86	2.7	2.6	2.82	2.86	-	2.8	-	2.8
19	-	6.5	-	6.5	-	6.5	-	6.5	-	6.5
20	5.17	5.17	-	5.17	-	5.17	-	5.17	-	5.17

Table 6.2(b) Observed and predicted periods in temperature (months)

TONES	DIBRUGARH		CALCUTTA		GAUHATI	
	OBS	PRED	OBS	PRED	OBS	PRED
1	11.01	11.13	11.01	11.13	11.01	11.13
2	13.12	13.12	13.12	13.12	13.12	13.12
3	-	5.75	5.76	5.75	5.75	5.75
4	-	6.24	6.24	6.24	-	6.24
5	-	10.14	10.24	10.14	-	10.14
6	-	5.48	5.75	5.48	-	5.48
7	-	3.67	-	3.67	-	3.67
8	4.15	4.14	4.13	4.14	4.13	4.14
9	3.42	3.3	-	3.3	3.43	3.3
10	-	9.14	-	9.14	-	9.14
11	-	17.67	18.62	17.67	-	17.67
12	2.6	2.5	-	2.5	-	2.5
13	-	2.1	-	2.1	-	2.1
14	-	7.11	7.53	7.11	7.58	7.11
15	5.15	5.17	5.15	5.17	5.15	5.17
16	-	3.53	-	3.53	-	3.53
17	2.62	2.6	2.69	2.6	2.62	2.6
18	7.58	8.00	-	8.00	-	8.00
19	2.93	2.8	-	2.8	-	2.8
20	-	6.5	6.57	6.6	-	6.6

Table 6.2(c) Observed and predicted periods in temperature (months)

TONES	DWARAKA		VERAVAL		POONA		BOMBAY	
	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED
1	11.14	11.13	-	11.13	-	11.13	-	11.13
2	13.12	13.12	13.12	13.12	13.12	13.12	13.12	13.12
3	5.75	5.75	-	5.75	5.75	5.75	5.75	5.75
4	-	6.24	-	6.24	6.28	6.24	-	6.24
5	9.57	10.14	-	10.14	-	10.34	-	10.14
6	5.75	5.48	5.15	5.48	-	5.53	-	5.48
7	3.42	3.67	-	3.67	3.78	3.69	-	3.67
8	4.09	4.14	4.09	4.14	4.09	4.13	4.09	4.14
9	-	3.3	3.42	3.3	-	3.3	-	3.3
10	-	9.14	-	9.14	-	9.14	-	9.14
11	-	17.67	-	17.67	-	17.67	-	17.67
12	-	2.5	2.68	2.5	-	2.32	-	2.5
13	-	2.1	-	2.1	2.02	2.1	2.02	2.1
14	5.15	5.27		5.36	5.15	5.17	5.15	5.17
15	7.59	6.92	-	6.78	-	7.11	-	7.11
16	-	3.8	-	3.62	-	3.53	-	3.53
17	2.25	2.27	-	2.52	2.69	2.6	2.69	2.6
18	8.19	8.00	8.19	8.00	8.19	8.00	8.19	8.00
19	2.69	2.8	-	2.8	-	2.8	-	2.8
20	-	6.57	-	6.56	6.28	6.5	-	6.5

Table 6.2(e) Observed and predicted periods in temperature (months)

TONES	TRV		PBN		BNG		MDS		PBL	
	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED
1	11.13	11.01	-	11.13	11.01	11.13	11.14	11.13	-	11.13
2	-	13.3	-	13.12	13.12	13.12	-	13.12	-	13.12
3	-	5.72	-	5.75	-	5.75	-	5.75	-	5.75
4	-	6.28	-	6.24	-	6.24	6.24	6.24	-	6.24
5	-	10.34	-	10.14	10.23	10.14	-	10.14	-	10.34
6	-	5.53	-	5.48	-	5.48	-	5.48	-	5.53
7	-	3.69	-	3.67	3.78	3.67	-	3.67	-	3.69
8	4.05	4.10	4.05	4.14	4.13	4.14	4.13	4.14	4.09	4.10
9	-	3.3	3.42	3.3	-	3.3	3.42	3.3	-	3.27
10	-	2.32	-	2.5	-	9.14	9.56	9.14	-	2.48
11	2.02	2.08	2.02	2.1	-	2.5	-	2.5	-	2.08
12	-	9.57	-	9.14	2.02	2.1	2.02	2.1	-	2.56
13	-	16.26	-	17.67	-	17.67	-	17.67	-	16.26
14	-	5.30	-	5.17	5.15	5.17	5.15	5.17	-	5.3
15	7.16	7.12	-	7.11	-	7.11	7.58	7.14	-	6.87
16	-	3.6	-	3.53	-	3.53	-	3.53	-	3.59
17	2.68	2.52	-	2.8	-	2.6	2.62	2.6	-	2.53
18	-	8.00	-	8.00	-	8.00	-	8.00	-	8.00
19	-	2.8	-	2.6	2.9	2.8	2.82	2.8	-	2.8
20	6.52	6.5	-	6.6	-	6.5	-	6.5	-	6.5

Table 6.2(d) Observed and predicted periods in temperature (months)

TONES	AKOLA		VSK		HYD		IND		NGP	
	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED
1	11.01	11.13	-	11.13	11.01	11.13	11.01	11.13	11.01	11.13
2	13.12	13.12	13.12	13.12	13.12	13.12	13.12	13.12	13.12	13.12
3	5.75	5.75	-	5.75	5.76	5.75	5.75	5.75	5.75	5.75
4	6.28	6.24	6.24	6.24	6.28	6.24	6.24	6.24	6.24	6.24
5	-	10.34	-	10.14	-	10.34	-	10.14	10.23	10.34
6	5.51	5.53	-	5.48	-	5.53	5.75	5.48	5.53	5.53
7	3.71	3.69	-	3.67	-	3.69	3.79	3.67	3.78	3.69
8	4.09	4.11	4.13	4.14	4.09	4.11	4.09	4.14	4.09	4.11
9	3.42	3.3	-	3.3	-	3.33	3.13	3.3	-	3.3
10	2.25	2.32	-	2.5	2.25	2.48	-	2.5	-	2.48
11	2.02	2.1	2.02	2.1	2.02	2.08	2.02	2.1	2.02	2.08
12	9.56	9.66	-	9.14	-	9.66	9.57	9.66	9.56	9.66
13	16.00	15.99	-	17.67	16.00	15.99	16.00	15.99	16.00	15.99
14	-	6.8	-	7.11	-	6.8	-	6.8	6.83	6.8
15	5.15	5.33	5.15	5.17	-	5.33	-	5.33	5.15	5.33
16	-	3.6	-	3.53	-	3.6	3.79	3.6	-	3.6
17	-	2.52	2.68	2.6	-	2.8	2.69	2.6	-	2.8
18	8.19	8.00	-	8.00	-	8.00	8.19	8.00	-	8.00
19	2.82	2.8	-	2.8	2.68	2.6	-	2.8	2.61	2.6
20	-	6.5	-	6.5	-	6.6	-	6.55	6.57	6.6

Table 6.3 Observed and predicted periods in sea-level pressure (months)

TONES	AGRA		AKOLA		JODHPUR		VERAVL		PBR		PBN		TRV	
	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED	OBS	PRED
1	-	11.13	-	11.13	11.01	11.13	-	11.13	-	11.13	-	11.13	11.01	11.13
2	13.13	13.12	13.12	13.12	13.13	13.12	13.13	13.12	13.12	13.12	13.12	13.12	13.13	13.12
3	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75	-	5.75	-	5.75
4	6.28	6.24	-	6.24	-	6.24	-	6.24	-	6.24	-	6.24	-	6.24
5	-	10.14	-	10.14	-	10.14	-	10.14	-	10.14	-	10.14	-	10.14
6	-	6.48	-	6.48	-	6.48	-	6.48	-	6.48	-	6.48	-	6.48
7	-	3.67	-	3.67	-	3.67	-	3.67	-	3.67	-	3.67	-	3.67
8	4.15	4.14	4.15	4.14	4.15	4.14	4.15	4.14	4.15	4.14	4.15	4.14	4.15	4.14
9	3.4	3.3	3.4	3.3	3.4	3.3	3.4	3.3	3.4	3.3	3.42	3.3	-	3.3
10	2.6	2.5	2.6	2.5	-	2.5	-	2.5	2.6	2.5	-	2.5	-	2.5
11	2.02	2.1	2.02	2.1	2.02	2.1	2.02	2.1	2.02	2.1	2.02	2.1	2.02	2.1
12	7.58	8.0	7.58	8.0	7.59	8.0	7.58	8.0	7.58	8.0	7.59	8.0	7.58	8.0
13	-	2.8	2.82	2.8	2.82	2.8	2.82	2.8	-	2.8	-	2.8	-	2.8
14	-	6.5	-	6.5	-	6.5	-	6.5	-	6.5	-	6.5	-	6.5

oscillation is detected in all the stations for sea-level pressure.

Prediction of rainfall:

An attempt has been made to predict the rainfall for 3 stations, Bombay, Vishakhapatnam and Trivandrum. The rainfall of Bombay is correlated with other stations and the stations having significance at the 90% level is selected. The stations chosen are Akola, Ahmedabad, Bikaner, Bangalore, New Delhi, Hyderabad, Jodhpur, Machilipatnam, Veraval, Vishakhapatnam, Poona and Trivandrum. Principal component analysis is carried out on these 12 stations and the first 7 PC scores having 80% of variance is chosen. The rainfall for Bombay is calculated from the equation

$$
\begin{aligned}
Y_{BMB} = 1958.2 &+ (159.67 * PC(1)) + (24.795 * PC(2)) \\
&+ (-67.948 * PC(3)) + (61.848 * PC(4)) \\
&+ (73.981 * PC(5)) + (-84.314 * PC(6)) \\
&+ (-141.23 * PC(7))
\end{aligned}
\qquad \ldots(6.7)
$$

The predicted and observed values of Bombay rainfall is shown in Fig. 6.2(a). It must be noted that only 43% of the variance in the predicted rainfall of Bombay is accounted by the rainfall at other stations. The standard error of estimate is 311.39, which gives the error in the prediction values.

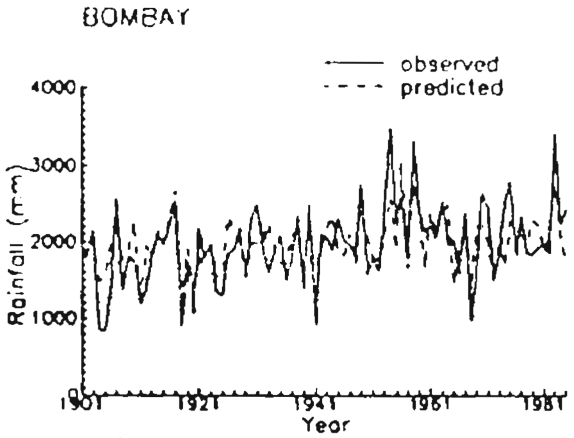


Fig. 6.2(a). Prediction for Bombay

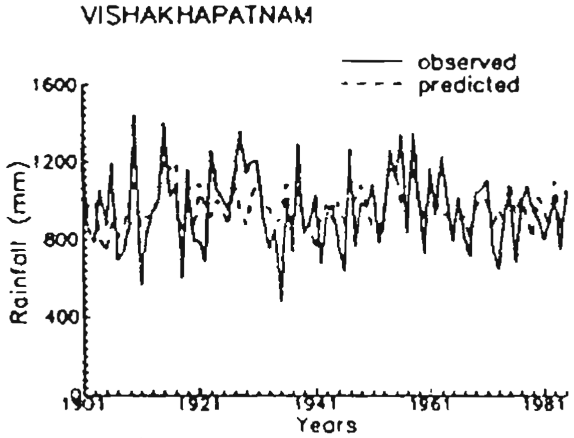


Fig. 6.2(b) Prediction for Vishakhapatnam

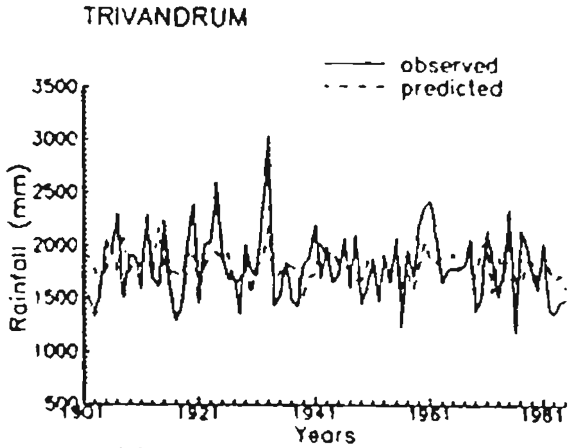


Fig. 6.2(c) Prediction for Trivandrum

The rainfall at an east-coast station, Vishakhapatnam is also predicted in a similar manner. The stations chosen are Bombay, Dibrugarh, Hyderabad, Machilipatnam, Mukteshwar and Poona. Four PC Scores are used for multiple regression equation and the predicted values of rainfall for the station calculated is from the equation

$$Y_{VSK} = 953.57 + (72.402*PC(1)) + (16.618 * PC(2)) + (-13.763*PC(3))+(15.065*PC(4)) \quad ...(6.8)$$

In this station however, only 25% of the variance is accounted by the predictor variables and the standard error of estimate is 159.43. Fig. 6.2(b) gives the observed and predicted rainfall values for Vishakhapatnam.

The rainfall at Bikaner, Bombay, Dibrugarh, Hyderabad, Machilipatnam, Minicoy, Nagpur and Poona is used to predict the the rainfall at the southern most station, Trivandrum. The first 5 PC scores of these stations are utilised in the regression model. Rainfall at Trivandrum is obtained from the equation

$$Y_{TRV} = 1805 + (27.513 * PC (1))+ (90.235 * PC (2)) + (20.163 * PC (3)) + (82.422 * PC(4)) + (5.7146 * PC(6)) \quad ...(6.9)$$

The predicted values for Trivandrum is illustrated in Fig.6.2(c). The standard error is calculated to be 297.28.

From the results it is clear that the standard error of estimate is found to be low if the number of input variables in the regression model is kept to a minimum. The technique of principal component analysis is a relatively better method which can be further modified to predict the temporal variations in the meteorological parameters more accurately.

6.4 SUMMARY

The method of harmonic analysis is not a suitable model to predict the seasonal variation compared to other techniques. The "summation" tones of the 11-year cycle and the CW oscillation with the 12-month annual term at 11.13-months and 6.6-months and a "difference" tone of these oscillations with the semi-annual term at 13.12-months and 10-months are clearly seen in all the stations for rainfall series. The western region of India are well influenced by the "combination of tones" as far as rainfall is concerned. The thermal regime of the subcontinent is dominated by a 4.2-month oscillation, which is due to the interaction between the 5-year cycle and the 4-month subharmonic of the annual term. The sea-level pressure pattern is not influenced by all the "combination of tones". Eventhough, principal component analysis is an efficient technique to predict the rainfall at a particular station, it cannot capture all the modes of variability that influence the rainfall pattern.

Chapter 7

SUMMARY AND CONCLUSIONS

The Indian subcontinent, with its unique physiographic features exhibits wide variations in surface meteorological parameters both in space and time. Studies on the variations of meteorological parameters have drawn the attention of many scientists. The present thesis is concerned with a detailed analysis of the spatial and temporal variations of rainfall, surface temperature and sea-level pressure.

The study on the rainfall distribution over Indian subcontinent reveals that the predominant feature of the distribution of rainfall is the orographic effect. It is seen that apart from the frequency, intensity and tracks of the migratory synoptic disturbances, the topographic configuration plays an important role on the influence of rainfall pattern over the Country. The Western Ghat region and the north eastern part of the country experiences large amplitudes in annual cycle, whereas and very low amplitudes are noticed in the northwestern part of the country. The amplitude of the annual cycle is found to be directly connected with the annual mean precipitation pattern, with large amplitudes in regions of high rainfall and vice versa. The western peninsular region, where the annual rainfall pattern is bimodal also experiences large amplitudes in semi-annual oscillation. The first three harmonics of the seasonal cycle account for most of the variance in annual rainfall distribution.

The phase of annual oscillation shows a maximum during the months of July and August in the entire country, except in the northeastern part when the annual rainfall maximum is noticed during the month of June. Regions coming under the sway of summer monsoon experiences a secondary maximum in rainfall during the month of January, and regions of winter rainfall experiences the phase maximum during the months of October and November.

The spatial distribution of the thermal regions over the Indian subcontinent is caused due to the topographical and atmospheric variations, which in turn influence local and regional thermal regimes. The highest peak in mean sea-level temperature is noted in central peninsular region and low temperatures are noticed in northeastern part of the country. A low amplitude annual cycle in temperature is noted in the central part of the Western peninsula and island stations in Arabian sea and Bay of Bengal. The highest annual oscillation in temperature is seen in the northwest part of the country, with scorching summers and freezing winters. The amplitudes of the semi-annual oscillation is much smaller in magnitude compared to that of the annual oscillation. The shorter period oscillations in temperature are significant in the Western Ghat region. The phase of annual oscillation in temperature is noted during April to June months, whereas the semi-annual oscillation attains its peak during middle of September to middle of November.

The amplitude of annual oscillation in sea-level pressure indicates very high values in the northwest part of the country and low values along the west-coast, south of Mangalore and the island stations. The highest amplitude of semi-annual oscillation of the order of 1-1.5mb is seen along Gujarat coast which is influenced by the monsoon trough. Over most of the country the highest pressure is noted during January, when the country is at the periphery of the Siberian high and a secondary maximum is observed during November. However, south of 15^{O}N the secondary maximum is seen only in February due to the cyclonic circulation in Bay of Bengal.

The spectrum of the meteorological parameters over Indian subcontinent is of particular interest because of the large interannual variability displayed by these parameters. The overall spectrum suggests that most of the variability is contained in bands of known physical origin and hence predictable. Apart from the annual cycle and its sub-harmonics the major periodicities detected are the 11-year oscillation, 5-year oscillation, quasi-biennial oscillation (QBO), quasi-triennial oscillation (QTO) and Chandler-Wobble (CW) Oscillation. The period of QTO for meteorological parameters over the Indian sub-continent is 33-40 months, while the QBO exhibits a periodicity of 28-29 months in rainfall and 24-months in temperature and sea-level pressure over India. The QBO, QTO and CW are well pronounced in coastal stations for rainfall and in interior stations for temperature. Rainfall over India does not show any significant trend during the last century, however the temperature is generally increasing and the mean sea level pressure is decreasing in most part of the country.

Principal component analysis produces a decomposition of the data field into spatial eigen vectors and temporal principal components. The rainfall and temperature data for a period of 85 years (1901-1985) show that PCA is a valuable and in gaining insight into the spatial and temporal behaviour of meteorological parameters. The similarity between western and central part of the country as far as annual rainfall distribution is concerned is brought out by the study. Rotation of principal components reveal the influence of EL-Nino oscillation on rainfall pattern. Monthly transitions of rainfall shows that September rainfall is an indicator for the rainfall during the first month of the northeast monsoon. While interannual variability in monthly rainfall is not clearly captured by the study, the second principal component of annual temperature indicates definite patterns. However, further detailed analysis is required to quantity the spatial and temporal patterns.

Among the various techniques adopted to predict the meteorological parameters, the method of harmonic analysis is not found suitable to predict the seasonal variation. The 'summation' tone of the 11-year oscillation and the Chandler-

Wobble oscillation with the 12 months annual term at 11.13 months and 6.6 months and a 'difference' tone of these oscillations with the semi-annual term at 13.12 months are well documented in all the stations for rainfall series. The western region of India are well pronounced by the "combination of tones" as far as rainfall is concerned. A 4.2-months oscillation, which is "combination tone" of the 5 year cycle and 4 months oscillation influences the thermal pattern of Indian subcontinent. Even though, the principal component analysis is an efficient technique to predict the rainfall at a particular station, it is unable to capture all the modes of variability that influences the rainfall pattern.

The outcome of the present thesis work is expected to provide a better understanding on the physical processes responsible for the climate variability and its predictability over the Indian subcontinent. The study is useful to delineate and emphasis the various boundaries and areas of transition to bring out the regional and temporal characteristics of the distribution of meteorological parameters over the country. The results obtained from the present study can be incorporated for climate modelling and long-term prediction of the meteorological parameters over Indian subcontinent.

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APPENDIX - A

```
C     PROGRAM FOR HARMONIC ANALYSIS
C     TMP IS THE DATA
C     N IS THE TOTAL DATA LENGTH
C     TMEAN IS THE AVERAGE VALUE OF THE PARAMETER
C     R2 IS THE AMPLITUDES AND PH THE PHASES OF THE HARMONICS
      DIMENSION TMP(12,199),TM(12),
     1 TTM(12),A(12),B(12),F(12),R(12),PH(12),R2(12)
     2 DTM(12,199)
      READ(5,*)N
      DO 10 J=1,N
      READ (5,*)(TMP(I,J),I=1,12)
 10   CONTINUE
      TMM=0.0
      DO 200 J=1,N
      DO 200 I=1,12
      TMM=TMM+TMP(I,J)
200   CONTINUE
      DN = N*12.
      TMEAN = TMM/DN
      WRITE (6,123) TMEAN
 123  FORMAT(/5X,'THE MEAN VALUE = ',F7.2)
      DO 20 I = 1,12
      TTM(I) = 0.0
      DO 30 J = 1, N
      TTM(I) = TTM(I) + TMP(I,J)
30    CONTINUE
      TM(I) = TTM(I)/N
      DO 34 J = 1, N
      DTM(I,J) = TMP(I,J)-TM(I)
34    continue
      WRITE(6,115)
115   FORMAT(//'   FREQ    MONTH      A    B    AMPLITUDE  PHASE
     1'/)
      DO 50 K = 1, 6
      F(K) = 2.0*3.14159*K/12.0
      A(K) = 0.0
      B(K) = 0.0
      DO 45 I = 1, 12
      A(K) = A(K)+TM(I)*COS(I*F(K))
      B(K) = B(K)+TM(I)*SIN(I*F(K))
45    CONTINUE
      A(K) = 2.0*A(K)/12.0
      B(K) = 2.0*B(K)/12.0
      R2(K) =SQURT(A(K)*A(K)+B(K)*B(K))
C     COMPUTE PHASE ANGLE
      PH(K) = ATAN2(-B(K),A(K))
C     TIME OF MAXIMUM VALUE
      PH(K) = -PH(K)/F(K)
      IF (PH(K).LT.0.0) THEN
      PH(K) = PH(K)+12.0
      ELSE
      ENDIF
```

```
      TJ = 12./K
      WRITE(6,60)K,TJ,A(K),B(K),R2(K),PH(K)
50    CONTINUE
60    FORMAT(I6,5F10.3)

C     ALPHA IS THE RATIO OF THE FIRST TWO AMPLITUDES
C     BETA IS THE VARIANCE
C     GAMMA IS THE CONTRIBUTION OF THE FIRST TWO HARMONICS TO THE
C     TOTAL VARIANCE
      ALPHA = R2(2)*R2(2)/R2(1)*R2(1)
      BETA = R2(1)*R2(1)+R2(2)*R2(2)+R2(3)*R2(3)+R2(4)*R2(4)+
     -R2(5)*R2(5)+R2(6)*R2(6)
      GAMMA=(R2(1)*R2(1)+R2(2)*R2(2))/BETA
      WRITE(6,124) ALPHA,BETA,GAMMA
124   FORMAT(//5X,'RATIO OF (AMPLITUDE)2 BY 1 = ',F9.4/5X,
     -'VARIANCE,',F9.4/5X, '(A1+A2)/VARIANCE=',F9.4//)
      STOP
      END
```

APPENDIX-B

```
C      PROGRAM SPECTRAL ANALYSIS
C      N - NUMBER OF DATA VALUES IN EACH ENSEMBLE
C      NN - FIRST NUMBER LARGER THAN N WHICH CAN BE EXPRESSED
C      AS A POWER OF 2
C      NK - DEFINED BY NN=2**NK
C      NSET - NUMBER OF ENSEMBLES IN THE DATA SET
C      DELT - INTERVAL OF DIGITISATION OF THE TIME SERIES
C      X IS THE TIME SERIES
       DIMENSION  X(1000),Y(1000),Z(1000),C(1000),S(1000)
       CHARACTER*32 FILL
       WRITE(*,*)'N,NN,NK,NSET'
       READ(1120,*)N,NN,NK,NSET
       WRITE(*,*)'delt'
       READ(1121,*)DELT
       WRITE(*,*) 'enter the name of the file'
       read(*,345)fil1
345    format(a32)
       DELN=1./DELT/NN
       NA=NN/2+1
       DO 15 I=1,NA
15     S(I)=0.
C      ENSEMBLE AVERAGE INCORPORATED THROUGH DO LOOP 21 & 22
       DO 21 ISET=1,NSET
       DO 55 I=1,NN
55     X(I)=0.
       open(7,FILE=FILL)
       READ(7,*)(X(I),i=1,n)
       close(7)
c       DO 9065 I=1,8192
       WRITE(*,*)N,NN,NK,NSET,DELT
       CALL SPCTRM(N,NN,NK,S,X,C,Y,Z)
21     CONTINUE
C      FAC IS THE SCALE FACTOR FOR HANNING WINDOW
       FAC=1./0.3750
       CONST=FAC*2*DELT/NN/NSET
       DO 22 I=1,NA
22     S(I)=S(I)*CONST
       NA=NN/4
       WRITE(9,201)
       DO 80 I=1,NA
       FRI=(I-1)*DELN
80     WRITE(9,202)I,FRI,S(I)
       do 818 i=1,NA
       J=I+NA
       FRJ=(J-1)*DELN
818    write(9,202)J,FRJ,S(J)
       I=NN/2+1
       FRI=(I-1)*DELN
81     WRITE(9,202)I,FRI,S(I)
100    FORMAT(5I5)
```

```
101   FORMAT(16F5.2)
102   FORMAT(F5.2)
200   FORMAT(5X,8F10.3)
201   FORMAT(5X,'NO.',6X,'FREQUENCY',4X,'SPEC. ESTIMATE',5X)
202   FORMAT(5X,2(I6,2f15.4,8X))
203   FORMAT(46X,I3,2E15.4)
204   FORMAT(10X,5E12.4)
205   FORMAT(//5X,12HTIME SERIES /)
206   FORMAT(1H1,7X,2HN=,I5/7X,3HNN=,I5/7X,3HNK=,I5/5X,5HNSET=,I5/5X,
     15HDELT=,E12.4/)
207   FORMAT(1H1)
      STOP
      END

      SUBROUTINE FFT(A,C,Y,Z,N,NK)
      DIMENSION A(1),C(1),Y(1),Z(1)
      PI=3.141593
      NA=N
      NR=1
      C(1)=1.1
      NC=1
      DO 10 J=1,NK
      NA=NA/2
      DO 11 I=1,NR
      NC=NC+1
11    C(NC)=C(I)+NA
10    NR=NR*2
      DO 12 I=1,N
      K=C(I)
12    C(I)=A(K)
      N2=N/2
      DO 13 I=1,N2
      IN=I+N2
      Z(I)=0.
      Z(IN)=0.
      Y(I)=C(2*I)+C(2*I-1)
13    Y(IN)=C(2*I-1)-C(2*I)
      NKO=NK-1
      KA=2
      NA=N2
      DO 20 II=1,NKO
      KAT=KA
      KA=KA*2
      ARG=2.*PI/KA
      WR=1.
      WI=0.
      ISET=0
      NA=NA/2
      DO 19 JJ=1,KAT
      DO 18 K=1,NA
      KSET=K+ISET
      KK=2*KSET
      KN=KSET+N2
```

```
      ZI=WI*Y(KK)+WR*Z(KK)
      ZR=WR*Y(KK)-WI*Z(KK)
      C(KN)=Z(KK-1)-ZI
      A(KN)=Y(KK-1)-ZR
      A(KSET)=Y(KK-1)+ZR
18    C(KSET)=Z(KK-1)+ZI
      ARJ=ARG*JJ
      WI=-SIN(ARJ)
      ISET=KSET
19    WR=COS(ARJ)
      DO 20 I=1,N
      Y(I)=A(I)
20    Z(I)=C(I)
      RETURN
      END

      SUBROUTINE SPCTRM(N,NN,NK,S,X,C,Y,Z)
      DIMENSION S(1),X(1),C(1),Y(1),Z(1)
      PIN=6.283186/NN
C     REMOVE LINEAR TREND
      NA=NN/2
      TX=0
      SX=0
      DO 21 I=1,N
      TX=TX+(I-1)*X(I)
21    SX=SX+X(I)
      DN=N
      P=(TX-(N-1)*SX*.5)*12./(DN**3-DN)
      Q=SX/N-P*(N-1)*.5
      DO 22 I=1,N
22    X(I)=X(I)-P*(I-1)-Q
50    CONTINUE
C     THE INPUT DATA IS MULTIPLIED BY THE HANNING WINDOW
      DO 24 I=1,NN
      WINDOW=0.5*(1+COS(PIN*(I-NN*0.5-0.5)))
24    X(I)=X(I)*WINDOW
25    CONTINUE
      CALL FFT(X,C,Y,Z,NN,NK)
      NA=NN/2+1
      DO 26 I=1,NA
26    S(I)=(X(I)**2+C(I)**2)+S(I)
      RETURN
      END
```

APPENDIX-C

```
C       PROGRAM TO FIND PRINCIPAL COMPONENT ANALYSIS
C       SUBPROGRAM COVA COMPUTES COVARIANCE MATRIX
C       SUBPROGRAM DJAC COMPUTES EIGEN VALUE & VECTOR
C       SUBPROGRAM VORS ROTATES THE VECTORS
C       DATA IS THE INPUT DATA
C       NS IS THE NUMBER OF ROWS AND NC THE NUMBER OF COLUMNS
        DIMENSION DATA(85,85),COV(85,85),CMEAN(85),
       -CRN(85,85),CENT(85,85),VECT(85,85),
       -VAL(85),VAR(85),TRAN(85,85),F(85,85),MM(85),
       -P(85),G(85,85),A(85),B(85),C(85),KX(85),KY(85),
       -KZ(85)
        READ(77,*)NS,NC
        M=NS
        NN=1
        WRITE(*,*) 'ENTER THE INPUT DATA'
        READ (1,*) ((DATA(I,J),J=1,NC),I=1,NS)
        CALL COVA (DATA,NS,NC,CMEAN,CENT,TRAN,F,COV)
        CALL DJAC (M,COV,NN,NR,VECT)
C       PRINCIPAL COMPONENTS ARE OBTAINED BY MULTIPLYING
C       EACH CENTERED VALUE WITH THE EIGEN VECTOR
        WRITE(7,115)
115     FORMAT (// 'EIGEN VECTORS OF THE MATRIX')
        WRITE(7,70)((VECT(I,J),J=1,22),I=1,22)
70      FORMAT (/22F8.2)
        DO 1 I=1,22
        DO 1 J=1,22
        G(I,J)=VECT(J,I)
1       CONTINUE
        DO 98 I=1,NS
        DO 99 J=1,NC
        CRN(I,J)=0.0
        DO 100 K=1,NC
        CRN(I,J)=CRN(I,J)+G(I,K)*CENT(K,J)
100     CONTINUE
99      CONTINUE
98      CONTINUE
        WRITE(8,110)
110     FORMAT (//'PRINCIPAL COMPONENTS OF THE MATRIX')
        WRITE (8,721)((CRN(I,J),J=1,NC),I=1,NS)
721     FORMAT (/22f10.2)
        DO 3 I=1,NS
        DO 3 J=1,NC
        IF(I.eq.J)then
        VAL(I)=COV(I,J)
        END IF
3       CONTINUE
        SUM  =0.0
        DO 4 I=1,NS
        SUM  =SUM+VAL(I)
4       CONTINUE
```

```
      DO 500 I=1,NS
      VAR(I) =(VAL(I)/SUM)*100.0
500   CONTINUE
      WRITE (99,116)
116   FORMAT (/'EIGEN VALUE',8X,'VARIANCE'/)
      DO 722 I=1,NS
      WRITE(*,*)'I=',I
      WRITE(99,90)VAL(I),VAR(I)
90    FORMAT (1X,22F15.2,3X,22F15.2)
722   CONTINUE
      CALL VORS (NS,NC,CRN,A,B,C,ND)
      WRITE(2,75)
75    FORMAT('PERCENTAGE VARIATION FOR ROTATED VECTORS')
      WRITE(2,*)(A(I),I=1,NC)
76    FORMAT(85f20.2)
      WRITE(3,81)
81    FORMAT('COMMUNALITIES FOR VARIABLES AS PERCENTAGES')
      WRITE(3,*)(B(I),I=1,NS)
80    FORMAT(85F20.2)
      WRITE(10,222)
222   FORMAT(//'FACTOR LOADING MATRIX')
      WRITE(10,224)((CRN(I,J),J=1,NC),I=1,NS)
224   FORMAT(1X,22F10.2)
      STOP
      END

C     PROGRAM TO COMPUTE COVARIANCE MATRIX
C     DATA=THE INPUT MATRIX
C     CMEAN=MEAN
C     CENT=CENTERED DATA
C     TRAN=TRANPOSE OF THE CENTERED DATA
C     F=PRODUCT OF CENT AND TRAN
C     COV=COVARIANCE MATRIX
      SUBROUTINE COVA (DATA,NS,NC,CMEAN,CENT,TRAN,F,COV)
      DIMENSION COV(85,85), DATA(85,85), CMEAN(85),
     -CENT(85,85),TRAN(85,85),F(85,85)
      DO 101 I=1,NS
      SUM=0.0
      DO 102 J=1,NC
      SUM= SUM+ DATA(I,J)
102   CONTINUE
      CMEAN(I)=SUM/NC
101   CONTINUE
      DO 103 I=1,NS
      DO 104 J=1,NC
      CENT(I,J) = DATA(I,J)-CMEAN(I)
104   CONTINUE
103   CONTINUE
C     COMPUTE COVARIANCE MATRIX
      DO 105 I=1,NS
      DO 105 J=1,NC
      TRAN(I,J) =CENT(J,I)
105   CONTINUE
```

```
      DO 106 I=1,NS
      DO 107 J=1,NS
      F(I,J)=0.0
      DO 107 K=1,NC
      F(I,J)=F(I,J)+CENT(I,K)*TRAN(K,J)
      COV(I,J)=F(I,J)/NC
107   CONTINUE
106   CONTINUE
c     write(*,*)((F(I,J),J=1,85),I=1,22)
      RETURN
      END

C     SUBROUTINE DJAC GETS THE EIGEN VECTORS
C     M=ORDER OF THE GIVEN MATRIX
C     A=GIVEN MATRIX,
C     ON RETURN ITS DIAGONAL ELEMENTS CONTAINS THE EIGEN VALUES
C     NN= A GIVEN INTEGER. IF EIGEN VALUES AND EIGEN VECTORS ARE REQUIRE
C     SET NN=ANY NON ZERO INTEGER ,FOR EIGEN VALUES ONLY SET NN=0
C     NR=NUMBER OF ITERATION
C     V=EIGEN VECTORS
      SUBROUTINE DJAC(M,A,NN,NR,V)
      DIMENSION A(85,85),V(85,85),P(85),MM(85)
      IF (NN)1,2,1
 1    DO 3 I=1,M
      DO 3 J=1,M
      IF (I.NE.J)GO TO 4
      V(I,J)=1
      GO TO 3
4     V(I,J)=0
3     CONTINUE
2     NR=0
5     MI=M-1
      DO 6 I= 1,MI
      P(I)=O
      MJ=I+1
      DO 6 J=MJ,M
      IF (P(I).GT.ABS(A(I,J))) GO TO 6
      P(I)=ABS(A(I,J))
      MM(I)=J
6     CONTINUE
C     P(I) CONTAINS THE LARGEST MAGNITUDE ELEMENT OF I-TH ROW
7     DO 8 I=1,MI
      IF(I.LE.1) GO TO 10
      IF (PMAX.GT.P(I)) GO TO 8
10    PMAX=P(I)
      IP=I
      JP=MM(I)
8     CONTINUE
C     THE LARGEST MAGNITUDE OF DIAGONAL ELEMENT RESIDES IN PMAX
      EPLN=ABS(PMAX)*1.D-9
      IF(PMAX.LE.EPLN)GO TO 12
C     THESE STATEMENTS ARE FOR TESTING WHETHER THE PROCESS FOR
C     DIAGONALISATION IS OVER
```

```
      NR=NR+1
      IF(A(IP,IP).GE.A(JP,JP)) GO TO 13
      TAN=-2*A(IP,JP)/(ABS(A(IP,IP)-A(JP,JP))
     1+SQRT((A(IP,IP)-A(JP,JP))**2+4*A(IP,JP)**2))
      GO TO 14
13    TAN=2*A(IP,JP)/(ABS(A(IP,IP)-A(JP,JP))
     1+SQRT((A(IP,IP)-A(JP,JP))**2+4*A(IP,JP)**2))
14    COS=1./SQRT((1+TAN**2))
      SIN=TAN*COS
      AI=A(IP,IP)
      A(IP,IP)=COS**2*(AI+TAN*(2*A(IP,JP)+TAN*A(JP,JP)))
      A(JP,JP)=COS**2*(A(JP,JP)-TAN*(2*A(IP,JP)-TAN*AI))
      A(IP,JP)=0
C     COMPUTATION OF TAN,SIN,COS,A(I,I),A(J,J) IS OVER
      IF(A(IP,IP).GE.A(JP,JP))GO TO 15
      TT=A(IP,IP)
      A(IP,IP)=A(JP,JP)
      A(JP,JP)=TT
C     INTERCHANGE OF A(IP,IP) AND A(JP,JP) IF
C     A(IP,IP) IS LESS THAN A(JP,JP).
      IF(SIN.GE.0)GO TO 16
      TT=COS
      GO TO 17
16    TT=-COS
17    COS=ABS(SIN)
      SIN=TT
C     SIN,COS ARE PROPERLY ADJUSTE FOR A(I,K),V(I,K)
C     SIN,COS ARE PROPERLY ADJUSTED FOR A(I,K),V(I,K)
15    DO 18 I=1,MI
      IF(I-IP)19,18,20
20    IF(I.EQ.JP)GO TO 18
19    IF(MM(I).EQ.IP)GO TO 21
      IF(MM(I).NE.JP)GO TO 18
21    K=MM(I)
      TT=A(I,K)
      A(I,K)=0
      MJ=I+1
      P(I)=0
C     THESE STATEMENTS ARE TO DETERMINE WHETHER ANOTHER
C     MAXIMUM SHOULD BE COMPUTED
      DO 22 J=MJ,M
      IF(P(I).GT.ABS(A(I,J)))GO TO 22
      P(I)=ABS(A(I,J))
      MM(I)=J
22    CONTINUE
      A(I,K)=TT
18    CONTINUE
      P(IP)=0
      P(JP)=0
C     NEXT 31 STATEMENTS ARE FOR CHANGING THE OTHER ELEMENTS OF A
      DO 23 I=1,M
      IF(I-IP)24,23,25
24    TT=A(I,IP)
```

```
      A(I,IP)=COS*TT+SIN*A(I,JP)
      IF(P(I).GE.ABS(A(I,IP)))GO TO 26
      P(I)=ABS(A(I,IP))
      MM(I)=IP
26    A(I,JP)=-SIN*TT+COS*A(I,JP)
      IF(P(I).GE.ABS(A(I,JP)))GO TO 23
30    P(I)=ABS(A(I,JP))
      MM(I)=JP
      GO TO 23
25    IF(I-JP)27,23,28
27    TT=A(IP,I)
      A(IP,I)=COS*TT+SIN*A(I,JP)
      IF(P(IP).GE.ABS(A(IP,I)))GO TO 29
      P(IP)=ABS(A(IP,I))
      MM(IP)=I
29    A(I,JP)=-TT*SIN+COS*A(I,JP)
      IF(P(I).GE.ABS(A(I,JP)))GO TO 23
      GO TO 30
28    TT=A(IP,I)
      A(IP,I)=TT*COS+SIN*A(JP,I)
      IF(P(IP).GE.ABS(A(IP,I)))GO TO 31
      P(IP)=ABS(A(IP,I))
      MM(IP)=I
31    A(JP,I)=-TT*SIN+COS*A(JP,I)
      IF(P(JP).GE.ABS(A(JP,I)))GO TO 23
      P(JP)=ABS(A(JP,I))
      MM(JP)=I
23    CONTINUE
C     THE FOLLOWING STATEMENTS TEST FOR THE REQUIREMENT OF EIGEN VECTORS
      IF(NN.EQ.0)GO TO 7
      DO 32 I=1,M
      TT=V(I,IP)
      V(I,IP)=TT*COS+SIN*V(I,JP)
32    V(I,JP)=-TT*SIN+COS*V(I,JP)
      GO TO 7
12    RETURN
      END

      SUBROUTINE VORS(NS,NC,CRN,A,B,C,ND)
C     VARIMAX (ORTHOGONAL) ROTATION OF A FACTOR-LOADING MATRIX.
C     NS=NUMBER OF VARIABLES (ROWS)OF THE MATRIX
C     NC=NUMBER OF FACTORS (COLUMNS) OF THE MATRIX.
C     CRN= MATRIX OF LOADINGS TO BE ROTATED
C     A= PERCENTAGES OF VARIATION FOR ROTATED FACTORS.
C     B= COMMUNALITIES FOR VARIABLES, AS PERCENTAGES.
C     C= TEMPORARY STORAGE VECTOR.
C     ND=NUMBER OF ROWS DIMENSIONED FOR CRN IN CALLING PROGRAM.
      DIMENSION CRN(85,85),A(85),B(85),C(85)
      T=NS
      WRITE(*,*)'vors'
C     NORMALIZE ROWS OF CRN.
      DO 5 I=1,NS
      B(I)=SQRT(SUMF(CRN, -I,-NC,ND))
      DO 5 J=1,NC
```

```
    5 CRN(I,J)=CRN(I,J)/B(I)
   10 KR=0
      DO 40 M=1,NC
      DO 40 N=M,NC
      IF(M.EQ.N)GO TO 40
C     COMPUTE ANGLE OF ROTATION.
      DO 15 I=1,NS
      A(I)=CRN(I,M)**2-CRN(I,N)**2
   15 C(I)=2.0*CRN(I,M)*CRN(I,N)
      AA=SUMF(A,1,NS,ND)
      BB=SUMF(C,1,NS,ND)
      CC=SUMF(A,1,-NS,ND)-SUMF(C,1,-NS,ND)
      DD=SCPF(A,C,1,1,NS,ND)*2.0
      XN=DD-2.0*AA*BB/T
      XD=CC-(AA**2-BB**2)/T
      Y=ATAN(XN/XD)
      IF(XD.GE.0.0)GO TO 20
      IF(XN.GE.0.0)Y=Y+6.2832
      Y=Y-3.1416
   20 Y=Y/4.0
      IF(ABS(Y).LT.0.0175)GO TO 40
C     ROTATE PAIR OF AXES
      CY=COS(Y)
      SY=SIN(Y)
      KR=1
      DO 35 I=1,NS
      Q=CRN(I,M)*CY+CRN(I,N)*SY
      CRN(I,N)=CRN(I,N)*CY-CRN(I,M)*SY
   35 CRN(I,M)=Q
   40 CONTINUE
      IF(KR.GT.0)GO TO 10
C     DENORMALIZE ROWS OF CRN.COMPUTE PCT. T AND C.
      DO 50 J=1,NC
      DO 45 I=1,NS
   45 CRN(I,J)=CRN(I,J)*B(I)
   50 A(J)=SUMF(CRN,J,-NS,ND)/T*100.0
      DO 55 I=1,NS
   55 B(I)=B(I)**2*100.0
      WRITE (2,75)
   75 FORMAT ('PERCENTAGE VARIATION FOR ROTATED VECTORS')
      WRITE(2,76)(A(I),I=1,NC)
76    FORMAT(22F15.2)
      WRITE (2,80)(B(I),I=1,NS)
80    FORMAT(22F15.2)
      WRITE(2,81)
81    FORMAT ('COMMUNALITIES FOR VARIABLES AS PERCENTAGES')
      RETURN
      END
```

```
      FUNCTION SCPF (X,Y,KX,KY,N,ND)
C   COMPUTES SUM OF CROSSPRODUCTS (SCALAR PRODUCT) OF TWO VECTORS.
C   X,Y = ARRAYS CONTAINING THE SCORES TO BE USED.
C   THEY MAY BE SENT AS THE SAME ARRAY.
C   KX,KY = ROW OR COLUMN NUMBERS FOR X AND Y, IF MATRICES.
C   SET = 1 IF VECTOR.
C   IF KX OR KY IS POSITIVE AND NOT 1, IT IS A COLUMN NUMBER.
C   IF KX OR KY IS NEGATIVE AND NOT 1, IT IS A ROW NUMBER.
C   N = THE NUMBER OF PRODUCTS TO BE SUMMED,ELEMENTS OF EACH VECTOR.
C   ND = THE NUMBER OF ROWS (OR ELEMENTS) DIMENSIONS FOR BOTH X AND Y
C   IN CALLING PROGRAM.
      DIMENSION X(ND,1),Y(ND,1)
      SCPF = 0.0
      J = IABS(KX)
      K = IABS(KY)
      IF (KX) 5,55,10
  5   IF (KY) 15,55,25
 10   IF (KY) 35,55,45
 15   DO 20 I = 1,N
 20   SCPF = SCPF + X(J,I) * Y(K,I)
      RETURN
 25   DO 30 I =1,N
 30   SCPF = SCPF + X(J,I) * Y(I,K)
      RETURN
 35   DO  40 I = 1,N
 40   SCPF = SCPF + X(I,J) * Y(K,I)
      RETURN
 45   DO 50 I = 1,N
 50   SCPF = SCPF + X(I,J) * Y(I,K)
 55   RETURN
      END

       FUNCTION SUMF(X, KK, NN, ND)
C
C COMPUTES SUM X OR SUM X**2 FROM A VECTOR
C X = ARRAY CONTAINING THE SCORES TO BE USED
C NN = NUMBER OF VALUES TO BE SUMMED.  IF NEGATIVE SUMX**2 COMPUTED
C KK = ROW OR COLUMN NUMBER IF X IS A MATRIX  SET = 1 IF X IS A VECTOR
C IF KK IS POSITIVE AND NOT 1, IT IS A COLUMN VECTOR
C IF KK IS NEGATIVE AND NOT 1, IT IS A ROW VECTOR
C ND = NUMBER OF ROWS (OR ELEMENTS) DIMENSIONED FOR X IN THE CALLING PR

      DIMENSION X(ND,1)
      SUMF=0.0
      N=IABS(NN)
      K=IABS(KK)
      IF (NN)  5,55,10
    5 IF (KK) 15,55,25
   10 IF (KK) 35,55,45
   15 DO 20 I =1,N
   20 SUMF = SUMF + X(K,I)**2
      RETURN
   25 DO 30 I= 1,N
```

```
30 SUMF = SUMF + X(I,K)**2
   RETURN
35 DO 40 I = 1,N
40 SUMF = SUMF +X(K,I)
   RETURN
45 DO 50 I = 1, N
50 SUMF = SUMF +X(I,K)
55 RETURN
   END
```