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SECOND AUTUMN WORKSHOP ON
CLOUD PHYSICS AND CLIMATE

(23 November - 18 December 1987)

MONSOON METEOROLOGY

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LECTURE NOTES - ICTP COURSE ON CLOUD PHYSICS AND CLIMATE: NOV - DEC 1987.

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1. Introduction

The single most conspicuous weather system is the annual cycle of monsoon over Asia. Though the monsoon is a regional phenomenon, it plays significant role in the atmospheric general circulation.

Historians have traced the origin of the term "monsoon" to the Arabic word "Mausim". This Arabic word "Mausim" is used for any thing that comes around but once a year, a fixed time, a season. The word was first used by sailors for many centuries to describe a system of the seasonal reversal of wind direction along the shores of the Indian Ocean, especially in the Arabian Sea. Over the Arabian Sea winds blow from the southwest for six months of the year and from the reverse direction, northeast, for the remaining six months. Several historical references have been made to the seasonal reversal of winds over India and other parts of Asia.

The seamen's concept of monsoon as periodic wind reversal failed to take into account the other major aspect of the monsoon: "the rainy season". According to Sanskrit literature as well as to folk knowledge, the monsoon is indeed the result of a periodic reversal, but the realization of this reversal is with the sun and rains, not winds. The early Aryans, who settled throughout norther India around 4000-1000 B.C., had known of a rainy season which occured over northern India with surprising regularity every year.

As monsoons have come to be better understood, the definition has been broadened to include almost all of the phenomena associated with the annual weather cycle within the tropical and subtropical continents of Asia, Africa and Australia. It is within these regions that the most vigorous and dramatic cycles of weather events on the earth take place.

The annual cycle of the monsoon systems lead the weather process over the region into two distinct phases: the "Wet" and the "Dry". The wet refers to "the rainy season" during which warm, moist and very disturbed winds blow inland from the oceans. The dry refers to the other half of the year, when the winds reverse bringing cool and dry winter air from the hearts of the winter continents. The cross equatorial flows at some locations along the equator link the dry of the winter monsoon to the wet of the summer monsoon, and vice versa.

The dominant characteristic of the great monsoon systems have exercised the minds of priests, writers, physicians, musicians, painters as well as philosephers and astrologers over the centuries and reflected in the every way of lives, such as, agricultural activities, economics, diets, customs,social cultures and festivals of the inhabitants of the region - there exists a fundamental alternation between the "Dry"and the "Wet" principles.

This field has attracted a considerable interest in the recent years. Further, recent studies on monsoons have been greatly encouraged by a series of international experiments, such as International Indian Ocean Expedition (IIOE) of 1963-65, Indo-Soviet Experiments (1 MEX) of 1973, Monsoon 1977 and Monsoon Experiment (MONEX) of 1979 (Part of FGGE Special Observation Period-I and II).

Works on monssonal evolution,dynamics,energetics, climatology, variability and short,medium and long-range prediction in regional and global scales have been explored in a large series of papers/publications by a number of groups. In the lecture series it is planned to give brief review of the major results obtained on monsoon climatology, variability, flow characteristics, numerical simulation, short, medium and long-range prediction of monsoon. The central problem in the monsoon studies is the veriability of monsoon rainfall, that is because of its association with droughts and floods. Therefore, major emphasis is given to the summer monsoon (SWSM).

A number of important publications on these topics are:

(i) Monsoon Meteorology, Ramage, 1971

(ii) Southwest Monsoon, Rao, 1976

(iii) Monsoon Meteorology, edited by Krishnamurti,1977

(iv) Monsoon Dynamics,edited by Lighthill and Pearce, 1980

(v) Monsoons, Das, 1976

(vi) Asian Summer Monsoon Circulation Statistics 1979-84, Mohanty,Hollingsworth and Dash,1985

(vii) Monsoons,edited by Fine and Stephens, 1987

2. Geographical Extent of Monsoon

The monsoon phenomenon has global as well as regional manifestations. To define the geographic extent of the monsoon we must first decide upon a definition of what constitutes a monsoon climate. Although monsoon is defined by the reversal of winds, their importance largely arises on account of rainfall. Therefore a most common definition uses characteristics of the annual variation of both wind and rainfall.

By these criteria, to be a monsoon climate, the following four principal features in the wind pattern are suggested by Khromov (1957) and Ramage (1971):

(a) A change in the prevailing wind direction by 120^0 between January and July;

(b) The average frequency of prevailing wind directions in January and July should exceed 40 per cent;

(c) The mean resultant winds in at least one of the months should exceed 3 MS^{-1};

(d) There should be fewer than one cyclone-anticyclone alteration every two years in either month in a five-degree latitude-longitude grid.

Thus, in general, the winds blow inland from the cooler oceans toward the warm continent during summer (Southwest Summer Monsoon SWSM) and from the cold continent toward the warm oceans or land areas during winter (Northeast winter monsoon NEWF). Such characteristics emphasize the seasonal nature of changes in wind direction and the persistence of the wind regime in each season. The change is not brought about by variation in the track of moving pressure systems, such as tropical cyclones. This definition, as stated above, is not related to rainfall.

The definition, to be a monsoon regime, with respect to the rainfall,it usually requires that the summer season (SWSM) must be very wet and the winter reason (NEWM) very dry.

The region where all of these criteria are met lies within the rectangles shown as dashed lines in the Figure 1 (Webster, 1987). Almost all of the Eastern Hemisphere of the tropics is included in the definition. Thus about one half of the tropics or one quarter of the surface area of the entire globe may be defined as a monsoon climate.

3. Driving Mechanisms of the Monsoon

The summer monsoon is an atmospheric process in which the dry hot air prevailing over the continent (Asia) in April and May has been completely replaced by very moist equatorial, oceanic air, upto an altitude of three to five kilometers. Naturally occuring physical processes taking place within this moist air causes the rainfall (the rainy season). The replacement of the premonsoon dry hot air over the continent by the deep moist equatorial oceanic air is a gradual process and marked by violent wind, lightning, thunder, strong up and down currents of air and moderate to heavy rain (called "pre-onset thunderstorm"). This process of replacement of dry air by the very moist air is called "onset of the monsoon".

The fundamental driving mechanisms of the large-scale monsoon are:

(a) The differential heating of the land and ocean and the resulting pressure gradient that drives the winds from high pressure to low pressure.

(b) The swirl introduced to the winds by the rotation of the earth.

(c) The deep moist processes that deternine the strength, vigor, and location of the major monsoon precipitation by storing, redistributing, and selectively releasing, in the visinity of the heated continents.

It is interesting to note that the first and second fundamental physical processes were identified and explained nearly 300 years ago by Halley (1686) and Hadley (1935).

The primary driving force for the annual cycle of monsoon: the differential heating between land and sea is mainly a result of solar heating. The differential heating results from a combination of the following two factors:

(a) The variation in space and time of the solar heating of the earth system that results from (1) the annual cyle of the sun and (ii) the characteristics of the earth's surface at a particular location (mainly land and water bodies).

(b) The spatial and temporal variation of the cooling of the earth to space.

Thus the differential heating at a particular location is actually the net radiative heating, which is the sum of heating from sun and the cooling of the earth to space.

The amount of energy received from the sun at the surface depends on the intensity of the incoming solar radiation and the length of the day (due to spherical shape of the earth, tilt of the earth's axis=24° and the rotation of the earth about the sun).

The heat loss from the earth's surface and the atmosphere to space depends on the temperature of the systems.

The distribution of the incoming solar radiation and the loss of the earth radiation to space as a function of latitude in the Northern Hemisphere (a) summer and (b) winter are reproduced here from Webstar, 1987 (Figure 2).

It is clear from Fig.2 that in general the winter hemisphere loses far more heat in the net than it gains. On the other hand, the summer hemisphere accumulate far more heat than it loses. As a result, a strong differential radiative heating exists between the summer and the winter hemispheres. In practice no such accumations or losses of heat do not occur and a transport of heat from the regions of heat abundance to regions of heat deficit takes place.

Another important aspect is the land-ocean heating contrast. With same amount of heat available to equal areas of ocean and land, the impact on the temperature of each area would be very different. In fact, due to the following two different physical properties of oceans and land, the rise in land temperature would be far greater than that over the ocean. They are:

(a) The specific heat of water (1.0 cal Cm^{-3} ^oC) is twice that of dry soil (0.5 Cal Cm^{-3} ^oC). Of course a wet land with increased precipitation have specific heat of about 0.8 cal Cm^{-3} ^oC.

(b) The effective heat capacity (a measure of a system as a whole to store heat) is many orders of magnitude larger for the ocean than for land.

Further, there is a fundamental difference in the manner in which land and ocean react to heating and cooling. It is mainly due to the way each can transfer itself and store heat internally. As for example, heat transfer through solids (land areas) is accomplished only by molecule to molecule diffusion of heat which is very inefficient and slow process. In case of fluids (oceans) along with molecular diffusion, very efficient process of turbulent mixing or stirring transfer heat.

All these factors lead to the establishment of differential heating between land and ocean.

Now we shall consider how heating patterns are converted into the motion field we call the monsoon. The processes involved for conversion and establishment of monsoon flow are :

(a) The creation by differential heating of regions with different potential energies

(b) Resulting in the creation of a body force, in this case the pressure gradient force.

(c) Atmospheric motion produced by work done by the pressure gradient force that converts the potential energy into kinetic energy.

Though the differential heating of the land ocean is the primary driving force to initiate the monsoon flow, the impact of the earth's rotation in the form of Coriolis force gives rise to southwest and northwest monsoon currents.

The moisture process plays a very crucial role. The physical processes of evaporation, formulation of clouds, release of latent heat and precipitation associated with the hydrological cycle increase the intensity of the monsoon circulation and provide an upper limit on its intensity. A positive feed back mechanism in the atmoshere. As far as the land surface is concerned, the major impact of moist processes is to wet the ground which leads to a cooling of the land due to increase of specific heat and increase of evaporation. It provides a negative feed back mechanism to mansoon intensity (as land becomes more "ocean-like") leads to (i) inner landward movement - progress of monsoon and (ii) break in monsoon. After a few days the land again dries out and warms up and leads to revival or active monsoon phase. Thus land surface moist process adds a variability - active and break epoches of monsoon.

Thus, if we consider only differential heating, moist processes and rotation of the earth, it appears that the essence of the diserved monsoon circulation and structure can be explained. It pertains to only a very broad structure of monsoon. In reality there exist a dramatic variability of monsoon which can not be explained by using only a few elementary physical principles.

The components of heating that are important for the monsoon are :

(A) Heat Balance of Land Area (Including the elivated Tibetan Platean):

(a) sensible heat flux from the land surface.

(b) latent heat flux from the land surface.

(c) incoming minus outgoing (or reflected) shortwave radiation,

(d) incoming minus outgoing longwave rediation.

(B) Air-Sea Interaction i.e. fluxes of latent and sensible heat from the Ocean.

(C) Heating with the atmosphere which includes warming (or cooling) by the following process:

(a) deep convection,

(b) shallow moist and dry convection,

(c) longwave radiation,

(d) shortwave radiation,

(e) adiabatic processes.

Among the above processes the more important are : deep convection, all of the elements of heat balance of the Earth's surface, evaporative fluxes from the ocean and the adiabatic warming and cooling within the atmosphere.

4. Planetary-Scale Monsoons

The plannetary component of the monsoon is defined by large-amplitude quasi-stationary long-waves of the tropical circulation. It is described by a first few zonal harmonics of the tropical stream function field in the latitude belt 10^{O}N to 30^{O}N (Fig.3 and 4). Observations during the norther summer monsoon season show that about 50% of the variance on these scale is carried by the quasi-stationary components. The pressure fields in the lower and upper troposphere appear to be nearly out of phase with respect to each other.

The principal components that contribute to the planetary-scale monsoons are given in table 1.

Table 1: Quasi-stationary Planetary-scale Monsoons

Parameters	Southwest Summer Monsoon	Northeast Winter Monsoon
1. Pressure Lower Troposphere	Monsoon trough over India	Sub-tropical high
2. Pressure Upper Troposphere	Tibetan high	Mid-ocean trough
3. Tropospheric Thermal Field	Warm	Cold
4. Tropospheric Moisture Field	Moist	Dry
5. Large-Scale Velocity Field	Upward	Downward
6. Divergence circulation in the upper troposphere	Outflow	Inflow
7. Heating of the troposphere	Net heating	Net cooling
8. Cloudiness	Clud covered	Relatively cloud free
9. Mean winds at 200mb	Easterly (Tropical Easterly Jet TEJ)	Westerly (Sub-tropical Westerly Jet STWJ)
10. Mean Surface winds	Southwesterly (Somali Jet)	Northeasterly

The climatological features given here essentialy describe the zonally asymmetric planetary-scale monsoons. It is well recognised that an understanding of the planetary-scale monsoons requires a detailed knowledge of the heat sources and sinks.

5. Elements of Summer and Winter Monsoon Systems C.Krishnamurti, 1979.

The common elements in both the large-scale summer and winter monsoonal gyres include low-level flows from a large high-pressure area (1) to a monsoon trough (2). The flows accelerate occasionally between 1 and 2 and a low level wind maximum (3) (a jet or a surge) is frequently noted. Large areas of cloudiness and ascent (4) are a characteristic of the monsoon trough. The general rising air diverges out of an upper anticyclone (5) along an upper-level jet stream (6). These six major elements of the monsoon thus comprise a complex local Hadley-type vertical circulation. These are illustrated schematically in Figure 5. We may tentatively equate the roles of:

(1) The Mascarene high of summer with that of the Siberian high of winter.

(2) The monsoon trough over northern India during summer with that of the trough over Indonesia during northern winter;

(3) The cross-equatorial low-level jet (somali jet) over East Africa during northern summer with the lower tropospheric surges in the winter monsoon;

(4) The summer monsoon rainfall and cloud cover over northern India with its counterpart near souther. Malaysia and Indonesia during winter;

(5) In the upper troposphere, the Tibetan high of summer with the western Pacific high of the winter;

(6) The monsoonal tropical easterly jet (TEJ) stream of summer with subtropical westerly jet (STWJ) stream of winter.

These features describe broad-scale monsoon systems.

A major difference between the two systems is in the gometry of the underlying surface;

(i) In the summer monsoon the general ascent and rainfall occur over warm land areas (SE Asia) while the descent occurs over the southern oceans (Indian Ocean).

(ii) During the winter monsoon the general ascent and rainfall occur over a marine environment (Northeast Indian Ocean and western Pacific) while the descent occurs over the land areas over eastern Asia and all the way to Siberia.

It seems that a crucial element in the driving mechanism for the summer monsoon is the shortwave radiative warming over the land areas; while it is the longwave cooling over the land areas that seems to be more important for the winter monsoon.

NORTHERN HEMISPHERE SUMMER MONSOONS

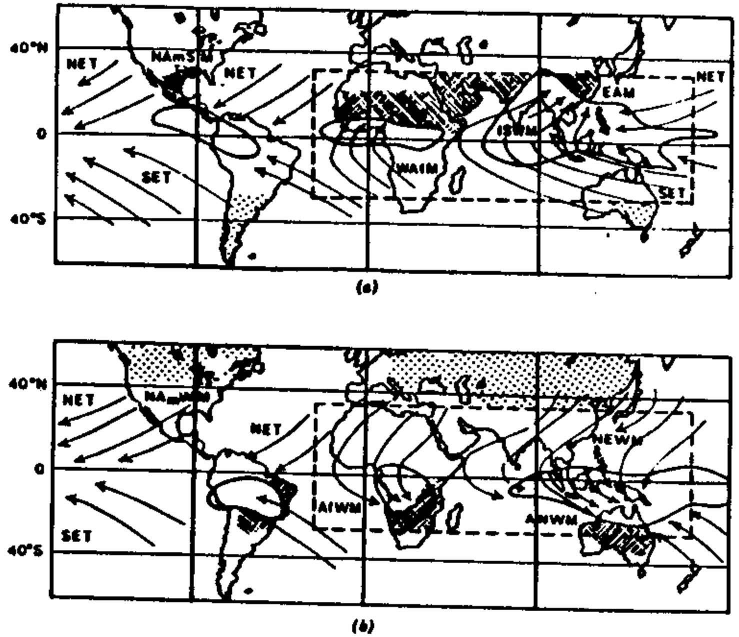

Fig. 1 The domains of the principal monsoon systems of the atmosphere during the Northern Hemisphere summer (a) and winter (b). Using the criteria of seasonal wind reversal and distinct wet summers and dry winters, the monsoon region is outlined by the dashed rectangle (1). The main surface wind and areas of maximum seasonal precipitation are indicated as arrows and shaded areas, respectively. The cross-hatching shows the land areas with maximum surface temperatures and the stippling indicates the coldest land surfaces. Key monsoon and tropical systems are indicated. NET and SET refer to the northeast and southeast tradewind regimes. EAM, ISWM, WAfM, and NAmSM indicate, respectively, the East Asia Monsoon, the Indian Southwest monsoon, the West African Monsoon, and the North American Summer Monsoon. NEWM, ANWM, NAmWM, and AfWM show the locations of the northeast Winter Monsoon, the Australian Northwest Monsoon, the North American Winter Monsoon and the African Winter Monsoon. Although often referred to as a monsoon region, the southwestern United States experiences a significant winter rainfall maximum in addition to the summer rainfall. Thus the North American monsoon system fails the precipitation criterion and is included here for interest only.

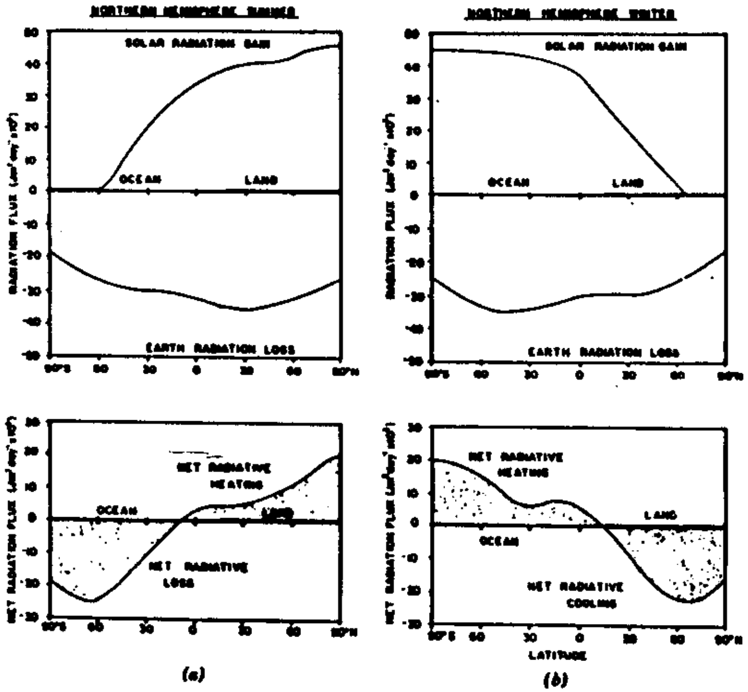

Fig 2 The distribution of the incoming solar radiation and the loss of the earth radiation to space as a function of latitude; distributions for the Northern Hemisphere summer (*a*) and winter (*b*). For each season, the upper curve shows the gain of radiation from the sun by the earth system. The radiation loss by the earth system to space is shown as the curve along the negative axis. The lower diagrams show the *net* radiative heating (i.e., the sum of the solar radiation input and the earth radiation loss) gained or lost by the earth system. The winter hemispheres lose more energy to space than they gain from the sun whereas the summer hemispheres gain more than they lose (units: $Jm^2/day \times 10^3$).

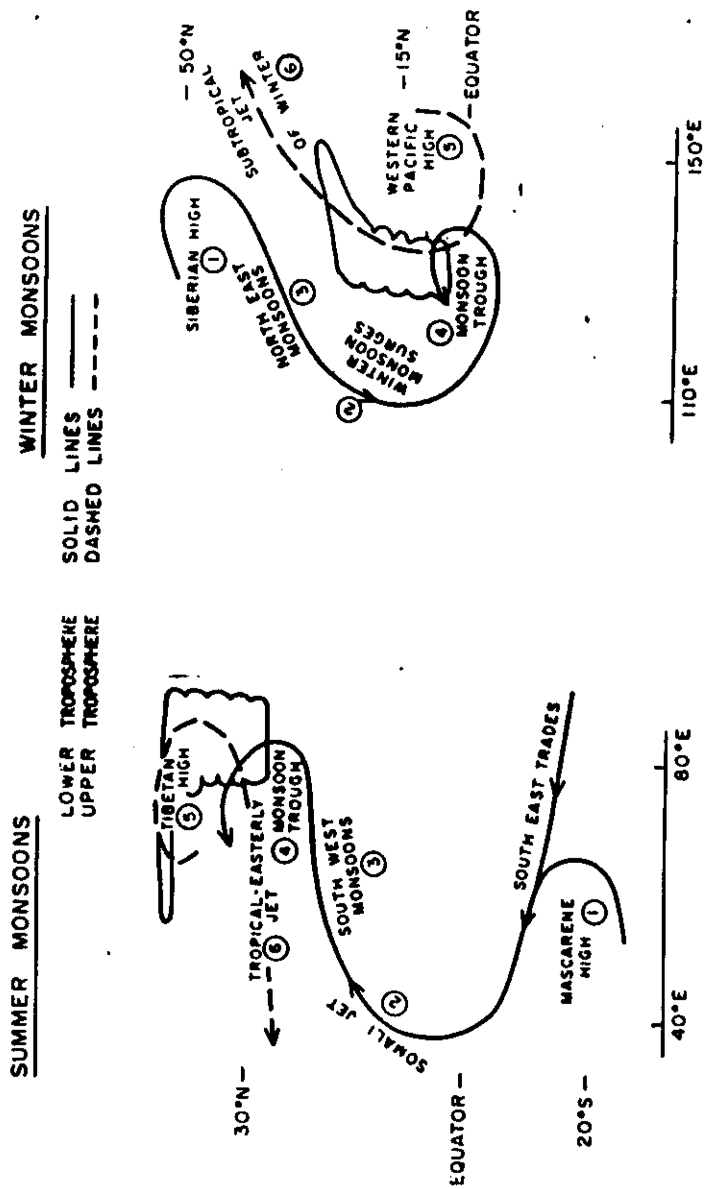

Fig 3 A schematic distinction, summer and winter monsoons

Circulation Statistics and Climatology

We have confined our discussion on large scale circulation statistics and climatology to the Summer Monsoon period.

1. Asian Summer Monsoon Circulation Statistics

Distribution of selected atmospheric circulation statistics for the months of May through August based on the ECMWF analyses for the period 1979-1984 are illustrated over the tropical eastern hemisphere (0^oE-180^oE and 45^oS-45^oN). The statistics for individual months and the season June-August are presented. Further, in order to have a better understanding of the different epoches of the monsoon, the four months are divided into eight periods of 15-16 days duration, and the diagnostics are computed for each period.

A brief description of the data set and analysis procedure along with the results on the large-scale features of the Asian Summer Monsoon are presented in Appendix A.

Regional Climatology

After discussion on broad large-scale features of the monsoon, here we will describe the mean distribution of some important climatological elements during the summer monsoon over the Indian sub-continent and adjoining seas.

The results and discussions on this aspect are mainly based on the materials presented in the monographs by Ramage, 1971 and Rao, 1976 and presented in Appendix B.

ASIAN SUMMER MONSOON

CIRCULATION STATISTICS: 1979-1984

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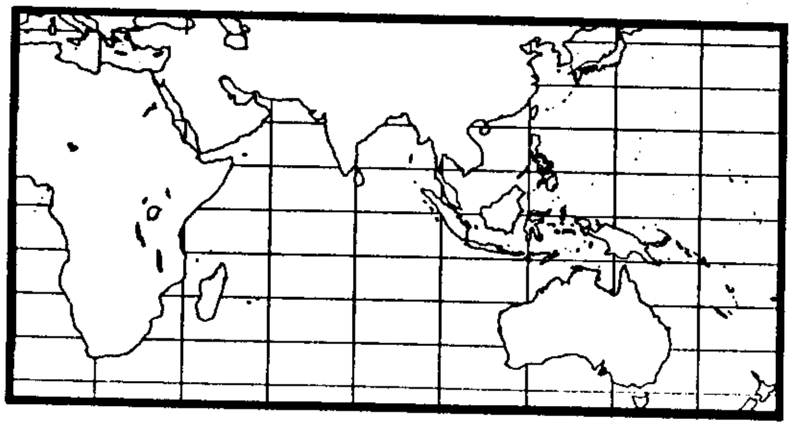

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June 1985

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Abstract

With the provision of geostationary weather satellites during and after the Global Weather Experiment (FGGE) in 1979, a large body of meteorological data became available over the otherwise data-sparse tropical regions. These data have been analysed at ECMWF using a modern data assimilation system. We present statistics on the Asian Summer monsoon based on ECMWF analyses from 1979 through 1984. Study of these statistics may help in understanding and ultimately in predicting the evolution of the Asian Monsoon. A geostationary satellite was positioned over the Indian Ocean during 1979. The European satellite Meteosat and the Japanese satellite Himawari have been available for most of the period since 1979, although they only provide coverage of part of the region of interest. Data from the Indian satellite Insat B began to be available in late 1984.

1. INTRODUCTION

The Asian summer monsoon is an important atmospheric phenomenon occurring every year from June to September. The land-sea heating contrast in summer is the main driving force for the monsoon circulation. The behaviour of the monsoon depends on many inter-dependent atmospheric processes. It is of critical importance for rainfall in the Indian subcontinent. The agriculture in this region depends very much on the timely distribution of appropriate amounts of rain. The monsoon may be discussed in terms of the onset phase, active or break periods and the withdrawal phase. Opinions differ on what constitutes the onset of monsoon. In general, the date of onset over the Indian peninsula is determined on the basis of a sharp increase and characteristic persistence in the rainfall over the southwest coast of India (Ananthakrishnan et al., 1968). The normal date of onset is 31 May. However, a survey of nearly 70 years of Indian rainfall data indicates that the extreme dates for the onset of rain over the southern tip of India are 11 May and 15 June (Das, 1984). The onset depends on a series of earlier events such as the change in the circulation pattern, and on the heat and moisture content of the atmosphere over the Arabian Sea (Mohanty et al., 1983). A zone of high pressure builds up over the Indian Ocean in May; in some years the high is more pronounced than others. About a week prior to the onset the Northern Hemisphere westerly jet moves to a new location north of the Himalayas and an easterly jet is established over the Indian peninsula. Monsoon rains first set in over southern India in early June and move northwards until they cover the entire subcontinent by mid-July. During a monsoon season there are periods of precipitation extremes; there are spells of reduced rainfall, and of floods, which have no regularity. The withdrawal of the monsoon begins from the north to the south. Given the shorter duration of monsoon over the northern than the southern regions of India, it is plausible that the rainfall variability is generally higher over the north.

The behaviour of the monsoon can be studied through the statistics of important meteorological parameters such as the wind, geopotential height, temperature/thickness, vorticity, divergence and the meridional fluxes of heat and moisture, etc. over a considerable length of time, and over the monsoon region. With the success of the global experiment (FGGE) in 1979 and the continued availability of some geostationary weather satellites, we have a large volume of data available over the tropical data sparse regions. The analysed fields used here are produced by a sophisticated data assimilation system. The statistics of the summer monsoon based on those analyses will be helpful for better understanding and, ultimately, prediction of the monsoon.

With this aim in mind, we have used the ECMWF analysed data from 1979 till 1984. We have prepared statistics of some relevant fields in the monsoon region for the months of May through August. In order to have a better understanding of the different phases of the monsoon, the four months are divided into eight periods of 15-16 days duration, and the diagnostics are computed for each period. The anomaly of the vector wind in each month and season from the six year mean fields are also presented. We believe, these statistics will be useful to scientists interested in studies of the Asian Summer monsoon.

2. DATA SET

The data base used for producing the statistics reported here comprises the 1979 FGGE level III-b analyses and the 1980 to 1984 operational analyses produced at ECMWF. The 1200 GMT values of the zonal and meridional winds, temperature, geopotential height, vertical velocity and relative humidity/specific humidity for the region from 45°S-45°N latitudes and 0°E-180°E longitudes at ten pressure levels (1000, 850, 700, 500, 400, 300, 200, 150, 100 and 50 mb) for the months May to August are used as basic

data for the computation of circulation statistics of the various phases of the monsoon. The geographical region of study covers the monsoon regime as defined by Ramage (1971).

The analysed fields are produced by a four-dimensional multivariate data assimilation scheme described in detail by Bengtsson et al. (1982) and Shaw et al. (1984). In this scheme the assimilation is carried out in three steps viz., multivariate optimum interpolation, nonlinear normal mode initialisation and six hours' forecast which provides the first guess for the subsequent analysis. In the last six years a number of improvements have been incorporated in this data assimilation procedure. Some of the more noteworthy changes are the introduction of interpolation of analysis increments from 10 December 1980, diabatic initialisation from 21 September 1982 and revised optimum interpolation statistics (structure functions) from 22 May 1984 (Shaw et al., 1984). Although these modifications will be reflected in the statistics presented here, the mean mass and velocity fields are not affected very much.

The mass and velocity fields are analysed by a three-dimensional multivariate optimum interpolation scheme with a geostrophic constraint in the extra-tropics. The humidity fields are analysed at six levels (1000, 850, 700, 500, 400 and 300 mb); the variable analysed for this purpose is the precipitable water content for the five layers. It may be noted that during the 1980 monsoon the humidity analysis was identical to the first guess. The temperature is derived from the thickness using the hydrostatic relation; the vertical velocity is obtained from the mass continuity relation. Initialised analyses are used for deriving both the temperature and the vertical velocity. The mass, velocity and humidity used are the uninitialised fields for 1979, 1983 and 1984 whereas for the years 1980, 1981 and 1982 all the fields are the initialised ones. While studying the statistics reported here, one should remember the above stated nonuniformity in the basic data set during the six year period considered.

3. COMPUTATIONAL PROCEDURE

Long term statistics show that the onset date of the summer monsoon over the Indian subcontinent may be delayed or advanced by as much as 15 days from its climatologically normal date which is considered to be 31 May at the Kerala coast. After the onset of the monsoon over the southern tip of India, it normally takes two weeks for the monsoon to cover the major part of the Indian land mass, except for north west India and Pakistan (Fig. 1a). We feel it appropriate to calculate the statistics of the analysed fields by dividing the period from May to August into eight phases of 15-16 days each as categorised below.

Pre-onset phase	:	Period A from 1 May to 15 May
Onset phase	:	Periods B and C from 16 May to 15 June
Established phase	:	Periods D, E and F from 16 June to 31 July
Last phase	:	Periods G and H from 1 August to 31 August

However, the complete withdrawal of the monsoon from the Indian subcontinent is not so abrupt as its onset, and the retreat process takes about three months (Fig. 1b).

Six-year (1979 to 1984) mean values of the basic fields, zonal wind (u), meridional wind(v), geopotential height (ϕ), temperature (T), humidity (q); some of their cross products uv, uT, vT, ωT, uq, vq and ωq; as well as a few important derived fields like relative vorticity and divergence are calculated for each of the eight periods, and for the period 1 June to 31 August (Period I). For calculating heat and moisture budgets we have preferred to estimate the omega field from the horizontal winds by a kinematic method

rather than using the archived omega values from the initialised fields. A number of techniques are available for the kinematic estimation of vertical motion (e.g. O'Brien, 1970 and Kung, 1973). In this study O'Brien's kinematic technique is adopted to estimate the omega profile; this ensures that the vertically integrated divergence over the entire atmospheric column (1000 to 50 mb) vanishes.

In pressure coordinates the total potential energy (heat energy) and latent heat energy budget equations may be written in flux form as

$$\frac{\partial(C_p T)}{\partial t} + \nabla.(C_p T\underline{V}) + \frac{\partial}{\partial p}(C_p T\omega) - \omega\alpha = Q_s$$

$$\frac{\partial(Lq)}{\partial t} + \nabla.(Lq\underline{V}) + \frac{\partial}{\partial p}(Lq\omega) = Q_L$$

The symbols used here are defined in Table 1.

In long term climate studies one can neglect the time rates of change; and, except in mountainous regions, omega at the top and the bottom boundaries of the atmosphere can be assumed to vanish. Therefore, the vertically integrat budget terms in the atmospheric column may be expressed as,

$$\widehat{\overline{\nabla.(\underline{V}T)}} = \frac{\widehat{\overline{\omega\alpha}}}{C_p} + \frac{\widehat{\overline{Q}}}{C_p}$$

$$\widehat{\overline{\nabla.(\underline{V}q)}} = \widehat{\overline{E}} - \widehat{\overline{P}}$$

Here $\overline{}$ and $\widehat{}$ denote the time average and vertical integration respectively.

Here:

Q_S : Net effect of all diabatic contributions to sensible heat = $Q_R + Q_P + Q_{TS}$.

Q_L : Net effect of all diabatic contributions to latent heat = $Q_{TL} - Q_P$.

Q_R : Diabatic heating due to radiative effects.

Q_P : Latent heat released due to the net effect of condensation C and evaporation E.

Q_{TS} : Diabatic heating due to vertical eddy transfer.

Q_{TL} : Latent heat flux convergence due to vertical eddy transfer (which, when integrated vertically, is determined by the evaporation at the surface)

C_p : Specific heat at constant pressure

L : Latent heat of evaporation

α : Volume density

T : Temperature in °K

ω : Vertical motion in 10^{-3} Pa s^{-1} (approx. mb day $^{-1}$)

$\underline{V}$: Vector wind in m s^{-1}

Table 1: List of symbols

The diabatic heating due to radiation, condensation and turbulent processes (Q), and the moisture source/sink ($\overline{E} - \overline{P}$) are estimated as residues from the above equations. E and P stand for evaporation and precipitation respectively. In all these computations space derivative terms are discretised by centred (second order) finite differences, while the trapezoidal rule has been used in the vertical and horizontal integrations.

4. SCOPE OF THE ATLAS

During different phases of the summer monsoon we depict the major changes in the circulation pattern in the lower and the upper troposphere, using data at 850 mb and 200 mb pressure levels respectively. For each of the nine periods (A to I) the spatial distribution of the fields of wind, geopotential height, temperature, vorticity, divergence, vertical velocity, kinetic energy and specific humidity (only at 850 mb) are illustrated at both 850 mb and 200 mb levels. Since major changes take place over the Arabian Sea with the establishment of the low level Somali Jet and upper level Tropical Easterly Jet, we present meridional cross-sections of zonal wind, meridional wind, vorticity and vertical velocity, as well as meridional transports of heat and moisture by the mean flow and eddies, averaged over the sector (45°E -75°E).

Since the increase of differential heating and the build-up of moisture over the Indian Ocean and adjoining land mass plays a very crucial role in the establishment of the summer monsoon, we also present the net tropospheric horizontal heat flux divergence, adiabatic enthalpy source, horizontal moisture flux divergence and diabatic heating (calculated as a residual) for each of the nine periods. The net tropospheric moisture (net precipitable water in the layer 1000 to 300 mb) and mean tropospheric temperature with their zonal asymmetries (deviations from the global mean) are also illustrated. The anomalies of individual months and seasons in the vector wind at 850 mb and 200 mb from their six year averages are reported in the last section.

5. BROAD CHARACTERISTICS OF THE STATISTICS

The discussion in this section is not a comprehensive review of the vast amount of information contained in the accompanying figures. We have attempted only to describe some of the obvious general features of the monsoon circulation.

Wind: The summer monsoon is associated with the establishment of a strong low level cross-equatorial flow off the east coast of Africa extending up to 500 mb, called the Somali Jet, and an upper tropospheric equatorial easterly jet known as the Tropical Easterly Jet (Koteswaram, 1958). A comparison of the spatial distribution of wind in the different phases shows a rapid intensification of both lower and upper level flows in phase C. These flows are strengthened/maintained in the subsequent phases D-G. During the last phase (H) the low level flow is seen to weaken. These facts are also brought out by the zonally averaged values of zonal wind (45°E - 75°E) at different levels. The averaged values of the meridional wind show the low level southerly and upper level northerly flows during the monsoon months.

Geopotential height: The geopotential height analysis at 200 mb during different time sequences shows the development of an upper tropospheric high during phase C which gradually covers the entire Indian subcontinent. This high is also reflected in the thickness of 1000-500 mb layer. Similarly at

850 mb, the Indian Monsoon low becomes organised in phase C and is strengthened/maintained during the successive phases until phase H, when it begins to dissipate.

Temperature: The temperature field shows that the Indian peninsula begins to heat up in May and this heating gradually spreads northwards, covering the Indian subcontinent. The heat low over north west India coincides with the pressure low there during the established monsoon. The mean tropospheric temperature and the zonal asymmetry in the mean temperature brings out clearly the fact that during the monsoon the temperature of the atmosphere over north west India and Pakistan increases, indicating a strong differential heating gradient.

Omega: The computations of omega show rising motion over southeast Asia during the established monsoon periods. The averaged values of omega over the Arabian sea region clearly depicts strong rising motion at the lower troposphere between 10° and 25°N latitude.

Divergence: With the establishment of the monsoon, low level convergence and upper level divergence are seen over eastern India and other south east Asian countries. In the Himalayan region there seems to be development of noise in the calculations due to orography.

Kinetic energy: With the strengthening of the low level and upper level flows the mean kinetic energy also increases during phase C and remains high during the established phase of the monsoon.

Vorticity: As the monsoon becomes established, the upper level anticyclonic vorticity intensifies from $-10 \times 10^{-6}\ s^{-1}$ to $-30 \times 10^{-6}\ s^{-1}$.

At low levels, positive vorticity is built up over the Arabian sea and the adjacent land mass. This sharp vorticity build up is clearly seen in the zonally averaged values over the Arabian Sea at different levels.

Diabatic heating: The diabatic heating is calculated as the residue in the budget equation. Hence the magnitude of the diabatic heating is sensitive to the approximations made in the other terms of the energy equation. However, qualitatively the distribution of diabatic heating agrees with the general pattern of the monsoon circulation. From phase C onwards, one finds that the net tropospheric diabatic heating increases over India and adjoining areas of south east Asia. The maximum values occur during the active phase of the monsoon, due to the strong latent heat release through condensation of water vapour.

Moisture: The variable we use to depict the tropospheric moisture field is the net precipitable water. With the advance of the monsoon there is a strong moisture build up over India and adjoining areas of south east Asia. The zonal asymmetry of net moisture clearly brings out the area of maximum moisture build up. The same region also shows the maximum diabatic heating. From phase C onwards there is moisture flux convergence over the Indian land mass accompanied by divergence over the Arabian Sea and Indian Ocean which weakens in phase H.

Heat budget: With the intensification of monsoon flow in phase C the south-east Asian region changes from having a negative to a positive net adiabatic enthalpy anomaly. The increase in the net enthalpy may be

attributed to the enhancement of the condensation of water vapour and of turbulent processes close to the surface. With the onset of monsoon there is a net horizontal heat convergence over the region. This is clearly indicated in the time sequence diagrams.

Meridional transports of temperature and moisture: The zonal averages of the meridional transports of temperature and moisture by the eddies and mean flow over the Arabian sea region are illustrated in each of the nine periods. It is seen that the mean flow is mainly responsible for the meridional transports. This is a characteristic of the flow pattern in the tropics. Starting with the onset phase, the low level meridional transports increase and persist through the active phases of the monsoon. Large cross-equatorial transports are seen to be associated with the low level cross-equatorial flow.

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PRESENTATION OF STATISTICS AND THEIR UNITS

The statistics are presented in the following format in each of the periods A to I and in the last section the wind anomalies are reported.

1.

Wind at 200 mb ($m\ s^{-1}$) Geopotential height at 200 mb (dm)	1000-500 mb Thickness (dm) Temperature at 200 mb (K)

2.

Wind at 850 mb ($m\ s^{-1}$) Geopotential height at 850 mb (dm)	Specific humidity at 850 mb (mm) Temperature at 850 mb (K)

3.

Omega at 200 mb (10^{-3} Pa s^{-1}) Divergence at 200 mb (10^{-7} s^{-1})	Relative vorticity at 200 mb ($10^{-6} s^{-1}$) Kinetic energy/unit mass at 200 mb ($m^2\ s^{-2}$)

4.

Omega at 850 mb (10^{-3} Pa s^{-1}) Divergence at 850 mb (10^{-7} s^{-1})	Relative vorticity at 850 mb ($10^{-6} s^{-1}$) Kinetic energy/unit mass at 850 mb ($m^2\ s^{-2}$)

Meridional-height cross-sections (zonally averaged in the region of 45°E-75°E).

5.

Zonal wind ($m\ s^{-1}$) Meridional wind ($m\ s^{-1}$)	Relative vorticity ($10^{-6} s^{-1}$) Omega (10^{-3} Pa s^{-1})

Meridional-height cross-sections (zonally averaged in the region of 45°-75°E)

6.

$\overline{v'T'}$ (K m s^{-1}) $\overline{v'q'}$ (mm m s^{-1})	$\overline{vT}$ (K m s^{-1}) $\overline{vq}$ (mm m s^{-1})

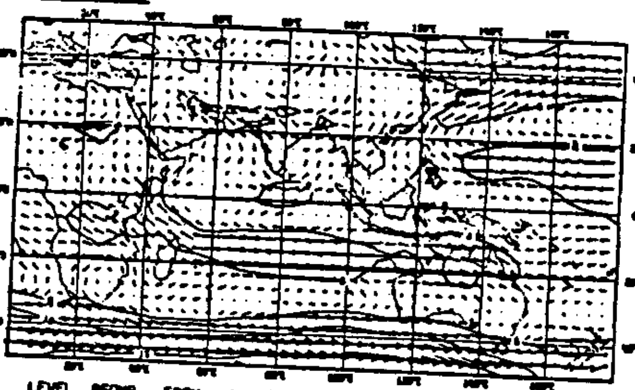
7.

Net horizontal heat flux divergence (W m^{-2}) Net tropospheric diabatic heating (W m^{-2})	Net horizontal moisture flux divergence (W m^{-2}) Net adiabatic enthalpy source (W m^{-2})

8.

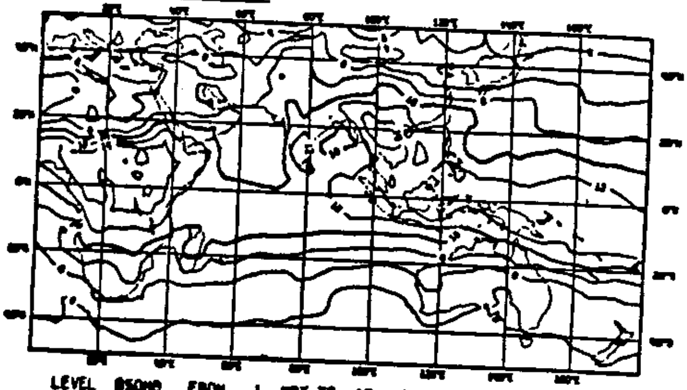
Net tropospheric moisture (mm) Mean tropospheric temperature (K)	Zonal asymmetry in net moisture (mm) Zonal asymmetry in mean temperature (K).

MEAN WIND



LEVEL 850MB FROM 1 MAY TO 15 MAY, 1979- 84

SPECIFIC HUMIDITY



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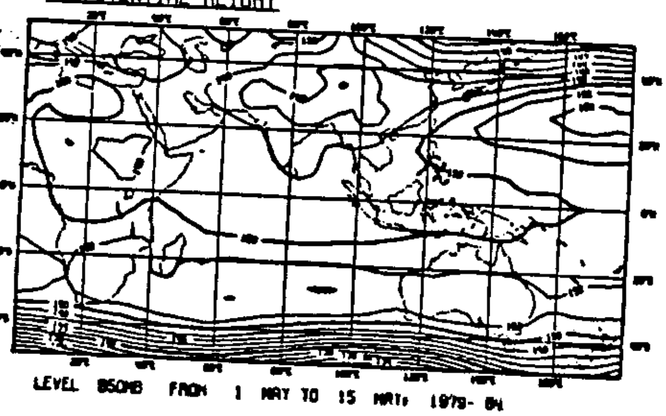

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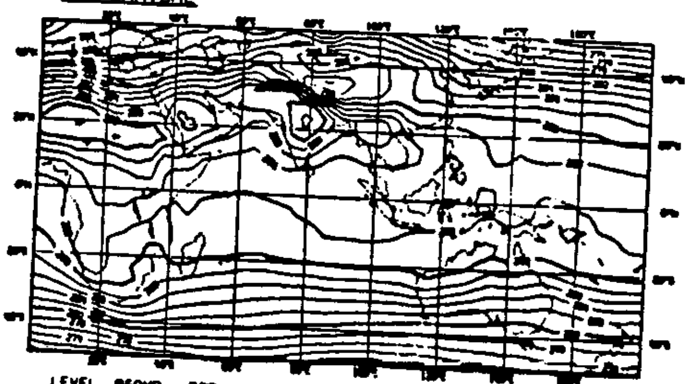
TEMPERATURE



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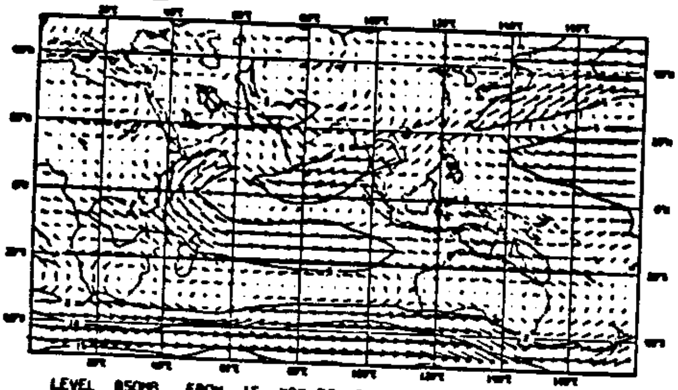
MEAN WIND



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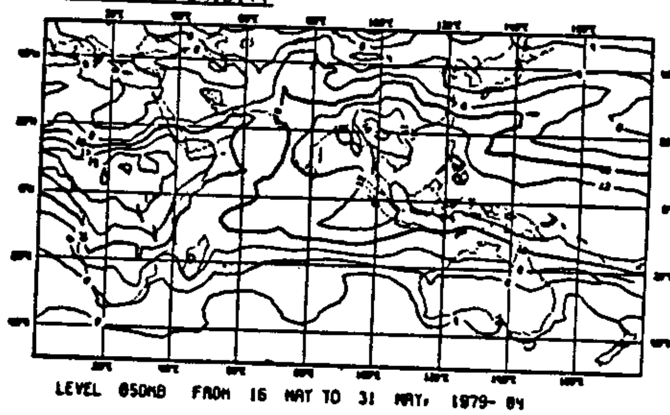

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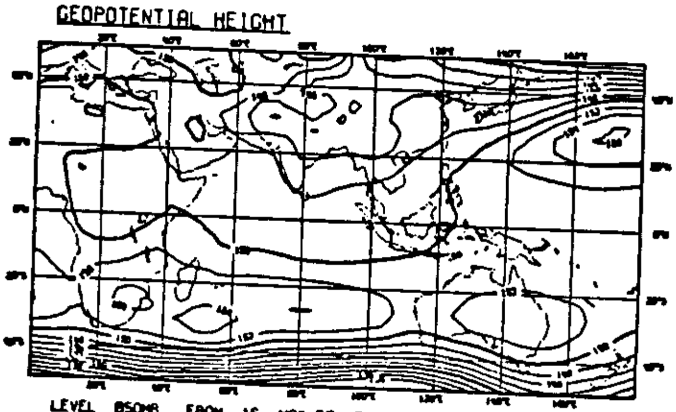

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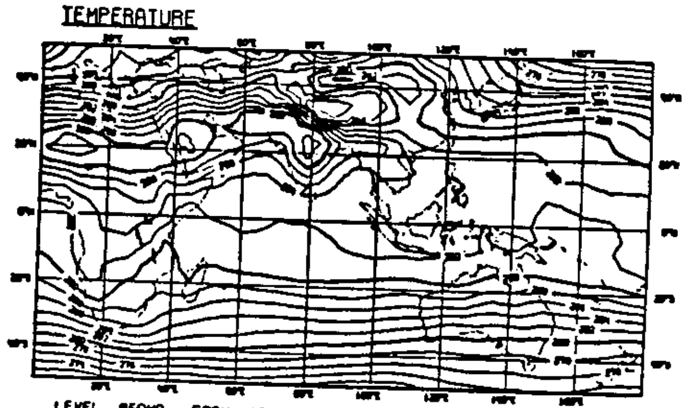

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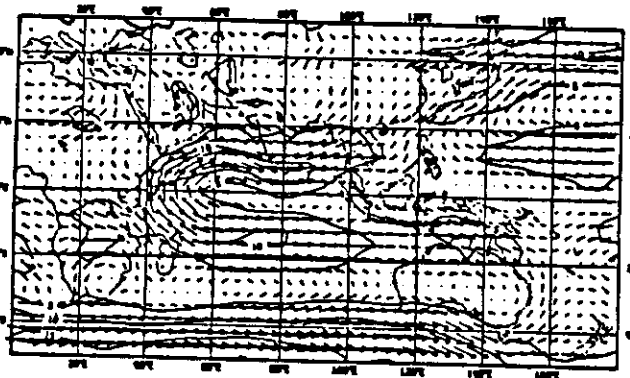

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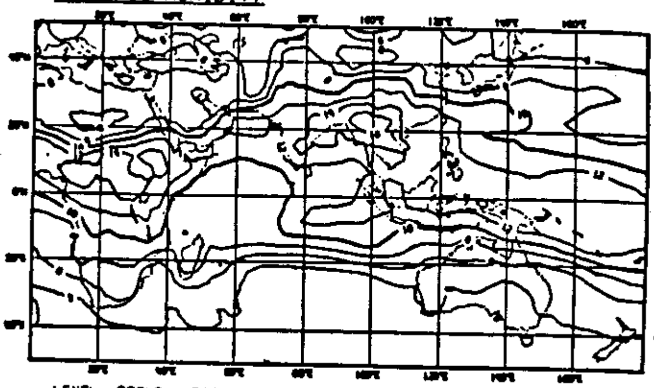

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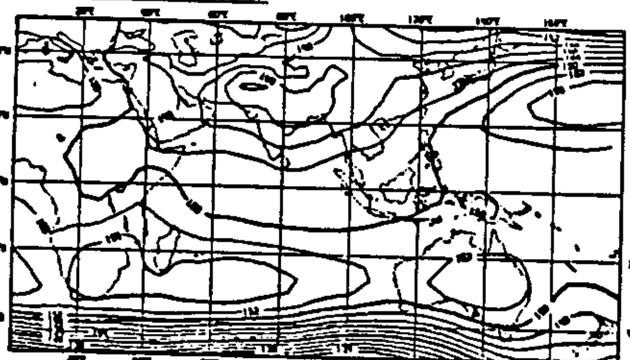

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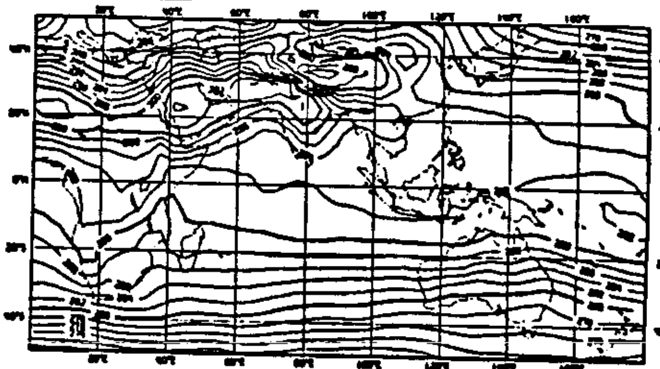

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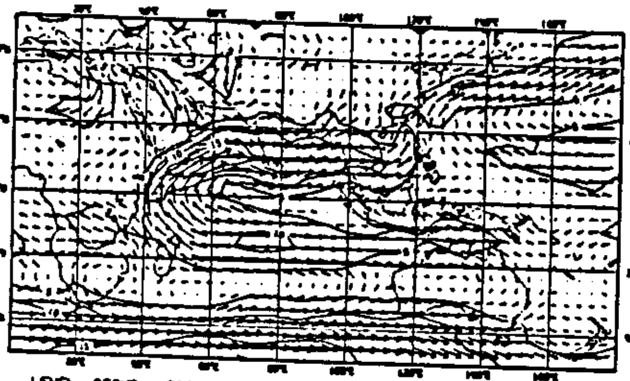

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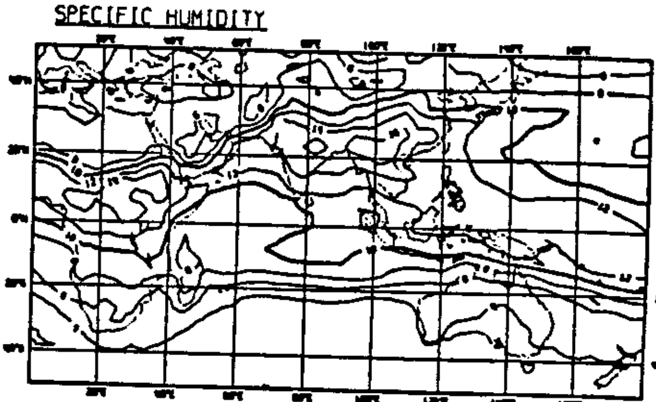

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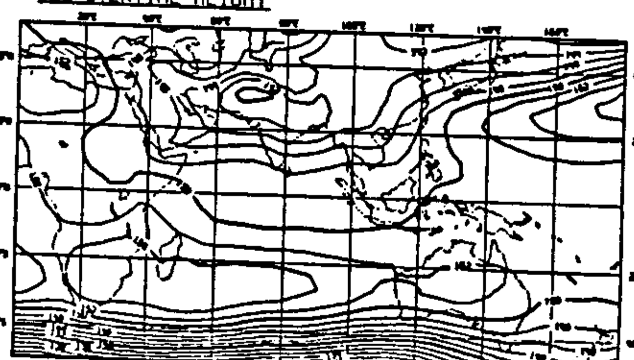

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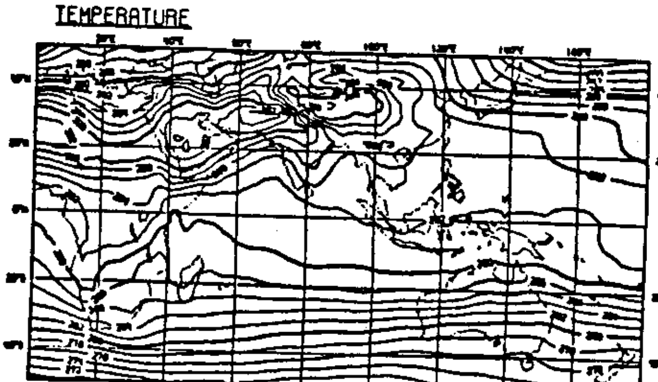

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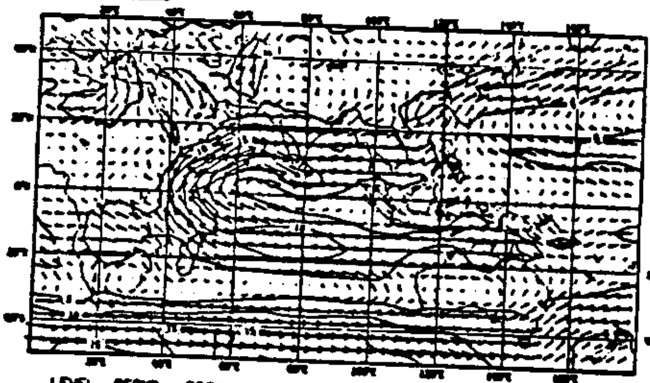

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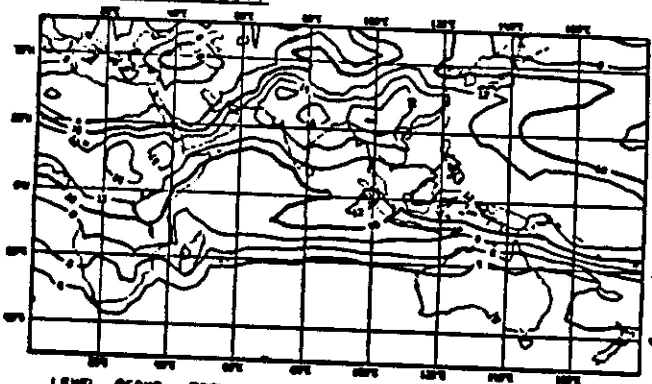

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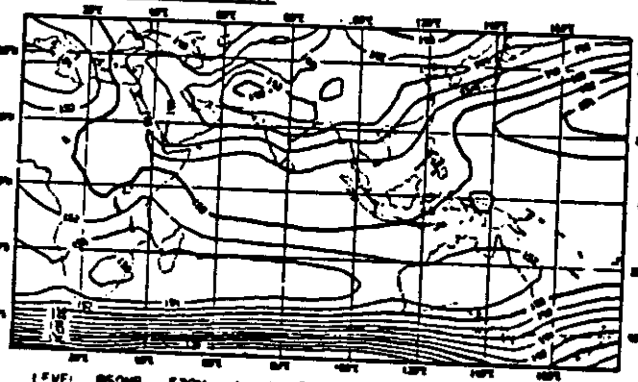

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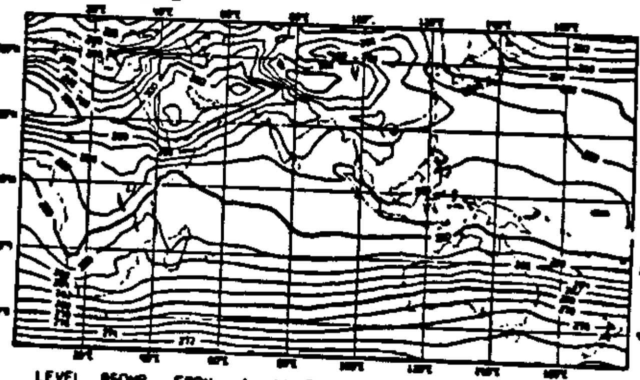

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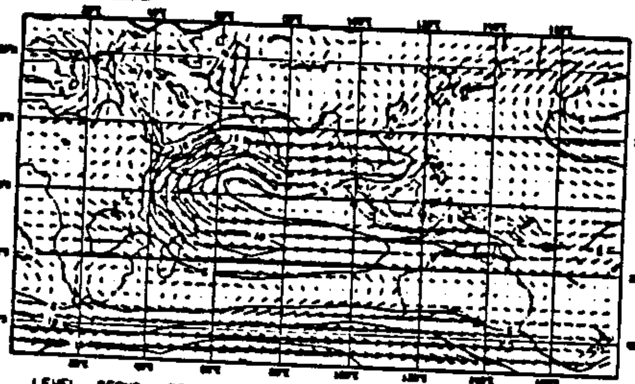

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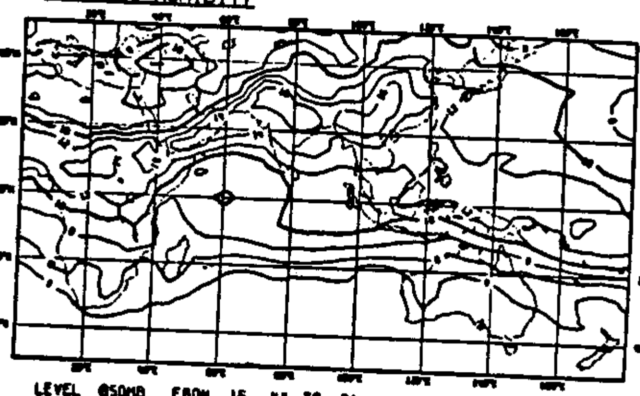

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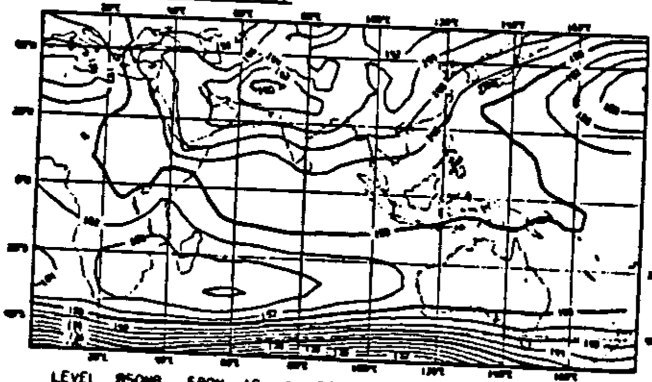

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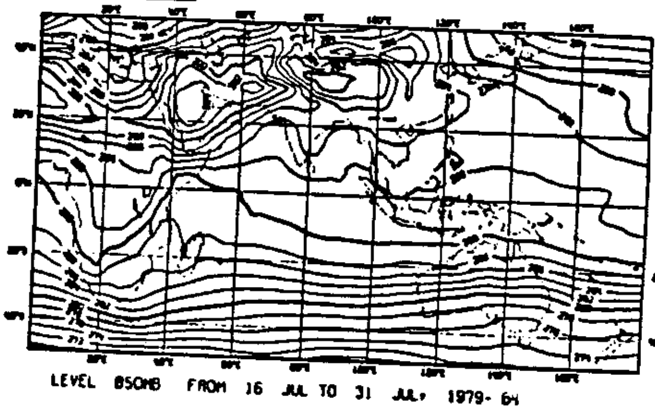

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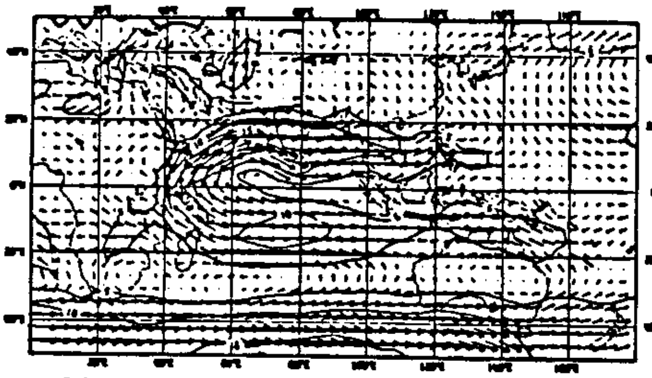

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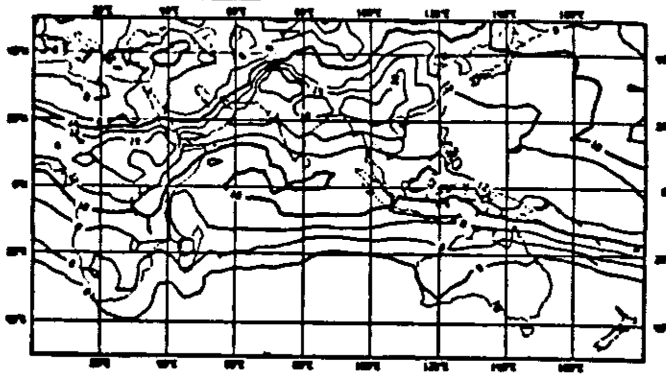

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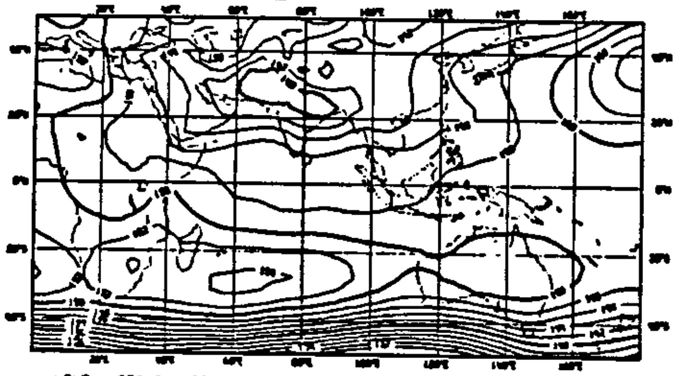

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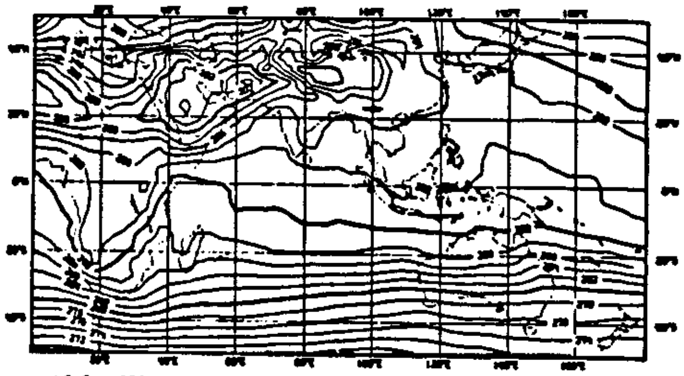

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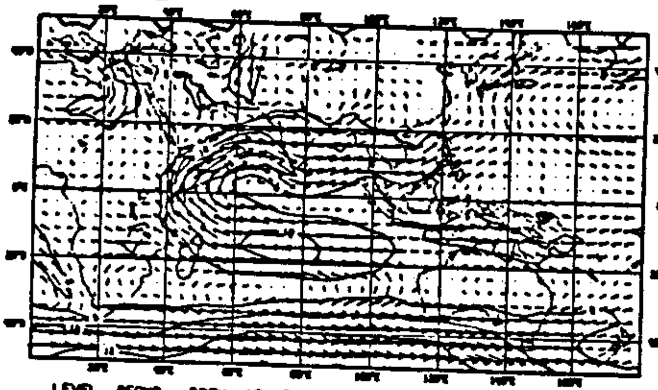

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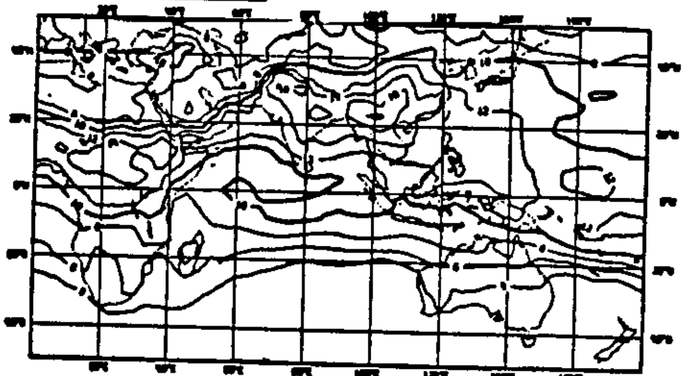

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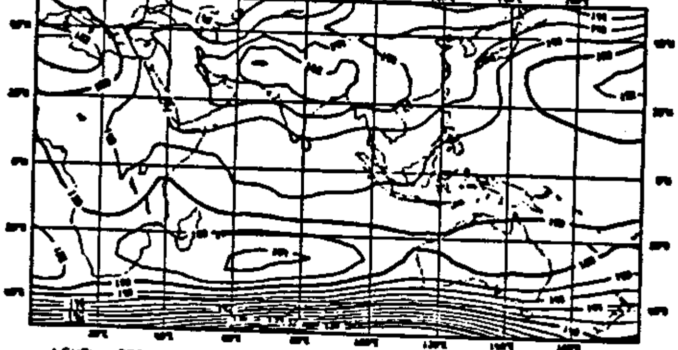

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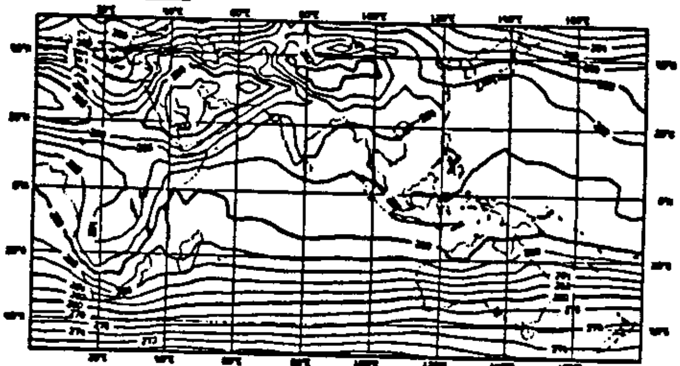

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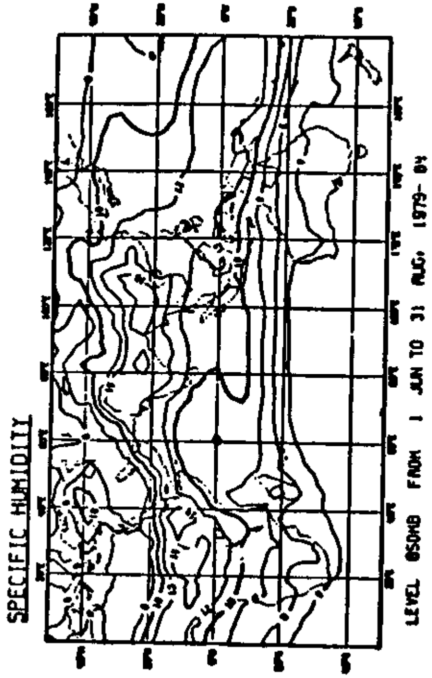
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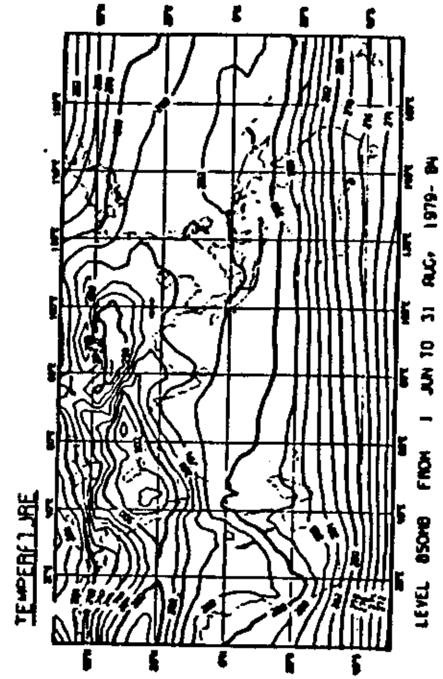
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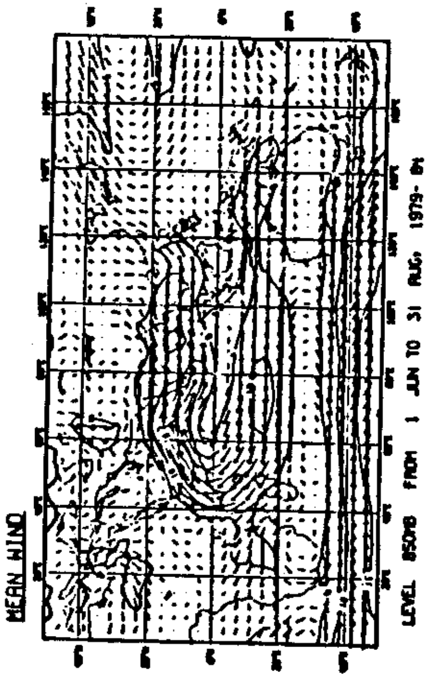
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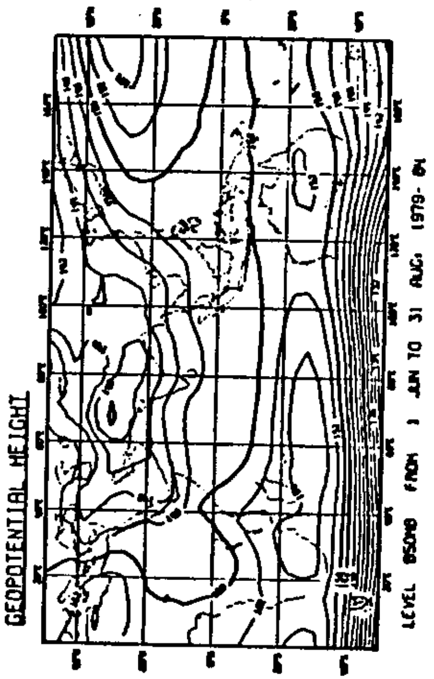
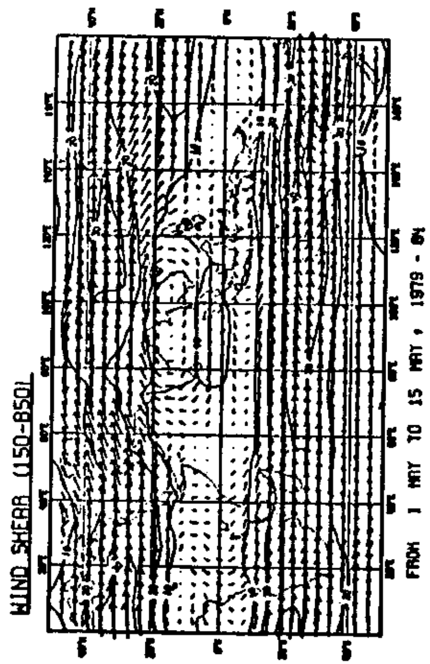
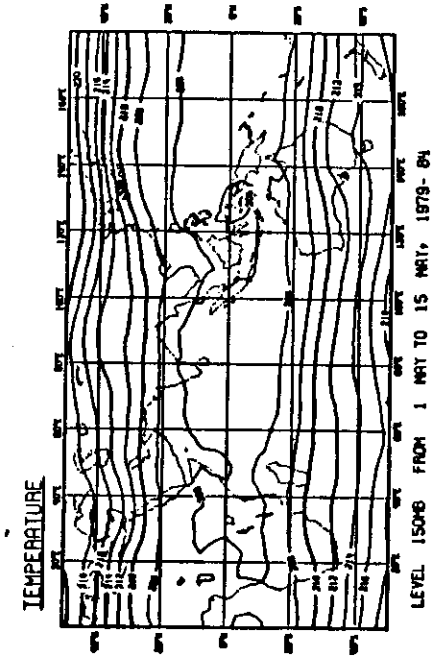
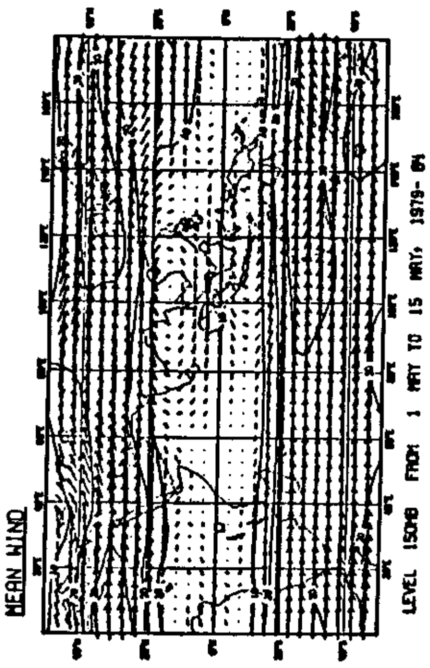
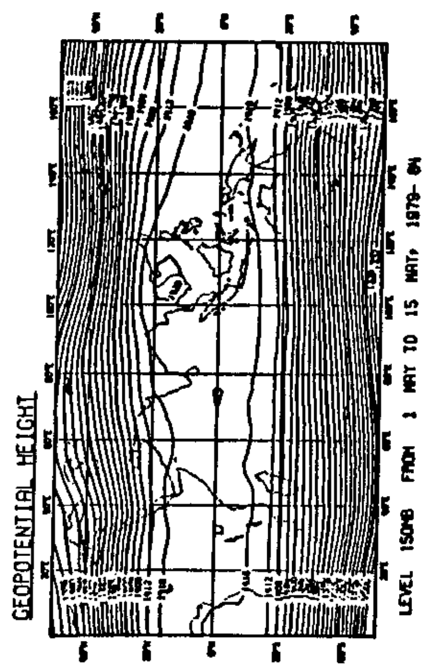
LEVEL 850MB FROM 1 JUN TO 31 AUG, 1979- 84


GEOPOTENTIAL HEIGHT
LEVEL 850MB FROM 1 JUN TO 31 AUG, 1979- 84

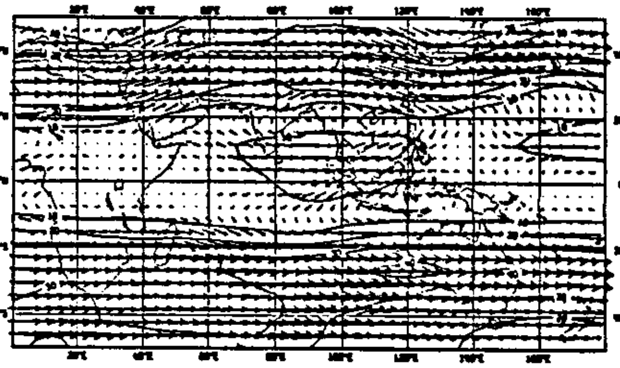

WIND SHEAR (150-850)
FROM 1 MAY TO 15 MAY, 1979 - 84


TEMPERATURE
LEVEL 150MB FROM 1 MAY TO 15 MAY, 1979- 84


MEAN WIND
LEVEL 150MB FROM 1 MAY TO 15 MAY, 1979- 84

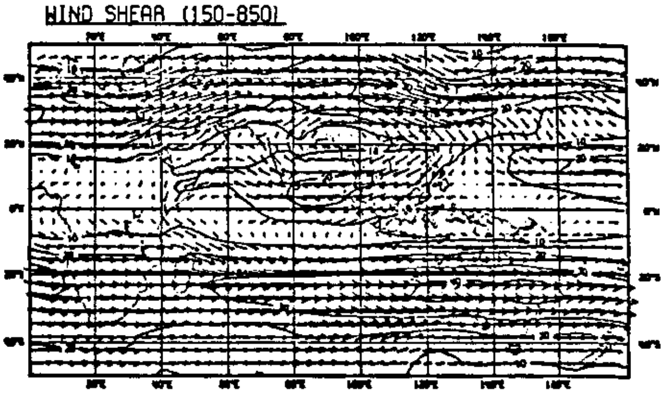

GEOPOTENTIAL HEIGHT
LEVEL 150MB FROM 1 MAY TO 15 MAY, 1979- 84

MEAN WIND



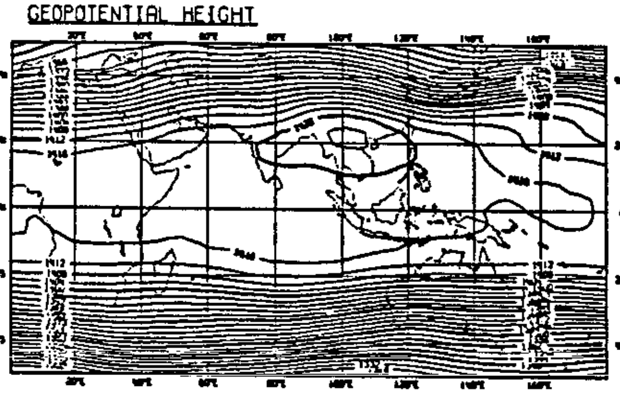
LEVEL 150MB FROM 16 MAY TO 31 MAY, 1979- 84

WIND SHEAR (150-850)



FROM 16 MAY TO 31 MAY, 1979 - 84

GEOPOTENTIAL HEIGHT



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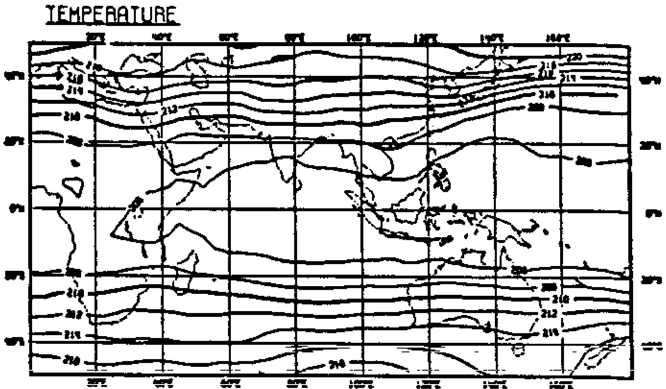
TEMPERATURE



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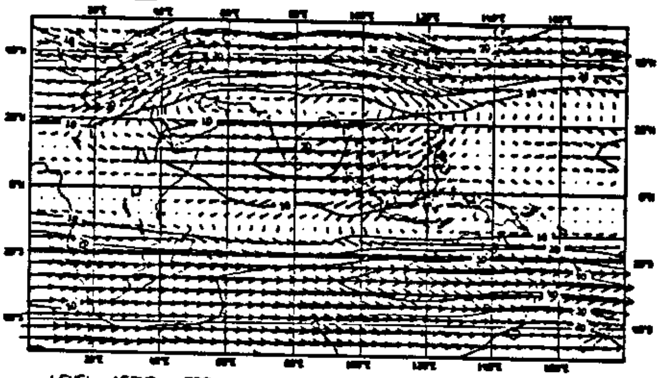
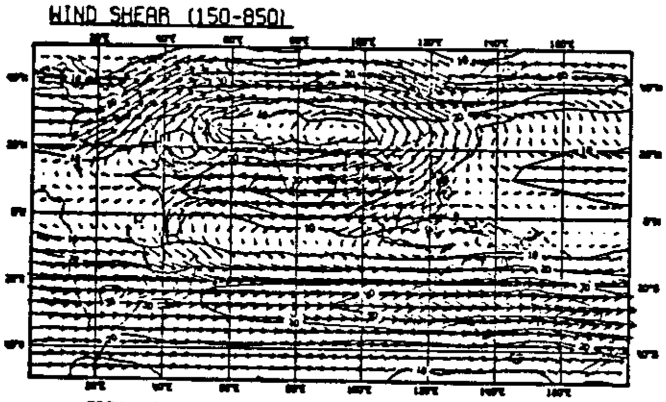
MEAN WIND



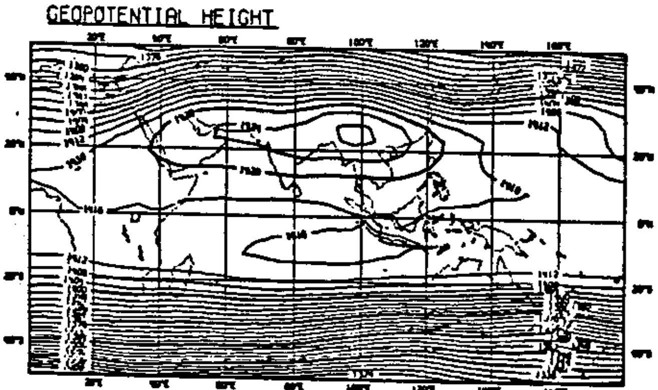
LEVEL 150MB FROM 1 JUN TO 15 JUN, 1979- 84

WIND SHEAR (150-850)



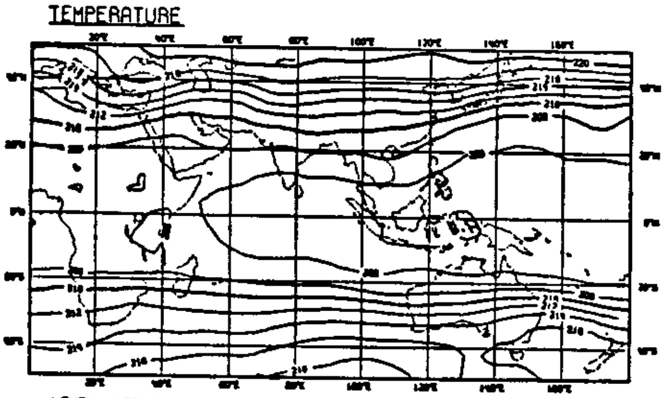
FROM 1 JUN TO 15 JUN, 1979 - 84

GEOPOTENTIAL HEIGHT



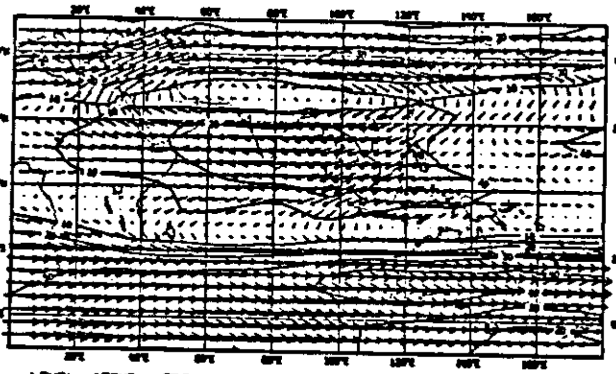
LEVEL 150MB FROM 1 JUN TO 15 JUN, 1979- 84

TEMPERATURE



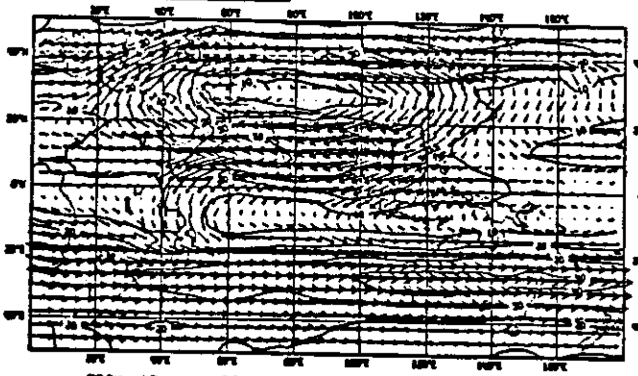
LEVEL 150MB FROM 1 JUN TO 15 JUN, 1979- 84

MEAN WIND



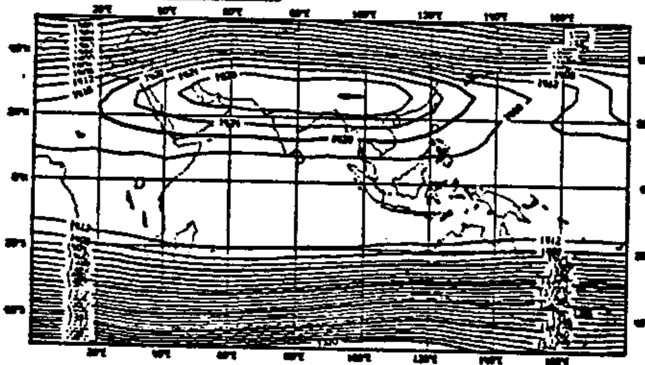
LEVEL 150MB FROM 16 JUN TO 30 JUN, 1979- 84

WIND SHEAR (150-850)



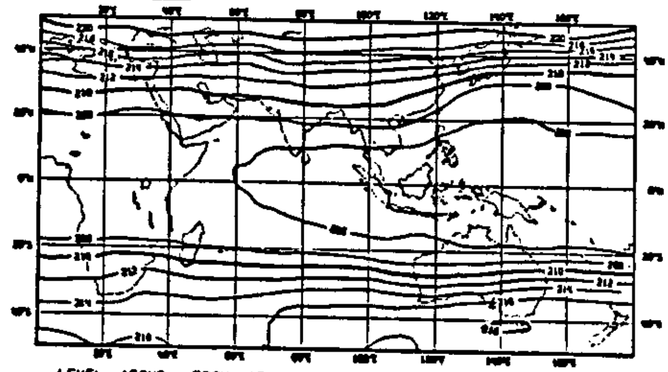
FROM 16 JUN TO 30 JUN, 1979 - 84

GEOPOTENTIAL HEIGHT



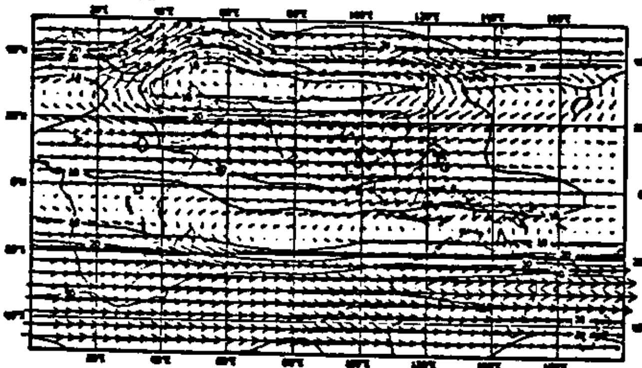
LEVEL 150MB FROM 16 JUN TO 30 JUN, 1979- 84

TEMPERATURE



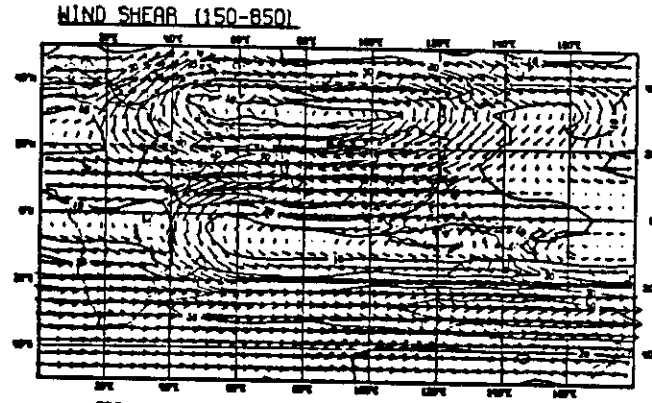
LEVEL 150MB FROM 16 JUN TO 30 JUN, 1979- 84

MEAN WIND



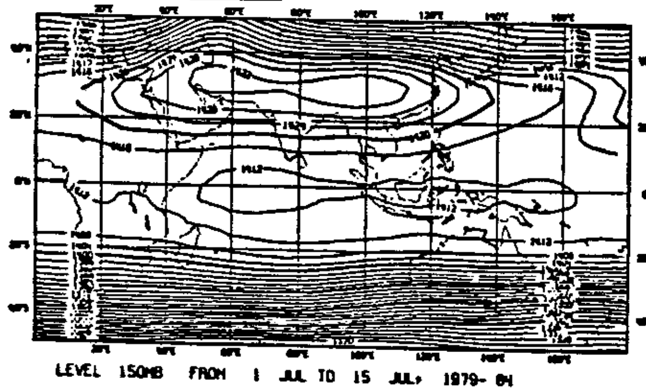
LEVEL 150MB FROM 1 JUL TO 15 JUL, 1979- 84

WIND SHEAR (150-850)



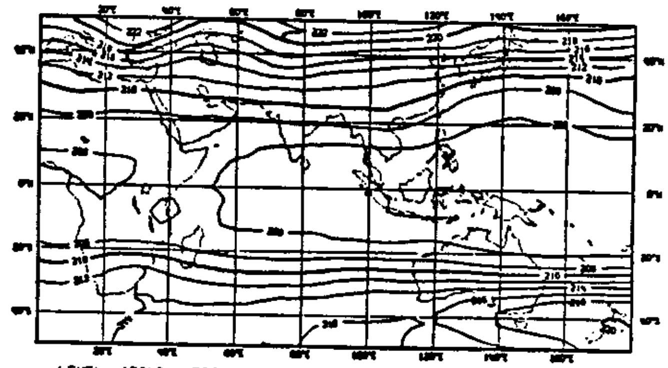
FROM 1 JUL TO 15 JUL, 1979 - 84

GEOPOTENTIAL HEIGHT



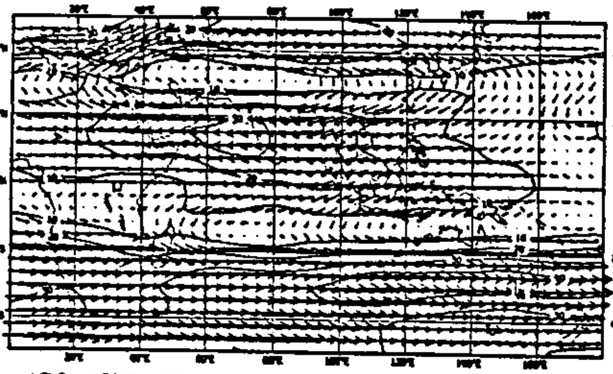
LEVEL 150MB FROM 1 JUL TO 15 JUL, 1979- 84

TEMPERATURE



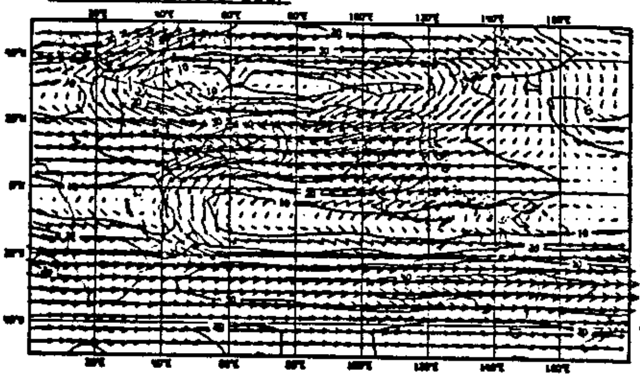
LEVEL 150MB FROM 1 JUL TO 15 JUL, 1979- 84

MEAN WIND



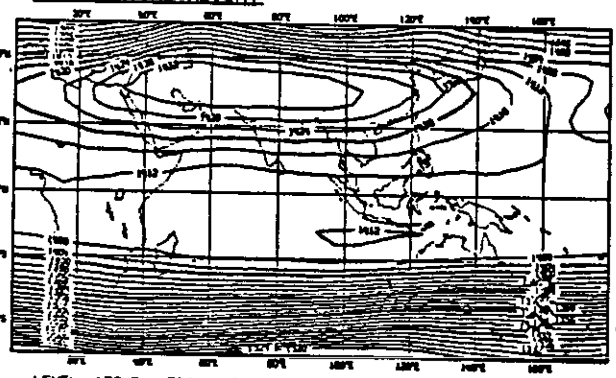
LEVEL 150MB FROM 16 JUL TO 31 JUL, 1979- 84

WIND SHEAR (150-850)



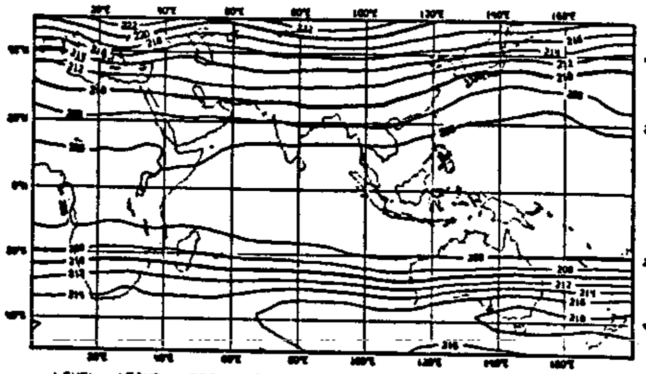
FROM 16 JUL TO 31 JUL, 1979 - 84

GEOPOTENTIAL HEIGHT



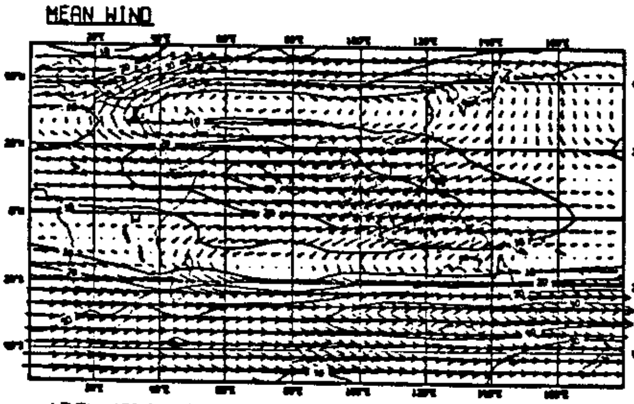
LEVEL 150MB FROM 16 JUL TO 31 JUL, 1979- 84

TEMPERATURE



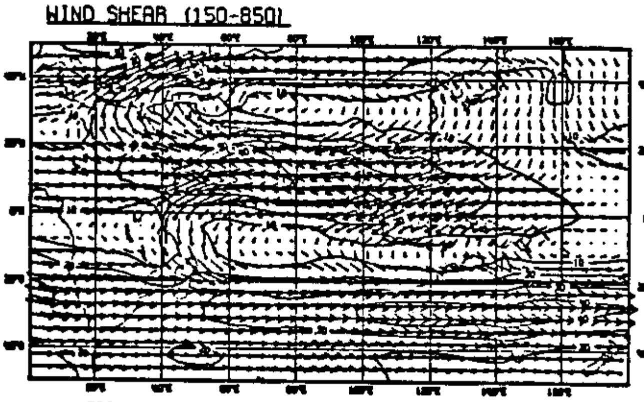
LEVEL 150MB FROM 16 JUL TO 31 JUL, 1979- 84

MEAN WIND



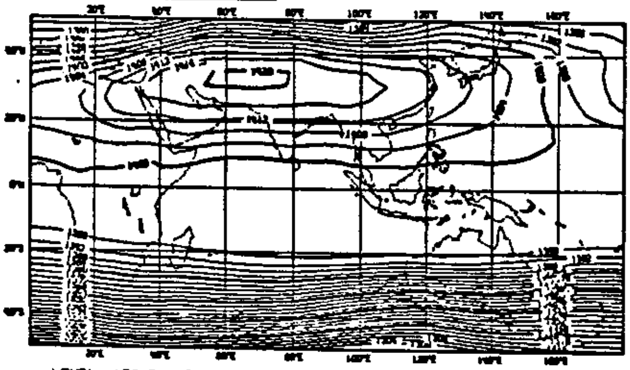
LEVEL 150MB FROM 1 AUG TO 15 AUG, 1979- 84

WIND SHEAR (150-850)



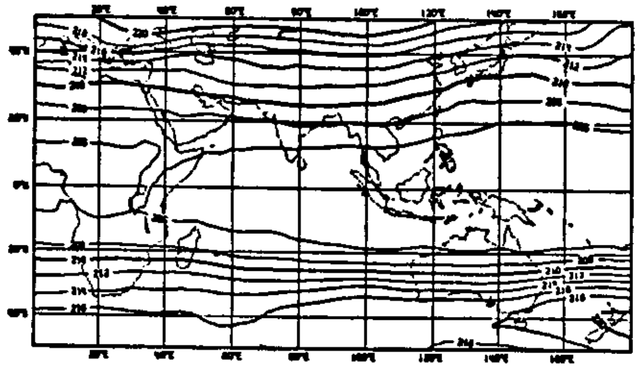
FROM 1 AUG TO 15 AUG, 1979 - 84

GEOPOTENTIAL HEIGHT



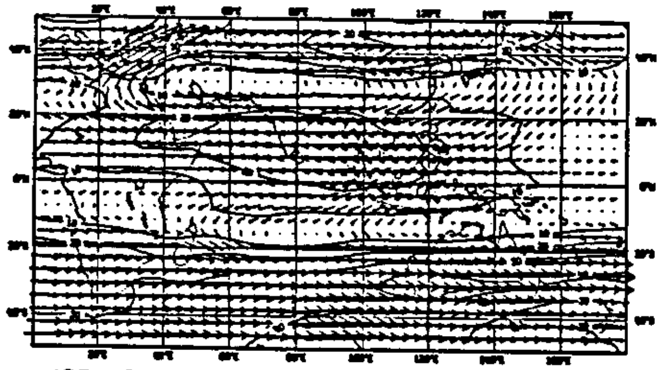
LEVEL 150MB FROM 1 AUG TO 15 AUG, 1979- 84

TEMPERATURE



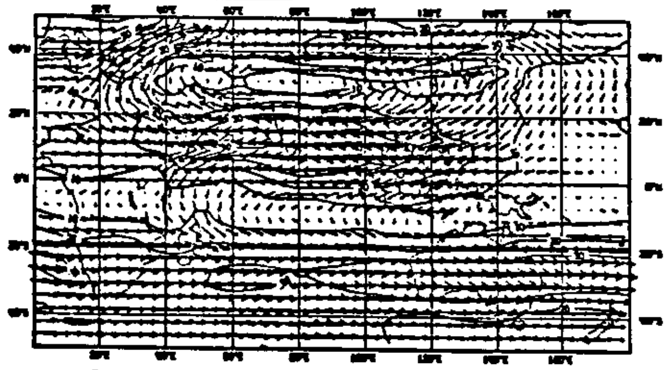
LEVEL 150MB FROM 1 AUG TO 15 AUG, 1979- 84

MEAN WIND



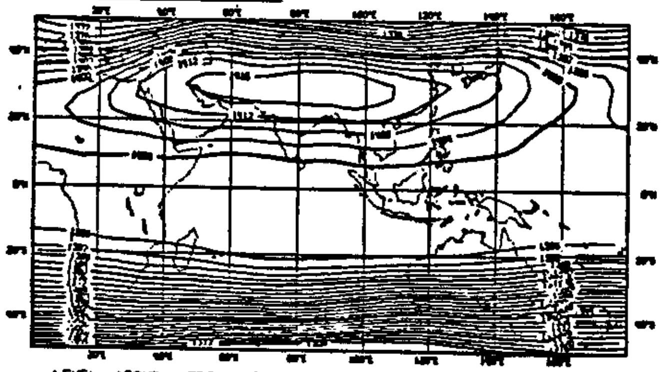
LEVEL 150MB FROM 16 AUG TO 31 AUG, 1979- 84

WIND SHEAR (150-850)



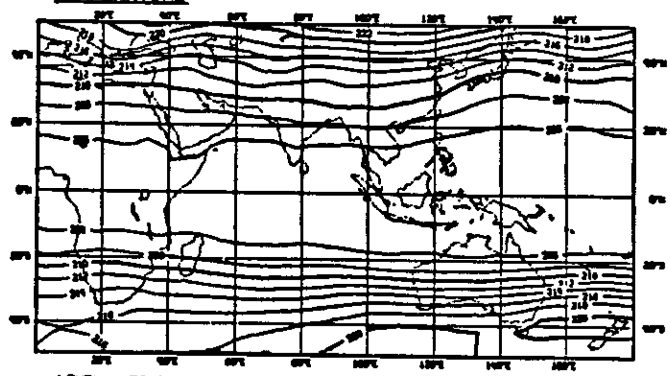
FROM 16 AUG TO 31 AUG, 1979 - 84

GEOPOTENTIAL HEIGHT



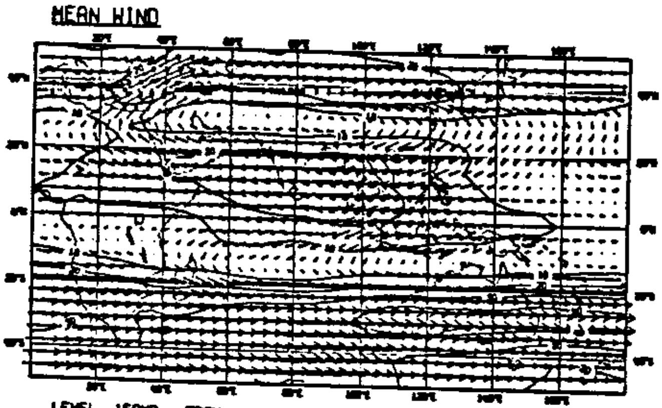
LEVEL 150MB FROM 16 AUG TO 31 AUG, 1979- 84

TEMPERATURE



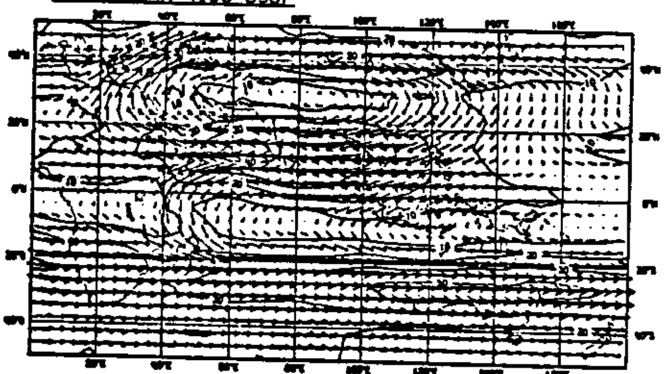
LEVEL 150MB FROM 16 AUG TO 31 AUG, 1979- 84

MEAN WIND



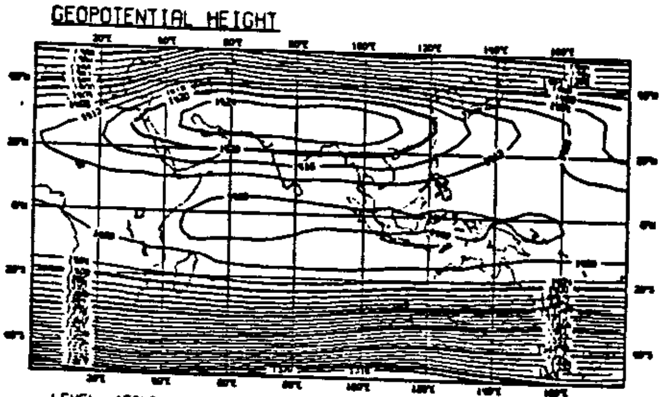
LEVEL 150MB FROM 1 JUN TO 31 AUG, 1979- 84

WIND SHEAR (150-850)



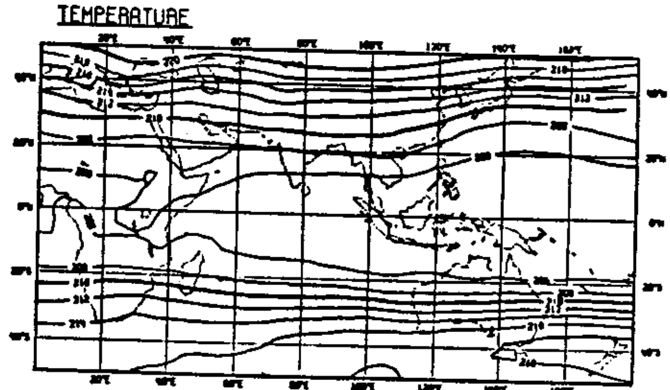
FROM 1 JUN TO 31 AUG, 1979 - 84

GEOPOTENTIAL HEIGHT



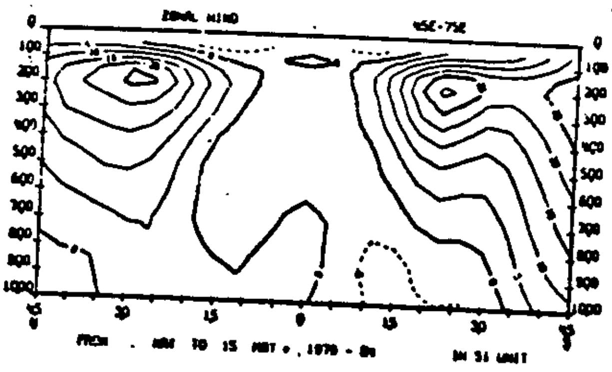
LEVEL 150MB FROM 1 JUN TO 31 AUG, 1979- 84

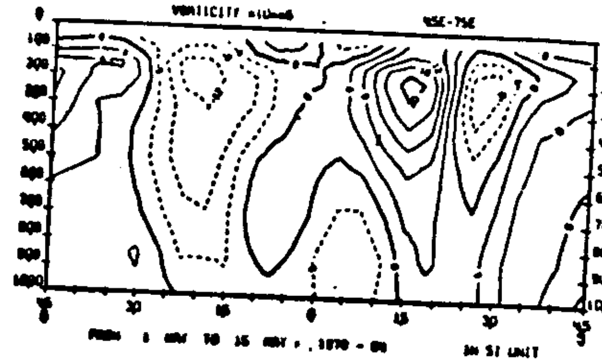
TEMPERATURE

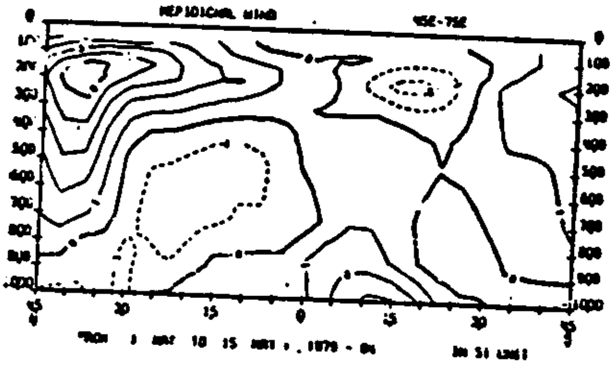


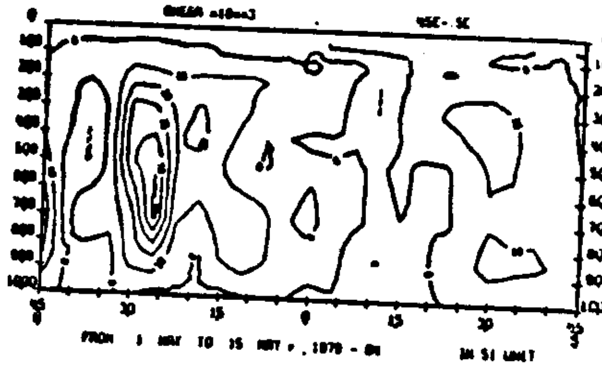
LEVEL 150MB FROM 1 JUN TO 31 AUG, 1979- 84

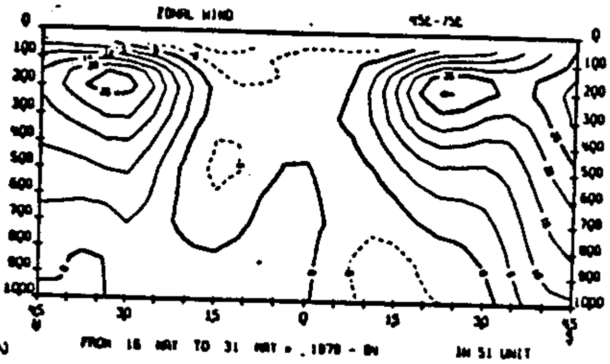
45°E-75°E ARABIAN SEA SECTOR

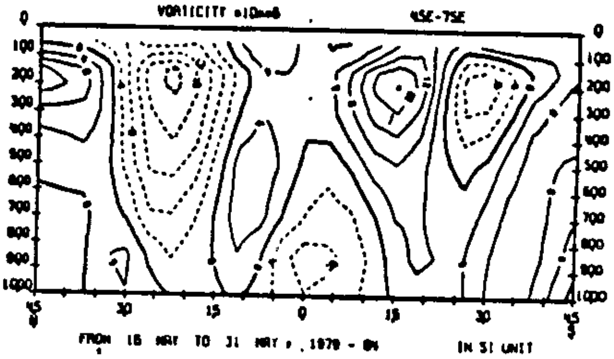


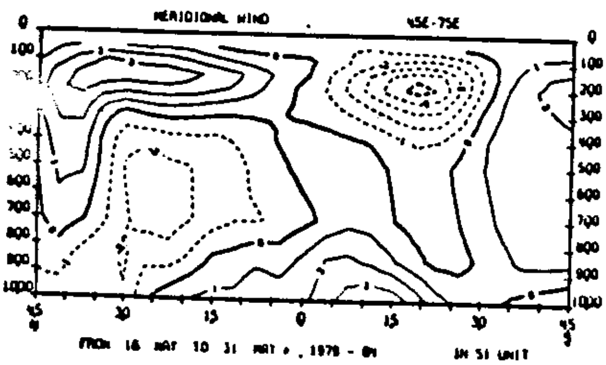


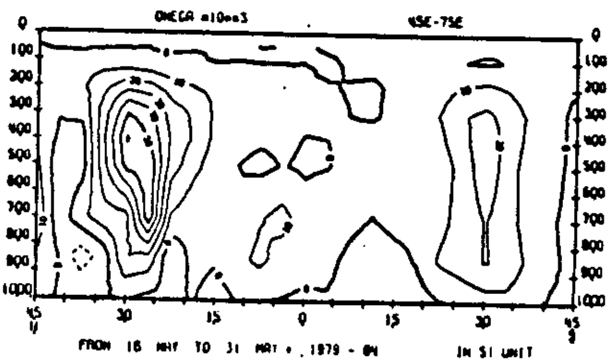


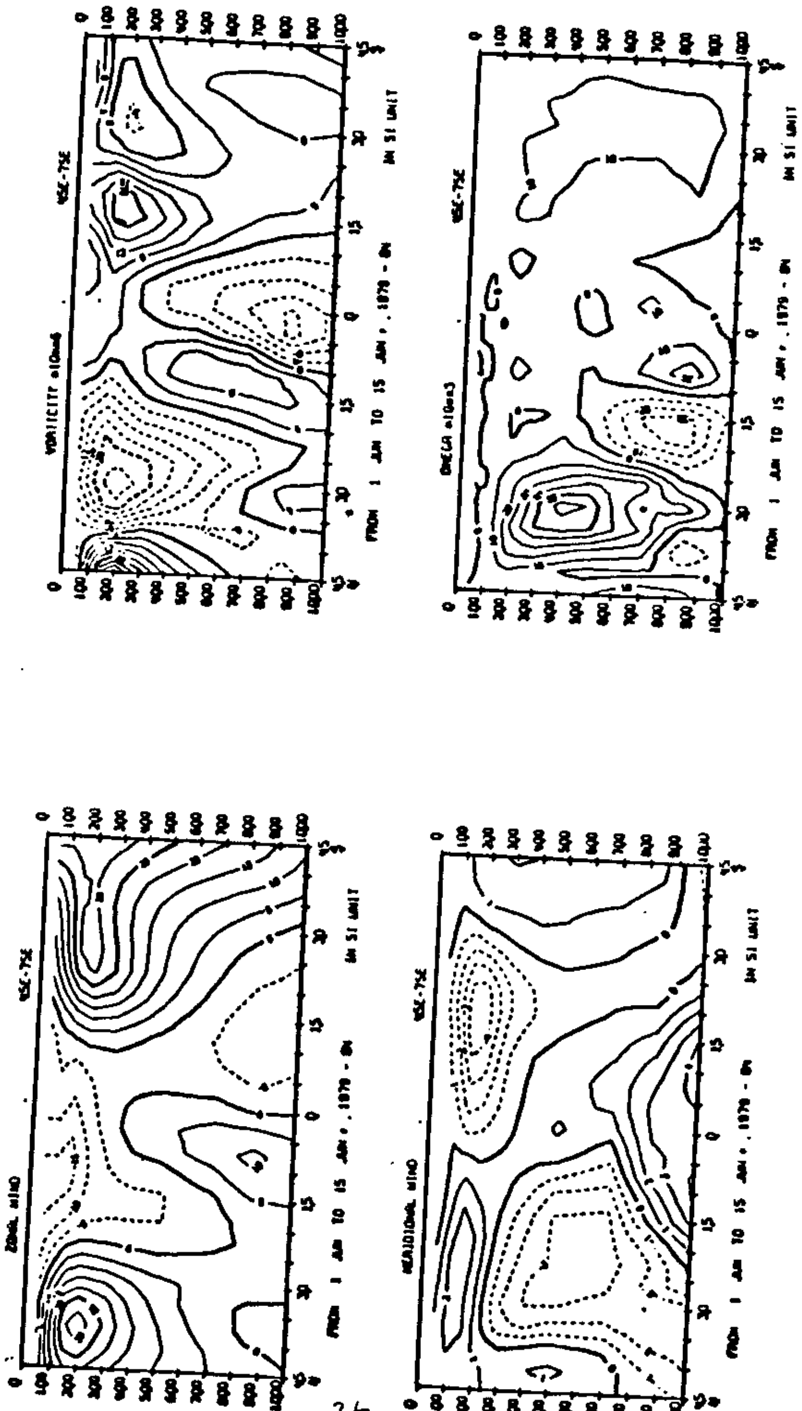




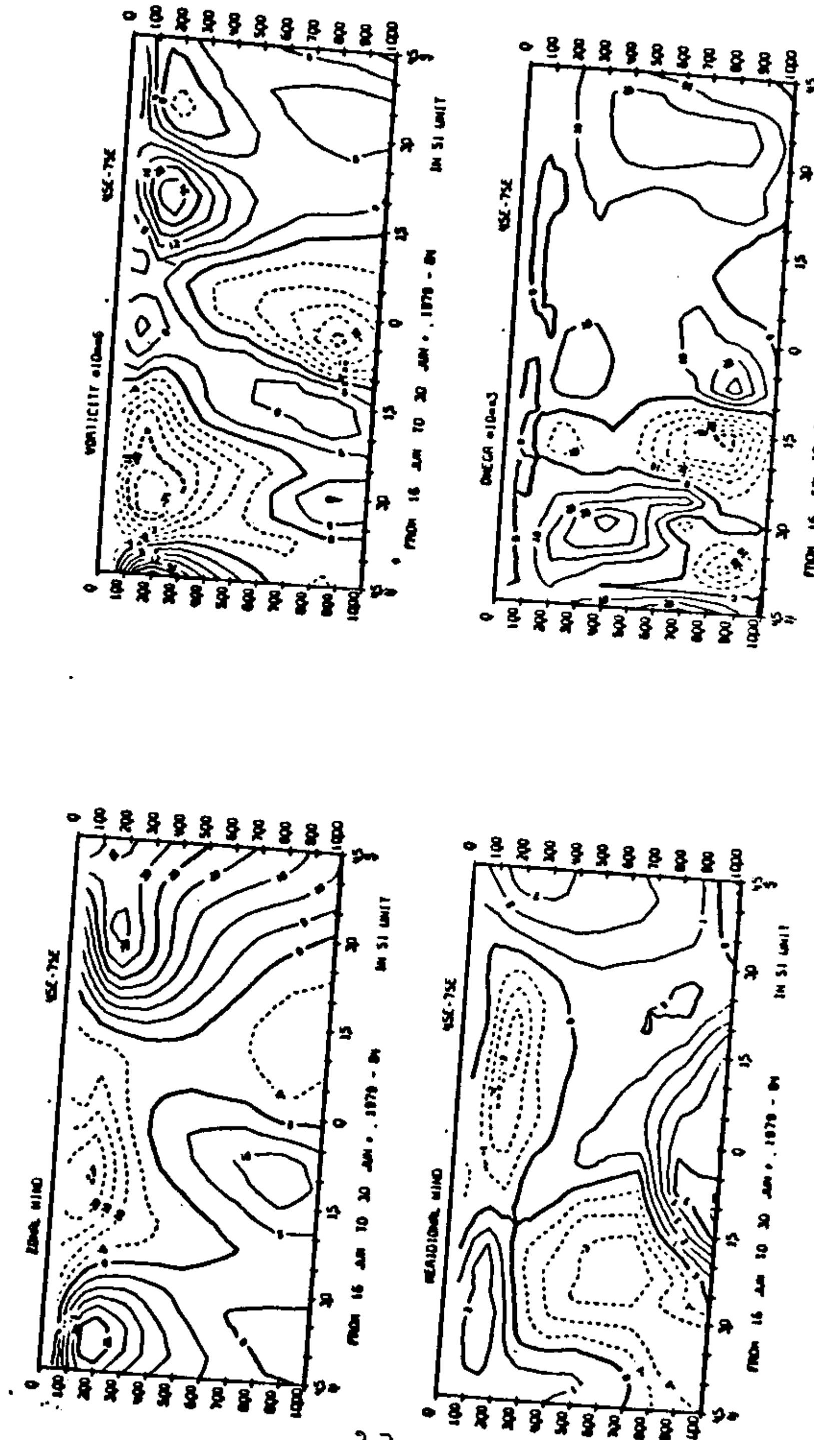




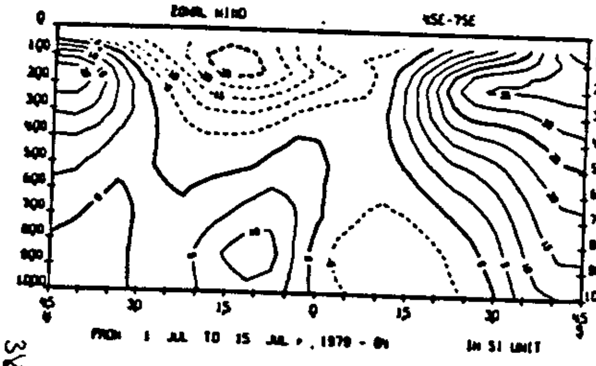


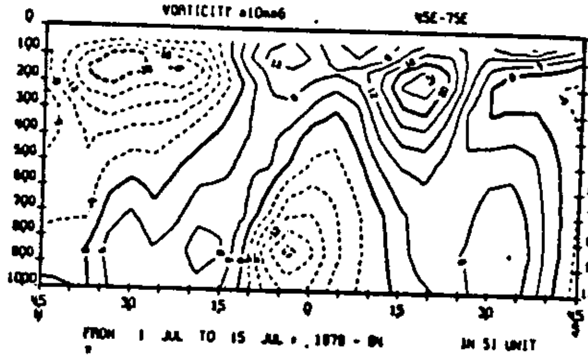

ZONAL WIND
MERIDIONAL WIND
IN SI UNIT

36

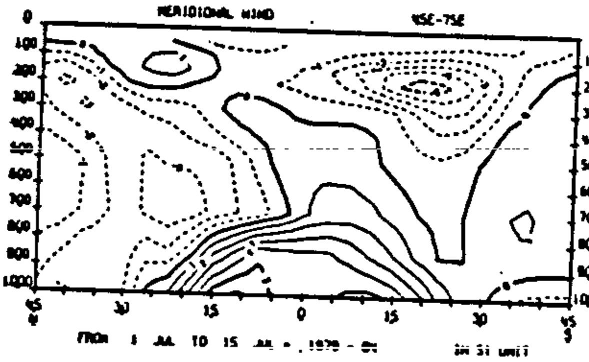

ZONAL WIND
MERIDIONAL WIND
IN SI UNIT

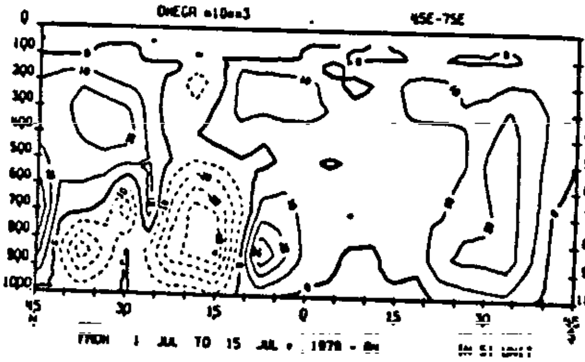
37

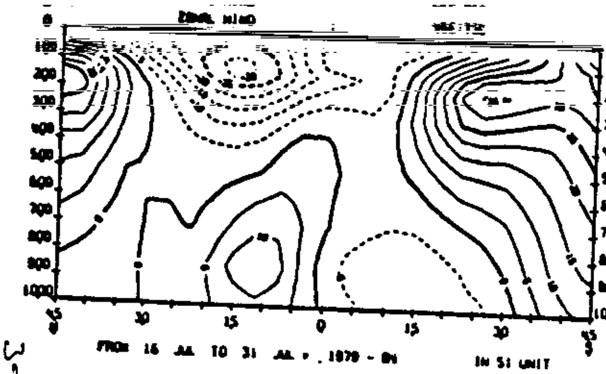

ZONAL WIND
45E-75E
FROM 1 JUL TO 15 JUL , 1979
IN SI UNIT

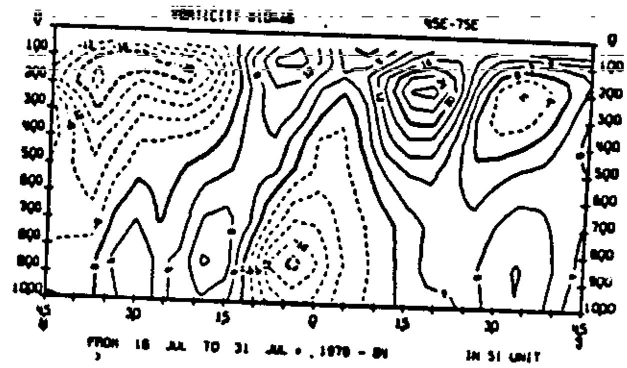

VORTICITY x10**6
45E-75E
FROM 1 JUL TO 15 JUL , 1979
IN SI UNIT

38

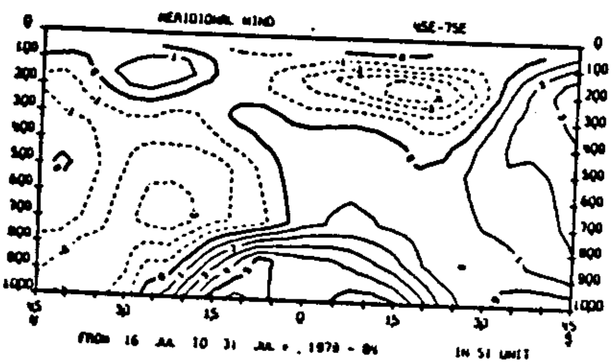

MERIDIONAL WIND
45E-75E
FROM 1 JUL TO 15 JUL , 1979
IN SI UNIT

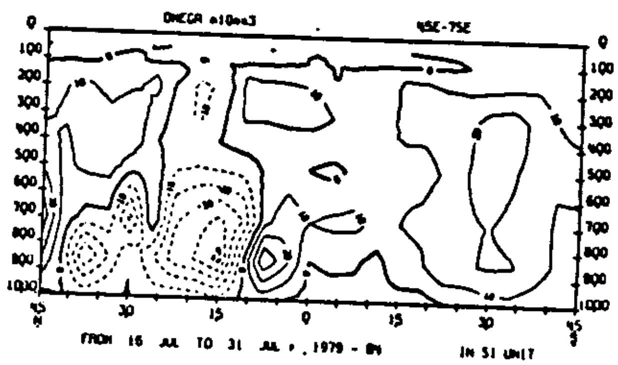

OMEGA x10**3
45E-75E
FROM 1 JUL TO 15 JUL , 1979
IN SI UNIT

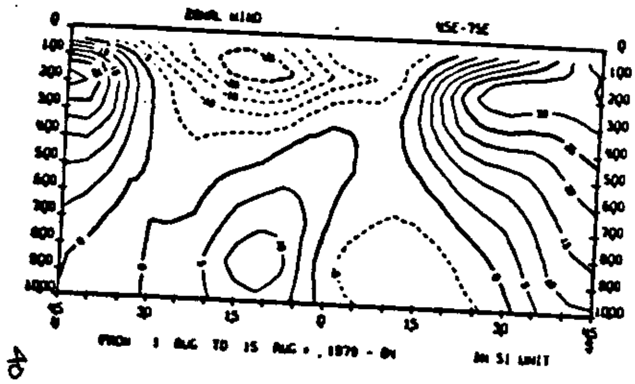

ZONAL WIND
FROM 16 JUL TO 31 JUL , 1979
IN SI UNIT

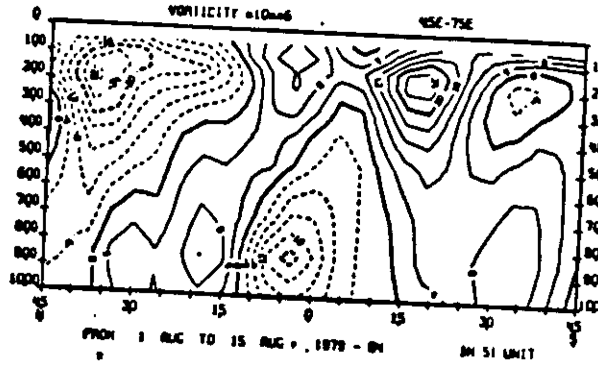

45E-75E
FROM 16 JUL TO 31 JUL , 1979
IN SI UNIT

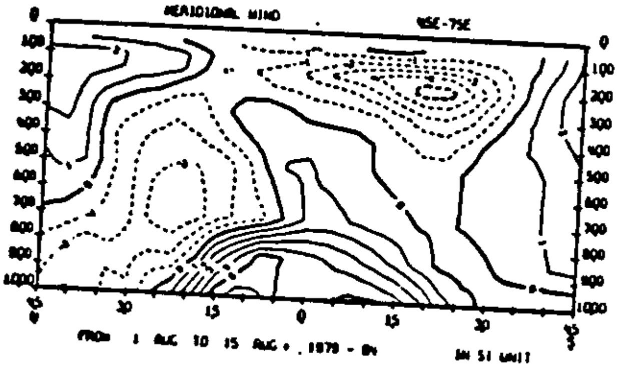
39

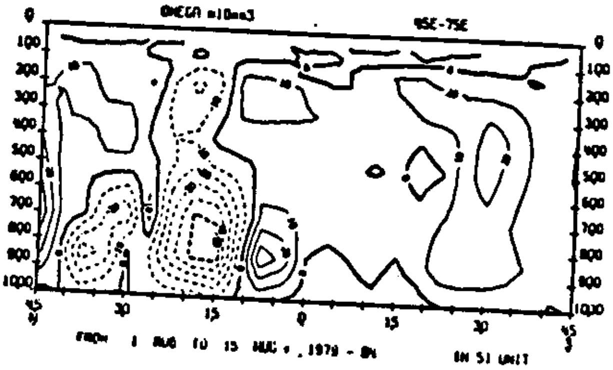

MERIDIONAL WIND
45E-75E
FROM 16 JUL TO 31 JUL , 1979
IN SI UNIT

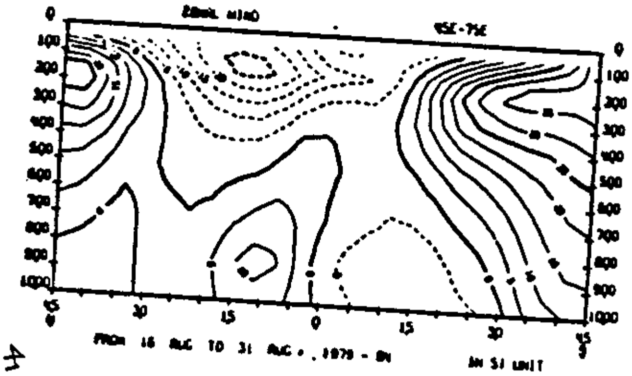

OMEGA x10**3
45E-75E
FROM 16 JUL TO 31 JUL , 1979
IN SI UNIT

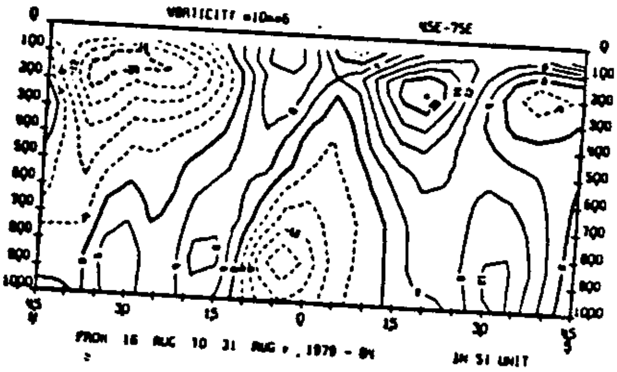

ZONAL WIND
45E-75E
FROM 1 AUG TO 15 AUG
IN SI UNIT

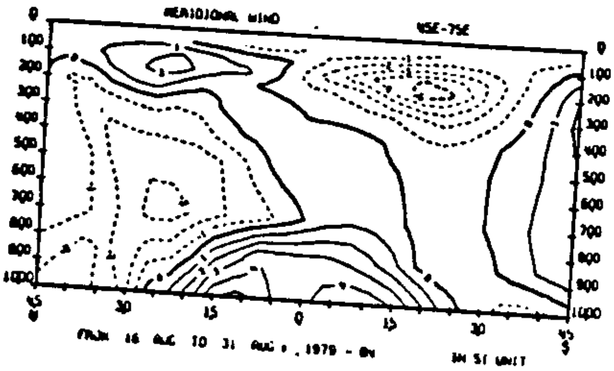

VORTICITY
45E-75E
FROM 1 AUG TO 15 AUG
IN SI UNIT

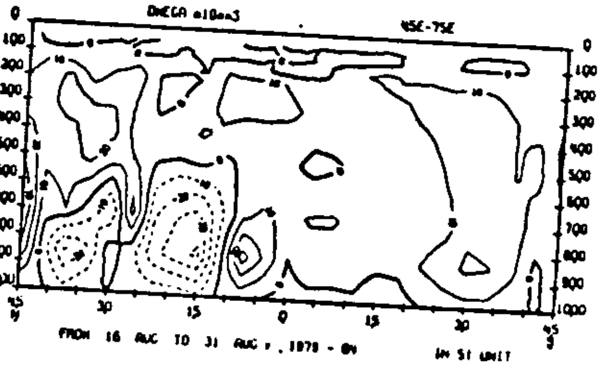

MERIDIONAL WIND
45E-75E
FROM 1 AUG TO 15 AUG
IN SI UNIT

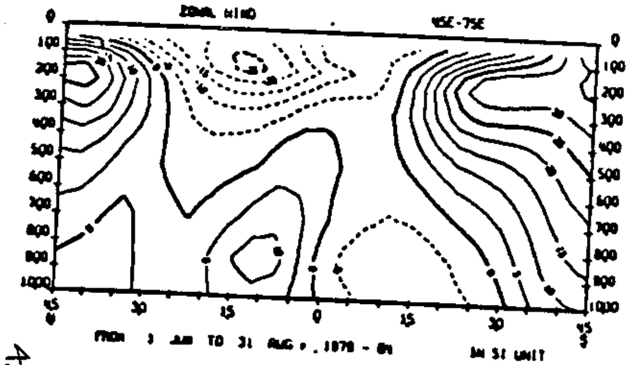

OMEGA
45E-75E
FROM 1 AUG TO 15 AUG
IN SI UNIT

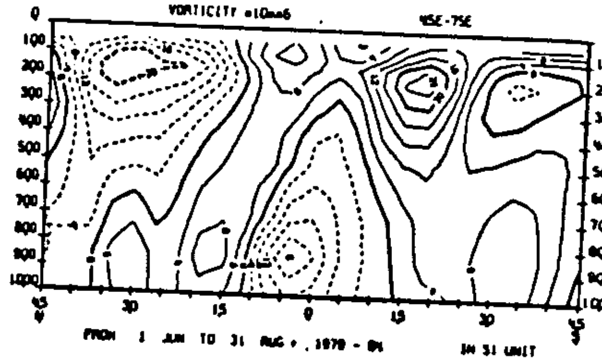

ZONAL WIND
45E-75E
FROM 16 AUG TO 31 AUG
IN SI UNIT

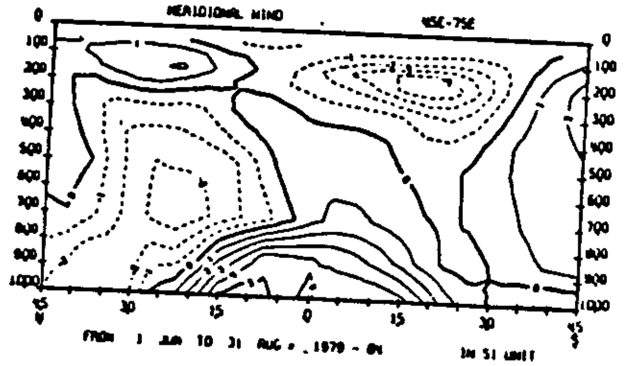

VORTICITY
45E-75E
FROM 16 AUG TO 31 AUG
IN SI UNIT

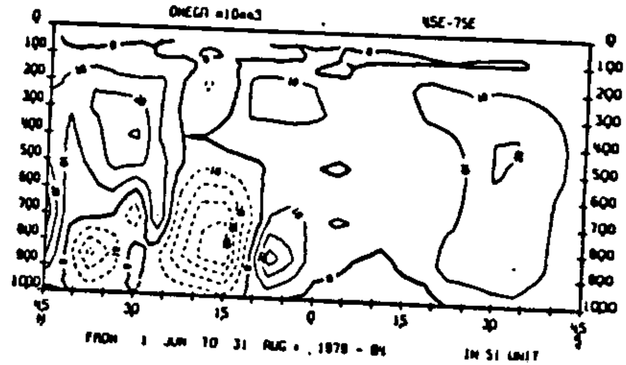

MERIDIONAL WIND
45E-75E
FROM 16 AUG TO 31 AUG
IN SI UNIT

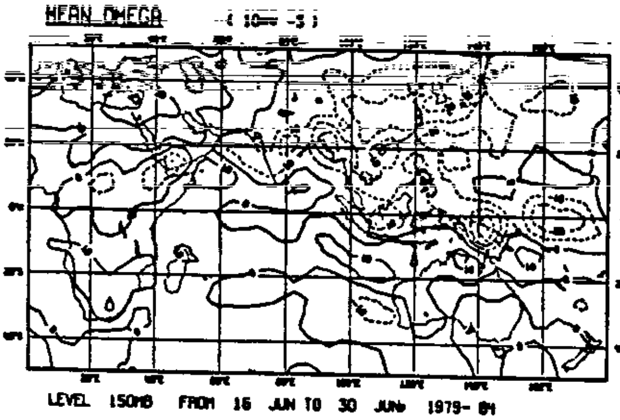

OMEGA
45E-75E
FROM 16 AUG TO 31 AUG
IN SI UNIT

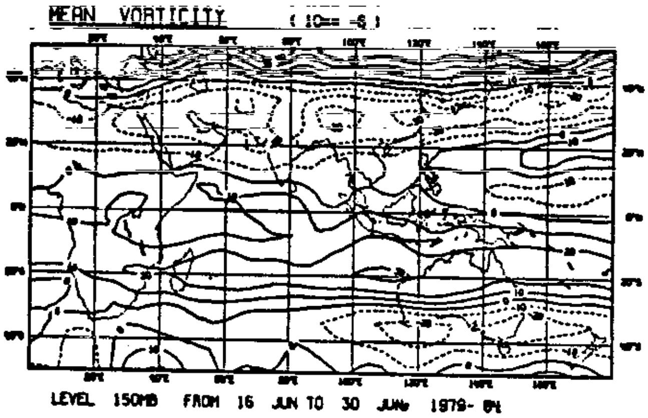

ZONAL WIND
45E-75E
FROM 1 JUN TO 31 AUG , 1979 - 84
IN SI UNIT

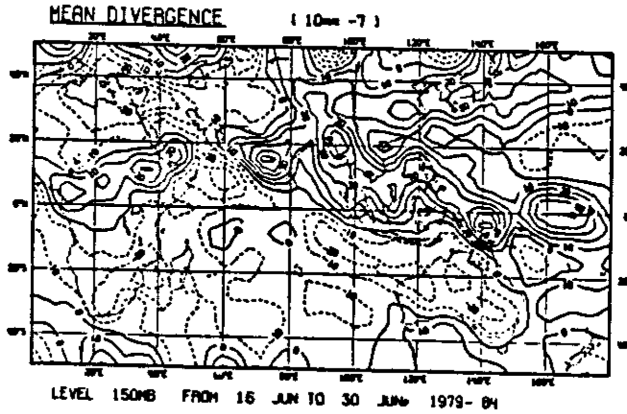

VORTICITY *10**6
45E-75E
FROM 1 JUN TO 31 AUG , 1979 - 84
IN SI UNIT

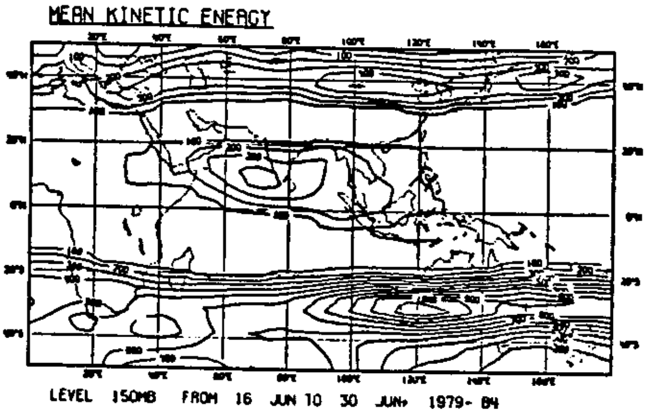

MERIDIONAL WIND
45E-75E
FROM 1 JUN TO 31 AUG , 1979 - 84
IN SI UNIT

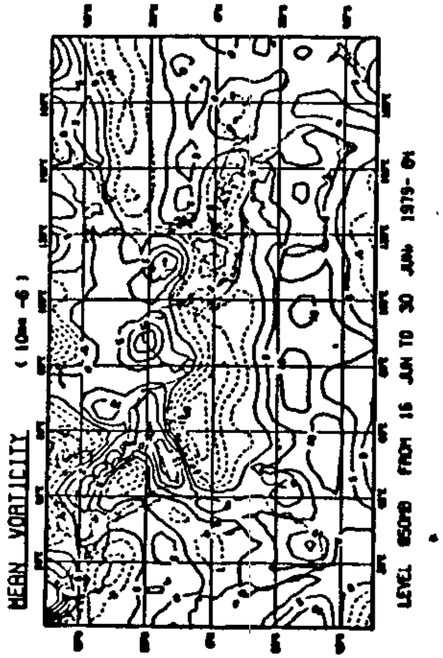

OMEGA *10**3
45E-75E
FROM 1 JUN TO 31 AUG , 1979 - 84
IN SI UNIT

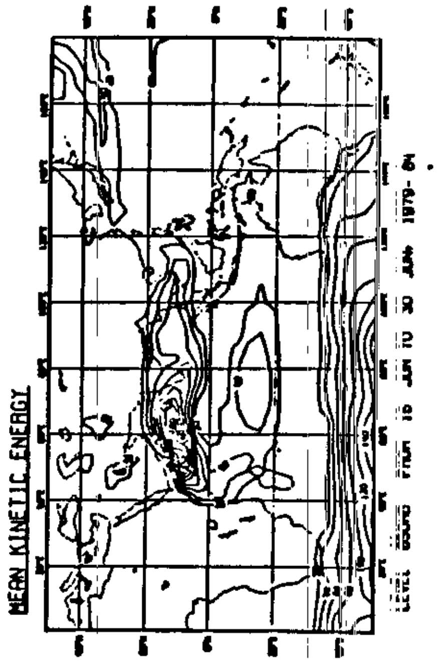

MEAN OMEGA (10** -3)
LEVEL 150MB FROM 16 JUN TO 30 JUN 1979- 84

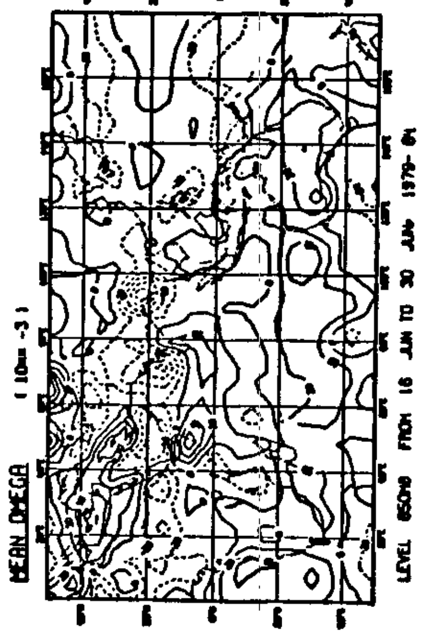

MEAN VORTICITY (10** -6)
LEVEL 150MB FROM 16 JUN TO 30 JUN 1979- 84


MEAN DIVERGENCE (10** -7)
LEVEL 150MB FROM 16 JUN TO 30 JUN 1979- 84


MEAN KINETIC ENERGY
LEVEL 150MB FROM 16 JUN TO 30 JUN 1979- 84


MEAN VORTICITY (10** -6)
LEVEL 850MB FROM 16 JUN TO 30 JUN, 1979- 84


MEAN KINETIC ENERGY
LEVEL 850MB FROM 16 JUN TO 30 JUN, 1979- 84


MEAN OMEGA (10** -3)
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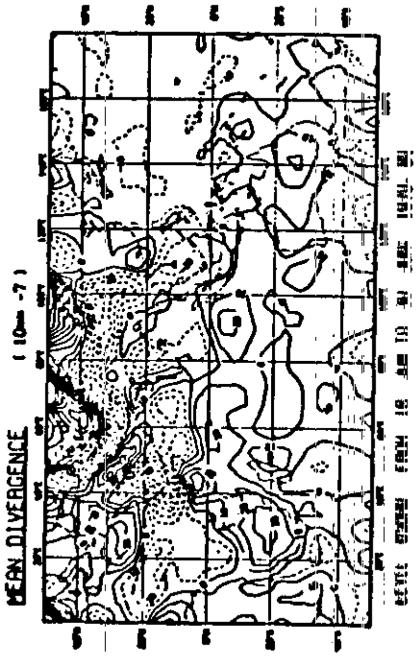
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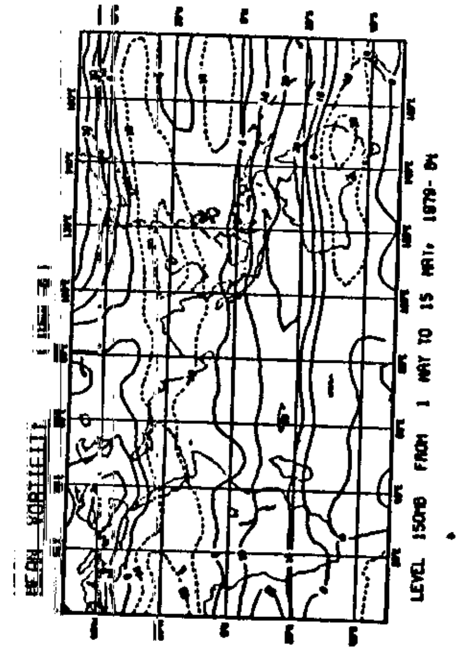
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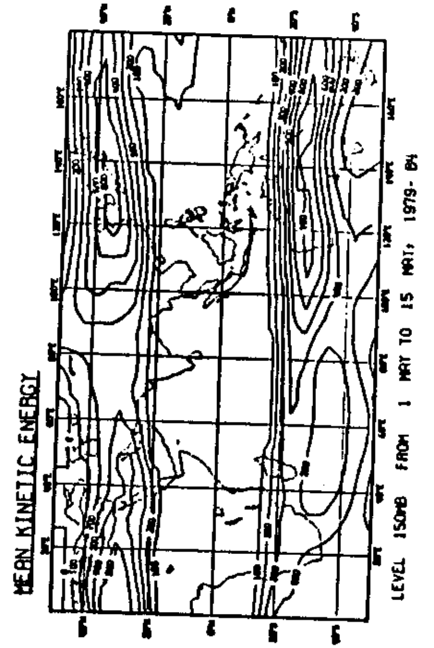
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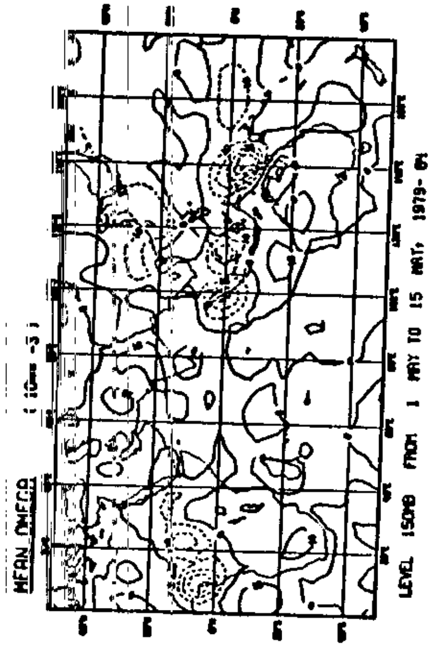
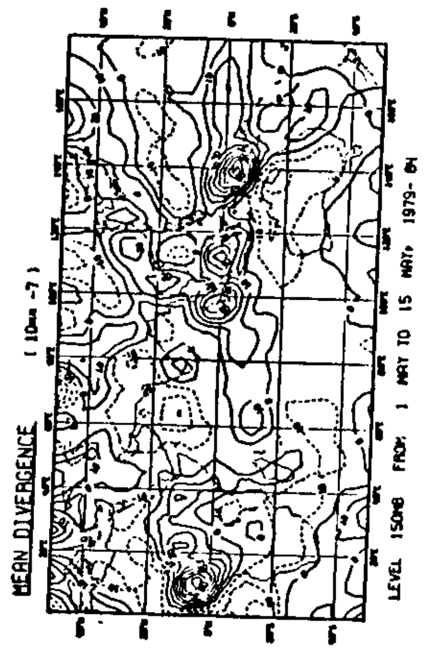
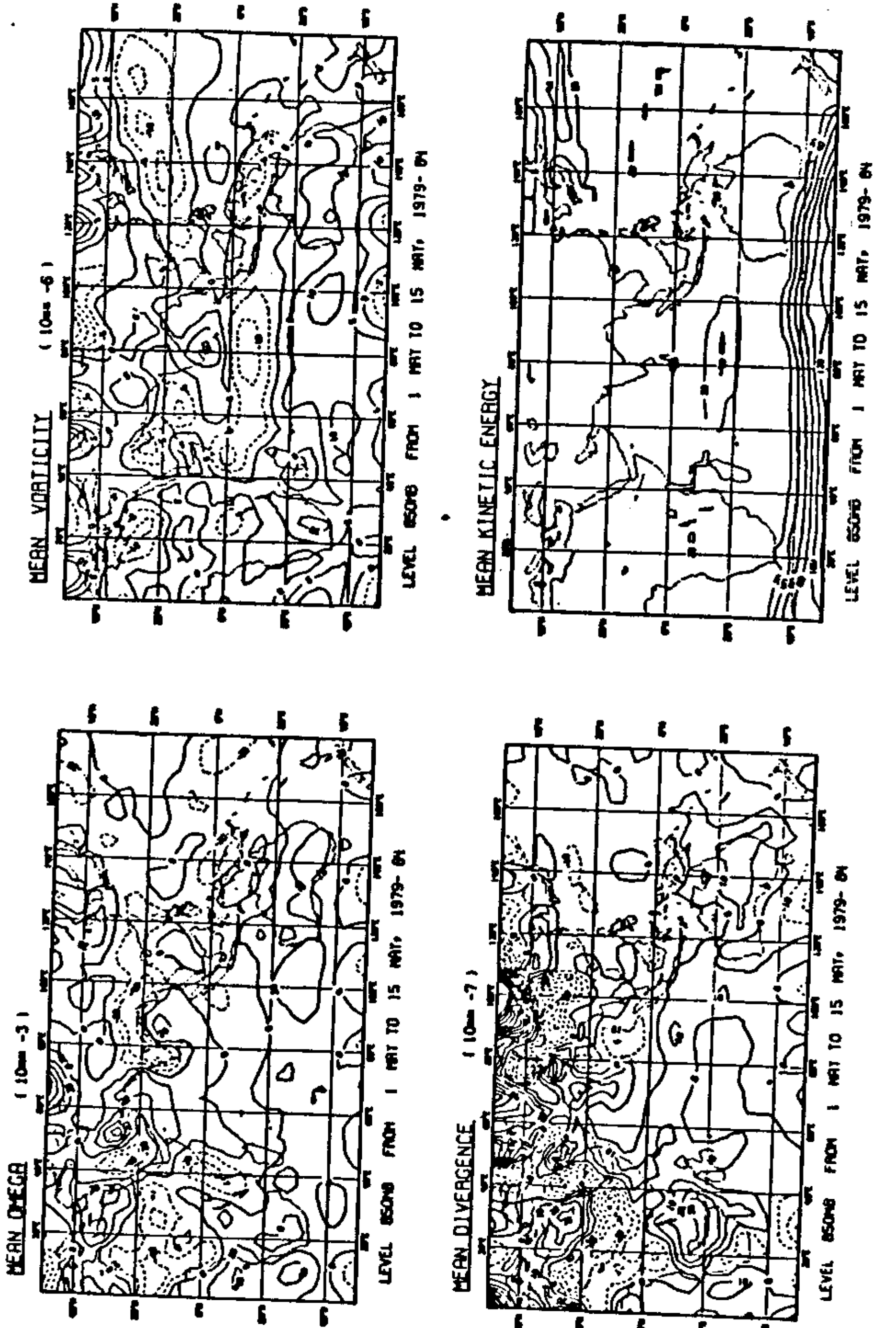
LEVEL 150MB FROM 1 MAY TO 15 MAY, 1979- 84


MEAN OMEGA (10** -3)
LEVEL 150MB FROM 1 MAY TO 15 MAY, 1979- 84


MEAN DIVERGENCE (10** -7)
LEVEL 150MB FROM 1 MAY TO 15 MAY, 1979- 84



Appendix - B

Southwest Monsoon Climatology

There are a number of monsoon systems, however, none is so phisically powerful or dramatic, so rich in folklore, literature, and history, or has such an enormous socio-economical impact as the Asian summer monsoon, in particular, the Indian summer monsoon. Further, a large number of literatures/monographs and long reliable records on monsoon phenomenon over Indian sub-continent are also available. Therefore, here under regional climatology of monsoon, we have confined our discussion on Asian summer monsoon over Indian subcontinent and adjoining seas.

Geographical distribution of a few important climatological elements such as sea-level pressure, surface temperature, rainfall, upper air temperature and upper winds are presented, tracing their evolution from the preceding season and decay at the end.

1. Sea-level pressure and surface winds

The mean sea-level pressure and surface winds for April, July and October are illustrated in figures 1-3. They represent mean surface climatological conditions during pre-monsoon, monsoon and post-monsoon periods respectively. By April the mean sea level pressure (MSLP) indicates the establishment of heat low over land at about Tropics of Cancer and high pressure cells over the Bay of Bengal and the Arabian Sea. The summer continental low pressure areas completely dominate north Africa and Asia by May. Its main centre lies over India (near 30^{o}N, 75^{o}E) with an extension as a trough upto east coast of India. The heat low is still more marked in June with the main Centre over Pakistan. Monsoon activity is maximum in July when the low pressure area extending from north Africa to northeast Siberia is most intense. Its main centre is over north Baluchistan and neighbourhood (Fig.2). A trough lies over north India with axis from Sriganganagar (NW India) to the Head Bay, which is referred to as the "Monsoon Trough". By October, the trough over northern India shifts to the Bay of Bengal, with trough line along 13^{o}N and the pressure field is flat over India (Fig.3). Thus, the main features of MSLP distribution in the monsoon season are (i) Heat Low over Pakistan, (ii) Monsoon Trough over north India and (iii) strong pressure gradient to the south.

In June, the surface winds mainly blow from west to southwest over India except north India (north of monsoon trough). Between 5^{o}N and 15^{o}N end west of 65^{o}E, the wind speed is 20 Kt in the Arabian Sea and elsewhere in the range of 10 to 15 Kts. In July the flow is further strengthened with more than 25 Kts over the Arabian Sea (west of 68°E and between 10°-20°N). By September, there is a weakening of pressure gradient and winds weaken, particularly over the sea areas.

2. Surface temperature

Mean surface temperatures reduced to sea-level at a lapse rate of 6°C per Km are illustrated in figure 4. Land gets progressively heated after December-January and by April the temperatures are of the order of 33°C to 35° over southern India upto 24°N. In July the southwest monsoon causes extensive cloudiness. Clouding is heavy between 17°N and 24°N in the Central regions, west of 77°E and south of 17°N in the Peninsula, and to the east of approximately 85°E in northeast India. Temperatures are even in these regions (between 28°C and 29°C) The hottest areas lie over Northwest India and Pakistan. Thus the region of highest temperatures shifts from near 20°N in April to 28°N by July.

3. Rainfall

The rainfall distribution in the principal "rainy season" of India, the southwest monsoon period (June-September) is illustrated in Figure 5. In most part of the country the annual rain is mainly accounted for by the falls in this season (except extreme south Peninsula and the east coast areas). Orographic influence is dominant in the distribution of rainfall in this season. In the north Indian plains, a minimum rainfall belt runs from northwest India to the north-east India, partically along the axis of the monsoon trough. Mean monthly rainfall amounts are not uniform during this period (June-September). Broadly, rains increase with the setting of the monsoon, reach a maximum in July and then decrease.

The coefficient of variation of rainfall (ratio of the standard deviation of the season's rainfall to the mean amount) is illustrated in Figure 6. This varies from 60 per cent in the western desert to 20 percent or less in the most rainy areas. In the southeastern tip of the Peninsula where this is not the rainy season (with less than 10Cm rainfall), it is 100 per cent. In general, the coefficient of variation decreases with increasing rainfall upto about 100 cm and then does not vary. Standard deviations of rainfall are generally comparable over the whole country but the wide differences in variability are due to the differences in mean rainfall. These fluctuations in rainfall affect economic activities, more so in areas of poor rainfall. Monsoon activity is so closely associated with rainfall that it is generally described by quantum of rainfall: As for example:

(i) Weak monsoon - Rainfall less than half the normal.

(ii) Normal monsoon - Rainfall ½ to 1½ times the normal

(iii) Active/strong monsoon - Rainfall 1½ to 4 times the normal

(iv) Vigorous monsoon - Rainfall more than 4 times the normal

Heavy rainfall of the order of 25-30cm are not infrequent in the monsoon season, but they are more probable north of 15°N along west coast and north of 20°N in the rest of the country, apart from the western ghats.

4. Upper air temperatures

By April a thermal high develops over central India with its centre at about 22°N and 80°N (Fig.7). A strong meridional gradient of temperature is observed to north and south of the centre. By 700mb, the thermal high shifts shouthwards to 15°N and temperature gradient is towards north. At 500mb also the temperature decreases to the north of 12°N and is uniform to the south. Even at 300mb a weak thermal high is observed over the south Peninsula. The tropical tropopause occurs in April near 100mb, to the north of 25°N.

The thermal high at 850mb shifts gradually to northwest. (May - 23°N and 78°E and June - extreme NW India and adjoining Pakistan).

In July (Fig.8), during well established summer monsoon, the thermal high lies over Iran, Iraq and Central parts of Arabia at 850mb and a thermal ridge runs from it to 35°N to north of India. A nearly similar pattern is observed at 700mb. At 500 and 300mb, a thermal ridge runs along 25°-30°N with appreciable temperature gradient to the south at 300mb.

Standard deviation of temperature is about 2° at 850, 700 and 500mb, increasing to 5°C alfot. The standard deviations are higher in the north than in the south.

Thus the warmest region shifts markedly in the monsoon period, more so in the upper troposphere. The thermal ridge at 200mb over Tibetan region is an important feature.

5. Upper winds

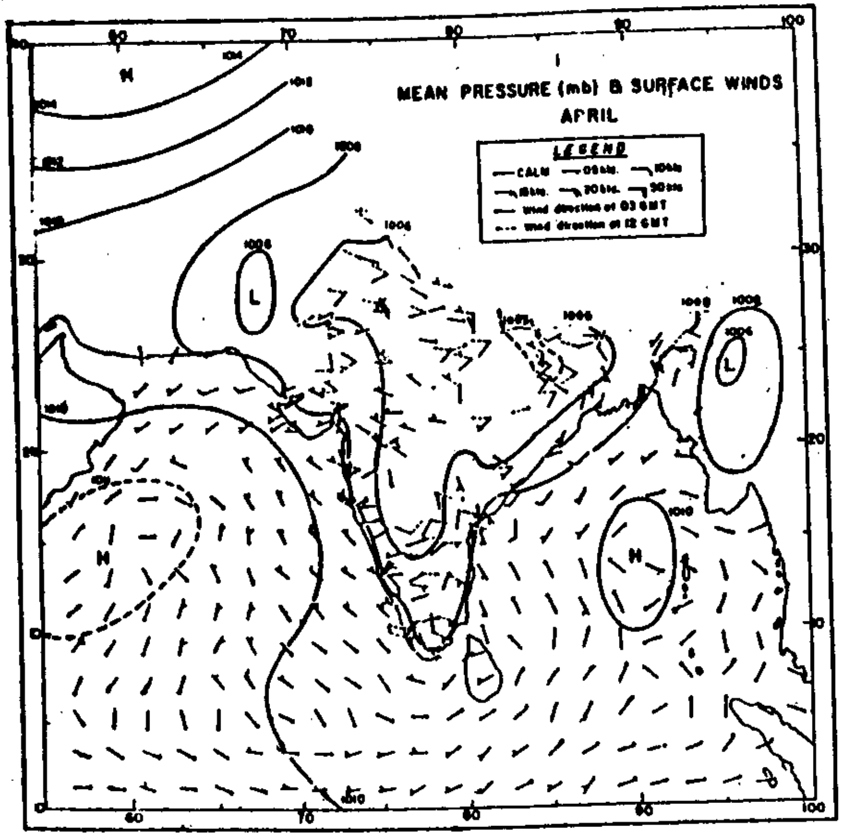
In April (Figs. 8 and 9), a trough line runs along 77°E at 900mb over the Peninsula as at sea level. The sub-tropical ridge (STR) appears over land near about 18°N at 850mb and persists at 700mb. Aloft, it gradually shifts southwards to 8°N at 200mb. Westerlies increase with height over northern

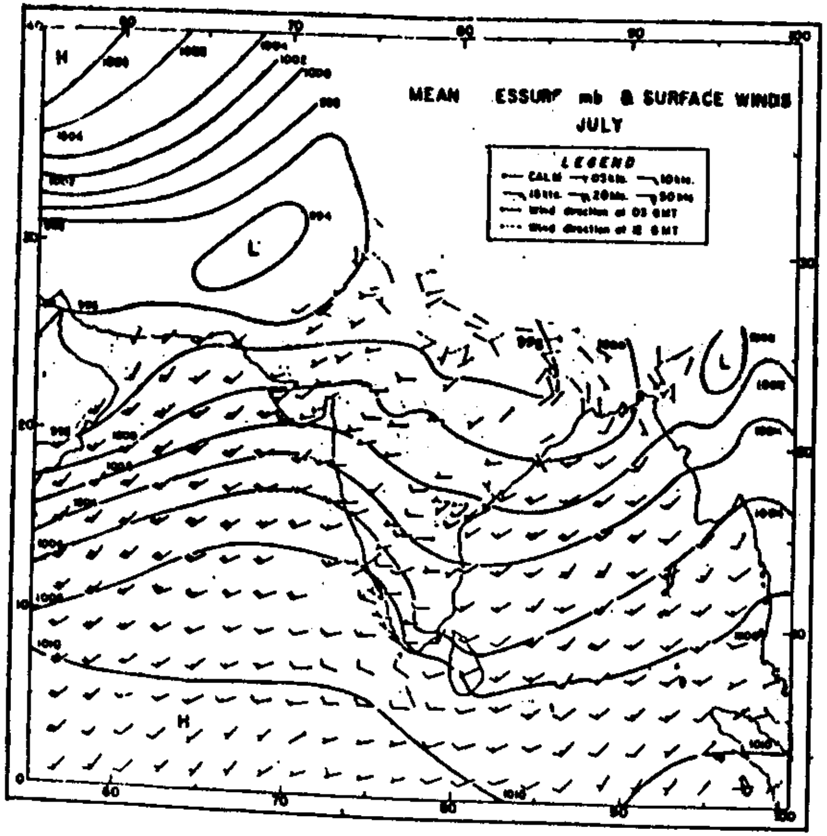
India and the adjoining Peninsula (40 Kts near 25^{o}N at 300mb and 50-60Kts near 27^{o}N at 200mb - Westerly jet)

With onset of summer monsoon, a trough is established over north India (Monsoon Trough:MT) To the south of the trough WSS to WNW winds prevail while to the north of the trough southeasterly winds (Fig.10 and 11). Westerly winds over the Peninsula increase. with height from ground and reach a maximum between 900 and 800mb level. (900mb along west coast and 800mb in eastern Peninsula). A wind maximum near 900mb is found in the Arabian Sea with more than 25kts wind (low level somali jet).

The monsoon trough shifts south with height and is near about 23^{o}N at 700mb but becomes diffuse above 500mb over the Peninsula. The warm surface low over Pakistan and neighbourhood is replaced by the subtropical high at 700mb. The southwesterly current becomes weak at 500mb and replaced by easterly over the whole country at 300mb. Easterly [illegible] strengthen with height from 300mb reaching a maximum in the layer 150-100mb. The wind speeds are between 60 and 80Kts over the Peninsula between 150 and 100mb (Tropical Easterly Jet TEJ). The subtropical westerly jet moves northward to the north of the Himalayas. While the wind patterns from June to July are intensified between 850-500mb and 200-100mb, winds are slightly weaker in August in these layers. In September, winds are further weaker upto 900mb.

To summarize, during summer monsoon a low-level westerly jet (at about 1.5km over Arabian Sea) and a easterly jet (at about 15Km over Penisnsula) are established. Thus a strong vertical shear is observed in southern Bay of Bengal, Arabian Sea and Peninsula. A monsoon trough is formed in lower tropophere extending from heat induced low over NW India and Pakistan to the Head Bay of Bengal. The sub-tropical high is intensified over the Tibetan Plateau with TEJ in the south and STWJ in the north (called Tibetan High). The southwesterly flow from the Arabian Sea across the Peninsula is usually refered as the "Arabian Sea Monsoon" and that of the southeasterly wind to the north of the monsoon trough (MT) is called as the "Bay monsoon Current".

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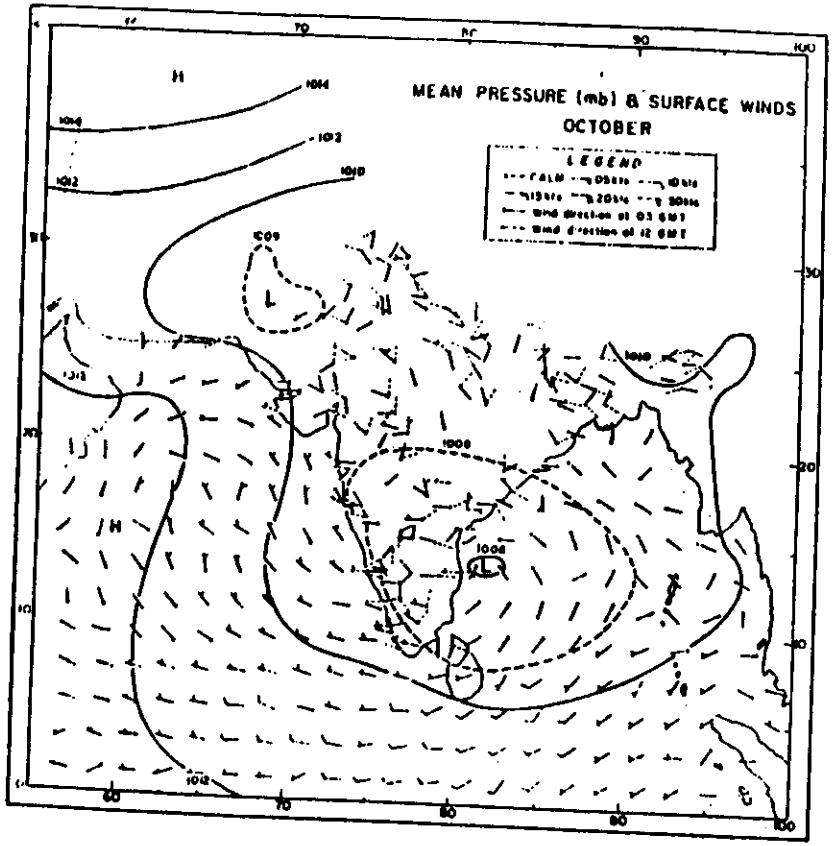
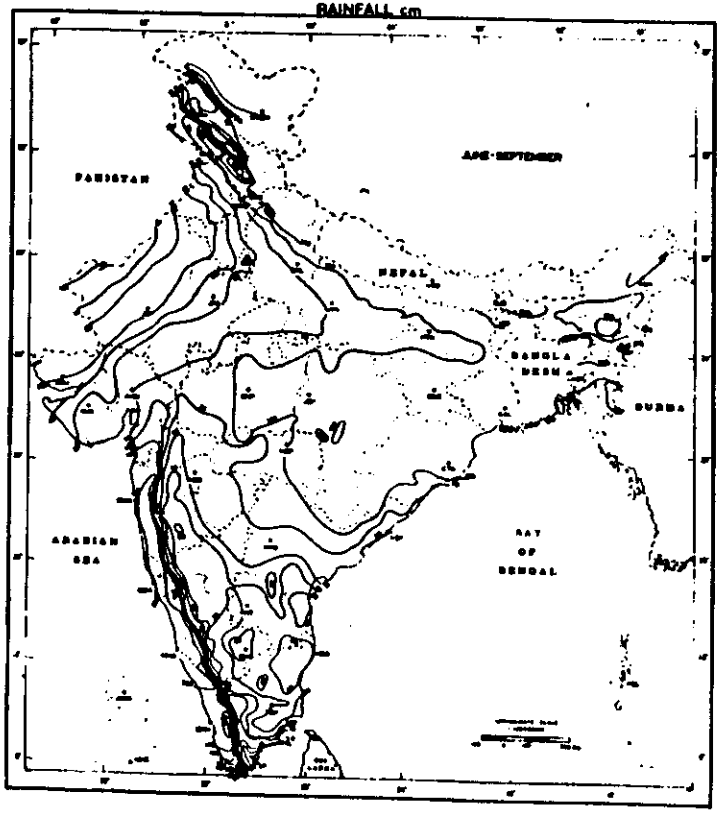

MEAN PRESSURE (mb) & SURFACE WINDS
OCTOBER
LEGEND

RAINFALL cm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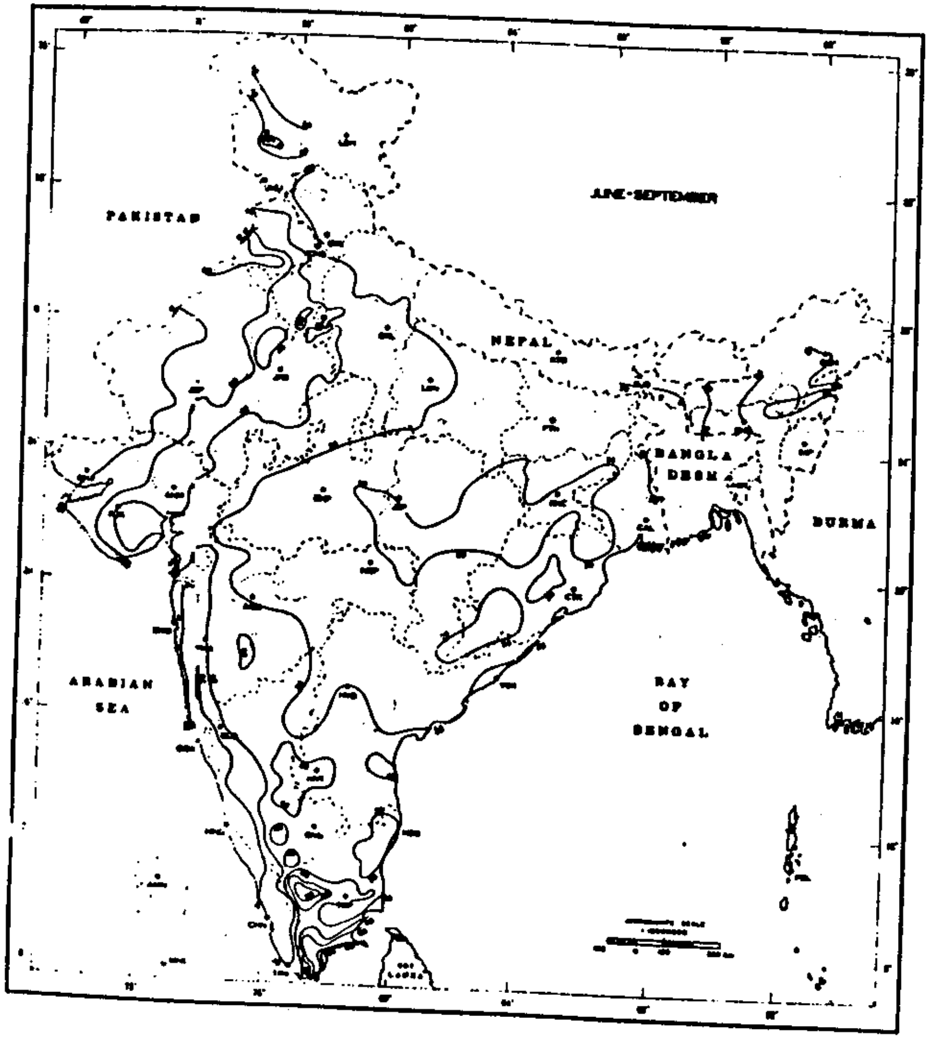
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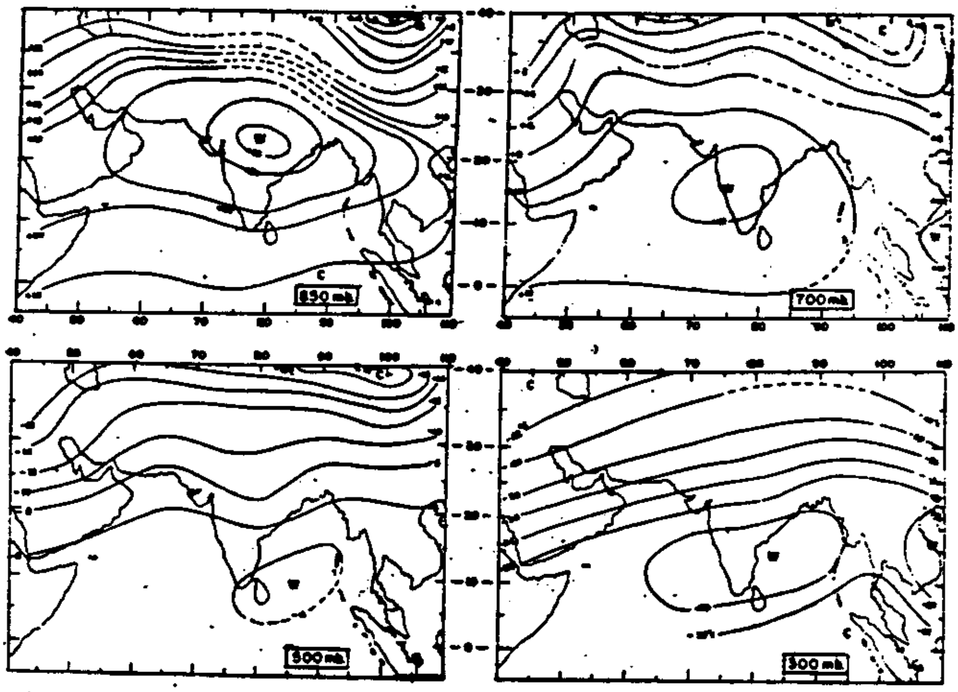

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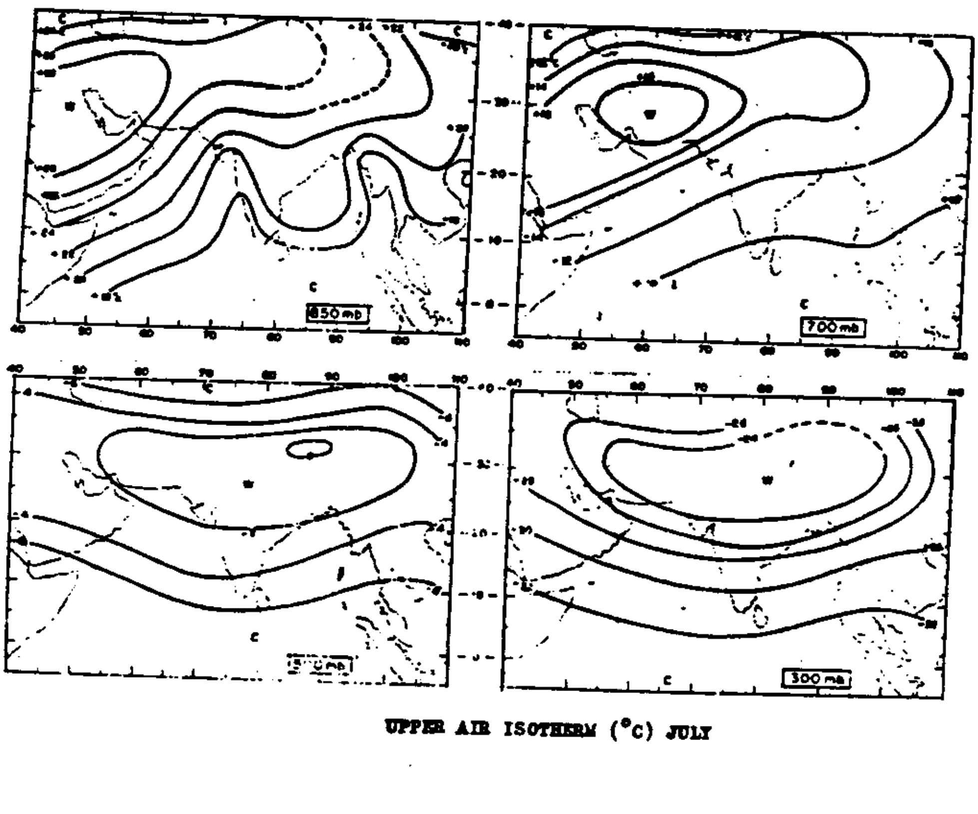
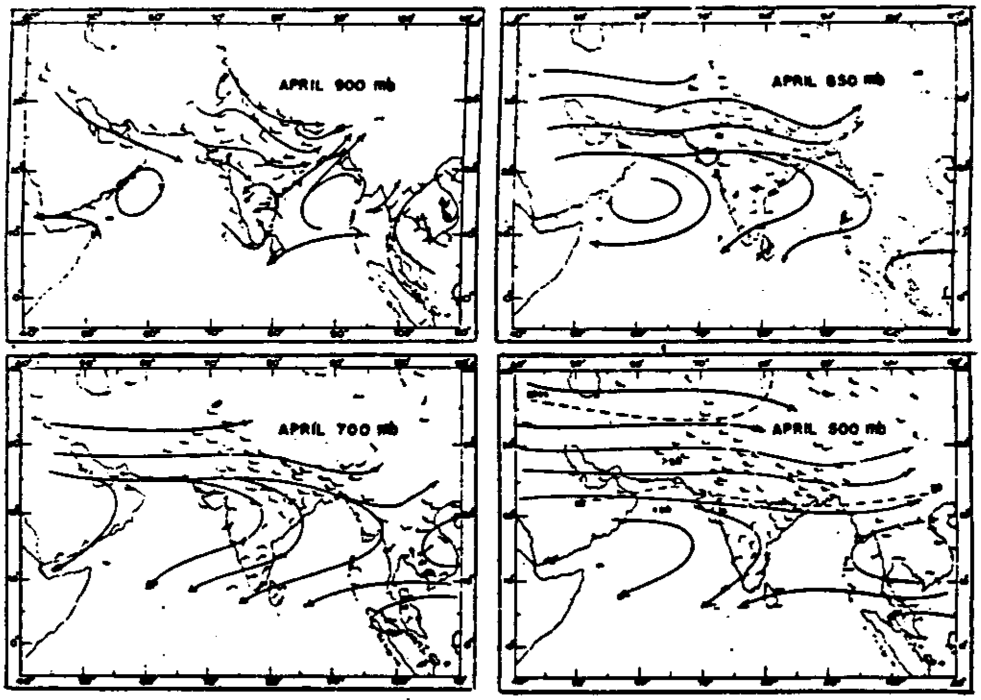


UPPER AIR ISOTHERM (°C) JULY



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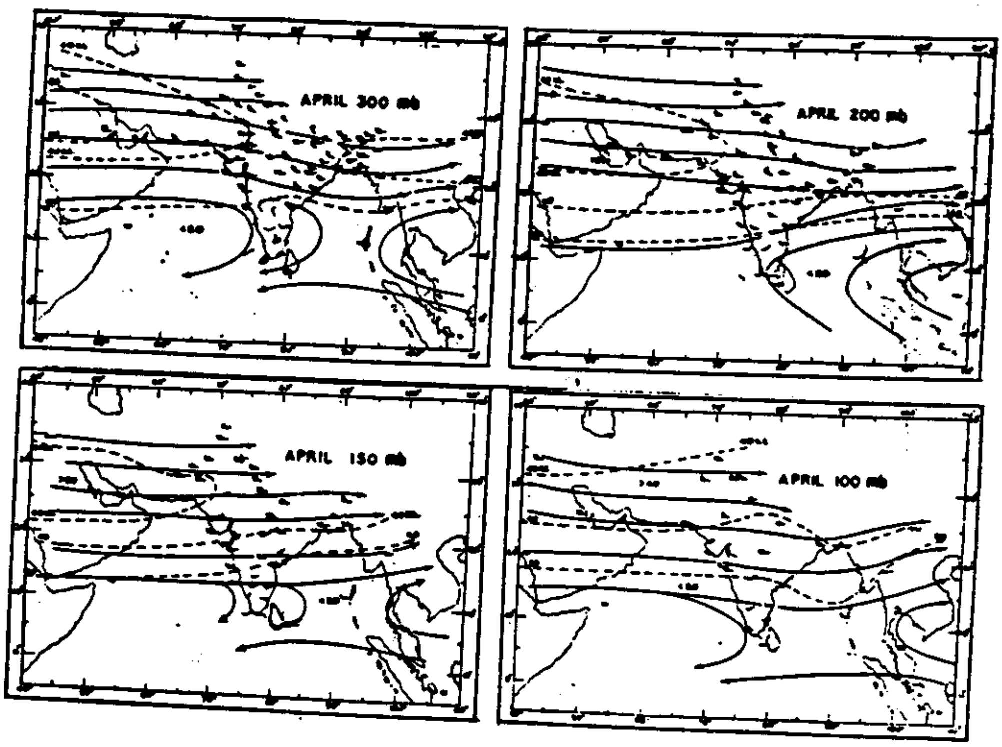

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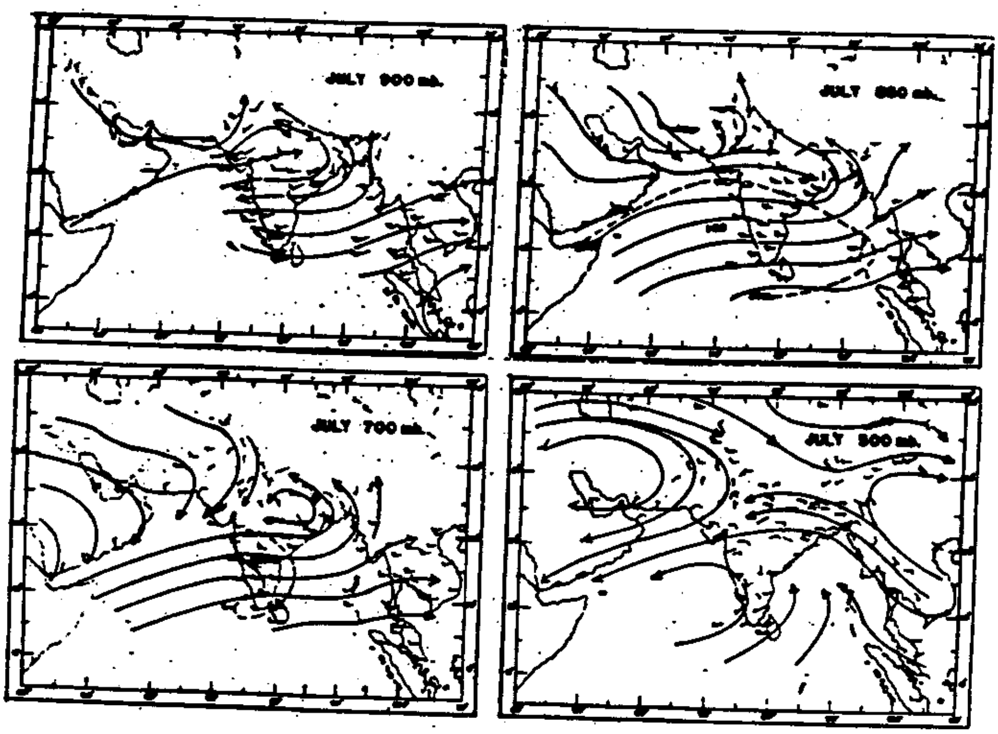

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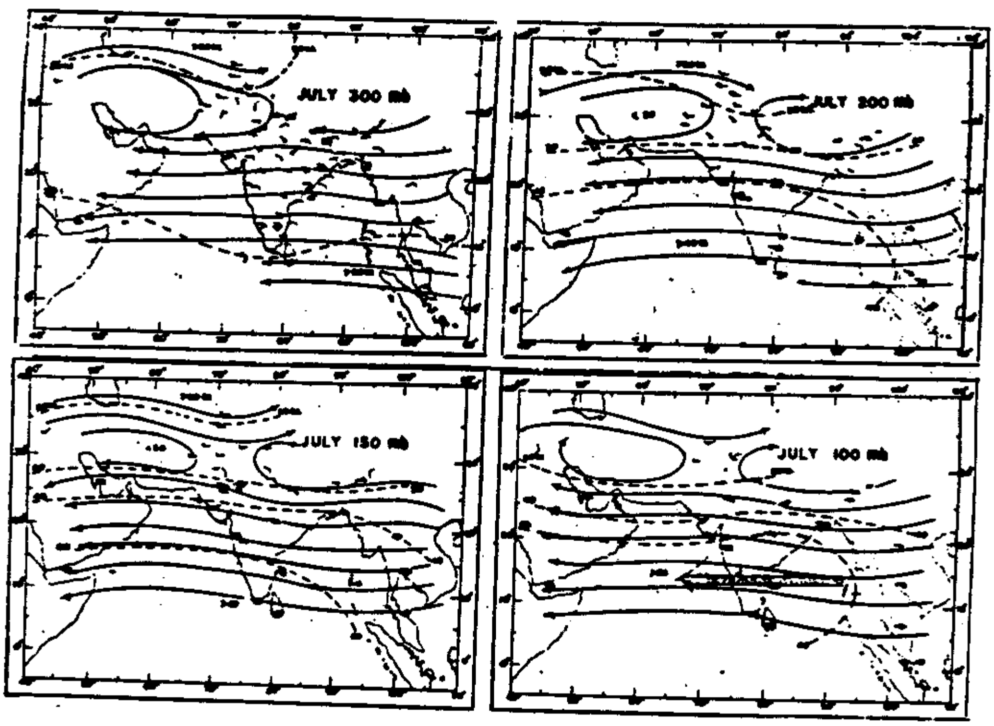


UPPER WINDS

Regional Aspects of Monsoons (Intraseasonal and Interannual Variability of Monsoon Rainfall over India)

1. Introduction

Regional aspects of monsoons occur on a small scale. Opinions differ on what the dividing line should be between the planetary and regional scales of motion. However, it is important to recognize that the different scales are coupled strongly, one often contributing to the other through complex interactions which are not yet fully understood. Here we will consider only some of the prominent features on which some agreement is apparent in the literature. Here some details will be left out either because they are based on insufficient data or because their relevance to the large aspects of the monsoon is not clear.

The variability of summer monsoon rainfall is the central problem because of its social-economic importance (association with droughts and floods). Further, reliable records of rainfall over India are available for a long period (80-100 years). Therefore, emphasis will be given to the interannual variability of summer monsoon rainfall over India. The regional features of the summer monsoon are associated with short period rainfall fluctuations (intraseasonal variability). The hundred-day monsoon over India from 1 June to mid-September consists of spells of heavy rain (Active phase) followed by lean periods (Break Phase). The duration of an active or a break phase is about a week, but on some occasions prolonged breaks also occur. The duration and frequency of breaks increase towards the second half of the monsoon.

The influence of the summer monsoon is spread over countries of east and south-east Asia. In China, the summer monsoon rains are known as Mia-Yu, over the southern part of Korea as Mae-Ue and in Japan as Baiu rains. Rainfall over monsoon lands exhibits extreme contasts. The wide variations in space of the monsoon rainfall are generated either by the alignment of mountain barriers or by the normal track of rain-bearing systems.

In this lecture we will consider the dates of onset and retreat of monsoon, principal rain bearing systems (such as monsoon depression, monsoon trough, mind-troposheric cyclone, off-shore vortices etc.), Break monsoon and certain aspects of inteannual variability of monsoon rainfall.

2. Onset and Withdrawal of the Monsoon

Perceptible changes on account of the monsoon, are (i) winds from about southwest, (ii) decrease in temperature from the heat of April and May and (iii) increase in rainfall. The first is mainly of interest to mariners, while

other two have more general impact. Dates of onset can be fixed by the changes in any of these features for any year. However, development of these three features are not simultaneous. Therefore, opinions differ on what really constitutes an onset of the monsoon. Many prefer to define it as the date on which the prevailing wind reverse their direction. On the other hand, for the purpose of agriculture it is more convenient to fix the dates of onset by the commencement of rains.

Table 1 (Yashino, 1971) provides approximate dates for the beginning of the summer monsoon season over a region from 75°-140°E and from 20°-45°N. The rainy season begins earliest in south China towards the beginning of May. Subsequently, it extends its influence over the south-eastern parts of Japan and Burma. Monsoon rains do not begin over India until the very end of May (though southwesterlies set in the Arabian Sea in early May).

The India Meteorological Department (National Meteorological Services of India) has fixed the dates of onset and withdrawal of monsoon with reference to the rather sharp increase and decrease respectively shown by the five-day means of rainfall, supported by the changes in the circulation. Figure 1 shows the normal dates of the onset and withdrawal of the monsoon (based on rainfall and synoptic features: nearly 70 years'data on a few working rules for an objective determination of the date of onset of monsoon. They are based on a specific number of stations receiving a 24-hour rainfall of 1 mm or more for several consecutive days.)

The arrival of the monsoon is a gradual process starting with a transition period when atmospheric characteristics change from a state of extreme dryness to one of high humidity and light continous rain. Thunderstorms are a feature of the pre-monsoon condition lead to genuine monsoon rainfall.

A survey of nearly 70 years of the onset of monsoon over the southern tip of the Indian peninsula reveals the normal date as 31 May with extremes of 11 May and 15 June. Consequently, any rainfall prior to 11 May is not regarded as genuine monsoon rain. The standard deviation of the dates of establishment of monsoon along the west coast south of 20°N is 6-7 days. The earliest date was 17-22 days before, while the most delayed arrival was 10-13 days after the normal date. To illustrate the variability of the advance of monsoon, a histogram giving the dates of onset of monsoon over Bombay from 1979 to 1975 is given in figure 2 (Rao, 1976).

3. Breaks in Monsoon

Within the monsoon season, there are periods when the monsoon activity in terms of rainfall considerably decreases or ceases over most part of India but increases over regions near foot of Himalayas and southern Peninsula. During such activity, the monsoon trough shifts to foot hills of the Himalayas. This situation is referred as "Break in Monsoon". This break phase may last for a couple of days to as much as 3 weeks. Ramamurthy (1969) has catalogued the "breaks" in July and August from 1888 to 1967 which was summarized by Rao (1976) and are presented in the table 2.

Table - 2

Statistic of breaks in monsoon

Month	No.of breaks	No.of break days	Average duration	Longest break days	Most frequent duration days	No.of break days in First 10 days	Second 10 days	Last days
Jul	53	306	5.8	17	4	81	117	108
Aug	55	356	6.5	20	3	115	159	82
Commencing July ending in Aug.	5	47		21				

Besides significant changes in rainfall distribution over most parts of the country, a number of imporant changes in the flow patterns are observed. They are :

(i) Shift of monsoon trough northwards near the foothills of Himalayas and absence of any low pressure or trough of low pressure in the North Bay of Bengal.

(ii) General decrease in pressure gradient over the country. For illustration, the pressure gradient between Bhuj (23.3N and 69.6E) & Trivandrum (8.3N, 76.9E) may reduce to 1-3mb during break situation compared to 7-10mb in good monsoon conditions.

(iii) The monsoon trough at 850mb and 700mb level also shifts northwards near the foothills or disappears. Instead, there is development of ridge over Northwest India.

(iv) The above changes result in general absence of easterlies over north India. There is also general decrease of strength in westerlies over peninsular India, where flow starts developing more northerly component.

(v) General shift of upper tropospheric sub-tropical ridge southward by over 2-3° latitude.

(vi) Occurrence of double easterly jet maxima over India, one around 10°N and another fairly north near 20°N. Sometimes instead of double maxima, we observe generally strong easterlies spread over a very broad area.

(vii) Appearance of westerly jet over the northern parts of the country.

(viii) In some cases, the ridge-trough system at 500mb over and east of Caspian sea may extend upto 300 or even 200mb level.

The middle of August is most susceptible to breaks.

Breaks in monsoon occur mainly due to the following activities:

(i) Northward shift of monsoon trough to the foot hills of the Himalayas when a depression moves to these mountains; which is associated with more southerly travel of extra-tropical systems.

(ii) Passage of westerly waves across the Tibetan Pateau and adjoining Himalayas in quick succession leads to 'breaks'.

(iii) The establishment of a well marked anticyclone with north-south ridge axis over and near the Caspian Sea in the lower and mid-troposphere and its eastward extension is a prominent feature in most break conditions.

(iv) Breaks are also associated with a typhoon or its remnant in the western Pacific moving to the north of Lat. 30°N, provided there is no depression or typhoon in the China Seas south of 30°N nor unsettled conditions or a depression already present in the Bay.

But not all the "Breaks" seem to develop in the same manner.

Monsoon most often revives after a "break" by the formation of a low or depression in the north Bay. Gradual formation of the monsoon trough in the normal position also takes place sometimes.

4. Principal rain-bearing systems

Of several rain-bearing systems that lead to short duration rainfall fluctuations, the leading ones are :

(a) Monsoon depressions in the Bay of Bengal;

(b) Fluctuations in the intensity and location of a monsoon trough over the plains of India and Pakistan;

(c) A mid-tropospheric low-pressure system off the coast of India; (MTC)

(d) Off-shore vortices;

(e) A low-level equatorial jet stream along the eastern coast of Africa.

The coupling between the regional rain-bearing systems of the summer monsoon and its larger planetary aspects is still not well understood. For example, in some summers there are more monsoon depressions than in others for reasons which are not yet known.

(a) Monsoon Depressions in the Bay of Bengal

These disturbances play a very significant role in the maintenance of the monsoon circulation. Much of the rainfall over India and Pakistan during the summer monsoon is generated by the westward passage of depressions and low-pressure systems in the Bay of Bengal. On an average, two to three systems are observed per month during the monsoon season. The highest frequency is observed in the months of July and August. The horizontal dimensions of these systems are around 500Km and their usual life span is about a week. A survey of their mean tracks reveals movement towards the north-west for the first three or four days; thereafter they tend to recurve towards the north or continue to move westwards. The strong easterlies over north India up to 500hPa were favourable for the westward movement of monsoon depressions towards Pakistan. The synoptic features which lead to recurvature are not well defined. Upper winds at 300 and 200hpa, which are reckoned to be steering levels, are used to anticipate recurvature, but success by such means is limited.

Rainfall generated by depresssions or low-pressure systems in the Bay are usually concentrated in the south-western sector. The structure of a Bay depression usually indicates a tilt in its vertical axis towards the south-west, but this has not found general agreement.

The factors that control the formation, subsequent growth and movement of monsoon depressions are :

(a) Horizontal and vertical wind shear;

(b) Convective and mesoscale systems leading to vertical transport of moisture, heat and momentum;

(c) Sensible and latent heat transfer from the surface of the sea, and latent heat realized through precipitation.

Recent research suggests instability as a possible mechanism for cyclogenesis over the northern sectors of the Bay of Bengal.

(b) Monsoon Trough

During the summer monsoon, an elongated low-pressure area is established over India, Pakistan and adjoining countries of the Middle East. It is known as "Monsoon Trough" (MT) and we refer to its position at sea level, although it has been observed to extend upto about 500mb, tilting southward with height.

Normally, MT axis is oriented in an east-west direction, roughly paralledl to the southern periphery of the Himalayan mountains.

MT is a quasi-permanent feature of the summer monsoon, but its axis displays wide variations. An active phase of the monsoon is observed when the axis lies to the south of its normal position and its eastern end extends into the northern part of the Bay of Bengal. On the other hand, when the axis moves north and is located close to the Himalayan foot-hill, a break phase is observed.

For many years it was believed that the MT was a mechanical effect brought about by the alignment of the Himalayan mountains and the mountains of Burma. However, recent model experiments suggest that the mountains by themselves are not sufficient to generate a quasi-permanent trough and flucturations in the radiation balance of the atmosphere are believed to have an important on the movement of the trough axis.

(c) Mid-Tropospheric Distrubances (MTC)

During the International India Ocean Expedition (IIOE) of the late sixties, it was observed that heavy rainfall over the north-eastern parts of the Arabian Sea and the adjoining areas of the Indian coastling was associated with cyclonic vortices confined to the middle troposphere. These vortices were observed to be between 3 and 6km and their largest amplitude was near 600 hPa. They were not visible on surface weather charts. Unlike the Bay depressions, mid-tropospheric disturbances have a core of warm air above 4 km with slightly colder air below. These systems exhibit little movement and appear to remain quasi-stationary for several days. The horizontal scale of these disturbances is of the order of 3000 km.

On many occasions, the rainfall associated with a mid-tropospheric system can amount to as much as 20 cm in 24 hours. Such systems are also observed over south China, but their frequency is much smaller.

As these disturbances are located between a westerly regime at the surface and easterly winds in the upper atmosphere, it is believed that large vertical shears are responsible for their formation.

Principal component analysis of monsoon rainfall shows similarity of rainfall patterns over the coastal regions of east India and the northwest coastal region of India, thereby indirectly indicating the positive relationship between the formation of a monsoon disturbance in the Bay of Bengal and MTC in the Arabian.

(d) Off-Shore Vortex

These are sub-synoptic scale systems with horizontal scale of 30-150 km and are generally observed off the west coast of India during the monsoon period. These are very shallow systems and are normally confined to low levels below 850mb.

First detailed study on the formation of an off-shore vortex along the west coast of India was done by George (1956). These vortices have been associated with heavy rainfall over the west coast (like that of MTC).

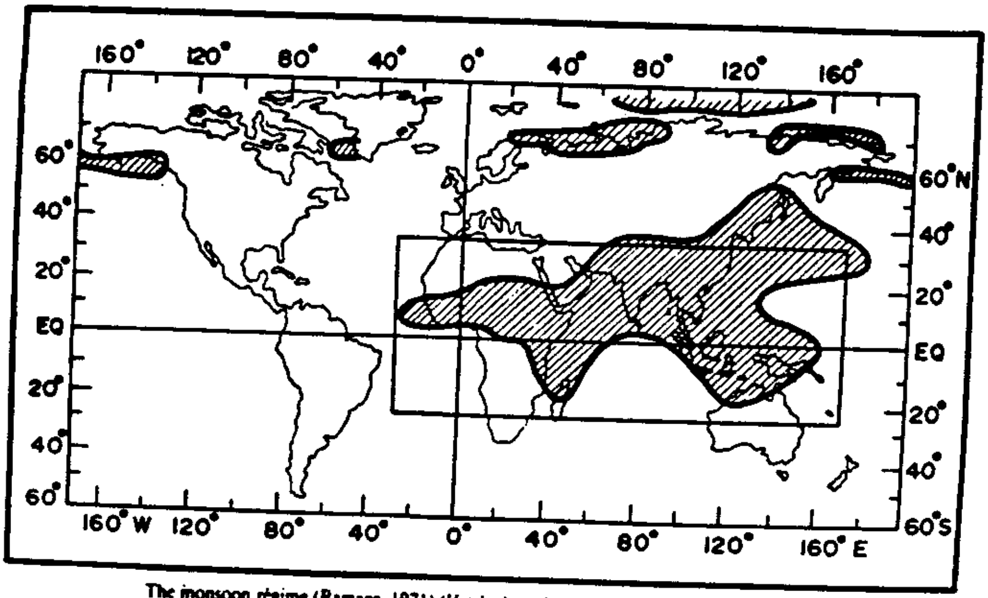
As already mentioned, from scale consideration, these vortices are sub-synoptic systems and would be normally difficult to track them from one synoptic chart to the other, but Mukherjee & Shah (1981) claim to have tracked an off-shore vortex during the period of Monex-79. However, it is believed that these are sub-synoptic scale systems and the movement of these systems is regeneration process at a new location like the movement of a squall line. Sometimes these vortices have been observed to remain stationary for a period of 24 hours or so.

(e) Low-level Cross-Equatorial Jet

In the late sixties and early seventies, Findlater (1966, 1969, 1971, 1972) observed strong winds in the form of a narrow current of air off the coast of east Africa. The low-level jet stream was most pronounced between 1 and 1.5km. The jet appears to flow from Mauritius and the northern part of Madagascar before reaching the coast of Kenya at about 3^oS. Subsequently, it covers the plains of Kenya, Ethiopia and Somalia before reaching the coast again around 9^oN. It appears to be fed by a stream of air which moves northwards from the Mozambique Channel.

The major part of the low-level jet moves further into eastern Africa during May and subsequently traverses the northern parts of the Arabian Sea before reaching India in June. The strongest cross-equatorial flow during the summer monsoon takes place in the proximity of the low-level jet. It is still not clear why this region is a preferred zone for cross-equatorial mass transport.

The location of the low-level jet coincides with a zone of coastal upwelling. This is responsible for creating a cold surface temperature off Somalia by upwelling. On many occasions the temperature is as low as 18^oC, but the temperature over the eastern part of the Arabian Sea is of the order of 25^o-30^oC. This leads to a strong temperature gradient over the Arabian Sea during the summer monsoon.



The monsoon régime (Ramage, 1971) (Hatched portions represent monsoon lands by Khromov (1957))

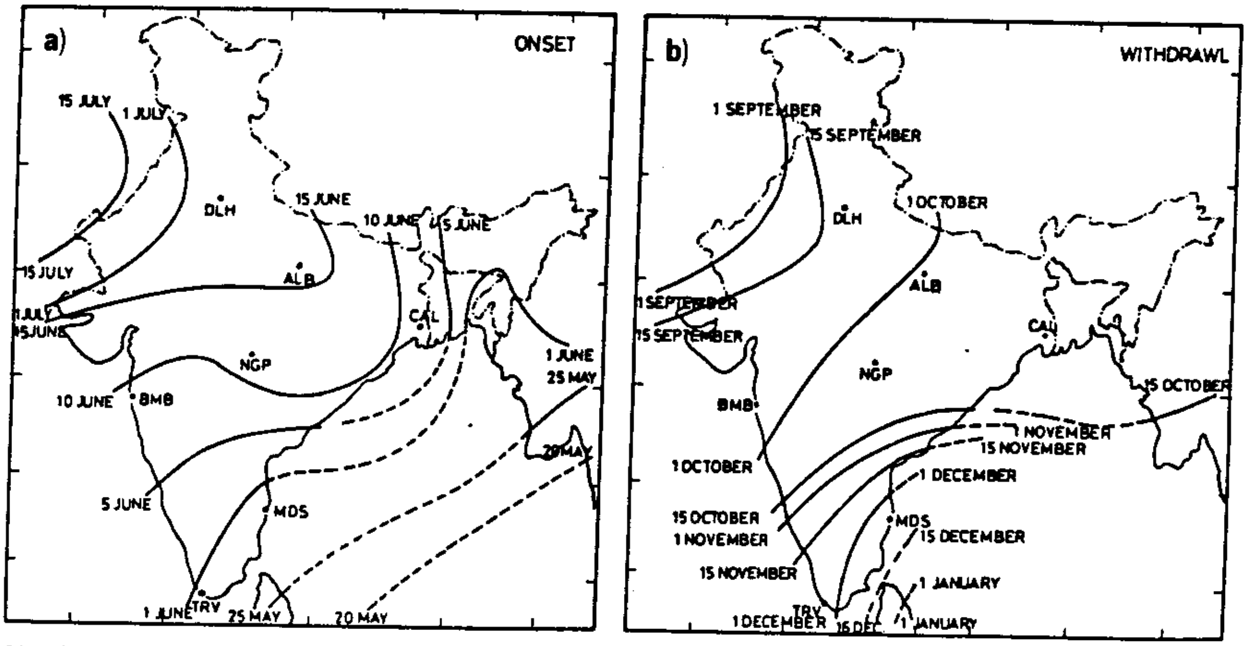
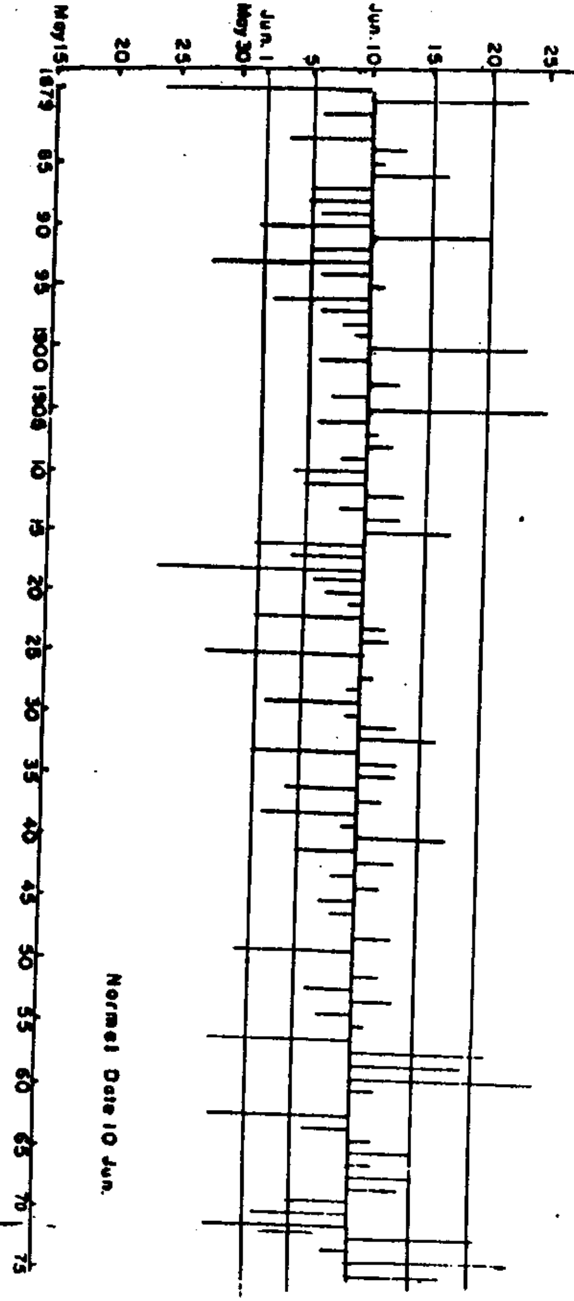
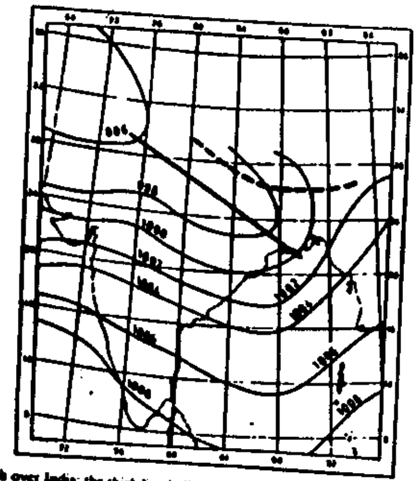


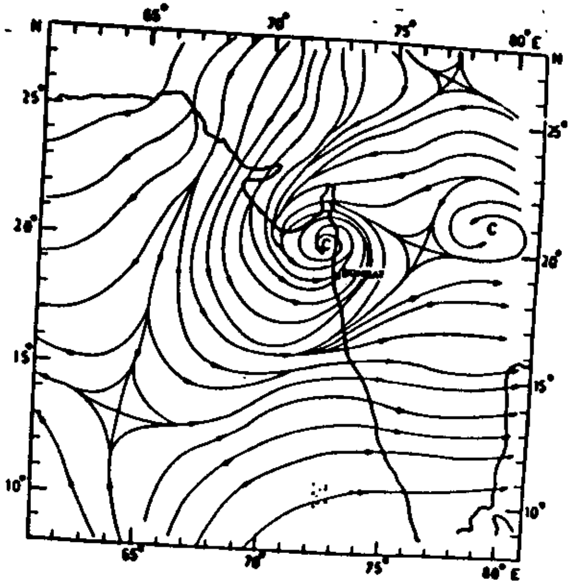
Fig. 1 Normal dates of (a) onset and (b) withdrawal of the summer monsoon.



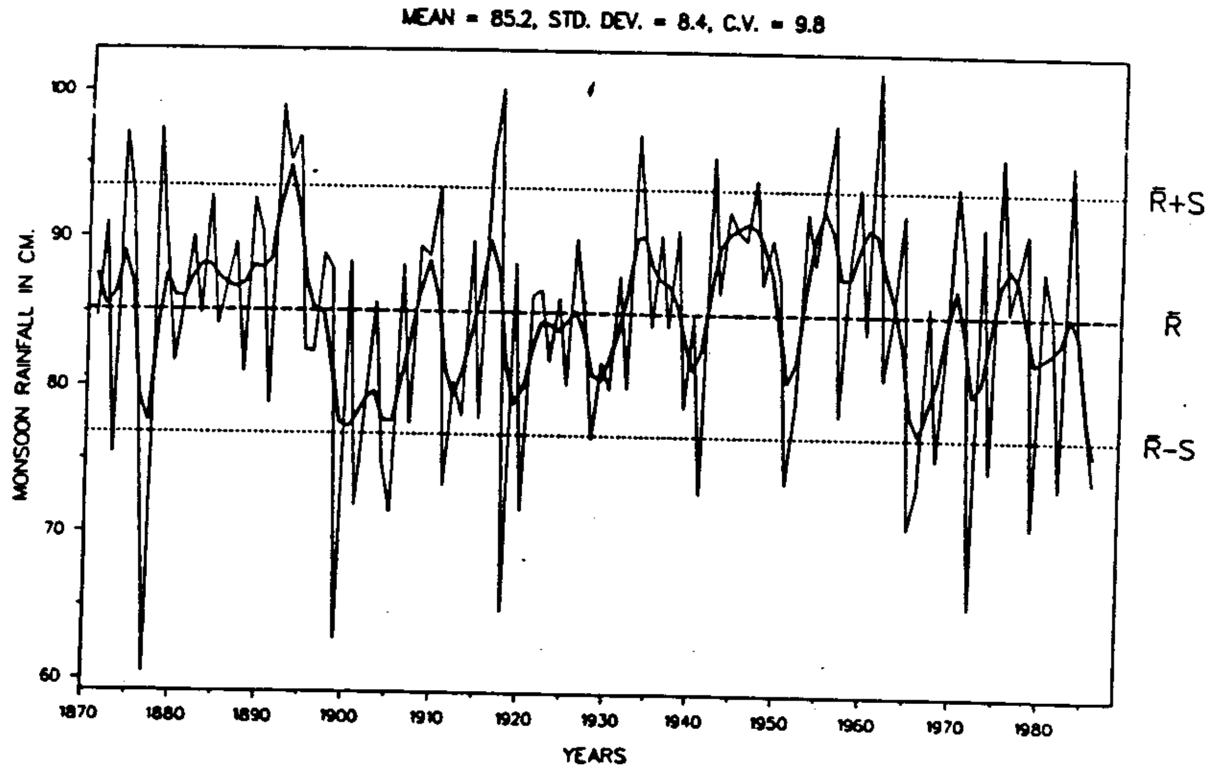
ACTUAL DATES OF ONSET OF SOUTHWEST MONSOON OVER BOMBAY (1879-1975.



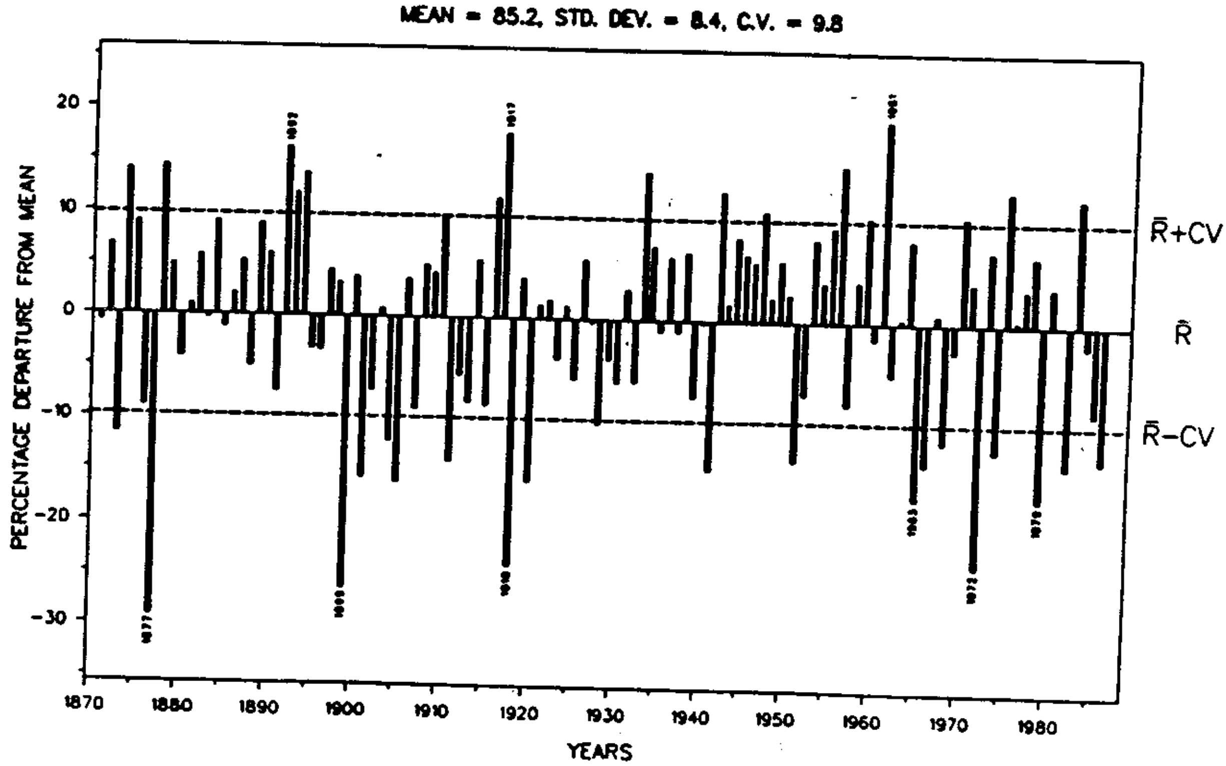
The monsoon trough over India: the thick line indicates the normal position of the trough, and the dotted line shows the trough position under 'break conditions'



Mid-tropospheric cyclone



ALL INDIA SUMMER MONSOON RAINFALL FOR THE PERIOD 1871–1986



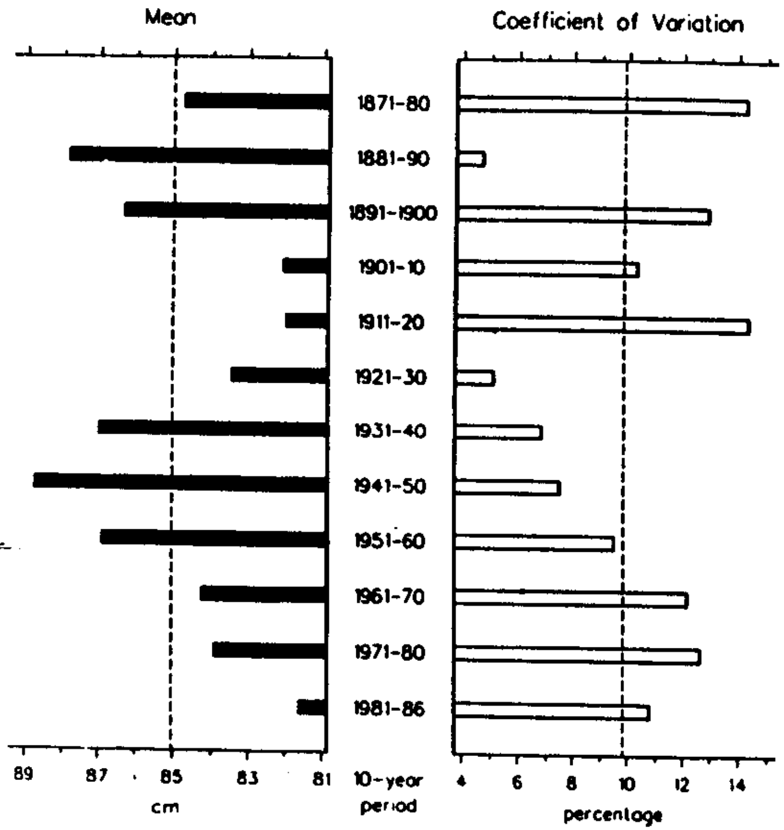
PERCENTAGE DEPARTURE FROM AVERAGE (1871–1984) OF
ALL INDIA SUMMER MONSOON RAINFALL FOR THE PERIOD 1871–1986

Table 3: Details of excess rainfall years

Year	Rainfall value mm	Per.Dep. from normal	Standardized value	rank	Percentage area of India with floods
1874	971	14.0	1.43	7	38
1878	974	14.3	1.47	5	33
1892	990	16.2	1.66	3	43
1893	953	11.9	1.22	12	28
1894	969	13.8	1.41	8	21
1910	935	9.8	1.00	17	18
1916	950	11.5	1.18	13	32
1917	1003	17.7	1.82	2	36
1933	973	14.2	1.46	6	43
1942	958	12.5	1.28	10	23
1947	942	10.6	1.08	14	17
1956	980	15.0	1.54	4	33
1959	938	10.1	1.04	16	29
1961	1017	19.4	1.98	1	45
1970	938	10.2	1.05	15	19
1975	960	12.7	1.30	9	30
1983	955	12.1	1.24	11	42

Table 2: Details of deficient rainfall years

Year	Rainfall value mm	Per.Dep. from normal	Standardized value	rank	Percentage area of India with droughts
1873	754	-11.5	-1.18	18	11
1877	604	-29.1	-2.98	1	49
1899	628	-26.3	-2.69	2	73
1901	719	-15.6	-1.60	9	24
1904	749	-12.1	-1.24	17	34
1905	715	-16.1	-1.64	7	36
1911	733	-14.0	-1.43	11	40
1918	648	-23.9	-2.45	3	68
1920	717	-15.8	-1.62	8	44
1928	766	-10.1	-1.03	20	16
1941	729	-14.4	-1.48	10	33
1951	737	-13.5	-1.38	14	42
1965	707	-17.0	-1.74	5	39
1966	735	-13.7	-1.40	12	37
1968	754	-11.5	-1.18	19	20
1972	653	-23.4	-2.39	4	41
1974	747	-12.3	-1.26	16	36
1979	708	-16.9	-1.73	6	36
1982	735	-13.7	-1.40	13	36
1986	740	-13.1	-1.34	15	24



DECADAL MEANS AND COEFFICIENTS OF VARIATION FOR ALL INDIA SUMMER MONSOON RAINFALL FOR THE PERIOD 1871-1986