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REGIONAL GCM FOR THE MONSOON AREA

SATISH CHANDRA
DIRECTOR

STUDY GROUP

DIVYA

S M SETH

M K SHARMA

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAWAN
ROORKEE - 247667 (UP)

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ABSTRACT

Monsoons, which affect the largest land masses, have been the subject of study on every scale from simple local studies to circulation simulation on giant computers (the so-called fifth and sixth generation computer systems like CYBER-205 and CRAY series) in recent years. An extensive work has been carried out on different physical aspects of monsoon viz., onset and withdrawal of monsoon, regional energetics, heat and moisture budgets, synoptic components etc. Indian monsoon, which is associated with abundant seasonal precipitation (mainly rains) has particularly attracted the attention of the world meteorological community leading to a number of extensive studies.

Precipitation, an important climatic element for hydrological processes has been simulated by various general circulation models. The global general circulation on one hand and the hydrologic cycle on the other are the nature's mechanism to maintain balance of water and temperature on earth. During the last two decades, many investigators have coupled the hydrologic processes (land surface) models and the atmospheric general circulation models (GCM). There are, however, gaps in the hydrological parametrization for the interlinking of atmospheric land surface processes. Sensitivity tests on general circulation models have revealed that the fluctuations in sea surface temperature, soil albedo, ground hydrology and snow cover are likely to influence the intensity of monsoon rains. These need to be validated using

surface and sub-surface data.

This note gives a review of the existing monsoon circulation models with special emphasis on the regional aspects. Different physical processes which affect Indian monsoon are also dealt with. The sensitivity of the monsoon circulation model outflow to surface albedo, soil moisture and evapotranspiration, snow cover, sea surface temperature has been discussed. The need of the quantitative forecast of precipitation for use in the forecasting of runoff is emphasized.

1.0 INTRODUCTION

Th term monsoon is traced to an Arabic root, meaning 'season', which is widely used to connote a seasonal wind that flows with consistency and regularity for one part of the year and is absent or blows from another direction for the remaining part of the year. The monsoons blow in response to the seasonal change that occurs in the difference in pressure - resulting from the difference in temperatre between land and sea. In the northern summer, when the sun is over the Tropic of Cancer, the sun's energy heats a shallow layer of soil (a few cm is depth), whereas it is able to penetrate to a much greater depth (at least 200 m) in the oceans because of the stirring action of the overlying wind. This differential heating of the land and the oceans results in the warmer air over land to rise and spread out towards sea. To compensate for the ascending air, monsoon winds begin to blow from the cooler sea towards the land. In the northern winter, when the sun recedes to the southern hemisphere and lies over the Tropic of Capricon, the situation is reversed, the layer heat storage of water leads to higher temperatures over oceans than over continents, resulting in the winds blowing from the land to the sea.

Figure 1 shows an idealised three dimensional structure of the summer monsoon circulation . The vertical motions are accompanied by a horizontal motion component (cross-isobar flow) directed from sea to land at low levels and from land to sea in the upper troposphere.

The regular visitation of monsoons of completely reversing and persistent wind regions is experienced by Asian continent only; however, Australia and Africa are also affected by monsoons upto some extent. North America also shows monsoonal tendencies, but the monsoon wind here is neither persistent nor the seasonal wind shift consistent.

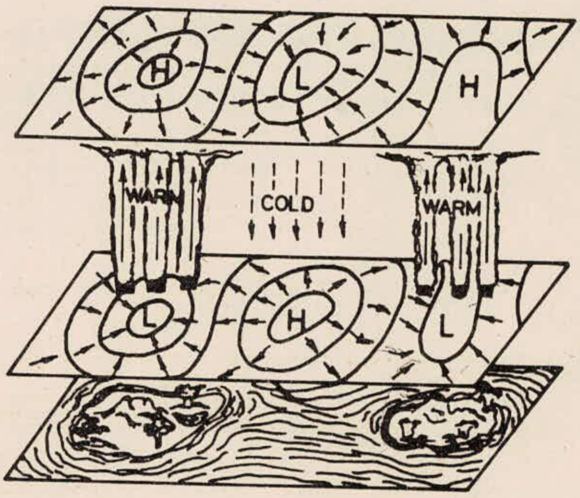


FIG. 1 : THREE DIMENSIONAL STRUCTURE OF THE MONSOON CIRCULATION

Ramage (1971), following with a slight variation to an earlier work by Khromov (1957), defined the monsoon area as encompassing regions with January and July surface circulations in which:

(i) the prevailing wind direction shifts by at least 120° between January and July,

(ii) the average frequency of prevailing wind directions in January and July exceeds 40%.

(iii) the mean resultant winds in at least one of the months exceed 3 m s^{-1},

(iv) fewer than one cyclone - anticyclone alternation occurs every two years in either month in a 5^{o} latitude - longitude rectangle.

From the above criteria Ramage (1971) delineated the monsoon region of the world in a rectangle bounded by latitudes 35^{o}N and 25^{o}S and longitudes 30^{o}W and 170^{o}E (Fig. 2). The three most decisive criteria (i) to (iii) are met in a zonally oriented band across sub-Saharan Africa, in the northern and equatorial Indian ocean and surrounding land areas, and the westernmost Pacific. Much of east Asia, satisfying the three wind criteria (i) to (iii) is excluded by the cyclone/anticyclone criterian (iv).

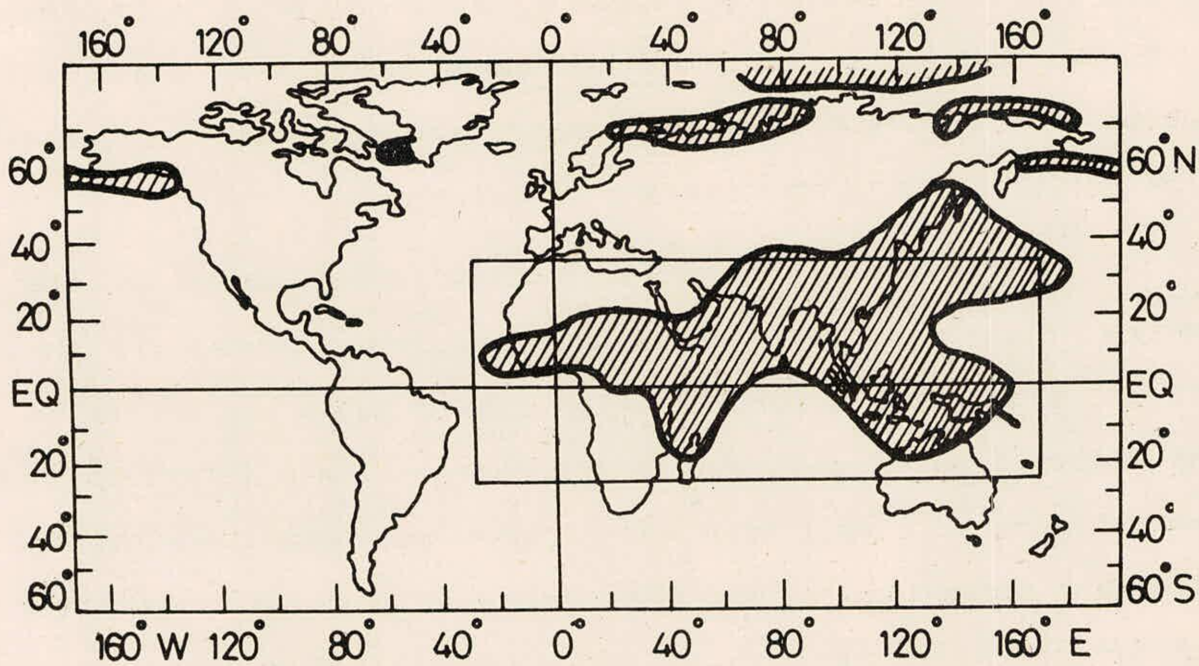


FIGURE - 2: THE MONSOON REGION (RAMAGE 1971; HATCHED PORTIONS REPRESENT 'MONSOONAL' BY KHROMOV, 1957)(REPRODUCED FROM DAS, 1986).

The monsoon winds are observed to be more prominent in the summer season of either hemisphere - during the period June to mid-September in the northern hemisphere and in-January and February in the southern hemisphere. During summer solstice time the south - east trades of the south equatorial Indian ocean after crossing the equator, due to the action of coriolis force, become southwesterly and invade the whole of south Asia, penetrating into Africa to a lesser extent. This constitutes the summer monsoon or southwest monsoon over India. On the other hand, the north east trades move southwards into south America, east Africa and north east Australia in the northern winter. A branch of the north-east trade winds moving around an anticyclone over Siberia sweeps across Indonesia, Malaysia and the southern half of Indian peninsula during winter or north-east monsoon. It is to be pointed here that the atmosphere over the northern hemisphere plays an active role not only for the northern summer monsoon circulation but also for winter monsoon circulation.

The atmospheric general circulation, which is the average flow of air over the entire globe, transports the hot air from the equatorial region toward poles and maintains the return flow of cold air from polar to tropical latitudes. Several general circulation models have been made to simulate different parameters as sea level pressure, surface temperature and precipitation etc, which are responsible for circulation patterns. The monsoon circulations are a miniature edition of the atmospheric general circulation. These are important to many countries of Asia, specially India and Africa as these generate seasonal rains, on which agriculture and the replenishment of water resources heavily rely. The economy of the country is thus also dependent on the timely arrival and subsequent distribution of rains. It becomes important therefore, to simulate the growth of monsoonal circulations using general circulation models and to develop a regional model for monsoon areas. The regional GCM may be used for making quantitative forecasts of precipitation that may be expected over a particular drainage basin. The parameters available from GCM may be used to determine runoff and hence for estimation of water yield and real time flood forecasting.

Concerted efforts on data gathering and undertaking of intensive studies on monsoon, particularly Indian southwest monsoon have been made by various meteorological services and world organisations during the last two decades and the attempts still continue .

The present note deals with different aspects of monsoon, which are necessary for developing a numerical model. A review of existing monsoon circulation models has been carried out with special emphasis on the regional perspective of monsoon circulation. Important features of Indian summer monsoon are reviewed in particular.

2.0 REVIEW

Over the past decades, the monsoon problem has been dealt with in various symposia and review volumes (Basu et. al, 1960; India Meteorological Department, 1965; Krishnamurti, ed., 1977; Lighthill and Pearce, ed, 1981; Fein and Stephens eds, 1986).

2.1 Global Perspective

For a global perspective of the monsoon phenomenon the pertinent fields as surface temperature, sea level pressure, upper and lower tropospheric flow patterns, cloudiness during the extreme seasons and annual rainfall are to be known. The pertinent fields have been documented in detail by many workers (Atkinson and Sadler, 1970; Sadler, 1975; Wyrtki, 1971; Ramage and Raman, 1972; Ramage et al, 1972; Robinson, 1976; Robinson et. al, 1979, Hastenrath and Lamb, 1977, 1978, 1979; Merle, 1978; Godbole and Shukla, 1981) and are reproduced here in Figures 3 to 8.

Figure 3(b) illustrates, for July, the far Northward excursion of the circumglobal band of highest surface temperature precisely over the Afro-Asian land masses. The circumglobal trough of low pressure (Fig. 4(b)) attains its northern most location together with the surface temperature maximum (Fig. 3(b)) in the same longitude domain. The surface pressure gradients are then established for the enormous lower-tropospheric inflow of air from the southern hemisphere (Fig. -6) and convergence, abundant cloudiness (Fig. -7) and rainfall (Fig. -8).

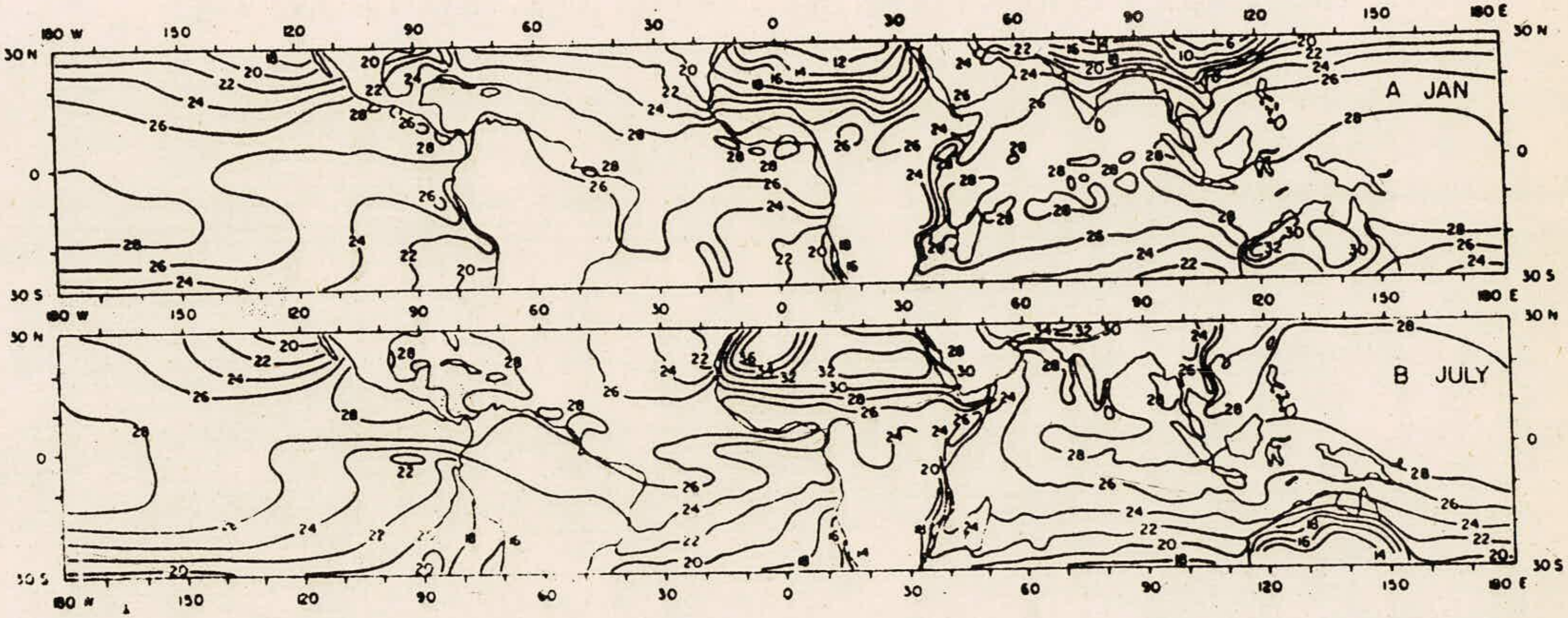


FIGURE-3: SURFACE TEMPERATURE IN THE GLOBAL TROPICS IN ^{o}C FOR (a) JANUARY (b) JULY (REPRODUCED FROM HASTENRATH, 1986).

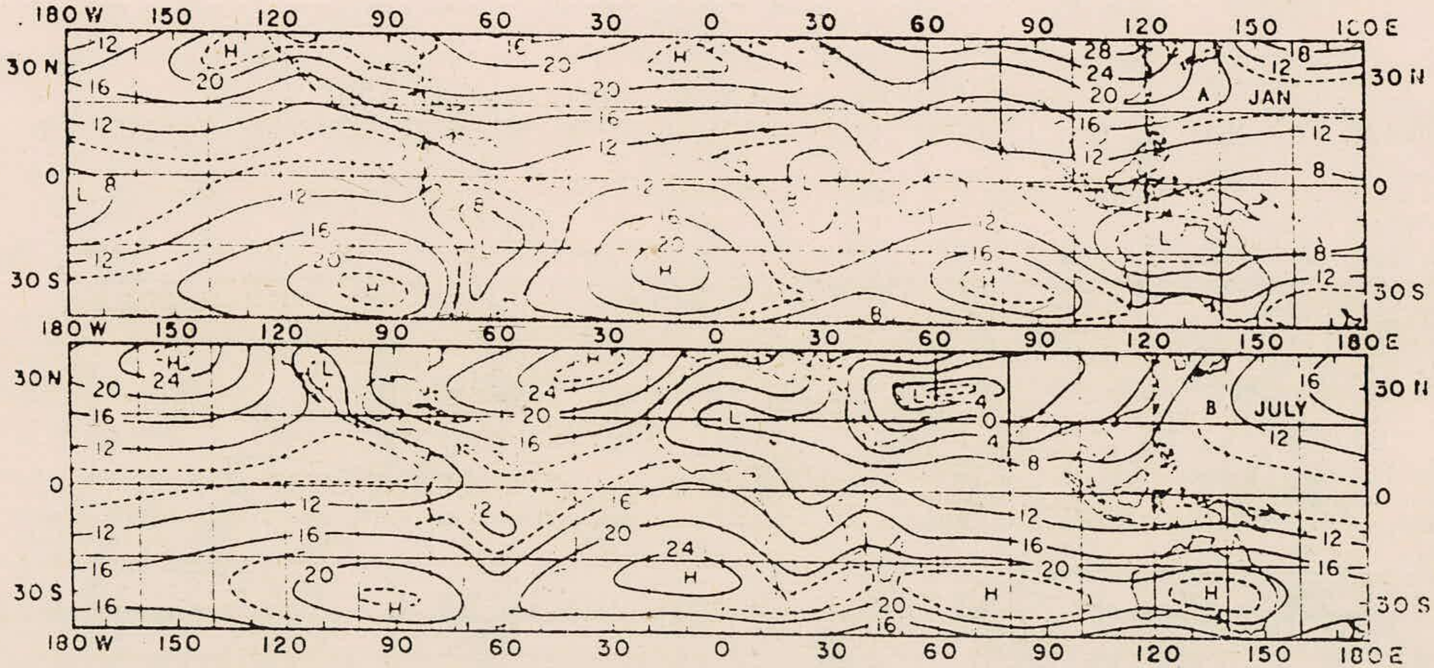


FIGURE-4 : SEA LEVEL PRESSURE OVER THE GLOBAL TROPICS IN 1000 +mb FOR (a) JANUARY, (b) JULY (GODBOLE AND SHUKLA, 1981) (REPRODUCED FROM HASTENRATH (1986)

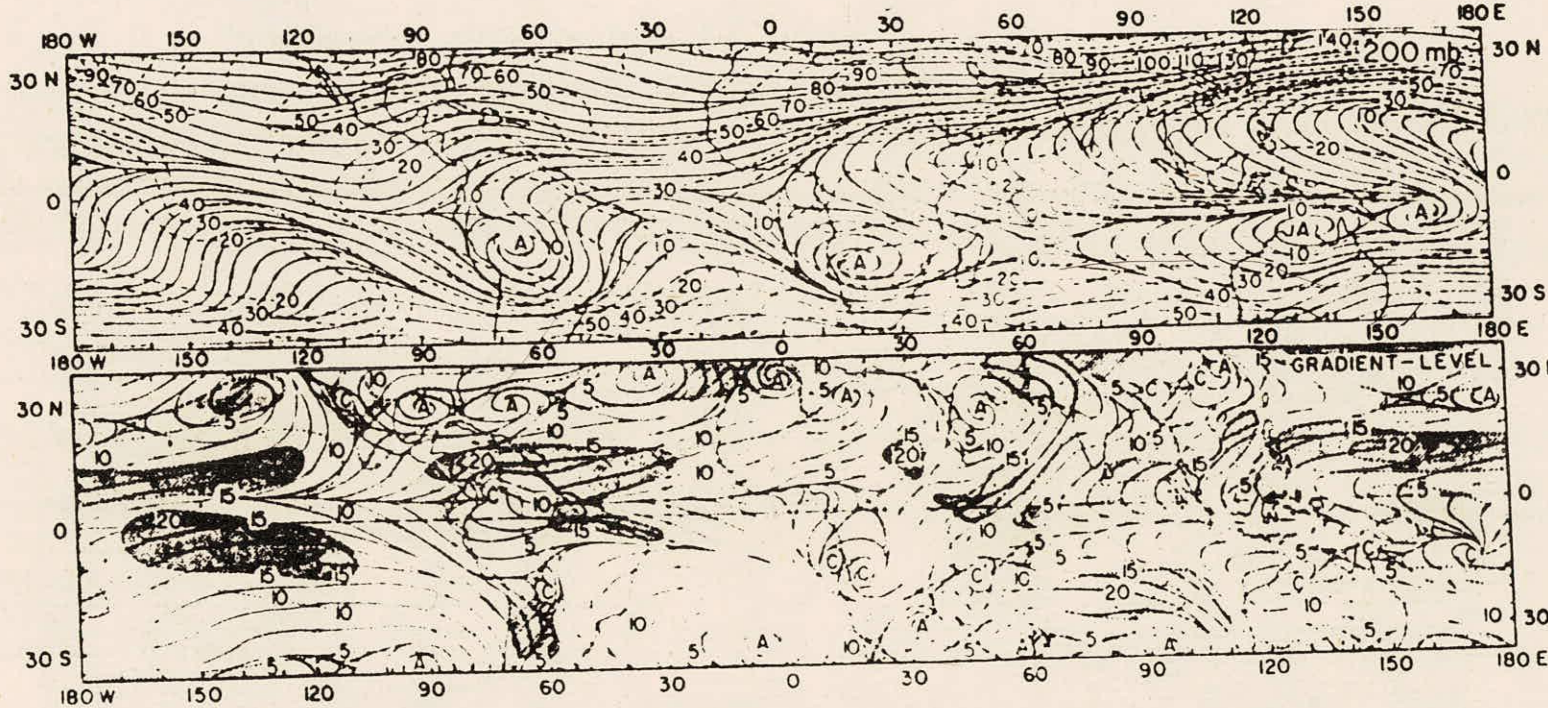


FIGURE-5 : CIRCULATION OVER THE GLOBAL TROPICS IN JANUARY. RESULTANT WIND STREAMLINES AND ISOTACHS IN KNOTS (a) 200 mb., AND (b) GRADIENT WIND LEVEL (RE-PRODUCED FROM HASTENRATH (1986)

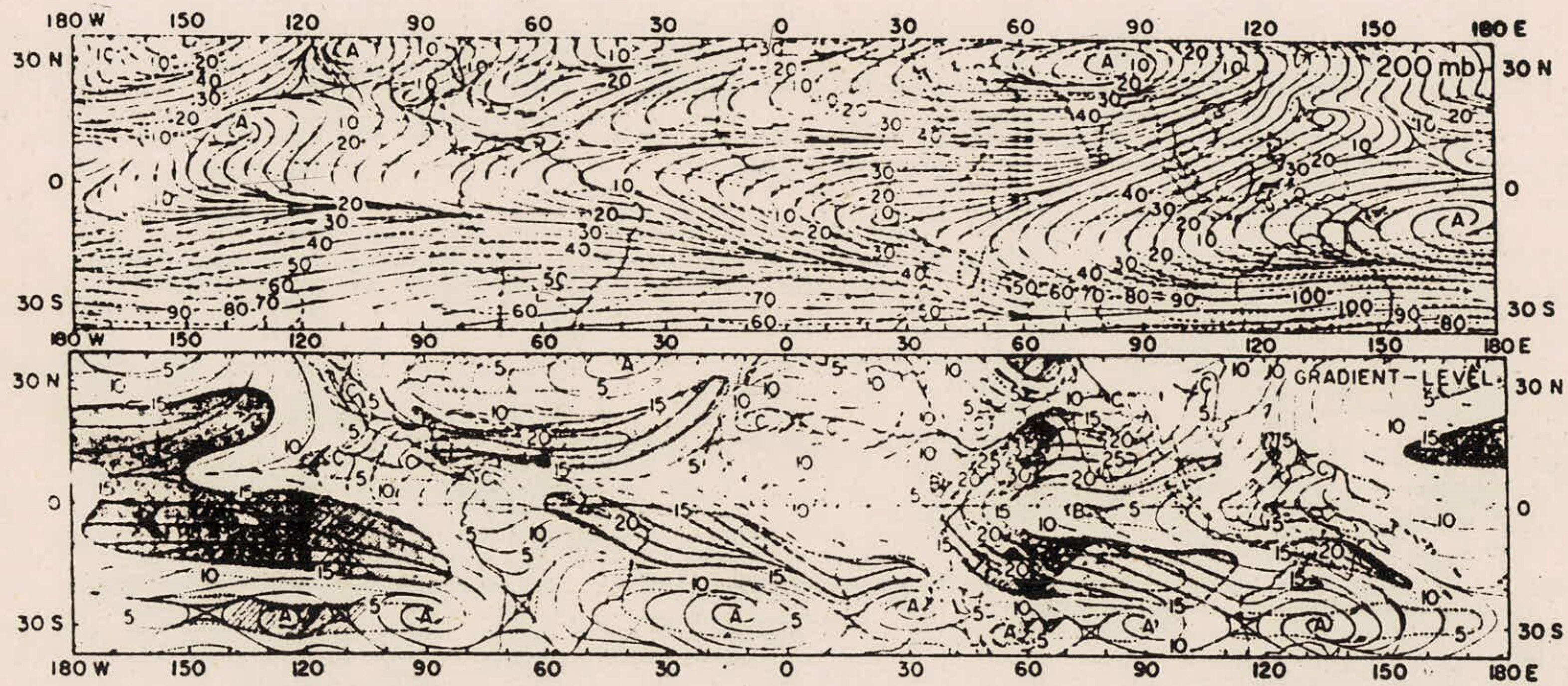


FIGURE 6- CIRCULATION OVER THE GLOBAL TROPICS IN JULY. RESULTANT WIND STREAMLINES AND ISOTACHS IN KNOTS. (a) 200 mb, AND (b) GRADIENT WIND LEVEL. (REPRODUCED FROM HASTENRATH, 1986).

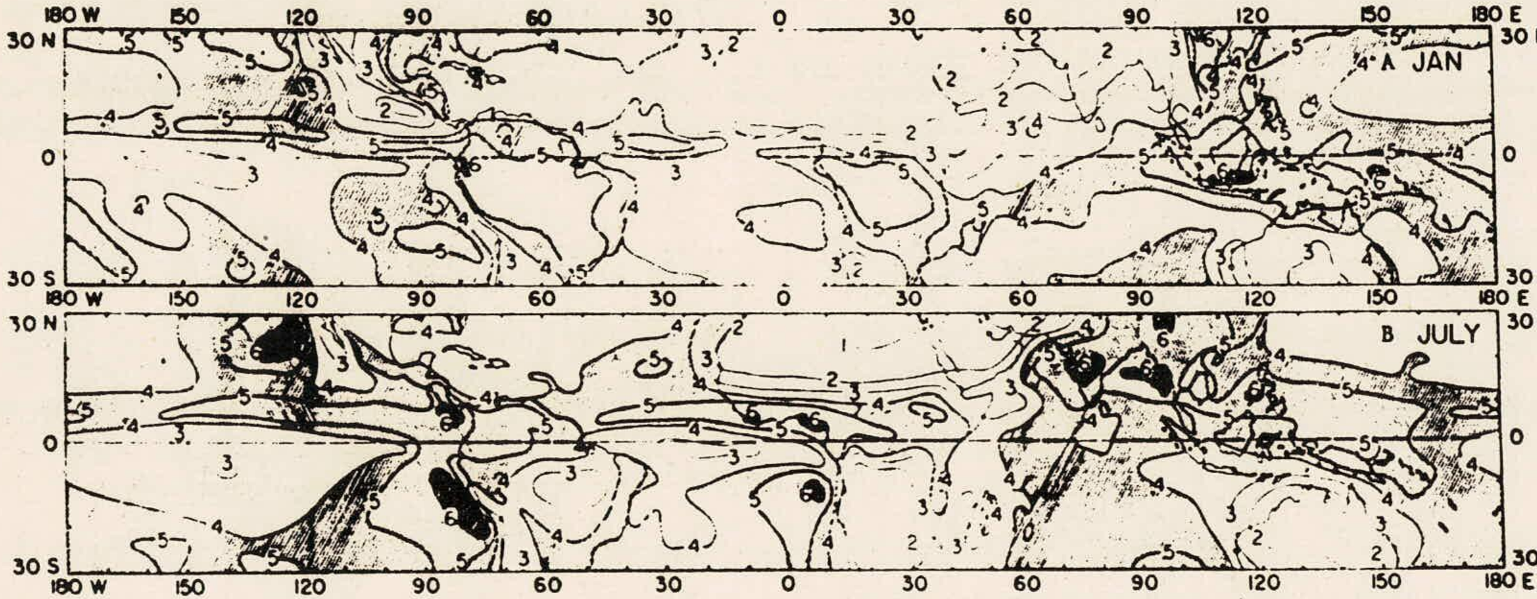


FIGURE -7 : CLOUDINESS OVER THE GLOBAL TROPICS IN OKTAS. (a) JANUARY, AND (b) JULY (REPRODUCED FROM HASTENRATH (1986)

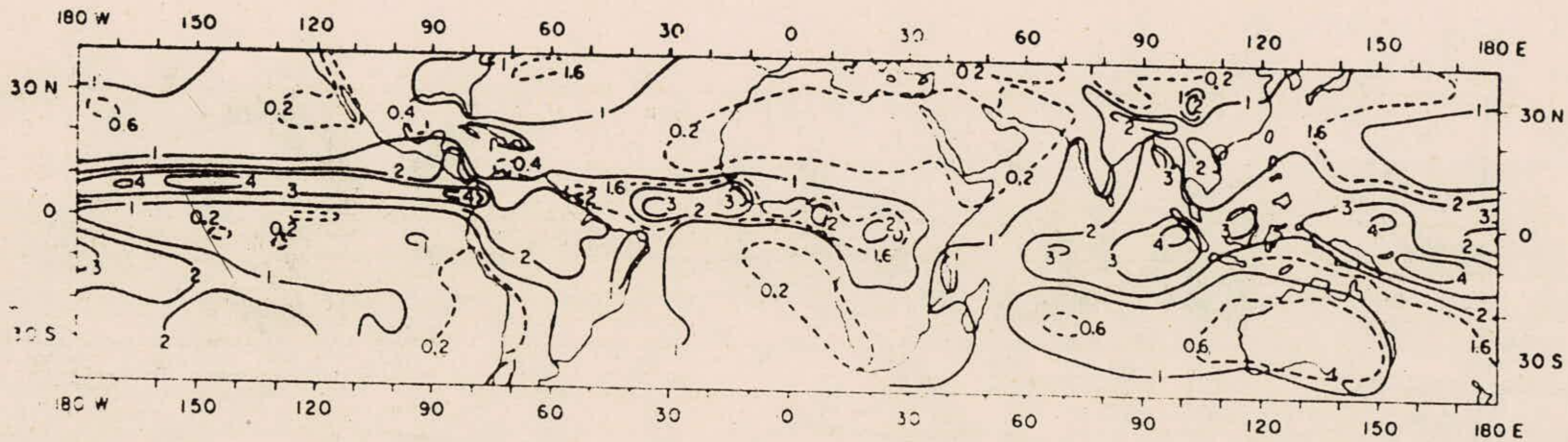


FIGURE-8 : ANNUAL RAINFALL TOTALS IN THE GLOBAL TROPICS IN m. (REPRODUCED FROM HASTENRATH, 1986).

Conversely, during northern winter, the Afro-Asian land masses are particularly prone to surface cooling and comparatively low surface temperatures thus favouring high surface pressure consistent with Fig. 3(a) and 4(a), while effects in the opposite sense would concurrently obtain in the summertime in southern hemisphere. The surface pressure pattern is thus established for an outflow of air from the northern into the southern hemisphere (Fig.5) and a more southward position of the band of maximum cloudiness (Fig. 7) and rainfall.

Global monsoons are dominated by large scale overturnings on meridional and zonal planes. The former is referred to as Hadley cell and the latter the Walker cell. These circulations are maintained by a pattern of non-adiabatic or diabatic warming which shows a characteristic alignment.

2.2 Regional Aspects of Monsoon

The regional aspects of monsoon occur on a smaller scale. A broad classification can be done in terms of scales, making a dividing line between the planetary and regional scales of motion (Table-1).

TABLE 1 : SCALES OF MOTION

Systems	Approximate dimensions		
	Horizontal scale (km)	Vertical scale(km)	Time(Hours)
1. Macroscale			
(a) Planetary waves	5000	10	200 to 400
(b) Synoptic perturbation	500 to 2000	10	100
2. Mesoscale	1 to 100	1 to 10	1 to 10
3. Microscale	$<1/10$	$<1/100$	1/10 to 1/100

The systems of different scales are coupled together strongly, the regional features being often obscured by a proliferation of synoptic details, whose relevance to the coupling mechanism is generally not clear. The summer and winter monsoons of south Asia specially India constitute the most spectacular manifestations of regional anomalies in the general circulation of the atmosphere. This is because the Indian ocean unlike the Atlantic and Pacific oceans is land-locked to the north by the Asian continent, resulting in extreme thermal contrast between the land and the sea-which is a crucial factor for development of most pronounced monsoon circulations. Patnaik et al (1977) suggested that the summer and the winter monsoon systems are essentially independent of each other, although they found significant positive correlations between the summer and the following winter monsoon rainfall in the far north and in portion of south India.

2.2.1 Summer monsoon

Regional features of summer or southwest monsoons are associated with over 75 percent of the annual rainfall for most of India. Lean periods commonly known as a break monsoon - of about a week's duration usually, follow the hundred-day monsoon period in Indian sub continent (first June - mid September). The duration and frequency of breaks increase towards the second half of the monsoon (Ramamurthy, 1969).

Rao (1976) studied the role of south-west monsoon circulation in the rainfall regime of India and emphasized that summertime convection and rainfall was greatly favoured by the thermodynamic properties of the moist and comparatively cool air mass that penetrate the continent with the south-west monsoon current, undercutting the dry and hot continental air.

Onset, Progress and Withdrawal of Monsoon:

Diffferent opinions have been given on the dates of onset of monsoon. It has been defined as the date on which the prevailing winds reverse their direction by many workers, while some prefer to fix the dates of onset by commencement of rains. Das (1986) compiling from the results of Yoshino (1971) gave the dates of beginning of the rainy season in monsoon region of Asia (Table 2).

Desai (1970, 1972, 1975) suggested that the onset of the monsoon over the west coast and its performance depend upon the flow of air across equator from the western Indian ocean and adjoining coast of East Africa, pressure gradient between westein India and equator being such that the air from the southern hemisphere can extend to the west coast of India.

Krishnamurti et. al (1981) considered the evolution of an "onset vortex over the Arabian sea as a characteristic circulation feature heralding the onset of the southwest monsoon. The vortex is described as forming on the cyclonic shear side of the low level jet and extending over a deep layer of the troposphere. Findlater (1969 a, b, 1972, 1977 a,b) from existing pilot baloon and air craft observations,

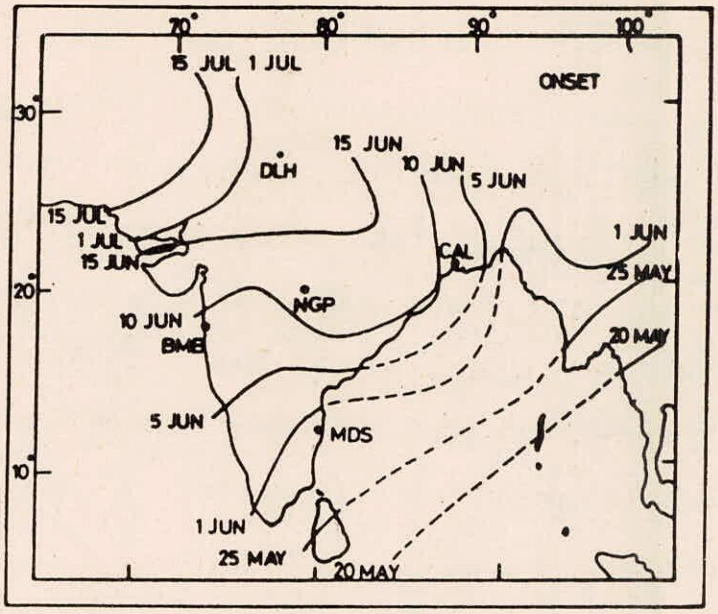
TABLE 2 : BEGINNING OF THE RAINY SEASON IN MONSOON REGIONS OF ASIA (Compiled from the results of Yoshino, 1971: Das, 1986)

	75°	80°	85°	90°	95°	100°	105°	110°	115°	120°	125°	130°	135°	140°
45°	–	–	–	–	–	–	–	–	–	Aug. 9–13	July 15–19	July 15–19	–	–
40°	–	–	–	–	–	–	–	July 20–24	July 20–24	July 20–24	July 15–19	–	–	June 25–29
35°	–	–	–	–	–	–	July 20–24	July 20–24	July 15–19	July 10–14	July 10–14	June 20–24	June 15–19	June 15–19
30°	June 30 –July 4	June 15–19	June 10–14	May 31 –June 4	–	June 5–9	June 25–29	June 20–24	June 15–19	June 15–19	June 15–19	June 5–9	May 26–30	May 21–25
25°	June 15–19	June 10–14	June 10–14	June 5–9	May 31 –June 4	May 31 –June 4	May 31 –June 4	June 10–14	June 5–9	May 30 –June 4	–	May 15–20	–	–
22.5°	June 10–14	June 10–14	June 10–14	June 5–9	May 31 –June 4	May 21–25	May 21–25	May 16–20	May 6–10	May 6–10	–	–	–	–
20°	June 10–14	June 10–14	June 5–9	May 26–30	May 26–30	May 21–25	May 1–5	May 1–5	–	–	–	–	–	–

showed that this jet system is a major lower tropospheric circulation feature over the western Indian ocean during summer monsoon in northern hemisphere.

Das (1984) pointed out that the onset of monsoon is usually not a spectacular event, but a gradual process starting with a transition period when atmospheric conditions change from a state of extreme dryness to one of high humidity and light rain. In the north eastern parts of India violent thunderstorms are a feature of pre-monsoon months of April and May. Frequent pre-monsoon thunderstorms lead to genuine monsoon rains without a period of transition in many areas.

According to Rao (1976), the India Meteorological Department fixes the on-set and retreat dates with reference to the rather sharp change of pentad rainfall totals and changes in the circulation. Das (1984) described some working rules to define the onset of the monsoon over Kerala : (i) starting with 10th May, if at least 5 out of 10 stations in Kerala report 24 hours rainfall total of 1 mm for two consecutive days, an onset is declared on the second day, (ii) if 3 out of 7 stations in Kerala report no rainfall for the next 3 days a recession of the monsoon is indicated, (iii) after the monsoon has advanced north of 13^{o} N even a temporary recession is a rare event. Using these working rules normal dates for the onset of summer monsoon rains over India are shown in Fig. 9. The standard deviation for the onset over the extreme south of the Indian Peninsula is approximately



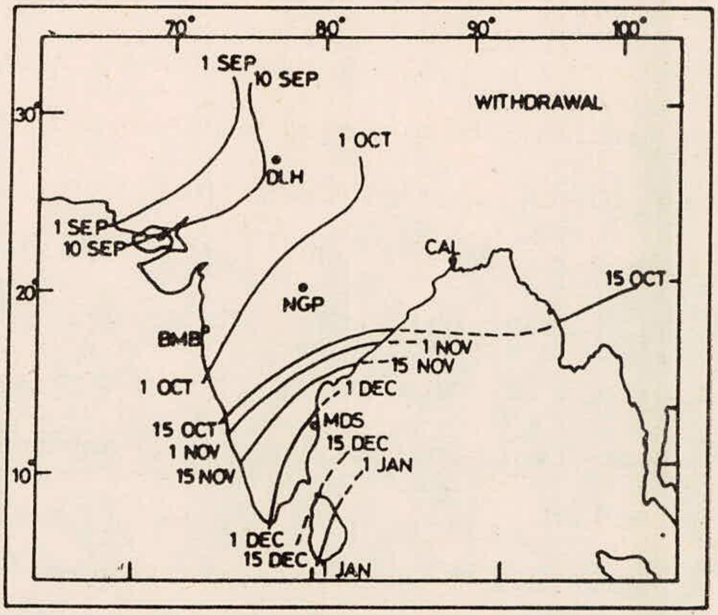


FIGURE - 9:NORMAL DATES FOR ONEST AND WITHDRAWAL OF SOUTH-WEST MONSOON.

7.7 days (Das, 1986).

Subbaramayya and Bhanukumar (1978) critically examined the onset of monsoon at a number of stations and studied the synoptic events associated with its advance over the Indian subcontinent during several years. They found that the advance of the monsoon was due to a series of synoptic and sub-synoptic rain bearing systems, that progressed northwards and westwards in contrast to the eastward moving disturbances of the winter and premonsoon seasons. Using the same concept, Subbaramayya and Ramanadhan (1981) studied the synoptic and sub-synoptic systems and their movement over India and neighbouring seas during the period of May to June 1977 from surface weather charts given in the Indian Daily Weather Reports and the satellite cloud pictures. The observations revealed that the advance of the monsoon was mainly affected by northwestward moving synoptic systems.

Fieux and Stommel (1977) defined monsoon onset from the change of wind direction along shipping lanes in the Arabian sea and distinguished four types, namely single, multiple, gradual and indeterminate onset. Subbaramayya et al (1984) distinguished three phases in the advance of the monsoon over India, the first affecting the southern peninsula, the second reaching the northern peninsula and central India and the third penetrating to the central parts of north India (Fig. 10). Pearce and Mohanty (1984) concluded from the analysis of FGGE year 1976, that the

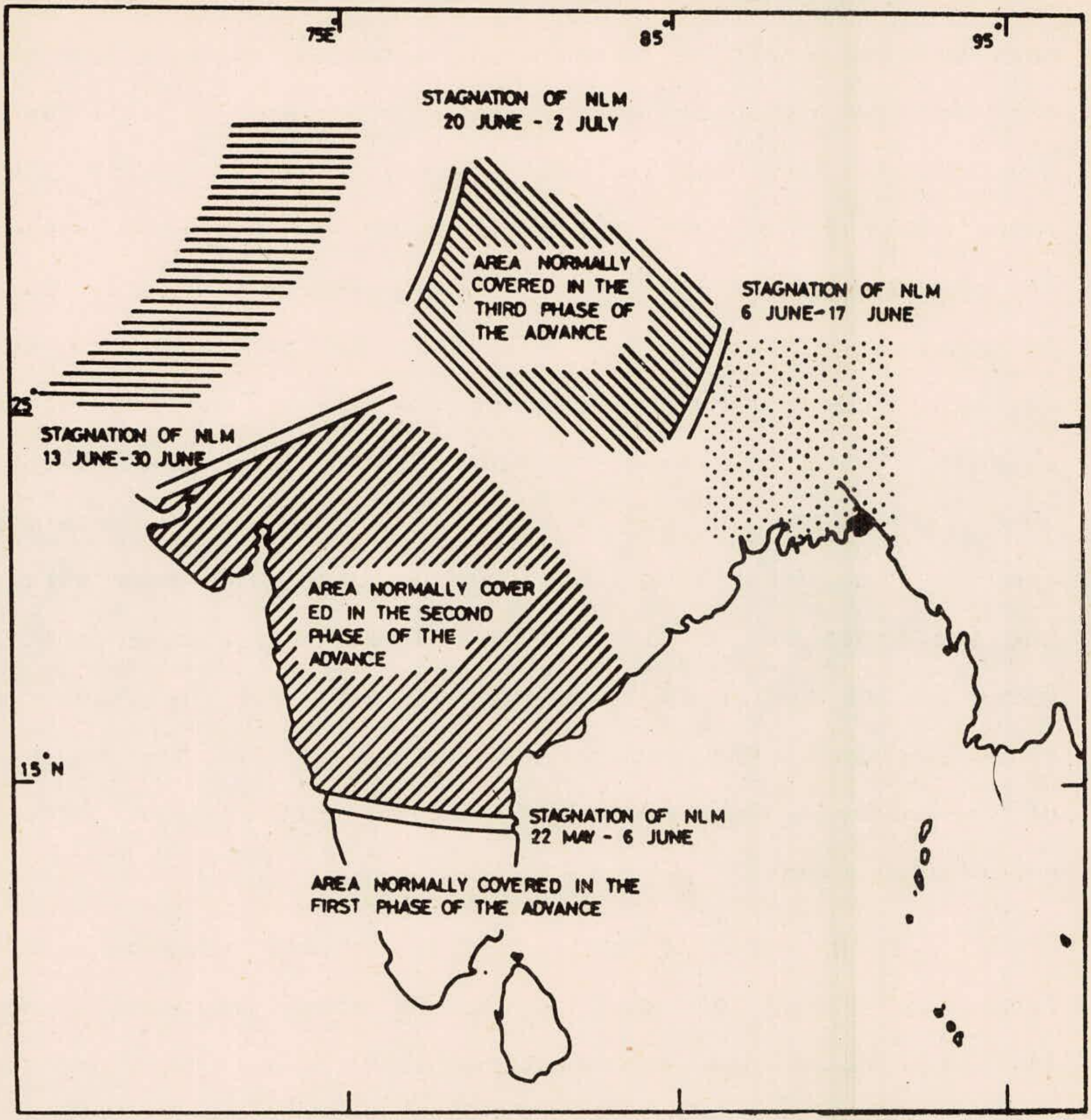


FIGURE-10: ADVANCEMENT OF THE SOUTH-WEST MONSOON.NLM MEANS 'NORTHERN LIMIT OF THE MONSOON' (SUBBARAMAYYA ET AL., 1984) (REPRODUCED FROM HASTENRATH, 1986).

onset consists of two phases - a moisture build up and a subsequent intensification of winds over the Arabian sea and increased latent heat release.

In fact, with the onset of monsoon the atmosphere undergoes conspicuous changes, the troposphere experiences a complete reversal in wind circulation. The moist south-westerlies of the monsoon extend vertically upto 6 km replacing the prevailing northeasterly winds of the premonsoon and northeast monsoon seasons and the intertropical convergence zone (ITCZ) from its mean winter position close to equator rapidly shifts to about 20° to 25°N establishing itself as a monsoon trough over the Indo-Gangetic plains.

During the break monsoon periods, the monsoon trough shifts northward to the foot of the Himalayas, and rains decrease over much of India except along the slopes of Himalayas and parts of northeast India and southern Peninsula (Ramanadhan et al, 1973; Rao, 1976; Das, 1986). The break in monsoon may be associated with a circulation cell essentially in a meridional vertical plane involving both the Indian lowlands and the adjacent Tibetan Plateau. Koteswaram (1950) connected break with west-ward moving lows at low latitude (10°N) in the Bay which are prominently seen at 700 mb. He further observed that during break in monsoon the easterly jet is well marked and occupies a more northerly position than average (1958). Koteswaram and Bhaskara Rao (1963) pointed out from consideration of the temperature characteristics of the westerly current and from the fact that very heavy rainfall occurs during this season along Himalayan foothills with record rainfalls at Cherapunji, the world's wettest spot and the westerly monsoon current is displaced to its northernmost limit. Anantha Krishnan and Ramakrishnan (1963) found that the area of strongest easterly shifts from the normal position to 19°N during the break.

Pant (1983) also considered the possible role of Tibetan Plateau for the "breaks in monsson". The breaks are most frequent in July and August, and they typically last from a few days to three weeks. Yasunari (1979) and Sikka and Gadgil (1980) found evidence for a northward shift of a belt of maximum cloudiness; and Krishnamurti and Subramanyam (1982) noted a meridional propagation of lower tropospheric trough and ridges lines from the equatorial region towards the Himalayas. Krishnamurti and Bhalme (1976), Krishnamurti and Ardanuy (1980), Yasunari (1981) related oscillations (see Appendix-III) around 10-20 & 40 days in various tropospheric parameters to the occurrence of "break in monsoon

Haldar and Sud (1987) examined the synoptic charts prepared in the Regional Meteorological Centre, Nagpur for the monsoon months during the period 1978 to 1982 to bring out the synoptic features that could have caused the rainfall activity. The following aspects were kept in view for the purposes - (i) Axis of the monsoon trough over mean sea level or in the lower troposphere upto 1.5 km a.s.l. has either shifted to the foot-hills of Himalayas or is not noticed at all, (ii) Widespread to fairly widespread rainfall distribution in any meteorological sub-division (northwest, northeast, southwest and southeast Madhya Pradesh and east and west Vidarbha) of the central region comprising Madhya Pradesh state and Vidarbha portion of Maharashtra state. The studies revealed that the month of August witnessed real breaks in monsoon when the rainfall strikingly decreased over Madhya Pradesh and Vidarbha, but in other months (i.e. July and September) break monsoon conditions might temporarily appear on same occasions in low levels.

With the advent of winter very large areas of Central Asia become so cold that the air subsides over them creating an intense high pressure cell. The associated wind circulation opposes the monsoonal flow and as a result, the withdrawal of monsoon takes place. This is preceded by a change in upper level easterlies over Bahrain, New Delhi and Allahabad to westerlies. The withdrawal pattern (Fig. 9(b)) shows that the timing of retreat is as early as the beginning of September in the northwest, a delay to October over northern and Central India and the northern Bay of Bengal, and dates as late as December and January in the South. Tables 3 and 4 give the actual dates of onset and withdrawal of summer monsoon for the years 1982-87 together with the normal dates for different divisions.

Singh (1988) studied the four cyclonic disturbances that formed in the first fortnight of October 1985 in the Indian seas. The longitude, where these disturbances recurved, progressively advanced from 75° E to 90°E.

TABLE 3 : ONSET OF MONSOON

(Compiled from the Weather Reports of Monsoon Season in Mausam (1983-88))

DIVISIONS	YEARS						
	1987	1986	1985	1984	1983	1982	NORMAL
1. KERALA	2 June	4 June	28 May	31 May	12 June	28 May	1 June
2. GUJARAT	13 June	23 June		18 June	21 June		15 June
3. ANDAMAN & NICOBAR ISLANDS	30 May				27 May	27 May	20 May
4. BIHAR	8 June						10 June
5. MADHYA PRADESH	16 June		28 June	7 July			15 June
6. TRIPURA, MIZORAM, MANIPUR	4 June						1 June
7. COASTAL KARNATAKA		5 June				1 June	5 June
8. PUNJAB	27 July	30 June					1 July
9. RAJASTHAN	27 July	24 July			4 July		1 July
10. U.P.			28 June	18 June			15 June
11. KASHMIR				18 July			1 July
12. ASSAM		16 June	4 June		18 June		1 June
13. MAHARASHTRA			28 June				10 June
14. ANDHRA PRADESH			28 June				5 June
15. ENTIRE COUNTRY			14 July	18 July	18 July	22 July	-

TABLE 4 : WITHDRAWAL OF MONSOON

(Compiled from the Weather reports of Monsoon season in Mausam (1983-1988))

DIVISIONS	YEARS						
	1987	1986	1985	1984	1983	1982	Normal
1. RAJASTHAN	2 Sept.	17 Sept.	11Sept.		13Sept.	3Sept.	15Sept.
2. GUJARAT	21Sept.	22Sept.	19Sept.				15Sept
3. UTTAR PRADESH	27Sept.	22Sept.	27Sept.	22Sept.			10 Oct
4. MADHYA PRADESH	27Sept.	8 Oct.	27Sept.				10 Oct
5. BIHAR	9 Oct.	16 Oct.					12 Oct
6. MAHARASHTRA	9 Oct.	8 Oct.	17 Oct				10 Oct
7. PUNJAB		17Sept.					15Sept
8. J & K		17Sept.		12Sept.		3Sept.	1 Sept
9. KONKAN & GOA		8 Oct.					10 Oct
10. MARATHAWADA		9 Oct.					10 Oct
11. VIDARBHA		9 Oct.					10 Oct
12. TELANGANA		9 Oct.					10 Oct
13. KARNATAKA		9 Oct.	21 Oct.				15 Oct.
14. WEST BENGAL		16 Oct.					-
15. SIKKIM		16 Oct.					-
16. HARYANA			11Sept.				15Sept.
17. HIMACHAL PRADESH			11Sept.				-
18. ANDHRA PRADESH			21 Oct.				13 Oct.
19. TAMILNADU			24 Oct.	3 Oct.	19 Oct.	11 Oct	-
20. KERALA			24 Oct.	3 Oct	19 Oct.	11 Oct.	-

This was due to the displacement of a quasi-stationary westerly trough in the upper atmosphere from 70°E to 90°E, which further led to the withdrawal of SW monsoon and onset of NE monsoon. The entire development process and steering of these disturbances took place because of their interaction with the westerly trough of middle latitude.

Rainfall Distribution:

India's agriculture and economy depend critically on the rains of the summer southwest monsoon. In order to have rainfall observations, India possesses one of the densest and most continuous surface climatological station networks in the tropics. The India Meteorological Department compiles rainfall observations for sub-divisions as illustrated in Fig. 11. An extensive work on long term interannual and shorter term variability of Indian rainfall follows from the above observations (Subbaramayya, 1968; Bhargava and Bansal, 1969; Jagannathan and

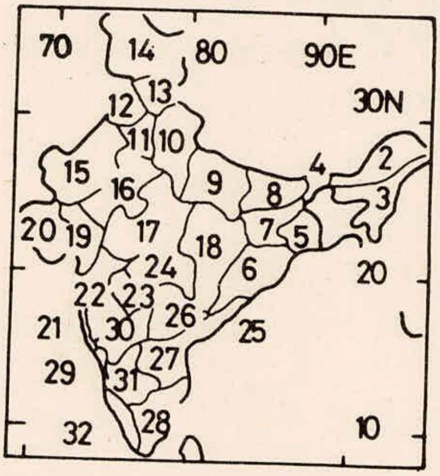


FIGURE -11: MAP SHOWING RAINFALL SUB-DIVISIONS OF INDIA AS USED BY INDIA METEOROLOGICAL DEPARTMENT (HASTERNRATH AND ROSEN, 1983).

Bhalme, 1972; Parthasarathy and Mooley, 1978; Bhalme et al, 1983; Cadet and Diehl, 1984; Shukla, 1986 and others).

Usually annual rainfall totals exceed 2000 mm at much of the Arabian sea coast, where the western Ghats are exposed to the southwest monsoon flow, decreasing eastward across the Peninsula dropping to less than 300 mm in some areas and the desertic regions to the northwest receive less than 100 mm (Hastenrath, 1986). The seasonal rainfall expressed as a percentage of annual rainfall for four Indian seasons (IMD, 1971) is shown in Fig.12.

The interannual variability of rainfall is not uniform throughout a subcontinent as large as India. The spatial correlation of annual rainfall between the various subdivisions identified in Fig. 11 are shown in Fig. 13. The positive correlation is seen to be largest between neighbouring subdivisions and distinct spatial patterns not merely related to distance are apparent.

Figure 14 shows the coefficient of variation, which expresses the ratio of standard deviation to the mean as a percentage for India. Two interesting facts are brought about from the Fig, viz. regions with a high standard deviation are usually regions which receive

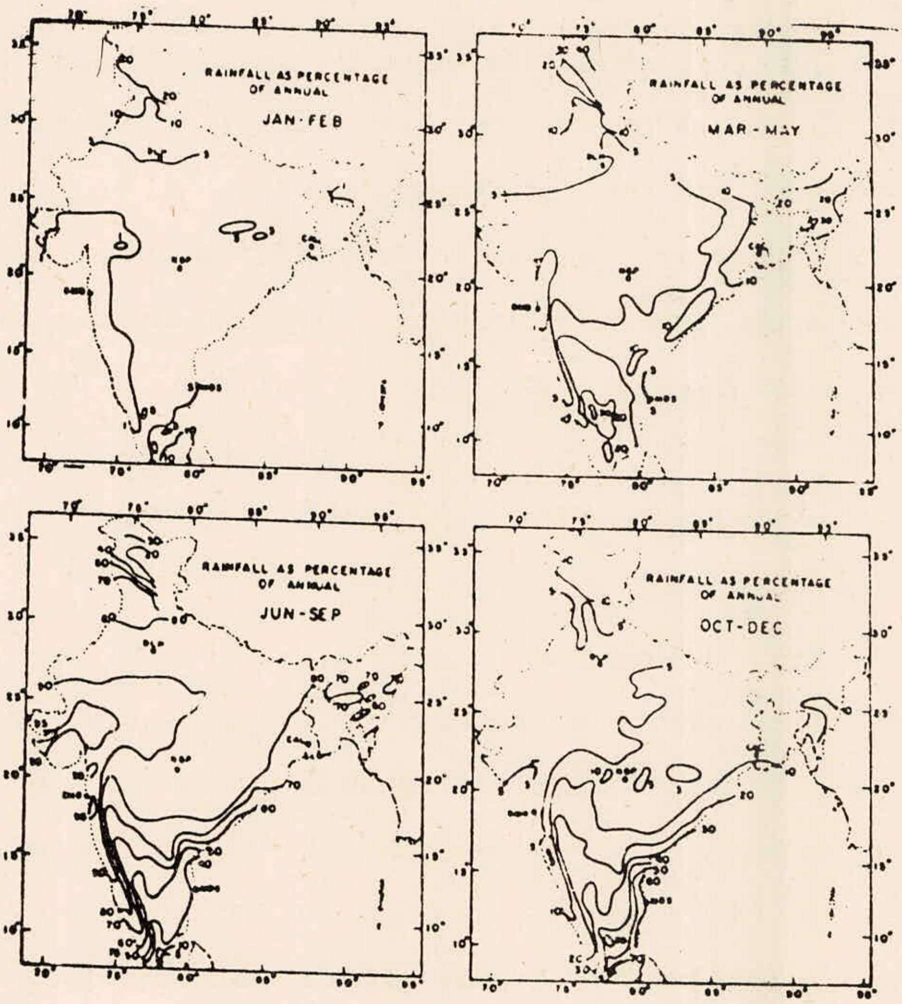


FIGURE -12: SEASONAL RAINFALL AS PERCENTAGE OF ANNUAL (I.M.D., 1971).

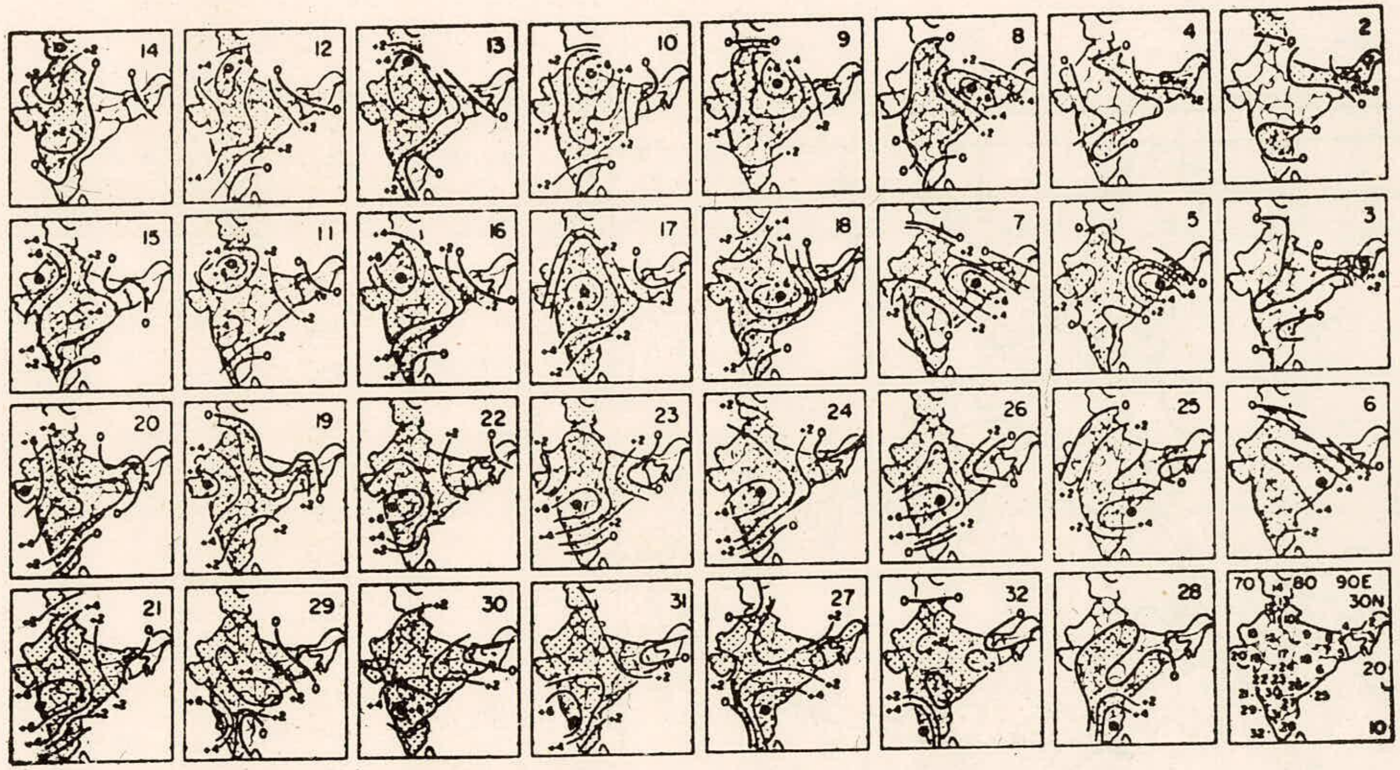


FIGURE- 13: MAPS OF CORRELATION BETWEEN ANNUAL RAINFALL IN SUB-DIVISIONS OF INDIA (HASTENRATH AND ROSEN, 1983) (REPRODUCED FROM HASTENRATH 1986).

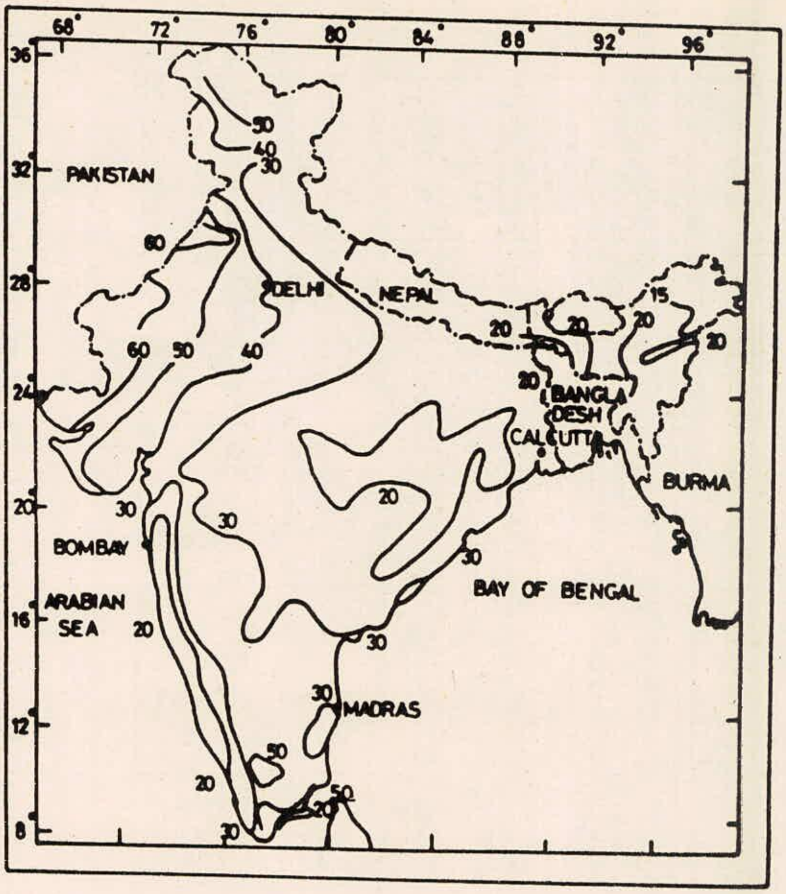


FIGURE -14 : CO-EFFICIENT OF VARIATION OF RAINFALL FOR INDIA (REPRODUCED FROM DAS, 1986).

TABLE 5 : RAINFALL DURING SUMMER MONSOON SEASON (JUNE-SEPTEMBER)(Compiled from the weather reports of Monsoon season in Mausam, 1983-88)

Sl. No.	Sub-Divisions	Normal value(mm) for						% Departure from Normal for					
		1987	1986	1985	1984	1983	1982	1987	1986	1985	1984	1983	1982
1.	Andman & Nicobar Islands	1652	1586	1609	1610	1622	1639	-27	-24	-15	-30	15	-10
2.	Assam & Meghalaya	1447	1733	1491	1437	1476	1471	7	-8	10	4	18	3
3.	Nagaland, Manipur, Mizoram and Tripura	1366	1712	1256	1236	1256	1256	-14	-13	-11	-2	-15	-11
4.	Gangetic West Bengal	1089	1169	1085	1102	1095	1115	26	0	14	42	0	-17
5.	East Uttar Pradesh	915	883	915	894	916	918	-37	-10	14	24	2	3
6.	Plains of West Uttar Pradesh	814	752	779	792	806	761	-50	-18	14	11	26	-6
7.	Hills of West Uttar Pradesh	1572	1269	1723	1649	1575	1711	-42	-18	-4	-32	-12	-23
8.	Haryana, Chandigarh & Delhi	535	498	527	520	518	518	-63	-24	17	4	48	-11
9.	Punjab	492	485	455	459	490	449	-65	-2	15	35	-4	-25
10.	Himachal Pradesh	1312	432	1374	1327	1300	1316	-55	-13	-9	-30	-24	-49
11.	Jammu & Kashmir	400	382	314	330	372	380	-27	12	-9	-19	-1	-37
12.	West Rajasthan	290	299	299	304	291	283	-60	-32	-30	-20	32	-31
13.	West Madhya Pradesh	937	913	958	954	950	950	-20	-1	-13	-8	11	-2
14.	Gujarat Region, Daman, Dadra and Nagar Haveli,	773	984	815	765	802	789	-58	-36	-5	-1	28	-27
15.	Saurashtra, Kutch & Diu	513	533	575	547	529	589	-80	-42	-55	-14	64	-46
16.	Konkan & Goa	2613	2582	2650	2649	2576	2522	3	-28	6	-7	41	-6
17.	Vidarbha	975	995	986	996	994	996	-36	-3	-27	-40	18	-27
18.	Coastal Andhra Pradesh	558	615	555	555	555	553	-41	-5	-9	-29	54	-18
19.	Coastal Karnataka	3164	3061	2955	2945	2945	2945	-15	-13	-13	-13	25	9
20.	Kerala	1754	2008	1743	1743	1743	1743	-25	-22	-15	-19	-3	-11
21.	Lakshadweep	940	949	950	977	950	950	-9	-3	-22	-22	17	-4

large amounts of rainfall and, the variability of rainfall is largest where the rainfall is the least. Long range forecasts are most useful over areas of large variability and hence preparation of long range forecast for a region where the rainfall differs little from one year to another is not so necessary.

Table 5 gives the normal value of the rainfall during the summer monsoon season (June to September) for the years 1982-87 and the percentage departure from the normal value. The departure 10% to -10% corresponds to the normal rain, the departure from normal $\geq$ 11% gives the excess rain and the departure from normal $\leq$ -11% corresponds to deficient or scanty rain.

Rain bearing systems:

There are several small synoptic or even subsynoptic and mesoscale systems embedded in the general rain-bearing monsoon current, which are given below:

(i) The monsoon trough

This semipermanent feature of the monsoon has its normal position over the Gangetic plains extending to Pakistan and the adjoining countries of Middle-East, however it shows north-south migrations both at the surface and in depth. The trough axis which is oriented in an east-west direction being roughly parallel to the southern periphery of the Himalayan mountains, shows wide variations (Fig. 15). The axis lies to the south of its normal position with the eastern end extending into the northern

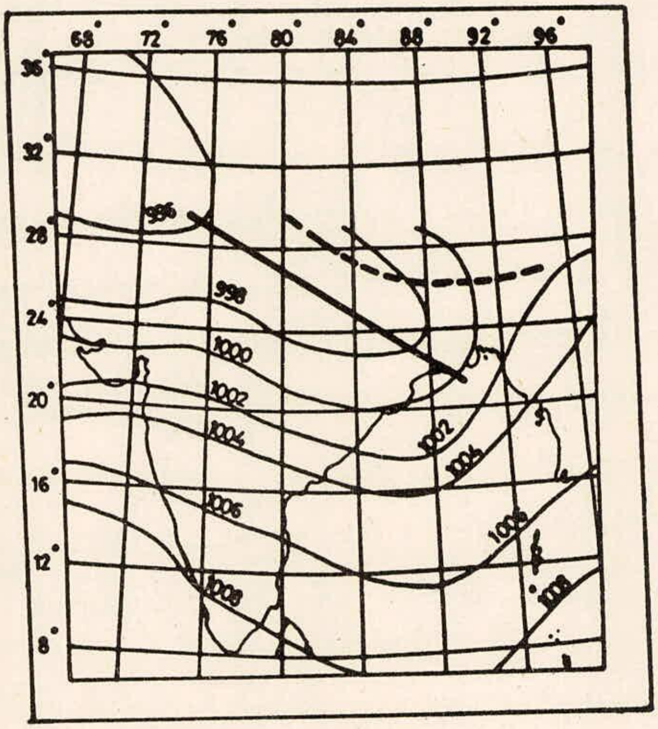


FIGURE -15 : THE MONSOON TROUGH OVER INDIA : THICK LINE INDICATES THE NORMAL POSITION OF TROUGH, AND DOTTED LINE SHOWS THE TROUGH POSITION UNDER 'BREAK CONDITIONS'.

part of the Bay of Bengal during active phase of the monsoon and a break in monsoon is observed when the axis moves north and is located close to the Himalayan foothills, resulting in heavy rainfall over north-eastern parts of India. Thus, a break in monsoon leads to heavy discharges and resultant floods in the eastern states, as several major rivers of India have their origin over eastern Himalayas.

Simpson (1921) expressed the view that the monsoon trough was a mechanical effect brought about by alignment of the Himalayan mountains and the mountains of Burma. However, recent model experiments suggested that mountains alone are not sufficient to generate a quasi permanent trough and that the radiation balance fluctuations of the atmosphere may effect the movement of the trough axis.

(ii) Monsoon depressions in the Bay of Bengal

When the monsoon trough drops down to the north-west Bay of Bengal, a low pressure area develops within this zone. This generates much of the rainfall over India during summer monsoon. Two to three systems are observed per month during monsoon with the highest frequencies in the months of July and August. These systems, with horizontal dimensions of around 500 km have a life span of about a week. Their movement for first three or four days is towards north-west and then they recurve toward the north or continue to move westwards.

Das (1986) suggested that the formation, growth and movement of monsoon depressions are controlled by the following factors:

(i) Horizontal and vertical wind shear,

(ii) Convective and mesoscale systems leading to vertical transport of moisture, heat and momentum.

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

Joseph and Chakravarty (1980) studied a monsoon depression during MONEX-79 and found that the depression had a cold core and there were horizontal temperature gradients between 2° - 4°C within the depression field in the lower troposphere.

(iii) Mid-tropospheric cyclones

The cyclonic vortices confined to the middle troposphere were observed to give copious rains over the north-eastern parts of the Arabian sea and the adjoining areas of the Indian coastline during the International Indian Ocean Expedition (IIOE) in late sixties. The vortices were between 3 to 6 km with largest amplitude near 600 hPa, unvisible on surface weather charts.

Mid-tropospheric disturbances have a core of warm air above 4 km with slightly colder air below and exhibit little movement remaining quasi-stationary for several days. Fig. 16 shows a mid-tropospheric cyclone. Since these cyclones are located between a westerly regime at the surface

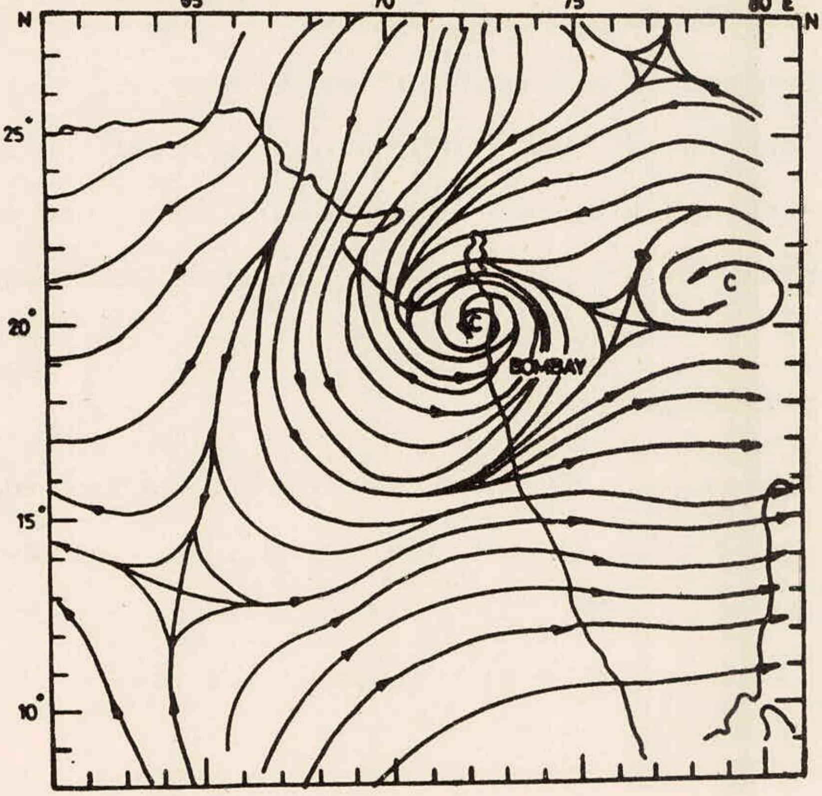


FIGURE -16 : MID TROPOSPHERIC CYCLONE.

and easterly winds in the upper atmosphere, it is believed that large vertical shears are responsible for their formation.

(iv) Low level trough of the west coast

Spells of heavy rain are also generated along the western coast of India. When westerly monsoon winds strike the mountains, they do not have enough energy to climb over the western Ghats, and as a result they deflect round the mountains (orographic barriers) and the return current forms an off-shore vortex. These have linear dimensions of the order of 100 km and their presence is detected by weak easterly winds at coastal stations

Heat and Moisture Budget:

The monsoons in the Indian Ocean sector entail differential heating and cooling of land and sea surface, large-scale transports of atmospheric moisture, and abundant precipitation and latent heat release. Accordingly, atmosphere, hydrosphere and lithosphere appear all essential for the energetics of the monsoon system. A number of investigations have been reported on the heat and moisture budgets of the summer monsoon (Pisharoty, 1965; Keshavmurty, 1968; Anjaneyulu, 1969; Rao and Rajamani, 1972; Saha and Bavadekar, 1973; Hastenrath and Lamb, 1979, 1980; Choudhury and Karmakar, 1981).

Pisharoty's (1965) calculations suggested that more than half of the moisture crossing the western coastline of India at the height of south west summer monsoon is supplied by evaporation from the Arabian sea, with the remainder, representing 80 x 10^{13} W. of latent heat, originating in the southern hemisphere and crossing the Equator between 42° and 75° E. Ghosh et al*s (1978) and Murakami et. al. *s (1984) investigations lend support to Pisharoty*s (1965) study. In contrast, the cross-equatorial water vapour transport computed for this season by Saha (1974) and Saha and Bavadekar (1973) is about double Pisharoty*s (1965). They proposed that 60-80% of the moisture crossing the West Coast of India during the summer monsoon emanate from the southern hemisphere. More recently, attention has been focussed on the important role of the East African low level jet for the cross-equatorial moisture transport (Hart et.al, 1978; Howland and Sikdar, 1983; Van de Boogaard and Rao, 1984).

Mohanty et.al. (1983) carried out investigations on heat and moisture budgets with MONEX and FGGE data. They used twice daily FGGE observations of temperature, relative humidity, geopotential and winds over tropics (Arabian sea and adjoining areas; 0°-30° N and 30°E-75°E) and made computations for ten pressure levels from 1000 to 100 hPa for the period 15 May to 15 July 1979, using an assimilation technique developed by the European Centre for Medium Range Weather Forecasts. The study indicated the significant increase in the net enthalpy, latent heat energy and a number of budget parameters well in advance of the onset of monsoon over Kerala Coast. A decreasing trend was observed in most of the above parameters about 5 days before the break monsoon condition, which started over India on 16 July, 1979.

Regional Energetics:

Keshavamurty and Awade (1970, 1974, 1976) calculated the energy conversions within summer monsoon region over India. They found that monsoon trough was largely maintained by the generation of kinetic energy through work done by the horizontal pressure gradient. The region of the monsoon trough was found to be of ascending air and subsiding cold air resulted in x-p overturning. They further found that the contribution of transient eddies was comparatively small.

Anjaneyulu (1969, 1971) also obtained similar results. The dissipation of energy was found to be 2.4 W m^{-2}, which equalled Brunt's often quoted dissipation rate of 3.0 W m^{-2}. These computations revealed that the establishment of the monsoon trough was related to quasi-stationary forcing mechanisms, since the transients played a comparatively small role.

The rate of energy production in a strong monsoon situation is approximately an order of magnitude larger than on a weak monsoon day. The conversion from zonal available potential energy to zonal kinetic energy is almost an order of magnitude smaller than that achieved by a meridional circulation.

Desai (1986) calculated the zonal and eddy kinetic energy, zonal and eddy components of total available potential energy for layers 1000-850 mb, 850-700 mb, 700-500, 500-200 and 1000-200 mb to study the energetics of break and strong monsoon days. They came out with the conclusion that in break monsoon, atmosphere is barotropically stable as eddy flow loses energy to the zonal flow and in strong monsoon, atmosphere is barotropically unstable as eddy flow gains energy from the zonal flow.

2.2.2 Indian ocean during summer monsoon

Indian ocean sector spectaculates the annual reversal of the surface wind most prominently on the globe. With the onset of the south-west monsoon winds, the southern hemispheric trades cross the equator eventually penetrating into the southern Asia, so that the trough of weak winds between the southern and northern hemispheric trades is eliminated. Consistent with this is the disappearance of the equatorial counter current in the south equatorial Indian Ocean. More importantly, however, the south equatorial current now develops a continuation into an intense boundary current along the coast of eastern Africa, the Somali current. The development of this intense poleward flowing boundary current in the western Indian Ocean is associated with marked changes in the sea surface temperature. Somali current is a striking example.

2.2.3 Winter monsoon

Winter or north-east monsoon generally sets in with the retreat of the south-west monsoon from India and adjoining sea areas. The spectacular change that takes place between the two monsoons is the change of wind direction from south-west to north-east over the Bay of Bengal, the Indian peninsula and the Arabian sea. Cold surges and convection in an conditionally unstable atmosphere are the main causes for winter monsoon rainfall. The winter monsoon rainfall is most abundant over most of Indonesia and parts of south-east Asia; the Indian sub-continent depends for rainfall mainly on northern summer monsoon. The main beneficiary of winter rainfall in India is Tamilnadu.

During the northern winter, upper tropospheric circulation is characterized by the prevalence of the sub-tropical westerly jet over the northern hemispheric portion of the monsoon area, alternating with the tropical easterly jet during summer. The north-east-earlies emanating from the area of surface high pressure over the comparatively cold continent of southern Asia sweep much of the northern Indian Ocean including the Arabian Sea, the Bay of Bengal and the south China sea. These air streams recurve to north-westerly still tc the north of the equator and meet the southern hemisphere south-east trades in a broad trough zone located to the south of the equator.

The difficulty in forming a coherent picture of the principal facets of winter monsoon was removed upto some extent after the observations of MONEX-1979 (See Appendix-I). Murakami (1981 a, b, c, d) discussed the Asian Winter monsoon giving emphasis on the orographic influence of the Tibetan Plateau.

Luo and Yanis (1983, 1984) studied the circulation and heat sources over the Tibetan Plateau during the early summer of 1979. An analysis of the winter monsoon circulation over south-east Asia during December 1978 was presented by Mower et. al. (1984) and Ramage (1952, 1954, 1955) studied the cool season weather conditions over south-eastern Asia. Lim and Chang (1981) and Change and Lau (1982) carried out theoretical studies on interactions between mid-latitudes and the tropics during the Asian Winter monsoon.

The winter monsoon does not have continuous rain as summer monsoon. It has short-period rainfall fluctuations, the forcing mechanism for the fluctuations is thought to be closely linked with cold surges. The weather producing systems in India during the season are (i) low pressure area (some of these can be traced from Andaman sea which move westwards across the extreme south peninsula, most of them forming insitu in southwest Bay of Bengal and moving towards the Indian Coast), and (ii) well marked seasonal trough of low pressure in the south Bay of Bengal off Tamilnadu and Sri Lanka Coasts.

2.2.4 Australian monsoon

The summer monsoon observed in Australia (between November and April) is an extension of northern hemisphere winter monsoon, which is followed by a dry southern winter and is associated with the seasonal movement of a southern near-equatorial trough. Though , the exact geographical extent of the southern hemisphere summer monsoon is not exactly known, the outflow from the Indonesian region is believed to be directed towards northern Australia. Well-marked periods of onset, followed by short-period rainfall fluctuation by way of break and active phases are the features of Australian summer monsoon. The study of synoptic features, some of them away from the Australian continent, has suggested that the onset of Australian monsoon is linked with enhanced cross-equatorial flow in the lower troposphere from the northern to the southern hemisphere. Breaks in southern hemisphere monsoon is associated with weak Hadley circulations; the ascending branch of the upper troposphere Hadley circulation being over Indonesia and New Guinea and the descending branch being towards east of Australia.

2.2.5 African monsoon

Most of the precipitation over Africa depends on the performance of the summer monsoon. Figure 17 shows the mean winds over Africa in January and July. Air from the northern anticyclone over Sahara brings in the north-eastern trades, along the low lands of Africa, which are usually dry and have a high dust load. This is known as the Harmattan . On the other hand, in July, counter clockwise circulation associated with an anticyclone to the south of the Equator generates a maritime south easterly wind which, on crossing the Equator, approaches the western part of Africa as a broad south-westerly

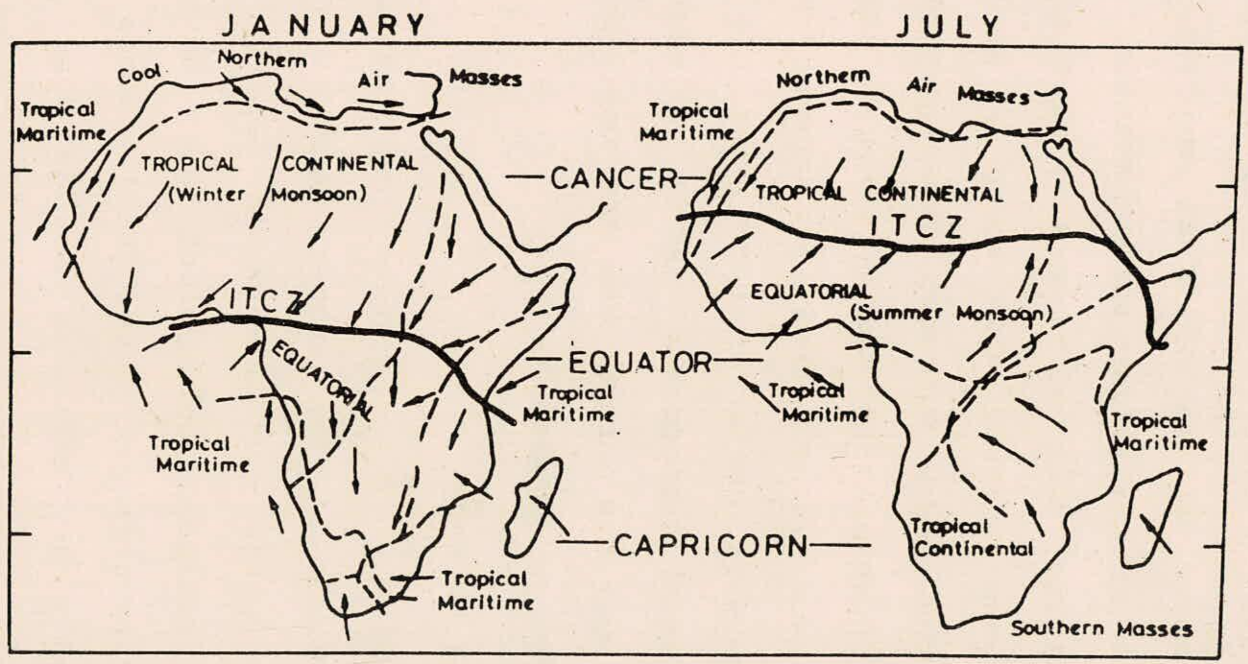


FIGURE -17 : AFRICAN MONSOON : MEAN WINDS OVER AFRICA IN JANUARY AND JULY (DASHED LINES INDICATE AIR MASS BOUNDARIES) current. This is the "summer monsoon". A characteristic feature of the Harmattan is the high frequency of dust haze with low precipitation. The dust haze is associated with subsidence from the Saharan anticyclone. The Saharan anticyclone is often referred to as a subtropical anti-cyclone (STA). The position of the highest temperatures in the northern summer coincides with a centre of low pressure between 15° and 25°N in July. This is the thermal low associated with the west African summer monsoon. Okulaja (1970) gave the main synoptic features as follows:

(a) Tropospheric jet streams

(b) Cyclonic vortices in the vicinity of ITCZ

(c) Easterly waves and squall lines, and

(d) Convection and cloud clusters

2.3 The Southern Oscillation and E1 Niño

Sir Gilbert Walker relating the fluctuations over the pacific with Indian Ocean found that when the pressure over the Pacific Ocean is high, it is low in the Indian Ocean from Africa to Australia, the temperature being low in both these areas and the rainfall varying in the opposite direction to the pressure; conditions are related differently in winter and summer. This was Walker's most important discovery known as "Southern Oscillation".

In the recent years, a resurgence of interest in Southern Oscillation has been witnessed due to its association with a phenomenon known as "E1 Niño". E1

Niño, which refers to the "Christ Child represents a warm coastal current that runs southward along the coast of equator around Christmas. There exists a possible link between El Nino events and the performance of summer monsoon rainfall. Warm anomalies over the western Pacific have brought about a reduction in summer rainfall over the Indian sub-continent. However, Keshavmurty's experiment (1982) with the central pacific warm anomaly suggests an association with weaker monsoons.

The studies of Rasmussen and Carpenter (1982) revealed that during the month of December, a weak warm sea-surface temperature anomaly appears along the coast of Peru which increases to its peak value in March and April of the following year. Subsequently, the warm anomaly begins to decrease off the coast of Peru and the warmest anomalies appear over the equatorial central Pacific in February of the following year. Thus it was contended that the signal for warm anomalies over the equatorial central Pacific in February could be traced back to the appearance of a warm anomaly off Peru, nearly fourteen months earlier. The warm February anomaly has been observed to produce significant changes in the winter circulation at mid-latitudes.

2.4 Regional Models

The review of empirical analysis of regional aspects of monsoon points to the apparent role of various factors in the development and simulation of Indian monsoon. The numerical simulation is an obvious choice to test the physical processes that make up a monsoon. If one begins with an initial state, albeit hypothetical, one could with the help of a computer, identify those features of the atmosphere, which help to generate monsoon. Moreover, mathematical modelling has advantages over conventional analysis of data as it enables the control experiments to be performed. The simulation experiments try to express the effect of small-scale motion referred as sub-grid scale process, in terms of motion on a large scale using a model which can at best represent the atmosphere, a continuous medium, with a specified degree of resolution. While developing a model three main aspects are generally considered:

(i) the physics, that a model can satisfactorily handle,

(ii) computational design of the model, and

(iii) its comparison with reality.

Monsoon can be regarded as atmospheric response to external body forces viz., solar and terrestrial radiation, effect of mountains, clouds and precipitation, impact of oceans, frictional effects over the land and the sea. All these forces should be incorporated in an ideal model so as to meet the reality. However, this is difficult due to our lack of appropriate knowledge about the physics of monsoon and limitations in the availability of data over ocean regions and mountains, which puts further constraints on modelling experiments.

Different meteorological services all over the world have been experimenting with models on a global scale. In these general circulation models, the thermal stratification of the atmosphere is simulated by dividing it into a finite number of layers, with each layer representing the thermal properties of a horizontal slice of atmosphere. The governing equations of the model are solved for each atmospheric slice and the relevant solutions for each layer are matched at the interface between two layers.

For certain types of motion having regional interest, it is convenient in terms of computer memory and ease of computation - to design regional models covering a limited area of the earth s surface. The boundary conditions along the sides of domain of integration have to be compatible with the process of numerical integration so as to make the problem determinate. The interesting possibility exists, however, of altering boundary conditions in a limited area model to see what their effect would be on the final result, or of using the outputs from a GCM to serve as the boundary conditions for a regional model.

The difficulties arising in monsoon modelling are with boundary conditions when Himalayas are included in a numerical model; the choice of boundary conditions that should be applied to the earth s surface becomes unclear, because the earth s surface is at 500 h Pa, which is roughly one half the depth of the atmosphere.

Similar problems arise with the selection of upper boundary. A no. of models now include the stratosphere. However, before including them in a model the coupling processes between the motions in upper and lower stratosphere or between mesosphere and upper stratosphere are to be known more precisely. The studies of coupling of ocean and atmosphere is also important for monsoon studies because the dynamics of the whole terrestrial climate cannot be separated from the heat storage effects of the upper ocean (Kraus, 1977).

The basic equations of a numerical model are: (a) the equation of motion - which represents Newton's second law of motion for an atmosphere rotating with the earth, the accelaration of a moving parcel of air being related to body forces, (b) the equation of continuity which represents the conservation of mass, (c) an equation of State - which provides a relation between the three scalar variables of the atmosphere, viz. pressure density and temperature, (d) the first law of thermodynamics - relates changes in entropy of air with non-adiabatic sources of heat.

Following are the basic equations in cartesian co-ordinates, where x,y,z are directed eastward, northward, and upward respectively. The equation of horizontal motion may be expressed as

$$\frac{d\vec{V}}{dt} + f\hat{k}\times\vec{V} = -\frac{1}{\rho}\vec{\nabla}\vec{p} + \vec{F} \qquad \ldots(1)$$

$$\vec{V} = u\hat{i} + v\hat{j}, \qquad \vec{\nabla} = \hat{i}\frac{\partial}{\partial x} + \hat{j}\frac{\partial}{\partial y}$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \vec{V}.\vec{\nabla} + \omega\frac{\partial}{\partial z}$$

Where, $\hat{i}$, $\hat{j}$, and $\hat{k}$ denote unit vectors in x,y and z co-ordinates, $\vec{\nabla}$ is the horizontal del operator, $\vec{V}$ the horizontal velocity, u and v the x and y components of $\vec{V}$, ω vertical velocity, $\frac{d}{dt}$ the total derivative, f the coriolis parameter ($= 2\Omega \sin\phi$), Ω the angular velocity of the earth s rotation, ϕ geographical latitude, ρ density, $\vec{p}$ pressure and $\vec{F}$ frictional force per unit mass.

For large-scale motions, the hydrostatic equation

$$\frac{\partial p}{\partial z} = -\rho g \qquad \ldots(2)$$

Where g denotes the earth s gravity, is a good approximation to the vertical equation of motion.

The mass continuity equation can be written as

$$\frac{d}{dt}\ln\rho + \vec{\nabla}.\vec{V} + \frac{\partial\omega}{\partial z} = 0 \qquad \ldots(3)$$

$$\text{Or, } \frac{\partial\rho}{\partial t} + \vec{\nabla}.(\rho\vec{V}) + \frac{\partial(\rho\omega)}{\partial z} = 0 \qquad \ldots(4)$$

The first law of thermodynamics may be expressed by

$$\frac{d}{dt}\ln\theta = \frac{Q}{C_pT} \qquad \ldots(5)$$

Where C_p is the specific heat at constant pressure, Q the rate of heating/cooling per unit mass per unit time and

θ is the potential temperature defined by

$$\theta \equiv T(p_o/p)^k \qquad ...(6)$$

With $k = R/C_p$ and po = 1013 mb, T is the temperature given by the ideal gas law

$$p = \rho RT \qquad ...(7)$$

R is related to C_p through

$$C_p - C_v = R \qquad ...(8)$$

Where C_v denotes the specific heat at constant volume. Another form of first law of thermodynamics is derived from (5), (6) and (7) as

$$C_p \frac{dT}{dt} - \frac{1}{\rho} \frac{dp}{dt} = Q \qquad ...(9)$$

Equations (1) to (9) constitute the basic dynamical principles of GCM. For large scale predictions, it is important to take into account the water vapour in the atmosphere. If the frictional term F and the heating term Q can be expressed by the dependent variables V, ω, p, and ρ (or T), the system, together with the proper boundary conditions is complete.

Most of the models employ the Eulerian Co-ordinates which are fixed in space. Starr (1945) proposed a quasi-Lagrangian system with Eulerian co-ordinates for horizontal axes, and Lagrangian co-ordinates (moving coordinate) for vertical axis. Gordan and Taylor (1975) and Kuctlner and Uni Nayer (1982) used the Lagrangian co-ordinates for computing trajectories of air mass.

Some prominent general circulation models currently in use are developed by

(i) Goddard Laboratory for Atmospheric Sciences (GLAS) (Shukla et al, 1981).

(ii) Goddard Institute of Space Studies (GISS) (Stone et. al, 1977).

(iii) U.K. Meteorological Office (Saker, 1975; Corby et al, 1977; Gilchrist, 1981).

(iv) National Centre for Atmospheric Research (NCAR) (Washington and Daggupaty, 1975).

(v) Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe et al, 1974).

(vi) University of California in Los Angeles (UCLA) (Mintz et al, 1972).

(vii) Laboratoire de meteorologie dynamique, Paris, France (Sadourny, 1983).

Besides these, the development of multi-level general circulation models in USSR is summarized in Marchuk (1974). Krishnamurty et al (1973) developed a limited area model for the tropics.

2.4.1 Summer Monsoon Simulation

The studies of the following atmospheric elements were made to simulate the regional monsoon in different models:

(a) Wind fields

One of the best methods of visualizing the patterns in GCM data simulating the Indian monsoon is to examine the wind fields. A three dimensional circulation of the Asian summer monsoon was constructed by Subbaramayya and Ramanadham (1966) using the results of wind studies in different regions from the west Pacific to the Atlantic (Fig. 18). The essential features of the circulation are, (i) the lower tropospheric monsoon air comes from the Southern hemisphere, (ii) the monsoon air stream, i.e. the flow with a westerly component has greater thickness and northward spread in the eastern region than in the west, (iii) there is a general ascending motion north of the equator in the lower troposphere, (iv) the easterlies in the upper troposphere are primarily subsiding and are associated with a northerly component, (v) most of the upper tropospheric air crosses the equator and subsides to low levels in the southern hemisphere, and (vi) the exchange of air takes place between the upper westerlies and the subtropical westerlies in the eastern and western flanks of the Tibetan and Middle East anticyclones.

The above model shows that the Hadley cell of the southern hemisphere extends into the northern hemisphere. The estimation of the air flow in the monsoon westerlies and the upper easterlies over India indicates that the size of monsoon circulation is comparable to the Hadley cell on the global scale.

Early experiments in India were conducted with a quasi-geostropic model (Mukherji and Datta, 1973 ; Ramanathan and Bansal, 1976). The model was used to predict

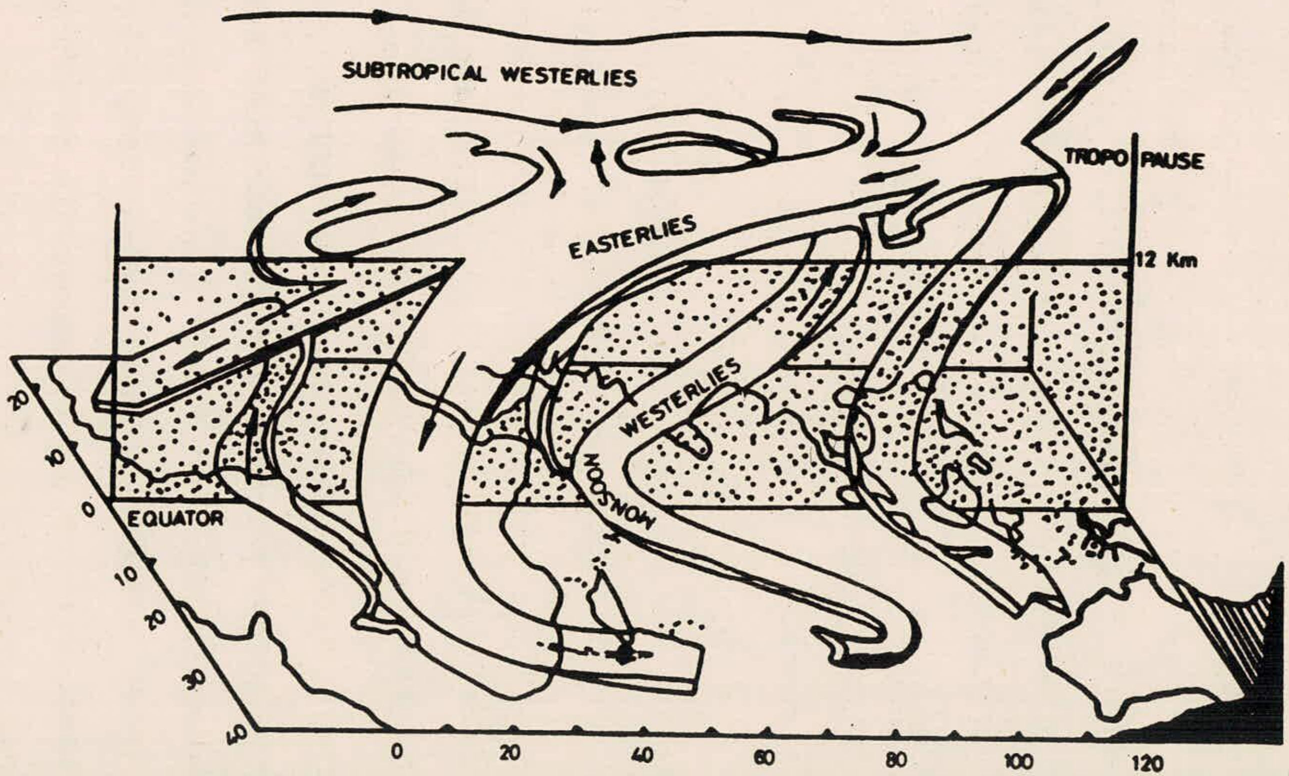


FIGURE-18 : A SCHEMATIC PICTURE OF THE THREE DIMENSIONAL CIRCULTION OVER THE MONSOON AREA (SUBBARAMAYYA AND RAMANADHAM, 1966).

upper winds over India and its neighbourhood on real time for commercial aviation.

The studies on low level, tropospheric wind distribution were made in GFDL model (Hahn and Manabe, 1975), the NCAR GCM (Washington and Daggupaty, 1975) and the British Meteorological Office Model (Gilchrist, 1977) which may be compared with the observed climatological gradient level winds (Atkinson and Sadler, 1970) [Fig. 19 (a) - (d)]. The GFDL winds are [Fig. 19 (b)] for a lower level ($\sigma = p/p^*$ = 0.99, p^* = surface pressure) and therefore expected to be backed with respect to the gradient level winds and less strong. The average wind in NCAR model [Fig. 19 (c)]are at 1.5 km from days 91 to 120 of a July integration. All simulations show a strong flow off the coast of Africa and Arabia, though the direction is nearer to southerly and its position closer to the coast than observed. Downstream, the ridge over the Arabian sea tends to be too pronounced and the simulated flows near the Indian coast are veered with respect to the relevant climatological normals. There is again a systematic bias in the simulations towards a too anticyclonic flow over the Bay of Bengal. None of them obtain a strong enough flow onto the south facing slopes of the Himalayas and thus fail to simulate the shape of monsoon trough in this region adequately. The Meteorological Office 11 layer model (Gilchrist, 1981) however follows the observed wind well (Fig. 19(d)). At a lower level σ = 0.987 the direction of winds in the Bay of Bengal with a direct current on

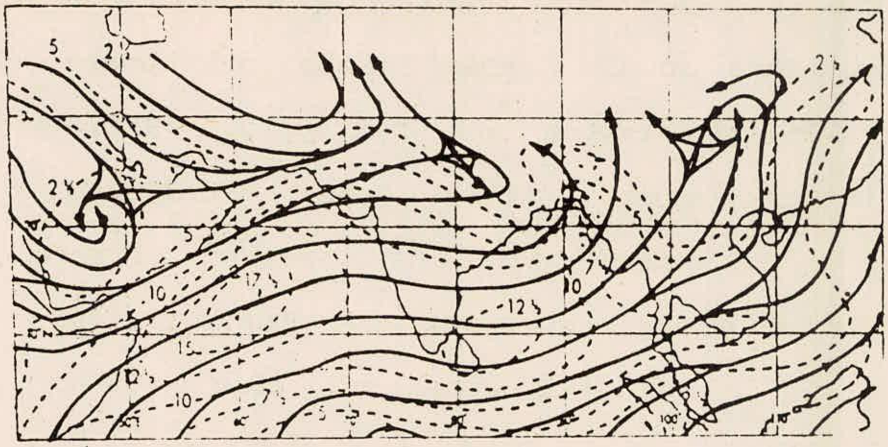


FIGURE- 19(a) : OBSERVED CLIMATOLOGICAL GRADIENT LEVEL WINDS (ATKINSON AND SADLER, 1970).

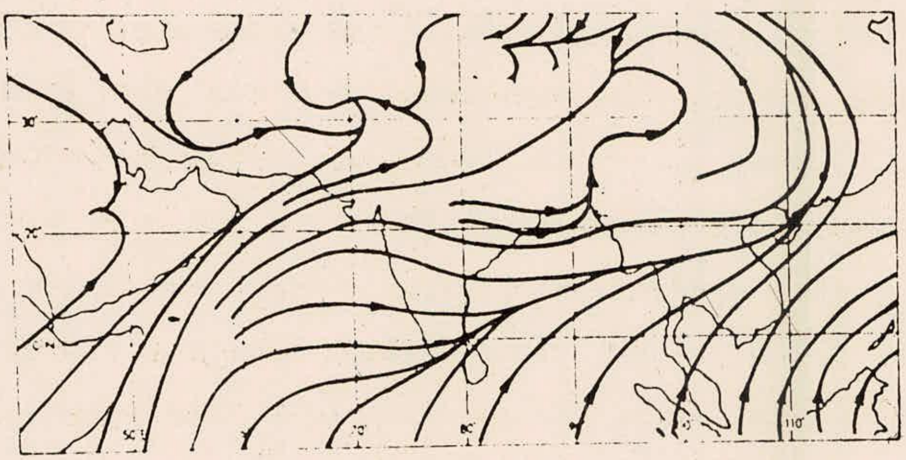


FIGURE -19(b): NEAR SURFACE WINDS FROM THE GFDL MODEL (HAHN AND MANABE, 1975).

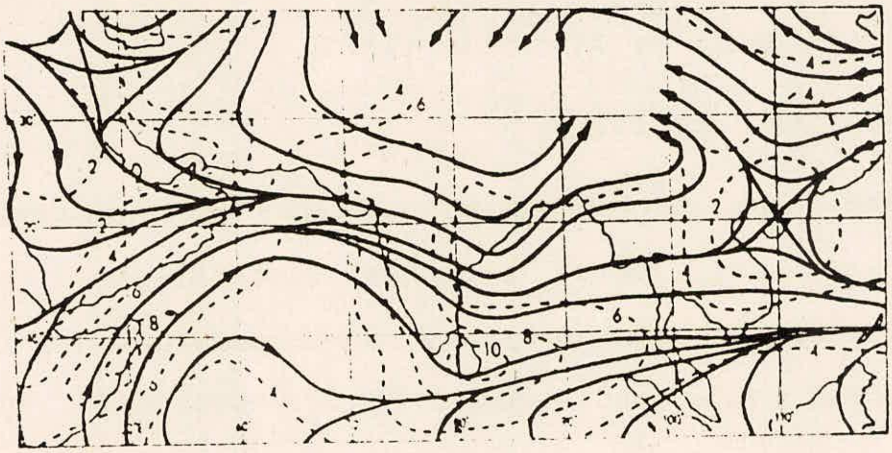


FIGURE -19(c): AVERAGE WINDS AT 1.5 KM. FROM NCAR MODEL (WASHINGTON AND DAGGUPATY, 1975)

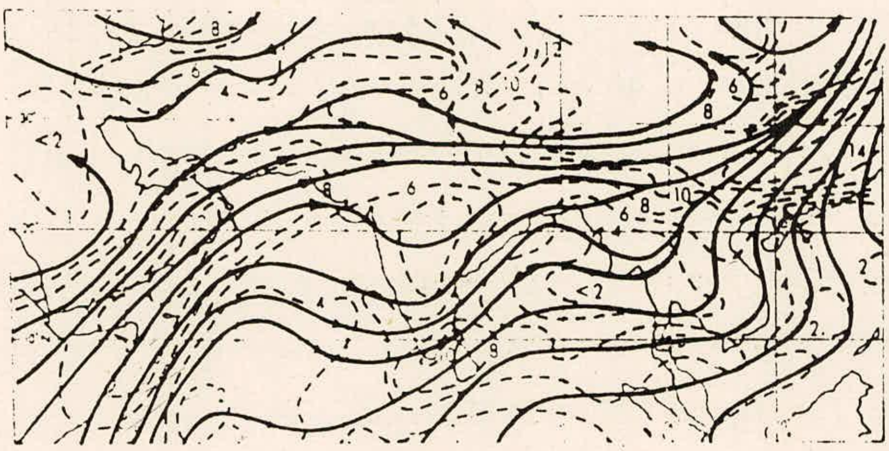


FIGURE -19(d) : AVERAGE WINDS AT THE LOWEST LEVEL ($\sigma = 0.9$) FROM METEOROLOGICAL OFFICE MODEL (GILCHRIST, 1977).

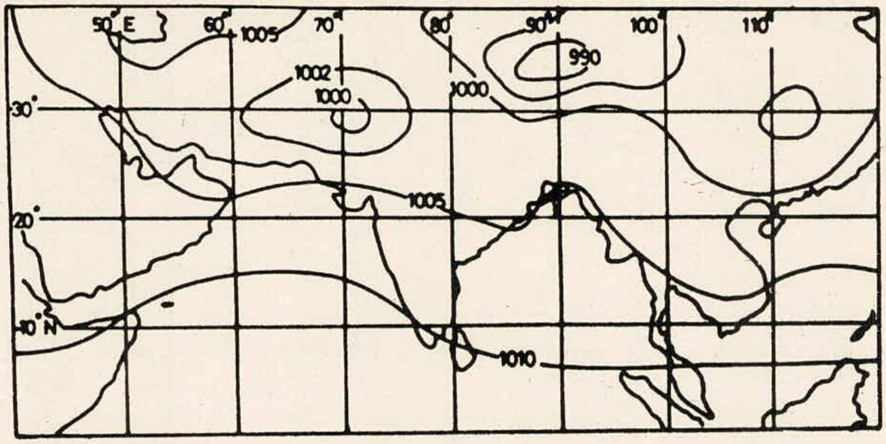
to the southern slopes of Himalayas is a consequence of the more realistic simulation of trough in this area.

The flow in the upper tropospheric model simulations has been dealt by Gilchrist (1977).

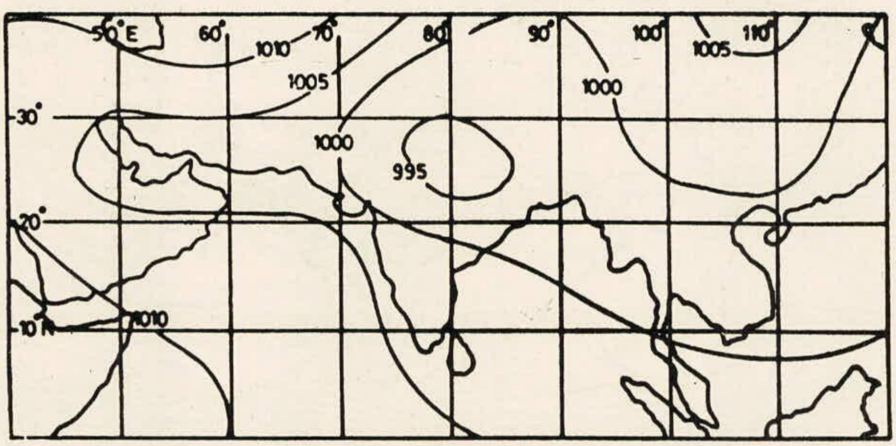
(b) Sea level pressure

The near surface wind patterns are induced by the low level horizontal pressure distribution. Figure 20(a) - (h) depict the mean sea level pressure for July by GFDL model (Hahn and Manabe, 1975), RAND model (Gates and Schlesinger, 1977), GISS model (Stone et al, 1977), model by Druyan (1981, 1982), model by Sadourny (1983), Meteorological office model (Gilchrist, 1983) and the observed pattern for July. The three prominent features of the summer monsoon are : (1) A thermal low extending from the Sahel to the Middle East and thence to north-west India, (ii) A monsoon trough over north India, with its axis running parallel to the southern periphery of the Himalayas, this generates a counter-clockwise rotation of winds from westerlies to southerlies and finally to easterlies over north-eastern India and (iii) A clockwise change in wind direction as monsoon winds strike mountain ranges of the Indian west coast. A successful model should be able to reproduce these freatures.

The model by Hahn and Manabe (1975) generates a thermal low too far to the east of its normal position. A similarly unrealistic displacement occurs with the model by Stone et al (1977), but the recent model by Sadourny

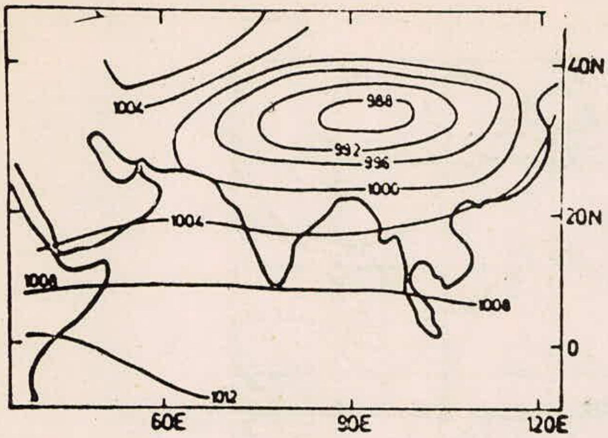


(a) GFDL MODEL (HAHN AND MANABE, 1975)

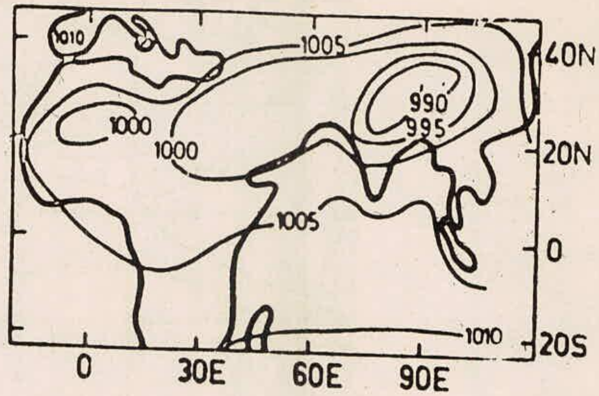


(b) RAND MODEL (GATES AND SCHLESINGER, 1977)

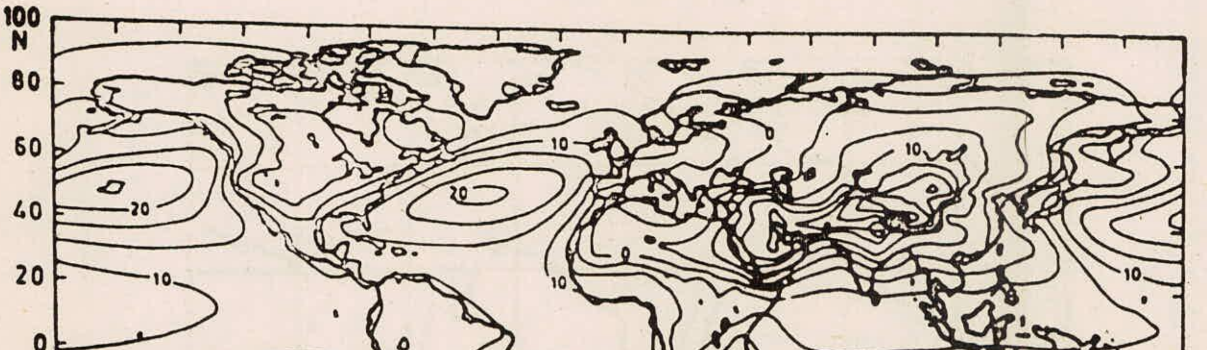
FIGURE - 20(a) AND (b): SEA LEVEL PRESSURE FOR JULY BY DIFFERENT MODELS.



(c) GISS MODEL (STONE ET AL, 1977)

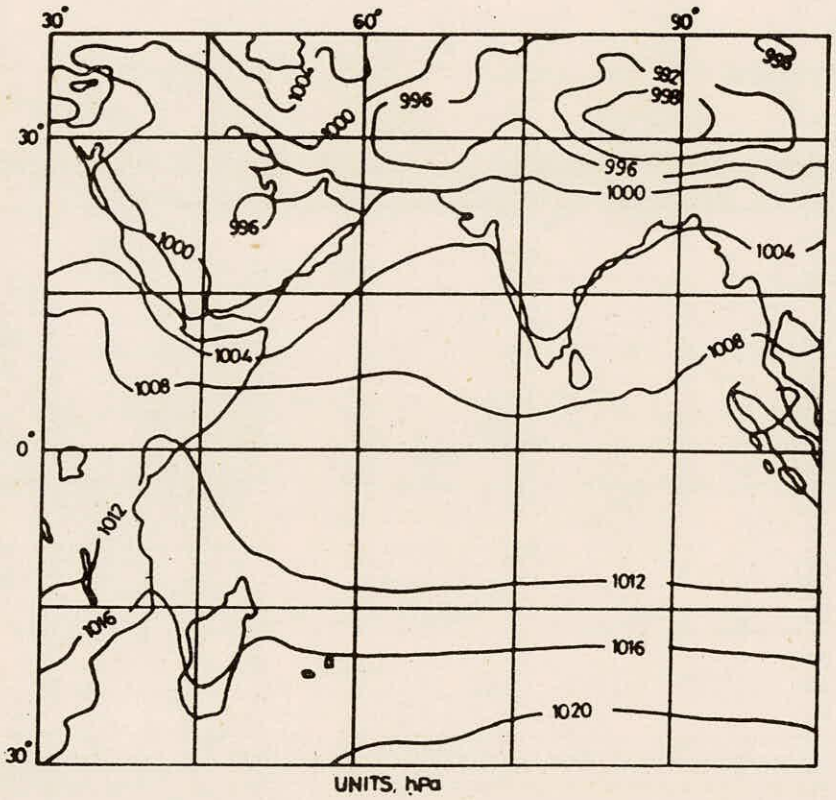


(d) MODEL BY DRUYAN (1981, 1982)

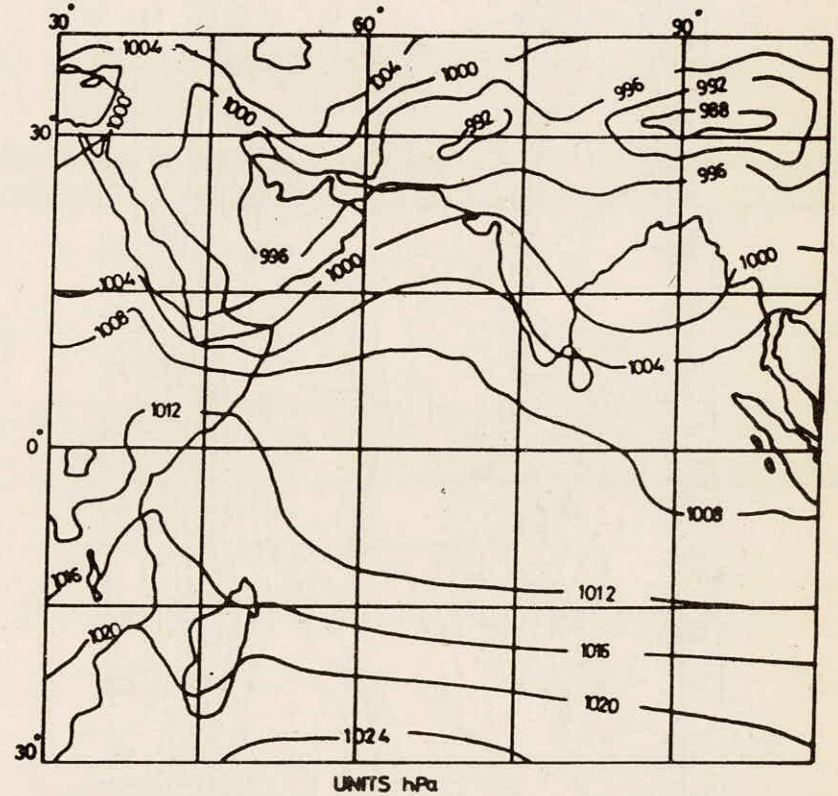


(e) MODEL BY SADOURNY (1983)

FIGURE 20(c)-(e) : SEA LEVEL PRESSURE FOR JULY BY DIFFERENT MODELS.



(f) MODEL BY GILCHRIST (1983) FOR SUMMER 1979.



(g) MODEL BY GILCHRIST (1983) FOR SUMMER 1980

FIGURE- 20(f) AND (g) SEA-LEVEL PRESSURE FOR JULY BY DIFFERENT MODELS

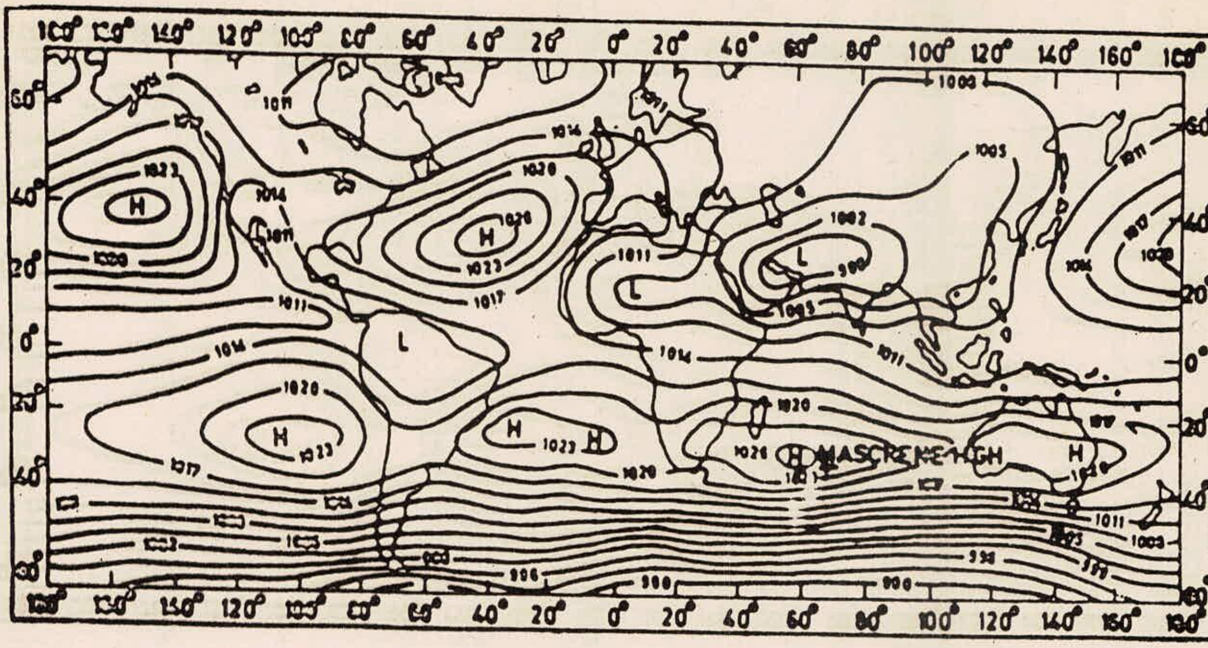


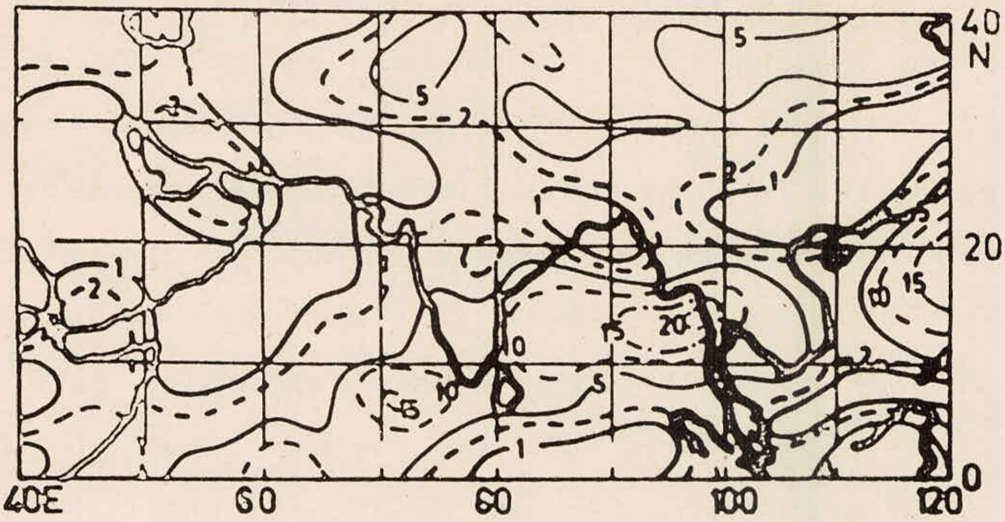
FIGURE -20 (h) : OBSERVED MEAN SEA LEVEL PRESSURE (hPa) FOR JULY (REPRODUCED FROM DAS, 1986).

(1983) gives a more realistic output. The model of Gates and Schlesinger (1977) gives an extension of the monsoon trough northeast-wards into China possibly due to the excessive heating on the Himalayan upslopes. Gilchrist's (1981, 1983) 11 layer model is an improvement over the other models. He used the parameterization scheme by Lyne and Rowntree (1976) for moist convection, and a cloud-radiation interactive scheme developed by Walker (1977) for zonally averaged cloud amounts taking the data from FGGE. The displacement of the thermal trough north of its normal position is observed in 1979 and 1980.

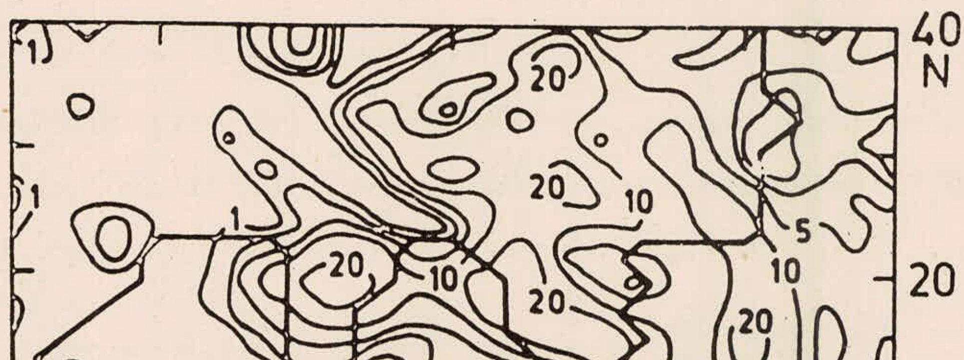
The main deficiencies in the models are unnatural displacement of the thermal trough and lack of precision in depicting the change in wind direction over east India. This could be due to difficulty in reducing surface pressure over high ground to sea level. One more problem in earlier models was that these could not reproduce some of the finer details of the monsoon trough adequately.

(c) Precipitation

Smagorinsky (1982), comparing different models inferred that the model outputs differ on July distribution of monsoon rain. Figures 21 (a) - (g), show the July mean precipitation for GFDL, RAND, NCAR, UK models and a model by Sadourny (1983). The first three models simulations give a greater proportion of the rain over the oceans. Figures 21 (a) - (e) show that maxima in precipitation is generated over the south-western coast of India and over north east India, but the observed rain-

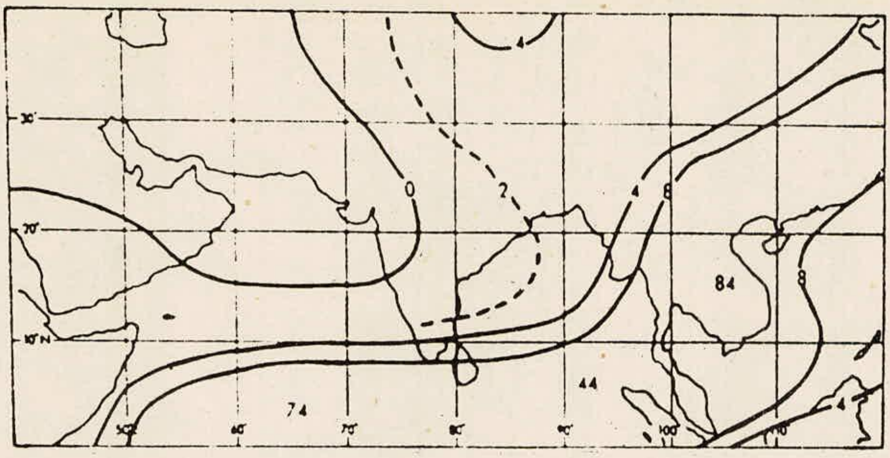


(a) : AFTER HAHN AND MANABE (1975)- FINITE DIFFERENCE 11 LAYER MODEL.

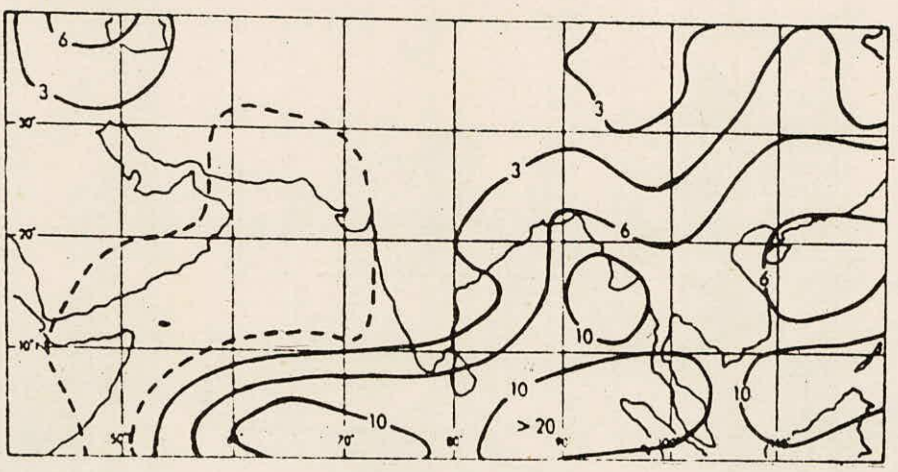


(b) AFTER HAHN AND MANABE (UNPUBL.) 9-LAYER SPECTRAL MODEL.

FIGURE-21 : SIMULATED MEAN PRECIPITATION (mm.day^{-1}) BY DIFFERENT MODELS.

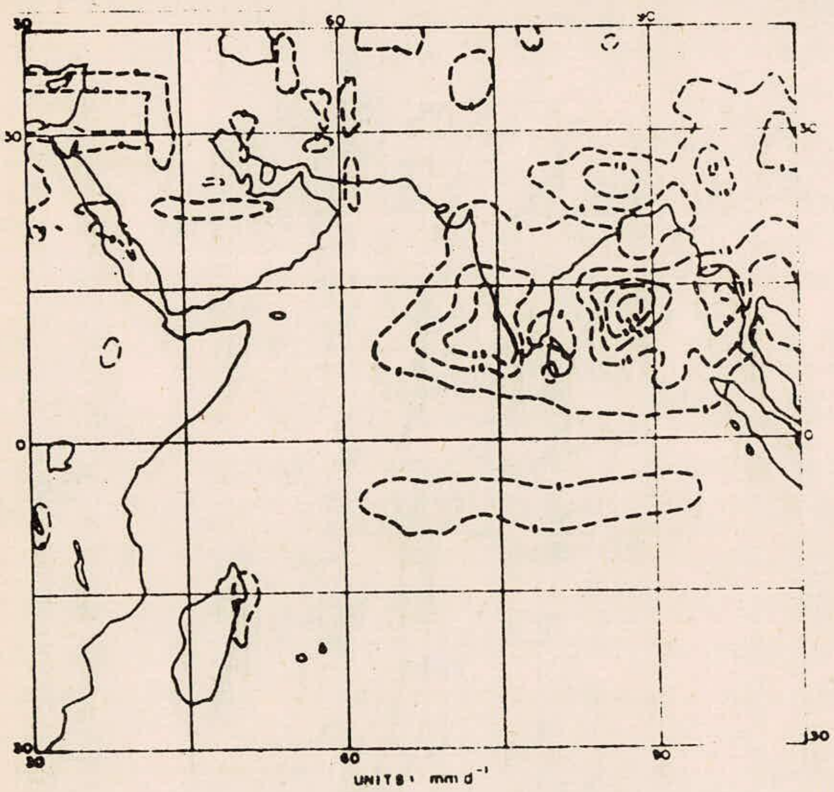


(c): FROM RAND MODEL (GATES AND SCHLESINGER, 1977)

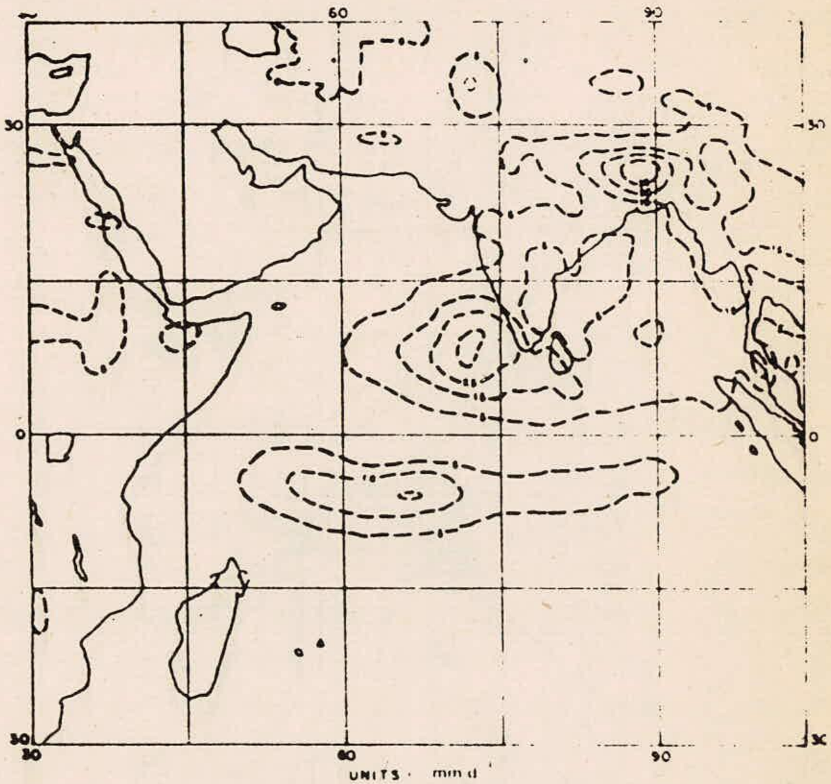


(d) : FROM NCAR MODEL (WASHINGTON AND DAGGUPATY, 1975)

FIGURE- 21: SIMULATED MEAN PRECIPITATION (mm. day^{-1}) BY DIFFERENT MODELS.



(e): 11-LAYER U.K. MODEL FOR 1979
(GILCHRIST, 1983)



(f): 11-LAYER U.K. MODEL FOR 1980
(GILCHRIST, 1983)

FIGURE 21- SIMULATED MEAN PRECIPITATION (mm. day^{-1}) BY DIFFERENT MODELS.

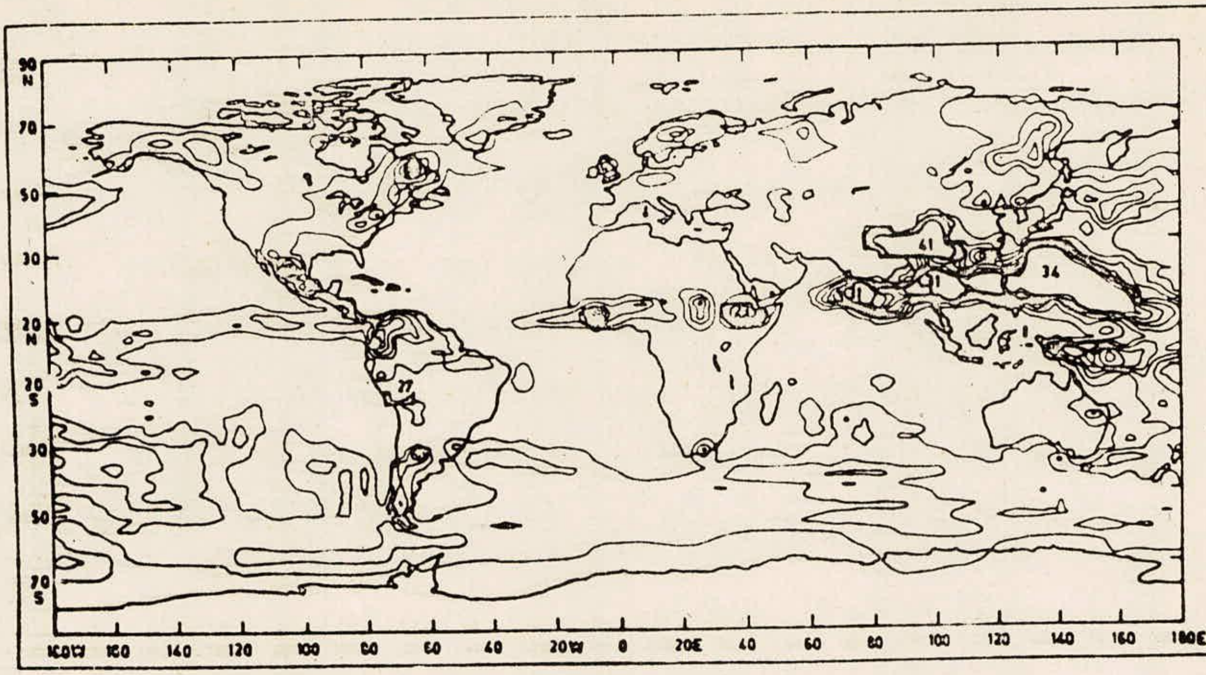


FIGURE -21(g) : MEAN PRECIPITATION FOR JULY (SADOURNY, 1983) fall maxima occur along the entire west coast and the Himalayan foothills of north India. Monsoon models have also succeeded in portraying the increasing trend of rainfall as one moves from the northern winter to summer.

2.4.2 Numerical sensitivity experiments

By repeating a simulation with a change in a single component of formulation, the sensitivity of the model to the prescribed change is demonstrated. To the extent that the simulation is realistic, the sensitivity of the actual climate to the prescribed change is implied.

a) Effect of topography:

Hahn and Manabe (1975) using 11 layer model performed numerical experiments first with a realistic gridded specification of terrain topography and then with an assignment of zero (sea level) altitude everywhere. They found that the Himalayan mountains strongly affect the Indian monsoon in the following way:

(i) The mountains are responsible for the intense summertime heating, which is a primary cause for monsoon trough over southern Asia. The simulation gives the observed temperature maximum over Himalayas only when the topography is taken into account.

(ii) The mountains are required for bringing copious rainfall to the northern half of India in the summer.

(iii) The greater part of the summertime diabatic heating over the Himalayas is from latent heat release. Without the orographic influences, sensible heat flux from the continent would be the principal source of thermal energy to the atmosphere over southern Asia.

(iv) The physical obstacle with the Himalayan Plateau represents to lower tropospheric flow causes an abrupt northward shift or jump in the latitude of the mid tropospheric westerly jet at about the time that the monsoon bursts upon India. The experiment shows that without mountains, the northward migration of the westerly jet and of the moist monsoon air progresses gradually.

(b) Albedo

Charney et al (1977) suggested that changes in surface albedo could bring about significant changes in local rainfall and atmospheric circulation. An increase in albedo leads to a decrease in rainfall. The impact of high albedo on local convection and hence rainfall was also tested for the semi-arid region of north-west India (Rajputana) for the mean July simulation. They found that provided terrestrial evaporation is sufficient, increasing the surface albedo from 0.14 to 0.35 over Rajputana resulted in a decrease in the mean precipitation rate of upto 4 mm/day over that area and to the east over the normally wet ganges valley. The rainfall was increased further south at the same time, especially over the Bay of Bengal. Thus it was concluded that the high albedo, (The albedo of natural surface is given in Appendix-II) inhibited surface heating to the extent of minimizing moist convection; the active precipitation zones of monsoon therefore remains south of their climatological position, not being able to penetrate to northern India with their usual frequency.

Sud and Fennessy (1981) supported the inferences drawn by Charney et al (1977). Increasing the albedo produced a reduction in rainfall over the Sahel and Thar desert, but this was not as prominent over the Great plains of USA. They extended the experiment over north-east Brazil, but the results were not conclusive.

(c) Sea-surface temperature (SST)

A substantial part of the moisture required for monsoon precipitation is supplied by southwesterlies over the Arabian sea, some of which comes as a result of evaporation over the Arabian sea. Such evaporation must be quite sensitive to the air-sea temperature difference, and the likelihood that sea-surface temperature anomalies have an impact on summer rainfall rates over India should be considered. A large number of model experiments have indicated on atmospheric response to sea-surface temperature anomalies in different parts of the world. Bjerknes (1966, 1969) and Namias (1974) seem to be the first to draw the attention to the effect of sea-surface temperature on atmospheric circulation.

Ramamurty et al (1976) with the date of the Indo-Soviet Monsoon Experiment of 1973 showed the preponderance of a moisture flux divergence from the Arabian Sea during an active monsoon period. An analysis of the ocean surface temperatures recorded by ships of the expedition during

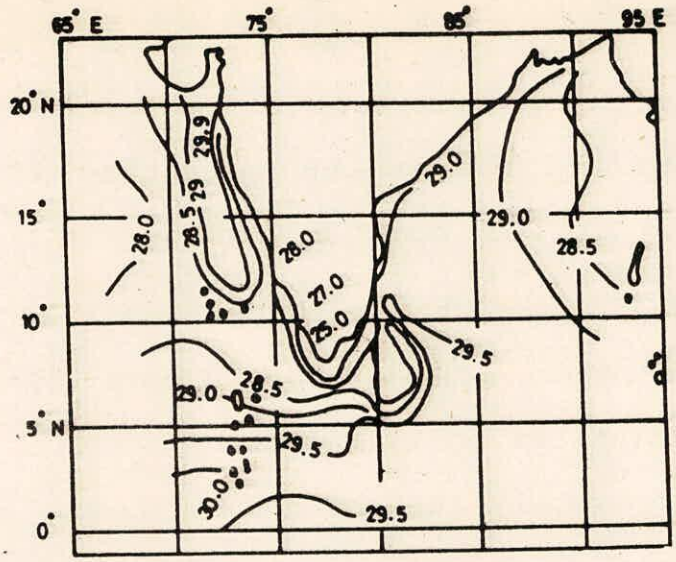


FIGURE -22: SEA-SURFACE TEMPERATURES RECORDED BY THE INS KRISTNA CRUISE OVER THE ARABIAN SEA (JUNE TO AUGUST 1963), AND OVER THE BAY OF BENGAL (AFTER ANAND ET AL., 1968)

1963 and 1964 indicated a warm tongue of water off the west coast of India during the summer monsoon (Fig. 22). It was hypothesized that this zone of warm water serves to increase the depth of the monsoon current to 4 or 5 km just before striking the west coast of India.

Shukla (1975) used the computer model by Manabe et al (1974) to test the consequences of a cold SST anomaly in the western Arabian sea on the simulation of the Indian summer monsoon. The anomaly pattern had a maximum of -3°C near the coast and decreased linearly to 1500 km east of the coast. Shukla found that a decrease in ocean temperature led to a decrease in precipitation over India and surrounding region. His hypothesis was that cold temperatures result in a decrease in evaporation and thus a decrease in the moisture available for downstream precipitation.

In a second set of experiments, Washington et al (1977) imposed prescribed temperature changes, first in the western Arabian sea, then in the eastern Arabian sea and finally in the Central Indian ocean. There was considerable divergence in model predictions. Anomalies over the Arabian sea, for example, produced effects that were either confined to a region very close to the anomaly or were not statistically significant. But the third experiment- a warm anomaly over the Central Indian Ocean - revealed an association with decreasing precipitation over Malaysia and the western Pacific. The result appeared to be statistically significant.

Moura and Shukla (1981) examined monthly mean anomalies in sea surface temperature over the tropical Atlantic in March and anomalies over north-east Brazil in March, April and May. They observed an association between severe droughts and the simultaneous occurrence of warm sea surface temperature anomalies over the northern parts of the tropical Atlantic and cold sea-surface temperature anomalies over the southern tropical Atlantic.

(d) Snow cover

Sensitivity tests on snow cover and monsoon rain (to correlate snow cover with monsoon rain) have not yet been performed in detail due to lack of data availability on snow hydrology. Shukla (1981) drew attention to an observation by Blanford (1984) concerning an inverse relationship betwen excessive winter snow cover over Himalayas and the subsequent performance of the summer monsoon over India.

Hahn and Shukla (1976) found an apparent relationship between Eurasian snow-cover anomalies and the summer monsoon rainfall over India. A large snow cover anomaly over Eurasia apparantly produces colder tropospheric temperatures the following spring thus leading to a delay in the onset of monsoon and a rainfall deficiency.

(e) Soil moisture and evapotranspiration

As soil moisture and vegetation provide valuable inputs to the water and heat balance of the atmosphere, it is important to see the effect of the former on circulation of large-scale systems.

Walker and Rowntree (1977) using a limited area 11-layer model tested the influence of variable soil moisture over west Africa. The westward moving low pressure systems were able to produce widespread rain over the Sahel and Southern Sahara for wet land, but if the land was dry only shallow heat lows were generated.

Shukla and Mintz (1982) in a more recent analysis, inferred that even if evapotranspiration exceeded precipitation, it did not follow that reduction in evapotranspiration would enhance precipitation. They performed two experiments for evapotranspiration studies : one for moist soil completely covered by vegetation and the other for dry soil with no evapotranspiration permitted. The integrations were performed for 60 days starting with 15 June in both the cases. The equilibrium conditions were reached in both the cases by end of July, when the integration period was extended by 15 days. The precipitation over Europe and over most of Asia was found to be more for wet soil than for dry soil. However, it was high over eastern India despite dry soil with no evapotranspiration. The precipitation over this region is apprently not dependent on surface conditions alone. The wide divergence in precipitation is born out by computations of simulated July surface pressure and temperature.

2.4.3 Simulation of the winter monsoon

In a seasonal simulation with the GFDL model, Manabe et al (1974) showed that over the Arabian sea the winter flow is from the northeast and is a reversal of the southwest flow in summer. Washington (1976) discussed the winter monsoon simulation with the NCAR model and compared the low and high level winds patterns with observed data. The flow pattern over the Arabian sea has a maximum of 7.5 ms^{-1} which compares favourably with the observed data of Sadler and Harris (1970) and Findlater (1971). The cross-section along the equator from 35°E to 75°E shows that the model generates a shallow jet close to the African highlands, but the jet is much wider than that observed by Findlater. The pressure over northern India, the Arabian area and the Sahara was relatively high and over the Arabian sea and near Kenya relatively low, being opposite to that in summer.

2.5 Recent Observations

Monsoons have been studied on the basis of data gathered by a series of international expeditions. The earlier experiments were the International Indian Ocean Expedition of 1963-65 and the Indo-Soviet Experiments (ISMEX) of 1973 and 1977 (Monsoon 1977). These followed an experiment on a much larger scale known as the Monsoon Experiment (MONEX). The experiment was launched to study monsoon systems for one full year beginning on December 1978. The experiment provided a basis for meteorologists to have a deep insight of the monsoon. The details of MONEX are given in the Appendix I.

TABLE 6: PREDICTORS FOR THE DATE OF MONSOON ONSET

1.	Direction of mean January wind at 300 hPa over New Delhi (India).
2.	Direction of mean January wind at 200 hPa over Darwin (Australia).
3.	Mean February wind direction at 200 hPa over Trivandrum and Madras (India).
4.	Mean meridional December wind direction of the previous year at 200 hPa over Calcutta (India).

TABLE 7: PREDICTORS FOR JUNE TO SEPTEMBER RAINFALL

(a) The Indian Peninsula

1.	South American pressure departures for Buenos-Aires, Cordoba and Santiago in April and May measured in mm of pressure departures from normal.
2.	Mean position of the axis of an upper-air ridge at 500 hPa in April along 75°E measured in degrees of latitude. The ridge is generally located around 12°N.
3.	Mean minimum temperature in March (°C) for three Indian stations (Jaisalmer, Jaipur and Calcutta).

(B) North-West India

1,.	South American pressure departures (mm) in April for Buenos Aires and Cordoba.
2.	Equatorial pressure departures during January to May for Seyehelles, Jakarta and Darwin in inches.
3.	Mean position of ridge at 500 hPa along 75°E in April measured in degrees latitude.
4.	Mean temperature departure from normal (°C) at a north Indian station (Ludhiana).

2.6 Long Range Prediction

The ultimate aim of a GCM is the real time long range prediction. However, long term predictions with realistic initial conditions have not yet been made. This is because such a study requires many regular measurements of high accuracy throughout the whole depth of the atmosphere and simulation of all the physical processes in the atmosphere with least assumptions. However, our knowledge of the atmosphere is still very much in its infancy and not surprisingly progress in long range forecasting is slow.

The prediction of monsoons is needed to provide three basic information viz., the likely date of onset of monsoon rains, the total quantum of rainfall for the monsoon season and the likely duration of precipitation extremes (floods or breaks in monsoon rains) within the monsoon season. Regression equations with different predictions are now used for predicting the date of onset of the monsoon over the southern tip of India and the rainfall during monsoon season. Table 6 and 7 summarize the predictors now used. However, the success achieved by these predictors has been limited as there is no means of knowing when the statistical association between the predictors and predictand will change .

Of late, ARIMA (Auto Regressive Moving Average) models have been developed for long range forecasting. Thapliyal (1982) fitted ARIMA models to forecast the total quantum of summer monsoon rainfall over India and the monthly rainfall forecasts for different states in India. His model gave an evidence to indicate a higher skill for ARIMA models over multiple regression equations when a suitable leading indicator is used, as for forecasts of seasonal rainfall. For monthly rainfall forecasts, where no satisfactory leading indicator has been discovered, experience shows that the method is not as successful. One more advantage of ARIMA model is that the output from a GCM can be used as input for an ARIMA model (sea surface temperature for example).

Precipitation, accompanying the monsoon is one of the most important climatic element for hydrological processes. On the basis of quantitative forecast of precipitation, hydrologists can forecast runoff for better flood management, water control and water project operation.

3.0 REMARKS AND RECOMMENDATIONS

Extensive studies on different aspects of monsoon have reflected that the global monsoons are maintained by Walker and Hadley circulations and the regional features of monsoon are coupled with the planetary features. However, the precise coupling mechanisms are not fully understood as yet. Many features of similarity appear in regional monsoons (Indian, Australian and African monsoons) for the northern summer and winter. They are closely linked for example, with Hadley and Walker circulations, on regional scale. A low level monsoon trough and an upper tropospheric anticyclone are the other common features, and the cross-equatorial flow yet another common characteristic. Despite the compilation of the data available from MONEX-79, the understanding of the physics (a basis to the development of a numerical model) is still deficient.

GCMs have led to a better understanding of the large scale features of the monsoon such as pressure, wind patterns etc, but have not well simulated the small scale features. The modelling of Indian monsoon has focussed on the significant role of mountains in the monsoon circulation.

The numerical simulation lends support to the thesis that the monsoon circulation is sensitive to the diabatic heating in the region over and around the Indian sub-continent. It might be conjectured that this sensitivity will show itself in significant variations in the strength of the monsoon as a result of variations in the heat input such as might be caused by extensive sea-surface temperature anomalies, changes in surface albedo, moisture availability at the surface or cloudiness.

This leads to the improvement of knowledge or parameterization of the boundary layer and inclusion of vegetation and improved ground hydrology, specially for regional models. Sensitivity tests with changes in snow cover have not yet been reported, but indications show that they too may be important.

It becomes vital therefore, that the regional GCM for monsoon areas should be well coupled with the land surface processes with parameters as soil moisture, albedo, evapotranspiration etc. to represent the real picture. Though, the work in this direction has been started in other countries, it is yet to begin in India. Pilot studies are to be conducted to obtain areal averages to account for heterogeneity of the soil moisture and vegetation and soil moisture determination using remote sensing satellites and other instrumentation techniques. The data for snow cover studies are to be obtained from ground station reports, satellite visible infrared microwave images and global data from NOAA satellites.

In India, where the terrain is highly irregular, the rainfall distribution during the year is highly skewed, 75% of rainfall being received during the monsoon months. This seasonal variability in Indian rainfall is responsible for causing floods or droughts in some parts of the country almost every year. The quantitative forecast of precipitation over a particular drainage basis can provide a basis for the forecast of runoff. Parameters to determine runoff may be used as available from GCM and procedure of on line upgrading may be followed for estimation of water yield and real time flood forecasting. Since the runoff delays makes difficult the use of smaller time period, it would be necessary to integrate the results of climate modelling annually on monthly runoff mapping to transfer from basins net to circulation model net grid.

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MONEX

The monsoon experiment (MONEX) was a sub-programme of the first GARP (Global Atmospheric Research Programme) Global Experiment (FGGE) (one of the biggest ever international experiment on global scale) under the aegis of the International Council of Scientific Unions (ICSU) and the World Meteorological Organisation (WMO) for one full year commencing from 1 December, 1978. Its purpose was to study the contribution of the monsoon, in different parts of the world, to the earth's atmosphere. The greatest value of this experiment lies in the expectation that it would reveal those features of the monsoon, which are needed to monitor every year.

The Monsoon Experiment (MONEX) was divided into three parts on the basis of its seasonal character:

(i) Winter MONEX from 1 December 1978 to 5 March 1979; this covered the eastern Indian Ocean and the Western Pacific Ocean along with the land areas of Malaysia and Indonesia.

(ii) Summer MONEX from 1 May 1979 to 31 August 1979 over the eastern coast of Africa, the Arabian Sea, the Bay of Bengal and the adjacent land areas. It also extended over the Indian Ocean from 10°N to 10°S.

(iii) West African Monsoon (WAMEX); this covered the western and central parts of Africa for the duration of the northern summer.

International MONEX Management Centres were set up in Kuala-Lumpur and in New Delhi to supervise (i) and (ii), and in West Africa for (iii). The data output has been divided into 3 categories-raw primary data, such as the original record of different sensors; meteorological variables as wind speed and direction from raw data and; processed data in the form of charts and weather maps. Indian scientists at the International MONEX Management Centre in New Delhi have drawn up computer programs for real time checks on the consistency and accuracy of incoming data.

A number of countries contributed to the success of the experiment. Five research ships from the USSR and three research air-crafts from the USA took part, while France contributed a ship and a constant level balloon programme. India contributed four ships and one air-craft. The observation programme over the country was intensified. On the space based platforms, a geostationary satellite launched by the USA-GOES Indian ocean-was specially moved to cover the MONEX region. Another geostationary satellite launched by Japan provided cloud imageries for the eastern sector of the MONEX region.

The research air craft from USA collected data on the radiation balance of the earth - atmosphere system measuring both the incoming radiation from the sun and the radiation emitted by the earth's surface. Indian ships were equipped for the first time to measure upper winds.

The flights by Indian aircraft from National Remote Sensing Agency recorded in analog form the total air temperature, static and dynamic pressure, dew point, liquid water content, radiometric surface temperature and radio altitude. The France ship tracked the path followed by the monsoon air with the help of balloon that flew at a constant altitude. A network of eight Automatic Picture Transmission (APT) stations was set up in India during MONEX to receive the transmitted signals sent by weather satellites.

ALBEDO OF NATURAL SURFACES

Surface	Albedo A	Surface	Albedo A
Water	0.03-0.40	Spring wheat	0.10-0.25
Black, dry soil	0.14	Winter wheat	0.16-0.23
Black, moist soil	0.08	Winter rye	0.18-0.23
Gray, dry soil	0.25-0.30	High, dense grass	0.18-0.20
Gray, moist soil	0.10-0.12	Green grass	0.26
Blue, dry loam	0.23	Grass dried in sun	0.19
Blue, moist loam	0.16	Tops of oak	0.18
Desert loam	0.29-0.31	Tops of pine	0.14
Yellow sand	0.35	Tops of fir	0.10
White sand	0.34-0.40	Cotton	0.20-0.22
River sand	0.43	Rice field	0.12
Bright, fine sand	0.37	Lettuce	0.22
Rock	0.12-0.15	Beets	0.18
Densely urbanized areas	0.15-0.25	Potatoes	0.19
Snow	0.40-0.85	Heather	0.10
Sea ice	0.36-0.50		

LOW FREQUENCY OSCILLATIONS IN MONSOON FIELD:

Low frequency oscillations in the northern hemispheric summer monsoon is a well established fact. These fluctuations can be broadly divided into two frequency modes - quasi biweakly oscillations of 10-20 days time span corresponding to active-break cycle and 30-60 days cycle which is recognised as a dominant component of monsoon circulation system. Studies by Yasunari (1980, 1981) showed that low frequency cycles propagate north- ward from equatorial Indian Ocean upto the Tibetan Plateau with a quasi periodic regularity. A northward shift in the tropospheric circulation anomalies was also observed by Alexander et al, (1978), which was associated with active break cycles in the summer monsoon over India. Ramasastry et al. (1986) showed that though the near 40 days mode was very prominent during 1979 it was rather obscure during 1980, 1981, 1982 and 1983, in the lower tropospheric circulations as well as the rainfall over the Indian subcontinent.

De et al (1988) studied the nature of 40 days mode using a comprehensive data set for six years over the Indian subcontinent. They analysed the zonal and meridional components of the wind by resolving it into harmonic components and studied the intra-seasonal variation in circulation. The study revealed that the periodicity of the low frequency model (30-60 days) has a significant interannual variability and during the same year it has a strong spatial dependence. Thus it could be of little use for extended or medium range prediction.

Chowdhury et. al. (1988) studied the spatial and temporal variations of different frequency modes - seasonal, 30-60 days and 10-20 days of the south west monsoon rainfall over India. They found that the 30-60 days periodicities was the predominant mode over central peninsula in the long term normal as well as individual years.

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