1. INTRODUCTION

1.1 General

'Monsoon' means rainy season. For Indian meteorologists, the word monsoon has come to be so much associated, that they identify even the other seasons as pre-monsoon (summer) and post-monsoon (winter) seasons. This word is derived from the Arabic word "Mausim" (Ramanathan, 1960) which means season and was used by the Arabs to designate the winds over the Arabian sea which blow for approximately six months from the southwest and for six months from the northeast. In course of time, it has become the synonym of rainy season. The monsoon is said to be good or bad according to whether the rainfall is in excess or in deficit.

1.1.1 Planetary oscillation concept of the monsoon

Monsoon, in reality, is a quasi-stationary wind system (India Met. Dept., 1949) over Asia which alternates in direction between northeast and southwest during the year. It thus forms a part of the global general circulation. The periodical change of wind direction on the surface and aloft results from the normal swing of the planetary circulation zones (Flohn, 1960 a). Figure 1.1.1 which is based on Byers (1959) shows the schematic representation of planetary circulation observed when the sun is at

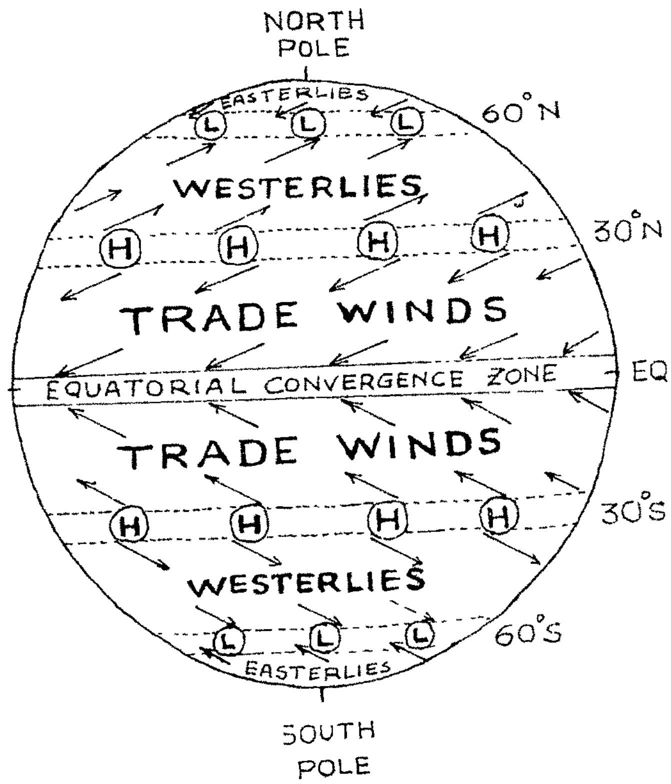


Figure 1.1.1 Schematic representation of winds at sea-level when the sun is at the equinox.

equinox. Three wind belts are present in each hemisphere; the trade winds of low latitudes, the westerlies of middle-latitudes and the easterlies of polar latitudes. The line of demarcation between the trade winds of the northern and southern hemispheres is the equatorial convergence zone. It is often known as the Intertropical Convergence Zone (ITCZ or ICZ). It is also called the Intertropical Front (ITF) (Sawyer, 1952), Intertropical Trough (ITT) (Saliman, 1960), and Near Equatorial Trough or Convergence (Ramage, 1971). This equatorial convergence zone is a narrow east-west band of vigorous cimulonimbus convection and heavy precipitation. (Holton et al, 1971).

During the northern summer, the whole system of planetary zones undergoes a shift towards the north and during the northern winter towards the south; a shift which follows the march of the sun in its zenith. The average zonal axis of the ITCZ which is at 13°N in July, is displaced to 4°S in January (Riehl, 1954). The zonal axis of the subtropical anticyclones (Figure 1.1.1) is displaced along the meridian only by half as much (Pedelaborde, 1963). Under these conditions, the tropical regions of the globe undergo two annual wind regimes. For example, during summer the southern hemisphere air-stream penetrates well into the northern hemisphere in India and southeast Asia and to a smaller extent in Africa whereas during winter the northern hemisphere air-stream penetrates farthest southward in south America (Brazil), east Africa and northeast Australia (Ramanathan, 1960).

The general circulation of the atmosphere stems from the inequalities in the solar radiation received and absorbed by the earth-atmosphere system. The equatorial region serves as heat source while the polar regions serve as heat sinks. The atmosphere is a gigantic, though inefficient, heat engine transforming the potential energy represented by the heat differences into kinetic energy of the mean motion (Byers, 1959) . Through this mean motion, called the general circulation, heat is transported from source to sink.

The global pressure distribution and the resulting winds represented by stream lines are shown in Figures 1.1.2 and 1.1.3 (based on Mintz et al, 1952) respectively for July (summer) and January (winter). The position indicated of the ITCZ (dotted line in the figures) is based on Sawyer (1952), though there are various versions about its positioning especially over the Asiatic continent in July. Whereas Sawyer (1952) and Mintz et al (1952) showed the ITCZ north of the Himalayas, Saliman (1960) and Pedelaborde (1963) showed it through India south of the Himalayas. But, Riehl (1954) does not show the July ITCZ over the portion of east Asia

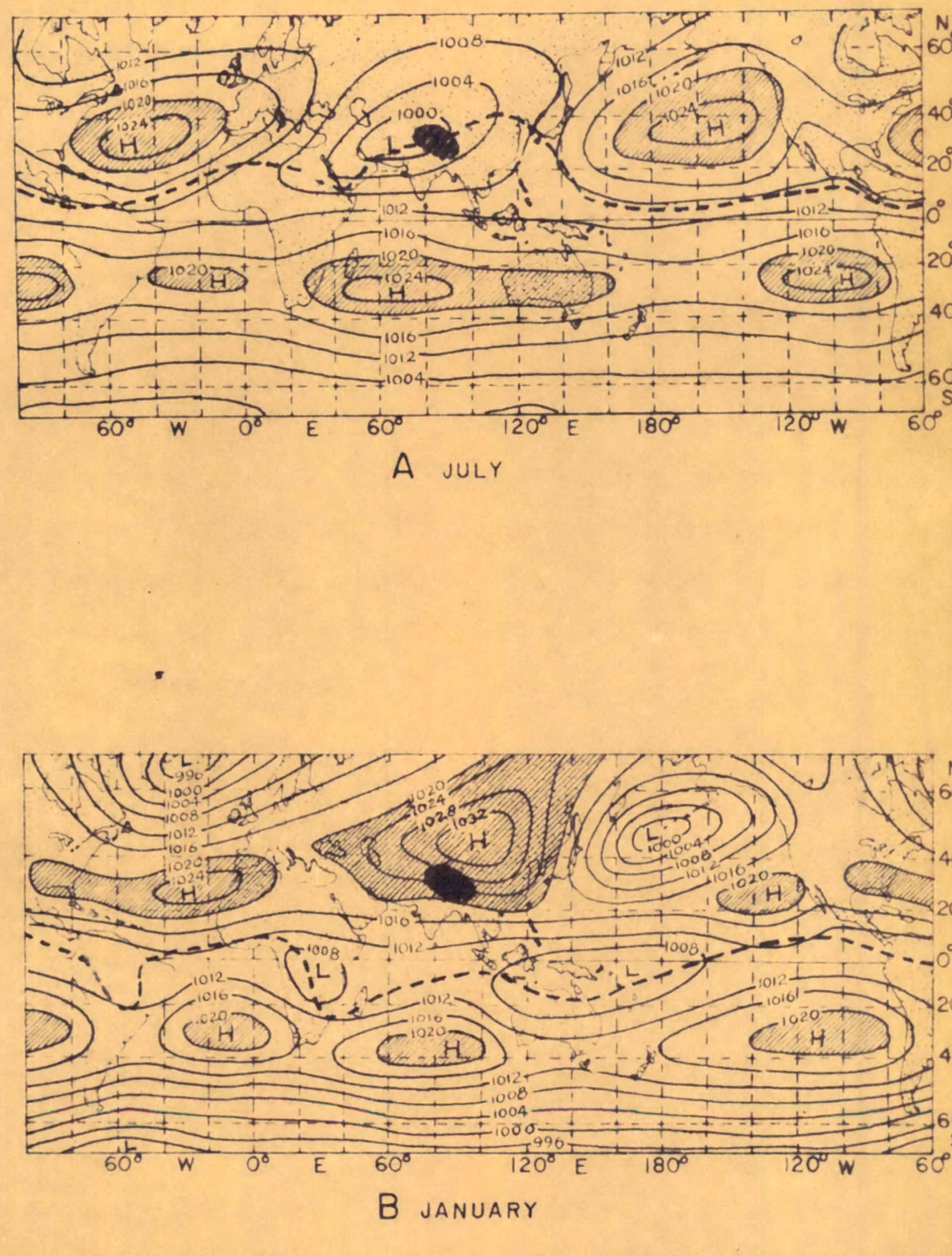
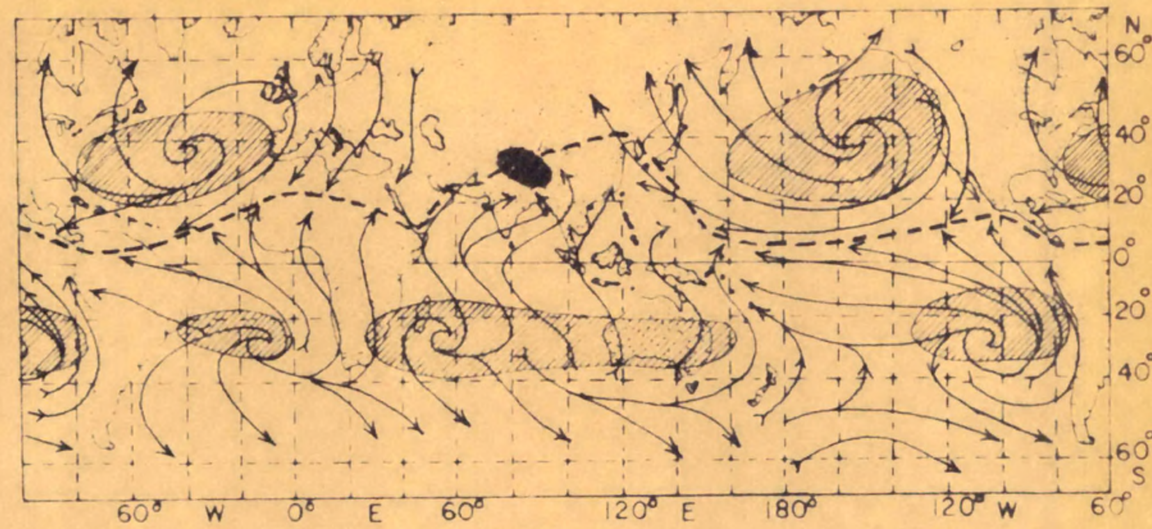
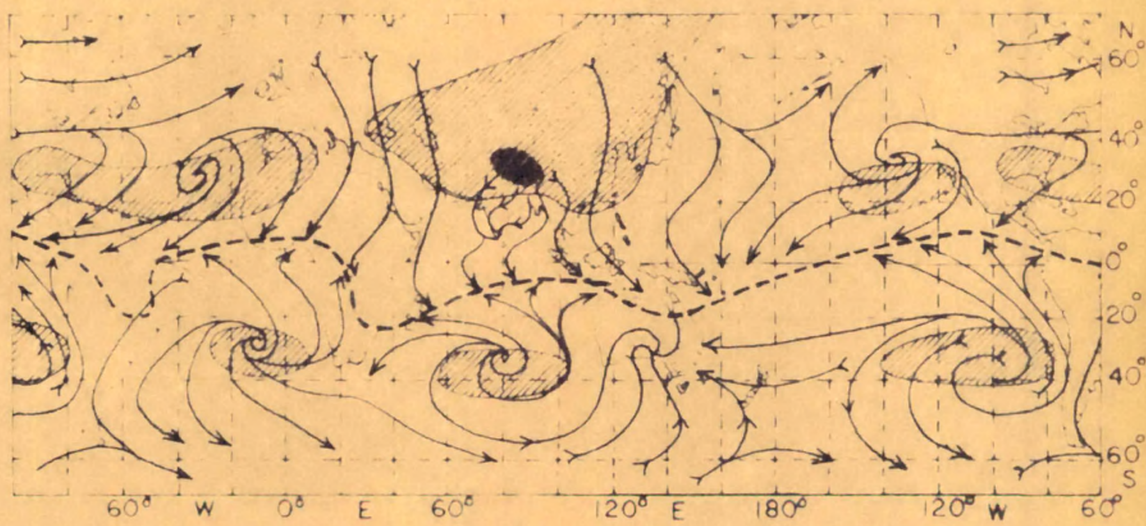


Figure 1.1.2 Global distribution of pressure at the surface for the month of (A) July -summer and (B) January -winter. Centers of high pressure (H) are hatched; the position of the Himalayas is shaded and the broken line represents the ITCZ.



A JULY



B JANUARY

Figure 1.1.3 Surface streamlines representing the surface winds for the month of (A) July -summer and (B) January-winter. Centers of high pressure (H) are hatched; the position of the Himalayas is shaded and the dotted line represents the ITCZ.

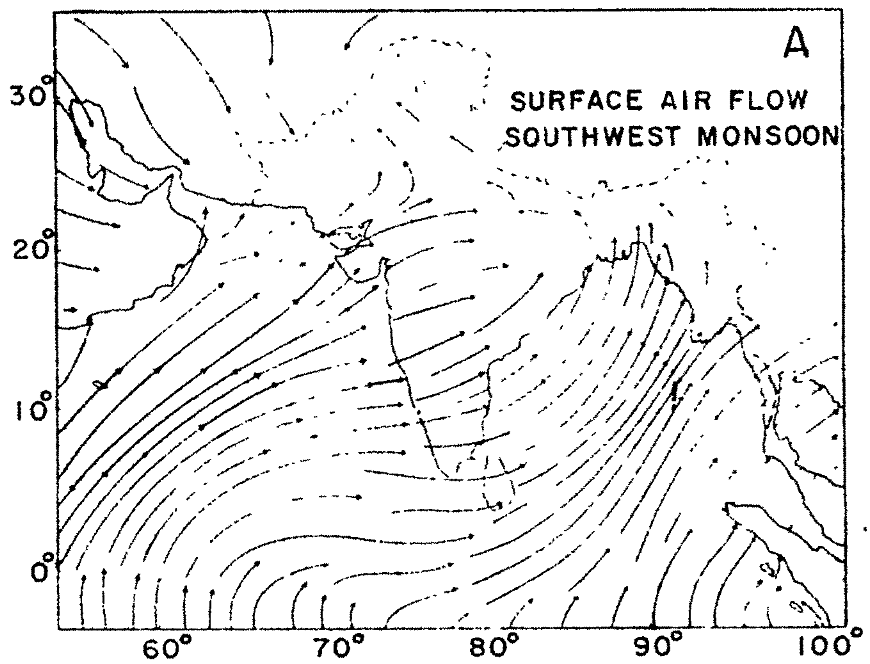
between about 90°E and 130°E, apparently due to lack of observational evidence.

The distribution of continents and oceans exerts profound influence on the distributions of pressure and wind. The strongly oceanic character of the southern hemisphere inhibits large seasonal changes. Hence the subtropical anticyclones over the Atlantic, the Pacific, and the Indian Oceans remain as prominent features in the southern hemisphere both in summer and winter (Figures 1.1.2 and 1.1.3) with comparatively small variations in their location and intensity. In the northern hemisphere, where continentality is very pronounced, the subtropical anticyclones are found only over the Atlantic and the Pacific oceans both in summer and winter whereas over the Asiatic continent, an area of intense low pressure centered over Afganistan is located in summer (Figures 1.1.2 and 1.1.3) and a well-developed anticyclone centered over Siberia in winter.

It is also seen from Figures 1.1.2 and 1.1.3 that the ITCZ undulates between 4°N (central Pacific) and 40°N (China) in July and between 25°S (Africa) and 8°N (off the California coast) in January. The seasonal displacement hardly exceeds 5° latitude in the western hemisphere (0° to 180° W), whereas it ranges upto 50° latitude in the eastern hemisphere (0° to 180°E). It is evident that the meridional distribution of oceans and continents with respect to the equator causes such contrasts. The Asiatic continent distorts the otherwise symmetrical distribution patterns of global pressure and winds. The continental stretch north of the equator and the oceanic spread to the south of it provides one special topographic feature causing differential heating of land and sea which is unique in itself. South America (Brazil) does not experience monsoon because of the narrowing down of the continent from equator to both north and south, thus restricting the areas in which heat lows might form. Thus, the monsoon, in addition to its being a part of the general circulation, is essentially of thermal origin.

1.1.2 Thermal concept of the monsoon

The thermal concept of the monsoon was first proposed by Halley in as early as 1886. In the summer hemisphere, the air over the Asiatic continent is warmer than that over the Indian ocean. A thermal low pressure is, therefore, developed over the warm continent (Figure 1.1.2A). Pressure increases in colder, denser air over the ocean. The flow of air is then from high pressure over the ocean towards low pressure over the land, as indicated by streamlines in Figure 1.1.3 A. During winter, a reverse current flows from the relatively cool land (high pressure) towards the heated ocean (low pressure) as shown in figure 1.1.3B. Thus, the monsoon winds are analogous to the sea breezes and the land



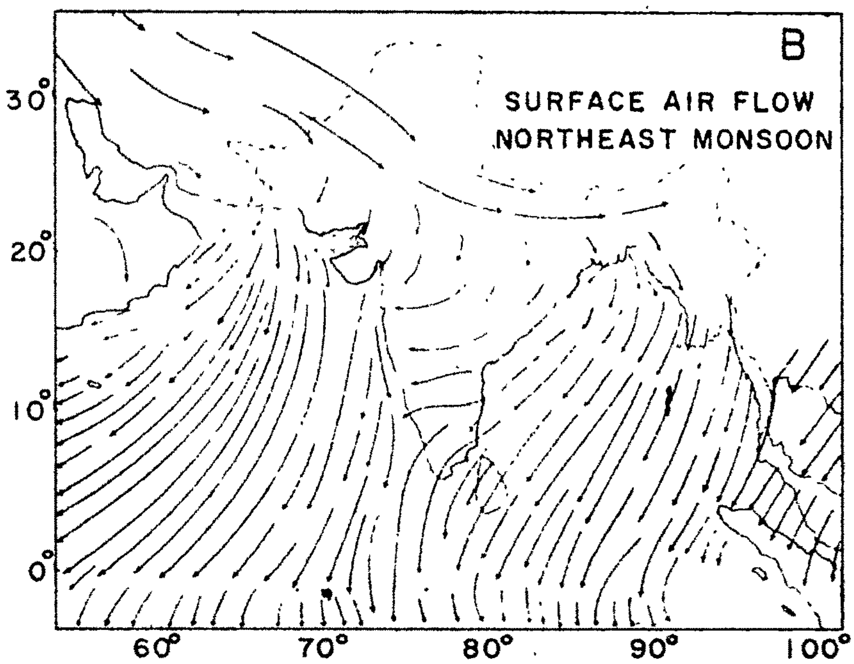


Figure 1.1.4 The general flow of wind during
(A) southwest monsoon and
(B) northeast monsoon

breezes on an annual time scale and a continental space scale (Flohn, 1960 b). It looks as though Asia breathes out during winter and breaths in during summer.

The Indian subcontinent furnishes the best large-scale example of the monsoon. In summer, from June to September, the general flow is from sea to land (Figure 1.1.4 A). The winds over major part of the country are from the southwest. The air being of oceanic origin has high humidity. Clouds and rain are of frequent occurrence and this period is the southwest monsoon. During winter, from December to February, the general flow is from north to south, northwesterly in the plains, northerly in the central parts and north--easterly in the south peninsula (Figure 1.1.4 B). The air over the country being mainly of continental origin has low humidity. This period is the northeast or winter monsoon.

1.2 Southwest Monsoon Season

The southwest monsoon or the summer monsoon (June to September) is the principal rainy season for most of India. Over 70 percent of annual rainfall is recorded during this season. (Das, 1963), Since the present investigation is limited to the southwest monsoon, the features relating to the southwest monsoon only are discussed in the following.

1.2.1 Surface features

The pressure configuration at sea level for a typical monsoon month of July is shown in Figure 1.2.1, which is reproduced from the paper by Rao et al (1968). The area of lowest pressure lies over northwest India with a trough of low pressure stretching across the Indo-Gangetic plains in the northwest-southeast direction. This trough is known as the monsoon trough and its periodic movements to the north and south have an important bearing on the rainfall over north India.

The monsoon first strikes the Kerala coast by about June 1. This feature is popularly known as the 'monsoon burst'. By the middle of July, it is established over the whole of India (Das, 1968). These are anxious weeks for the Indians, since a late monsoon may mean crop failure.

The advance of monsoon over the sea areas (Arabian sea and Bay of Bengal) is usually accompanied by squally weather, rough seas, and heavy rain showers (Ananthakrishnan et al, 1968). It is frequently ushered by cyclonic storms with the associated heavy rainfall (India Met. Deptt. 1949). As the monsoon extends north-wards it branches off into two currents (Simpson, 1921; Ramage, 1971). The Bay of Bengal current impinges on the south Burma coast almost at right angles and after crossing the coast it is deflected westwards up the

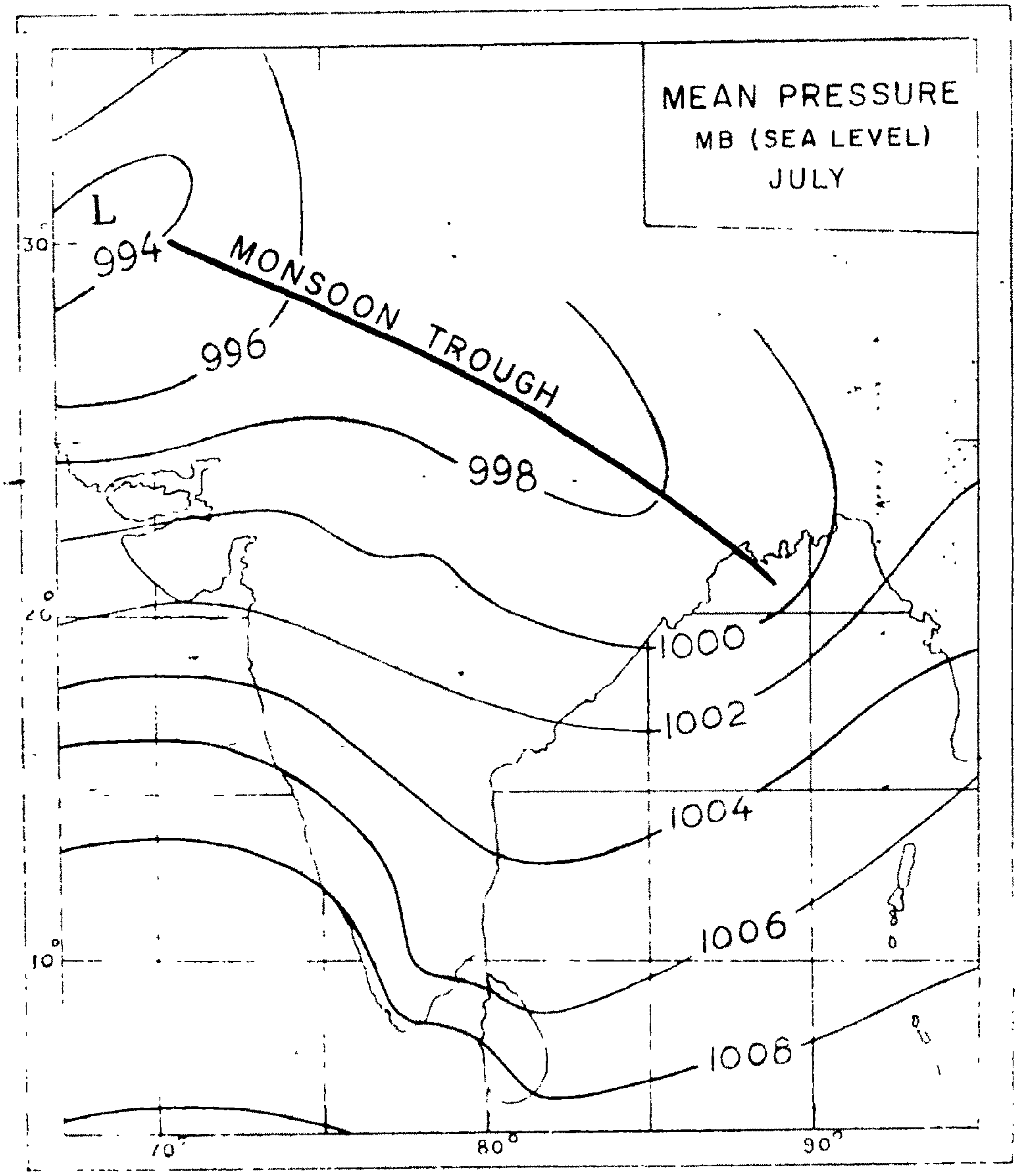


Figure 1.2.1 Mean pressure at sea-level for July.

Gangetic plains. The Arabian sea current strikes the west coast of India almost at right angles and after surmounting the Ghats, advances over the Deccan Plateau from West to east. When the monsoon is fully established, the monsoon trough becomes the meeting ground for the Arabian sea current and the Bay of Bengal current. Depressions form in succession in the north Bay and move along this trough. The depressions intensify the monsoon (India Met. Deptt., 1949).

Figure 1.2.2 shows the rainfall distribution during July. The data are based on the Climatological Tables, India Met. Deptt. (1945, 1960). The regions of heaviest rainfall are the west coast and the northeastern parts of India and the west coast of Burma. In these regions, orography plays important role in modifying the flow of the monsoon. (Petterssen, 1953). The trough over the Gangetic plains and the depressions which move along the axis of the trough play an important role in the general distribution of rainfall over India (India Met. Deptt., 1949; Rahmatullah, 1952). The fluctuations in the position of the monsoon trough in any given season determine the pattern of the rainfall distribution over the country in that season. When the trough shifts southward from its mean position, the monsoon activity is widespread. On the other hand, when it shifts northward its activity is limited only to northeast India. When the latter condition persists, there is a ceasation

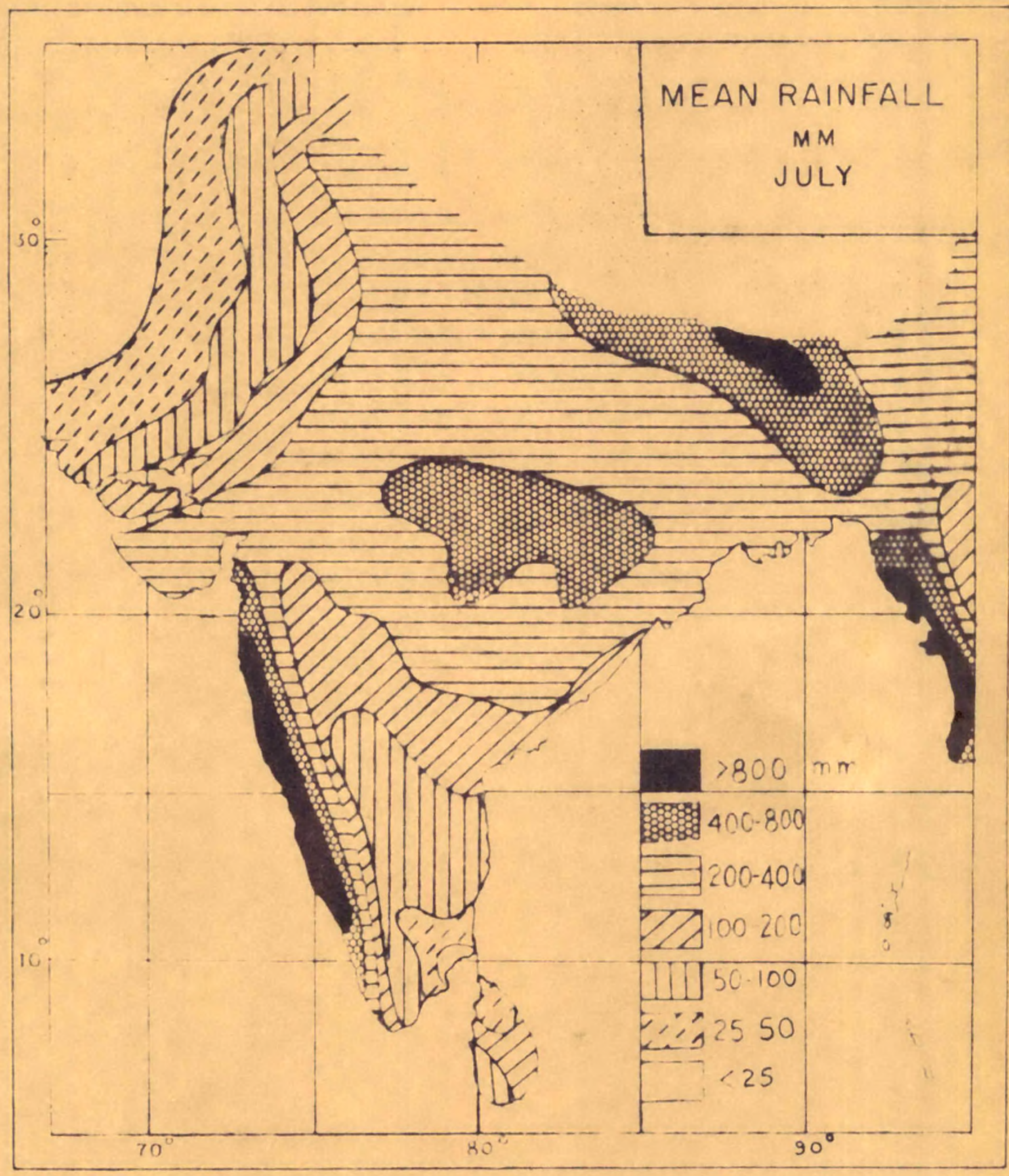


Figure 1.2.2 Mean rainfall (mm) during July.

of rainfall over most of north India. This is known as the 'monsoon break' condition. Consequently, the monsoon period is not one of continuous rain in any part of India. The pulsatory character of air movements and of rainfall is one of the most striking features of the monsoon period.

The monsoon begins to withdraw from Punjab and Rajasthan by the middle of September and from the remaining parts of the country by the end of November (Ananthakrishnan, et al, 1971). With the help of brightness values (which is a measure of cloudiness) obtained from the meteorological satellites ESSA III and ESSA V, Godbole et al (1970) have been able to demonstrate clearly the latitudinal advance of the monsoon with reference to months. Their results are reproduced in Figure 1.2.3 which also show that the advance of the monsoon is more spectacular than its retreat.

1.2.2 Upper air features

The westerly flow near the surface decreases in strength with height and eventually turns into an easterly flow. The height at which this reversal takes place varies with latitude and longitude. It decreases with increasing latitude and increases with increasing longitude. In general, the mean depth of the westerlies from 70°E to 100°E is 5 km over the equator, 6 km over 10°N and 2 km over 25°N (Desai, 1971). Also, it is 1.3 km over the west Arabian Sea, 3 km over the east Arabian Sea and 6 to 7 km over the peninsular India extending from the Western Ghats to the Burma Coast (Desai, 1971). The vertical structure of the monsoon is, thus, characterised by two wind regimes, the westerlies in the lower troposphere and the easterlies aloft.

The streamline analysis for the 200-mb level is shown in Figure 1.2.4 which is reproduced from the paper by Koteswaram (1958). The pattern reveals the existence of a large anticyclone over the Tibetan Plateau. This is the subtropical high over the Asiatic continent which builds up only above 500 mb and extends upto the tropo- -pause. The special feature of this subtropical high is that it is characterised by an upward vertical motion which is opposite to what is observed in the subtropical anticyclones over the Pacific and the Atlantic (Staff Members Academia Sinica, 1958). This is due to the fact that the Tibetan plateau which has an average height of over 4 km and which occupies, on that account, more than 1/3 of the troposphere, acts as an eleveted heat source, generating higher temperatures over there than in the free air at the same pressure level.

Tropical Easterly Jet : A feature of considerable interest as seen in Figure 1.2.4 is the existence of Tropical Easterly Jet (TEJ). It is a belt of strong easterly winds running along the southern periphery of

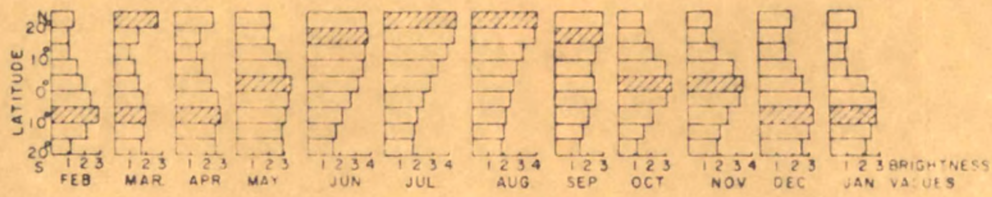


Figure 1.2.3 Block diagram of brightness values against latitude (20°S to 20°N) for different months. Hatching indicates the region of maximum brightness.

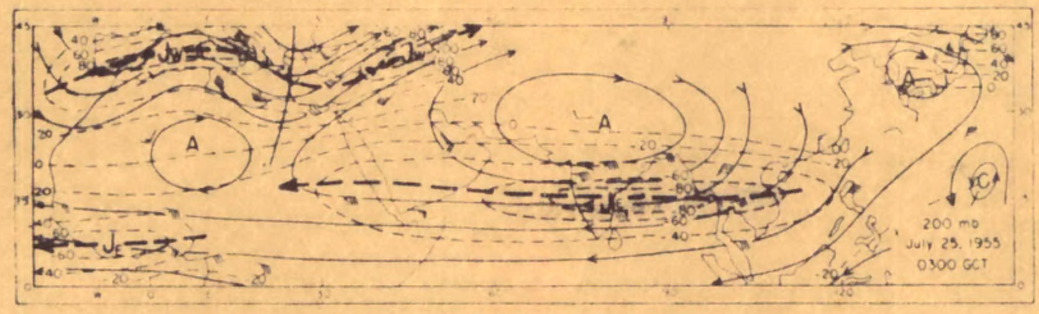


Figure 1.2.4 Streamlines and isotachs at 200 mb. The jet axis is marked by heavy dotted line and the wind maxima shaded.

Tibetan anticyclone. The core of the easterly Jet has an average maximum speed of about 70 knots and occurs along 15°N at a height of about 13 km (150 mb). It has been shown that the TEJ is quasi-geostrophic in nature with speeds consistent with the observed horizontal tempera--ture gradient (Koteswaram, 1958). Below the level of strongest winds, temperatures decrease from right to left across the current looking downstream; above the level of strongest winds, the reverse is true. The TEJ stretches across the Asiatic continent as a whole with its origin over the South China sea and exit over Africa (Flohn, 1964). The strongest winds are attained over southern India. The axis of the TEJ on a typical monsoon day is shown in the figure.

Subtropical Westerly Jet : It is also seen from Figure 1.2.4 that, in addition to the TEJ over Asia, there is another jet called the Subtropical Westerly Jet (STJ) located at higher latitudes north of the African conti--nent. Over Asia it is located north of the Tibetan Plateau. Its mean position in winter (not shown by Figure) is at much lower latitudes; its axis running just along the southern periphery of the Tibetan plateau. Yin (1949) was able to show that a sudden shift of the STJ from its winter-time position (south of Himalayas) to its summer-time position (north of the Himalayas) ushers the monsoon over India. Subsequently, Yeh et al (1959) and Koteswaram et al (1961) also confirmed Yin's findings, namely, that the retreat of the westerlies over northern India coincides with the 'burst' of the Indian summer monsoon. Chakravorty and Basu (1957) and Ramaswamy (1962) further showed that the reappearance of the westerlies south of the Himalayas impedes the advance of the monsoon giving rise to the 'monsoon breaks' referred to earlier. Finally, the withdrawal of the monsoon is heralded by a breakthrough of the STJ south of the Himalayas (Reiter and Heuberger, 1960).

A relationship has been shown to exist between the position of the TEJ and the rainfall amount over Asia and Africa (Koteswaram, 1958; Raman et al, 1964; Miller et al, 1967). The vertical velocity induced by the TEJ is upward north of it in the 'entrance' region and south of it in the 'exit' region (Flohn, 1964), and this feature is consistent with the heavy precipitation noticed north of the TEJ in the 'entrance' region (Asia) and south of it in the 'exit' region (Africa). However, recent studies based on the 1961-67 climatic data for India did not reveal definite relationship between the TEJ and the rainfall amount (Ananthakrishnan et al, 1969). It has been pointed out (Rex, 1969) that since the baroclinicity associated with the TEJ is more confined to the upper troposphere no organised vertical motion along the inclined isentropic surfaces would occur in the lower troposphere. Consequently, the monsoon precipitation is of non-frontal character. It is associated with strong convective systems due to destabilisa--tion of deep tropospheric layers.

1.2.3 ITCZ and monsoon trough

Very little information is available about the relationship between the ITCZ and the monsoon trough. According to Riehl et al (1958) and Flohn (1965), these appear to be one and the same. But, it is not so if the positioning of the ITCZ is considered according to Sawyer (1952), Mintz et al (1952), and Pedelaborde (1963). Since the ITCZ is essentially due to the convergence of air masses from the two hemispheres, it is the opinion of the author that the monsoon trough over India and the ITCZ over Asia are two different systems differing in their nature and scale. The ITCZ over the Asiatic continent is purely of thermal origin and represents a large-scale discontinuity between the two hemispheric trades whereas the monsoon trough over the Indiansub--continent, besides being thermal in origin, is dynamical in nature, being produced only by the deflected monsoon air on account of the presence of the Assam and Burma mountains. A similar view has also been expressed by Desai (1967). It would, thus, appear that just as the periodic movement of the monsoon trough influences the rainfall over India, the periodic movement of the ITCZ should influence the overall rainfall activity over Asia.

REFERENCES

Ananthakrishnan, R., V. Srinivasan, A.R.Ramakrishnan, R. Jambunathan.	1968	Forecasting Mannual, Part IV. Monsoons of India. India Met. Dept., Poona. 16 pp.
Ananthakrishnan, R., A.R. Ramakrishnan.	1969	Fluctuations in the Upper Tropospheric Easterlies over India during the Southwest Monsoon Season. Sc.Rep. 102, India Met. Dept. Poona. 27 pp.
Ananthakrishnan, R., J.M. Pathan.	1971	Rainfall Patterns Over India and Adjacent Seas. Sc. Rep. 144, India Met. Dept. Poona. 32 pp.
Byers, H.	1959	The General Meteorology. Mc Graw Hill Book Co. New York. pp. 260-264
Chakravorty, K.C., S.Basu.	1957	The Influence of Western Disturbances on Weather over Northeast India in Monsoon Months. Indian J. Met. and Geophys. 8 (3). pp. 261-272.
Das, P.K.,	1968	The Monsoons. National Book Trust, New Delhi. pp. 11-37.
Desai, B.N.	1967	The Summer Atmospheric Circulation over the Arabian Sea. J. Atmos. Sci.24. pp. 216-220
Desai, B.N.	1971	Synoptic Climatology of the Indian Subcontinent Met. and Geophy.Rev.No.2. India Met. Dept. Poona. 34 pp.

Flohn, H.	1960 a	Monsoon Winds and General Circulation. <u>Monsoons of the World. India Met. Dept. New Delhi</u>. pp. 66-74
Flohn, H.	1960 b	Some recent Investigation on the Mechanism of the Summer Monsoon of Southern and Eastern Asia. <u>Monsoons of the World. India Met. Dept. New Delhi</u>. pp. 75-88.
Flohn, H.	1964	Investigations of the Tropical Easterly Jet. <u>Meteor. Inst. der. Uni. Bonn. Heft 4</u>. 83 pp.
Flohn, H.	1965	Comments on a Synoptic Climatology of Southern Asia. <u>W.M.O. Tech. Note No. 69</u>. pp. 245-252
Godbole, R.V., Bh.V. Ramana Murty	1970	The Indian Summer Monsoon as Seen by the Weather Satellite. <u>J.Met.Soc. of Japan. 48</u>. pp. 360-368.
Holton, J.R., J.M.Wallace, J.A.Young	1971	On Boundary Layer Dynamics and the ITCZ.<u>J.Atmos. Sci. 28</u>. pp. 275-280
India Met. Dept.	1945	Climatological Charts of the Indian Monsoon Area.
India Met. Dept.	1949	Meteorology for Airmen in India. Part I. <u>Govt.Central Press, Bombay</u>. 26 pp.
India Met. Dept.	1960	Climatological Tables of Observatories in India (1931-1960).
Koteswaram, P.	1958	Easterly Jet Stream in the Tropics. <u>Tellus 10</u>. pp.43-57.

Koteswaram, P., N.S.Bhaskar Rao. 1961 Formation and structure of Indian Summer Monsoon Depressions. Proc. symp. Monsoon Meteorol., Pacific Sci. Congr. 10th, Honolulu. Australian Met. Magazine 41. pp. 62-75.

Miller, F.R., R.N.Keshavmurthy. 1967 Structure of an Arabian sea Summer Monsoon System. I.I.O.E. Met. monographs No. 1 East-West Center Press, Honolulu. 91 pp.

Mintz, Y., 1952 The Observed Mean Field of Motion of the Atmosphere. Geophy. Res. paper No. 17. U.S. Air Force Cambridge Research Centre. pp.11-65

Pedelaborde, P. 1963 The Monsoon. Methusen and Co. Ltd. London. pp. 1-22, 91-94.

Petterssen, S. 1953 On the Dynamics of the Indian Monsoon. Proc. Indian Acad. Sci. 37 A. pp. 229-233.

Rahmatullah, M. 1952 Synoptic Aspects of the Monsoon Circulation and Rainfall Over Indo-Pakistan. J. Met. 9. pp.176-179.

Ramage. 1971 Monsoon Meteorology, Academic Press, New York. pp. 26-27.

Raman, C.R.V., Y. Ramanathan. 1964 Interaction Between Lower and Upper Tropical Troposphere. Nature. Vol. 204. pp. 31-35.

Ramanathan, K.R.	1960	Monsoons and the General Circulation of the Atmosphere - A Review. Monsoons of the World. India Met. Dept. New Delhi. pp. 53-64
Ramaswamy, C.	1962	Breaks in the Indian Summer Monsoon as Phenomenon of Interaction between the Easterly and the sub-tropical westerly Jet Streams. Tellus 14 (3). pp. 337-349
Rao, Y.P., K.S.Ramamurty	1968	Forecasting Mannual, Part I Climatology of India and Neighbourhood. India Met. Dept. Poona. 17 pp.
Reiter, E. R., H. Heuberger.	1960	Jet Stream and Retreat of Indian Summer Monsoon and Their Effect Upon the Australian Cho-oyu Expedition 1954. Geografiska Ann., 42 (1). pp. 17-35.
Rex, D.F.,	1969	Climate of the Free Atmosphere. World survey of Climatology. Vol.4. Elsevier Publishing Co. Amsterdam. pp. 158-164.
Riehl, H.	1954	Tropical Meteorology. Mc-Graw Hill Book No. New York. pp. 10-13, 256-264.
Riehl, H., J. Malkus.	1958	On the Heat Balance in the Equatorial Trough Zone. Geophysica (Helsinki), 6. pp. 503-538.
Saliman, K.H.	1960	On the Intertropical Front and Intertropical convergence Zone Over Africa and Adjacent Oceans. Monsoons of the World. India Met. Dept. New Delhi. pp.130-135.

Sawyer, J.S. 1952 Memorandum of the Inter-tropical Front. Met. Rep. No. 10. Met. Office.London. 14 pp.

Simpson, G.C. 1921 The Southwest Monsoon. Quart. J.R. Met. Soc. 47. pp. 151-172.

Staff Members Academia Sinica. 1958 On the General Circulation over Eastern Asia (II). Tellus 10. pp. 58-75.

Yeh, T.C., S.Y.Deo, M.T. Li. 1959 The Abrupt Change of Circulation over the Northern Hemisphere During June and October, The Atmosphere and Sea in Motion. Oxford Univ. Press. pp. 249-267.

Yin, M.T. 1949 A synoptic aerologic study of the Onset of Summer Monsoon over India and Burma. J. Met. 6. pp. 393-400.