THE STRUCTURE OF THE ASIAN SUMMER MONSOON*

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Abstract: The wind and thermal structure of the Asian summer monsoon in the lower and upper troposphere have been examined during different stages of development of the monsoon. It is seen that an upper tropospheric warm ridge overlies the lower monsoon trough and shifts along with it. The activity of the monsoon is affected by the upper ridges as well as perturbations in the upper flow patterns. It is suggested that the summer monsoon circulation represents a Hadley type of meridional cell with its heat source over the monsoon trough near the thermal equator and 'sink' over the cooler oceanic areas near the geographical equator.

1. INTRODUCTION

The existence of the Summer Monsoon over South Asia has been known for centuries, not only by people of the lands affected by the monsoons but also by different seafaring peoples of the world. In early literature of India, copious references are made to the monsoonal winds and clouds. The Greeks learned about the existence of these winds during Alexander’s expeditions to India. According to the observation of Hippalus, this wind was known to appear in the Indian Ocean at the same time as the Etesian winds prevailed in the Mediterranean, and navigation from the Grecian ports was not practicable until the appearance of this southerly wind which blew from the sea towards the land. Marco Polo heard of the monsoons at Mangi, whose inhabitants sailed in winds to the Spice Islands near Ceylon and returned in summer with a wind in the opposite direction. In 1554 Sidi Ali of Arabia, in his work on Mohit, on the navigation of the Indian Ocean gave the times of commencement of the monsoon at fifty different places.

Halley (Phil. Trans. 1686, p. 158) described the summer monsoon as follows:

"To the northward of 30S latitude, over the whole of Arabian or Indian Sea and Gulf of Bengal, from Sumatra to the Coast of Africa, there is another monsoon, blowing from April to October, upon SW and WSW and with rather more force than the other (NE monsoon) accompanied with dark rainy weather, whereas the NE blows clear; 'tis likewise to be noted that the winds are not so constant, either in strength or point in the Gulf of Bengal, as they are in the Indian (Arabian) Sea, where a certain steady gale scarce ever fails. 'Tis also remarkable that the SW winds in those seas are generally more southerly on the African side, more westerly on the Indian."

This description can hardly be improved upon. Halley also attempted an explanation of the monsoon as due to differential heating of the land and sea.

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In a classical paper on the Indian Southwest Monsoon, Simpson (1921) treated the problem as that of an extensive closed heat low over India, bound by orography. He laid special emphasis on the effect of the Himalayas and the Arakan Yomas of Burma, which contain most of the moist monsoon air within the confines of India and Burma, increasing its rainfall. Ramanathan and Ramakrishnan (1933, 1938) studied the upper air circulation during the Southwest Monsoon with the aid of pibal winds and found that the monsoon current is 4 to 5 km deep with an easterly flow aloft. Southerly components are confined to the sub-cloud layer and the flow is westerly and sometimes even northwesterly at 1 km and above. In a volume of climatological charts of the "Indian Monsoon Area" extending to 30°S, prepared by Ramanathan and Venketeshwaran, published by the Indian Meteorological Department (1945), the monsoon westerlies have been indicated as extending up to 5°S. The turning of the SE trades into the SW monsoon was indicated as taking place even to the south of the equator, a fact which was noticed by various workers since the time of Halley (e.g., Mienardus 1893). Fletcher (1945) considered this trough south of the equator as a southern I. T. C. zone as distinct from the northern I. T. C. over northern India in summer.

Though it is generally believed that the SW monsoon originates from the SE trades of the Southern Hemisphere and gets deflected towards the heated land areas of India and SE Asia after crossing the equator, doubts were expressed from time to time regarding the correctness of this theory as the Southwest Monsoon is westerly, not southwesterly, above the sub-cloud layer and the turning of the SE trades into westerlies takes place mostly to the south of the equator. The belief has however persisted widely among meteorologists, as evidenced from general circulation maps published in various textbooks where the surface streamlines are drawn from the sub-tropical anticyclones of the Southern Hemisphere to the monsoon trough zone of the Northern Hemisphere. Ramanathan in a recent paper (1960) considers that the strengthening and advance of the moist monsoon current from the Southwest or West links up the Indian Monsoon with the trades of the South Indian Ocean.

Malurkar (1950) attempted to determine the link-up between the Indian Monsoon and SE trades of the South Indian Ocean. He was of the opinion that shallow low pressure areas travelling westwards to the south of the equator cross into the northern Indian Ocean at preferred locations and move across the Arabian Sea or the Bay of Bengal carrying the monsoon current in their wake. Such "lows" which he called "pulses" could be traced as feeble isobaric "lows". The mechanism as to why the lows cross from one hemisphere to the other and how they are transformed after crossing was, however, obscure. Apart from this attempt, no other evidence is available of trans-equatorial surges of the monsoon except along the East African Coast where strong southerlies have been noticed even from the time of Halley. Forecasters in the Indian area have, long since, attempted to anticipate monsoon surges along the west coast of the peninsula from the northward shift of the sub-tropical high pressure cells in the South Indian Ocean.

Flohn (1950, 1953, 1957, 1960) consistently opposed the concept of the Southern Hemispheric origin of these monsoon winds. In a number of articles he pointed out the existence of westerlies to the south of the equator even during the SW monsoon season. He postulated two different patterns of the planetary circulation of the atmosphere — one idealised for a land covered earth and the other for an oceanic globe. In a continental area, the thermally controlled pressure pattern will be displaced according to the sun's zenithal position and hence the thermal trough lies near 23°N in summer with a westerly current to its south.

The influence of high tropospheric flow on the onset of the monsoon was pointed out by Yin (1949) and Riehl (1954) who considered that the SW monsoon burst on the west coast of India as a result of the northward diversion of sub-tropical westerly flow over northern India in late Spring. The sub-tropical westerly jet stream shifts to the north of the Tibetan Plateau rather abruptly at the time of the monsoon burst. This abrupt shift of the upper westerly flow was observed by a number of other authors. (Sutcliffe and Bannan 1954, Suda and Asakura 1955, Flohn 1956, Shih-Yen and Lung Shun 1957). Koteswaram (1956, 1958a), while confirming the above mentioned "singularity"; however, pointed out that strong upper westerlies persisted over northwest India even after the onset of the SW monsoon. He drew attention to the setting in of an Easterly Jet Stream at low latitudes over South India which coincided with the burst of the monsoon there. He considered the upper divergence associated with the left "exit" sector of
the easterly jet induced convergence in the lower levels and the subsequent "burst" of the monsoon on the southwest coast of India. He noticed that this easterly jet shifted northwards during 'breaks' in the monsoon when the monsoon rains decreased considerably over peninsular India, and considered that this easterly current aloft is intimately connected with the SW monsoon in the lower levels.

The influence of the seasonal warming of the Tibetan Plateau in "switching" and maintaining the upper level circulation over the Asian Summer Monsoon came into prominence during recent years (Flohn 1957, 1960, Staff members of the Academica Sinica 1958, and Koteswaram 1958, 1960). Koteswaram (1960) postulated a Hadley type of meridional circulation functioning in summer over South Asia, with the source over the monsoon trough over northern India and further east, as well as the elevated heat source of the Tibetan Plateau and the "sink" over the cold equatorial sea areas. He pictured the southwest monsoon in the lower levels as a "return current" in this meridional Hadley circulation working in a reverse direction to the usual tropical Hadley cell. The role of perturbations in the upper easterlies on the formation of monsoon depressions and the fluctuations in the southwest monsoon current were investigated by Koteswaram and co-workers (Koteswaram and George 1958, Srinivasan 1959). Ramaswamy (1958) examined the effect of the lateral shift of the circumpolar westerlies over Asia on the strengthening of the southwest monsoon and monsoon 'breaks', and concluded that the sub-tropical anticyclone shifts over Tibet during strong monsoon while an extratropical westerly trough extends over North India in the upper troposphere in the 'break' period. A number of Russian workers have also given thought to this monsoon problem. A summary of their contributions has been given by Drozdov, Sorochnan and Logvinov (1960).

2. FLOW PATTERNS DURING THE SOUTHWEST MONSOON SEASON

In order to get an integrated picture of the summer monsoon circulation, it is necessary to examine the flow pattern in the entire troposphere, if not further aloft. The data collected during the IGY have been examined with this end in view in order to study the general patterns in the lower and upper troposphere over South Asia during various stages of the development of the SW monsoon during 1958, and daily charts extending over a wide area were prepared at different levels. A few sample situations are cited below to illustrate typical patterns.

(a) Monsoon Burst

The "burst" of the monsoon on the west coast of India was rather late in 1958, having been delayed to the middle of June instead of the usual late May or early June. The sub-tropical ridge line in the upper troposphere which generally lies along 15°N in Spring (Koteswaram and Parthasarathy 1953) shifted to 20°N by the 5th of June. Two waves were noticed in the easterlies to the south of this ridge, one along 100°E and the other at 80°E. The westerlies over North India had a trough roughly along 80°E and the core of the westerly jet stream lay near its normal position near 27°N, skirting the southern rim of the Himalayas and extending into higher latitudes over China. A westerly flow (the SW Monsoon) had set-in in the lower levels over the South Bay of Bengal. The two troughs over India apparently got interlocked and remained almost stationary for a number of days. A well-marked ridge formed over the west coast of India and another over the Bay of Bengal. The divergent southward meridional flow apparently induced a "low" in the lower levels off the southwest coast of India during the second week of June. As is well known in India, such low level "lows" over the southwest Arabian Sea are the precursors of the southwest monsoon along the west coast of India. They gradually move northwards or northwestwards and carry the monsoon westerlies to higher latitudes. A similar extension of the monsoon in the wake of northward moving "lows" occurs in the Bay of Bengal. In some years these "lows" intensify into tropical depressions or even tropical cyclonic storms which precede the monsoon burst over the country. The monsoon burst occurred on the west coast south of 15°N on June 14 with heavy falls of 10 to 16 cm in 24 hours at some stations.

Figs. 1a and 1b give the contour and isotherm patterns at 700 mb and 1c and 1d the corresponding patterns at 200 mb at 0000 hr GMT on 16 June 1958. The east-west "monsoon trough" is well marked at the 700 mb level, extending from about 10°N in the Arabian Sea to
Fig. 1 (c) Contour pattern at 200 mb at 0001 GMT on 16 June 1958
Fig. 1 (d) Isotherm pattern at 200 mb at 0001 GMT on 16 June 1958
20°N in the Bay of Bengal. At lower levels a trough line is not generally noticeable, as the wind flow is westerly in the dry current also due to the influence of the heat low over Northern India. It is therefore preferable to locate the monsoon trough at 700 mb. The important features at this level are the "lows" over the sea areas and the "highs" over land. An extensive westerly current exists to the south of the monsoon trough. The warmest air at this level lies over North and Central India and over South Arabia. The Tibetan Plateau does not seem to have affected the temperature distribution over North India as the winds continue westerly and increase with height, indicating a northward decrease of temperature over the Indian plains.

Figs. 1 (c and d) show the existence of SW to W winds over most of North India though the jet stream core had shifted over the Tibetan Plateau. The monsoon had already advanced to about 15°N and widespread rainfall occurred along the west coast of India to the south of 15°N with heavy falls amounting to 9 to 13 cm during the 24 hours following the map time. The core of the sub-tropical westerly jet lay to the north of the Tibetan Plateau near 35°N. A station just to the north of Lhasa in Tibet, however, reported 60 kt winds at 200 mb on the 17th. The warmest temperature in the upper troposphere lay over India and Burma.

The west coast rainfall occurred ahead of the easterly upper trough over South India at 200 mb where marked upper divergence is indicated. An easterly jet probably exists at higher levels, as can be judged from the 60 kt easterly wind reported at 100 mb at Pt. Blair.

The "burst" of the monsoon on the west coast of India occurred after the core of the westerly jet stream shifted to the north of the Indian plains and probably beyond the Tibetan Plateau. The "switch over" of the monsoon circulation, however, appears to have been accomplished by the heating effect of the Indian land area itself as the upper anticyclone had not shifted to Tibet by then.

(b) Active Monsoon

Figs. 2 (a and b) illustrate the low level conditions on 9 July 1958 when the monsoon had extended almost over the entire Indian sub-continent. A weak depression lay at the head of the Bay of Bengal and rain fell extensively over the whole country outside Madras State. The west coast north of 15°N and Gujarat had some very heavy falls of rain (15 to 24 cm in 24 hours) during the next two days. The warmest air extended from Iran to Burma along the north Indian plains.

Fig. 2c indicates the upper ridge lying almost over the monsoon trough. Two waves in the upper easterlies and one in the westerlies are seen, the latter having extended into North India from higher latitudes. The strong anticyclone extending from the Caspian Sea to NE Arabian Sea is conspicuous. This ridge lies over the lower "heat low" in this region. The marked upper divergence to the east of this ridge line over Gujarat probably triggered the very heavy rain in this area during the next 48 hours. The warmest air at 200 mb was in the upper anticyclones over Iran and West Pakistan, North and Central India, and Burma (Fig. 2d).

The situation on this day was complex; it however illustrates how even at the height of activity of the monsoon, the upper anticyclone did not shift over Tibet as postulated by some authors (e.g. Ramaswamy, 1958) but lay over the plains of India and Iran. On a number of occasions in July 1958, the upper ridge lay almost over the low level trough as in the present occasion.

(c) Monsoon 'break'

The weakening of the monsoon over Peninsular India and its simultaneous activation over the sub-Himalayan region occurs periodically during the monsoon season, particularly in August and September. The usual signs are the shift of the monsoon trough to the foot of the Himalayas and the disappearance of the easterlies over North India in the lower troposphere. Such situations have been called "breaks" in the monsoon and it is believed that the monsoon is "broken" off from its source in the southern hemisphere during such periods. Many Indian meteorologists consider that the monsoon easterlies over North India are replaced by circumpolar extratropical westerlies during such "break" conditions. Ramaswamy (1958) who studied two situations of active and weak monsoon in 1953 and 1954 was of the opinion that a trough in
Fig. 2 (d) Isotherm pattern at 200 mb at 0001 GMT on 9 July 1958
the westerlies extends from middle latitudes to North India during the weak monsoon conditions. He considered that the upper level easterlies were replaced by westerlies up to 200 or 150 mb level over north India and up to 350 mb over northwest India during such "breaks". Koteswaram (1958) on the other hand pointed out that the easterlies continue over India in the upper levels even during these "breaks" and that the easterly jet shifts northwards indicating an increase instead of decrease in the upper easterly circulation.

Fig. 3 (a to d) illustrates the lower and upper tropospheric conditions during a "break" period on 11 August 1958. The "monsoon trough" shifted to the extreme north of the country and the Tibetan Plateau was surrounded by an anticlockwise (cyclonic) circulation at 700 mb. The warmest area extended from Iran to Tibet. At low latitudes a weak "low" had formed over the Bay of Bengal and westerlies appeared to its south indicating a revival of the monsoon there. The existence of such "lows" in low latitudes during 'breaks' in the monsoon and their role in the revival of the monsoon was explained by Koteswaram (1950).

In the upper troposphere (200 mb) the pattern was typical. An anticyclonic cell was located over Tibet and the easterlies to the south extended up to latitude 30°N. The ridge line had shifted northwards over to Tibet. The circumpolar westerlies blew to the north of the ridge line and the westerly jet stream shifted to 42°N. Temperatures of -40°C and above occurred in the ridge and decreased towards the south and the north. The maximum northward extension of cold air from the south occurred during this period. The rainfall on this occasion was mainly concentrated along the sub-Himalayan region, though some rain appeared along the west coast under the influence of an upper trough in the easterlies (Fig. 3d). Heavy rainfalls of 5 to 10 cm in 24 hours were reported from the sub-Himalayan regions.

It will be seen from Fig. 3a that the westerlies over most of North India were the extension of the monsoon current from the south. To the north of Tibet there were easterlies instead of westerlies and the circumpolar westerly belt was shifted further north. The corresponding pattern in the upper troposphere is noticed in Fig. 3c. The monsoon westerlies were overlain by high level easterlies and the upper anticyclone was located above the trough surrounding Tibet. The highest temperatures also occurred over Tibet during the period. The "break" seems to be a stage of maximum extension of the monsoon circulation with its core shifted furthest north over Tibet instead of one of disruption of the monsoon caused by the incursion of circumpolar polar westerlies.

The heating effect of the Tibetan Plateau is felt best on this occasion. By August the monsoon trough and its associated upper ridge are displaced to their maximum northward location. The Tibetan highlands are heated to the maximum and the monsoon trough is displaced towards this heat low over Tibet. Its cyclonic circulation consequently builds upwards to 500 mb and even higher, and the monsoon westerlies to the south of the trough extend up to the rim of the plateau. The extension of westerlies to the Himalayas made a number of writers believe that dry circumpolar westerlies replace the monsoon current causing a monsoon 'break'. This belief, however, doesn't agree with the fact that the highest rainfall in India occurs over and near the Himalayas during this period in the zone of these westerlies. If they are extratropical westerlies, rainfall should decrease and not increase. Temperature should fall and not rise as shown in Fig. 3.

The above mentioned views regarding the continental origin of the westerly current over North India during the 'break' period apparently arose from the fact that rainfall diminished sharply over the peninsula during such 'breaks'. As earlier workers considered the monsoon as a moist current from the Southern Hemisphere, they felt it unlikely that the current could produce copious rain near the Himalayas without causing any over the peninsula, particularly to the windward of the Western Ghats, a perpetually rainy area. They thought therefore that the 'break' in the peninsular rains was caused by the cutting off of the monsoon current from the Southern Hemisphere and the consequent extension of extratropical westerlies over India.

If, however, the monsoon is considered as a circulation centered round the monsoon trough over North India, the events during the 'break' are a logical consequence. It is a period when the monsoon trough is at its northern-most location and the associated heavy rain
Fig. 3 (c) Contour pattern at 200 mb at 0001 GMT on 11 August 1958
Fig. 3 (d) Isotherm pattern at 200 mb at 0001 GMT on 11 August 1958
Fig. 4 Circulation of the "Monsoon cell"
also shifts to the north. The easterly jet stream at the periphery of the upper anticyclone is also displaced northward (Koteswaram, 1958). Air subsides to the south of the core of the jet stream causing the diminution of rain over the peninsula.

(d) Monsoon Withdrawal

In September, with the southward migration of the thermal equator, the monsoon trough also shifts progressively southward and the circumpolar westerlies extend into North India by the end of the month. The area of maximum heating also shifts southward and with it the sub-tropical ridge. The westerly jet stream sets in during late September or early October over northwest India and later further east. The process of withdrawal is the reverse of the onset. Easterlies persist in the upper troposphere though their strength diminishes with the southward shift of the sub-tropical ridge line. Mean upper air conditions in October-November have been described by Koteswaram and Parthasarathy (1953).

3. THE MONSOON MECHANISM

From the illustrative maps cited in the previous section, it would appear that the summer monsoon circulation over India as well as SE Asia is primarily based on the differential heating between the land and sea areas in the Northern Hemisphere itself. The close relationship between the warm areas in the lower and upper troposphere at different stages of the monsoon development, its onset, activation and "break", lead us to centre the monsoon mechanism on the heating in the monsoon trough instead of flow of cold winds from the Southern Hemisphere. A Hadley type of circulation with its heat source in the monsoon trough and sink over the cooler equatorial sea areas to the south, as suggested by Koteswaram (1960) (Fig. 4), seems to account qualitatively for circulation in this "monsoon cell". If such is the case, the circulation should be amenable to numerical computation as in the case of any other type of circulation caused by differential heating like the sea breeze worked out by Estoque (1960).

(a) Role of the Tibetan Plateau

The question arises regarding the role of the Tibetan Plateau and its heating which has been given primary importance in recent years. The effect of Tibetan heating in producing the "break" of the monsoon over India has been pointed out. It is difficult to evaluate its influence on other occasions from qualitative considerations. At least during the onset of the monsoon, it seems to be somewhat removed from the scene of activity (viz. SW India) in order to directly supply the heat source for the circulation. May is a period when the westerly jet stream still lies over North India and hence a south to north decrease of temperature occurs over North India and Tibet. The Tibetan Plateau is therefore probably still not sufficiently warm during the onset of the monsoon. It was seen that during the whole of June and July 1958, the upper level ridge line remained mainly over North India and it was not till August that it shifted over Tibet. Probably the heating of the north Indian plains as well as the heat released by convective hot towers in the monsoon trough (Riehl and Malkus 1958) are predominant in the upper level anticyclogenesis over India compared to the heating effect of the Tibetan highlands till July. By August, however, the plateau gets heated to the maximum and exerts its influence in attracting the monsoon trough as well as the upper ridge towards it. The circulation during this month seems to be definitely affected by the heating of the plateau.

(b) Differential Heating

The effect of differential heating of land and sea over India is apparent in the thermal pattern of Figs. 1 to 3. The warmest air is over land and drifts westwards in the upper easterlies. Warm ridges extend seawards off the west coasts of India and Burma and a cold trough lies along the east coast of India. These ridges persist at these locations in the upper levels almost throughout July and their divergence probably contributes to the heavy rainfall along the coasts (apart from orography). Warm thermal advection takes part in the formation of monsoon depressions as shown in another paper at this symposium. A similar effect is also seen during the formation of low pressure areas which usher in the monsoon.
(c) The Monsoon Surges

The pulsatory nature of the monsoon current, i.e., the periodical increase and decrease of its activity over different parts of India, particularly along the west coast of the peninsula, was one of the factors which apparently supported the conjecture about its southern hemispheric origin. The southern sub-tropical anticyclones were supposed to build up, shift nearer the equator and disgorge their load of accumulated air across the equator, which appeared as a monsoon "pulse". Further north it was however seen that this "pulse" or strengthening of the monsoon often appeared along the northern parts of the west coast of the peninsula without affecting the southern half. This was explained away as due to the fact that the "pulse" travelled over the Arabian Sea away from the Malabar Coast and therefore struck the Bombay coast without affecting other areas. It was also seen that the monsoon generally strengthened along the Bombay coast whenever a depression formed in the head Bay. The influence of the perturbations in the upper easterlies on the strengthening of the lower monsoon current was recently explained by Koteswaram and George (1958) and Srinivasan (1959). In a current with standing or slowly moving waves, an upper trough upstream apparently strengthens during the formation of a depression in the head Bay. The formation of waves in the upper easterly current also depends upon the strength of the current, the waves being less frequent and of larger wave length when the upper current is strong, as during the "break" periods. With the diminution of speed, there is a tendency for wave formation and the monsoon trough is brought back to the head Bay of Bengal and over North India.

We have also seen how the strengthening of an upper ridge over Iran (Fig. 2c) led to the activation of the monsoon along the west coast of India. Strengthening of the upper anticyclones over other parts of North India, the consequent southerly flow and associated upper divergence also activated the low level monsoon over North India.

It is also well known that the southward extension of extratropical westerly troughs over northwest India causes strengthening of monsoon activity there. One such case is explained in another article by the authors in this symposium. Some very heavy rainfalls over North India during the monsoon season occur due to this cause.

It therefore appears that surges in the activity of the monsoon occur due to the perturbations in the upper easterlies and/or westerlies or by the activity of the upper anticyclonic cells over the monsoon area.

4. CONCLUSION

An examination of typical situations mentioned in the previous sections has shown how the Southwest Monsoon first appears as a circulation centred over the heated continental areas of India and further east during the summer. A good part of the circulation seems to originate from the heating of the plains of India and southeast Asia, the effect of the elevated Tibetan Plateau being felt during the later stages of the development of the monsoon circulation. The monsoon bursts along the southwest coast of India as a result of circulation set up by the intense heating over southeast Asia and India, and advances inland following the contraction of the heat "low" to the north. It attains its maximum northward location when the heat low shifts over Tibet and causes the 'break' in the monsoon rains over the peninsula and central India. Its withdrawal follows the southward extension of circumpolar westerlies over North India. The surges and weakening of the monsoon over India are caused by perturbations in the upper flow. The meridional circulation appears to be a Hadley cell in the reverse, with the heat source over the monsoon trough and sink in the equatorial sea areas as postulated by Koteswaram (1960). This explanation seemed more logical than the classical concept where the 'source' of the circulation is located in the colder hemisphere and the 'sink' in the warmer hemisphere— a thermodynamic paradox.

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