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Remarks on three papers of Prof. H. Flohn read in the symposium on "Monsoons of the World" at New Delhi-19 to 21 February 1958

B. N. DESAI

173, Swami Vivekananda Road, Vile Parle (West), Bombay

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1. *The effect of the Tibetan Plateau to the mid-tropospheric flow, July-August ("Monsoons of the World," India met. Dep., 1960, p. 82, Fig. 7) and The migration of the tropical easterlies towards northern India — known under the misleading name "Bay of Bengal Branch of the Monsoon" — 4(b) on p. 85 of the above publication*

The topographical features of India have a very important bearing during the southwest monsoon season on the circulation in the lower levels (Fig. 1). They govern the intensity and distribution of rain over the sub-continent; the coastal Burma mountains, the Assam hills and the Himalayas deflect the westerly to southwesterly monsoon current and the monsoon thus extends to the Punjab, the deflected current being confined to the north of the axis of the seasonal trough of low pressure over the Gangetic plain (Simpson 1921).

Desai (1951) has discussed that as a result of the Burma and Assam mountains, air from the Pacific Ocean side is not able to enter India across China upto about 600-mb level. The southeasterly to easterly air over the Indian subcontinent in the first 4 km is, therefore, the westerly to southwesterly air which has been deflected by the mountains on the Burma coast and of Assam and the Himalayas and with which the subsided air from the hills has also mixed, as can be seen from the data of upper winds during the southwest monsoon season. The tropical easterlies are present over the Indian subcontinent only above 4 km or so.

Petterssen (1953) has stated that the steady state of the monsoon is realised as a result of the creation of vorticity by thermal processes and its balancing by frictional dissipation and export, particularly downwind to the Bay of Bengal; the resulting large-scale cyclonic system will create and maintain an area of low pressure in the lower levels over India. The topographical features of the subcontinent contribute significantly in making the Indian southwest monsoon a self-sustaining system.

The axis of the trough over the Gangetic plain slopes equatorwards with elevation (Fig. 1); at 6 km it is south of Bombay. At the western end of the Gangetic trough there is a wedge of drier continental air. The partition between the middle latitude westerlies and the tropical easterlies at 9·0 and 12·0 km runs along about Lat. 30°N across Tibet during the normal as well as active and weak monsoon conditions (Circulation over India and neighbourhood during the southwest monsoon season by B. N. Desai — under publication).

Moisture is generally more and temperature higher in the easterly to southeasterly air to the north of the trough axis than in the southwesterly to westerly air to its south; the equatorward slope of the trough axis is presumably due to this effect. The fresh monsoon air which has entered the Bay directly and not travelled over land is colder and has less moisture than the westerly air which has travelled over the Peninsula (Desai 1951, Desai and Koteswaram 1951 and Rao 1960). If the topographical influence on the southwesterly to westerly monsoon current in the lower levels, *i.e.*, upto about 4 km was not there, we would have drier air in the northern portion of the low as over north Africa. For the same reason we cannot also perhaps say that ITCZ or ITF in the usual sense of the term, *i.e.*, meeting place of the trades of the two hemispheres, is present over India during July and August the months of usual maximum activity of the monsoon.

Regarding Flohn's remarks on p. 70 of his first paper about Secondary Intertropical Convergence Zone (SITCZ) near the equator during the monsoon increasing rain and cloud frequency, it may be stated that the IIOE observations have confirmed the presence of a trough just to the south of the equator; it extends between Long. 58° and 110°E and the associated westerlies extend upto about 500 mb (Desai 1965 a, 1965 b). Convergence due to this trough is responsible for absence of inversion over Gan near equator at Long. 73°E (Desai 1965 a).

It is the influence of topography of the Ind i subcontinent which makes the southwest mons

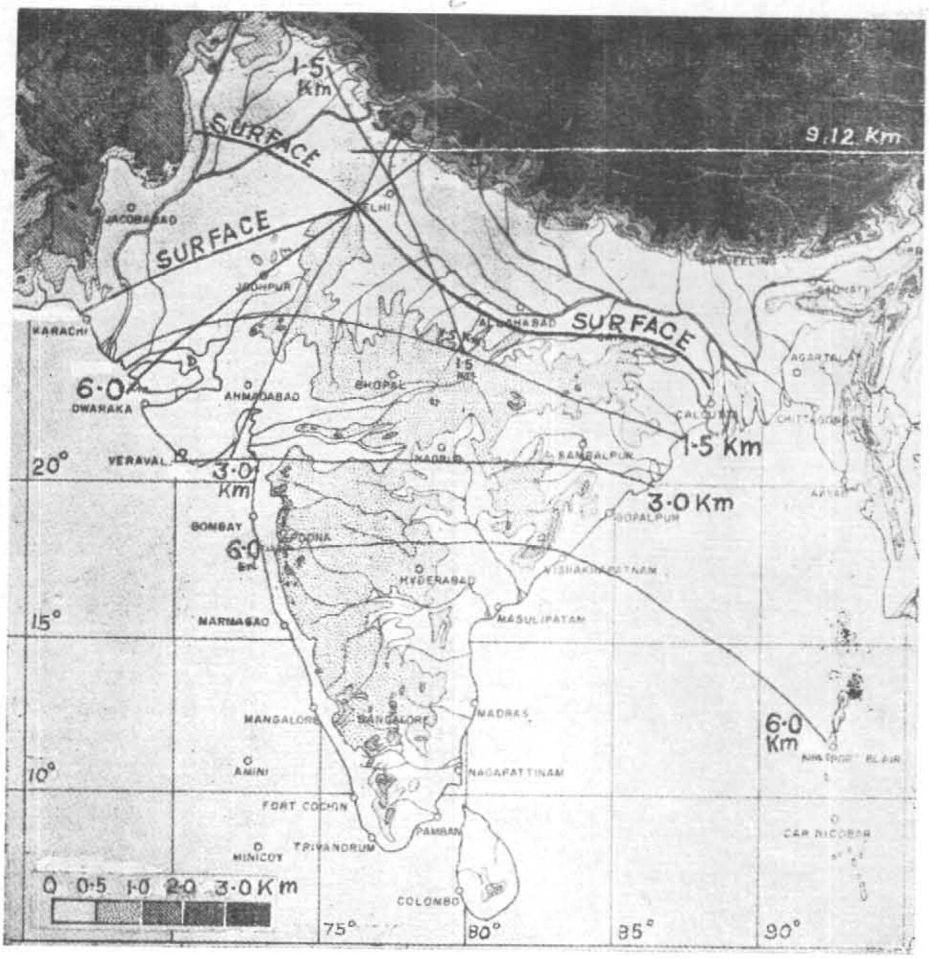

Fig. 1. Approximate positions of partitions between different air masses of different levels

quite unique here from what it is in other parts of the world like West Africa.

Desai (1953) has discussed in a general way the influence of orographical features of India over its weather and climate during different seasons. If India was a flat country without the existing hills and mountains, the history of the Indian civilisation and culture would have been quite different. The hills and mountains make India during the southwest monsoon season something like a box as suggested by Simpson (1921) and the southwesterly to westerly monsoon air has no escape but to rise and give precipitation in the process; the influence of the Western Ghats changes the depth of the moist current from 1·5 km over the Arabian Sea to 5 km over the subcontinent (Desai 1965 a), again a feature peculiar to India alone and to no other monsoon region of the world.

The northwest India box — mountains on two sides — has an important bearing also on the winter precipitation which helps the winter crops over and near there. The hill ranges (Satpura and Vindhya) across the central parts of the country and the Aravali hills running southwest to northeast across Rajasthan are to some extent responsible for the position of the trough axis over the Gangetic plain at and near the surface during the southwest monsoon season (Fig. 1); they also influence formation of secondaries during the winter season (Desai 1948). The movement of the post and pre-monsoon cyclones and of monsoon depressions is also influenced by the topographical features.

The author is in agreement generally with Flohn's approach regarding influence of Tibetan Plateau on circulation at 500 mb and above on the basis of facts of observations and theoretical considerations, making the altitude of 0°C isotherm highest in the world. The lower levels are, however, influenced significantly by the topographical features of the Indian subcontinent as shown above.

In view of what has been stated above, it does not appear correct to say that the name "Bay of Bengal Branch of the Monsoon" is misleading.

TABLE 1(a)

Pressure (mb)	Temperature (°C)							
	1*	2	3	4	5	6	7	8
1000	23·6	22·0	24·5	26·3	27·0	28·3	28·0	27·5
950	21·5	19·5	21·0	23·4	24·0	—	—	—
900	17·5	15·5	22·5	22·0	22·5	22·0	—	—
850	13·3	14·3	21·0	25·0	20·0	18·6	19·0	18·2
800	13·5	12·6	20·0	24·5	18·0	16·3	—	—
750	13·6	11·5	20·5	21·0	14·0	—	—	—
700	8·5	8·5	13·3	15·7	12·0	11·0	12·0	11·0
600	1·0	—1·0	2·0	5·5	6·0	4·8	—	5·2
550	—1·5	—3·5	—3·0	1·4	2·0	—	—	—
500	—3·0	—	—5·5	—	—1·0	—3·0	—2·0	—1·2

TABLE 1(b)

Pressure (mb)	Specific humidity (gm/kg)							
	1*	2	3	4	5	6	7	8
1000	16·5	16·3	19·2	21·2	22·0	19·0	21·4	19·7
950	14·0	15·0	17·0	17·7	19·0	—	—	—
900	10·5	13·8	10·5	12·0	17·5	15·0	—	—
850	7·5	10·5	8·8	6·7	16·5	13·5	14·5	14·4
800	5·0	6·8	7·0	6·5	12·5	11·8	—	—
750	4·2	3·8	6·5	5·7	10·5	—	—	—
700	3·0	2·0	4·8	3·5	9·0	8·5	9·5	8·3
600	2·0	1·0	3·3	2·0	7·8	7·0	—	6·8
550	—	—	—	—	7·0	—	—	—
500	—	—	—	—	6·0	5·4	5·0	5·0

*	Position	Date	Time	
1	0·4°N, 45·3°E	1-7-63	0747 GMT	Taken from curves of 1963 paper by Colon
2	4·7°N, 48·7°E	1-7-63	0915 GMT	
3	13·7°N, 56·9°E	2-7-63	0925 GMT	
4	18·6°N, 63·5°E	2-7-63	1131 GMT	
5	Bombay (near Western Ghats)	2-7-63	1100 GMT	
6	Do.	available data for July 1964 (supplied by Dr. P. R. Pisharoty)		
7	Do.	available data for July 1956-60 (supplied by Dr. R. Ananthakrishnan)		
8	Do.	available data for July upto 1955 (from 1960 paper by Rao)		

Note — Data for Bombay for different periods in Cols. 5 to 8 for the same level are comparable and they show high moisture content at all levels above about 900-mb level with reference to data over the Arabian Sea

(2) *Water vapour transport — 5 on pp. 86 and 87, 'Monsoons of the World'*

Recent IIOE observations (Colon 1963 Tables 1a and 1b) have shown that the deflected southeast trades over the Arabian Sea west of about Long. 68°E are only about 5000 feet deep, and above there is drier unstable westerly air with an inversion between the two air masses; this peculiar air mass stratification is very favourable for condensation and rain if the inversion can be destroyed. This mechanism is provided by the Western Ghats on the west coast of India as a result of which we get over the Peninsula a more or less homogeneous air mass (Desai 1965a) about 5 km deep. The moist layer about 1.5 km deep above the sea surface (deflected southeast trades), acts as a reservoir from which moisture is transported upwards due to the forced ascent of moist air against the barrier of the Western Ghats, leading to cloud formation and precipitation — *Cu* and *Cb* activity and mixing with the upper drier current. Thus we find difference in moisture and temperature level for level over the Arabian Sea to the west of Long. 68°E (where there is also no convective cloud and rain) and to its east towards the west coast and over the Peninsula; there are *Cu* and *Cb* clouds above a layer of nimbostratus and rain and sharp variations in moisture content upto about 5-km level within about 300 miles of the coast. As stated earlier the easterly to southeasterly air upto about 4 km is the westerly to southwesterly air from the Peninsula which has been deflected due to topographical features; moisture from the east will probably be there over the subcontinent north of about 19°N only above 4 km or so.

(3) *Three special questions formulated for future investigations — 6 on pp. 87 and 88 of 'Monsoons of the World'*

(*a*) Retreat of the monsoon can, it is felt, to some extent be treated as a reflected image of the advance although it is more gradual and slower than the advance. We are, however, not still quite sure about what actually causes the "weakening or break" of the monsoon even during July for short periods and in August and September for long periods. The facts associated with such "breaks" are — (*i*) disappearance of the trough at the surface, (*ii*) extension of the influence of the troughs in the westerlies to more southerly latitudes than during active monsoon periods (Pisharoty and Desai 1956), (*iii*) absence of deflected trades over the subcontinent — these being replaced over the Arabian Sea by drier air from Arabia side as in May (Simpson 1921), (*iv*) easterly winds over the Bay of Bengal roughly south of Lat. 20°N and upto Lat. 8°N or so even in the lower levels and (*v*) positive pressure departures from the normal over the area extending from west India to south Bengal and neighbourhood.

(*b*) Low intensity of monsoon rains over Rajasthan and West Pakistan is due to the inversion above the lower moist air being not destroyed and whatever clouds form due to insolation dissolve as soon as they reach the upper warmer and drier westerly to northwesterly air (Simpson 1921, Desai 1965 a, 1965 b, 1966). Rainfall occurs over these areas in association with depressions from the north Bay of Bengal moving west to northwestwards (Desai, 'A critical examination of the papers of (1) Sadler and (2) Miller and Keshavamurthy etc' — under publication). Rainfall over other parts is due to topography, seasonal trough of low pressure and depressions, the last factor contributing a good amount of precipitation in the interior of the country.

(*c*) During April and May under the influence of the heat low over and near the central parts of the country, there is already influx of moist southwesterly to southerly winds into Burma, Assam and Bengal. The southern hemispheric air which has been flowing near the equatorial latitudes as a result of the equatorial trough, gets into the circulation over the Bay causing early occurrence of monsoon there. At this time over the Arabian Sea, there is still air of land origin — westerly to northwesterly winds — extending up the southern tip of the Peninsula. As the monsoon air extends northwards into the Bay due to deflection of the same by the Burma coast and Assam mountains and the Himalayas, the trough of low pressure over the Gangetic plain gradually develops and the winds over the Arabian Sea back to west to southwest and the deflected trades get into circulation over the area and are drawn towards the west coast of India at the beginning of June. With this, the trough over the Gangetic plain becomes better oriented and defined and the monsoon current extends over other parts of the country.

(4) *Depth of deflected trades and cloudiness and precipitation — pp. 79-80 and 100 of 'Monsoons of the World'*

As stated earlier, the depth of the deflected trades over the Arabian Sea is only about 5000 feet and we get more or less homogeneous moist air mass 5 km deep over the Peninsula due to the effect of the Western Ghats. It may be quite interesting to compute convergence between Lats. 5° and 20°N along Longs. 90°, 80°, 75°, 70°, 65° and 60°E; these may throw considerable light on precipitation patterns over the Bay of Bengal and the Arabian Sea as well as over the Peninsula.

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Comments

by

H. FLOHN

(*University of Bonn*)

The influence of the topographical features — especially of the mountains enclosing the Indo-Pakistan subcontinent from Baluchistan to Burma —on the development of the summer monsoon circulation can by no means be underestimated. The rapid increase of aerological data (upto at least the tropical tropopause (near 100 mb) since 1956 enables meteorologists now to check former hypotheses on the base of empirical data as well as of basic physical principles. However, we should never forget, that all types of aerological instruments are subject not only to random errors but also to systematic (instrumental) errors. In the whole area of the subcontinent including its surroundings — which we have to consider if we wish to obtain a complete understanding of the large-scale processes interacting between tropical and extratropical circulations — there are at least seven different types of radiosondes in use — India (Chronometer and Fan), Pakistan, U.K., U.S.A., U.S.S.R. and China. In 1956, the WMO (CIMO)—organised radiosonde comparisons at Payerne (Switzerland) have revealed some of the differences (excluding the Chinese Peoples Republic); since then instrumental improvements and procedure revisions have altered substantially the relative differences. Remarkable differences are still existing especially when regarding temperatures above 300 mb and humidities, which are especially important in an area (and season) with relatively weak baroclinicity and high absolute moisture content.

With much interest I noted the occurrence of a second trough south of the equator — as indicated already by Meinardus (1886) and defined by myself as southern branch of the ITCZ. My objection against the term "Bengal Branch" of the Monsoon is only derived from a more or less planetary view of the large-scale features of the wind field: the predominant ESE-winds along the slopes of the Himalayas are the lower extensions of the planetary easterlies between the ITCZ or monsoon convergence in the south and the subtropical divergence zone in the north. There is no doubt, that trajectories of air could be frequently followed from the Bay of Bengal through the monsoon convergence situated above Bengal, Assam and East Pakistan near 25°N to the warm and moist easterlies along the Himalayas. The existence of such a more or less permanent low level convergence zone right across northeastern India is supported by the rainfall distribution, especially by the enormous amounts at the relatively low

Khasia Hills compared with the much smaller amounts along the southern fringes of the high Himalayas.

Unfortunately the different humidity sensors between USA dropsondes and Bombay radiosondes do not sufficiently warrant the interpretation of Colon's data as given by Desai. According to the Payerne comparisons (Beelitz 1958), the relative humidity values measured by the India Chronometersonde were 7-8 per cent higher than those of the US-sonde (and 7-15 per cent higher than the French sonde). Colon's measurements agree quite well with the quasi-permanent occurrence of a speed divergence of the SW monsoon above the Arabian Sea west of 65°E and south of 15°N (Flohn 1964 a, 1965 a). This divergence is converted into (orograhically enforced) speed convergence west of the peninsula: here the subsidence inversion near 750 mb is destroyed and water vapour spreads with increasing convection into the middle troposphere. While the average moisture content (precipitable water) above Bombay may be about 5-8 per cent too high compared with humid tropical stations like Yap (Equatorial Pacific) or Abidjan (West Africa), an increase of humidity along the surface trajectories of the SW monsoon (Table 1 b of Desai's paper) is correct in principle. "Breaks" of the monsoon seem to be frequently correlated with monsoon disturbances travelling into the advance part of an upper westerly trough penetrating into the subcontinent as far as 26°–28°N. If such a monsoon disturbance deviates northward and intensifies below the upper divergence area of the trough, the monsoon current above the interior is forced to diverge and consequently to suppress convective activity. Certainly a lot of synoptic research ought to be done on the retreat of the whole monsoon system, the decay or displacement of the tropical easterly jet and the re-establishment of the subtropical (westerly) jet south of the Himalayas.

The aridity of Rajasthan and the former Sind during the summer monsoon, in spite of the occurrence of moist monsoon air and southerly flow during that season, has been treated by Ruprecht (*see* Ref.). Based on a thorough computation of the low-level mass divergence he was able to compute the average vertical wind components at altitudes of 1·5 and 2·1 km, which are evidently strongly correlated with the average rainfall map. Widespread and effective rainfall is only possible when travelling monsoon disturbances – along unusual tracks–reach that area. Two examples of this kind have been experienced by the author during September 1961.

I strongly support Dr. Desai's suggestions on further research. Especially careful studies of the divergence of the low-level wind field can substantially contribute to a more complete understanding of the monsoon phenomenon. Features formerly described as conservative air mass properties (thermal stability, moisture content) are in most cases related to the kinematical properties of the wind field. Furthermore the large-scale dynamics and kinematics of the wind, temperature and moisture fields should be investigated during the transitional periods, taking into account the inhomogeneity of the aerological data. Perhaps I should suggest further studies on the cyclonic rainfall mechanism along the eastern coast of the peninsula during October–December: similar events are frequent at the Gulf of Thailand, but are apparently rare at the Arabian Sea (why?).

Apart of studies on the Tropical Easterly Jet (Flohn 1964 b), I have recently stressed (Flohn 1965 b, 1965c) that the establishment of a warm anticyclonic cell in the vicinity of 30°N, 88°E – which plays such a significant role at the onset of the Indian summer monsoon – is caused by the release of latent heat of condensation at this region as well as by the transfer of sensible heat into air from the elevated Tibetan highlands. The latter source of energy can be estimated to be not much higher than 300—350 calories per cm² (Langleys) per day, while the release of latent heat increases up to 1000 Ly/d and more. The early onset of summer rains above Assam, Bengal and East Pakistan (1-2 months before the seasonal shifting of tropospheric wind systems) contributes much to these events; it is produced by the establishment of a low-level southerly flow of moist air into the upper divergence area of the weak, but persistent (and orographically preformed) Bengal trough of the westerlies.

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Remarks on Comments of Prof. Flohn

by

B. N. DESAI

Para 1 — I quite realise that when different types of instruments are used in the same or different countries to measure temperature and humidity, one has to be very careful in using the data for verifying any theory or hypothesis in view of random and systematic (instrumental) errors which they are subject to. I have, however, not made any *quantitative* estimates, and it is considered that the temperature and moisture data up to about 500 mb (the errors increase considerably above that level) are sufficiently accurate to draw the inferences on the basis of facts of weather, climatology and topography.

Para 2 — The "Bay of Bengal branch of the monsoon" would not have become a distinct entity if the Indian subcontinent was flat without hills and mountains. The rainfall over the Khasi hills of Assam is considerable when the winds striking it, have a large southerly component; the larger the easterly component of the winds the lesser the amount of rainfall. In fact, when the trough of low pressure over the Gangetic plain is well-marked due to deflection of moist southwesterly monsoon air current, the precipitation over the Khasi hills is not appreciable.

Para 3 — Inspite of the different humidity sensors between the USA dropsondes and Bombay radiosondes, it is seen from the data in Table 1 for positions west of Long. 68°E (col. 4) and for Bombay (col. 5) that above 900 mb, the moisture at Bombay is considerably more than to its west and that even if the values given by the Bombay radiosonde were reduced by 20 per cent, the moisture difference will be adequate enough to interpret the IIOE data as done by me. In fact the dropsondes data between Long. 70°E and the west coast given in the paper of Miller and Keshavamurthy presented in the July 1965 symposium at Bombay, do show moisture more than 10, 7 and 5 g/kg at 800, 700 and 600 mb respectively as a result of the forced rise of the moist monsoon air in the lower levels.

Para 4 — It is our experience that the monsoon depressions take a northerly course when the influence of the eastward moving upper westerly trough extends to more southerly latitudes than usual; they also intensify below the upper divergence area of the trough (Pisharoty and Desai 1956). Heavy to very heavy rain occurs while the depression curves and moving north to northeastwards, breaks up in the hills; at times with the breaking up of the depression in the lower levels, a trough also moves eastwards in the upper levels.

It may be stated that the westerly jet is not a part of the monsoon circulation (Petterssen 1953) and it is to its north near about Lat. 40°N. Desai (Circulation over India and neighbourhood during the southwest monsoon season -under publication) has shown that the partition between middle latitudes westerlies and the tropical easterlies at 9·0 and 12·0 km runs roughly along Lat. 30°N both during active and break monsoon as in normal July monsoon conditions (Fig. 1).

It is also seen (Desai—'Circulation over India etc' — under publication) that during normal and active monsoon conditions the area of strongest easterlies at 14·0 km is near Lat. 10°N, while during break monsoon conditions, it shifts to Lat. 19°N (Bombay). The implications of this are not clear at present.

Para 5 — Desai (1966) has discussed in detail causes responsible for little precipitation over and around the West Pakistan heat low area. When rain occurs under the influence of the monsoon depressions moving towards the area, the upper drier air is replaced by the moist easterly air and convergence and ascent of the moist air takes place at and near the air mass partitions (Desai 1951, 'A critical examination of the papers of (1) Sadler, (2) Miller and Keshavamurthy etc — under publication).

Para 6 — A number of papers have been published in the department in the past giving rainfall distribution associated with the postmonsoon cyclones approaching the east coast. A further examination of the disturbances approaching both the east and the west coasts of the Peninsula is necessary to understand the exact mechanism of rainfall with a view to help forecasters in their day-to-day work.

Para 7 — A critical review of Prof. Flohn's paper (Flohn 1965 c) on "Comments on a synoptic climatology of southern Asia" with reference to conditions over the Indian subcontinent, is being made by me and will be published in due course. I may, however, mention here that it is not clear how the early onset of summer rains above Assam and Bengal (1 to 2 months before the seasonal shifting of tropospheric wind systems) and the latent heat released (during those rains), the bulk of it in the cloud layer between 850 and 500 mb according to his paper (Flohn 1965 b) will help *establishment* of a warm anticyclonic cell near Lat. 30°N, Long. 88°E as the heat will be advected away further from the Tibet region with the prevailing winds at those levels. It is felt that the flux of sensible heat into the atmosphere contributes more than the latent heat in establishing the warm anticyclone.

It will not be out of place to mention here regarding a possible new approach different from the hitherto accepted ideas of the Indian meteorologists about the implications of the monsoon low circulation over the Indian subcontinent. If the circulation is self-sustaining (Petterssen 1953), one would like to ask "does the break in the rains and more southerly tracks of the troughs in the middle latitudes westerlies precede or follow the disappearance of the Gangetic trough and if the latter, why the trough disappears?" These and other points arising from the suggested new approach will be dealt with in a separate paper.