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Role of mountains in the development of the Indian summer monsoon circulation and the associated weather

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ABSTRACT. Some special features of the Indian summer monsoon mentioned by Hahn and Manabe (1975) in their model simulated with mountains are discussed with reference to the model for surface layers given by Banerji (1930 a and b) while taking into account the effect of mountain ranges on the air flow and configuration of isobars on the basis of thermo-dynamical and hydrodynamical consideration and the experience of the author for fifty years about the facts of weather.

It is observed that the lower monsoon circulation and the upper tropospheric circulation developed independently. The barriers to the west of the east coast of Africa are responsible for the deflection of the south-east trades north to northeastward across the equator under the influence of the heat low (location influenced by barriers) over south Pakistan and the monsoon trough circulation in the levels upto about 600 mb which is set up due to the influence of the mountains on the Indian sub-continent.

The westerly jet is not a part of the monsoon circulation and its shift from the south to the north of Tibet need not necessarily coincide with the onset of the monsoon.

There would not appear any cause and effect relation between the development and strength of easterly jet and the onset and performance of the monsoon in terms of rainfall.

The low level jet is embedded in the monsoon current and is noticed even to the east of Madagascar and in the western Indian Ocean and the adjoining parts of eastern coastal areas of Africa (Findlater 1969 a and b) and would not appear to be developing due to upwelling of water off the Somalia coast which has led to its being named Somalia jet (Bunker 1965).

The seasonal rainfall can be understood on the basis of influence of mountains, although proximity of the tracks followed by the depressions while moving west to northwestwards from the north Bay of Bengal, increases the amount of rainfall. Small amounts of rainfall over the northwest of the sub-continent would appear to be due to absence of barriers over the coast extending from Karachi in Pakistan to Veraval in Gujarat (India) and the presence of low level inversion due to spreading of relatively warmer drier air between about 1 and 3 km from the Baluchistan plateau side over the lower cool moist monsoon air. There is no ITCZ over the monsoon trough area upto about 600 mb once the monsoon is established. 'Breaks' in monsoon rain would appear to be associated with the high pressure anomalies over the monsoon trough area and the adjoining area to the south which prevent the southern hemispheric air from being drawn to the west coast of India.

1. Introduction

In their paper, Hahn and Manabe (1975) have considered models with and without mountains to simulate the south Asian monsoon to understand the effect of mountains on the same and compare the actual conditions prevailing at the time with those indicated by the models. They have also stated in what respect their model with mountains does not explain fully some of the conditions noticed during the period. Rao (1976) has pointed out some of the shortcomings in their model. In the present paper it is proposed to mention some of the important conclusions arrived at by Banerji (1930 a and b) in his two important papers dealing with the influence of mountains on the air motion and the configuration of the isobars on the basis of thermodynamical and hydrodynamical considerations as well as to consider the results brought out by model of Hahn and Manabe (1975) with the mountains in the light of experience of the author of the monsoon weather extending over 50 years, to enable theoreticians to decide in what manner their models should be modified to simulate the Indian summer monsoon circulation, so that they can explain most, if not all, the facts of observations about the same.

2. Discussion

(*i*) *Influence of mountains on the airflow*

In Figs. 1 and 2 are given the topographical maps of the Indian area and eastern Africa and neighbourhood respectively and in Fig. 3 are shown the mountain barriers considered by Banerji in his two papers referred to above. On comparing Fig. 1 with Fig. 3, it will appear that Banerji has considered — (a) the Western Ghats, (b) the hills on the Tennassarian coast, (c) the mountains on the Arakan coast joining up with the Himalayas in

* This paper was prepared by Dr. Desai, about a month before his demise on 23 June 1978.

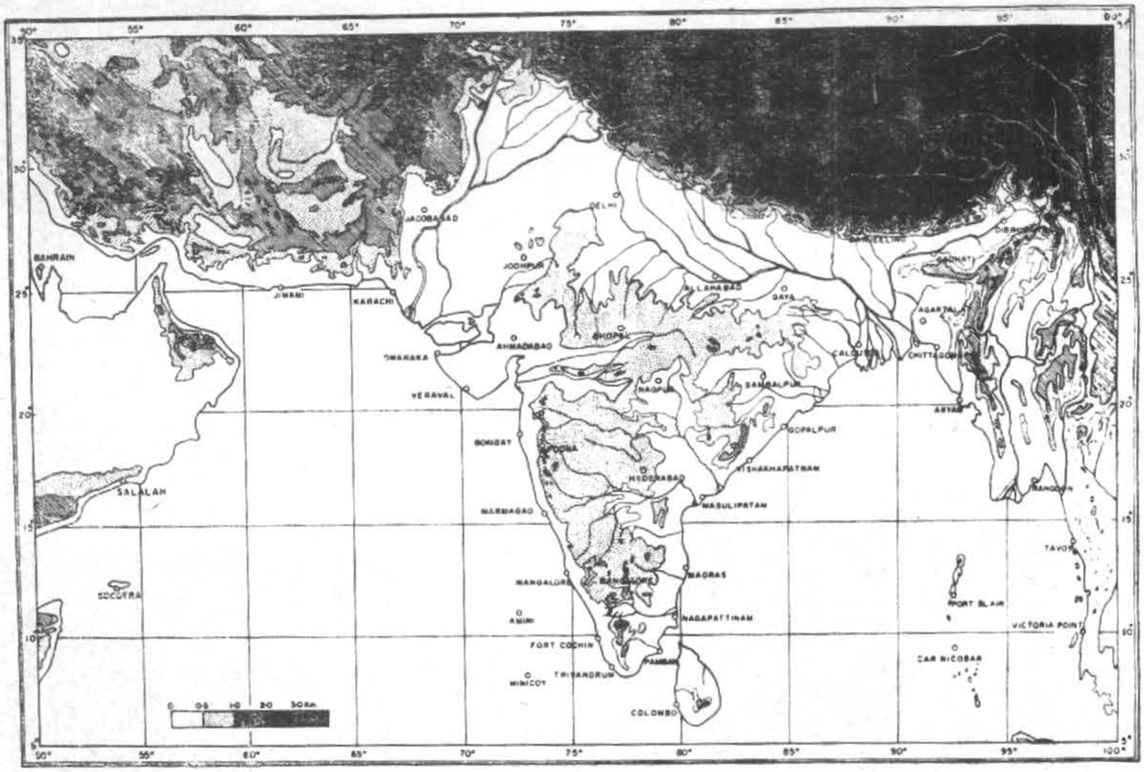

Fig. 1

the north, (d) the eastern Himalayas extending from Assam to the central Uttar Pradesh, (e) the Himalayas extending from there to the northwest frontier State of Pakistan and (f) the hills on the northwest frontier of the Indian sub-continent. It will be seen that in order to facilitate computations, various barriers have been smoothened out, and the angle between the barriers (c) and (d), and (e) and (f), has been taken as right angle. The barriers (a) and (b) being relatively low, have been taken as surmountable to the air flow, although the southern end of the barrier (a) has mountains ranging from 1.2 to 2.5km height.

According to Banerji, the low over the northwest of the sub-continent is located over Sind in south Pakistan and neighbourhood because of the presence of the barriers (e) and (f), and its depth is also more than the low over Sahara because of its mode of formation. If those barriers were not there, the low would not have been so far west and not so deep.

Again, according to Banerji, the trough over the Gangetic plains develops because of the presence of the barriers (c) and (d), the barriers deflecting the monsoon current, the wind backing from westsouthwest to east through south; this will also make the trough well marked. If the barriers (e) and (d) were absent, the trough over the Gangetic plains would not develop. The trough is connected at its northwestern end with the heat low over northwest of the sub-continent.

The southern hemisphere air extends northwards through the western Indian Ocean and neighbourhood across the equator (Fig. 1b of Rao and Desai 1973 a) under the combined influence of (*i*) topography of Africa (Fig. 2) and (*ii*) the heat trough extending from Somalia to Pakistan across Arabia and south Iran (Fig. 1a of Rao and Desai 1973 a). This is the southwesterly current over the Arabian Sea.

The southwesterly monsoon current, as it approaches the Western Ghats (barrier 'a'—Fig. 3), gets cyclonic curvature in the northern portion of the Ghats and anti-cyclonic curvature at the southern end; this gives bulging of the isobars over the Bay of Bengal, as stated by Banerji. If the cool southern hemisphere monsoon air was not drawn northward towards the west coast of India under the influence of the heat low, there would not have been the possibility of the development of the Gangetic valley trough of the monsoon circulation. Thus, over the Bay north of about 8°N, there will be the monsoon air which has gone from the Arabian Sea side across the Peninsula, once the monsoon has got established (Fig. 1b of Rao and Desai 1973 a).

The southeast trades as they move towards the African coast veer under the influence of the hills and mountains just to the west of the east coast of Africa (Fig. 2). The topography helps to accentuate the speed of the southerly flow. If the barriers to

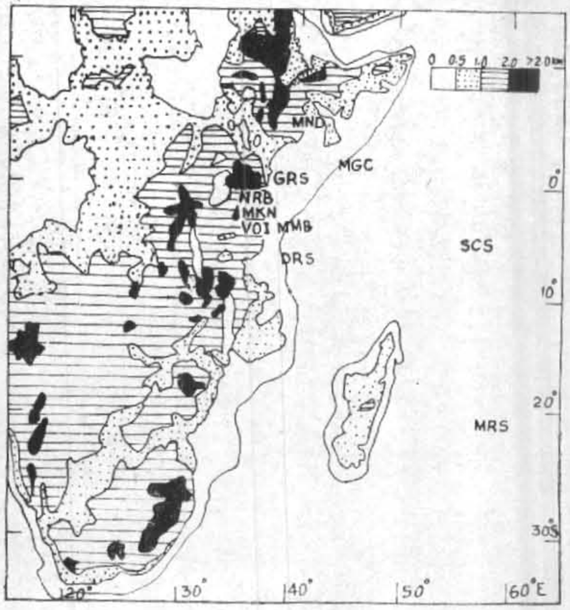

Fig. 2

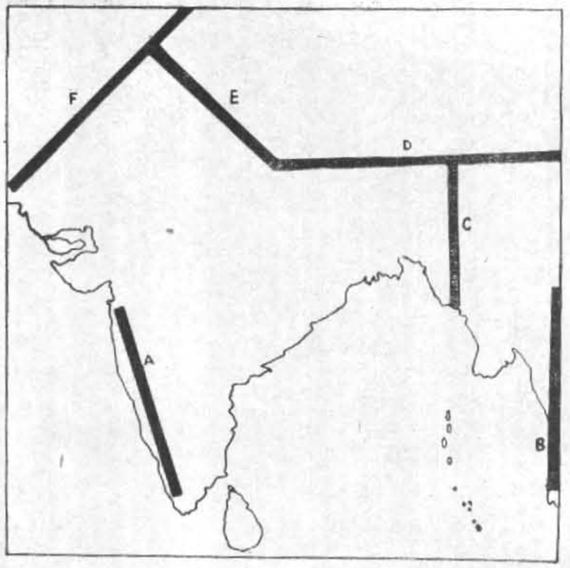

Fig. 3

the west of east coast of Africa were absent, the bulk of the southern hemisphere air crossing the equator in the western Indian Ocean and neighbourhood would not occur and the trades would have moved further westward towards the Atlantic across Africa south of equator.

It has been shown by Petterson (1953) that the topographical features of the sub-continent make the southwest monsoon a large scale self-sustaining cyclonic circulation in the lower levels of the atmosphere. The influence of the topographical features will extend atleast upto their height, if not to somewhat higher levels. From the normal July upper air charts at the standard levels (Figs. 3-5 of Rao and Desai 1973 a), it is clear that upto about 600 mb the easterly flow to the north of the trough axis over the Indian sub-continent is the deflected southwest monsoon current which will be slightly warmer than the southwesterly current and also having somewhat more moisture due to evaporation of the same from the wet surface. Thus, upto about 600 mb there is no northern hemisphere air over the trough area, the axis of the trough sloping southwards with height, extending from near Delhi to near Calcutta at the surface and being near latitude 18°N near Bombay at 500 mb level (Fig. 8 of Rao and Desai 1973 a).

(*ii*) Hahn and Manabe (1975) have stated that the mountain model simulates the Somalia jet and under-estimates the intensity of the monsoon trough. They have also stated that an ITCZ forms near 10°-15°N.

In connection with the Somalia jet, it may be stated that as seen from Findlater's paper (1969 a), the low level jet occurs both to the east of Madagascar and over the Mozambique channel area and it is also present sometimes over some stations over eastern Ethiopia. While it is recognised that the mountain barrier will accentuate the wind speed, it is probably not correct to say that the jet is produced only by the mountain barriers. It would appear that the jet is known as "Somalia Jet" because it has been considered by some that the same is produced (Bunker 1965) due to upwelling of water near and off the Somalia coast. The probable cases of the low level jet have been discussed by Desai (1972) and by Desai *et al.* (1976).

It will appear that considering the problem in the manner done by Banerji, does not lead to under-estimating the monsoon trough.

From the above description of the manner in which the monsoon trough forms, it will appear that over the area of the monsoon trough at the surface and upto about 600 mb, there is no ITCZ when the monsoon is active because on its two sides there is only the southern hemispheric air.

(*iii*) Ramage and Raman's (1972) upper air charts for 850 mb level have been referred to stating that the maximum of mean wind speed is found to coincide with the position of the ITCZ in the M-model, particularly over the Bay of Bengal.

It may be mentioned that no experienced Indian meteorologist can accept their streamlines for 850, 700 and 500 mb levels (Desai and Subramanian 1978). The monsoon trough, according to their charts, is shown to occur at 850 and 700 mb levels in the northern hemispheric air and this is not correct in view of the manner in which the monsoon trough forms as a result of the effect of the mountains (see *ii* above).

(*iv*) Hahn and Manabe (1975) have stated that according to the mountain model, the onset of the monsoon is preceded/or is simultaneous with an abrupt shift on the westerly jet from the area south of Tibet to its north; the onset of the monsoon is about 15 days later than the usual date.

It has been shown by Rao and Desai (1973 a) that although on some occasions the shift of the westerly jet from the south to the north of Tibet may be associated with the onset of the monsoon, there is no cause and effect relation between the two, as in numerous years the onset of the monsoon occurs even before the westerly jet has shifted to the north of Tibet.

The fact that the onset of the monsoon in the mountain model occurs about 15 days after the abrupt shift of the westerly jet would incline one to the view that there is no cause and effect relation between the two. As stated by Petterson (1953), the westerly jet is not a part of the monsoon circulation.

(*v*) *Changes from winter to summer type conditions*

It has been shown by Ananthakrishnan (1970) that the transition from the winter to the summer type conditions across the Peninsula occurs at the surface by middle of March and is transmitted upward and at 100 mb by the end of April and it is transmitted downwards, the two joining at about 500 mb level by the beginning of June when the monsoon sets in; over northern India the two converge at 500 mb level at the end of June. Thus, the circulation in the upper troposphere would not appear to give rise to the lower troposphere monsoon circulation, although there might be simultaneous development of both, there being no cause and effect relation between the two (Desai 1971).

(*vi*) *Changes preceding the onset of monsoon*

Rao and Desai (1973 a) have discussed the manner in which the normal pressure and wind changes occur from April to May, leading to the onset or burst of the monsoon. The southerly flow in the Bay of Bengal till the onset or burst of monsoon is due to the pressure pattern, the southerly air being from the northern hemisphere itself. It is only when the southern hemisphere air reaches the south or southeast Bay of Bengal that the onset or burst of monsoon occurs; at such time, there may be presence of ITCZ over the area. The onset of the monsoon is generally accompanied with the formation of depressions or cyclones at the northern boundary of the advancing southern hemisphere airmass. It is generally noticed that the depressions or cyclones do not form in the Bay during the monsoon season, unless the monsoon is active. Once the disturbances form, the monsoon current may get strengthened further.

(*vii*) It is stated by Hahn and Manabe (1975) that in the mountain model, a large anti-cyclonic circulation at 190 mb is located over Tibet, which acts as a source region for the easterly jet and that both the features were located 5°further south.

It may be stated that even if temperatures are relatively high over Tibet in the upper troposphere, there is anti-cyclonic circulation and there cannot be appreciable rise of air over Tibet.

As shown by Rao and Desai (1973 a), there is no connection between the development of the easterly jet and the onset of monsoon, although the two phenomena may occur simultaneously at times. Observations show that at times the upper easterlies may be weaker during active or strong monsoon period in terms of rainfall than during weak monsoon period.

(*viii*) It is stated by Hahn and Manable (1975) that three preferred latitudes of upward motion exist in the mountain model; over the winter time position of the ITCZ near the equator, along the ITCZ which develop in July near 15°N, and along the monsoon trough and south Asian low pressure system.

As stated earlier, there is no ITCZ near 15°N when the monsoon has got established and is active, and the preferred upward motion along that latitude does not tally with facts.

Along the monsoon trough, there will be certainly upward motion due to convergence near the axis of the trough. It is seen that even without a depression when the monsoon trough is active, widespread rain occurs within about two to three hundred miles of the position of the axis at the surface, there being rain along the entire length of the axis and to its south. Little or no rain occurs over the area of the heat low over south Pakistan and neighbourhood because in spite of there being cool moist monsoon air upto about 900 mb, present above is the warmer drier air from Baluchistan plateau side upto about 700 mb, and the clouds which grow due to insolation effect are not able to penetrate and break up the inversion. Above about 700 mb, there is again more moist air from east, the humidity becoming as much as 75 per cent near 500 mb (August 1963 mean sounding for Karachi given by Ramage 1966). In fact, it is considered that the desert over the northwest of Indian subcontinent is due to presence of the hot dry air from Baluchistan plateau side between about 900 and 700 mb (Desai 1967; Rao and Desai 1973 a).

(*ix*) *Orography and rainfall*

If one compares the June to September normal rainfall (Fig. 9, Rao and Desai 1973 a) over the subcontinent with hills and mountains shown in Fig. 1, it is clear that the mountains play an important part in producing precipitation, the lee side of the Western Ghats and the Arakan coast mountains having much less rain. Over the central India plateau, there is relatively more rainfall. Much of it is due to low pressure areas and depressions, which move west to northwest from the north Bay of Bengal during the monsoon season.

The normal rainfall during the monsoon season along Saurashtra, Kutch and Sind coasts, is smaller than over the west coast south of Surat. This is due to the fact that there is no mountain barrier in the former case, while there are Western Ghats in the latter case.

(*x*) *Effect of barriers on the formation of depressions*

It may be mentioned that the hills and mountains around the head of Bay of Bengal, *viz*., the Arakan coast mountains, the Khasi Jaintia hills of Assam, the Chota Nagpur plateau and the Eastern Ghats (Fig. 1) help setting up of cyclonic circulations and development of depressions in the north Bay when monsoon is active or is strengthening. This is in contrast to the northeast Arabian Sea where there are the Western Ghats alone on one side and only a small number of depressions usually form during the monsoon season (Rao and Desai 1973 a).

(*xi*) *Transport of moisture across equator*

From a study of the MONEX 1973 data over the equatorial area, it is seen that as one proceeds west of 50° E over the equator, the southerly component and the speed of the winds as well as humidity of the air increases (Desai *et al.* 1976). It is also seen that about two-third of the moisture which is found over the west coast of India, comes from the southern hemisphere across the equator, only one-third of the moisture being added over the Arabian Sea as the cold air from the southern hemisphere moves northeastward towards warmer latitudes under the influence of the hills and mountains along of the coast of Kenya and Somalia and the heat low over south Pakistan.

(*xii*) *Conditions during break in monsoon*

During the break monsoon period, the monsoon trough over the Gangetic plain is either weak or absent. It has been shown (by Desai 1970, Rao and Desai 1973 a, b and Desai 1975, Desai and Rao 1976) that during break period higher than usual pressure prevails over the area of the monsoon trough or even further south, there being relatively low pressure over the south Arabian Sea, over the Peninsula south of 15°N and over the south Bay. The higher than usual pressure decreases the pressure gradient between the south Indian Ocean where there is quasi-permanent anticyclone and northwest India (Fig. 1a, Rao and Desai 1973 a). This would mean decrease to some extent in the flow of southern hemisphere air across equator. Under such circumstances, even if there is sufficient flow of air across equator from the south, the same may not be able to progress north to northeastward over the Arabian Sea and to the west coast of India north of about 10°N; the rain that has crossed the equator will move directly from the south Arabian Sea to the south and east Bay and cause normal or above normal precipitation over northeast India, as it happened during the great famine year of 1899. The higher than usual pressures, in spite of higher temperatures upto about 850 mb, are considered to be due to presence of colder than usual air in the levels above about 700 mb.

(*xiii*) *Nature of monsoon circulation*

As stated by Rao and Desai (1973 a), the monsoon circulation is not a closed cell, in the sense of the Hadley cell. It is difficult to define limits of the monsoon circulation in a similar sense, necessarily both longitudinally and latitudinally. The extent of the Asiatic summer low is large. Hence monsoon circulation cannot be postulated as if air rising in one part sinks in another part to an equal extent. Reversal of flow in zonal and meridional directions from lower to upper troposphere has led some authors to justify for mass continuity. South of 25°N zonal winds are westerly in lower troposphere and easterly in upper troposphere. But the origin of most of the upper tropospheric flow is not likely to be that from the flow in the lower troposphere in the monsoon area, made possible through vertical motions. The inflow into the monsoon area and outflow may be linked through the general circulation in other areas. The role of the monsoon would be to distribute the excess heat gained in the continental areas to other regions of the northern hemisphere and also of the southern hemisphere. It has been shown by Rao and Desai (1973 a) that the various models suggested for monsoon circulation so far cannot be accepted.

3. Concluding remarks

The Indian sub-continent is something like a box with three closed sides and one open side through which the monsoon air flows into it. There is no escape for the monsoon air entering such a box except to rise and cause cloud and precipitation (Simpson 1921). The Indian summer monsoon circulation would not be there if the Western Ghats, the Burma coast mountains, the Himalayas and the hills of the northwest frontier were absent. The southeast trades will not veer and cross the equator in the western Indian Ocean and the adjoining coastal areas of Kenya if the hills and mountains to the west of east coast of Africa were absent. Thus, it would be clear that the mountains have profound influence in setting up and maintaining the monsoon circulation in the lower troposphere. The circulation in the middle and upper troposphere might also be considerably influenced by the Tibetan plateau. It would appear that the lower monsoon circulation and the circulation in the upper troposphere develop independently, although the disturbances moving eastward in the westerlies or westwards in the easterlies might considerably influence the synoptic situations in the lower troposphere.

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