THE SOUTH-WEST MONSOON

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Abstract

A review has been made of the ideas about the south-west monsoon upto 1963 and the modifications necessary in the same in the light of the results of the International Indian Ocean Expedition (IIOE) during 1963-64. Important papers on the IIOE results published in India and elsewhere have been discussed in brief from the point of their usefulness in forecasting, indicating in what respects the interpretations are against weather, climatic and topographical features of the Indo-Pakistan sub-continent. Taking into account the presence of the Western Ghats, changes which occur within about 500 km. of the west coast of the Peninsula regarding clouds and weather and depth of the moist current brought to light by the IIOE results, become intelligible. There are no cyclonic circulations inthe north-east Arabian Sea and Bombay area and in the South Bay of Bengal of the type of 'subtropical cyclone' in the eastern Pacific; existence of the same has been postulated due to inadequate appreciation of the Indian conditions by the workers concerned.

Introduction

Position upto 1963.—Till the results of the IIOE during 1963 and 1964 became available, it was considered that the depth of the monsoon current (deflected trades) was about 6·0 km. over the Arabina Sea, the Peninsula and the Bay of Bengal; it was also taken on the basis of earlier observations that the depth of the monsoon current over Sind in West Pakistan and the adjoining areas was only about 1·0 km., there being drier warmer air from Baluchistan side above which was responsible for inversion at about 1·0 km. between the two air masses. The monsoon winds were drawn northwards into the circulation around the heat low over West Pakistan and the associated trough of low pressure over the Gangetic Valley. It has also been considered (Simpson, 1921; Banerji, 1930–31; Petterssen, 1953) that as a result of the Burma coast mountains, Lushai, Khasi and Jayantia hills of

Assam and the Himalayas, the south-westerly monsoon winds in the Bay of Bengal are deflected north and north-westwards to the Punjab through Bengal, Bihar and the Uttar Pradesh. The topographical features mentioned above and the Western Ghats have been considered important in producing the trough of low pressure over the Gangetic Valley; if these topographical features were absent the flow of the monsoon current over the Indo-Pakistan subcontinent would have been quite different as discussed by Banerji (1930–31). Petterssen (1953) has also shown that the topographical features contribute significantly in making the monsoon circulation self-sustaining in the lower levels of the atmosphere; the westerly jet which is to the north of the subcontinent during the monsoon season is not a part of the monsoon circulation. It is also known that although the heat low is there throughout the monsoon season, the position of the trough of low pressure shifts with the strength of the monsoon current, being southernmost when the monsoon current is strong and northernmost near the foot of the hills when it is weak and it may not be there at all during the breaks in monsoon. It is also recognised that the heat low over West Pakistan is shallow, while the trough of low pressure is deep extending upto about 500 mb., its axis sloping equatorwards with height from the surface, being near 19° N at 500 mb. (Desai, 1967). It has been shown by Sawyer (1947) that subsidence takes place in the continental air over north-west India above about 3·0 km. in the rear of the westerly troughs.

Modifications due to the IIOE results.—The results of the IIOE have shown that the depth of the monsoon current (deflected trades) is only 1·0–1·5 km. over the Arabian Sea west of about 65° E, there being drier westerly air above with an inversion or isothermal region between the two air masses and little rain over the area; further east, the depth of the moist current increases, the inversion weakens and its height is raised and the cloudiness and rain increase, there being about 6·0 km. depth of the moist current, absence of inversion, presence of Cu and Cb clouds and considerable precipitation on the coast. It has also been observed that on other occasions there might be air with near moist adiabatic lapse above the deflected trades upto about 500 mb. instead of the drier air with unstable lapse and with or without an inversion between the two air masses.

Over the Bay of Bengal the depth of the monsoon current was observed to be about 6·0 km. and the inversion was generally absent in the lower levels in line with the hitherto prevailing ideas.

The IIOE results have lead to the publication of a number of papers in the Proceedings of the Symposium at Bombay (1965) and elsewhere (Colon, 1964; Ramage, 1964, 1966; Desai, 1966–67) discussing the causes of the shallowness of the monsoon current over the Arabian Sea west of about 65° E and the depth of the moist current becoming about 6·0 km. over the west coast of the Peninsula; models for the Bay of Bengal and the Arabian Sea monsoon have also been proposed by Ramage (1964, 1966). As the IIOE results and their interpretations are important from the point of forecasting weather during the monsoon season, a summary of these interpretations with discussions about the same in the light of facts of weather and climatology and topographical features of the subcontinent, is given in this paper.

DISCUSSION OF INTERPRETATIONS OF THE IIOE RESULTS

Arabian Sea monsoon.—Colon (1964) has considered that the inversion over the Arabian Sea is due to air masses, the upper warmer and drier air being from Arabia and north-east Africa. He suggested that the inversion might be lifted and weakened or destroyed and the depth of the moist current increased due to the transport of moisture upwards over the east Arabian Sea east of about 68° E by (i) oceanic interactions and vertical mixing processes in low levels across the inversion layer by the penetration of active cloud formations, (ii) orographic effects due to the Western Ghats, the influence probably, however, extending only some distance upstream and (iii) formation of perturbations in the low level flow in the vicinity of the coast mentioned by George (1956). The following remarks might be made regarding the above three factors:

(i) This influence might not extend beyond about 700 mb. as observed by Bunker (1965) and might give only light rain.

(ii) It has been shown by Banerji (1930–31) that the configuration of the isobars and the streamflow will get affected by the barrier of the Ghats across the path of the monsoon current; this will bring a trough into existence off the coast which might explain extension of weather area as actually observed even upto about 500 km. from the coast. It is well known that a trough of low pressure frequently appears off the west coast when the monsoon is active or strong. The falling off of speed at 1500 ft. in the east Arabian Sea noticed by Colon (1964) would indicate speed convergence in the trough off the coast. It is considered that the Western Ghats might be mainly responsible for the changes east of about 68° E (Desai, 1966–67).

Considerable precipitation occurs along and over the windward side of the Ghats when the monsoon is active or strong.

During the monsoon season the temperature increases eastwards over the Arabian Sea from the Arabia–Somalia coast rapidly at first and slowly later; over the west coast, however, the temperatures are slightly lower than those off the coast within about 200 km. as seen from the climatological charts. This would give rise to relatively warmer water surface and layer of air above off the coast. It is possible that the trough off the west coast might get accentuated slightly due to this effect.

(iii) The low level perturbations could be produced due to the barrier of the Ghats when the monsoon current strikes them at a suitable angle; it is considered that they are not due to middle tropospheric developments. The latter might actually be produced by the former or by the trough referred to under (ii) due to the normal climatic features over the area north of 15° N as the partition between the westerlies and the easterlies at 700 mb. runs west-east along about 21° N. near Surat and at 500 mb. along about 19° N near Bombay. The conditions in the lower levels would give rise to cyclonic circulation or vortex above 800 mb. between about 18° and 21° N. These middle tropospheric developments ordinarily do not occur during the monsoon season on the west coast further south because there are no air mass partitions over there.

The breakdown of the inversion and increase in the depth of the moist current to about 6·0 km. on the west coast is considered to be mostly due to the influence of the Ghats (Desai, 1966–67). If the Western Ghats were not there, the depth of the moist current on the west coast would be only 1·0–1·5 km. as to the west of 65° E and over the Sind and Kutch coasts. The lower layer of deflected trades 1·0–1·5 km. deep acts as a reservoir from which moisture can be transported continuously upwards if there are suitable agencies for convective processes like the trough off the coast referred to above.

Pisharoty (1965) has considered that as the transport of moisture across the equator by 1·0–1·5 km. deep deflected trades cannot account for double or more moisture on the west coast of the Peninsula where the moist layer is about 6·0 km. deep, other agencies like evaporation from the Arabian Sea and from droplets associated with breaking waves should be considered. Desai (1966–2) has shown that it is not possible to accept arguments advanced by Pisharoty; the important fact of the IIOE observations is that marked changes in the moisture content and depth of the moist current in such cases take place *only within about 500 km. of the west coast.*

Ramage (1966) has given schematic section extending south-west from the Indo-Pakistan heat low. He has stated that the heat low is maintained and intensified through the summer by subsidence of air originally lifted and warmed by the release of latent heat in monsoon rain systems to the east and south; the subsidence also severely restricts low cloud formation over the central and western Arabian Sea, besides dominating West Pakistan, Arabia and Somalia over which the summer heat low systems extends. According to Ramage, the heat low exports cyclonic vorticity in the middle and upper troposphere to the north Arabian Sea and when a deep layer of moist air is present over the eastern part of the area, subtropical cyclogenesis occurs, producing a burst of West Indian monsoon rains; this in turn by increasing subsidence over the heat low, intensifies it and its associated low level monsoon circulation. When the supply of moist air is cut off, the subtropical cyclone fills, the heat low weaknes and a break takes place in the monsoon rains. With renewal of moisture supply, the sequence is repeated. The circulation over the north east Arabian Sea described above is intense in the middle troposphere and relatively weak at the surface, and it resembles, according to Ramage, the subtropical cyclone of the eastern Pacific (Ramage, 1962).

In support of his subtropical cyclone hypothesis over the north-east Arabian Sea, Ramage has quoted work of Miller and Keshavamurthy (1965), according to whom it is most intense at around 600 mb. and to have a cold core character below that level and a warm core character above; ocnvergence is weak at the surface and strongest in the middle troposphere. A critical examination of the 1st to 10th July 1963 charts referred to by them shows that the low extended right from the surface to 500 mb. or so on the 2nd, 3rd and 4th. The low while moving slowly north-north-westwards weakened into a trough over Saurashtra which became unimportant in due course. The cyclonic circulation at 700 mb. and above was produced as a result of conditions at the surface (strong monsoon and influence of the Ghats) and of the air mass partitions between about 21° and 18° N referred to earlier. Miller and Keshavamurthy have prepared composite charts for low level on the basis of data for 2nd and 4th only, while for 700, 600 and 500 mb. they have used data for these two days as well as for 7th, 8th, 9th and 10th July *although there was no cyclonic vortex after the 5th.* They have given from their composite charts centres of the vortex at 20·8° N, 73° E, 20° N, 72° E and 18·8° N, 72° E for 700, 600 and 500 mb. respectively. These centres are near the air mass partitions at those levels and referred to earlier; they have thus taken triple point conditions on or near the coast for the centres of vortex after the 5th although there was no vortex at any level. As is known the axis of the trough slopes equatorwards with height and the so-called centres at 700, 600 and 500 mb. also slope the same way. The triple point and perpendicular action conditions give heavy to very heavy precipitation at and near them and the equatorward slope of the axis causes rain to the south of the trough axis at the surface over an area extending to about 300 km. even without a depression when the trough is active (Desai, 1967).

Miller and Keshavamurthy have stated that their temperature composites show that the cyclone was cold-cored at 700 mb., its centre lay in a warm tounge at 500 mb. and the temperature field was neutral at 600 mb. and that this system had temperature structure similar to the 'subtropical cyclone' and the system in the Bay of Bengal studied by Ramage (1964). Their temperature composites show that there is a bias in their drawing of isotherms. It is considered that the centres were at the boundary between the air masses. The air masses involved in these west coast systems in the north-east Arabian Sea and Bombay-Gujerat-Saurashtra area are the continental and moist ones; the former is warmer than the latter at the surface and has nearly dry adiabatic lapse. As a result of differences in lapse rates, the moist air becomes actually warmer than the continental air above a certain level—reversal level. The height of the reversal level varies on different occasions and can be even 700 mb. or more. Thus at the reversal level there will be same temperature of both the moist and continental air masses which means neutral temperature field. The 600 mb. level temperature conditions mentioned by Miller and Keshavamurthy were probably of this type. As the centres at 700, 600 and 500 mb. were generally between Bombay and Ahmedabad, day-to-day temperatures at these stations at different levels were compared and they generally supported the above view. Miller and Keshavamurthy have utilised RFF data for 7th and 8th July in support of their temperature model. As stated earlier there was no vortex on the 7th and 8th; under the circumstances to utilise data of these dates for verifying structure of a vortex some three days earlier is not justified. The inversions noticed in these data of 7th and 8th were due to air masses and not subsidence as presumed by them to support their subtropical cyclone hypothesis.

Due to peculiar temperature conditions at the surface and difference in lapse rates of the continental and moist air masses, the former flows over the latter (dry warm front) upto the reversal level and the latter flows above the former (usual warm front) above that level. As such, the cyclonic circulation below the reversal level is generally not well marked and extends over a smaller area when compared with conditions above the reversal level. It is because of this influence that troughs only are generally noticed off the coast in the lower levels when the monsoon is active or strong as mentioned earlier.

Further, Miller and Keshavamurthy have composited data for different synoptic hours; this is not correct as the system was not stationary.

From the foregoing discussion it will be clear that Miller and Keshavamurthy's analysis and conclusions are not justified and cannot be accepted by synoptic meteorologists.

Dixit and Jones' Report (1965) has been utilised by Ramage to support his hypothesis of subsidence over the heat low stating that comparing a monsoon rain with a monsoon lull along the west coast of India, they located by far the greatest middle and upper tropospheric temperature differences above the heat low, with rain situation 2°–6° C. warmer than the lull situation. Ramage has concluded that subsidence over the heat low by raising the temperature of the middle and upper tropospheric air reduces surface pressure below what is observed in heat lows elsewhere. He has also used August, 1963 upper air data for Karachi to support subsidence and stated that it limits the height to which surface air from the Arabian Sea can ascend, restricting cloud development and thus favouring strong insolational heating.

From a critical examination of the conditions studied by Dixit and Jones it is observed that there was *no* Gujarat low associated with the 'monsoon rain situation' on the west coast; their drawings are against some of the winds not plotted by them. The differences in temperatures between the 'monsoon rain and monsoon lull' situations at 500, 300 and 200 mb. given in Fig. 16 of their report are not correct; in fact the differences worked out from temperatures given in the *Indian Daily Weather Reports* for the days in question give quite a diffrent picture from that of Dixit and Jones. One should judge the temperature differences with reference to the air masses involved which were quite different on the two days. It is not clear from what source Dixit and Jones took their temperatures for 500, 300 and 200 mb. levels. In view of the above remarks Ramage's using Dixit and Jones' conclusions to support his hypothesis is not justified.

In connection with Ramage's model (1966) a reference is invited to Desai's paper (1967) where a critical survey has been made of different aspects mentioned by Ramage. It is also shown there that the Karachi data both of temperature and humidity used by him can be understood if one considers air masses as responsible for inversion at about 900 mb. and for increase in humidity above about 700 mb.

Sadler (1965) has discussed synoptic conditions at 1·5 km. and 500 mb. for the 26th June and 1st and 10th July 1963, studying the spell 26th June to 10th July; he has considered the 26th as the preactive phase of the Arabian Sea Monsoon (ASM), 1st July as midpoint for active phase and 10th July one day after the definite break in the ASM. Sadler has also considered conditions for the 12th and 13th August 1964, the former day representing active and the latter ending phase of ASM. The period 2nd to 10th July is the same as that discussed by Miller and Keshavamurthy (1965) and referred to earlier.

Even according to Sadler 10th July is a day of break in the monsoon. As such and as mentioned earlier, Miller and Keshavamurthy are not justified in taking data of 10th July for their active monsoon study. The following remarks are relevant regarding Sadler's paper on the basis of detailed study of the periods by the author:

(i) His drawings cannot be accepted. Further, there was no vortex at 500 mb. either on the 1st or 10th. There were only air mass partitions, the western end of which he has taken as a vortex and which is not justified as mentioned earlier for Miller and Keshavamurthy's paper (1965).

(ii) The period 26th June to 10th July does not refer to one simple ASM system. It is observed that there was one surge of ASM between the 25th and 30th June and another between 30th June and 8th July. 1st July therefore does not represent midpoint of one ASM system.

(iii) Tiros cloud pictures of any one particular moment cannot explain rainfall for a period of 24 hr. as the weather system is not stationary.

(iv) Rainfall between 03 GMT of any two successive days can be corelated with the synoptic conditions during about the middle of the period, *i.e.*, at 12 GMT of the 1st day and not with 12 GMT of the second day.

Sadler has done the latter; as such, his explanations for rainfall on the coast cannot be accepted.

(v) There were no cold-cored and warm-cored lows; one has to consider air masses involved in the systems and their characteristics.

The following points are significant regarding the August 1964 period:

(i) There was no cyclonic cell between Bombay and Ahmedabad at 500 mb. on the 12th; there were only triple point conditions near 21° N, 73° E. There was also no vortex at 500 mb. on the 13th.

(ii) His drawings cannot be accepted.

Sikka and Mathur (1965) have studied transport of water vapour over the Arabian Sea and adjoining Indian region—for an active monsoon period 7th–10th July 1963, compositing data for the 7th and 8th and 9th and 10th. Actually the Arabian Sea monsoon was weakening during the period 7th–10th July. There was also no active cyclonic circulation between 700 and 500 mb. between the 7th and 8th as discussed earlier. Further, as a result of a depression from the Bay, conditions were varying each day from the 7th to the 10th. Their interpretations of the moisture results cannot be taken to represent average monsoon conditions as movement of a depression affected the area on all the days. The discussions of thermal structure of the lower levels over the Arabian Sea cannot also be accepted in the light of examination of the same data by the author in view of the weather and climatic features. Sikka and Mathur's classification of the air masses over and around the Arabian Sea cannot be accepted in all the cases. There are different types of air masses over the equator to the west and east of about 60° E (Desai, 1966, 1967). The ascents taken for Bahrain and the north Arabian Sea by them do not represent the same air masses. Similarly the two cases given for the central Arabian Sea do not also represent the same air masses conditions.

It is observed that during the south-west monsoon season June–September there can be three main type of air masses combirations over the Arabian Sea, *viz.*, (1) characteristic air mass stratification of the type observed by Colon (1964), (2) moist air in all the levels with or without an inversion and (3) continental air right from the surface with an inversion beginning at the surface due to travel of warmer air over colder sea. The rain-giving potential of these three types for the west coast of the Peninsula under the same conditions of winds is different for each case, being maximum for the first type. Detailed discussions of some of the data collected during the IIOE period are given in papers under publication in the India Meteorological Department and in a paper read by the author in the Symposium at New Delhi on the "Indian Ocean" in March 1967 and which will be published in due course as *Proceedings in the National Institue of Sciences in India.*

Bay of Bengal monsoon.—Ramage (1964) has stated that two distinct types of monsoon rain depressions can be identified. The first, which is apparently more common over the north Bay of Bengal appears to be warm-cored with a vigorous surface circulation and to resemble a tropical storm; these depressions retain the same characteristics when they move inland and are over the Gangetic Valley or neighbourhood. The second, more usually found over the north-east Arabian Sea, resembles the subtropical cyclone of the eastern Pacific in being intense in the middle troposphere and relatively weak at the surface. He has then discussed the second type in the south Bay of Bengal which as stated by him was extensively probed by research aircrafts during 1st–2nd June 1963. He has given in his paper the model for the western sector of the particular Bay system in the Andaman Sea. Maximum pressure gradients and horizontal convergence were found at around 600 mb.; compensating vertical motion was upward above 600 mb. and downward below that level. The air in the upper portion of the system was warmer than the environment possessing positive buoyancy. The descending air warming at the moist adiabatic lapse rate was cooler level for level than the non-saturated (although descending) environmental air, the lower portion of the system thus also possessing positive buoyancy. In his study, Ramage, however, did not find subsidence inversion near 850 mb. and concluded that the descending air reached the surface in contrast to conditions in the north-east Arabian Sea; he, therefore, postulated compensating divergence in the lowest layers. Rao and Desai (1965) and Desai (1967) have examined critically the data presented by Ramage as well as his model and shown that one cannot accept the model. In fact on an examination of RFF flight data sheets in the Office of the India Meterological Department at Poona the following was noticed:

RFF flight 30602 A for 2nd June (same day when according to Ramage cyclonic circulation approximately 50 km. in diameter was located near 11° N, 95° E at 500 mb.)—The aircraft at 11077 N, 95221 E at 0625 GMT had wind 248–39 kt.—pressure 698·6 mb.—height 10443 ft.—Temp. 7° C. and at 11031 N, 94990 E at 0631 GMT wind 253–36 kt.—pressure 699·0 mb. —height 10431 ft.—Temp. 6° C. There is a pencil remark in the data sheet 'Passed just S of cyclone centre' against observations between these two times.

From the above it would appear that there was a vortex not only at 500 mb. but also at 700 mb.

Examination of synoptic charts for 00 and 12 GMT for the 1st and 2nd June, 1963 shows that there was no cyclone at 500 mb. at 11° N, 95° E. Yet one has to believe the aircraft reposts near that location both at 700 and 500 mb. on the 2nd June. It is observed that there was fresh monsoon air boundary near 11° N, 95° E area at 12 GMT of the 1st and 00 GMT of the 2nd. It is well known that cyclonic vortices of small extent and short duration giving plenty of precipitation develop at this partition. What was reported by the aircrafts on the 2nd at 700 and 500 mb. was not the cyclone of the usual type, but only a vortex of small extent and short duration near the monsoon air boundary. The circulation hardly extended beyond 50 km. and Port Blair at a distance of about 300 km. was naturally not affected as seen from the synoptic charts.

It may be mentioned that when fresh monsoon air from the south Bay reaches the head of the Bay, depressions form at its boundary (Desai and Koteswaram, 1951) due to favourable topography and air mass partitions right from the surface upwards over the area instead of only above 850 mb. in the Bombay area where the air mass partitions are further north of 21° N below 700 mb. (Fig. 1—Desai, 1967). Desai has also discussed the structure of the depressions in the Bay in another paper (1951) which has been referred to by Ramage. The circulations first appear at 700 mb. and above as they are sloping westwards with height and in the lower levels the mountains of Burma running north-south prevent their movement westwards into the Bay and not because they are of the subtropical cyclone type. The air in the circulation is colder than the environment from the surface upto about 700 mb. as the fresh monsoon air which advances northwards is the coldest of the air masses present and higher up it becomes warmer due to a difference in the lapse rates of the air masses involved or the other air mass may be tropical easterly air which is warmer than the monsoon air. However, the occasions when the fresh cold monsoon air reaches the head of the Bay are relatively few, and a large number of depressions have the westerly and deflected moist air in the lower levels which is warmer than the fresh monsoon air entering the Bay directly from across the equator east of about 60° E. The deflected easterly air is generally warmer than the westerly air which has travelled across the Peninsula. Thus the depressions without the fresh cold monsoon air have a different thermal structure. As a result of the absence of warmer continental air in these depressions at the head of the Bay, they have vigorous surface circulation extending over a relatively large area even at the surface in contrast to depressions in the north-east Arabian Sea where the continental air is also involved as mentioned earlier. At the beginning of the monsoon in June and in May in the Bay when there is continental air in the area and there are depressions, the circulation in the lower levels is not vigorous and does not extend over a large area; conditions, however, become different above the reversal level. Due to inadequate appreciation of the Indian conditions, Ramage (1964) has drawn incorrect inferences from the paper of Desai (1951).

CONCLUDING REMARKS

From the foregoing comments of some of the papers on the IIOE results which are relevant from the point of forecasting, it will be seen that it is not possible to accept the interpretations given in them; these results can be understood without difficulty if one keeps in mind the weather, climatic and topographical features over the Indo-Pakistan subcontinent and the adjoining seas. The important point which has come to light from the IIOE observations which is against the hitherto accepted ideas is that the depth of the deflected trades is only 1·0 to 1·5 km. over the Arabian Sea to the north of about 10° N and west of 65° E where above the moist current there is at times upper drier air with unstable lapse with an inversion or isothermal region between the two air masses; on other occasions there is air with near moist adiabatic lapse above the deflected trades with or without an inversion between the two air masses. East of 65° E the depth of the moist current increases in the former and the inversion weakens and its base is raised and it may be even destroyed, the cloudiness and weather increasing at the same time in both the cases. Over the west coast the depth of the moist layer is about 6·0 km.; the presence of the Western Ghats helps to understand modifications produced within about 500 km. of the coast.

For the Bay of Bengal and the Indo-Pakistan subcontinent no new facts have come to light during the IIOE period.

The topographical features of the Indo-Pakistan subcontinent make the south-west monsoon in India unique from monsoons in other parts of the world.

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