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ORIGIN OF THE SOUTH-WESTERLY MONSOON CURRENT OVER THE ARABIAN SEA*

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ABSTRACT

Various facts of observations, climatology and topography over the Indian monsoon area during the northern summer have been considered and it is shown that there is *no* reason to think that the south-west summer monsoon current over the Arabian Sea is primarily of northern hemisphere origin ; it is shown that the quantity of air from the west that passes over the Peninsula from the surface to about 600 mb can be accounted for satisfactorily only if one considers the same a continuation of the southerly mass of air which crosses Equator near east African coast in those levels in the longitudinal belt 30°-45°E.

The atmosphere over the Indian monsoon area can with advantage be considered as consisting of two layers, one extending from the surface to about 600 mb level and the other from about 500 mb to 200 mb, the 600 mb to 500 mb layer being considered as transitional layer, the lower and the upper layer developing independently of each other although both may develop simultaneously in some years.

INTRODUCTION

IN recent years considerable confusion has been produced about the origin of the southwesterly monsoon current over the Arabian Sea during the northern summer season as a result of the interpretation by some workers of the results of the International Indian Ocean Expedition. It is proposed to discuss briefly the question from various points and see whether the view prevailing prior to 1963, i.e. the Arabian Sea monsoon current having its origin in the southern hemisphere can be considered still valid.

DISCUSSION

Ideas about the origin of the monsoon current over the Arabian Sea till 1963 :

We have learnt that the origin of the south-westerly monsoon current over the Arabian Sea is in the southern hemisphere ; the direction of the trades of that hemisphere changes while crossing the Equator and they blow from the south-west over the Arabian Sea, and as a result the south-westerly monsoon current over the Arabian Sea is also known as the deflected trades current. From the upper air observations over the Peninsula it was seen that the depth of the westerly moist current was about 6.0 km ; it has, therefore, been assumed that the depth of the monsoon current over the Arabian Sea was also about 6.0 km. It has been argued that the trades would

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pick up considerable amounts of moisture while travelling long distances northwards over warmer latitudes from the south Indian Ocean to the west coast of the Indian subcontinent across the Arabian Sea.

The International Indian Ocean Expedition (IIOE) results :

During 1963-64 the IIOE took extensive upper air observations over the Indian seas. The observations during 1963 June to August showed that the depth of the monsoon or the deflected trades current was only about 0.5 to 1.5 km over the Arabian Sea west of about Long. 68°E and that above it there was drier airmass with an inversion between the two (Colon, 1964) ; the lapse rate in both the lower moist and upper dry airmasses was nearly dry adiabatic. The depth of the moist current increased and the height of the base of the inversion was raised and its depth decreased between about Lat. 10°N and 20°N east of Long. 68°E, and over the west coast of the Peninsula the depth of the moist current became about 6.0 km and there was absence of any low-level inversion during active or strong monsoon conditions as judged from the rainfall on the coast. It was also observed that over the west Saurashtra-Kutch-Sind coast the depth of the moist current remained less than 1.5 km as over the Arabian Sea west of Long. 68°E and there was presence of an inversion between about 1.0 and 2.0 km as judged from data over Karachi (Ramage, 1966). Desai (1966a, b ; 1969a) has suggested that the depth of the moist current increased to about 6.0 km over the west coast of the Peninsula as a result of the barrier of the western Ghats across the path of the moist monsoon current in contrast to its remaining less than 1.5 km on the coast between Veraval and Karachi as over the Arabian Sea west of Long. 68°E due to absence of any barrier there.

Colon (1964) also observed that over the Arabian Sea west of about Long. 68°E there were Strato-Cumulus clouds whose tops were at the base of the inversion and there was little rain from the same ; east of Long. 68°E the cloudiness and rain increased considerably, there being also Cumulus and Cumulonimbus clouds off and over the west coast.

Ramage (1966) has put forward the view that the low-level inversion above the shallow moist current is caused by subsidence in the air above.

The IIOE observations during 1964 August-September showed that there was above the moist current with nearly dry adiabatic lapse, less moist air upto about 600 mb with nearly saturation adiabatic lapse with or without an inversion between the two in contrast to 1963 IIOE observations when there was drier unstable airmass above (Desai, 1968, 1969b). The depth of the moist current also became about 6.0 km over the west coast of the Peninsula.

During June, 1967 the U.S.A. vessel *Oceanographer's* soundings over the north-east Arabian Sea showed that above the unstable moist air mass, there was less moist air with nearly saturation adiabatic lapse upon about 500 mb (Desai, 1968).

Ideas about the origin of the monsoon current over the Arabian Sea in the light of the IIOE and other observations :

Pisharoty (1965) calculated moisture over the Equator over the Indian Ocean west of Long. 75°E in layer from the surface to 450 mb and over the west coast of India during July, 1963 and 1964 and observed that the moisture was about double over the west coast when compared with that over the Equator. The moist current being shallow, he put forward the hypothesis that the monsoon current over the Arabian Sea was primarily of northern hemisphere origin, the air from north-east Africa and Arabia side picking up moisture while travelling over the sea.

Pisharoty and Sreenivasiah (1969) have stated that the air that crosses the Equator from the southern hemisphere turns towards the east by the time it reaches about Lat. 10°N and so does not apparently participate in the circulation of the heat-low over Pakistan and the Gangetic Valley trough. According to them the zone of partition between airmasses of northern hemispheric and southern hemispheric origins appears to run more or less east-west along Lats. 5°N to 10°N.

In a later paper Pisharoty (1969) has stated that the mean flow of air in the equatorial belt from Longs. 80°E to 100°E corresponded to a southerly wind of 6-8 kt and from Longs. 40°E to 60°E of a southerly wind of 2-4 kt, the flux from the south in the belt between Longs. 60°E and 80°E being relatively negligible. As the transport of air across the Equator between Longs. 40°E and 60°E is comparatively small, Pisharoty concluded that greater attention to northern hemisphere phenomena was necessary for understanding the pulsations of the Arabian Sea branch of the monsoon. It may be mentioned that for the equatorial belt between Longs. 40°E and 80°E, Pisharoty has used data of Nairobi near Long. 37°E, Seychelles near Long. 55°E and Gan near Long. 73°E.

Rama (1968) has taken measurements of radon at deck-level of ships in the equatorial area of the west Indian Ocean off the East African coast and over the Arabian Sea and Gulf of Aden and the Red Sea during the monsoon season of 1966 and 1967. He observed that the south-east trades air in the equatorial area had radon content only 2-4 dpm/m^3 ; the radon content of the air over the Arabian Sea north of about Lat. 5°N was found to be 20 to 40 dpm/m^3 both during active and weak monsoon conditions as judged from rainfall over the west coast of the Peninsula. Over the west Gulf of Aden and the south Red Sea the radon content of air was 60-160 dpm/m^3. Rama concluded from his radon results that the monsoon air over the Arabian Sea north of about Lat. 5°N was not a continuation of the air from the southern hemisphere but was from the northern hemisphere itself from north-east Africa and Arabia as presumed by Pisharoty. He has explained that the radon content of the air over the Arabian Sea having its origin in north east Africa and Arabia was only 20-40 dpm/m^3 against 60-160 dpm/m^3 over its source region as radon from the source air decreased due to its vertical transport and due to its decay during travel.

Rama (1969) also suggested that radon values of 20-40 dpm/m^3 might be due to mixing of the radon-poor trades air with the radon-rich continental air which subsided over the area.

Arguments against hypothesis of Pisharoty and Rama :

a. The IIOE data have shown that as the warm air from north east Africa and Arabia side flows over the adjoining cooler sea surface an inversion develops in it right from the sea surface (Desai, 1968, 1969b). The inversion will prevent transport of appreciable amounts of moisture from the sea surface upwards into the dry air from the west.

b. Off the Arabian coast and north-east Somalia coast, however, the inversion began at some height *above* the sea surface *instead* of from the sea surface itself (Desai, 1968; 1970b). Thus while at Lat. 12°N, Long. 52°E the inversion began from the sea surface, at Lat. 12°N, Long. 54°E it began only at about 930 mb level on 26th June, 1963 as shown by the IIOE data. The wind at 1500 ft. at 12°N, 52°E was SW—10 kt while at 12°N, 54°E it was SW—40 kt (Desai, 1970b). There were no unusual conditions over the area to show that dry air mass at 12°N, 52°E could change to moist airmass with unstable lapse during its travel to 12°N, 54°E and the inversion base be lifted to 930 mb level. This would show that the low-level inversion over the west Arabian Sea was an airmass one (Desai, 1969a, b ; 1970b) and *not* due to subsidence in the upper air as suggested by Ramage (1966).

c. Appreciable amounts of moisture are not transported upwards west of about Long. 68°E, only but within about 500 km of the west coast of the Peninsula (Desai, 1966b, c ; 1967).

d. The depth of the moist current increased and the inversion base was raised within 500 km of the west coast as shown by the IIOE data on the 8th and 9th July, 1963 along about Lat. 18°N and 15°N respectively (Desai, 1970b). To the west of 500 km from the west coast of the Peninsula, there was no appreciable change in the depth of the moist current or the height of the base of inversion as noticed during the IIOE period on 4th July, 1963 (Desai, 1970a) at 19°N, 64°E and 19°N, 66°E ; this would also show that significant changes in the depth of the moist current and the base of the inversion take place only within about 500 km of the west coast and appreciable changes in depth of the moist current do *not* take place over the entire Arabian Sea as the length of travel of air increases over it.

e. There is little rain over the west coast of the Peninsula in May when there is continental air which has travelled over the Arabian Sea, is there. During June to September there is considerable rain over the coast and this would show that the same is not due to the air which is of continental origin from the west ; the air during the monsoon season is therefore from across the Equator.

f. Desai (1969c) and Rao and Desai (1970b) have shown that it is not easy to draw inferences from radon data about airmasses as pure airmasses ordinarily do not exist over the Arabian Sea. The radon content of the air from across the Equator which is 2-4 dpm/m^3 increases to 20-40 dpm/m^3 depending upon the amount of the continental air from the west with radon content 60-160 dpm/m^3 which mixes with it. The decrease in radon content of the continental air from 60-160 dpm/m^3 to 20-40 dpm/m^3 is not due to vertical transport of radon as the same will not occur due to presence of inversion from the sea-surface [see (*a*) above] ; there was also no descent of radon-rich dry air over the north-east Arabian Sea to mix with radon-poor deflected trades air as the lapse rate in the upper air was near saturation adiabatic (Desai, 1968; Rao and Desai, 1970b) and hence there was no dry air over the area. Decay due to horizontal movement will be small considering the time that the air will take to move from near the Arabian coast to the west coast of the Peninsula in view of the speeds of 20-30 kts or more in the south-westerly moist current over the Arabian Sea.

g. The wind direction and speed at different levels upto about 6.0 km over the Somalia-Arabian coast north of Lat. 10°N are not such as to account for the amount of air that passes from the surface to about 600 mb level over the Peninsula as judged from the direction and speeds there (Rao and Ramamurti, 1968 ; Rao and Desai, 1970b, c). This would show that the origin of the monsoon air cannot be in north-east Africa and Arabia.

h. The transport of air across the Equator is not comparatively small but is very large. Using data available for stations between Nairobi and Seychelles (Pisharoty has used data of only Nairobi and Seychelles), Findlater (1969a) has given in Fig. 2 of his second paper meridional flow at the Equator in July; this shows immense flow of air across the Equator between Long. 38°E and 45°E in the layer surface to 600 mb, the maximum being between 950 mb and 750 mb or the layer 0.6 to 2.4 km (Figs. 10 and 11 of his first paper) in which the low-level southerly jet stream occurs.

In Table I of his second paper Findlater (1969b) has also given comparative values of meridional flow at the Equator in July for the lower troposphere across (*a*) whole Equator and (*b*) Equator between Long. 35°E and 75°E in the layer surface to 600 mb. It is seen from these computations that the effect of the south monsoon current near east Africa is to produce a value of 7.68×10^{12} metric tons per day of meridional transport of air and this value is nearly half of the total estimated transport of air across the whole Equator in the lower troposphere from the surface to 600 mb during the northern summer typical month July. Such bulk transport of air across the Equator between Longs. 38°E and 45°E can only account for the moderate to strong westerly winds over the peninsula from the surface to about 600 mb during the periods of active and strong monsoon conditions.

In view of the data presented by Findlater (1969), one cannot accept Pisharoty's findings (1969) about cross-equatorial flow between Longs. 40°E and 60°E.

Evidences of the origin in the southern hemisphere of the South-westerly monsoon air over the Arabian Sea :

i. From the data presented by Findlater (1969) a brief summary of which has been given by Rao and Desai, 1969 ; also (see Rao and Desai, 1970c), it is seen that

a. A persistent high-speed air current in the form of a system of low-level jet stream blowing from south to north across the Equator exists in the lower layers of the air in the vicinity of the western Indian Ocean during the south-west monsoon season.

b. The southerly flow is accelerated into a well-defined stream which crosses the equatorial area in a limited zone of Long. 38°E to 42°E, speed being maximum near Long. 40°E and decreasing further west and east and becoming minimum near Long. 70°E. The flow becomes south-westerly to the north of the Equator over and off Somalia.

c. The flow patterns reveal that the south monsoon in the equatorial area is contained below 600 mb level, maximum speeds of 50 to 100 kt occurring intermittently in the layers 600 to 2,400 m.

d. Variations in the cross-equatorial speed of the current were found to have an important regulating effect on the rainfall producing capacity of the south-west monsoon over India during a two-month (July-August, 1962) sample period.

e. Low-level jet speed currents as in the equatorial region of the west Indian Ocean also occur over the Arabian Sea and over the Peninsula (Figs. 10 and 11 of Findlater's 1st paper, 1969).

Findlater's observations show that the winds over the Peninsula upto about

RELIEF MAP OF INDIA AND NEIGHBOURHOOD

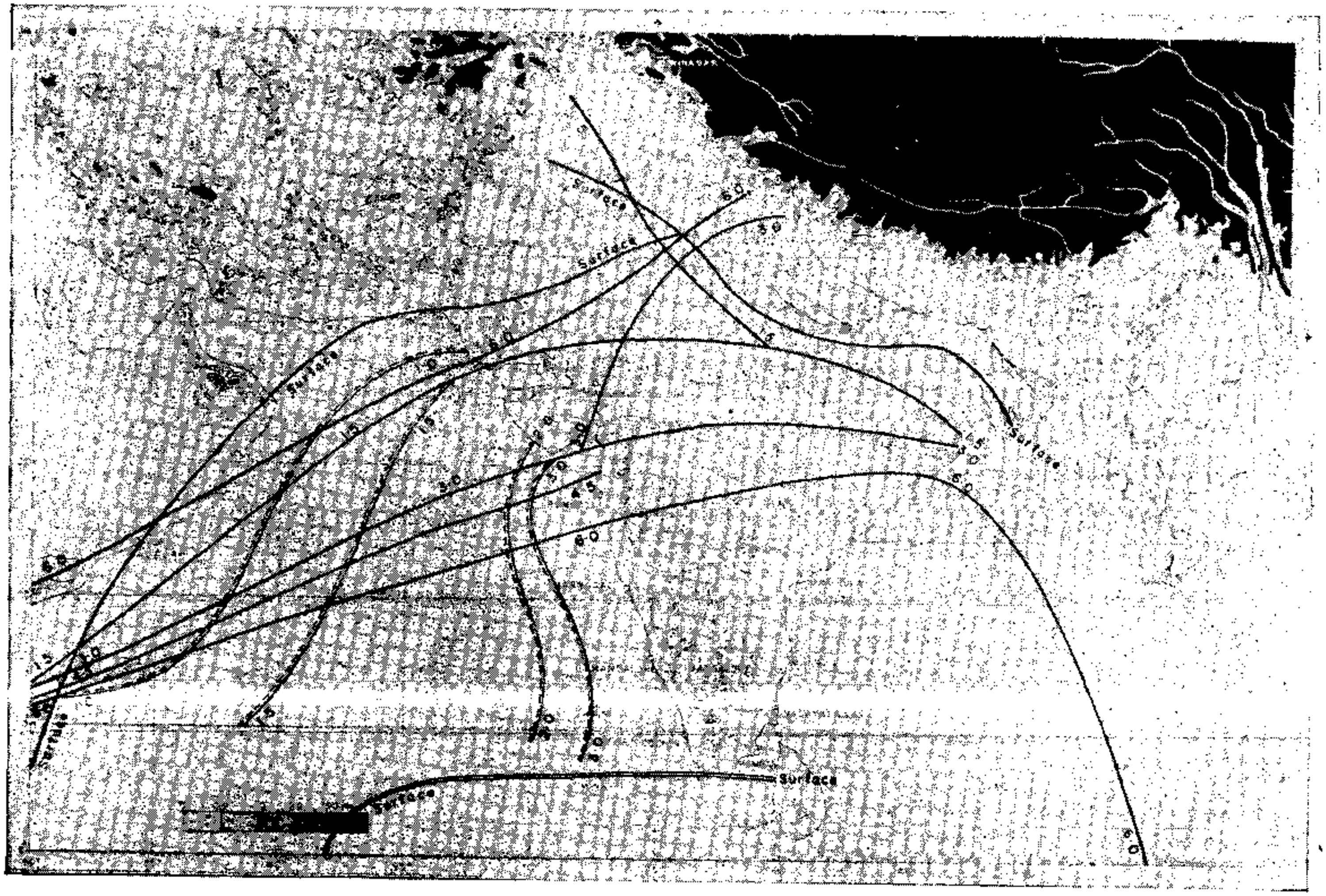

PLATE I. Overland to the south of the partition (———————) there is westerly moist monsoon air at all levels and to its north easterly moist air upto and at 3.0 km and tropical easterly air at 6.0 km ; in the wedge at the western end of the partition there is mixed air (moist monsoon air and continental dry air) at the surface and drier continental air at 1.5 and 3.0 km as well as to the west of the partition running southwest-northwest at 6.0 km.

Over the Arabian Sea to the east of the partition (———————) there is deflected trades airmass upto about 1.5 km and less moist airmass with nearly saturation adiabatic lapse above upto about 4.5 km and drier continental air to its west ; when there is absence of the less moist air above the deflected trades airmass and instead there is presence of drier continental air, the partitions are indicated by double continuous and broken lines (- - - - - - - - - -). At 6.0 km there is moist air to the south of the southernmost partition and drier continental air to the north of the northernmost partition there being tropical easterly air between the two partitions. To the west of the double continuous lines (═══════) from about 5°N, 62°E deflected trades move to the west coast of the subcontinent across the Arabian Sea and to the east move directly into the Bay of Bengal.

4.5 km and rainfall over the west coast of the Peninsula when the monsoon is active or strong can be understood easily if one considers the south-westerly monsoon current over the Arabian Sea as a continuation of air from the southern hemisphere crossing Equator between about Long. 38°E and 60°E.

ii. Results of Rangarajan, Gopalakrishnan and Vora (1969) show that the radio-active fall out debris from the French explosions in Polynesia—20°S, 138°W, during July to Sept., 1966 to 1968, travelled westwards into the Indian Ocean and reached India.

Remarks about the south-west monsoon circulation over the Indian area (Rao and Desai, 1970a) :

The topographical features so affect the flow of air across the Equator under the influence of the heat-low over Pakistan that a self-sustaining monsoon circulation is set up in the lower levels of the atmosphere upto about 600 mb over the subcontinent and neighbouring sea areas which make the Indian monsoon circulation distinct from similar monsoon circulations in other parts of the world, the flow of air from across the Equator being most important in the development of the monsoon trough ; without the flow of air from across the Equator between Long 38°E and 60°E, the monsoon circulation will not develop and there would be circulation as in May when little rain falls over the west coast of the Peninsula.

The atmosphere over the Indian summer monsoon area might probably be considered with advantage to consist of two layers, one extending from the surface to about 600 mb level and the other from 500 mb to 200 mb level, the layer 600-500 mb being the transition layer ; each layer can develop independently of the other. The circulation in the middle and upper troposphere does not give rise to the lower level monsoon circulation although at times there might be simultaneous development of both i.e. there is *no* cause-effect relation between the two (Desai, 1969d). The westerly and the easterly jets are thus not a part of the monsoon circulation although changes in the upper layer might affect weather in the layer surface to about 600 mb considerably at times.

CONCLUDING REMARKS

From the foregoing discussion it can be concluded that the south-westerly monsoon current over the Arabian Sea *is* from the southern hemisphere, it being a continuation of the air which crosses Equator between about Long. 38°E and 60°E between surface and about 600 mb ; it is *not* primarily of northern-hemisphere origin. There is no difficulty to understand either the presence of the drier unstable continental air above the deflected trades current over the west and north Arabian Sea or of less moist air with saturation adiabatic lapse over the south, central and east Arabian Sea as noticed during the IIOE years 1963 and 1964 respectively ; considerable increase in moisture as well as depth of the moist current which occurs within about 500 km of the west coast can be understood if the influence of the western Ghats on the air motion is taken into account.

In Fig. 1 reproduced from paper of Rao and Desai (1970a) are given approximate positions of boundaries between different airmasses over the Indian area. The figure is based on the information available upto the end of 1969. Most of the observations available over sea and land and climatic features of the area can be understood if it is accepted that the south-west monsoon current over the Arabian Sea is from across the Equator.

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