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A comparative study of the summer monsoons over Africa and India

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ABSTRACT. A comparative study has been made of the summer monsoons over Africa and India. Important points of similarities and differences between the monsoons over the two regions from the point of their incidence, circulations associated with them and nature of weather have been summarised at the end.

1. Introduction

The monsoons are primarily caused due to differential heating between the continents and the oceans. The heating of the continents produces lows, under the influence of which air from the winter hemisphere is drawn into its circulation. During the northern summer there is a low pressure area extending from North Africa to North India across Arabia and Iran, but the nature of the monsoon rains over Africa and the Indian subcontinent is very different. It is proposed to discuss in this paper the causes responsible for the differences in the monsoons over the two areas.

2. Discussion

(a) *Temperature and pressure distribution*

During summer (July is taken as representative month for the northern summer throughout the discussion) average surface temperatures are high over North Africa, Arabia, Iran and northwest of the Indian subcontinent, the region of highest temperatures being over northwest Africa and central Iran (Thomson 1965, Rao and Ramamurthi 1968, Rao and Desai 1973). Corresponding to this temperature distribution, pressures are low over the region, but instead of centres of lowest pressure being over the area of highest temperatures, the lowest pressure of less than 994 mb occurs over Pakistan; there is also a trough of of low pressure over the Gangetic Valley over India, its northwestern end being joined with the Pakistan heat-low.

At 850 and 700 mb the region of highest temperatures occurs generally near Lat. 25°N over the entire area, but temperatures at the latter level are higher over and around Iran than over central West Africa. At 500 mb the region of highest temperatures is located betwen about Lats. 25° and 35° N and Longs. 55° and 105°E, temperature of 0°C occurring near Lat. 30°N, Long. 87°E; temperatures of—6° to—7°C occur over Africa west of about Long. 40° E and between equator and Lat. 15°N temperatures being lower both to the north and south. At 300 mb highest temperature occurs along about Lat. 30°N to the east of Africa, the area of the same being somewhat southwards along about Lat. 20°N over Africa. The region of highest temperatures at 200 mb occurs along about Lat. 35°N to the east of Africa and it is located along about Lat. 30°N over Africa.

The pressure distribution in upper levels is somewhat as under—

850 mb — The highest pressure is over West Africa over Lat. 30°-35° N and there is a shallow trough roughly near Lat. 16° N between the highs over Africa and to the south of the equator over the Atlantic Ocean; the trough extends northeastwards to the east of Long. 10° E to near Lat. 20° N near Long. 35° E. There is a high near Caspian Sea area and lowest pressure is over the Gangetic Valley over India.

700 mb — The highest pressure occurs over West Africa over the area between Lats. 25° and 30° N, and a trough just to the south of the coast near Lat. 5° N between the two highs north and south of the equator. There is a high over north Iran and lowest pressure occurs along Lat. 21°N over India.

500 mb — The highest pressure is over West Africa and Iran (somewhat lower) along Lat.

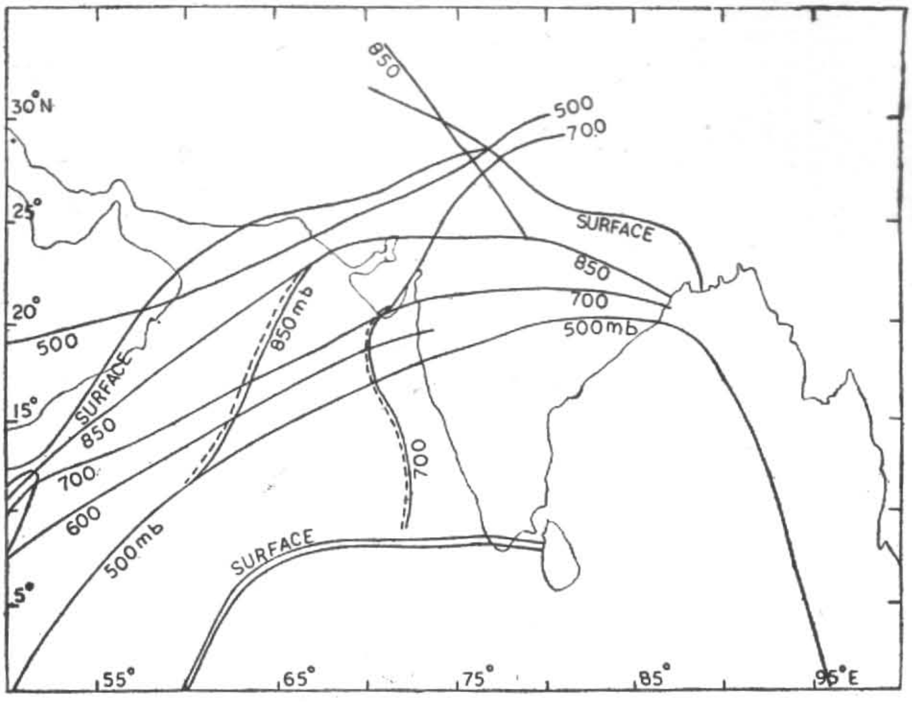

Fig. 1

30°N. There is a weak trough near equator south of the West African coast and a trough over India south of latitude of Bombay.

300 mb — There is a high pressure belt near Lat. 25°N over Africa and near Lat. 30°N between Longs. 40° and 100° E over Asia, pressures being lower over Africa than over Asia. There is trough near equator in the east Atlantic and in the West Indian Oceans.

200 mb — The pressure pattern north of the equator remains the same as at 300 mb. There are westerly winds south of Lat. 5°S over the Atlantic and south of Lat. 15°S over the Indian Ocean.

The important points to be noted regarding temperature and pressure distribution are that the heat-lows are shallow in vertical extent and the low over Pakistan is the deepest; the trough over the Gangetic Valley over India is not associated with high temperatures at any level and it moves southwards and weakens with height, particularly above 700 mb and there is absence of trough above 500 mb. Over North Africa there is a trough at the surface and 850 mb, but it is an extension eastwards of the heat-low.

(b) *Wind distribution*

The wind distribution follows roughly the pressure distribution at all levels.

The westerly moist winds over India are stronger than over Africa; this is due to the fact that winds over the Indian Peninsula are a continuation of the strong winds over equator between Longs. 38° and 45° E (Findlater 1969; Rao and Desai 1970). No such strong winds are known to occur near equator on the east Atlantic side.

(c) *Airmasses over India and Africa upto 500 mb level*

Rao and Desai (1970 b, 1971, 1973) have discussed the airmasses over the Indian Seas and the subcontinent during July, a typical monsoon month and their diagram of airmasses at different levels in which slight changes in the positions of the boundaries have been made in view of the climatological charts of Thomson (1965) and note of Frost (1969) on wind flow over Tropical Africa is reproduced as Fig. 1.

There is moist airmasses on both the sides of the Gangetic Valley trough, the SW'ly to W'ly air from across the equator to the south of its axis and SE'ly to E'ly moist air— SW'ly to W'ly moist air deflected by the Burma coast Arakan mountains and the Eastern Himalayas — to its north, there being a wedge of dry continental air at its northwestern end. The continental air overlies the moist air, its eastern end being near Delhi at the surface, near Lat. 25°N, Long. 85°E at 900 mb, near Lat. 24° N, Long.

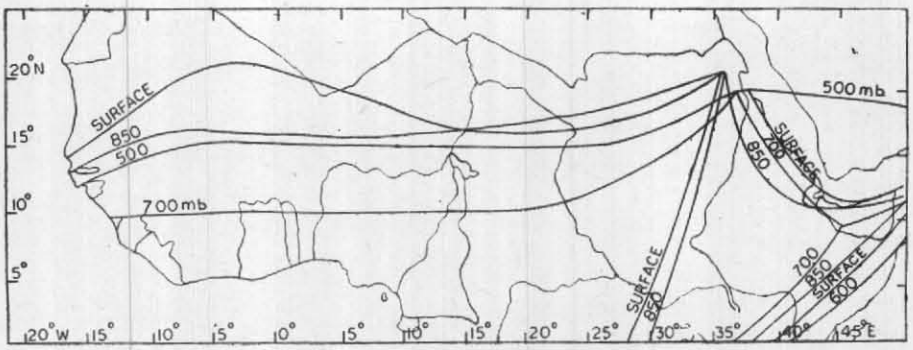

Fig. 2

78° E at 850 mb and near Lat. 20° N, Long. 70° E at 700 mb; at 500 mb there is tropical easterly air between the southern boundary (to the south of which there is SW'ly to W'ly moist air) and northern boundary (to the north of which there is continental air W'ly to NW'ly turned to NE'ly under pattern of pressure distribution) and which flows from NE'ly direction across the equator west of Long. 50 °E. The moist air at the surface from the southern hemisphere which crosses equator to the west of about Long. 60°E moves northeastwards to the west coast of India across the Arabian Sea and then to the Bay of Bengal across the Peninsula, while that which crosses equator to the east of Long. 60°E directly enters the Bay of Bengal south of about Lat. 8°N.

In Fig. 2 are indicated approximate positions of boundaries between different airmasses over Africa at different levels on the basis of the climatological charts of Thomson (1965) and note of Frost (1969) for July; the same for the Indian area are taken from the paper of Rao and Desai (1973) and given in Fig. 1.

At the outset it may be mentioned that while the northern boundary of the southern hemispheric air in the northern winter is just near the south coast of West Africa to the north of the equator upto about Long. 30° E. it is to the south of the equator in the Indian Ocean (Sawyer 1952). Thus during the northern summer the distance which the air from across the equator has to travel to the heat-low over West Africa is much less than which it has to travel to the west coast of India under the influence of the heat-low over Pakistan.

The following points should be noted for different levels for Africa (Fig. 2) with reference to Fig. 1 :

Surface below about 1000 m

To the north of the boundary there is dry warm continental air (northeasterly to easterly direction) and to its south moist deflected trades airmass (SW'ly to W'ly direction) from the South Atlantic Ocean upto the west of the Kenya-Ethiopia plateau; to the east of that plateau there is deflected trades airmass from the South Indian Ocean. Towards the Red Sea and the Gulf of Aden side there is dry warm continental air.

850 mb level

To the north of the boundary there is dry warm continental air. To its south there is southwesterly to westerly moist airmass (from the South Atlantic Ocean and from the South Indian Ocean which has moved over land south of the eqator) upto the west of the Kenya-Ethiopia plateau, *i.e.*, to the west of the line running from the equator and Long. 30°E to Lat. 20°N, Long. 35°E and to the east of that plateau or the line from equator and Long. 38°E to Lat. 11°N, Long. 50°E, there is southwesterly airmass from the South Indian Ocean (SE'ly to S'ly winds veering to SW'ly). Towards the Red Sea and Gulf of Aden side there is continental air.

700 mb level

To the north of the boundary there is continental air from northeasterly to easterly direction; to its south there is moist air (variable winds or winds with pronounced easterly component) upto the west of the boundary from 0°, 37°E to 9°N, 45°E, to the east of which there is moist airmass (southwesterly direction) from the South Indian Ocean side (SE'ly to S'ly winds veering to SW'ly).

600 mb level

In the absence of winds, it can be only surmised that the position of the boundary of the dry continental air (easterly direction) might be between that at 700 and 500 mb levels, the boundary at 700 mb level being probably the southernmost limit of the continental air. To the west of the boundary running northeastwards from near 0°, Long. 40°E, there might be moist air (variable winds or winds with pronounced easterly component) as at 700 mb level or tropical northeasterly to easterly air as at 500 mb and to its east moist southwesterly airmass from the South Indian Ocean (SE'ly to S'ly winds veering to SW'ly).

500 mb level

To the north there is dry continental air (northeasterly to easterly direction) and to its south tropical northeasterly to easterly air from the Indian subcontinent side upto the west of the boundary running from near equator and Long. 50°E northeastwards, to the east of which there is southwesterly airmass (westerly winds from the South Atlantic Ocean backing under pattern of pressure distribution to SW'ly in the South Indian Ocean to SW'ly to W'ly to the north of the equator). The boundary between the dry continental air and less dry tropical easterly air might be diffuse and not sharp: there might be only humidity difference and not temperature contrast as over northwest India at 500 mb where the boundary between easterly dry subsided continental air and less dry tropical air is diffuse as the temperature is about the same in the two airmasses. The tropical northeasterly to easterly air to the west of the boundary might even move across the equator southwards. The inversion noticed over Khartoum (near Lat. 15·5°N, Long. 32·5° E) near 550 mb level might probably be an airmass one, the northeasterly to easterly warm air from India — it might be subsided dry air or less dry tropical air flowing over the cooler air; this inversion might not be due to subsidence as contemplated by Ramage (1970).

From the foregoing discussion about airmasses it would be clear that the airmass which crosses the equator to the east of about 37°E constitutes the moist southwesterly to westerly airmass which moves to the Indian subcontinent across the Arabian Sea. While the moist SW'ly to W'ly current is about 6·0 km deep over the Peninsula, it is only about 2·0 to 2·5 km deep over West Africa.

It may be mentioned that relative humidity over the surface is more than 90 per cent over the coast of West Africa and decreases inland as the cool moist air travels over heated land and becomes less than 30 per cent over the heat-low. The northern limit of the SW'ly air does not extend to the heat-low, but is actually to its south. The southern limit of the drier continental air at 850, 700 and 500 mb (Fig. 2) is roughly supported by the D. Ps at those levels (Thomson 1965).

From the above discussion the following points regarding airmass distribution over the Indian subcontinent (Fig. 1) and North Africa (Fig. 2) might be mentioned.

At the surface and at 850 mb there is dry easterly to northeasterly continental air from the southern side of the North African subtropical anticyclone to the north of the boundary over North Africa and moist SW'ly to W'ly air to its south. At 700 mb there is dry continental air (NE'ly to E'ly) to the north of the boundary and to its south there is moist air (variable winds or winds with marked easterly component) upto some distance; the layer of moist air at 700 mb for some distance southwards has probably resulted from the easterly continental air which has been humidified due to organised convective processes over land and falling rain. Further south at 700 mb there might be air (with winds having easterly component from the southern hemisphere —SE'ly diverging to SW'ly towards Arabian Sea and E'ly towards West Africa). At 500 mb to the south of the drier continental easterly air, there is a belt of moist tropical easterly air which has moved from India north of about 18° N. The depth of SW-W'ly moist air increases southwards with height and is about 2·5 km to the north of the West African coast.

Over India (Fig. 1) the heat-low has relatively dry airmass as over West Africa, the boundary of the SW-W'ly moist air being south of the heat-low. The trough over the Gangetic Valley connected with the heat-low over Pakistan at its northwestern end has moist air both to the south and north of the trough axis below about 600 mb, the easterly moist air being the SW-W'ly moist air which has been deflected by the Burma coast Arakan mountains and the eastern Himalayas. At 500 mb there is easterly tropical air to the north of the trough axis and this extends to Africa as stated above. The boundary of the E-SE'ly moist air slopes equatorwards with height.

Over West Africa the depth of the SW-W'ly moist air is too shallow at the northern boundary and about 2·5 km on the coast; above it there is dry air and there might be an inversion between the two airmasses as noticed in India, the inversion being weaker, the higher the surface of separation between the moist and dry airmasses.

Over the Arabian Sea there are two types of airmasses stratifications upto about 600 mb level (Desai 1968, 1969 a). In the layer about 0·5 to 1·5 km there is air from across the equator (deflected trades) with high humidity and lapse rate near dry adiabatic; above the surface layer there is in one case less moist air with nearly saturation adiabatic lapse and with or without an inversion between the two airmasses, while in another case there is continental air with nearly dry adiabatic lapse with an inversion between the two airmasses. The depth of the deflected trades airmass in the Western Inidan Ocean over the equator between about Long. 60°E and 45°E is 2-3 km according to the IIOE data and its depth decreasss as it advances north eastwards as a wedge; according to Findlater (1969), the depth of the southerly moist airmass at the equator between Longs. 37° and 55°E might be as much as about 4·5 km. No data are available for the depth of the moist current from across the equator in the Atlantic upto the West African coast, but on the basis of coastal data there it can be stated that it may be about 2·5 km; in this case also the air from across the equator advances northwards as a wedge under the warm dry easterly continental air on the southern side of the subtropical anticyclone over North Africa and there is also a low-level airmass inversion (Carlson and Prospero 1972).

Sawyer (1947) has shown the nose of warm continental air overlying the cool maritime air with slope of about 1/350 in the layer 1000-900 mb steeping to 1/200 in the layer 900-800 mb, and 1/100 from 800-700 mb. Above 700 mb there was little or no temperature contrast, but the airmass boundary sloped back towards the north, presumably due to moisture discontinuity, the monsoon air being more moist than the continental air. Desai (1970 a) has shown that temperature contrast might exist even over sea above 700 mb. Over Africa the warm continental air overlies the cool maritime air upto about 1000 km the south of the position of the ITF at the surface, but there is no evidence of the airmass boundary sloping back northwards, the maritime SW-W'ly air current being only about 2·5 km deep over Africa against about 6 km deep over the Peninsula in India; the slope of the boundary at 0 meridian is about 1/500 from surface to about 700 mb level as seen from Fig. 5 of the vertical cross-section for July given by Thomson (1965). According to Carlson and Prospero (1972) the continental air might become relatively colder than the tropical environment over the Caribbean area above about 650 mb level.

(d) *Causes of* (*i*) *deepest heat-low over Pakistan,* (*ii*) *Gangetic Valley trough and* (*iii*) *absence of regular monsoon rains over Arabia and Iran*

(*i*) Banerji (1930, 1931) has discussed the causes of location of the low pressure over Pakistan and shown that the same is due to mountains on the northwest frontier of the Indian subcontinent and the Western Himalayas; without these barriers, the lowest pressure would be to the west over Iran. The pressure over Pakistan is lowest when compared with pressure in the heat-lows elsewhere due to orographic causes of its location as mentioned above, presence of hot dry air between about 1 and 3 km, of warm subsided air from north between 3 and 6 km and/or of warm moist easterly air above 3 km over the area. Further, the temperature between 500 and 200 mb is relatively higher over the heat-low area over Pakistan than over West Africa.

(*ii*) The trough of low pressure over the Gangetic Valley is not due to heat, but due to dynamical causes. Banerji (*loc. cit.*) has shown that it comes into existence as a result of influence of the Western Ghats, the Burma coast Arakan mountains and of the eastern Himalayas on the motion of moist air from the southern hemisphere drawn northwards across the equator in the circulation of the heat-low over Pakistan. If these mountain barriers were not there, the trough would not come into existence (Rao and Desai 1970 b); the air on both the sides of trough is moist.

No dynamic trough is produced over North Africa although there is heat trough there upto about 850 mb as there is absence of orographic barriers of the type over the Indian subcontinent; the absence of a dynamic trough over Africa is responsible for the occurrence of rain there only at some distance to the south of the boundary between the dry and moist airmasses, while over India the rainfall distribution is of a different type (Rao and Ramamurthi 1968). Raghavan (1973) would not appear to have appreciated the difference in distribution of rainfall over the trough area as well as the nature of the troughs.

(*iii*) Over Arabia and Iran no moist air is drawn into the heat-low circulation and it moves parallel to the coast, presumably due to the presence of the African continent with peculiar topographical features which deflects the moist flow across the equator from the South Indian Ocean to the Indian subcontinent where it causes considerable precipitation and from the South Atlantic Ocean to West Africa whence the moist air moves eastwards and causes rain on the western slopes of the Kenya-Ethiopian plateau and the hilly regions of eastern Sudan (towards the Red Sea).

(e) *Weather over North Africa and the Indian subcontinent*

This discussion as far as Africa is concerned, is based on papers of Hamilton and Archibold (1945), Eldridge (1957), Walker (1958), Johnson (1965), Samson (1965) and Frost (1969).

There are five zones of weather over West Africa. Zone A to the north of the boundary of SW-W'ly moist air at the surface, without any rain; zone B extending to about 3° to 4° south of the boundary between the drier and moist air-masses, having isolated thunderstorms on one to five days in a month in the afternoon or evening with about 3 inches rain; zone C extending to about 7° to the south of zone B—traversed by Disturbance Lines (D/Ls or line squalls) from east to west associated with thunderstorm and rain of short duration but of high intensity, total rain being nearly 5 inches per month, thunderstorms starting over high ground or near hills; zone D extending to about 3° south of zone C, having rain practically every day, being prolonged but less intense although it brings substantial amounts; it is called 'monsoon rain' and the belt of rain is east-west oriented rather than north-south as in zone C. Zone E is south of zone D and it is only a short distance inland and has cloudy weather with rain much less than in zone D and decreasing southwards. Dry thunderstorms in zone A may start later sometimes than thunderstorm in zone B. Rainfall is generally south of storm in Lat. 15°N in July in the SW-W'ly moist airmass, *i.e.*, to the south of the ITF at the surface.

According to Okylaja (1970) who studied wind data at different significant levels upto 300 mb, 700 mb level chart is most useful for following easterly waves which are associated with the westward moving semi-vertical lines of thunderstorms across West Africa during the rainy season; the 850 mb level chart is not considered as useful as the 700 mb level chart for tracking organised perturbations of synoptic scale.

In India at the beginning of the monsoon when there is a layer of moist SW-S'ly air about 0·5-1·5 km deep over West Bengal and Bangladesh and there is dry westerly continental air above, thunderstorms locally known as 'Nor'westers' develop, majority of them occurring in the afternoon and evening and moving from between SW and NW to between NE and SE, *i.e.*, in the direction of the upper drier current and many of them starting over and near plateau (Desai 1970); some of them are also caused in connection with the movement of troughs in the westerlies. Some thunderstorms occur during early mornings due to katabatic flow from hills. Rainfall is of short duration but often heavy. Tops of *Cb* clouds may extend to 12 to 15 km. Thus the Nor'westers of Bengal are very much like the D/Ls or line squalls of West Africa, the direction of movement being that of the upper drier air; the speed of their movement is more than that of the upper current in whose direction they move, larger speed being probably due to descent of air which has been humidified and cooled by falling rain.

Distribution of rainfall in India (Rao and Ramamurthi 1968; Rao and Desai 1973) is much different from that in Africa although effect of topography on rainfall is noticed in both the cases, but more in India than West Africa. In India rainfall distribution is considerably affected by the monsoon depressions which move W to NW-wards from the north Bay of Bengal and later change course to N or NE under influence of the troughs in the westerlies moving eastwards. There is much less rain in the lee areas of the Western Ghats and the Burma coast Arakan mountains as in West Africa in the Ivory coast and Ghana to the lee of the highlands of Liberia, Siera Leone and Guinea and in the eastern part of Ethiopia and in Somalia to the lee of the Ethiopian highlands. There is little rain in coastal areas of Kenya and in Somalia in spite of jet-speed S'ly moist winds between 600 and 2400 m over the area as there is no convergence and there is probably some divergence upstream from the equator northwards, S'ly changing to SW'ly towards the east and SE'ly to E'ly towards the west. The flow of moist winds is roughly parallel to the Kenya-Ethiopian highlands and little rain falls over their eastern slopes just as flow of moist southwesterly winds parallel to the western side of Aravallis cause little rain over their western slopes.

Rainfall in zone D is due to low level convergence in the SW'ly to W'ly air having humidity more than 80 per cent, which explains low base of the cloud nimbostratus; in the afternoon convection inland may give rise to *Cu* clouds and showers, but there are no thundersqualls as the *Cu* cloud, grow in moist air and there is probably no drier air above upto 500 mb or so in contrast to zone C where there is dry continental air above.

Over India a few of the depressions from the Bay of Bengal and low pressure areas which form over the north of the Peninsula moving westwards pass into the northeast Arabian Sea and intensify into storms; moving further westwards, they weaken and carry rains over the Oman Peninsula. According to Gilchrist (1960) over West Africa, depressions are best developed at 850 mb. Carlson (1969) has stated that wave disturbances from West Africa between Lats. 10° and 15°N move into the Atlantic Ocean and some of them intensify into hurricanes; according to him, the wave disturbances originate primarily east of the African bulge possibly over mountainous terrain.

The important point to be noted about rainfall is that while in Africa it begins to occur only at a distance of about 200 miles south from the northern boundary of the SW-W'ly moist air, in

India it begins right at the boundary and extends over a distance of 300 to 500 km in the SW-W'ly moist airmass even without presence of a disturbance, the easterly air to the north of the SW-W'ly air being dry in Africa and moist in India.

Both over West Africa and India, low pressure areas develop at the axis of the trough at the surface and at 850 mb and move westwards causing rain. It is possible for a cyclonic vortex to develop near the Somalia tip and move northeast to eastwards (Findlater 1971); they may stimulate the flow of SW'ly moist air in the West Arabian Sea. In India low pressure waves move from the east across Burma and stimulate monsoon activity; in Africa movement of low pressure waves from east from the Arabian Sea does not seem to occur below 500 mb.

The troughs in the westerlies affect considerably the monsoon activity in various ways (Desai 1967, 1970; Rao and Desai 1970, 1973); no such effects of westerly troughs would appear to be felt on rainfall in Africa except over Sudan and Eritria although the same pass over the area and there are no topographical barriers to obstruct their effect extending southwards in contrast to India where there are mountain barriers in the north. Over Sudan the ITF would appear to be pulled up northwards under the influence of the forward portion of the westerly troughs and cause rainfall there; over Eritria the ITF would appear to be pushed down southwards by the airmass in the rear of the troughs and cause rain over the area.

Desert over Sahara is due to absence of moisture and presence of anticyclone which prevents upward motion. Desert over northwest of the Indian subcontinent is there in spite of the presence of moist SW-W'ly air about 1 km deep because there is warm dry continental air above with an inversion between the two airmasses, the convective processes due to solar heating only weakening and not being able to break up the inversion to cause growth of large *Cu* and *Cb* clouds and rain (Desai 1969 b; Rao and Desai 1970 b).

(f) *Incidence of monsoon*

The northern boundary of the moist air in West Africa in January is over land near coast to the north of the equator and to the south of the equator in the Indian Ocean as mentioned earlier. With the heating of the continent as the summer advances the northern limit of the SW-W'ly moist air (deflected trades from South Atlantic) advances northwards in Africa, and over the Indian Ocean the trades from the South Indian Ocean crossing the equator flow as SW-W'ly winds to the Indian subcontinent. The setting up of the monsoon circulation both in Africa and India is due to heat, orography playing a considerable part in the formation of the Gangetic Valley trough in India and making the trough circulation self-sustaining in the lower level of the atmosphere, *i.e.*, upto about 600 mb level. The development of the easterly jet over India as well as over North Africa is not connected with the lower monsoon circulation. It should, however, be noted that over West Africa it often happens that greater depth of westerlies in the lower levels is associated with strong easterlies in the upper troposphere (Frost 1969); such association between the lower level westerlies and the strength of the upper tropospheric easterlies is not always present over India, there being no cause-effect relation between the two. Over India the shift of the westerly jet to the north of the Himalayas is not always related to the setting in of the lower level monsoon circulation (Rao and Desai 1970 b). It would appear that over India the atmosphere might be considered to consist of two layers, one extending from the surface to about 600 mb and the other from about 500 to 100 mb, the two layers developing independently of each other although sometimes the changes may occur simultaneously.

In Africa there is evidence of rainfall increasing over Sudan as the ITF moves northwards with surges in the moist air (Solot 1943) and periods of rainfall over Eritria being associated with the southward movement of the ITF (Samson 1965); these are associated with the forward and rear portions respectively of the troughs in the westerlies as mentioned earlier. In India with the surges in the moist SW-W'ly air rainfall increases considerably over the west coast of the Peninsula and the Arakan coast of Burma; on such occasion, however, there is generally no advance northwards of the axis of the Gangetic Valley trough and actually there may be frequently its movement southwards due to increase in the deflected moist easterly current to the north, rainfall increasing to the south of the axis due to increase in the slope of the boundary between the W'ly and E'ly moist airmasses (Desai 1970 a). Increase in rainfall also occurs over West Africa when the slope of the ITF increases between about 850 and 700 mb or so (Thomson 1965 – vertical cross-section in July from equator to Lat. 30°N along 0° meridian in his Fig. 5 in which rainfall is also given).

(g) *Some remarks on Thomson's (1965) statements*

(1) The pressure gradient between the southern hemisphere anticyclone and the heat-low is more in the case of the Pakistan heat-low than in the case of the West African one. This will mean more flow of air across the equator in the Arabian

Sea than in the Atlantic Ocean south of West African coast.

(2) The ridge of high pressure to the north of the equator over Somalia at the surface and 850 mb level has cyclonic circulation to its east; the west-east pressure gradient over Somalia is due to temperature contrast, high temperatures over land and low temperatures off the coast due to upwelling of water.

(3) Absence of rain north of about Lat. 15°N and to the south of the northern limit of the moist SW-W'ly air would appear to be due to considerable decrease in relative humidity as the air travels over heated land which would mean its rising to much higher level for the formation of cloud than further south and prevention of growth of cloud and its dissipation as soon as it meets overlying hot dry air and also due to shallow moist layer and not only due to subsidence on account of anticyclone above 850 mb level over the area; south of 15°N the depth of the moist layer is 1.5 km or more and surface humidity is also high. There might be an airmass inversion or isothermal layer between the lower moist and upper dry airmasses (Carlson and Prospero 1972), but insolation is apparently able to destroy the same to enable *Cu* and *Cb* clouds to grow and give thunderstorm rain — squall lines or disturbance lines in zone C.

(4) Less rainfall in zone E than in zone D is probably due to wind divergence over the area as a result of change in direction from SE to SW-W north of equator and cyclonic convergence occurring only to about north of the zone E. Further, winds blow either parallel to the coast or are very slightly offshore or onshore. There is also presence of locally cool water, the same being a northward extension of the Benegulla current. It should also be mentioned that in the Accra area air temperature is abnormally low. It is doubtful if the decrease in rainfall in zone E is due to extension of subsidence across the equator from the South Atlantic anticyclone from the surface to 850 mb level in spite of the ridge shown by Thomson in his 850 mb level chart near Long. 5°W as relative humidity at the surface and D.P. at 850 mb would not support the same. Further, the 850 mb level stream lines chart of Frost (1969) does not show presence of any ridge over the area.

As discussed earlier rainfall is less to the east of the Ethiopian mountains and over Somalia as the westerly moist air which is forced to rise by the mountain barrier, descends to the lee-side, thus increasing temperature, decreasing relative humidity and dissipating the clouds; further there is wind divergence over the area in spite of the presence of strong S'ly winds between about 600 and 2400 m, one branch going towards the Arabian Sea as SW'ly to W'ly current (running practically parallel to the eastern side of the Ethiopian plateau) and the other branch to the west as easterly current. It is doubtful if less rain is due to subsidence on account of high pressure ridge in the surface and 850 mb level charts over the area because as stated earlier the winds are SW'ly to the east side of the ridge and are also strong, the same being continuation of the strong flow across the equator in those levels.

(5) Less rainfall over Ghana and Ivory Coast is probably due to the causes mentioned under (4) besides the fact that they are on the lee-side of the highlands of Liberia, Sierra Leone and Guinea. Convergence between the moist current from SW to W and drier current from between W and N at the surface on the coast might also be responsible besides topography for high rainfall over Guinea, Sierra Leone and Liberia, the zone of convergence fluctuating north or south.

3. Summary and concluding remarks

Important points about the summer monsoons of Africa and the Indian subcontinent on the basis of the discussion are given below :

(*a*) The air from across the equator gets into circulation to the north of the equator under the influence of the heat-lows. The heat-lows are shallow in vertical extent, the one over Pakistan having lower pressure than that over North Africa.

(*b*) The depth of the moist SW'ly to W'ly current over the Indian Peninsula is about 6 km and over West Africa about 2.0 to 2.5 km.

(*c*) The SW-W'ly moist air causes orographic rain, the effect being more pronounced over India than over Africa. On the lee-side of the orographic barriers rainfall is considerably less, *e.g.*, the lee-side of the Ethiopian highlands in Africa, of the Western Ghats in India and of the Arakan coast mountains in Burma.

(*d*) Disturbances develop at the northern boundary of the moist air at the surface and at 850 and 700 mb and they move westwards ; over India such developments also occur in addition at the northern boundary of the moist airmass at 500 mb. The associated weather developments are small in Africa while they are considerable over India.

(*e*) There is an airmass inversion between the lower cool moist and upper warm dry airmasses. The continental air becomes colder than the moist air over India and the East Arabian Sea above the reversal level due to a difference in the lapse rates in the two airmasses; over West Africa such changes are not noticed as the moist current is shallow there, but the continental air becomes relatively colder than the tropical environment above 650 mb over the Caribbean area.

(*f*) Both over India and Africa there is tropical easterly air above 500 mb.

(*g*) The monsoon rain occurs with little ascent of air as it has 90 per cent or higher humidity at the surface and nimbostratus base might be only at about 100 m or so.

(*h*) There is anticyclone over the heat-low in Africa above about 850 mb ; over India there is anticyclone to the west of the heat-low at the surface, only at 700 and 800 mb and also to the east at the latter level. Over the heat-low over Pakistan there is dry warm air from west to north from 1 to 3 km and warm subsided dry air and/or moist easterly air above between about 3 and 6 km. Over Sahara there is absence of moist air from across the equator and there is subsidence of air, while over the northwest of the Indian subcontinent there is moist air upto about 1 km, but the development of clouds and rain is prevented by the hot dry air above, besides the fact that cloud development can take place at much higher level inland than over the coast as the relative humidity decreases considerably as the moist air travels over heated land.

(*i*) There is development of a dynamic trough over the Gangetic plain associated with the heat-low over Pakistan and this trough extends to about 500 mb, its axis sloping southwards with height; on both the sides of the axis of the trough there is moist air, the easterly moist air upto about 600 mb being the SW'ly to W'ly moist air which has been deflected by the Arakan coast mountains and the eastern Himalayas. No such dynamic trough is associated with the African heat-low although there is a heat trough over Africa at the surface and 850 mb; the air to the north of the axis of the trough is dry easterly air having its origin in the anticyclone over Sahara.

(*j*) While over Africa rain begins only at a distance of about 300 km to the south of the northern boundary of the SW'ly to W'ly moist air, over India it begins right from the northern boundary at the surface and extends south in the moist air upto about 400 km to the south of the surface position of the boundary even without the presence of a depression. Over Africa upto about 1000 km south of the axis, *i.e.*, upto about Lat. 10°N, rain generally occurs in the afternoons and evenings and is associated with Disturbance Lines or 'Squall Lines' moving from east to west in the direction of the upper drier continental airmass ; no such disturbance lines occur over India to the south of the axis in the moist air at the surface. In India such an airmass stratification as over West Africa between about Lats. 17° and 10°N, occurs over northeast India in April and May when there is moist S'ly to SW'ly air in the lower layers and dry continental W'ly to NW'ly air above with an inversion between the two airmasses and 'Nor'westers' or thundersqualls occur which travel E to SE-wards in the afternoons and evenings giving heavy rain for a short duration.

(*k*) The rainfall distribution both in space and amounts is much better over India than over Africa, the movement of depressions from the north Bay of Bengal W to NW-wards giving considerable rain in the southwest quadrant of the depression.

(*l*) The troughs in the westerlies moving eastwards have little effect on the weather during the summer monsoon over Africa except in Sudan and Eritria south of the northern boundary of the moist air ; in India they affect the weather considerably.

(*m*) The moist W'ly winds over the Peninsula over India are much stronger than over Africa as they are a continuation of southerly strong winds across the equator between about Longs. 38° and 45°E. No strong winds occur over the eastern Atlantic south of the West African coast.

(*n*) The length of travel of the air over the seas from near the southern anticyclones is considerably more in the case of India than West Africa.

(*o*) Temperatures are higher by about 5°C at 500, 300 and 200 mb level and occur generally in more northerly latitudes over the Indian area (actually over Tibet) than over Africa.

(*p*) Both the westerly and easterly jets occur in more northerly latitudes over the Indian area (near 40°N and 15° N respectively) than over Africa.

It will appear from the above summary that there are many similarities and differences between the summer monsoons of Africa and India. The primary cause of the monsoon is the same in both the cases, but the southerly strong winds across the equator in the Western Indian Ocean and the adjoining coastal area of Kenya and Somalia and peculiar topographical features of the Indian subcontinent which affect the flow of air from across the equator upto about 600 mb, make the summer monsoon circulation more intense from the point of its performance in terms of rainfall in India than in Africa.

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