

Zonal anomaly of sea surface temperature in equatorial Indian ocean and its possible effect upon monsoon circulation

By KSHUDIRAM SAHA, *Institute of Tropical Meteorology, Poona-5, India*

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ABSTRACT

The paper calls attention to the existence of a well-defined zonal anomaly of sea surface temperature between the equatorial west and east Indian ocean. The effect of this anomaly on ocean-atmosphere exchange and low-level air circulation in the equatorial Indian ocean as well as the Arabian Sea are discussed. It is shown that phenomena like the equatorial westerlies, the double intertropical convergence zone, and the Somali Jet receive plausible explanation on the basis of the observed zonal anomaly of ocean temperature. The effect of upwelling and its eastward advance in the Arabian Sea during the southwest monsoon are discussed in detail and it is suggested that this effect through air-sea interaction may change the low-level air circulation over the Arabian sea in a manner which may affect the distribution of rainfall along the west coast of India as well as inland during August and also explain frequent occurrence of feeble low pressure troughs in the southeast Arabian Sea during this period. Vertical circulation cells attributable to the observed anomalies of ocean temperature and their possible effect upon monsoon circulation and rain are discussed.

1. Introduction

The Indian monsoon is the most dominant feature of tropical circulations, which is set up and maintained by large-scale seasonal temperature differences between the ocean and the continent. During summer, the monsoon wind converges towards the hot continent where it rises and then returns to the ocean via the upper troposphere. In winter, the temperature field reverses and the circulation is in the reverse direction with rising air over the warm ocean and sinking air over the cold continent. This mean circulation which is controlled by meridional temperature differences is, however, considerably modified by zonal anomaly of continental or ocean temperature. Bjerknes (1966, 1969) has discussed the possible response of atmospheric Hadley circulation to equatorial anomalies of ocean temperature in the Pacific. In the Indian ocean, similar equatorial anomaly of ocean temperature is observed. The paper discusses the distribution of this anomaly and its possible effect upon atmospheric circulation in this region.

2. Zonal anomaly of sea surface temperature

If T_s is the sea surface temperature at five degree longitude points along a latitude circle and $\bar{T}_s$ the average sea surface temperature over the parts of that latitude lying over the Indian ocean, the zonal anomaly may be defined by ΔT_s , where $\Delta T_s = (T_s - \bar{T}_s)$. Fig. 1 shows the values of ΔT_s over the Indian ocean between about 25° N and 25° S during Jan.-Feb. and July-Aug. 1964, adapted from a paper by Miller & Jefferies (1967). The values of $\bar{T}_s$ are given on the ordinate at five-degree interval. It may be seen that during both the winter (January-February) and the summer (July-Aug.) monsoon seasons of 1964, departures of sea surface temperature from the zonal mean are negative over the West Indian Ocean and positive over the east Indian ocean, the mean dividing line along the equator being about 60° E. Similar distributions were also obtained during 1963 but not presented for lack of space. The anomalies over the Arabian sea are pronounced during the summer as compared to

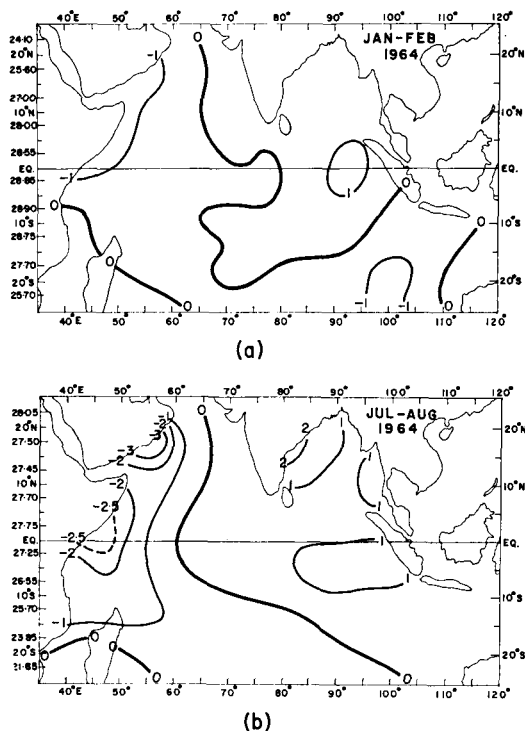


Fig. 1. Distribution of zonal anomaly of sea surface temperature ΔT_s in degree centigrade during 1964: (a) Jan.-Feb., (b) July-Aug. Zonal mean sea surface temperature T_s is given on the ordinate at 5-degree latitude intervals in °C.

the winter because of the effect of intense upwelling caused by strong off-shore winds during the summer at the coasts of Somalia and Arabia. The progressive eastward movement of cold water brought to surface by upwelling may be seen in Fig. 2 which shows the longitudinal position of the 80°F isotherm of both water and air during June through October

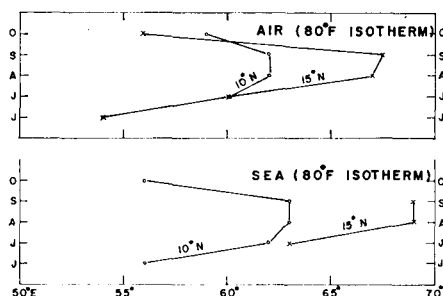


Fig. 2. Longitudinal position of average air and sea surface isotherm, 80°F, along 10° N and 15° N during June through October in the Arabian sea.

along latitudes 10° and 15° N over the Arabian sea. Fig. 3 shows the monthly variation of mean air and sea surface temperature at two fixed points, one in south Arabian sea (position 5° N, 50° E) and the other in south Bay of Bengal (position 5° N, 90° E). Data for Figs. 2 and 3 were taken from Air Ministry (1949). It is believed that these temperatures are sufficiently representative of conditions in the west and east Indian ocean and bring out the characteristic difference between the thermal energy regimes between the two parts of the ocean. In particular, it may be noted that sea surface temperature is greater than air temperature in the east Indian ocean practically throughout the year, whereas in the west Indian ocean, the sea surface temperature falls markedly below the air temperature during the summer monsoon season. As it will be shown later, this difference which is principally caused by upwelling of cold water over the Arabian sea during the summer monsoon months not only accounts for marked differences in the weather and climatic conditions over the two parts of the north Indian ocean but also has great significance in the context of the monsoon circulation and rainfall over India.

3. Ocean atmosphere interaction

During the HIOE period (1963-64) a large number of reports from sea-going vessels in the Indian ocean were available at the International Meteorological Center, Bombay. Based on these reports, the center (Miller, Sivaramakrishnan, and Suryanarayana, 1963) computed mean energy fluxes across the air-sea interface during different months. The fluxes computed comprised the latent heat of evaporation (Q_E) and the sensible heat (Q_h). Figs. 4 and 5 present respectively the values of latent heat and sensible heat fluxes during January and July 1964.

Fig. 4 shows the following features: (a) During January, latent heat flux is high over the central and south Arabian sea as well as over the Indian ocean south of about 15° S, but low over a wide belt of the east Indian ocean extending from near Mauritius to Malaya and also over north Bay of Bengal. (b) During July, the latent heat flux is high over the central and south Arabian sea as well as over the south

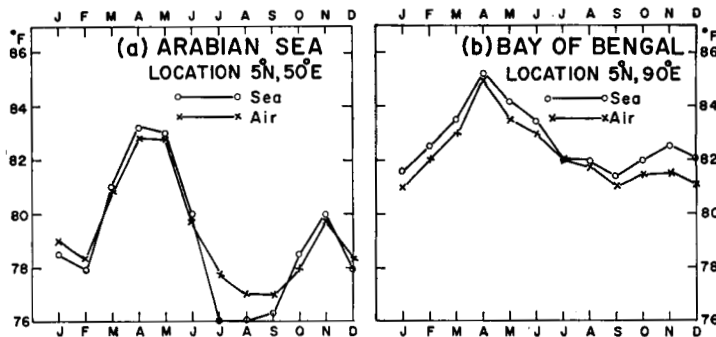


Fig. 3. Monthly variation of average air and sea surface temperatures in (a) the Arabian sea (location, 5° N, 50° E) and (b) the Bay of Bengal (location, 5° N, 90° E).

Indian ocean as in January but low over the equatorial Indian ocean. The belt of high latent heat flux over the south Indian ocean appears very prominent during July. The distribution of latent heat flux during July 1964 as presented in Fig. 4, agrees broadly with that found by Suryanarayana & Sikka (1965) for 1963.

Fig. 5 which shows the distribution of sensible heat flux (negative values indicate downward fluxes) shows the following features: (a) During January, sensible heat flux is positive over most of the Indian ocean north of about 15° S except a small area in equatorial west Indian ocean. High upward fluxes appear over most of the Arabian sea and the northern part of the Bay of Bengal as well as over a wide belt of the east Indian ocean with maximum values about 5° to 10° south of the equator. Low values of positive sensible heat flux appear over southeast Arabian sea and central Bay of Bengal. (b) During July, a wide area of negative sensible heat flux appears over the west Arabian sea with values exceeding -40 gm-cal/cm²/day near cape Guardafui and a small area of feeble negative sensible heat flux off the east coast of Indian peninsula. Positive values of sensible heat flux appear generally over the east Indian ocean with maximum values of about 20–30 gm-cal/cm²/day along about 5° south of the equator.

The response of the atmosphere to the above distribution of heat energy fluxes may now be considered. Broadly, non-adiabatic heating or cooling of the atmosphere through the air sea exchanges will affect the temperature, pressure, humidity, and the vertical stability of the lower atmosphere. The equation of continuity for

water vapour demands that flux divergence should balance the difference between the rates of evaporation and precipitation in any volume of air. Hence one may expect water

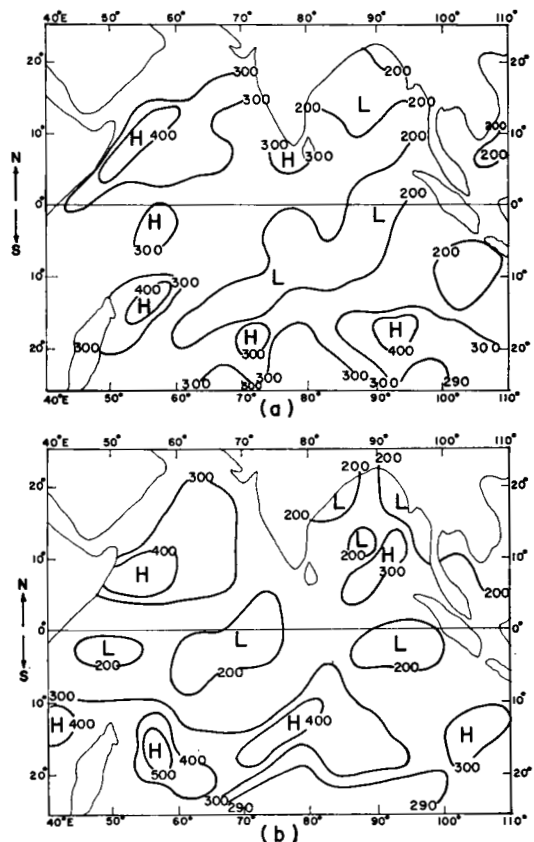


Fig. 4. Distribution of latent heat of evaporation over the Indian ocean during 1964: (a) January, (b) July. Unit: gm-cal/cm²/day.

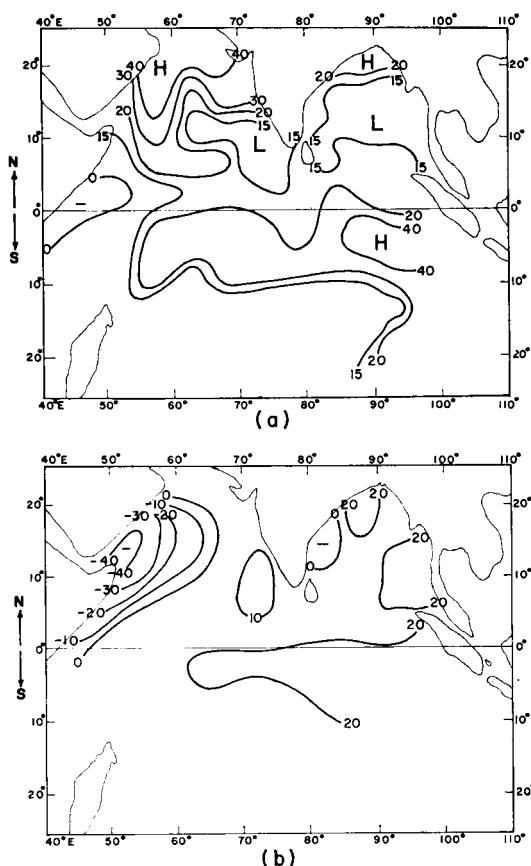


Fig. 5. Distribution of sensible heat flux over the Indian ocean during 1964: (a) January, (b) July. Unit: gm-cal/cm²/day. Negative values indicate downward flux.

vapour to diverge from areas of high evaporation over the west Arabian sea and the south Indian ocean where there is little precipitation and converge to areas of low evaporation over the equatorial east Indian ocean to become available there for condensation and precipitation. The release of latent heat of condensation will lead to atmospheric heating. This appears to be an important point, for although water vapour diverges from areas of high evaporation, the latent heat becomes available for atmospheric heating in areas of condensation and precipitation only. Continued non-adiabatic heating of the atmosphere in areas of condensation and upward sensible heat flux will lead to lowering of atmospheric pressure, and cooling of the atmosphere in areas of high evaporation and downward sensible heat flux will lead to raising of pressure. Fig. 6 shows the equatorial distribution of m.s.l. barometric pressure as well as mean sea surface temperature during July 1964. The data of sea surface temperature east of 97.5° E relates to 2.5° S latitude since data along the equator in this region were not available. It may be seen from Fig. 6 that the distribution of m.s.l. barometric pressure is highly correlated with the mean sea surface temperature, high pressure appearing over cold sea in the west and low pressure over warm sea in the east.

4. Effect on airflow

(a) Equatorial Westerlies

The response of the atmosphere to anomalies of sea surface temperature would seem to set up

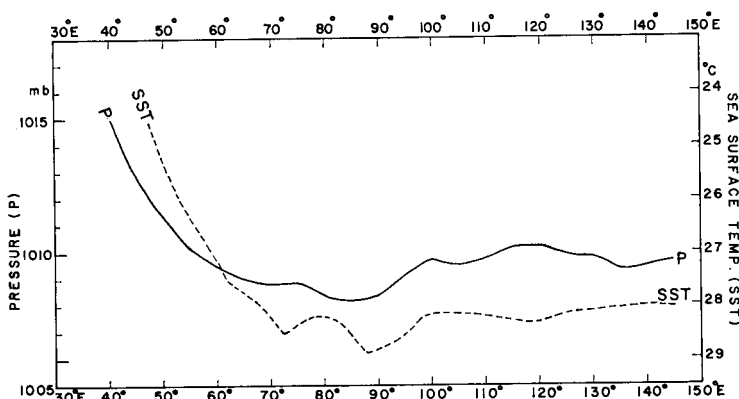


Fig. 6. Equatorial distribution of m.s.l. pressure (p) and sea surface temperature (SST) during July, 1964. Values of SST east of 97.5° E longitude refer to 2.5° S latitude.

secondary air circulations. Perhaps, the most conspicuous of these in the equatorial Indian ocean are the equatorial westerlies, no fully satisfactory explanation for which has yet been advanced. The bending of the southeast trades of the southern hemisphere on approaching the equator during the northern summer was first noted by Meinardus (1893). Later, it was noted that during the northern winter also, the northeast trade winds of the northern hemisphere undergo similar transformation into equatorial westerlies in some regions on approaching the equator. But observations show that equatorial westerlies are more of a characteristic feature of the east Indian ocean than the west Indian ocean. Raman (1965) had hinted at a possible connection between equatorial westerlies and distribution of sea surface temperature in the Indian ocean, but no detailed discussion of the type of connection that may exist is presented. As shown in Fig. 6, the presence of a secondary high pressure ridge over the west Indian ocean and a low pressure over the east Indian ocean that develop in response to zonal anomalies of sea surface temperature would accelerate air along the equator under the observed pressure gradient which runs from west to east, giving rise to the westerlies. Matsuno (1966) in a theoretical treatment has shown the feasibility of such westerly winds when mass sources and mass sinks in the form of high pressure and low pressure are introduced along the equator in the manner described above.

(b) Double equatorial trough or intertropical convergence zone

The tendency for the trade winds approaching the equator to turn into the equatorial westerlies in response to equatorial anomalies of sea surface temperature leads to the formation of the so-called double ITCZ, one in each hemisphere, in the Indian ocean region. The general low pressure area over the warm equatorial waters, is separated by the equatorial westerlies resulting in two troughs, one north of the equator and the other south of the equator. According to this concept, one may see that the presence or absence of equatorial westerlies or, for that matter, the double equatorial troughs on any occasion is very much dependent upon equatorial anomaly of sea surface temperature. It is only when a large warm area lies across the equator

extending into both the hemispheres that these winds and troughs should be expected. This may explain why equatorial westerlies as well as double equatorial troughs or ITCZs are not a permanent feature of the Tropics over the whole globe but appear only when and where the above conditions are fulfilled. It is a fact in those regions where warm equatorial water extends into both the hemispheres and may be seen, on global basis, in the Pacific as well as the Indian ocean.

(c) Somali Jet

A most interesting case of atmospheric interaction with the underlying surface in the Indian ocean region occurs in the West Indian ocean near the coast of Somalia during the northern summer monsoon. This is the Somali Jet (Findlater, 1969). As noted before, the sea surface near the coast of Somalia is extremely cold with a mean temperature which is even lower than 24°C during this period and by contrast the northeastern part of the continent of Africa is extremely hot (~34°C). The steep pressure gradient that develops across the Somalia coast in response to these extreme temperature differences guides a system of very strong low-level winds over the west Indian ocean known as the Somali Jet. An explanation of these winds, based on air-sea interaction, was first offered by Bunker (1965).

(d) Low-level circulation over the Arabian sea and monsoon rain

The ridge of high barometric pressure that develops over the Arabian sea off the coast of Somalia during June and progressively shifts eastward as cold water advances towards India during July and August appears to bring about a profound change in the low-level air circulation over the Arabian sea. In June, when the ridge lies near the coast of Somalia, the winds over practically the whole Arabian sea blow from a direction between west and southwest. Even during July when the ridge advances eastward, there is little change in the direction of the wind except in the central parts of the Arabian sea where slight veering is observed. Sometime during August, the tongue of cold water and the associated pressure ridge reaches its maximum eastward position to about 69° E longitude (Fig. 2). In this position, the air flow over the Arabian sea is markedly affected.

There is general veering of the winds especially over the east Arabian sea where the wind now blows from a direction between west and north-west. This change in wind direction appears very significant, for it may mean that monsoon flow across the northern part of the west coast of India is suddenly weakened, resulting in deficient precipitation not only over the coast but also inland. If the flow is directed towards south India, it may be that the southern part may experience more rain than the northern part. During this period, a number of low level pressure troughs are also observed to form in the southeast Arabian sea off the west coast of India. It is plausible that a large proportion of these troughs are generated in situ between the high pressure area over the south Indian peninsula and the Arabian sea high pressure ridge approaching the coast of India in the manner described above.

5. Secondary vertical circulation cells

Lastly, the paper considers the possibility of local or regional vertical circulation cells arising in both meridional or zonal planes, in response to observed anomalies of sea surface temperature in the Arabian sea as well as in the equatorial Indian ocean. During the northern summer, a vertical circulation cell with its descending branch over the west Arabian sea near the coast of Somalia and ascending branch over the east Arabian sea near the west coast of India would seem to be in order. This will have W/SW winds in its lower limb and E/NE winds in the upper. Another vertical circulation cell may be visualised across the coast of Somalia with its descending branch over the cold waters and ascending branch over the hot desert land of Somalia and Eritrea. An Equatorial vertical circulation cell with its ascending branch over the warm equatorial waters of the east Indian ocean and descending branch over the cold waters of the west Indian ocean is a distinct

probability. It will have equatorial westerlies in its lower limb and equatorial easterlies in the upper limb (above about 500 mb level). Such east-west equatorial circulation has been termed "Walker circulation" by Bjerknes (1969). Secondary meridional circulation cells may also be set up between the warm equatorial waters and the cold waters that lie in the south Indian ocean.

It is possible that the above vertical circulation cells have important effects upon monsoon circulation especially its interhemispheric exchanges. The formation of a strong Walker circulation along the equator with its rising branch over the east Indian ocean and descending branch over the West Indian ocean in response to equatorial anomalies of ocean temperature is likely to divert the moisture-bearing lower-tropospheric trade winds which ordinarily cross the equator in the west Indian ocean with strong meridional components into air currents with strong westerly components with the result that interhemispheric exchanges may be reduced. Such reduction of air and moisture fluxes from the southern hemisphere during the SW monsoon may considerably affect monsoon rainfall over India.

6. Conclusion

The paper calls attention to existence of zonal anomalies of Sea surface temperature in the Indian ocean region and its possible effect upon the monsoon circulation. Some of the outstanding features of the monsoon circulation, such as the equatorial westerlies, the double equatorial trough or ITCZ, the Somali Jet and secondary vertical circulation cells appear to find plausible explanation in terms of the observed anomalies of ocean temperature. Possible effect of the secondary circulation cells arising out of anomalies of ocean temperature upon monsoon rainfall over India is briefly discussed.

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ЗОНАЛЬНАЯ АНОМАЛИЯ ТЕМПЕРАТУРЫ ПОВЕРХНОСТИ МОРЯ В ЭКВАТОРИАЛЬНОЙ ЧАСТИ ИНДИЙСКОГО ОКЕАНА И ЕЕ ВОЗМОЖНОЕ ВЛИЯНИЕ НА МУССОННУЮ ЦИРКУЛЯЦИЮ

Статья обращает внимание на существование хорошо выраженной зональной аномалии температуры поверхности моря между западной и восточной частями Индийского океана в экваториальной области. Обсуждается влияние этой аномалии на взаимодействие океана и атмосферы и циркуляцию воздуха в нижних слоях в экваториальной части Индийского океана и в Аравийском море. Показано, что такие явления, как экваториальные западные ветры, двойная внутритропическая зона конвергенции и Сомалийское струйное течение, получают правдоподобное объяснение на основе наблюдаемой зональной аномалии температуры. Детально обсуждается эффект подъема глубин-

ных вод и их распространения на восток в Аравийском море во время юго-западного муссона. Выдвигается предположение, что этот эффект, вследствие взаимодействия океана и атмосферы, может изменить циркуляцию нижних слоев атмосферы над Аравийским морем и тем самым повлиять на распределение осадков вдоль западного берега Индии и на самом материке в августе. Указанный эффект объясняет также частую повторяемость слабой депрессии на юго-востоке Аравийского моря в этот период. Обсуждаются вертикальные ячейки циркуляции, вызываемые аномалиями температуры океана, и их возможное влияние на муссонную циркуляцию и осадки.