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THE DOUBLE INTERTROPICAL CONVERGENCE ZONE IN THE INDIAN OCEAN : FACT OR FICTION ?*

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ABSTRACT

The question of occurrence of double intertropical convergence zone in the Indian ocean is examined with available daily satellite cloud photographs during the period July, 1966 through September, 1970. The evidence indicates that its occurrence in the Indian ocean is much more frequent than that in other oceans. Theoretical studies as well as observational evidence suggest that its formation in the Indian ocean may be intimately related to geographical distribution of ocean surface temperature. Possible nature of this relationship is discussed.

INTRODUCTION

DURING the Second World War, pilots flying the India-Australia route during the northern summer monsoon had reported strong equatorial Westerlies and a concentrated latitudinal zone of cloudiness and precipitation a few degrees south of the equator (Fletcher, 1945). During the period of the International India ocean Expedition (1963-64), a number of workers had noted the presence of a double equatorial trough zone a few degrees south of the equator with the primary ITCZ lying over northern India during northern summer. After the introduction of satellites, the presence of a double cloud zone south of the equator during northern summer was more clearly seen. However, Hubert, Krueger, and Winston (1969) who computed mean cloudiness over tropical oceans on the basis of cloud brightness data for 1967 have recently concluded that the Indian ocean does not exhibit any double tropical cloud zones. In an article to be published shortly, Saha (1971) has produced direct evidence from daily satellite photographs of days of occurrence of double cloud zones in the Indian ocean in different months over a 51-month period and compared the position with similar statistics in respect of the Pacific ocean. The present study constitutes an extension of the earlier work with a possible physical explanation for the double cloud zones on the basis of thermodynamical processes that are forced by distributions of ocean surface temperature. Theoretical studies which suggest involvement of ocean surface temperature in the formation of double ITCZ have been recently reviewed by Saha (1970).

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OBSERVATIONAL EVIDENCE

Plate IA-D present four satellite photographs of typical double cloud bands in the Indian ocean, two during the winter monsoon and two during the summer monsoon. Table 1 gives the number of days of occurrence of double cloud bands in the Indian ocean during the period July, 1966 through September, 1970, as derived from daily APT satellite photographs. It may be seen that during the 51-month period double cloud bands formed in all months except two. This position may be compared with that in the eastern Pacific ocean shown in Table 2 which gives the number of days of occurrence of double cloud bands in that ocean during the period February, 1967 through March, 1969. The contrast is very glaring. The statistics shows that whereas in the eastern Pacific Ocean the double cloud bands occur mainly during northern late winter and spring, in the Indian ocean they occur practically throughout the year.

No double ITCZ has been reported from the Atlantic Ocean so far.

TABLE 1. *Number of days of occurrence of double cloud bands in equatorial Indian Ocean during July,* 1966 *through September,* 1970

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1966 ..	*	*	*	*	*	*	23	15	12	12	8	15
1967 ..	4	6	4	3	3	3	3	6	4	2	0	3
1968 ..	4	4	8	5	3	7	5	8	12	9	14	14
1969 ..	3	3	1	0	6	4	6	7	7	2	3	1
1970 ..	5	11	6	2	3	11	4	4	5	—	—	—

* APT pictures not available.

THEORY OF DOUBLE ITCZ

A fully satisfactory theory to explain formation of double cloud bands in tropical oceans is yet to come. However, very encouraging efforts have recently been made by a number of workers, using numerical models. The work of Charney (1967) and Pike (1968, 1970) stand out amongst these. An earlier theoretical work of Matsuno (1966) on stationary atmospheric circulation in equatorial region also appears to have bearing on the problem. For a brief review of these theoretical treatments in so far as they relate to the formation of double cloud bands, a reference may be made to paper by Saha (1970). It may, however, be noted here that although the results of theoretical experiments are all different depending upon different simplifying assumptions, they all seem to emphasise the role of ocean surface temperature in the genesis of double convergence zones or double cloud bands. While Matsuno's ideas of stationary atmospheric circulation in equatorial region envisages a mass flow from high pressure to low pressure along the equator when mass sources and sinks are placed alternately along the equator, thereby bifurcating original mass sink into two sub-sinks each forming a low pressure or trough on either side of the equator, Charney has used both linearised as well as non-linear models to simulate the formation of an intertropical convergence zone. The main idea advanced by Charney is that continued boundary layer convergence under conditions of conditionally unstable thermal stratification may lead to development of a convergence zone which in tropical oceans will be attracted to region of maximum ocean surface temperature. Pike using a two dimensional non-linear primitive equation model has proceeded on similar lines but, through different parameterisations, shown that although frictional boundary layer convergence as visualised by Charney plays an important role in deciding the initial location of an ITCZ, it is ultimately the ocean surface temperature maximum that decides the stable location of the convergence zone. In the present paper, conditions over Indian ocean are studied in relation to ocean surface temperature in order to assess the likely formation of double intertropical convergence zone over this ocean. The effect of meridional distribution of ocean surface temperature only are considered.

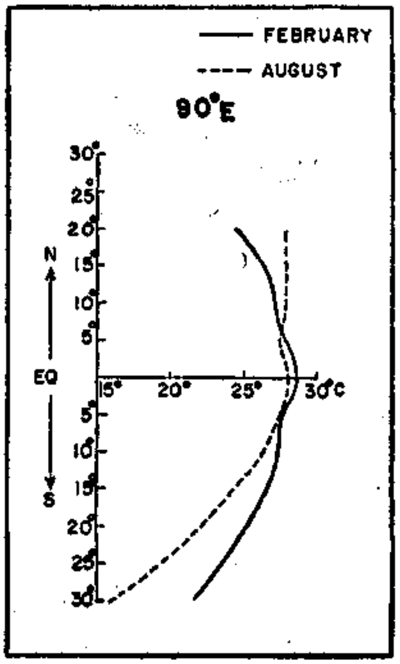

Fig. 1. Meridional profiles of mean ocean surface temperature during February and August, along 90°E. (After Sverdrup *et al.* 1942).

Meridional Distribution of Mean Ocean Surface Temperature

Observations show that double cloud bands in the Indian ocean are characteristic features of equatorial eastern Indian ocean, east of about 60°E. During the northern summer, the double ITCZ is located between the equator and latitude about 10°S, whereas during the northern winter its location may be anywhere between the equator and latitude about 10°N. In view of this observational evidence, it may be appropriate to consider the distribution of mean ocean surface temperature in equatorial eastern Indian Ocean. Fig. 1 shows meridional profiles of mean ocean surface temperature during February and August along 90°E, taken from Sverdrup *et al.* (1942). It may be seen that during both February and August which may be taken as representative months of winter and summer monsoons respectively, equatorial eastern Indian ocean is warm compared to latitudes lying away from the equator. In fact, the August distribution shows a uniformly warm equatorial ocean northward of about 5°S with temperatures decreasing south of this latitude. During February, the surface temperature maximum appears to be located almost on the equator.

Conditionally Unstable Atmosphere

Observations show that the equatorial eastern Indian ocean being the warmest oceanic region, airstreams approaching this region get continuously warmed and humidified in their lower layers during both the monsoon seasons. Table 3 gives the values of mean air temperature and humidity-mixing-ratio of Calcutta and Port Blair during February, 1964 and Table 4 the corresponding quantities in respect of Mauritius (Vacoas), Cocos Island, Diego Garcia and Gan Island during August, 1963. It is evident from Table 3 that the atmosphere over Port Blair which lies nearer the equator is warmer and more humid than Calcutta during February. Table 4 shows that Diego Garcia and Gan Island are much warmer and more humid than Mauritius or Cocos Island during August. The vertical distributions of temperature and humidity as shown in Tables 3 and 4 suggest that there must be mechanisms over warm equatorial waters to cause increased convection and lifting of heat and water vapour to higher levels of the atmosphere. Continued upward flux of heat and moisture into the lower layers of the atmosphere leads to conditions of conditional or convective instability in which the equivalent potential temperature decreases with height but a convergence mechanism must operate to cause large-scale upward motion and realise the energy of the unstable atmosphere. In Fig. 2 are presented the values of equivalent potential temperature at different pressure levels

Table 2. *Number of days of occurrence of double cloud bands in equatorial Eastern Pacific*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1967 ..	0	4	18	0	0	0	0	0	0	0	0	0
1968 ..	0	0	6	7	0	0	0	0	0	0	0	0
1969 ..	0	0	4	0	0	0	0	0	0	0	0	0

in respect of Calcutta and Port Blair during northern winter (February, 1964) and Mauritius and Diego Garcia during northern summer (August, 1963). It is evident from the vertical distribution of equivalent potential temperature shown in Fig. 2 that the lower troposphere over Port Blair is convectively more unstable $\left(\frac{\partial \theta e}{\partial z} < 0\right)$ than that over Calcutta during northern winter. Likewise, the lower troposphere over Diego Garcia is much more unstable than that over Mauritius during northern summer.

Boundary Layer Convergence

Charney (*loc. cit.*) has discussed in detail the role of frictionally induced boundary layer convergence in the development of tropical circulation systems such as the ITCZ by causing increased upward motion and lifting and condensation of water vapour in a conditionally unstable atmosphere. He has, however, shown that the location of the system is determined by the joint effects of the boundary layer convergence and the ocean surface temperature maximum which produces the maximum convective instability. Charney has also clarified that the effect of an ocean surface

TABLE 3. *Vertical distribution of mean air temperature (°C) and humidity-mixing-ratio at Calcutta and Port Blair during February, 1964*

Pressure level	Calcutta 22.7°N 88.5°E (00Z)		Port Blair 11.7°N 92.7°E (00Z)	
	TT	m.r.	TT	m.r.
1000	18.2	11.0	24.0	17.3
950	18.2	8.2	22.8	12.6
900	16.1	7.2	20.6	10.8
850	13.3	6.0	17.4	9.5
800	10.2	4.4	14.7	6.9
700	3.6	2.9	9.0	3.8
600	−3.6	1.3	2.8	2.4
500	−11.6	—	−5.8	—

TT Stands for air temperature and m.r. for humidity-mixing-ratio.

temperature maximum lies not so much in producing greater vertical instability as increased horizontal convergence in the boundary layer through 'thermal wind' effect. It is proposed to discuss this 'thermal wind' effect in some detail in relation to conditions in the Indian ocean. An appropriate area for this discussion may be the southern Indian Ocean where a steep meridional ocean surface temperature gradient exists during northern summer between about 15°S and 5°S, east of longitude about 60°E (Fig. 1). Table 3 shows equatorward increase in air temperature in this belt practically at all levels in the lower troposphere.

The thermal wind equation derived under geostrophic approximation may be stated in the following form :

$$\frac{\partial \vec{V}}{\partial p} = -\frac{R}{p\bar{f}}\,\vec{k}\times\nabla_p\,\bar{T}$$

where $\vec{V}$ is the wind vector,
p is the pressure co-ordinate
R is the Gas constant for dry air ($= 2.87 \times 10^6$ ergs per degree absolute)
T is the air temperature in degrees Absolute
f is coriolis parameter
$\vec{k}$ is vertical unit vector
and ∇_p is gradient vector along an isobaric surface and the bar denotes mean values.

With an equatorward increase of air temperature at the rate of about 1°C per 200 km near ocean surface at location 7.5°S, where the mean sea level pressure is about 1010 mb and the value of f may be taken as about -2.0×10^{-5} sec^{-1}, it may be shown from the above thermal wind equation that a zonal wind component

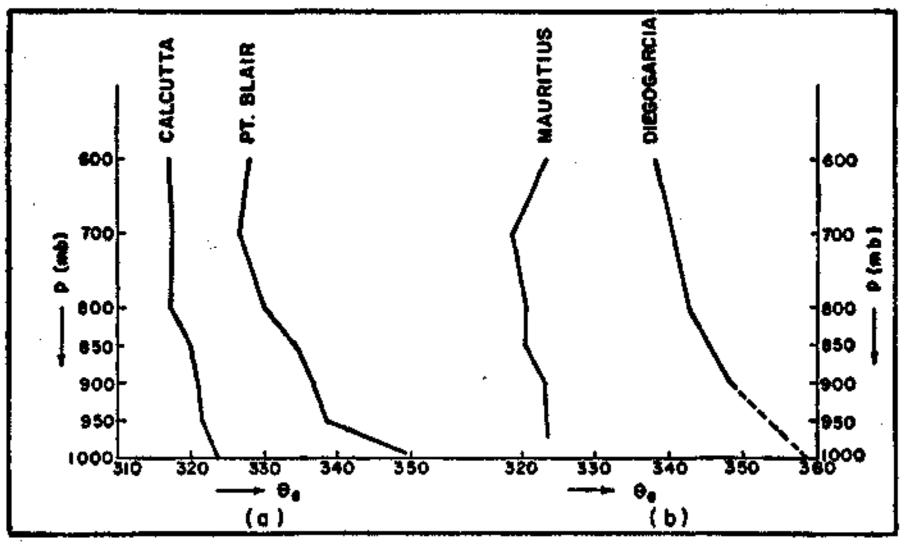

Fig. 2. Distribution of mean equivalent potential temperature with pressure at (a) Calcutta and Port Blair during February, 1964 and (b) Mauritius and Diego Garcia during August, 1963.

of —7.5 m/s of the south-east trade wind will reverse its sign at an altitude of about 1.0 km above ocean surface. In other words, a westerly thermal wind causes a continual gain of westerly momentum with height. The consequence of this variation of wind with height is creation of increased negative relative vorticity with height a few degrees south of the equator, which would in all probability lead to increased boundary layer convergence in this region. Fig. 3 shows schematically the streamline patterns at the top and bottom of a boundary layer of approximate thickness 1.5 km a.s.l. that should be expected under 'thermal-wind' effect discussed above. Fig. 3 also shows corresponding streamline patterns over the Bay of Bengal where the thermal wind effect produces increased positive relative vorticity with height in equatorward moving air during northern winter. Available actual wind observations over equatorial eastern Indian Ocean appear to confirm these patterns. Figs. 2 and 3 would seem to explain how increased boundary layer convergence in equatorward moving airstreams under conditions of convectively unstable atmosphere may lead to formation of marked cloud and precipitation zones near the equator by pumping up moisture to layer above condensation level. Actual observations show that during August, 1963, the mean cloud amounts and precipitation at Mauritius were 5.2 Oktas and 25.2 mms respectively, whereas those at Diego Garcia were 6.0 Oktas and 440.3 mms respectively. Also during February, 1964, the mean cloud amount and the mean precipitation at Calcutta were 2.7 Oktas and 9.0 mm respectively, whereas at Kondul (7.2°N, 93.6°E) which lies near the equator the corresponding quantities were 5.3 Oktas and 119.2 mms respectively.

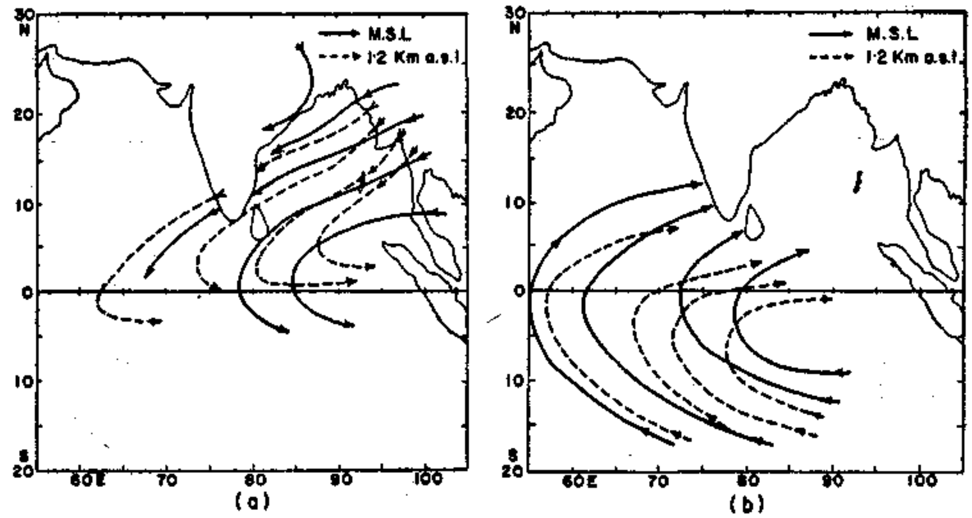

Fig. 3. A schematic diagram showing streamline patterns at top and bottom of the boundary layer in equatorial eastern Indian Ocean under the 'thermal wind' effect. Continuous lines show streamlines near surface, dashed lines at about 1.2 km a.s.l.

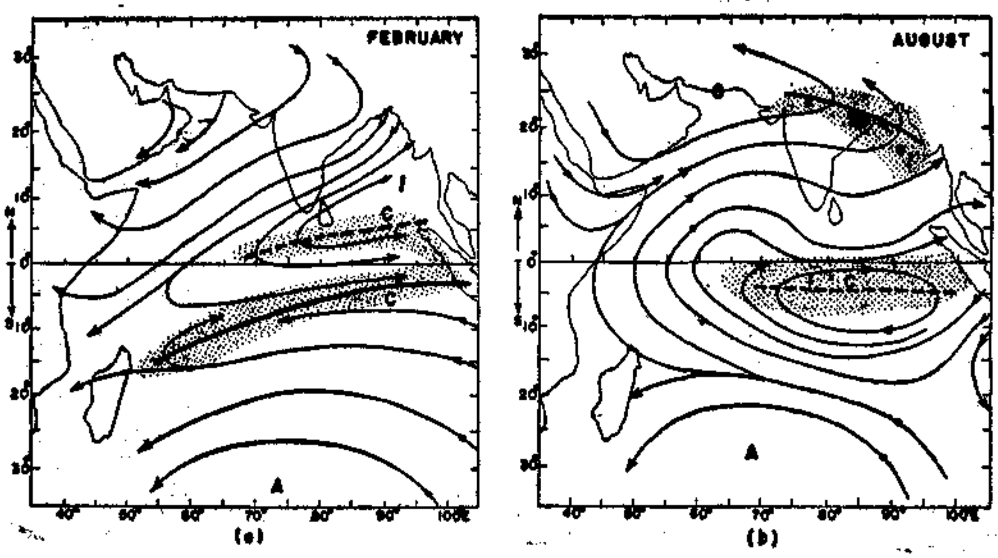

Fig. 4. Sketches showing typical air flow patterns near surface (say, 900 mb) over the Indian Ocean during (a) February, and (b) August. Thin lines with arrow-heads are streamlines. Thick lines show the approximate locations of the intertropical convergence zones, full line representing primary ITCZ and dashed line double ITCZ. Stippled areas show approximate locations of cloud bands associated with the ITCZs.

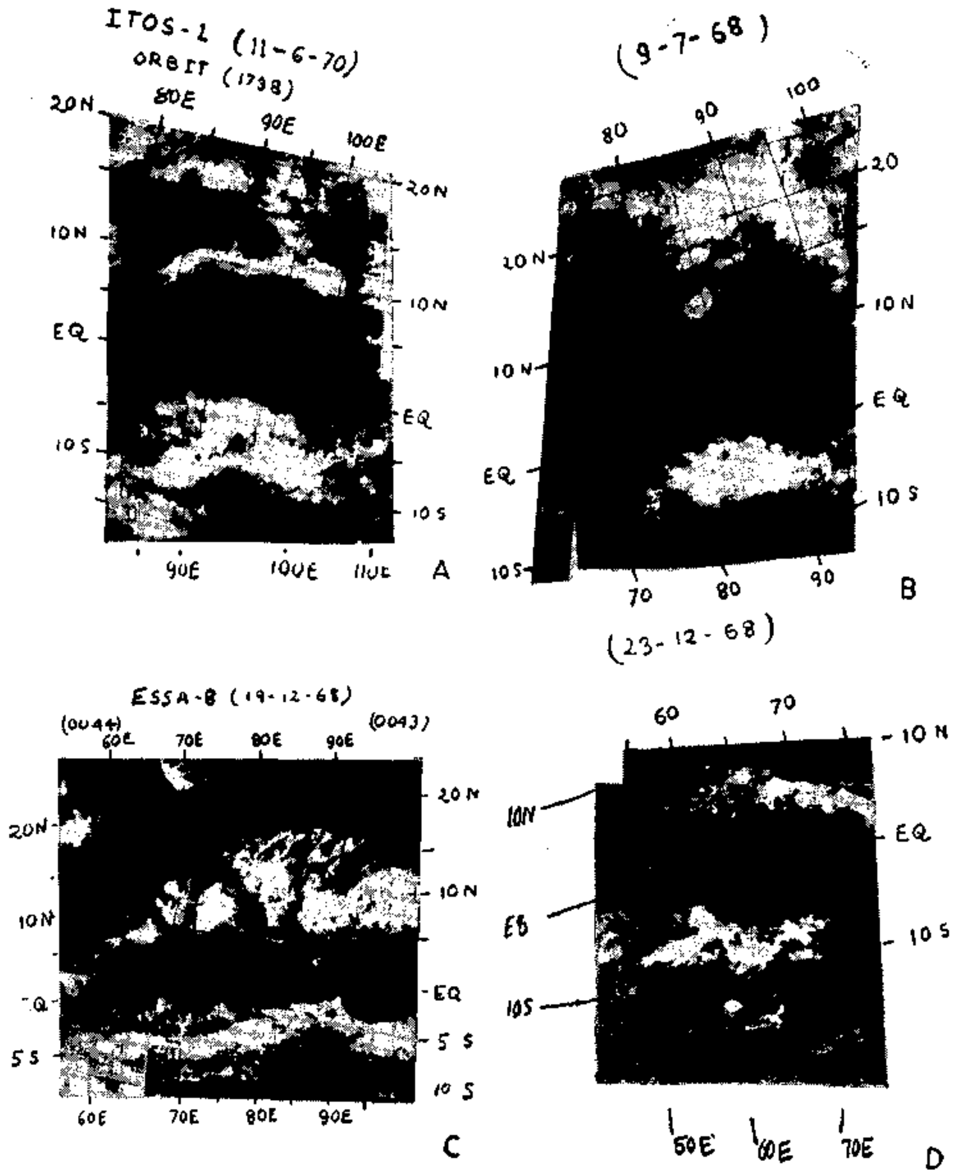

PLATE I. Satellite photographs of double cloud bands in the Indian Ocean. A. an ITOS-1 photograph on 11 June, 1970 (orbit nos. 1738, 1739), B. an ESSA-8 photograph on 9 July, 1968 (orbit nos. 3026, 3027), C. an ESSA-8 photograph on 19 December, 1968 (orbit nos. 0043, 0044), and D. an ESSA-6 photograph on 23 December, 1968 (orbit nos. 5119, 5120).

A sketch showing the approximate locations of primary and double ITCZs and associated low level flow patterns and cloud distributions over the Indian

TABLE 4. *Vertical distribution of mean air temperature (°C) and humidity-mixing-ratio (gm/Kgm) at Mauritius, Cocos Island, Diego Garcia, and Gan Island during August*, 1963

Pressure level (mb)	Mauritius 20.3°S 57.5°E		Cocos Island 12.1°S 96.9°E		Diego Garcia 7.2°S 72.4°E		Gan Island 0.7°S 73.2°E	
	TT	m.r.	TT	m.r.	TT	m.r.	TT	m.r.
Surface	18.5	9.7	24.9	13.8	27.1	19.3	—	—
1000	—	—	24.0	13.8	26.5	—	27.5	18.5
950	17.0	—	20.8	11.4	23.5	—	23.0	15.2
900	13.2	9.1	17.4	9.6	19.7	15.1	20.0	12.5
850	10.2	7.4	13.8	8.6	17.5	13.0	17.2	10.4
800	9.3	5.9	10.9	7.0	15.3	11.1	14.6	8.8
700	7.6	2.1	9.1	2.6	10.2	7.7	8.9	5.9
600	2.6	1.1	—	—	3.1	5.0	1.8	3.6
500	−6.1	0.6	−4.9	0.4	−4.9	2.8	−2.0	—

TT stands for air temperature and m.r. for humidity-mixing-ratio.

Ocean during northern winter and summer are presented in Fig. 4 a and b respectively.

CONCLUSION

On the basis of evidence furnished in the paper, it is concluded that a double ITCZ is a feature of tropical atmospheric circulation which is observed fairly frequently in the Indian Ocean. Its occurrence appears to be intimately related to distributions of ocean surface temperature. It appears to form in warm equatorial ocean where boundary layer convergence in a conditionally unstable atmosphere arising largely from the thermal-wind effect due to ocean surface temperature causes increased lifting of moisture and condensation to form a concentrated cloud zone a few degrees away from the equator.

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DISCUSSION

V. SRINIVASAN: Is the presence or absence of the double bands related to the presence or absence of typical synoptic situations or flow patterns?

K. SAHA: No individual case studies were undertaken.

P. K. DAS: Do you really feel confident about the thermal wind equation so near the equator? This implies geostrophic balance and f, the coriolis parameter, is in the denominator. I feel because f is small, you will get unrealistic changes of wind with height.

K. SAHA: As evidenced by meridional distribution of Ocean surface temperature, the 'thermal wind' effect upon equatorward-moving trade winds appears to take place at latitudes well away from the equator. On approaching latitudes near equator, where f becomes extremely small, perhaps the effect of boundary layer convergence due to friction may become important. The geostrophic approximation itself will, of course, fail at the equator.

R. N. KESHAVAMURTY: The east-west temperature gradient in the equatorial Indian Ocean would result in a westerly current.

K. SAHA: Yes, at the equator where the coriolis parameter is zero, the east-west temperature gradient with warmer water in equatorial eastern Indian Ocean is likely to produce a westerly wind component at surface.

D. R. SIKKA: How are the sea surface temperature distribution related to the cloudiness in other oceanic areas?

K. SAHA: In general, the western parts of both the Pacific and the Atlantic Ocean are warmer than the eastern parts and are found to have more cloudiness. In the Indian Ocean, the eastern Indian Ocean which is warmer is found to have more cloudiness than the western Indian Ocean. The above remarks, of course, apply to the equatorial regions of the respective oceans.