Indian J. .Met. Geophys. (1971) **22**, 389-396

551.576.2:551.507.362.2(267)

Cloud distributions over equatorial Indian Ocean as revealed by satellites

KSHUDIRAM SAHA

Institute of Tropical Meteorology, Poona

ABSTRACT. The paper gives some satellite evidence to show that the equatorial eastern Indian Ocean (east of about 60°E) experiences greater clouding than its western counterpart throughout the year. With a view to suggesting a possible explanation for this difference between the two parts of the ocean, the distribution of mean ocean surface temperature and barometric pressure for the period of the International Indian Ocean Expedition (IIOE, 1963-64) was examined. The findings suggest a semi-permanent vertical circulation cell with equatorial westerlies below, equatorial easterlies above, ascending branch over equatorial eastern Indian Ocean and descending branch over equatorial western Indian Ocean. Possible mechanisms for the formation of cloud clusters and cloud bands are briefly, discussed.

1. Introduction

From the year 1966 polar-orbiting satellites carrying television and infra-red radiation sensors have provided numerous photographs of synoptic-scale cloud cover over the equatorial Indian Ocean. They appear to reveal the following distinctive features—

(a) The equatorial Indian ocean, within about 5 degrees of the equator, has much more clouding east of about 60°E, than west of this longitude throughout the year.

(b) Clouds in the equatorial eastern Indian Ocean tend to occur more in the form of clusters, big or small, than in bands. A big cluster may occupy an area of one million square kilometers or even more.

(c) Cloud clusters, as and when they occur, appear to be randomly distributed with respect to the equator. In fact, they appear as much over the equator as to the north or south of it.

(d) Occasionally, there are two major cloud bands, one on either side of the equator. During the northern summer, the cloud band north of the equator is located as far north as 20°—25°N. During the rest of the year, the cloud bands are located within about 10—15 degrees of the equator.

Fig. 1 shows the variation of mean cloud amount within five degrees of the equator with longitude during Jan-Feb., April, Jul-Aug, and October, 1967. The values were estimated in oktas (eighths) of 5°×5° latitude-longitude squares from ESSA-3 and ESSA-5 television cloud photographs (U. S. Department of Commerce, 1969). Fig. 2 shows an ESSA-8 satellite photograph of a typical cloud cluster in the equatorial eastern Indian Ocean on 11 September 1970 (orbit Nos. 7965, 7966). It may be seen that the cloud cluster occupies more than a million square kilometres of ocean area. Fig. 3 shows satellite photographs of two typical double cloud bands in the Indian Ocean, one an ESSA-6 photograph on 23 December 1968 (orbit Nos. 5119, 5120), and the other an ESSA-8 photograph on 9 July 1968 (orbit Nos. 3026, 3027). In the present study, the cloud distribution associated with depression and cyclones, which occasionally form within a few degrees of the equator, have been excluded from our consideration.

Lack of adequate meteorological data on a routine basis from oceanic regions makes a study of atmospheric conditions that give rise to above cloud distributions over the equatorial Indian Ocean, particularly the much greater cloud activity of the region east of about 60°E, well-nigh impossible. But, during the IIOE period (1963-64) a concerted effort was made to collect as much meteorological information as possible from the Indian Ocean and this information is now available. Unfortunately, satellite coverage during the period was very scanty. It is believed that mean meteorological conditions over the Indian Ocean during the IIOE period, which were good monsoon years, were not very different from those in the years 1967-70, which were equally good monsoon years and during which period

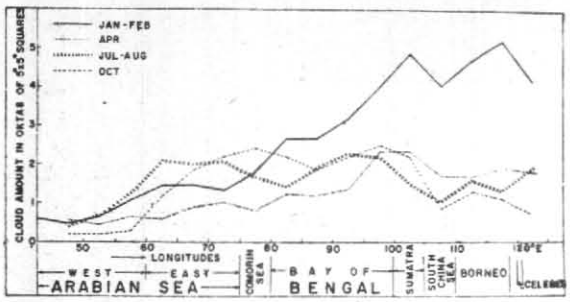


Fig. 1

Longitudinal variation of mean cloud amount in equatorial Indian Ocean during different months/seasons 1967 (Unit : Okta of 5°×5° Lat-Long. square)

Fig. 2

ESSA-8 Sat. photograph showing a typical cloud cluster over equatorial eastern Indian Ocean on 11 Sep 1970 (Orbit Nos. 7965 & 7966)

3(a)

3(b)

Satellite photographs of two typical double cloud bands in the Indian Ocean

(a) ESSA-6 photograph on 23 December 1968 (Orbit Nos. 5119 & 5120)

(b) ESSA-8 photograph on 9 July 1968 (Orbit Nos. 3026 & 3027)

satisfactory satellite coverage was available. On this assumption, the author has proceeded to apply and interpret mean ocean meteorological conditions and distributions of mean ocean surface temperature and ocean-atmosphere interaction during the IIOE period. Two earlier studies by the author (Saha 1970, 1971) are relevant in the present context.

2. Distribution of mean ocean surface temperature

A comparison of mean ocean surface temperature between the eastern and the western parts of the equatorial Indian Ocean during the period 1963-64 shows that throughout the year the eastern Indian Ocean, east of about 60°E, is warmer than its western counterpart. Fig. 4

shows the distributions during January and July along two selected meridians, 52.5°E representing the western Indian Ocean and 87.5°E representing the eastern Indian Ocean. The values are taken from Miller and Jefferies (1967). It may be seen that during January, the maximum mean ocean surface temperature (~ 29·1°C) along 87.5°E occurs at a latitude of about 2·5°S, whereas along 52·5°E, the maximum temperature (~ 28·8°C) occurs at about 7·5°S. North of about 7·5°S the eastern Indian Ocean is the warmer, the maximum difference of temperature of about 1°C occurring between 2·5°S and 7·5°N. South of about 7·5°S, the temperature difference changes sign with eastern Indian Ocean registering lower temperature than the western Indian Ocean. At the equator, the eastern Indian Ocean is clearly more than 1°C warmer than the western Indian Ocean. From latitudes of highest temperatures, the temperature decreases both to the north and south in both oceans, the average meridional temperature gradient being about 0·76°C/500 km north of the maximum and 0·93°C/500 km south of the maximum along 52·5°E and 1·0°C/500 km north of the maximum and 1·12°C/500 km south of the maximum along 87·5°E. During July, the disparity in ocean surface temperature between the eastern and the western Indian Ocean widens, with the eastern ocean distinctly warmer than the western. But this is mostly north of about 15°S, for south of this latitude the difference changes sign with the western Indian Ocean becoming warmer than the eastern Indian Ocean. At the equator there is clearly a difference of about 2°–3°C and this difference appears to be maintained at all latitudes north of about 7·5°S. A remarkable feature of the July distribution is that a steep meridional temperature gradient amounting to about 1·7°C/500 km exists along 87·5°E south of about 2·5°S with little or no gradient north of this latitude. The meridional temperature gradient along 52·5°E is small throughout but south of about 10°S, it amounts to about 1·2°C/500 km. The cause of marked contrasts in ocean surface temperature between the eastern and the western parts of the Indian Ocean as brought out by Fig. 4 is not far to seek. Sometime towards the latter part of May every year, the strong SW monsoon sets in along the coast of east Africa. These winds cause intense upwelling along the coast of Somalia and the cold water spreads over the western Arabian Sea with the advance of the summer monsoon season. The progressive eastward advance of the cold Somali current is well shown by the eastward shift of air and water isotherms across the Arabian Sea (Saha 1970). In fact, a comparative study of air and water temperatures at a near-equatorial point in western

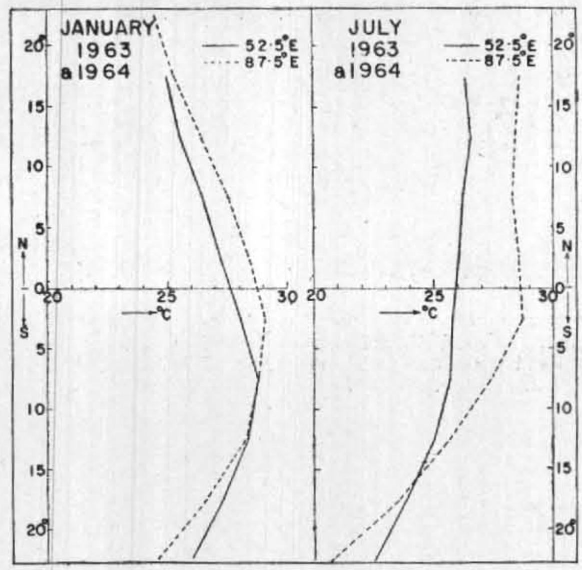


Fig. 4

Meridional Distribution of mean Ocean surface temperature along Long. 52·5° E and 87·5° E during January & July 1963-64

Arabian Sea and a corresponding point in south Bay of Bengal brings out the characteristic differences in the thermal regime between the western and the eastern parts of equatorial Indian Ocean. In the western Indian Ocean, both air and water temperatures are lower than their counterparts in the eastern Indian Ocean. During the summer monsoon water temperature drops significantly below air temperature in the west, whereas it remains higher than air temperature in the eastern Indian Ocean practically throughout the year. The above distribution of mean sea surface temperature in equatorial Indian Ocean appears to exercise a profound influence on the properties and circulation of the overlying atmosphere through air-sea interaction.

3. Air-sea interaction

Continued exchange of sensible and latent heat across the ocean-atmosphere interface appears to modify the properties of the atmosphere in the following manner:

In the case of a cold airmass moving over a warm ocean, there is upward flux of sensible heat and water vapour. Non-adiabatic heating across the lower boundary and addition of a large quantity of water vapour leads gradually to vertical destabilisation and mixing of the atmosphere with the result that the airmass is sooner or later modified into a warm and humid atmosphere, the depth of the modified layer increasing downstream. There is a fall of barometric pressure accompanying the process and this leads to convergence and rapid lifting of moist air. Condensation occurs with the release

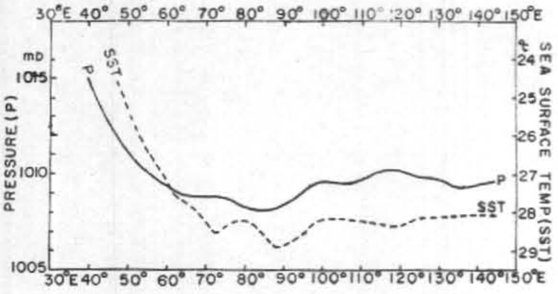
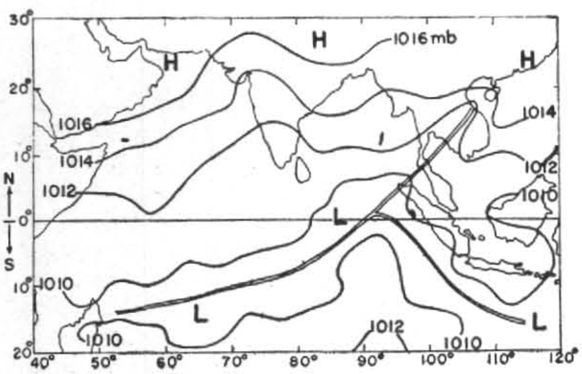


Fig. 5

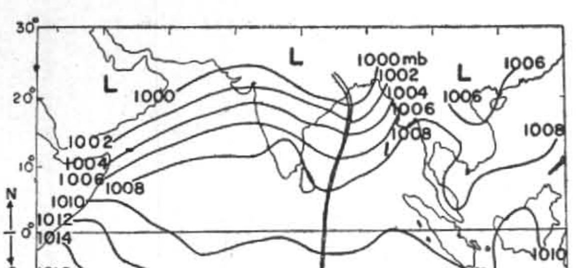
Equatorial distribution of mean Sea surface temperature (SST) and barometric pressure (p) during July 1964. Values of SST east of Long. 97·5°E refer to Lat. 2·5°S.



(a)

Fig. 6 (a)

January 1963-64



(b)

Fig. 6 (b)

July 1963-64

Fig 6 (a—b). Mean sea level pressure distribution over the Indian Ocean

The double thick lines show approx. positions of pressure troughs. H-High and L-Low pressure ; isobars are in millibars

of a large quantity of latent heat with further accelerated vertical motion and development of the system. Clouds thus form over a warm ocean and the longer the stretch over warm water the more developed the cloud is likely to be. The above process would appear to be reversed over a cold ocean, when warm air flows over it. There may be rapid loss of sensible heat across the interface to the ocean, and this may lead to slow descent and stabilisation of air. The cooling of the lower layers of the atmosphere may lead to rise of barometric pressure and divergence of air. The above processes may, however, be considerably influenced by the presence of convergence or divergence in the moving airmass. Normally, rapid cloud growth may be expected to occur when a system with convergence of air, such as pressure trough or front, enters or lies over a warm ocean. Cloud growth may be retarded or subdued when a system with divergence lies or moves over a cold ocean. Intermediate cloud growth may be expected when a system with convergence moves over a cold ocean or a system with divergence moves over a warm ocean.

Saha (1970) presented the mean values of flux of latent and sensible heat over the Indian Ocean during (a) Jan-Feb and (b) Jul-Aug 1964. They appear to show upward flux of sensible heat in equatorial eastern Indian Ocean and downward flux of sensible heat in equatorial western Indian Ocean. They also appear to show the western Indian Ocean as a major source of water vapour and eastern Indian Ocean a major sink of water vapour. Fig. 5 shows the equatorial distribution of barometric pressure during July 1964. It appears to suggest a high correlation between ocean surface temperature and barometric pressure, relatively higher pressure appearing over colder western Indian Ocean and lower pressure over warmer eastern Indian Ocean.

4. Pressure distribution and air flow

(a) *Pressure distribution*

The distribution of ocean surface temperature presented in Fig. 4 and the close correlation between ocean surface temperature and barometric pressure indicated by Fig. 5 would seem to suggest that relative to the western Indian Ocean, the equatorial eastern Indian Ocean will have a lower barometric pressure throughout the year. Daily as well as mean synoptic pressure charts prepared with IIOE data appear to confirm this view. In Fig. 6, two mean sea level pressure charts, one during January and the other during July averaged for the IIOE period 1963-64 are presented. The basic data for these charts for the oceanic region are the averaged ships reports over 5-degree latitude-longitude squares (Miller *et al.* 1963). It is evident from Fig. 6 that during both the monsoon seasons a low pressure trough lies across the equator in equatorial eastern Indian Ocean. By contrast, a high pressure ridge extends across the equator in equatorial western Indian Ocean during both the seasons.

(*b*) *Air flow*

One may ask what is the effect of the above distribution of barometric pressure, particularly its zonal and meridional gradient on air circulation near the equator. A zonal pressure gradient along the equator with relatively higher barometric pressure over western Indian Ocean and lower barometric pressure over eastern Indian Ocean may, in the absence of any other influences, cause a direct flow of airmass from west to east. In fact, Matsuno (1966) in a theoretical study of stationary air circulation set up by a mass source and a mass sink placed side by side along the equator indicated the possibility of such direct flow of mass from source to sink along the equator producing strong zonal winds. But in the presence of a meridional pressure gradient across the equator which guides the basic monsoon circulation, the situation becomes somewhat complex and a direct flow of mass from source to sink along the equator due to ocean temperature differences in the manner visualised above may not be realised. In a paper to be published shortly (Saha 1971b), the author has discussed the mode of formation of equatorial westerlies on the basis of meridional ocean surface temperature gradient in equatorial ocean, using a thermal wind concept. This concept is further discussed in Section 6.

5. Vertical circulation—Walker circulation

Observations show that equatorial westerlies of variable strength blow in equatorial eastern Indian Ocean (east of about 60°E) practically throughout the year. The westerly winds are the strongest between about 850 and 700 mb and weaken aloft. Above about 500 mb, equatorial easterlies set in. Thus if air is to subside over cold western Indian Ocean and rise over warm eastern Indian Ocean, it is possible to visualise a vertical circulation cell along the equator with westerlies below, easterlies above, the descending branch over the western Indian Ocean and the ascending branch over the eastern Indian Ocean. A schematic representation of the proposed vertical circulation cell is shown in Fig. 7. Frost and Stephenson (1965) who studied mean streamlines and isotachs at standard pressure levels over the Indian and West Pacific Ocean also suggested a similar vertical

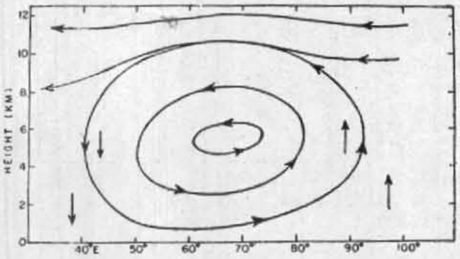


Fig. 7

Schematic diagram showing an equatorial vertical circulation cell with westerlies below, easterlies above, descending branch over western Indian Ocean (west of above Long. 60°E) and ascending branch over eastern Indian Ocean

circulation cell but with the ascending branch over the heated land mass of Indonesia and descending branch over the equatorial Indian Ocean at about longitude 60°E. Bjerknes (1969) who studied possible response of the atmospheric circulation to equatorial anomalies of ocean surface temperature in the Pacific visualised a vertical circulation cell along the equator with equatorial easterlies below, equatorial westerlies above, descending branch over cold Eastern Pacific and ascending branch over warm Western Pacific.

From the above, it may be seen that an equatorial vertical circulation cell in the Indian Ocean has been considered as a distinct possibility by quite a few workers. However, the model suggested by Frost and Stephenson differs from that suggested in the present paper in respect of the location of the ascending branch. Frost and Stephenson's suggestion that ascent occurs over the heated landmass of Indonesia appears to imply that heating of the scattered islands of Indonesia is the main cause of ascent of air. A major difficulty that besets this explanation is that the islands of Indonesia are not heated uniformly or to the same extent throughout the year. Yet, according to their own finding, steady westerly winds are found at all times of the year at the equator between longitudes 60°E and 140°E. Fig. 1 also appears to show that except during the winter season when the cloudiness maximum appears to shift to more eastern longitudes, cloudiness is maximum over the equatorial eastern Indian Ocean. The islands of Indonesia no doubt act as heat sources and sinks and their mountains as orographic barriers but it is considered that these influences may not cause such large-scale circulation features as equatorial westerlies over a span of 80 degrees of longitude. A more plausible model appears to emerge from considerations of ocean-atmosphere interaction occurring over a warm ocean surface which extends from about 60°E to about 140°E or even beyond practically throughout the year (Saha 1970b).

TABLE 1

Number of days of occurrence of double cloud bands in equatorial Indian Ocean during July 1966 through September 1970

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1966	*	*	*	*	*	*	23	15	12	12	3	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	3	11	6	2	3	11	4	4	5	—	—	—

*APT pictures not available

6. Cloud clusters and bands

The existence of a warmer ocean surface and a lower barometric pressure and the operation of the ascending branch of a vertical circulation cell would appear to make conditions very favourable for formation of large scale cloud systems over the equatorial eastern Indian Ocean as against its western counterpart. In Section 3, a qualitative discussion of the type of clouds that may form by ocean-atmosphere interaction was presented. Observations appear to show that clouds or cloud-groups that form over equatorial eastern Indian Ocean are usually of the convective type. Large groups of convective clouds known as cloud clusters are frequent occurrences. They range in size from thousands to millions of square kilometres and develop to heights where their tops are sheared by strong upper winds. They appear to occur as much over the equator as to the north or south of it. Little is known about their life cycle but it is believed that like all convective phenomena the individual cloud clusters may have short life spans, say at best one or two days. However, as already mentioned, cloud clusters in equatorial eastern Indian Ocean occasionally get organised in the form of bands, one cloud band lying on either side of the equator. The bands usually lie within about 10°—15° of the equator except during northern summer when the northern band lies in the latitudes of northern India. A doubt has recently been cast regarding the occurrences of double cloud bands in the Indian Ocean by Hubert, *et al.* (1969) who studied seasonally-averaged cloud distributions during 1967-68 over the tropical belt. They conclude, *inter alia,* that the Indian Ocean does not exhibit any double tropical cloud zones. Daily satellite pictures, however, appear to reveal a different situation. Table I gives the number of days of occurrences of double cloud zones in the Indian Ocean during period July 1966 through September 1970, as revealed by satellites. It is evident that double cloud bands in the Indian Ocean are of fairly frequent occurrence on shorter time scale. The life period of a double cloud band appears to be highly variable with an average at about 5 to 6 days and extremes at 1 and 12 days.

Little definite is known regarding the mechanism of formation of cloud clusters and cloud bands in equatorial Indian Ocean. Following an idea originally advanced by Charney (1967), the author has recently suggested (Saha 1971b) that a plausible explanation for the formation of double cloud zones in the Indian Ocean region may be sought in terms of bounday layer convergence due to thermal-wind effect. It may be seen from Fig. 4 that during northern summer there is little or no meridional temperature gradient north of about 2·5°S in the eastern Indian Ocean and north of about 10°S in the western Indian Ocean. However, over the latitudes of northern India a strong meridional temperature gradient exists, which may well explain the formation of a deep boundary layer convergence zone and associated cloud band over India. A sketch showing the locations of the convergence zones in the low-level wind field and associated double cloud bands during February and August is presented in Fig. 8.

7. Conclusion

The paper has produced satellite evidence to show that the eastern part of the equatorial Indian Ocean (east of about 60°E) experiences far greater amount of clouding than its western part. In particular, large cloud clusters and cloud bands are more of characteristic features of equatorial eastern Indian Ocean than its western counterpart. A qualitative explanation of this differential distribution has been sought in terms of mean ocean surface temperature and ocean-atmosphere interaction. It is suggested that equatorial westerlies which are observed in equatorial Indian Ocean during practically the whole year may have its origin as strong thermal winds that are created by steep meridional ocean surface temperature gradient on either side of the equator in equatorial eastern Indian Ocean. It is further suggested that a

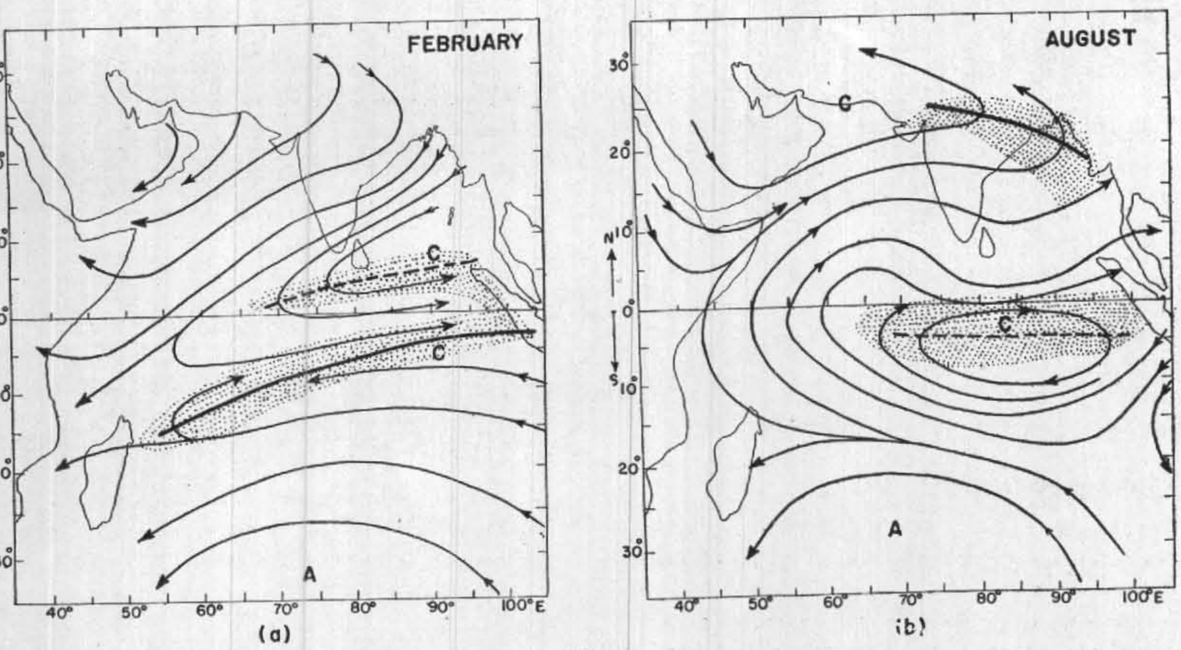


Fig. 8

Sketches showing tropical air flow patterns near surface (say, 900 mb) over the Indian Ocean during (a) February and (b) August. Lines with arrow heads are streamlines. Thick lines show approx. locations of the convergence zone. Stippled areas show approx. locations of cloud bands associated with convergence zones. (C-cyclonic & A-anticyclonic)

vertical circulation cell with equatorial westerlies below, equatorial easterlies above, descending branch over equatorial western Indian Ocean and ascending branch over equatorial eastern Indian Ocean may be consistent with the observed cloud distribution in the equatorial Indian Ocean.

REFERENCES

Bjerknes, J. 1969 *Mon. Weath. Rev.*, **97**, pp. 163-172.

Charney, J. G. 1967 The intertropical convergence zone and the Hadley circulation of the atmosphere. Unpublished manuscript, Dep. Met., M.I.T., U.S.A.

Frost, R. and Stephenson, P. M. 1965 Mean streamlines and isotachs at standard pressure levels over the Indian and West Pacific Oceans and adjacent land areas. Meteorological Office (London), Geophysical Memoir No. 109.

Hubert, L. F., Krueger, A. F. and Winston, J. S. 1969 *J. atmos. Sci.*, **26**, pp. 771-773.

Matsuno, T. 1966 *J. Met. Soc., Japan*, **44**, Ser. II, pp. 25-43.

Miller, F. R., Sivaramakrishnan, M. V. and Suryanarayana, R. 1963 Preliminary results and future plans of the IIOE meteorology programme (computer plans). Proc. Seminar held in Bombay on 1 August, 1963.

Miller, F. R. and Jefferies, C. 1967 Mean monthly sea-surface temperatures of the Indian Ocean during the International Indian Ocean Expedition, Hawaii Inst. Geophys. (HIG-67-14).

Saha, K. R. 1970 (a) *Tellus*, **22**, 4, pp. 403–409.

1970 (b) On the nature and origin of the double intertropical convergence zone. Proc. Symp. Tropical Meteorology, Hawaii, June 2-11.

REFERENCES (Contd)

1971(a) *Tellus*, **23**, 2.

1971(b) The double intertropical convergence zone in the Indian ocean—fact or fiction? Presented at the Symp. Indian Ocean and its adjacent seas, their origin, science and resources, held at Cochin, India, Jan 12-19, 1971.

U. S. Dep. Commerce 1969 Catalog of Meteorological Satellite Data—ESSA 3 and ESSA 5 Television cloud photography, 1967. ESSA Environmental Data service, Key to Meteorological Records, Documentation Nos. 5·313—5·316.

DISCUSSION

SHRI JAGAN MOHAN RAO : With reference to Sawyer's diagram of the ITCZ, it may be possible to connect the cloud distribution along the equator at different longitudes with the ITCZ.

DR. K.R. SAHA : There are many anomalies in the location and movement of the ITCZ around the globe and it is not everywhere that the position of the ITCZ is marked by the presence of cloud.

SHRI R.K. DATTA : Are there certain areas over the equator permanently clouded and some other clear ? If so, are there stationary systems along the equator ?

DR. SAHA : Quasi-stationary systems do develop in the equatorial regions, but there are seasonal variations.

PROF. K.R. RAMANATHAN remarked that the features might be connected with sea surface temperatures and sea circulations.

SHRI DATTA : Sometimes rainfall is noticed over the Malaysian strip and after 2 or 3 days rainfall occurs over the Peninsula without the occurrence of rain over the Bay during the intervening period. Any comments ?

DR. SAHA : These may be due to perturbations in the mean zonal flow.