

Some aspects of broad-scale cloud distribution over Indian Ocean during Indian Southwest Monsoon Season

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(Received 15 April 1966)

ABSTRACT. Satellite cloud information and ship data collected during the I.I.O.E. period are utilised to study the broad-scale cloud distribution over Indian Ocean during Indian southwest monsoon season. Examination of a large number of satellite observed cloud patterns over the Indian Ocean during the southwest monsoon season reveals some aspects of broad-scale cloud features. These features are looked into in relation to the low level wind field and an attempt is made to establish a linkage between the cloud field and the wind field. Analysis of I.I.O.E. ship data collection also leads support to the conclusions derived from satellite data. Certain features of equatorial cloud distribution are also pointed out. The difference in the cloud distribution between tropical Atlantic and Pacific and tropical Indian Ocean is added to the differences in sea surface temperature distribution as well as geographical distribution of land and sea areas.

1. Introduction

Clouds are visible symbols of atmospheric activity. Studies of large scale cloud systems should, therefore, provide basis for visualising atmospheric circulation patterns. The examination of large scale cloud distribution may very profitably form the first step towards the understanding of atmospheric processes over any region. A study* was, therefore, undertaken to look into some of the features of the broad-scale cloud distribution over the Indian Ocean during the Indian southwest monsoon season.

The advantages of the use of satellite cloud information in such studies particularly over data sparse vast ocean areas, are well known. TIROS cloud information in the form of graphic and coded nephanalyses as well as photographs for selected orbits for the summers of 1963—1965 were utilised in the study. The experience of extended daily map analysis at the International Meteorological Centre, Bombay (IMC) during the three-year period (1963—1965) provided a very valuable background to draw upon.

Examination of a large number of nephanalyses, construction of mean cloud cover charts for short periods of typical synoptic situations as well as detailed study of TIROS mosaics for selected orbits were undertaken from which emerged some aspects of broad-scale cloud features over Indian Ocean. Thereafter, these features were looked into in relation to the low level circulation patterns to see

whether the cloud field could be linked with the wind field. Finally, the large volume of ship observations collected during the I.I.O.E. period were analysed to provide additional support for the conclusions drawn from the satellite data.

The existence of two east-west oriented troughs† in the lower troposphere over the Indian Ocean, one on either side of the equator, has been noticed earlier (Koteswaram 1960). The mean resultant wind charts for Indian Ocean (Raman and Dixit 1964) brought out the double trough into prominence. The daily analysis of Indian Ocean charts at IMC during the I.I.O.E. period provided an opportunity to look into this feature of the equatorial circulation in detail and study its daily variations. The two troughs are noticed in all the seasons and will be referred to as Northern Equatorial Trough (NET) and Southern Equatorial Trough (SET) in this paper. The NET shifts far north from the equator to the latitude of Indo-Gangetic plains during the northern summer. The mean monthly location of the troughs have been given by Raman *et al.* (1965). This will provide helpful reference for the discussions that follow.

2. Pre-monsoon season

Before entering into the analysis of the Indian southwest monsoon situations, it may be useful to examine TIROS data for a typical pre-monsoon day and later compare it with the monsoon cloud distribution.

* Some results of a preliminary study of the problem had been presented at the WMO Inter-Regional Seminar on Interpretation and Use of Meteorological Satellite Data (Tokyo—November-December 1964), in a paper entitled 'Use of Satellite Weather Information in Low Latitude Analysis at the International Meteorological Centre, Bombay, with particular reference to near equatorial cloud distribution' by V. Srinivasan, C.R.V. Raman and V.R. Neralla.

† Since the IMC charts were analysed by streamline-isotach method, the troughs referred to in this paper are troughs in the wind field rather than in pressure field

During the pre-monsoon season (in May) it is often seen that the Indian Ocean near the equator is heavily clouded and fairly widespread weather with strong west winds are reported by ships and island stations in the area. Active cyclonic vortices develop in the two troughs on either side of the equator. One such period was 28 April to 4 May 1964. The TIROS nephanalyses for 2 May 1964 (Fig. 1) over this area (TIROS VIII Orbit 1924 at 0424 Z and TIROS VII Orbit 4698 at 0532 GMT) show an area of heavy *Cb* extending from Maldives to Sumatra. Scattered *Cb* activity extends over a large area in the east Indian Ocean south of the equator. The sharp transition from heavy overcast to clear or lightly clouded areas to the north of Lat. 10°N is noteworthy.

3. Average cloud distribution during selected epochs of Indian Southwest Monsoon

As the Indian southwest monsoon is the main theme of study, the cloud distribution during the southwest monsoon period will be dealt with in detail illustrated with mean cloud cover charts for typical periods as well as TIROS mosaics for selected orbits.

Typical synoptic situations extending over a period of a few days were selected: the choice was to a large extent dependent on the availability of the satellite data. For each selected situation cloud amounts reported in the TIROS nephanalyses were averaged over the area 45°E to 105°E and 35°N to 20°S. The method of averaging was similar to the one used by Sadler (1965) and is reproduced in Appendix A.

In view of the large area covered by each of the satellite orbits, data from a few orbits may suffice to give an idea of the distribution of cloudiness. With 1447 TIROS III photographs, Arking (1964) obtained a global distribution of cloud coverage which was in good agreement with the long term mean cloud cover distribution obtained from ground observations. Sadler (1965) feels that a reasonable picture can be obtained of the average monthly cloud cover over the tropical regions with as few as ten satellite observations per month. The selected periods for which the cloud cover averages were prepared and the number of nephanalyses utilized in each case are given below —

Period	No. of nephanalyses
11 to 21 Aug 1964	12
27 Aug to 1 Sep	12
4 to 6 Sep	4
12 to 18 Sep	12

Of the four cases studied, three are presented in the following paragraphs.

(i) 11 to 21 August 1964

During the period, the monsoon activity was very good over central and northwest India. For the week 12-19 Aug, Gujarat region had rainfall which was 123 per cent of the normal. Two depressions from northwest Bay of Bengal moved across Orissa and Madhya Pradesh and merged into the season NET.

The mean cloud distribution during the period is shown in Fig. 2. There was a well-marked belt of maximum cloudiness extending from Orissa and east Uttar Pradesh to Kuria coast — the cloudiness being generally 6 oktas or more reaching overcast conditions over portions of the area. There was considerable decrease of cloudiness between latitudes 5° and 15°N, some area being only one quarter of sky covered. Further south towards the equator, an increase in cloudiness is noticed between Lat. 5°N and Lat. 2.5°S in the western Indian Ocean and Lat. 10°N and equator in the eastern Indian Ocean. This near-equatorial increased clouding is separated from another area of maximum clouding, still further south, in the southern hemisphere by a region of minimum clouding which over the eastern Indian Ocean coincided closely with the mean location of SET during the period.

(ii) 27 August to 1 September 1964

During this week the monsoon was fairly active over most parts of north and central India and the Peninsula. At the beginning of the period, a depression weakened over north Madhya Pradesh, later a low pressure wave from central Bay of Bengal moved northwest and merged into NET. The cloud analysis is not available for eastern Indian Ocean. The mean cloud chart (Fig. 3) for this period shows a broad area of maximum cloudiness extending from northeast India to Kuria Muria coast, with 6-7 oktas of cloudiness over an extensive area. Between Lat. 10°N and Lat. 15°N there is a rapid decrease in cloud amount, reaching clear sky conditions in the western Arabian Sea, followed by a marked increase in cloudiness between equator and Lat. 10°N with overcast sky conditions over some areas. There is a second minima in cloudiness near about the equator — which corresponds to the mean location of SET during the period, followed further south by another pronounced maximum in the southern hemisphere between Lat. 3° S and Lat. 10°S.

(iii) 4 to 6 September 1964

This was a period of break in monsoon rains over India and the axis of NET was close to the foothills

of the Himalayas, north of the normal position. On the surface chart a trough of low pressure also moved from the southwest Bay of Bengal across the Indian Peninsula into southeast Arabian Sea.

The cloud distribution chart (Fig. 4) is available for the western half of the area under study. The chart shows a region of maximum cloudiness of about five-degree latitude width centred over Lat. 20°N . Another region of cloudiness is in the south Arabian Sea between Lat. 10°N and the equator and the third one in the southern hemisphere between Lat. 5°S and Lat. 15°S . These three regions of cloudiness are separated from one another by wide areas of reduced clouding.

The four cases studied (of which three have been discussed above) bring out the following broad features of cloud distribution over the Indian monsoon region during the northern summer. They are —

- (a) There are three well-defined cloud belts extending east-west — (i) northern cloud field in the latitudes 15°N – 25°N , (ii) near equatorial belt generally between Lat. 10°N and equator, and (iii) southern hemisphere belt.
- (b) These three regions are separated by two markedly less clouded regions which are more pronounced over sea than over land areas where local heating contribute to increased cloudiness.
- (c) This characteristic relative cloud distribution is apparently present irrespective of the activity of the monsoon over India and is noticeable with some fluctuations during most of the days of the monsoon period. This may, therefore, be taken to be characteristic of the summer monsoon cloud field. The two regions of maximum clouding in the northern hemisphere during the summer monsoon — one near Lat. 20°N and another near Lat. 5°N — are in contrast to the single near equatorial clouding seen in pre-monsoon months (Sec. 2 : Fig. 1).

4. TIROS mosaics for selected orbits

Mosaics of TIROS and NIMBUS I cloud photographs were prepared for selected orbits. Of these a few are shown in Figs. 5–7 along with the corresponding graphic nephanalyses. The surface charts for the standard synoptic hours nearest to the times of TIROS passes are also included—Figs. 5(a) to 7 (a). The cloud distribution on these orbits will be discussed in this section with reference to the surface synoptic features.

(i) 16 August 1964 : TIROS VIII—Orbit 3467 R/O 3464 ; Time 0904Z (Fig. 5).

On the surface chart (Fig. 5a) NET was from Gulf of Aden to East Pakistan across Gulf of Oman, Sind, and Chota Nagpur where three well-marked cyclonic vortices were located. The major cloud belt was from Kuria Muria coast to south Rajasthan and Konkan and it was overcast. This cloud belt was located mainly to the south of the trough line and over the region of the strongest southwest monsoon current. There was a clear break between Makran coast and the northern edge of heavy clouds. To the north of NET the clouding is considerably less, being mainly of *Cu* type oriented along the low level streamlines. Further to the north, over Iran, Afghanistan and north Baluchistan, the TIROS photograph indicates possible haziness due to dust; some *Ci* cloud also could be faintly recognised. These *Ci* streaks appear to be aligned along the high level anticyclonic flow over this region. *Ci* clouds were reported by stations in Afghanistan and Baluchistan at 1200 Z of 16th. To the south of Lat. 15°N , the clouding decreases rapidly, the decrease starts over the West Coast of Indian Peninsula where streamlines commence to difflue. Over this area of almost clear skies a well-marked anticyclone is located on the surface chart. The southern Indian Peninsula and Ceylon are easily recognisable landmarks in the picture. In the southern hemisphere a well marked cyclonic vortex is centred near Lat. 5°S , Long. 80°E and clouding is more massive to the south and west of the centre of the vortex. When this disturbance moved westwards and came close to Gan-Diego Garcia area, Diego Garcia reported at 0.9 km 130°/37 kt at 1200 Z of 17th and Gan reported NNW/N-20/25 kt at 0000Z of 18th at 0.9 km and 1.5 km. Thus this disturbance was of deep depression intensity.

(ii) 31 August 1964 : TIROS VIII—Orbit 3680 R/O 3679; Time 0500Z (Fig. 6)

The SET was lying with its axis roughly along Lat. 4°S with three cyclonic circulation embedded in it between Long. 45°E and Long. 95°E (Fig. 6a). Of these, the middle one centred near Lat. 4°S , Long. 68°E was very pronounced. The winds in its circulation were of the order of 30 knots, so that the disturbance was of the deep depression stage. At 0.9 km Gan reported 31 knots at 0000 Z and this system was affecting even southeast Arabian Sea. Minicoy recorded 6 cm of rain at 0300 Z of 31 August and 9 cm at 0300 Z of 1 September. The cloudiness associated with NET is along Arabia coast and in Arabian Sea north of Lat. 20°N . In the central Arabian Sea, *Cu* clouds either in the form of cells or streets, are mainly

to the east of Long. 63°E. To the west it is clear or lightly clouded. The southern hemisphere system near 4°S, 68°E is associated with a large area of heavy overcast extending well into northern hemisphere as far north as Lat. 10°N. The alignment of low level *Cu* in the south Arabian Sea around cyclonic circulation near Lat. 4°S, Long. 68°E is indicative of the extent of the southern hemisphere system.

This particular case is representative of extensive heavy cloudiness due to active systems in southern hemisphere trough extending across the equator well into northern hemisphere.

(iii) 6 September 1964: TIROS VIII—Orbit 3766 R/O 3765; Time 0330Z (Fig. 7)

The axis of NET had shifted to the foothills of Himalayas over northwest India and Uttar Pradesh and a ridge had formed over Arabian Sea (Fig. 7a). The SET ran from north of Seychelles to Diego Garcia and further eastwards to Singapore. The near equatorial cloud belt between Lat. 5° N and Lat. 10°N is more pronounced than the clouding further north. This is probably continuous eastwards upto Laccadives, where heavy rainfall occurred (at 0300Z of 6th. Amini Devi reported 6 cm and Mimicoy 5 cm). The cloudiness associated with SET is more to the south of the trough line. The clouds were of cumuliform type aligned to the cyclonic circulation in southern hemisphere trough over Diego Garcia area. Further south, the *Cu* streets become less where the southeast trades fell below 20 kt in strength.

The examination of individual clouds photographs (in this section) has shown a number of other features of the monsoon cloud field and circulation patterns, apart from confirming the conclusions arrived at in the earlier section from the mean cloud configuration. They are —

- (a) The main cloud fields are associated with two hemispherical troughs in the low level wind circulation and the vortices in them. The cloud fields have variations depending on the strength of the troughs and the vortices.
- (b) The cloud field in association with NET is confined mainly to the south of the trough line in the Arabian Sea. Due to the absence of adequate supply of moisture there is very little clouding to the north of NET in this area where a milky appearance indicative of dust haze and cirriform type clouds is noticed in TIROS pictures.

- (c) Major organised cloud bands are often associated with regions of strong winds (for instance in the case of 16 August 1964 and 6 September 1964).
- (d) In the southern hemisphere trough, well defined vortices reaching the intensity of deep depression form and travel westwards. Frequently, when such circulations come rather near the equator, they affect both the hemispheres, with associated heavy clouding extending well into northern hemisphere. This also shows that the equatorial regions are not always dry in the Indian Ocean.
- (e) In the central Arabian Sea the cloudiness is generally of *Cu* type often arranged in the form of streets. While the western Arabian Sea is practically clear, small *Cu* clouds start forming east of Long. 60° E and grow to significantly large dimensions east of Long. 65°E. Bunker (1965) and Sikka and Mathur (1965) have pointed out how the strong inversion in west Arabian Sea lifts up gradually and is finally broken as we proceed eastwards towards the West Coast of Indian Peninsula.
- (f) Large patches of cirriform clouds are frequent in the region of strong upper tropospheric easterlies.

5. Break monsoon conditions in August 1965

In August 1965, there was a prolonged *break* in monsoon rains over India for nearly a fortnight. With TIROS X in operation during the period, there was a large number of passes over Indian Ocean region — on an average two or three per day — at about local noon time. It afforded a good opportunity to prepare a typical mean cloud chart illustrating a *break* in monsoon over Indian monsoon area. A mean cloud cover chart (Fig. 8) was prepared for period 3-14 August utilising TIROS data from 24 orbits.

The well-known features of *break* conditions, viz., heavy rains along and near Eastern Himalayas and over Arakan, as well as rainfall in south Peninsula and Comorin-Laccadives areas seen in the mean cloud chart. In addition the following other points are also brought out—

- (a) Even during the *break* a belt of relatively higher cloud amounts, although slightly diffuse in the western sector, extends from northeast India to Kuria Muria coast as on days of normal monsoon activity.

- (b) The near equatorial cloudiness is nearly overcast over many areas across the entire Indian Ocean between Lat. 5°S and Lat. 5°N.
- (c) To the north of the near equatorial cloudiness, there is a well defined region of minimum clouding extending from Gulf of Aden to Laccadives in the western sector and between Lat. 10°N and Lat. 20°N in Bay of Bengal.
- (d) The region of minimum clouding in the southern hemisphere is better marked in the west Indian Ocean. It may be mentioned that during this period a tropical vortex (presumably a storm) formed in the east Indian Ocean. The southern hemisphere trough was also south of the normal position.

These features of the mean cloudiness would lead to a conclusion that the *basic relative distribution* of large scale clouding over the Indian monsoon area even during a prolonged *break*, is similar to the one during active or normal monsoon days.

In order to examine further the mean values of cloudiness during the period, coefficients of variations of cloud amounts were worked out for each 2½-degree square grid and analysed. The coefficient of variation has been taken as the ratio of standard deviation to arithmetic mean expressed as a percentage. Standard deviations of cloud amounts in each 2½-degree square (see Fig. 8) were worked out and the coefficient of variation was determined for each square. Small coefficients of variation would indicate that there were no large day-to-day changes in cloudiness, while large values of the coefficients would suggest, particularly in areas of relatively large cloud amounts, that these high values were contributions mainly by a few days of overcast conditions which could be due to moving disturbances over the area. The distribution of coefficients of variation is shown in Fig. 9. It may be seen from this figure that the areas of low coefficients of variation are —

- (i) North Bengal, Assam, East Pakistan and Arakan coast where overcast conditions had been persisting,
- (ii) Over central portion of India and north Arabian Sea where clouding had been uniformly moderate due to absence of moving disturbances in NET, and
- (iii) In the near equatorial regions.

The areas of high coefficients of variation are —

- (i) Over northwest India indicative of passage of a perturbation,

- (ii) Off Kuria Muria coast suggesting that the relatively large cloudiness in association with NET did not extend far to west on all the days,
- (iii) Over Gulf of Aden and Somalia, and
- (iv) Over western half of Indian Ocean between latitudes 5°S and 15°S.

This analysis has brought out the areas of persistent cloudiness due to quasi-stationary circulation features and areas of temporary clouding due to perturbations.

6. Ships' data : Longitudinal cross-sections

The ship observations during the I.I.O.E. period (1963-1965) form a formidable collection. It is the single intensive systematic data collection over Indian Ocean area so far available. It was, therefore, considered very desirable to take advantage of this unique data collection to examine the cloud cover information. Many ship logs were also examined.

Due sparse data over many parts of the Indian Ocean and the inherent limitations in the ground based observations of clouds, the ship data may not be adequate on a day-to-day basis to delineate the large scale cloud systems. However, they were found satisfactory, when the average cloud covers over small grids were worked out for relatively long periods. The low cloud amounts reported by ships were averaged out, irrespective of the time of observation, for each two-degree square latitude-longitude grid for every five days during July and August of 1963 and 1964, using the IBM electronic computer in IMC. From these grid values two representative longitudinal cross-sections — one each for the east and the west halves of the Indian Ocean — were prepared. The cross-sections were so selected as to reduce the influence of land masses to a minimum, consistent with the necessity to have sufficiently representative number of observations. Continuous time cross-sections were prepared for the eastern and the western Indian Ocean for the whole of July and August of 1963 and 1964. On these cross-sections isopleths of cloud amounts were drawn and axes of maximum and minimum cloudings were located. Additionally the location of the axis of SET (as on the analysed daily sea level charts) was also indicated on these sections. From an examination of these sections (Figs. 10-13), the following facts emerge —

- (a) There is a very good agreement in the location of broadscale cloud areas between satellite data (discussed in the earlier sections) and ship data. This is rather interesting considering that the satellite-

observed cloud conditions refer to daytime while ship data refer to both day and night.

- (b) The northernmost cloud field associated with NET is the most pronounced and persistent in all the sections.
- (c) The three major cloud fields with relatively clear areas in between are seen in all these sections. They are seen both in the western and the eastern Indian Ocean and also throughout the monsoon period. It again leads to the important conclusion that this basic configuration in the cloud field is the characteristic feature of the monsoonal circulation over the Indian Ocean and is independent of the monsoon rainfall over the Indian mainland although there are changes in the intensities of the cloud belts and slight shifts in their location.
- (d) The SET is often located in between the two near equatorial cloud bands on either side of the equator. A similar feature in the eastern Pacific has been noticed by Sadler (1963). Presumably, cloudiness increases in the region of the axis of SET only when disturbances form and move along the trough line.
- (e) The cloudiness in the extreme southern portion of the section (*i.e.*, south of Lat. 15°S) appears to be due to disturbances in the southern hemisphere upper westerlies. The minimum of cloudiness in the southern hemisphere which separates the clouding in the easterlies from that in westerlies, is nearer to the location of the subtropical ridge line in the higher levels rather than in the lower levels.

7. Ships' data : Latitudinal cross-sections

As SET is close to the equator during the southwest monsoon and two cloud bands lie between Lat. 10°N and Lat. 10°S , a time-section of average cloud cover (similar to those discussed in Section 6) between Lat. 10°N and Lat. 10°S should throw some more light on SET and the two near equatorial cloud belts. Time-sections of five-day averages of low cloud amounts between Lat. 10°N and Lat. 10°S , for July–August of 1963 and 1964 are shown in Figs. 14 and 15. Smooth isopleths of cloud amounts are drawn on these sections. It is possible to recognise in these diagrams quasi-stationary or very slow west-moving cloud maxima. (The dotted lines joining the various maxima indicate tracks of the maxima). The maxima are located at intervals of roughly 15 to 20 degrees longitudinal separation and during

any period there are 3 to 4 maxima over the equatorial Indian Ocean between Africa and Indonesia. Over the monsoon periods of 1963 and 1964, the maximum clouding in the entire equatorial region was between Long. 65°E and Long. 80°E . It is noteworthy that in the mean (Raman and Dixit 1964) at 500-mb level a trough in southern hemisphere westerlies extends upto equator in this longitudinal belt and cyclonic circulation extends from surface to 500-mb level over Gan-Diego Garcia area.

Another diagram (Fig. 16) shows the zonal profile of average clouding for the whole of July and August over equatorial Indian Ocean between latitudes 10°N and 10°S . Profiles for 1963 and 1964 are shown separately. These profiles also show the existence of four peak values located approximately at — (1) 45°E – 50°E , (2) 60°E – 65°E , (3) 70°E – 80°E and (4) 90°E – 95°E (intervals of roughly 15 to 20 degrees longitude). The equatorial Indian Ocean is an area of minimum variation of cloud amount as discussed in Section 5. This would, therefore, suggest that these four peaks are quasi-stationary.

All these features lead us to infer that over the equatorial Indian Ocean area, there are quasi-stationary zones where heavy clouding is frequent, located at intervals of 15 to 20° longitude. In the daily map analysis at IMC we have noticed cyclonic vortices in SET which are generally associated with heavy cloudiness. We may, therefore, postulate that SET contains quasi-stationary cyclonic vortices at intervals of 15 to 20-degree longitude; if these vortices move at all, they do so very slowly westward and they appear to be rigidly linked to each other. With the existence of such quasi-stationary vortices, it becomes more difficult to trace the movement of disturbances in SET (such as the deep depression discussed in Sec. 4). Normally, we may expect alternate intensification and weakening of the moving disturbances as they approach and recede from the quasi-stationary vortices. Similar features are also noticed in NET particularly when it overlies the oceanic area.

The 15–20 degrees longitudinal interval between the vortices in the equatorial troughs is close to the wave length of the easterly waves in the Caribbean (Riehl 1954). Presumably, this is a characteristic spatial distribution of low latitude disturbances.

8. Semi-Global composites

From the nephanalysis charts, composites of significant largely distributed *Cu* and *Cb* cloud fields were prepared for the tropical area from east Atlantic (40°W) to west Pacific (170°E) on two occasions. These occasions were 30–31 July 1965

(Fig. 17), a period of active monsoon conditions over India, and 6-7 August 1965 (Fig. 18), a period of *break* monsoon conditions. Each composite was made out of all available TIROS passes over the area, for a period of 48 hours in each case. The area not covered by TIROS passes is very small. The most significant feature of the composites is that the *Cu-Cb* cloud field is in the form of single belt west of Long. 30°E and it splits into a number of east-west oriented cloud masses to the east of this longitude. It has been shown earlier that the multiple cloud belts in the Indian Ocean area are due to the presence of the two hemispherical troughs on either side of the equator. Comparing the land-sea distribution between longitudes 40°W and 170°E, it may be noted that west of Long. 40°E the whole stretch of the area along any longitudinal cross-section is covered entirely either by sea (Atlantic) or land mass (Africa). However, to the east of Long. 40°E, the conditions are different. The vast Indian Ocean is flanked in the north by the massive Asiatic continent and the west Pacific is flanked in the south by Indonesia and Australia which are of fairly large size. Apart from the distribution of sea surface temperature (Raman, Srinivasan and Ramanathan 1965) the meridional distribution of large ocean-land masses seems to affect the near equatorial low level wind circulation, *viz.*, with prominent double troughs in the longitudes where land-sea contrast is very marked and the absence of well marked double troughs in the longitudes where there is no such land-sea contrast. As a consequence of the difference in the circulation features, the equatorial cloudiness is also correspondingly different with a single large cloud belt over Atlantic and Africa and multiple cloud belts over Indian Ocean and west Pacific.

Conclusions

(i) The study shows that the Indian southwest monsoon field is not uniformly clouded but has characteristic regions of maximum and minimum cloudiness. These cloud fields could be associated with the two hemispherical troughs in the low level wind circulation and the vortices in them.

(ii) Depressions similar to those in the northern equatorial trough, *i.e.*, the seasonal monsoon

trough over India — form and move in the southern equatorial trough also which lies close to equator in the southern hemisphere during the northern summer.

(iii) There is evidence to suggest that the relative distribution of clouds over Indian Ocean does not vary appreciably with the monsoon rainfall over Indian mainland.

(iv) The cloud field near the equatorial region of Indian Ocean is somewhat quasi-stationary, with areas of maximum cloudiness located at intervals of 15 to 20 degrees longitude.

(v) While the major tropical clouding in Atlantic and over Africa is in the form of a single east-west oriented zone, that over Indian Ocean and southwest Pacific splits into a number of east-west oriented belts. The main reason for this difference appears to be the distribution of sea surface temperature and meridional distribution of ocean-land masses.

10. Acknowledgement

The author is highly grateful to the Director, National Environmental Satellite Centre, Washington (U.S.A.) for the supply of TIROS photographs for selected orbits. The graphic nephanalyses utilised in the study were also obtained through the publications of NESG, Washington. The author is also indebted to Shri C. R. V. Raman, Director, IMC, for his keen interest in the work, encouragement and the valuable discussions. Shri V. R. Neralla (Scientific Officer, A.E.D. Trombay, Bombay) was closely associated with this work in the earlier stages when he was at IMC. The author would also like to acknowledge the help given by Shri J. M. Korkhao and Shri Y. Ramanathan of IMC by drawing up the computer programmes required in this study and working them out. Thanks are also due to Dr. P. Koteswaram, Visiting Professor, University of Miami and Mr. L. F. Hubert and Mr. P. K. Rao of National Environmental Satellite Centre, Washington for kindly going through the manuscript and giving valuable suggestions.

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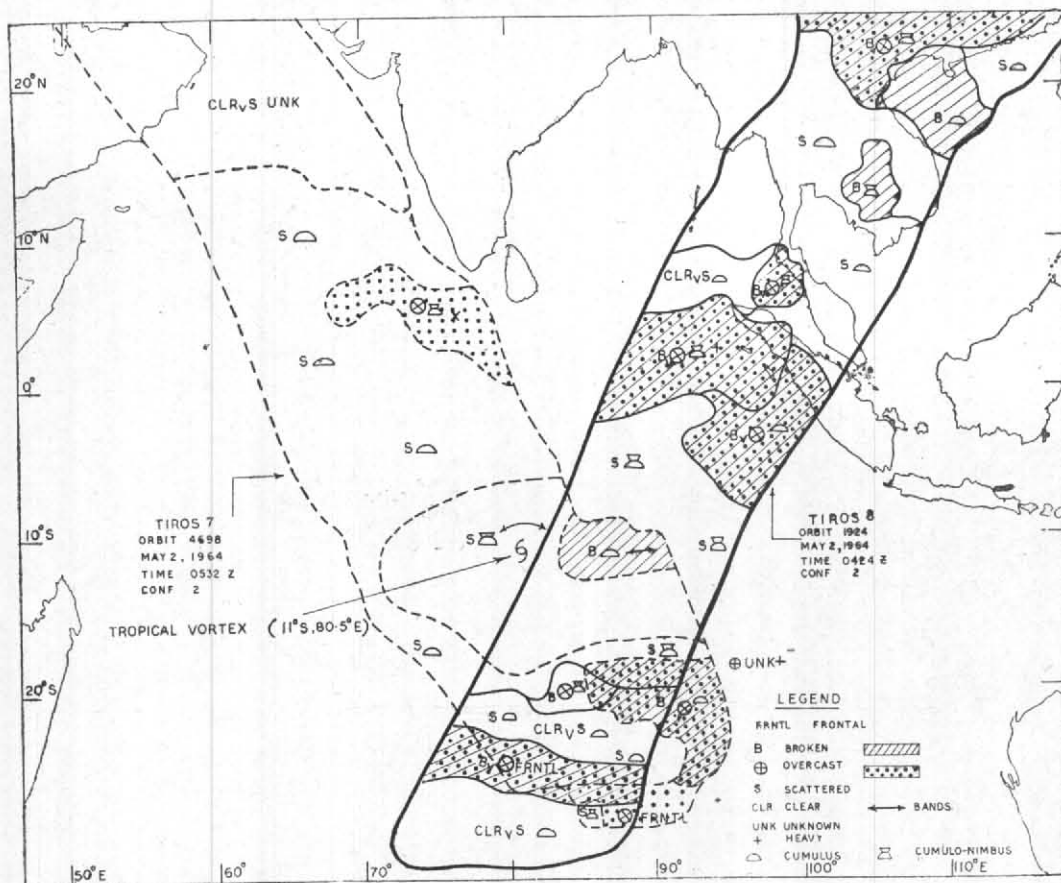


Fig. 1

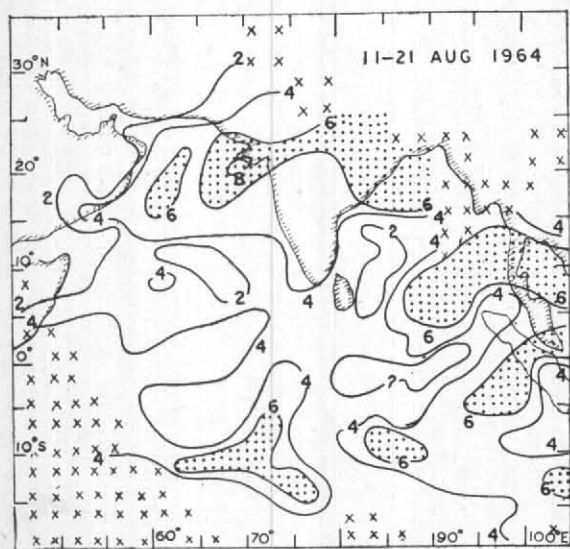


Fig. 2. Average cloud cover distribution

- 2—Clear to scattered (1 to 2 oktas)
- 4—Scattered to broken (3 to 4 oktas)

X—No data available

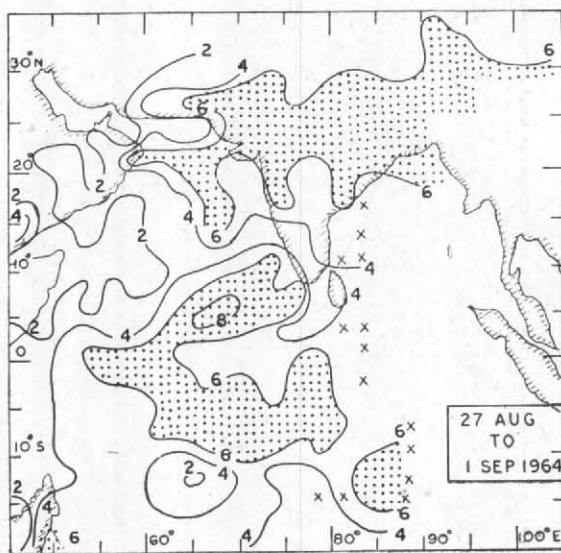


Fig. 3. Average cloud cover distribution

- 6—Broken to overcast (6 to 7 oktas)
- 8-9—Overcast to heavy overcast (8 oktas)

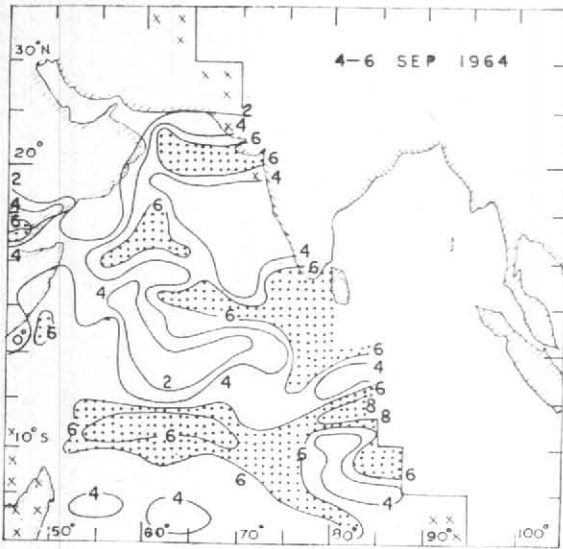


Fig. 4. Average cloud cover distribution
(also see legend of Figs. 2 & 3)

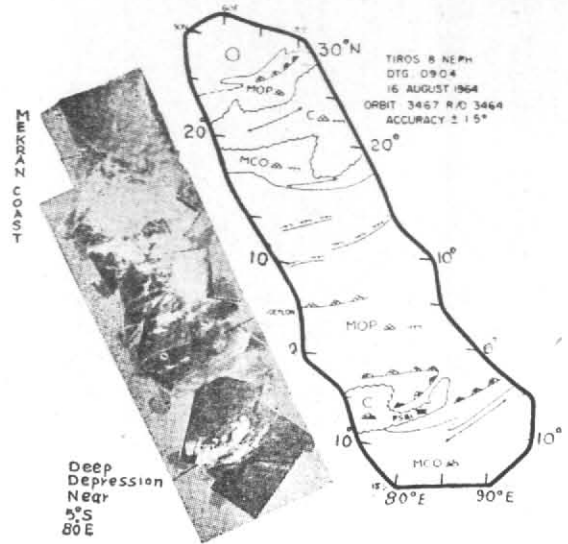


Fig. 5

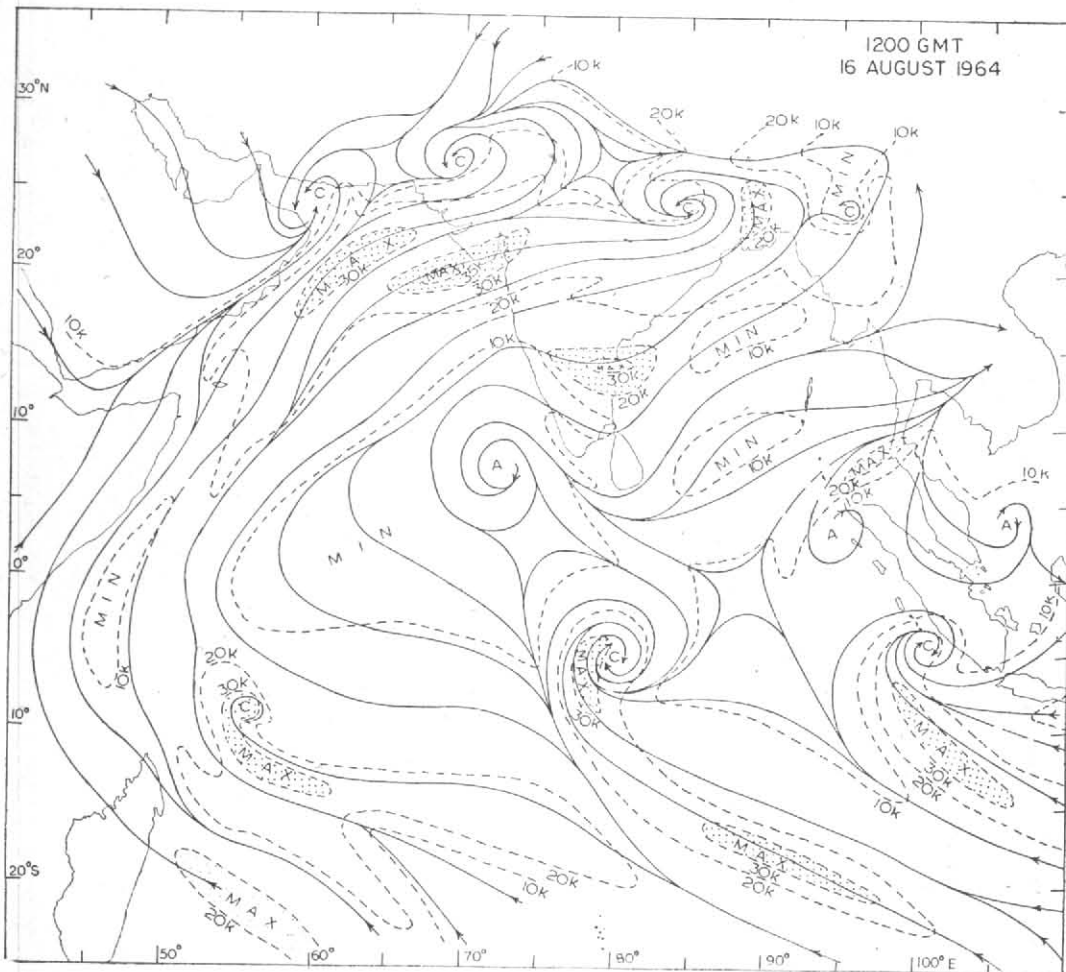


Fig. 5(a). Streamline analysis of surface

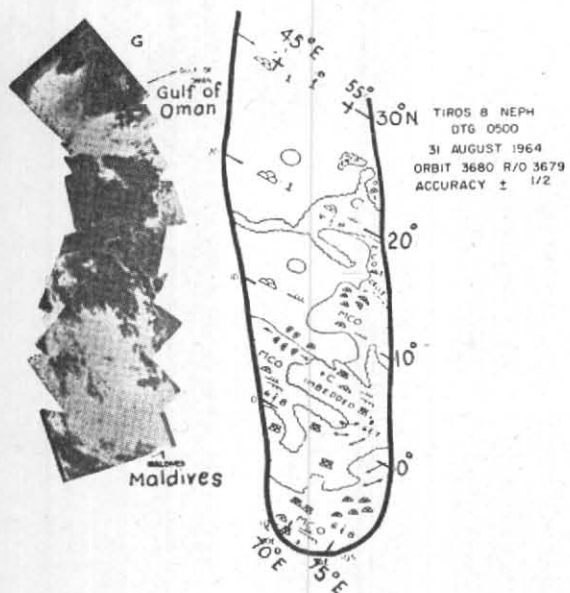


Fig. 6

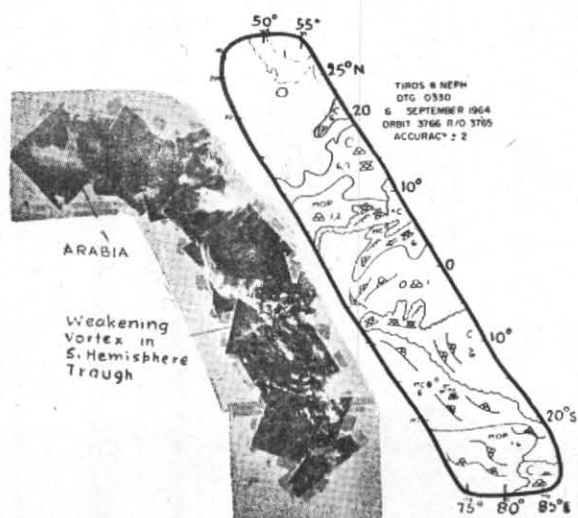


Fig. 7

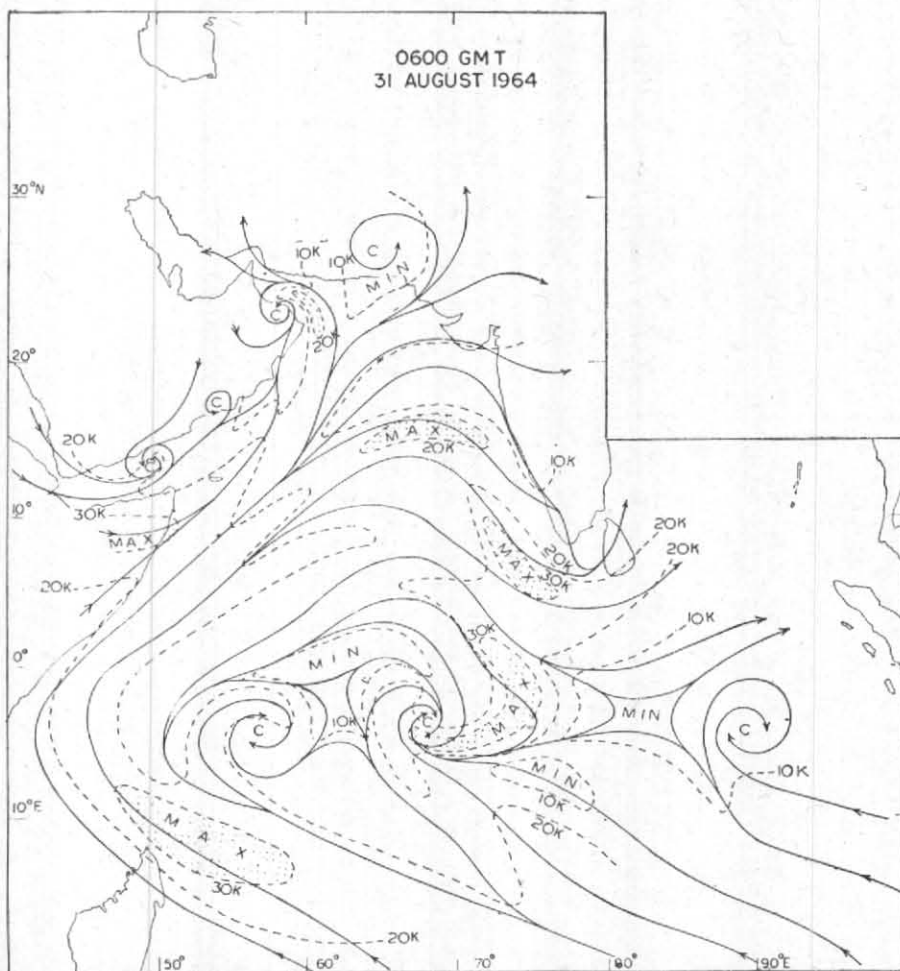


Fig. 6(a). Streamline analysis of surface

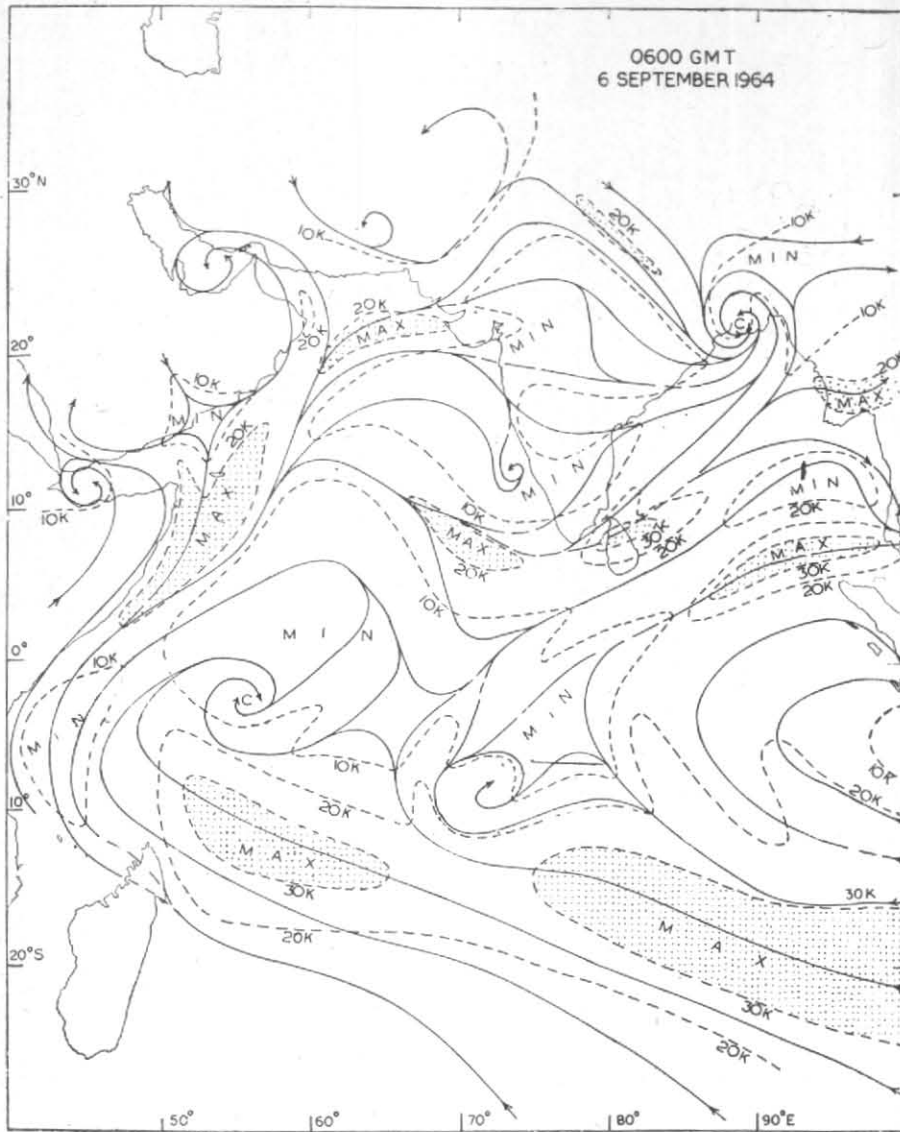


Fig. 7(a). Streamline analysis of surface

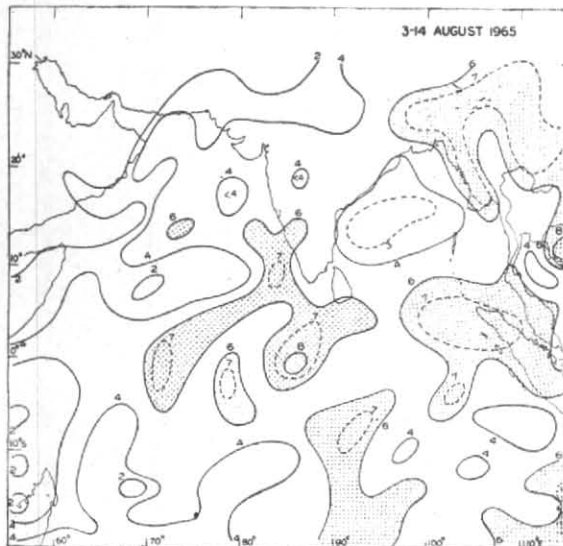


Fig. 8. Average cloud cover distribution
(also see legend of Figs. 2 & 3)

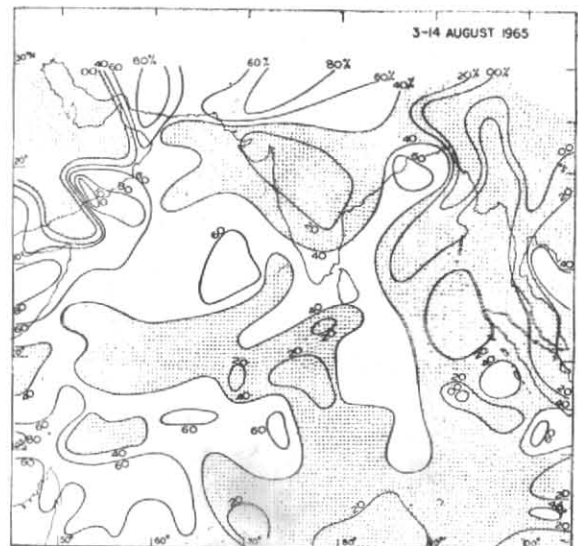


Fig. 9. Coefficient (%) of variation of cloud amount

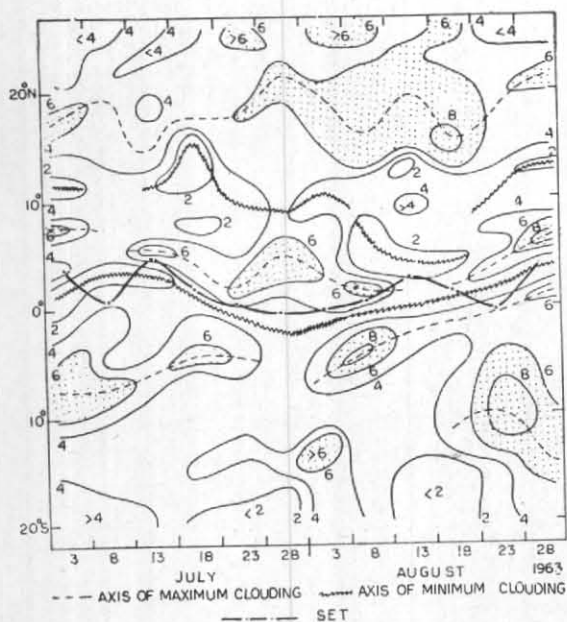


Fig. 10. Western Indian Ocean (Long. 60°E–88°E)

(Total No. of observations : 1544)

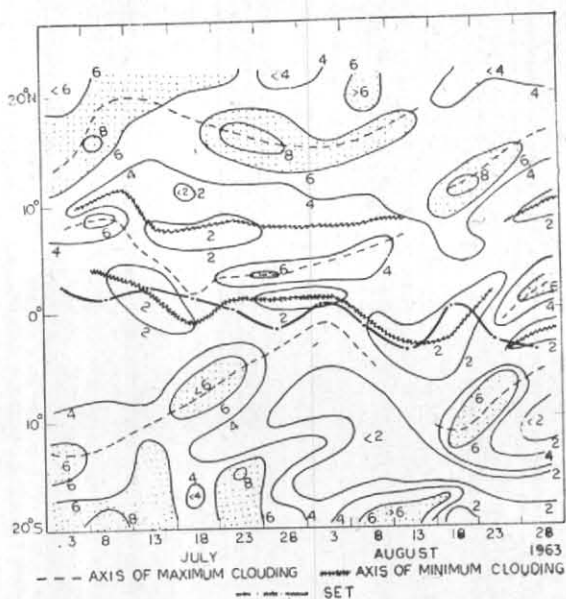


Fig. 11. Eastern Indian Ocean (North of equator Long. 84°E–90°E, South of equator Long. 84°E–94°E)

(Total No. of observations : 1200)

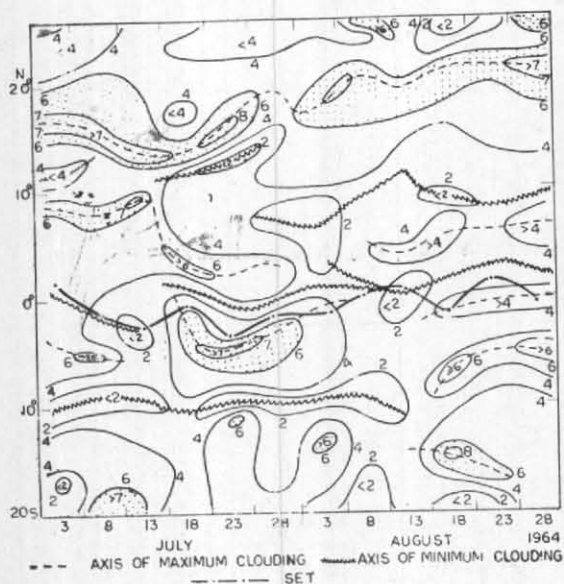


Fig. 12. Western Indian Ocean (Long. 60°E–68°E)

(Total No. of observations : 1402)

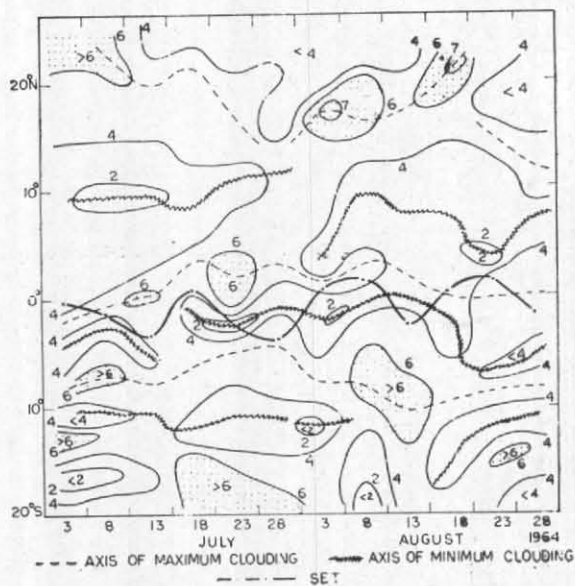


Fig. 13. Eastern Indian Ocean (North of equator Long. 80°E–90°E, South of equator Long. 84°E–94°E)

(Total No. of observations : 2353)

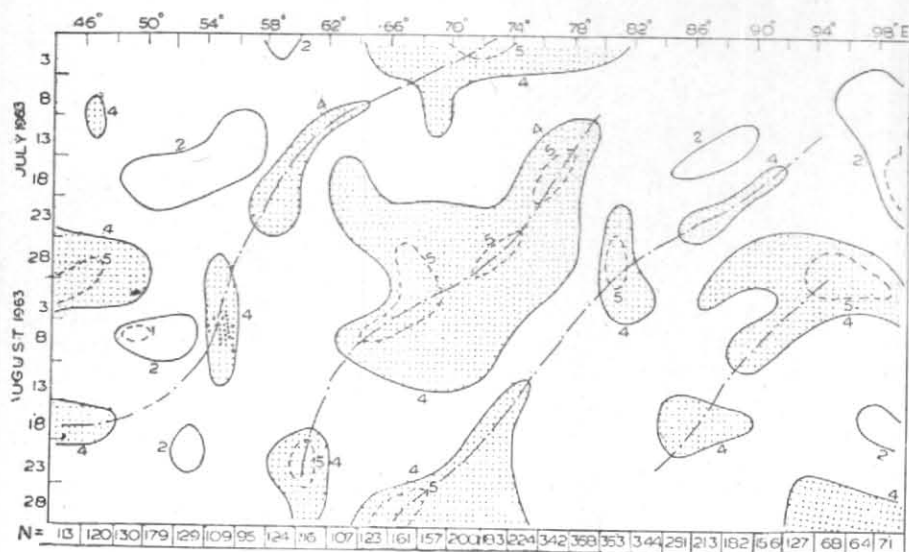


Fig. 14. Latitudinal cross-section of cloud amounts (10°N – 10°S) July and August 1963



Fig. 15. Latitudinal cross-section of cloud amount (10°N – 10°S) July and August 1964

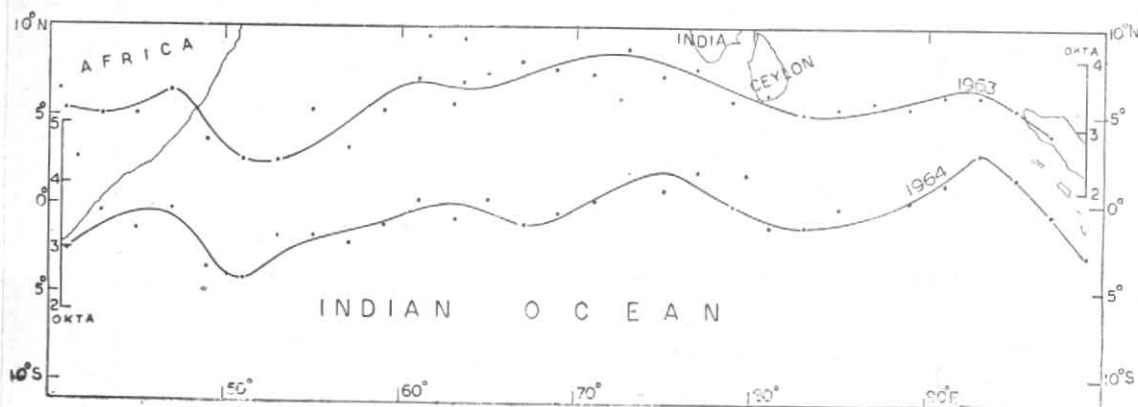


Fig. 16. Zonal profile of average clouding over Equatorial Indian Ocean, July and August 1963 and 1964

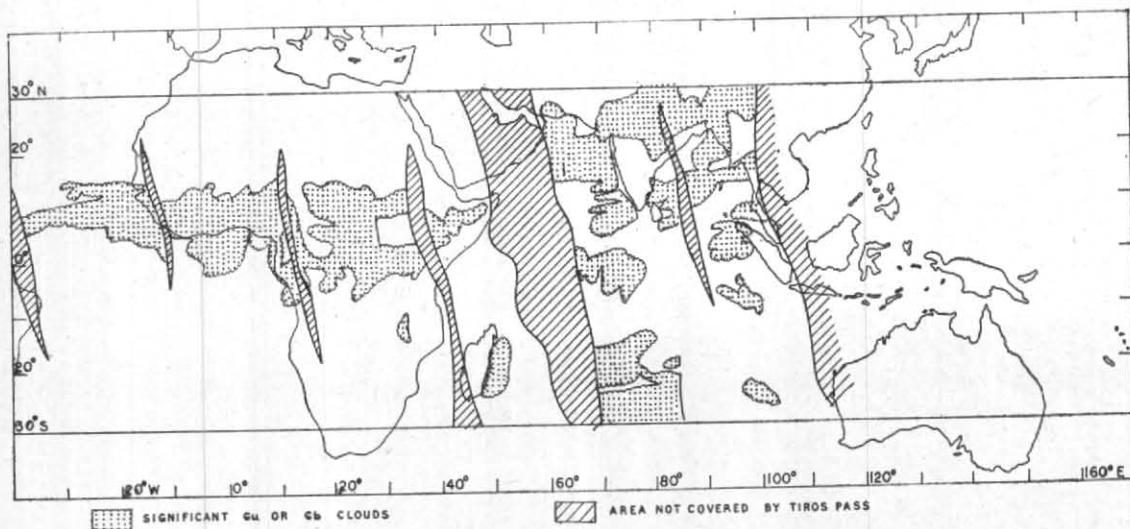


Fig. 17. Composite of significant largely distributed *Cu* or *Cb* clouds on 30-31 July 1965
Frontal clouds omitted from the composite (Data from 15 orbits utilised)

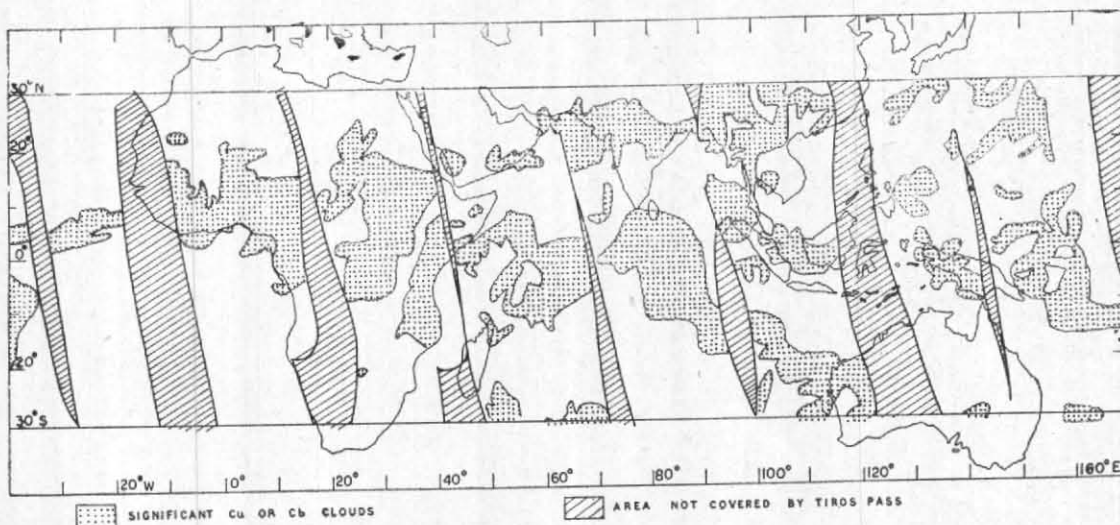


Fig. 18. Composite of significant largely distributed *Cu* or *Cb* clouds on 6-7 August 1965
Frontal clouds omitted from the composite (Data from 15 orbits utilised)

APPENDIX A

Method of averaging cloud amount from satellite nephanalysis (Sadler 1965)

The most representative cloud amount symbol for each $2\frac{1}{2}$ -degree latitude—longitude square is determined for each orbit's nephanalysis and recorded in the appropriate grid square as a numerical value assigned in accordance with the scheme shown in Table 1. The numerical values are averaged and plotted on a base map at the centre of the square. Isoleths are constructed which can be interpreted in terms of cloud amount by reference to column 3 of the table.

TABLE 1

Nephanalysis Symbol	Assigned numerical value	Approximate cloud cover in tenths
O or CLR	1	1
MOP	3	3
MCO	5	6
C	7	10
+C	9	10