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A STUDY OF SATELLITE OBSERVED CLOUDINESS OVER THE EQUATORIAL INDIAN OCEAN AND INDIA DURING THE SW MONSOON SEASON*

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ABSTRACT

Cloud cover photographed by weather satellites during the last five years (1966-70) for the months of July & August, are utilised to study the following aspects :

(i) The relation, if any, between the cloudiness in equatorial regions of Northern and Southern Hemisphere over the Indian Ocean.

(ii) The relation between the characteristic monsoon cloud bands over India and the synoptic features.

(iii) Organisation of clouds into oval-shaped structures.

Bands straddling the equator have been found to generally generate and decay *in situ* with the average life duration of about 3-4 days. Cloud configurations associated with the monsoon trough over India have been classified into different categories and their synoptic associations attempted. An interesting finding is that whereas the characteristic monsoon cloud band follows small oscillations of the 700 mb trough axis, its large northward shift in association with the displacement of the trough to the foothills is subsequently followed by the regeneration of the cloud band and the trough at about 15°N. The frequency of occurrence of oval-shaped cloud clusters over the Bay of Bengal and the Arabian Sea is about the same and the clusters occur in preferred areas.

INTRODUCTION

WITH the availability of daily cloud pictures observed by the polar orbiting satellites since 1966 it is now possible to gain information on daily basis on the occurrence and organisation of clouds over vast oceanic regions of the Indian ocean. This information can be utilised to investigate some of the problems connected with the Indian SW monsoon. The present investigation is directed to examine the following aspects :

(i) ' pulses ' or ' surges ' in the monsoon field,

(ii) organisation of clouds into bands near the equator as well as in the region of the monsoon trough,

(iii) organisation of clouds into oval-shaped structures.

Malurkar (1950) after a systematic examination of synoptic charts extending well into the southern Indian Ocean had evolved the concept of monsoon ' pulses '. According to him pressure gradient across the latitudes near the equator south of

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India was on an average small during SW monsoon and the air stream in the equatorial zone of the south Indian Ocean was associated with the low pressure systems moving in west or west-northwest direction. Some of these low pressure systems crossed the equator into the northern Indian Ocean bringing with them ' pulses ' of fresh monsoon air. These ' pulses ' were considered by him to strengthen the south-west monsoon or feed into the tropical depressions over the Indian seas. The ' pulses ' were considered to cross along preferred longitudinal belts thus strengthening the monsoon in those belts. For example if the pulses crossed between 80-90°E or 90-105°E they would strengthen the monsoon over the Bay of Bengal and SE Asia region respectively and if they crossed over western longitudes into SE and SW Arabian Sea, they would strengthen the monsoon in east or west Arabian Sea. Desai (1951) discussed the concept of ' Surges ' in SE trades which according to him were stimulated by the intensification and changes in the location of the sub-tropical anticyclone in the south Indian Ocean and in turn affected the crossing of the air stream across the Equator between favourable longitudinal belt of 60°E and African coast. The surges of rising pressure near the Equator were associated by him with the surges or pulses of monsoon air across it.

Koteswaram (1960) suggested the existence of a near equatorial trough in the southern Indian Ocean too during the Northern Hemispheric summer. Raman and Dixit (1965) brought out the existence of lower tropospheric double equatorial trough on either side of the Equator in the Indian Ocean in all the months of the year in their analyses of the mean monthly circulation charts. Raman (1965) emphasised the existence of double equatorial troughs and the associated convective activity on either side of the Equator. Srinivasan (1968) studied the distribution of clouds during the SW monsoon as observed by the TIROS series of weather Satellites. By studying a few typical situations with composite cloud pictures, he observed that the monsoon field was not uniformly clouded but had characteristic maxima and minima in cloudiness which could be associated with the two hemispherical troughs and the existence of vortices within them. He also suggested that during the SW monsoon season the axes of the maximum cloudiness over the near equatorial region of the Indian Ocean are located at intervals of 15-20 degrees longitude.

The formation of monsoon depressions in the Bay of Bengal and their associated cloud organisations are well known features of the SW monsoon season. The satellite cloud pictures of these depressions have confirmed the synoptic climatological feature of these monsoon depressions having the maximum convective activity in the SW sector. Besides the near circular cloud masses associated with these depressions, the satellite pictures have also shown several other types of oval-shaped clusters in different stages of development. Sadler (1965) has documented the existence of such oval-shaped cloud masses in association with the active phase of a mid-tropospheric cyclone off north Konkan and Gujarat coasts.

The authors are thankful to the Office of the Deputy Director-General of Observatories, Poona, for extending the facility of consulting the APT pictures and the synoptic weather charts.

Data Used in the Study

In the present investigation we have examined in detail the daily satellite cloud pictures as obtained by the APT station, Bombay, for the months of July and August during 1966-70. A study of the daily cloud pictures and their changes from day to

day was made with a view to elucidate the points (i) to (iii) mentioned in the introduction. Since compositing of cloud over several days leads to loss of information of synoptic nature, this study is done on the basis of daily data only. The cloud information contained in each daily picture was catalogued into bands and ovals separately in three latitudinal belts *viz.* 10°S to Equator, Equator to 10°N and 10°N-27°N representing the southern hemisphere equatorial trough (SHET), Northern Hemisphere equatorial belt and the monsoon field. Special attention was paid to the existence of bands across the Equator extending from the Southern to Northern Hemisphere, termed as cross equatorial bands (CEB) as it was thought that they may be of relevance to the problem of ' pulses '. Daily synoptic charts for surface, 850, 700 and 500 mb levels were examined to seek associations of cloud patterns with the synoptic features.

Organisation of Clouds into Bands

Cross Equatorial Bands (CEB) :

Cross equatorial bands have latitudinal extent of about 6-8 degrees. Their daily patterns fall into the following three categories :

1. Single Band of longitudinal extent of about 10-15 degrees with preferential location generally between 60-70°E, 80 to 90°E or east of 95°E.

2. Simultaneous existence of two bands of the type (i) separated by cloudless belt of 10-15 degrees in longitude.

3. A nearly continuous extended single band covering the belt 60-100°E. While some of the bands are oriented east-west across the Equator, quite a few bands particularly the single ones are inclined from WSW to ENE. The longitudinal extent of such bands in this study has been taken from the beginning of the band to its end. Fig. 1 shows the longitudinal extent of these bands for the year 1968. Table 1 shows the observed frequencies of these bands for the period under study. It is seen that over the period (July-August 1966-70) there was no CEB on 35 per cent of the occasions, single band occurred on 45 per cent occasions, two bands and extended band each on 10 per cent occasions. There are year to year variations in the above frequencies. For want of data in the relevant regions on daily basis it was not possible to find out any synoptic associations with the formation, development or decay of these bands. However, the cloud pictures showed the following features :

Table 1

Month	Year	*Band Type* Type 1	Type 2	Type 3	No. Band
July	1966	13	1	3	7
,,	1967	7	0	3	21
,,	1968	19	2	4	6
,,	1969	8	0	1	22
,,	1970	17	0	0	14
August	1966	18	1	3	9
,,	1967	13	8	2	8
,,	1968	15	2	2	12
,,	1969	16	8	1	6
,,	1970	9	8	4	10

(i) Single or double band may form *in situ* along a longitudinal belt, expand and merge to become an extended band.

(ii) Single or double bands may decay *in situ* or with slight oscillation in their positions. The extended band may first split into two bands and subsequently decay *in situ*.

(iii) The average life duration of a single band was 3-4 days. However, there were occasions when the band disappeared within 24 hours and other occasions when it persisted for about 10 days. The average life of simultaneous existence of two bands was about two days, although some persisted upto 4 days. The extended bands did not, however, persist for more than two days.

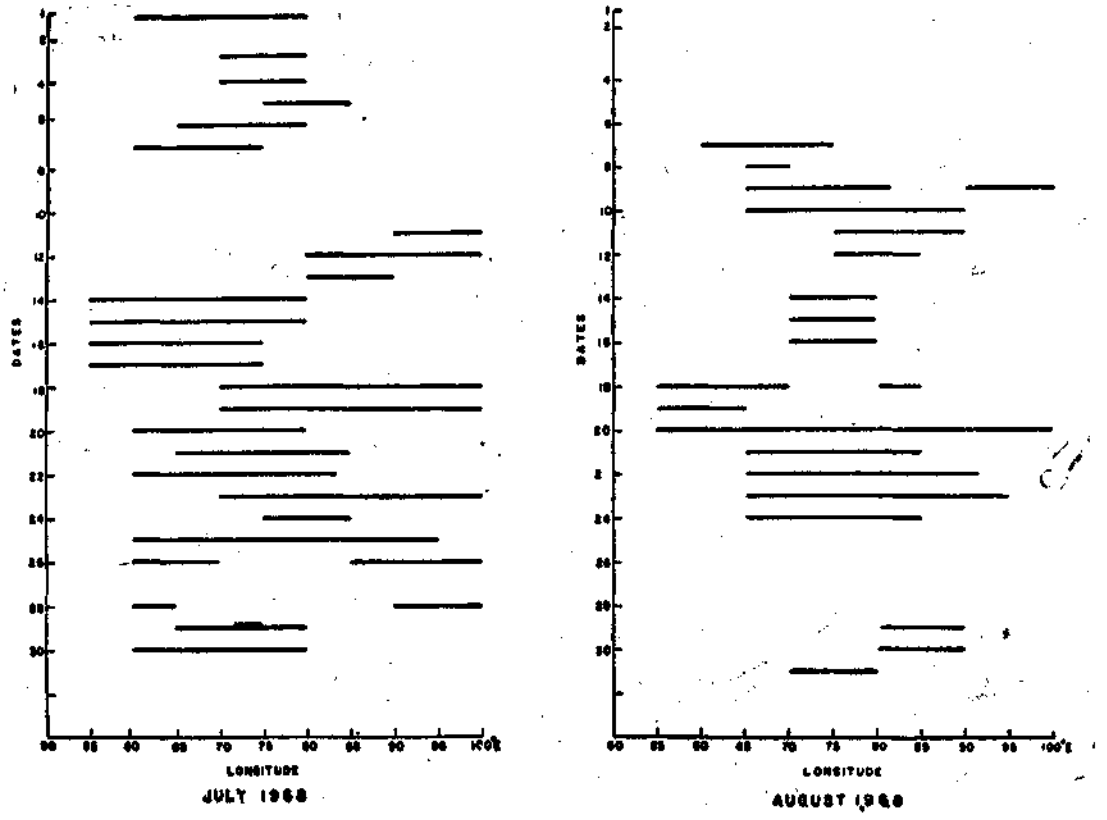

Fig. 1. Longitudinal extent of cross equatorial bands.

(iv) No systematic movement of these bands was seen. However, there were a few occasions when the Northern Hemispheric portion of the band in the longitudinal belt 60-80°E extended upto about 10°N and subsequently the band split up into two separate branches in the two hemispheres. An instance of an inclined equatorial band is shown in Plate IA which is the HRIR imagery of the band. Plate IB shows the same area after 3 days when the band had completely disappeared.

If these cross equatorial bands are interpreted as clouds associated with ' pulses ', the relatively small frequency of the occurrence of simultaneous two bands would seem to indicate that simultaneous occurrence of ' pulses ' in two distinct preferred zones is relatively less probable as compared to the occurrence of a ' pulse ' restricted to one preferred zone. The small frequency and the small life duration of the extended single band would seem to suggest that large scale occurrence of ' pulses ' is relatively rare event of comparatively short life time. These bands did not show any regular movement from south to north or west to east as one would expect with a moving disturbance. *In situ* formation and decay of these bands with some lateral expansion is, however, not inconsistent with the idea of ' pulses ' crossing the Equator. The ' pulse ' with its associated low level cyclonic vorticity in the near equatorial zone of the Southern Hemisphere would inject anticyclonic vorticity in the Northern Hemisphere equatorial zone, thus inhibiting its cloud patterns being sustained in the Northern Hemisphere. The frequency of occurrence of no band across the Equator being comparable to the frequency of occurrence of single bands suggests that the weather activity in the equatorial zone occurs in spurts. What is observed is the periodic activation of a particular longitudinal belt near the Equator. On a few occasions the end of the band in the Southern Hemisphere was found to be linked up with a frontal system. This may be indicative of a surge in the SE trades but for want of synoptic data this could not be established. However, the equatorial cloudiness prominently flares up on the Equatorward penetration of the cold frontal system of the southern latitudes.

Although these spurts in the weather activity in the equatorial zone may correspond to pulses or surges, yet no evidence was found between the occurrence of CEB and the spurts in cloudiness near the Equator and the subsequent or simultaneous strengthening of the monsoon over India north of 15°N. However, there were a few occasions when the weather activity increased off Kerala coast and in South Arabian sea within 2-3 days of the occurrence of such a spurt across the Equator. As a result of the behaviour of these cross equatorial bands discussed above, the authors feel that although at times the monsoon activity over Kerala coast and S. Arabian Sea could be connected with the occurrence and expansion of the cross-equatorial cloud band between 60-80°E, they had apparently no connection with the monsoon activity north of 12°N.

Bands associated with the Southern Hemisphere Equatorial Trough (SHET) :

The study of the bands associated with the near equatorial trough (exclusive of CEB's) in the Southern Hemisphere showed similar features to those described with respect to the CEB's. In general, the frequency of extended bands was greater than in the case of CEB's. Table 2 shows the percentage, frequency of occurrence of all types of bands in the SHET.

TABLE 2. *Percentage frequency of cloud bands in the SHET*

Year	July	August
1966	75	40
1967	50	75
1968	50	45
1969	35	50
1970	60	40

It is seen that on an average about 50 per cent of the days in the months of July and August (1966-70) there were practically no clouds in the S.H. equatorial trough zone (SHET). The cloud bands covered an extensive longitudinal belt (more than 30 degrees at a stretch) for only about 25 per cent of the days. Since the bands in this region are associated with the SHET and the trough would not migrate to south of 10°S in the seasons, these features of the cloud bands would lead us to the conclusion that the trough shows large fluctuations in its associated weather activity varying from 25 per cent of the days of extensive clouding to 50 per cent days of practically no clouding. This behaviour is in sharp contrast to the Northern Hemisphere summer trough lying over India (Monsoon trough) which is accompanied by extensive cloudiness on most of the days in the season.

Bands in the Northern Hemisphere near equatorial regions :

In addition to the expected cloud bands associated with the Southern Hemisphere equatorial trough and the monsoon trough over India (15-25°N) Srinivasan (1968) also observed another well defined cloud belt in the Northern Hemisphere near equatorial region of the Indian Ocean (0-10°N) in the composites studied by him. We studied day to day occurrence of such a cloud belt. Cloud bands (more than 20° in longitudinal extent) in this belt were found to occur either in conjunction with extensive cross-equatorial bands straddling the Equator or independently of it. Table 3 gives the percentage frequency distribution of the occurrence of these bands for the five-year period studied.

TABLE 3. *Percentage frequencies of the occurrence of cloud bands in Northern Hemisphere Equatorial Region*

	Year	July	August
	1966	45	25
	1967	50	35
	1968	70	50
	1969	35	60
	1970	55	75
Average	1966-70	51	49

The average frequency of occurrence of these bands (50 per cent) for the five-year period studied is comparable to the average frequency of the cloud bands associated with the SHET. The synoptic features associated with these bands could not be also studied for want of adequate data. The monthly average shown in Table 2 and Table 3 show no direct correspondence. It was also generally observed that on a daily basis the two bands were not linked to each other. This would suggest that except for the cases which are associated with extensive CEB's, the near equatorial cloud belts of the two hemispheres behave independently.

Cloud Bands associated with the Monsoonal trough over the Indian Region :

The following features were observed with regard to the characteristic cloud band associated with the seasonal moonson trough over India :

(i) The band was generally oriented East-west from 65°E to 100°E along 15 to 25°N.

(ii) Oval-shaped clusters existed within this band on several occasions which are discussed in detail in the next section.

(iii) The latitudinal width of this band varied generally between 5 to 10 degrees.

Several types of variations (Table 4) to this characteristic band were observed which have been broadly classified into the following nine categories :

Category No.	*Description*
1.	Nearly continuous E-W Band from 65° to 100°E running along 15° to 25°N.
2.	Nearly continuous band with separation into two branches at about 80°E, one branch running NE-ward toward Assam and the other SE-ward towards South Bay.
3.	Bands present over the Arabian Sea and the Bay of Bengal with broken cloudiness over the land.
4.	Band present east of 80°E only.
5.	Two East-West Bands, one along the foot hills and the other along about 10-15°N.
6.	North-South Band over land.
7.	Band present west of 80°E only.
8.	Band present only over the foot hills.
9.	Scattered cloudiness or mostly open conditions.

TABLE 4. *Frequency distribution of the various categories of monsoon bands for the months under study*

		Frequency distribution of various categories of monsoon band									
		Category Number									
Year	Month	1	2	3	4	5	6	7	8	9	No. of obs.
1966	July	6	3	3	7	4	0	0	1	0	24
	Aug.	7	2	0	3	1	0	3	6	9	31
1967	July	10	1	9	0	6	0	3	1	1	31
	Aug.	15	1	3	8	3	1	0	0	0	31
1968	July	14	2	1	3	3	0	0	6	1	30
	Aug.	8	6	2	8	0	0	1	0	6	31
1969	July	12	4	2	8	4	0	0	0	1	31
	Aug.	11	6	0	2	5	0	4	0	3	31
1970	July	11	6	1	6	6	0	0	1	0	31
	Aug.	14	5	1	2	6	2	0	0	0	30

The percentage frequency distribution for July and August separately as well as combined for the two months for the 5 years period under study is given in Table 5.

TABLE 5. *Percentage frequency distribution of various categories of monsoon trough cloud band*

Month	Percentage frequency distribution of various categories								
	Category Number								
	1	2	3	4	5	6	7	8	9
July (1966-70)	36	11	11	16	16	0	2	6	2
August (1966-70)	35	13	4	15	10	2	5	4	12
July & Aug. (1966-70)	35	12	8	16	13	1	3	5	7

The bands under category 1, 2, 3, 4 and 5 comprise about 85 per cent of the total. Nearly continuous band from 65° to 100°E under category 1 which corresponds to the mean monsoon or the composited picture over several days, although of most frequent occurrence comprises only nearly 35 per cent of the total occasions and categories, 2, 3, 4 and 5 which are frequent variations of it contribute nearly half of the total occasions. Obviously these variations are due to the oscillations in the activity of the monsoon under a variety of synoptic situations. An attempt was made to find out the relationships, if any, between the occurrence of different categories of bands and the associated synoptic situations as shown in the analysis of synoptic charts at surface, 850, 700 and 500 mb. The analyses used for the purpose were as contained in the charts of the Weather Central, Poona, and are independent of the cloud pictures examination made by the authors. Whereas for some categories typical predominant synoptic situation could be associated, other categories occurred in association with a large variety of the synoptic situations. Thus it was difficult to associate each category with a typical synoptic feature as sometimes a combination of several synoptic situations were associated with a particular category of band. However, frequently associated synoptic features with different categories of bands are given in Table 6.

TABLE 6

Cloud band Category No.	Remarks on typical synoptic situations generally associated with the cloud band category
1.	Active monsoon trough with two or three embedded vortices (Depression or low pressure areas). Some of these vortices may not extend to the surface level. The surface trough on some occasions runs east-west between 20-25°N and on other occasions runs from NW/SE from Punjab to Andhra coast through Madhya Pradesh.
2.	Trough axis at the surface level displaced northward of its normal position east of 80°E with vortices embedded in it at a latitude north of 23°N. At surface and 700 mb in addition the trough shows a SE-ward orientation toward North Andaman Sea.
3.	No typical synoptic situation. On occasions there are twin vortices in the Bay of Bengal and the Arabian Sea in lower troposphere with ridge between 75° to 80° E.
4.	Surface trough north of its normal position in the western sector and normal position in the Bay of Bengal with an embedded vortex east of 80°E. On occasions trough of low pressure is also present over Mysore and Kerala coast. At 700 mb the trough is delineated easily in the eastern sector but is less marked in the western sector and on some occasions even replaced by a ridge.
5.	Surface trough lying near the foot-hills. On occasions trough of low pressure is present off Kerala, Mysore coast. Downstream decrease of westerlies is also observed on a few occasions along 10-15°N. At 700 mb the trough lies south of its normal position at about 15°N.
6.	A westerly trough between 850 mb and 500 mb lying between 70-90°E on some occasions only.
7.	Occurs in association with several types of situations. Surface trough is along normal latitude west of 80°E and there is a vortex embedded in it west of 75°E, or there is an upper level cyclonic circulation off Gujarat and north Konkan coast and cyclonic shears at the surface level. On occasions there is a trough of low lying along 70°E off west coast or low over Sind and Rajasthan under the influence of a large amplitude trough at 500 mb. In the Bay of Bengal there is a ridge at 700 mb and 500 mb.
8 and 9.	Generally occurs with intense break condition.

Fig. 2 shows the time variation of the latitudinal location of the axis of the cloud band as well as the monsoon trough axis at 700 mb along 80°E, the central meridian of the region for two typical years 1968 and 1969. The cloud axis is generally 3° to 5° south of the trough axis though on a few occasions the separation may be twice this. Sikka (1970) and Bedi and Sikka (1970) also observed that the axis of the maximum cloudiness on the mean monthly basis and the axis of the maximum brightness on 6-day mean basis respectively were in general Equatorward of the mean positions of the 700 mb trough axis. Fig. 2 also shows that the oscillations in the axis of the cloudiness and the axis of the 700 mb trough are in good correspondence. A very important feature which is brought out by Fig. 2 is that on majority of the occasions when the 700 mb trough axis shifted to north of 25°N (foot-hills), it appeared again at about 15°N within a couple of days. The displacement of the trough from north of 25°N to about 15°N is rather too large to be accounted for by the progressive shift of the trough from the foot-hills. The authors are of the view that on

majority of the occasions when the trough axis moves to the north, a distinct trough and its associated cloudiness is regenerated at about 15°N, the progressive movement of which restores normal conditions. During the months of July and August for the years 1966-70, there were 15 occasions when the 700 mb trough axes and their associated cloud belt shifted to north of 25°N out of which on twelve occasions the regeneration occurred from the south.

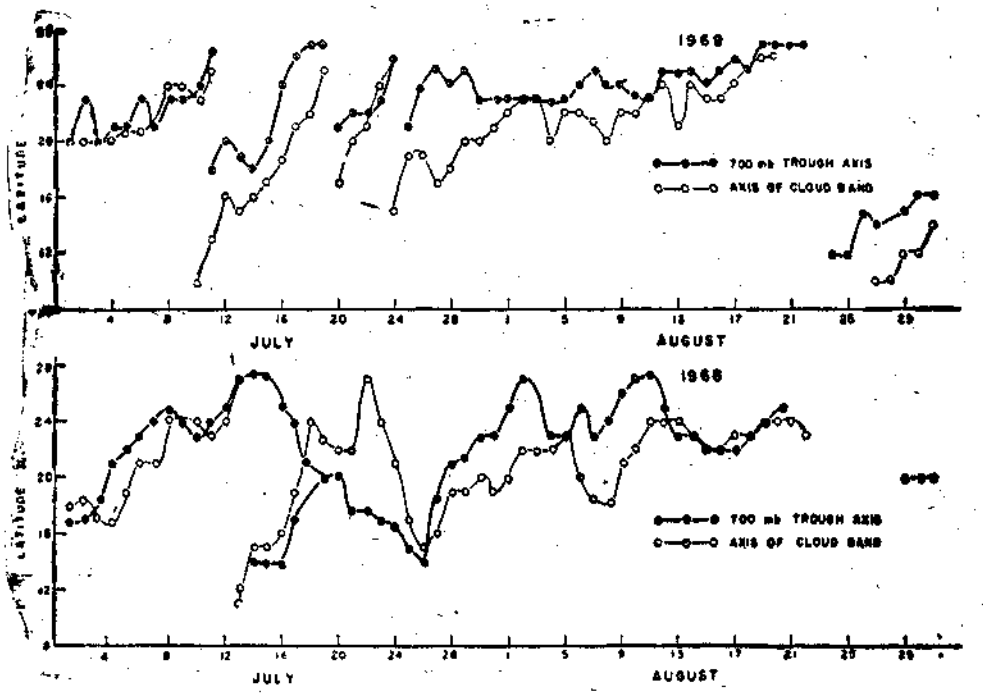

Fig. 2. Time variations of the location of the monsoonal cloud band and the 700 mb. monsoon trough at 80°E for the months of July and August, 1968 (bottom) and 1969 (top).

Oval-shaped Cloud Masses

Several oval-shaped cloud masses were observed either within the cloud bands or in isolation. These cloud masses have a wide range of sizes. The location of geometric centres of all such cloud masses having a size greater than 3 degrees in diameter have been shown in Fig. 3 in which each oval was tallied once a day, for July and August separately. Although each depression was associated with an oval-shaped cloud mass, majority of the ovals were not associated with cyclonic circulations at the surface. In the case of those associated with the depressions or cyclonic circulations at the surface the centres of the ovals were generally to the south-west of the circulation centres. Of the other ovals those occurring north of 15°N were generally associated with cyclonic circulations within the monsoon trough in the middle troposphere only. A large number of ovals to the south of 15°N occurred in association with the cyclonic shears or downstream decrease of westerly wind at the surface. The ovals which have occurred off the west coast of India were mostly in association with a trough of low pressure at sea level. The life duration of

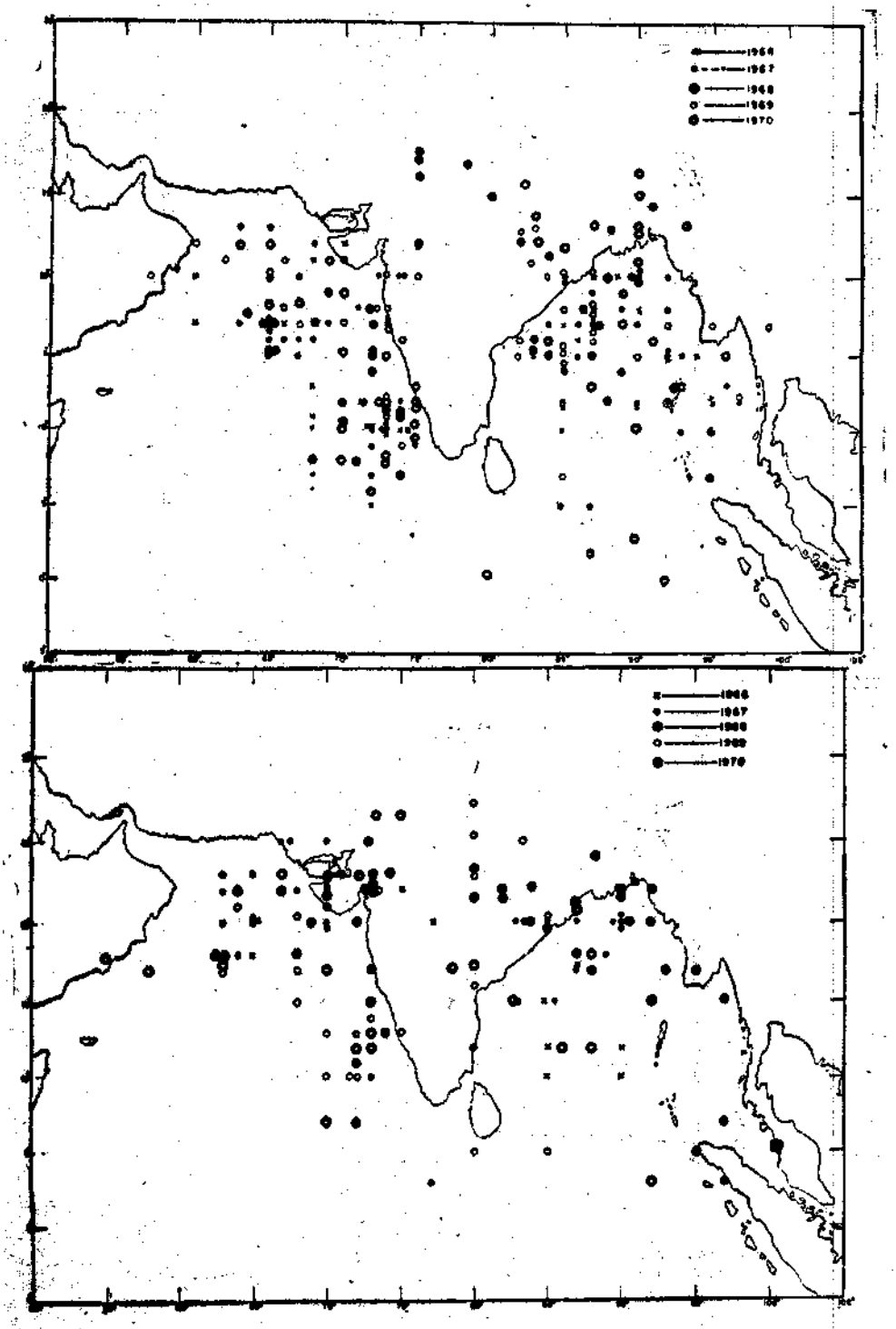

Fig. 3. (Top). Positions for the centres of oval-shaped cloud (tallied once a day) during July for the years 1966–1970, and (Bottom) Positions of the centres of oval-shaped cloud masses (tallied once a day) during August for the years 1966–1970.

these ovals was generally two days except when they were associated with a depression moving from the Bay of Bengal or associated with the slow northward moving surface trough along the west coast of India.

The frequency of the ovals forming in the Bay of Bengal and the Arabian Sea is comparable though the occurrence of cyclonic circulations at surface level is much larger over the Bay. Fig. 3 also shows that the frequency of oval formation is least over SW Arabian Sea, SE Bay of Bengal and over land. Over the rest of the Arabian Sea there are two preferred areas *viz.* (i) off Kerala, Mysore coast and SE Arabian Sea, (ii) between 15-23°N and 63-73° E. Over the rest of the Bay of Bengal though there is a suggestion of a preferred zone of ovals between 15-20°N and 85-90°E, the distribution is more or less uniform. It is interesting to note that the preferred zones of ovals in the Arabian Sea correspond to the thermal ridge in the mean sea surface temperature distribution charts (U.S. Naval Oceanographic Chart, 1967). Over the Bay of Bengal the sea surface temperature distribution shows rather a flat field of temperature ranging between 82-84°F in July, whereas the sea surface temperature in August are more than 83°F within 300 to 500 Km off the east coast of India. The preferred zones of oval formations both in the Arabian Sea and the Bay of Bengal seem to correspond with the warm waters exceeding 82°F.

Conclusion

An attempt has been made to study some of the aspects of the SW monsoon through a day-to-day examination of the satellite cloud pictures during the month of July and August for the years 1966-70. The characteristic features of the monsoon cloudiness are :

(i) cross-equatorial cloud bands.

(ii) cloud bands in the southern and northern hemisphere equatorial region;

(iii) cloud bands in association with the oscillations of the monsoon trough over India.

(iv) oval-shaped cloud masses.

Cross-equatorial bands have been found to occur over preferred longitudes and the single bands generally have a life span of 3 to 4 days. The fact that these bands have been found to form and decay *in situ* does not go well with the concept of travelling monsoon 'pulses' across the equator. There were a few cases when such bands extended towards Kerala coast but their existence or non-existence was not found to be related with the activity of the seasonal monsoon trough over India. The Southern Hemisphere Equatorial cloud band is associated with the presence of the SHET and occurs over extended longitudinal belt only for about 25 per cent of the days. Although the occurrence of the Northern Hemisphere Equatorial cloud band is comparable to the occurrence of the Southern Hemisphere Equatorial cloud band, there was no systematic relationship between the two bands.

The typical extensive cloud band in association with the seasonal monsoon trough over India from 65-100°E occurs only for about 35 per cent of the days. The band shows a wide variety of organisation on other days. Whereas the cloud band follows small oscillations of the 700 mb monsoon trough, its large northward shift

Plate I. A. HRIR photoprint of a cross equatorial band existing between 80° to 90°E on 18 July, 1966, and B. HRIR photoprint on 21 July, 1966, showing rather cloud-free zone along the equatorial belt between 80° to 100°E.

and associated displacement of the trough to the foot of the Himalaya is subsequently followed in majority of cases by the regeneration of the cloud band and associated trough at about 15°N. These observations underline the essentially dynamic nature of the phenomenon and require further investigation.

Oval-shaped cloud masses were found to occur quite often unassociated with cyclonic circulations at surface and have some preferred regions in the Arabian Sea and the Bay of Bengal.

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Discussion

K. R. SAHA : Would it be correct to deduce from your study that on about 65% occasions cloud band or cloud bands are situated away from the Equator ?

D. R. SIKKA : No. However, this study has dealt with the existence of clouds in the near equatorial zones both in the Southern and Northern Hemispheres and it is found that on an average extended clouds are present in these zones on about 50% of the occasions.