

A satellite study of intensities of cyclonic storms in the Bay of Bengal

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ABSTRACT. Seven sequences of satellite pictures of severe cyclonic storms, which developed in the Bay of Bengal have been examined and day to day changes in their intensities have been discussed with reference to the application of Dvorak's technique for the analysis and forecasting of tropical cyclone intensities. Salient features of storm development in Bay of Bengal, as observed in the satellite pictures, have been high-lighted. A comparison of this technique has also been made with synoptic inferences.

1. Introduction

Dvorak (1972) developed a technique for the analysis and forecasting of intensities of tropical cyclones from the satellite photographs, using the pictures of tropical storms and disturbances of western Pacific Ocean. Erickson (1972) evaluated this technique with reference to independent measurements and estimates of storm intensity made from aircraft reconnaissance, surface observations, post-analysis best track interpolation etc for storms in Pacific and Atlantic Oceans. Dvorak (1973) subsequently modified the technique, and this modified version has been adopted for the operational use by the U.S. National Oceanic and Atmospheric Administration.

Dvorak's technique has definite advantage over the older classification of tropical disturbances based on the work of Fett (1964) and Fritz, Hubert and Timchalk (1966). The new technique provides a more detailed and objective method of storm classification and affords forecasts of storm intensity for the next day. The technique has also provided better relation between the classification and the observed (i) maximum sustained wind speed and (ii) minimum central sea level pressure for storms occurring in Pacific and Atlantic Oceans.

The present note examines the application of this technique to the tropical storms and disturbances occurring in Indian Seas.

2. Data

Seven sequences of severe cyclonic storms were selected from satellite pictures obtained from National Oceanic and Atmospheric Administration, U.S.A. These global readout pictures were taken by television cameras aboard the U.S. polar orbit-

ing satellites ESSA-3, ESSA-9, ITOS-1 and NIMBUS-3, and were received at Command and Data Acquisition Stations in U.S.A. All the storms occurred in Bay of Bengal during the period 1967-1971. The sequences show the daily progression of each storm at approximately 24 hr interval (Figs. 1 to 7). Fig. 1 to 6 show cloud pictures taken in the afternoon between 07 and 09 GMT. In Fig. 7 pictures of Orissa cyclone of October 1971, taken by NIMBUS-4 as well as ESSA-9 satellites have been presented with a view to maximise the available data. The NIMBUS-4 pictures of the storm were taken between 05 and 06 GMT from 27 to 30 October 1971. The ESSA-9 pictures were taken between 08 and 09 GMT from 25 to 29 October 1971. The corresponding pictures taken by the two satellites on 27th, 28th and 29th have a time difference of 2-4 hours but they show substantially the same cloud patterns. The individual pictures in Figs. 1 and 2 are computer produced digital data products in Mercator projection (Bristor 1968), while those in Figs. 3 to 7 are individual picture frames taken by satellites on which geographical referencing has been superposed by computer. In pictures of 4 May 1970 (Fig. 4) and 19 May 1970 (Fig. 5), two frames taken in consecutive orbits have been joined in order to show the complete system. These storm pictures have been analysed and daily storm intensities estimated in accordance with Dvorak's technique (1973). The detailed analysis of each storm is described in para 3 below.

3. Data analysis

3.1. Severe cyclonic storm of 12-19 May 1967 (Fig. 1)

The disturbance originated as convective cloud mass around 12.5°N and 92.5°E on 12 May 1967.

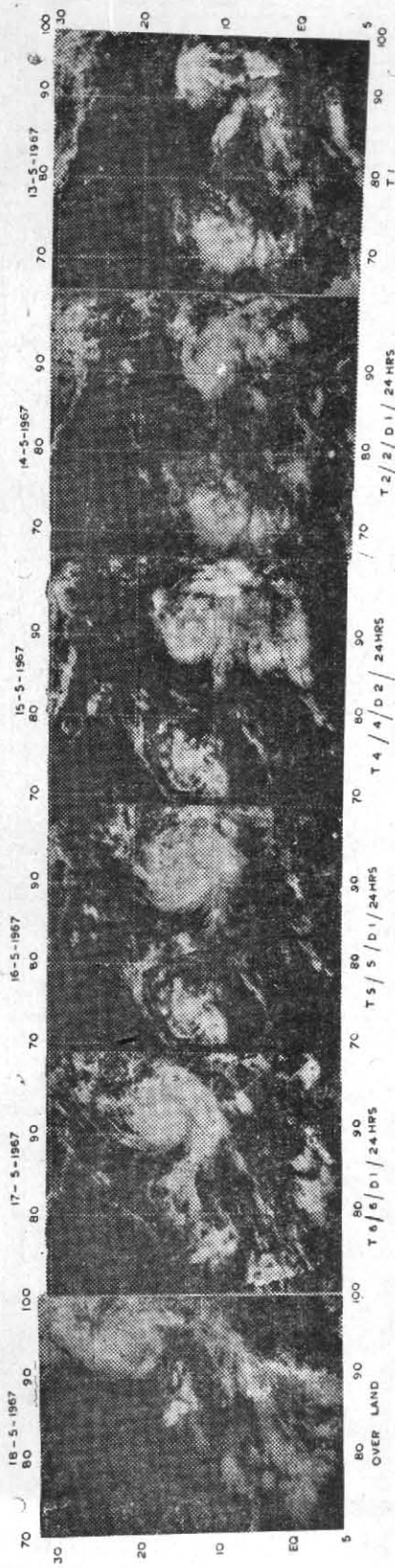


Fig. 1. Severe cyclonic storm of 13-18 May 1967 (ESSA-3 pictures)

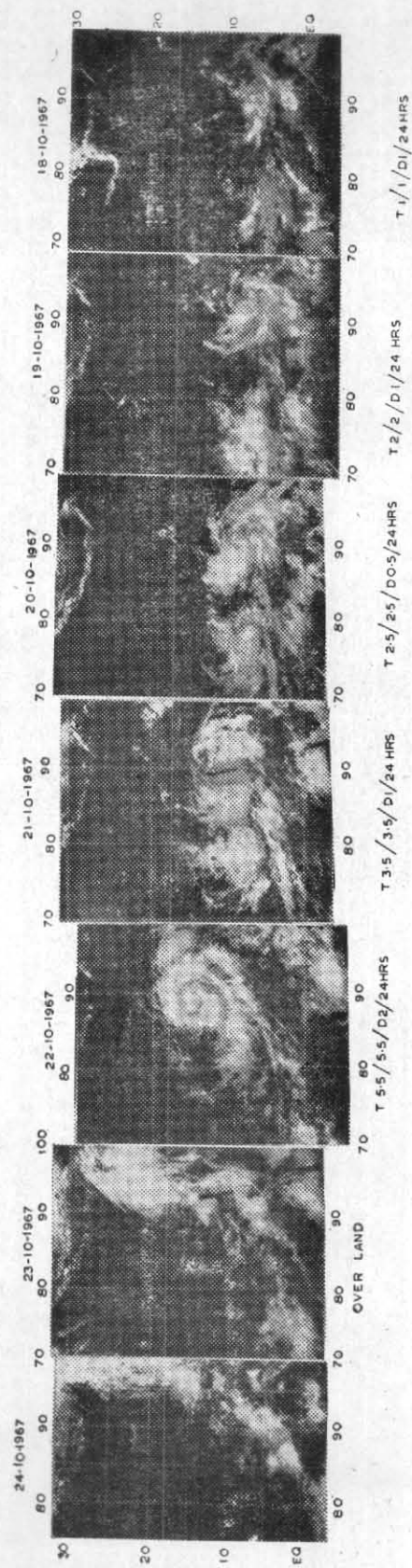


Fig. 2. Severe cyclonic storm of 18-24 October 1967 (ESSA-3 pictures)

On 12th and 13th it showed little curved banding and could be classified as T1. The initiation of development started on 14th when convective cloud elements developed to the northeast and to the south of the main cloud mass, indicating curved bands, and the central cloud mass showed weak anticyclonic flow at cirrus level. These features on 14th indicated T2.

On 15th the system intensified and the satellite picture showed an irregular Central Dense Overcast (CDO) of about $2\frac{1}{2}$ degrees in size and surrounded by a curved convective band. This specified central feature CF=3, bending feature BF=1 and T4. There has been a marked development from 14th to 15th and this is reflected in the increase of T number by 2. On 16th CDO further increased in size and had oval shape, about 3 degrees in size; the corresponding intensity is given by CF=4, BF=1 and T5.

On 17th the storm developed its maximum severity. CDO became round, increased in size to $4\frac{1}{2}$ degrees diameter, and showed more tight banding around it. About 2-3 degrees wide band was encircling more than half the central feature and the corresponding intensity is given by CF=5, BF=1 and T6.

The severe cyclonic storm crossed Arakan coast near Sandoway on 18th morning and weakened thereafter.

3.2. Severe cyclonic storm of 18-24 October 1967 (Fig. 2)

Two similar convective cloud masses may be seen in the area of inter-tropical convergence in the satellite picture of 18th. There is little evidence of curved banding in either and as such each can be classified as T1. During the next 24 hours both these cloud masses developed. However, the cloud mass around $5^{\circ}\text{N}, 91^{\circ}\text{E}$ developed curved convective cloud bands spiralling into a small area around $8^{\circ}\text{N}, 94.5^{\circ}\text{E}$, marking the initiation of development on 19th. The other cloud mass has merely shown an increased convective activity but no curved banding. In fact due to its proximity to the land mass it did not show further development during the next two days. The cloud mass towards east developed and intensified into a cyclonic storm. The curved convective bands and weak upper level flow indicate intensity T2 on 19th. On 20th the convective bands were more marked and the system showed anticyclonic cirrus outflow. This gives the intensity T 2.5. The system further intensified to T3.5 (CF=3, BF=0.5) on 21st as the cloud system developed a CDO and the curve bands were more organised. Between 21st and 22nd the storm intensified rapidly. On 22nd the CDO deve-

loped to about 2-degree size. It appeared generally oval but was irregular at its northern edge. The average of values for oval and irregular shapes gives CF=3.5. The CDO had more than 1 degree wide curved band coiled once around it (BF=2). Thus, storm intensity on 22nd was T 5.5. This also meets the model constraint. From 21st T-No. (T3.5) and subsequent development, the expected T-No. on 22nd is 4.5, and the actual T5.5 lies within 1 T-No. of the model expectation. The storm crossed coast on 23rd and weakened over the land.

3.3. Severe cyclonic storm of 3-8 November 1969 (Fig. 3)

The satellite picture of 3rd shows convective cloud elements aligned in curved bands over the sea area to the north of Lat. 10°N . Although the bands are not well defined they do curve around a cloud-free area at $11.5^{\circ}\text{N}, 96^{\circ}\text{E}$. There is a weak anticyclonic cirrus flow around this feature. The large cloud mass south of 10°N is an area of strong convection. The initiation of development seen in these cloud features indicates T 1.5.

The picture quality on 4th is poor. However it indicates pre-eye type curved cloud bands at the northern edge of 3-degree overcast and the system centre at $12.5^{\circ}\text{N}, 93^{\circ}\text{E}$ within the cloud-free area. The system intensity is T3 (CF=3, BF=0).

On 5th the system developed an almost oval CDO of about 1.5-degree diameter but no eye was discernible. More than 1 degree wide band was encircling half the central feature giving intensity T 4.5 (CF=3.5, BF=1). On 6th CDO developed a large ragged eye of about $\frac{3}{4}$ degree diameter, giving system intensity T5 (CF=4, BF=1). The storm had maximum intensity T6.5 (CF=6, BF=0.5) on 7th when the CDO became circular and embedded distance of the eye was about $1\frac{1}{2}$ degrees.

The storm crossed coast on 7th afternoon between Kakinada and Masulipatnam and weakened.

3.4. Severe cyclonic storm of 1-7 May 1970 (Fig. 4)

The disturbance originated as a convective cloud mass, with a weak wind field at the cirrus level, on the 1st. The initiation of development started on the 2nd and the following features indicated intensity T2 —

- (i) A lumpy central overcast appeared at the system centre with a curved convective feeder band towards the east. The alignment of cumulus elements in the band was



Fig. 3. Severe cyclonic storm of 3-8 November 1969 (ESSA-9 pictures)

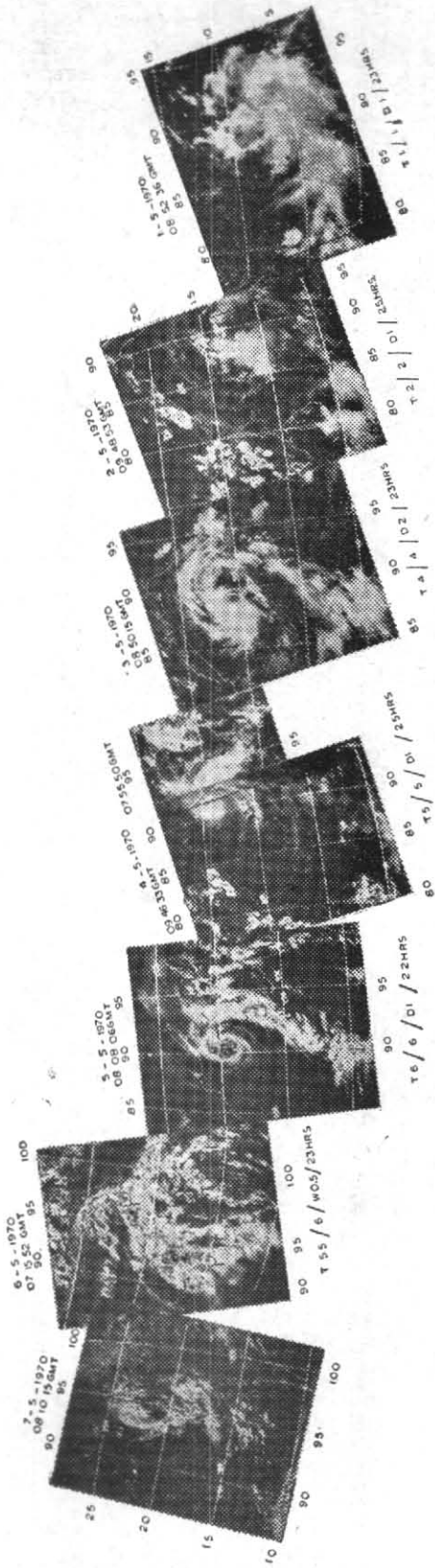


Fig. 4. Severe cyclonic storm of 1-7 May 1970 (ITOS-I pictures)

distinct in the northeast sector where the band approached the central feature.

- (ii) Cirrus flow appeared towards the west and north of the system centre in anti-cyclonically curved bands.
- (iii) The cloud pattern just started developing into comma shape.

On 3rd the cloud pattern developed into comma shape. CDO increased in size and the convective feeder band originating from the equatorial region got brighter and better organised, indicating the on-going intensification. The upper wind field appeared to be weak anticyclonic over the storm area. With irregular CDO of 2 to 3-degree size (CF=3) and more than 1-degree wide band encircling about half of the central feature (BF=1) the intensity indicated is T 4.

On 4th the storm is seen at the edge of two picture frames. The lack of clarity and the distortion of cloud mass associated with the storm are due to the slant viewing angle of satellite camera. The CDO developed into an oval shape of $1\frac{1}{2}$ to 2 degrees size (CF=4) and had $1\frac{1}{2}$ degrees wide band surrounding half of the central feature (BF=1) giving intensity T5. A strong easterly flow at the cirrus level was indicated to the south of the storm.

On 5th the CDO became more round and a distinct eye was seen in the overcast at 19.5°N , 91.0°E , the embedded distance of the eye being about 0.8 degree (CF=5). A solid convective feeder band, 2-3 degree wide, originated in the equatorial region and joined the CDO (BF=1). Besides, short tight bands merged with CDO at small angles. The storm was at its maximum intensity T 6, and no further intensification took place due to its proximity with land.

On 6th the storm moved closer to the coast. The CDO decreased in size to about $2\frac{1}{2}$ degrees, was oval in shape and did not show an eye. This indicated CF=4. However, CF was taken as 4.5 due to two conflicting reasons —

- (i) The eye could be present, but was possibly not seen due to oblique viewing angle of the satellite camera, so that CF was nearer its value on 5th and
- (ii) Storm had weakened from the previous day as suggested by overall decrease in cloudiness.

A $1\frac{1}{2}$ degree wide band encircled half the central feature (BF=1) and the storm was T 5.5.

The storm crossed Bangla Desh coast near Cox Bazar on 7th early in the morning and the satellite picture shows the associated cloud pattern completely disintegrated.

3.5. Severe cyclonic storm of 18-23 October 1970 (Fig. 5)

The storm originated as dense convective overcast area off south Andhra-Tamil Nadu coast on 18th. On 19th and 20th it was located around 15°N , 82°E . On 20th the system consisted of two distinct cloud masses. The cloud mass towards east had greater longitudinal extent and was less dense compared to that towards west. The two together clearly showed a region of lower level convergence and weak cirrus level flow in Bay of Bengal. The cloud feature towards east weakened after 20th, whereas the western cloud mass showed intense convection and ultimately intensified into a cyclonic storm. The development was initiated on 20th when the intensity of the system was T 1.5.

On 21st the satellite picture showed a circular dense overcast area of about 3-degree diameter around 15°N , 85°E , with anticyclonic cirrus outflow aloft. Also a curved convective band was indicated to the east of cloud mass. The intensity of system was T 2.5.

The satellite picture of 22nd showed rapid development of the system into an oval CDO of $2\frac{1}{2}$ -degree diameter (CF=4) and narrow bands surrounding half the central feature (BF=0.5). This gave intensity T 4.5.

The storm crossed coast on 23rd afternoon close to West Bengal-Bangla Desh coast. The satellite picture of 23rd showed the storm just crossing the coast and weakening. Strong cirrus outflow from the storm field towards northeast obscured the central feature. CDO appears to be circular having a diameter of about 3 degrees (CF=5) surrounded by a well defined curved convective band and a narrow cirrus band (BF=0.5).

3.6. Severe cyclonic storm of 7-13 November 1970 (Fig. 6)

The system appeared on 7th as a large convective area over central and south Bay of Bengal. On 8th, convective overcast clouds covered most of the area at 10° - 20°N and 85° - 95°E with breaks in between. Three convective cloud bands starting from equatorial region merged into the cloud mass and showed a loose organisation. Although bands indicated a weak lower level inflow and appeared converged, yet no system centre could be defined. The development of the system had started and it could be classified as T2.



Fig. 5. Severe cyclonic storm of 18-23 October 1970 (ITOS-I pictures)

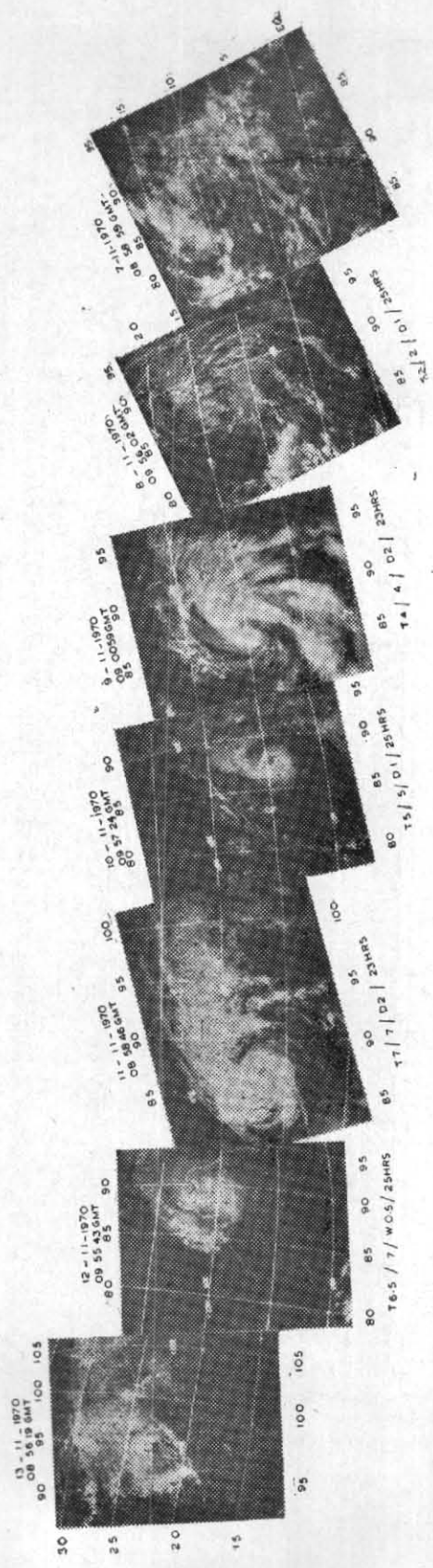


Fig. 6. Severe cyclonic storm of 7-13 November 1970 (ITOS-I pictures)

The cloud pattern on 9th showed the storm in the making. An oval CDO of 2-degree size ($CF=3.5$) had a well organised convective feeder band merging into it ($BF=0.5$). The system had curved bands towards its east with conspicuous curved breaks. The storm intensity was T 4.

On 10th the system appeared at the edge of the frame and was distorted. A ragged eye $3/4$ degree in size appeared inside the CDO. The embedded distance of the eye was about $3/4$ degree. A broad feeder band existed to the east of CDO. The large ragged eye limited the storm to T5. On 11th CDO became circular and had a round distinct eye with an embedded distance of 1 degree ($CF=6$). A broad convective band encircled more than half of the central feature ($BF=1$). Curved breaks in the CDO were covered by cirrus aloft and showed tight curvature. The fact that the system had acquired super storm structure (T7) is evident from —

- (i) increase in the size of CDO from 3 degrees on 10th to 6 degrees on 11th,
- (ii) increase in tightness of bands,
- (iii) appearance of spiral wall clouds around the eye, and
- (iv) the cirrus outflow from the storm extended eastwards upto east China Sea.

Although the storm appeared at the edge of the frame on 12th, yet it showed a slightly ragged eye with embedded distance of 1 degree ($CF=5.5$, $BF=1$ and $T=6.5$). The satellite picture shows the storm on 12th afternoon at 0856 GMT when it indicated evidence of slight weakening as it approached the coast. Subsequently the storm crossed coast on 12th night and weakened thereafter.

The satellite pictures clearly showed rapid development of the storm between 8th and 9th and between 10th and 11th.

3.7. Severe cyclonic storm of 25-30 October 1971 (Fig. 7)

On 25th a convective cloud mass with curved banding appeared over southeast Bay and adjoining south Andaman Sea. The curved convective bands around a relatively cloud-free area at 8.5° N, 93.0° E indicated initiation of development (T1.5).

On 26th a central break of pre-eye type was seen within the cloud mass around 12.5° N, 91.0° E. The intensity of system was T 3 ($CF=3$, $BF=0$).

On 27th the cloud pattern showed a large eye with, no CDO the circular break had a diameter of more than 1 degree ($CF=3.5$). A $1/2$ degree wide

overcast band completely encircled the central feature ($BF=1$) and the storm intensity was T 4.5. The cloud pattern underwent significant changes from 27th to 28th as the system intensified, the curved bands became more tight and the size of eye decreased thereby increasing the area of dense overcast around the system centre. The ragged eye had about $3/4$ degree of embedded distance ($CF=4$) and CDO was encircled by curved banding ($BF=1$) giving intensity T 5.

On 29th the Nimbus-4 picture shows a rather ragged eye with embedded distance between $3/4$ and 1 degree ($CF=4.5$) whereas ESSA-9 picture is nearer to a large circular eye without CDO ($CF=4.5$). Dense overcast bands of more than 1 degree width ($BF=1$) are encircling about $3/4$ th of the central feature ($BF=1.5$) giving storm intensity T6. The storm crossed coast close to Paradeep in the early morning of 30th.

4. Comparison with synoptic data

Tracks of these storms and their day-to-day intensities based on synoptic data are shown in Fig. 8. Table 1 provides a comparison between the satellite data and the synoptic data. The date on which initiation of storm development was first detected in satellite pictures, and the date when a storm progressively intensified into cyclonic storm and severe cyclonic storm are given with its corresponding intensities inferred from satellite pictures based on Dvorak's technique. The date on which the system was first detected as depression based on synoptic data are also given with corresponding T-numbers in the same table. Intensities within brackets have been obtained after interpolating between T-numbers derived from consecutive satellite pictures in order to coincide with conventional data. Storm intensity corresponding to severe cyclonic storm stage of October 1967 cyclone is not given because the satellite picture shows that the storm was located on 23rd evening at 22° N, 94.5° E after crossing the coast, whereas according to synoptic inference it crossed coast on 24th morning. Another large difference was in case of October 1970 cyclone which was declared a depression on the basis of conventional data on 18 October 1970 but satellite picture showed initiation of development only on 20 October 1970. An examination of T-numbers, corresponding to instants when the systems attained cyclonic storm stages, are appreciably lower for October 1970 cyclone as compared to others. These discrepancies may be attributed to insufficient synoptic data from the storm field on which the inferences might be based. A depression forming in the Bay of

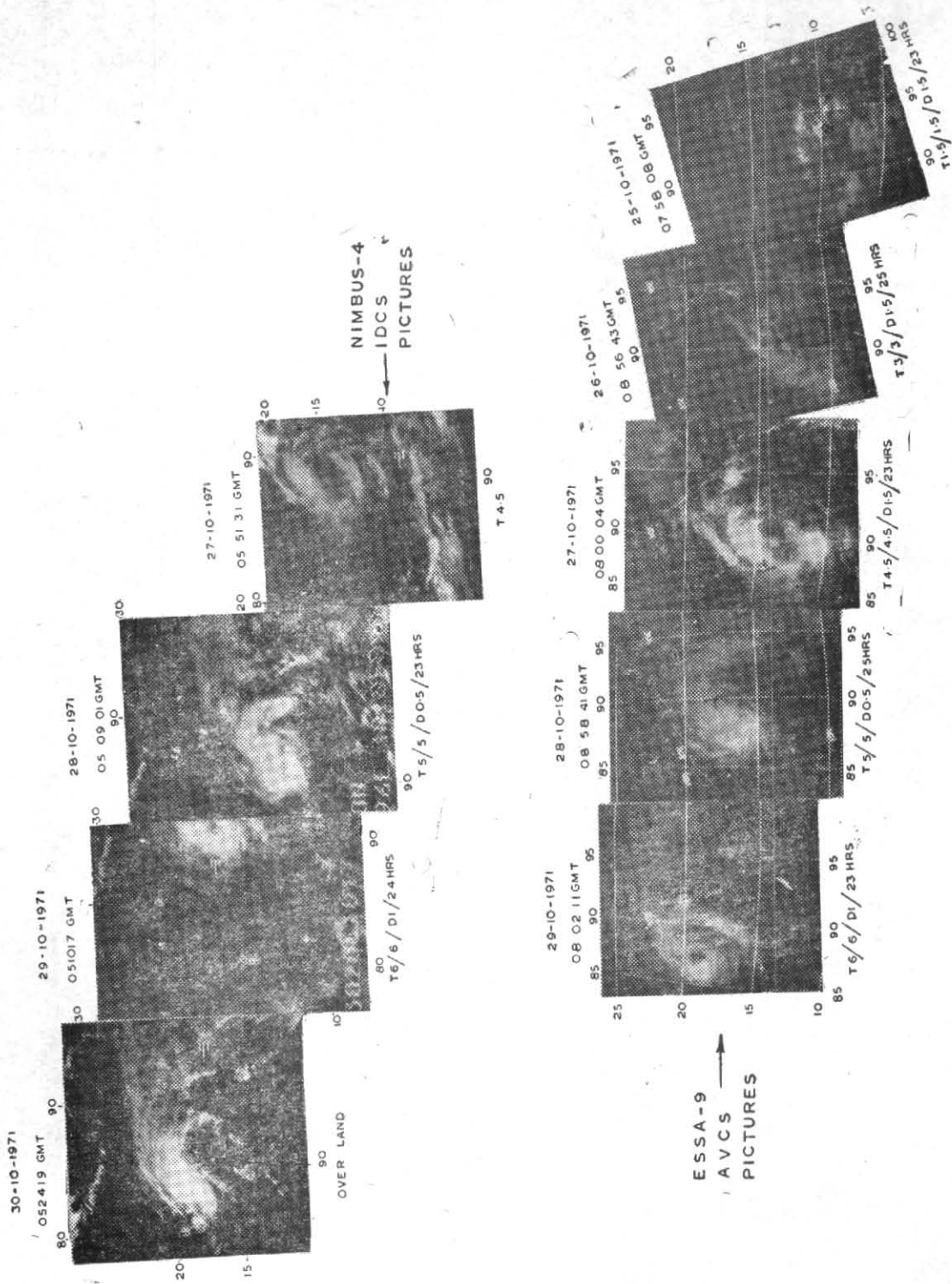


Fig. 7. Severe cyclonic storm of 25-30 October 1971

TABLE 1

Comparison of cyclone intensity based on Dvorak's technique with synoptic features

S. No.	Cyclonic storm	Initiation of storm development detected in satellite pictures		Depression stage		Cyclonic storm stage		Severe cyclonic storm stage	
		Date	Intensity	Date	Intensity	Date	Intensity	Date	Intensity
1	12-19 May 1967	14-5-67	T2	15-5-67	(T3)	16-5-67	(T4)	16-5-67	T5
2	18-24 Oct 1967	19-10-67	T2	20-10-67	T2.5	22-10-67	(T4.5)	23-10-67	—
3	3-8 Nov 1969	3-11-69	T1.5	4-11-69	T3	5-11-69	(T4)	6-11-69	T5
4	1-7 May 1970	2-5-70	T2	2-5-70	T2	3-5-70	T4	4-5-70	T5
5	18-23 Oct 1970	20-10-70	T1.5	18-10-70	—	20-10-70	T1.5	21-10-70	T2.5
6	7-13 Nov 1970	8-11-70	T2	8-11-70	T2	9-11-70	T4	10-11-70	T5
7	25-30 Oct 1971	25-10-71	T1.5	26-10-71	T3	27-10-71	T4.5	28-10-71	T5

TABLE 2

Synoptic description	Wind speed (kt) attributed to synoptic feature	Cyclone intensity in terms of T. No.	Wind speed (kt) obtained from Dvorak's technique
Depression (including deep depression)	17-33	T1.5-3.5	25-50
Cyclonic storm	34-47	T4-4.5	60-75
Severe cyclonic storm	48 onwards	T5 and above	85 kt and above

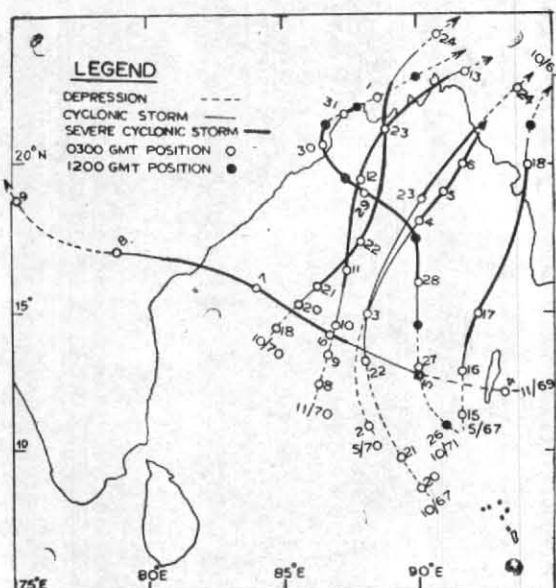


Fig. 8. Tracks of severe cyclonic storms

Bengal during pre-monsoon and post monsoon seasons has a potential for development into a cyclonic storm. In this sense the concentration of a low pressure area into a depression, as inferred from synoptic data, corresponds to the 'Initiation of Development' seen in satellite pictures. It will be seen from Table 1 that on four occasions out of seven, the initiation of storm development in satellite pictures was detected one day before any indication of the formation of a depression was given in the synoptic data.

5. Maximum wind speed in storms

Table 1 also indicates a correspondence between the synoptic classification of low pressure systems as adopted in Indian region and Dvorak's

intensities in T-numbers. This is shown in Table 2. The table shows large differences between wind speeds inferred from synoptic data and those derived from Dvorak's technique. Qualitatively, some difference could be attributed to regional characteristics of storms. For Atlantic storms, Erickson (1972) has observed a mean difference of 10.9 kt between the observed maximum sustained wind speeds (MWS) and those obtained from the older current intensity (CI) MWS relationship (Dvorak 1972) which was empirically derived from data on Pacific storms and disturbances. Erickson has concluded that this is due to a real physical difference between Atlantic storms and Pacific storms. The CI-MWS relationship has subsequently been modi-

fied to provide the best fit for both Pacific and Atlantic storms (Dvorak 1973). However, this modified relationship may not hold exactly for storms occurring in Indian Seas. From Erickson's data it may appear that there may be a mean difference of the order of 10-20 kt between the computed and the observed MWS. As systematic observational data on wind speed from the storm fields of cyclonic storms in Indian Seas are not available, in absence of an organised aircraft reconnaissance, it is difficult to verify this relationship. Some isolated observations are, however, available. For example, when Orissa cyclone (25-30 October 1971) crossed coast at Paradeep at 0430 IST on 30 October 1971, maximum wind speed of 100 kt was recorded. CI-6 for this storm about 15 hours before its landfall gives wind speed of 110 kt. Similarly when Andhra cyclone (3-8 November 1969) crossed coast on 7th afternoon, a maximum wind speed of 93 kt was reported from Kakinada. The current intensity of the storm at the time of crossing coast was 6.5 giving maximum wind speed of 122 kt.

It is evident from the above that Dvorak's CI-MWS relationship may be taken as a rough guide for the estimation of maximum wind speed in storms occurring in Indian Seas. As this is a statistical relationship there may be large differences between the estimated and the observed wind speeds in individual cases. It may also be mentioned that CI number can at best be derived with an accuracy of 0.5 and this difference corresponds to wind speed differences ranging from 5kt to 20kt for the complete range of CI numbers. These limitations have to be kept in view while estimating MWS from satellite pictures.

6. Conclusions

(1) Mostly the initiation of storm development took place in an area of convective overcast

cloudiness. As a cyclonic circulation developed progressively, curved bands appeared, they increased in size as well as curvature and the central overcast became more organised. With further intensification an eye appeared within central dense overcast. At this stage the storm was well developed and further intensification till its landfall was relatively slower.

(2) On two occasions (Figs. 3 and 7) the system started as curved convective bands surrounding a circular break of 1-2 degrees in diameter. As the circulation developed and curved bands became tighter, a central dense overcast appeared. Further development was similar to other storms.

(3) When there are two convective cloud masses in close proximity and under favourable conditions of development, either of them may develop into a storm. In Fig. 2 the eastern cloud mass intensified into cyclonic storm whereas in Fig. 5 the western mass became a storm.

(4) The maximum sustained wind speed estimated from Dvorak's CI number is considerably higher than that inferred from synoptic data. Maximum wind speeds thus derived from satellite pictures may as such be taken as a rough guide till a suitable relationship is evolved, for storms occurring in Indian Seas, on the basis of the satellite and the reconnaissance data.

(5) Storm sequences examined in this paper suggest that in a developing storm the cyclone intensity of T3.5 or below corresponds to depression, T4.4.5 to cyclonic storm, and T5 or above to severe cyclonic storm.

(6) On many occasions the initiation of storm development is detected in satellite pictures well in advance of any indication given by conventional data.

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