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Possibility of diurnal variation and formation of secondary vortices in the cyclone field as revealed by the radar study of the Arabian Sea cyclonic storm of June 1976

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ABSTRACT. A diurnal variation in the organisation of cloud bands around the cyclonic storm was the main peculiarity of the Arabian Sea cyclone of June 1976, as observed by the radar. Also, the occurrence of heavy rainfall on the coast was seen to lag behind the cyclone. This has been explained on the basis of possible formation of vortices on the right rear quadrant of the cyclone as indicated by the radar observations. Detailed radar observations and tentative explanations for the phenomena are presented.

1. Introduction

A depression formed in the east central Arabian Sea and intensified into a cyclonic storm on 31 May 1976. It came within the range of the S-band cyclone warning radar located at the Regional Meteorological Centre, Colaba, Bombay by the early morning of 1 June 1976. The international airport at Bombay has an L-band Air Route Surveillance radar. The cyclone was tracked with the help of these two radars until it crossed the south Gujarat coast by the morning of 3 June. The technical characteristics of these two radars are given in Table 1. The centre of the cyclonic storm was estimated by a spiral overlay of 15 degree crossing angle. During the routine radar observations of this cyclone for operational purposes, some peculiar features of the storm were observed on the cyclone warning radar as well as by the airport radar. One was the waxing and waning of the organization of the cloud bands; the second feature was the indication of vortices on the outer periphery of the storm. These were, besides the normal features of the cyclonic storm as seen by radar. The purpose of this paper is to present these two features in detail and to propose tentative explanations for the same.

2. Observational data and analysis

From the time, the cyclonic storm came within the radar tracking range, observations were made as frequently as possible and photographs taken. The track of the storm as determined from the radar fixes may be seen in Fig. 1. Some selected photographs are presented in Fig. 2. Details of the features observed in these photographs are described below. It may be mentioned here that photography of the display on the L-band radar could not be done systematically, as the radar was mainly used for air surveillance by the Civil Aviation Department most of the time it was in operation. For this reason, these pictures taken by hand-held cameras are not considered good enough for reproduction, and not presented here.

2.1. *Changes in the orgnization of the clouds*

1 June 1976

Though the centre of the cyclonic storm itself was not seen, definite organization of the cloud bands into spirals around the centre was evident from the early morning of 1 June (Fig. 2a). By about 0400 GMT, the storm apparently started weakening (Fig. 2b); a broken spiral near the centre and another long one to the northeast and east were the only remains of the system observed earlier. A pre-hurricane squall line was also seen to the north of the cyclone. Even at 1200 GMT of the same day, the poor organization of the bands around the cyclonic storm was still in evidence, the only clouds being the solid squall line at 100 km to the southwest of Bombay with a continuation as a broken line at its western and southern ends and weak echoes near the centre of the storm (Fig. 2c). Observations on L-band radar also showed poor organization of cloud bands.

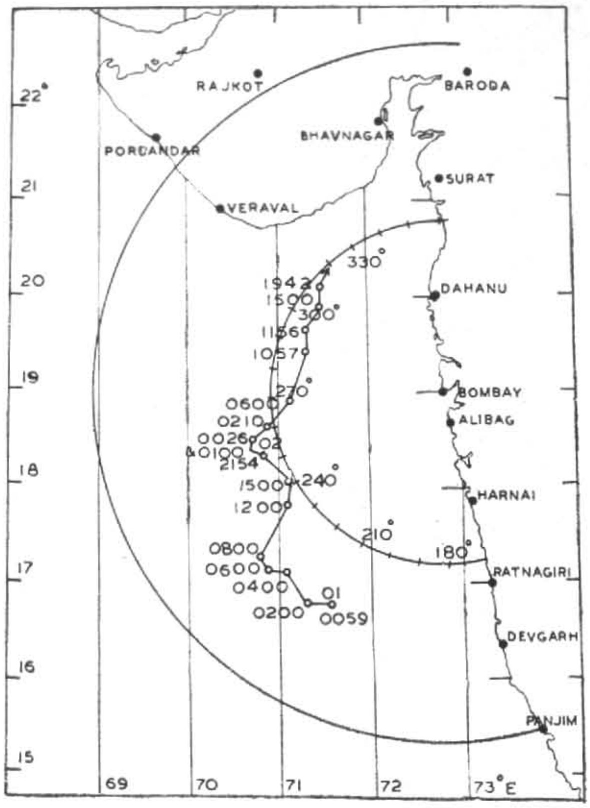

Fig. 1. Track of the cyclonic storm on 1 and 2 June 1976 as determined by S-band radar at Bombay

2 June 1976

Re-organization of the cloud bands seems to have taken place during the late night of 1 June and the early morning of 2 June (Fig. 2d) and reached its maximum by about 0300 GMT (Fig. 2e) though the eye of the cyclone was not seen clearly. However, the L-band radar showed the complete eye and the inner spiral bands at 0400 GMT.

By about 0600 GMT, the bands started breaking up (Fig. 2f). The field of the cyclonic storm was disorganized even upto 1130 GMT (Fig. 2g) but after half an hour the tendency for reorganization could be seen on both radars (Figs. 2h & 2i). The organization of the spiral bands continued as seen at 1500 GMT and 1830 GMT (Figs. 2j & 2k). After this hour, the system moved into the blind zone for the S-band radar and the spiral bands when observed were broken by the blind zones. As for the L-band radar, the operation was suspended by the C.A.D. for operational reasons.

2.2. *Vortices in the spiral bands*

The rainfall observations along the coast are presented in Table 2. Normally the rainfall distribution in low-altitude cyclones is more or less symmetrical (Dunn and Miller 1960) but in the present case, the rainfall was very heavy at a few places along the coast *after* the passage of the storm across the corresponding latitude. The

TABLE 1

Technical characteristics of the two radars which tracked the cyclonic storm

	BEL Cyclone Warning Radar PSS 500	Selenia Air Route Surveillance Radar ATCR-2
Frequency band	S Band : 3100-3200 MHz	L Band : 1300-1400 MHz
Peak power	1 ·0 Megawatt	1 ·5 Megawatt
Pulse duration	2 ·0 μ sec	2 ·0 μ sec
Pulse repetition frequency	250 pps	400 pps
Receiver noise figure	$<$10 db	4 db
Max. effective range	400 km	..
Antenna beam shape	Pencil beam	Cosec^2 beam with added high angle lobe
Antenna beam width	1 ·8 degree	Horizontal 1 ·25, vert. 7 ·5 degree
Antenna rotation speed	5 RPM	5 and 10 RPM

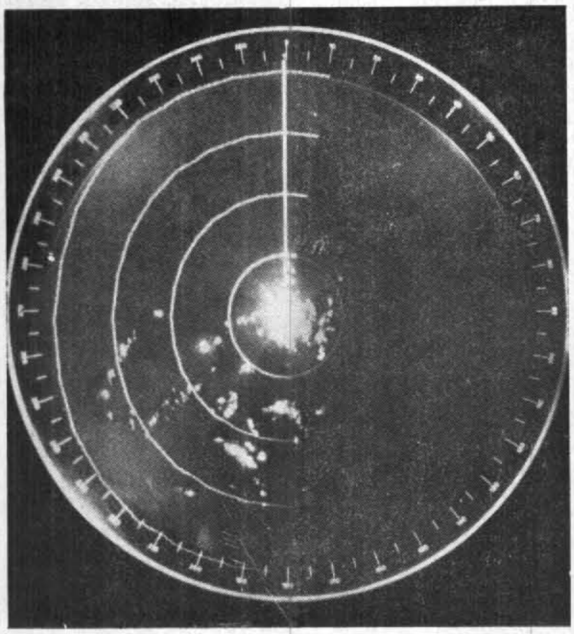

Fig. 2(a). 1 June 1976 at 0058 GMT

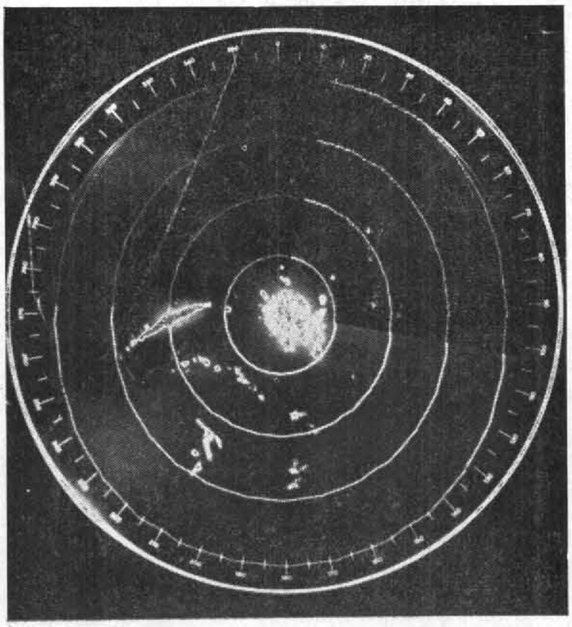

Fig. 2(b). 1 June 1976 at 0401 GMT

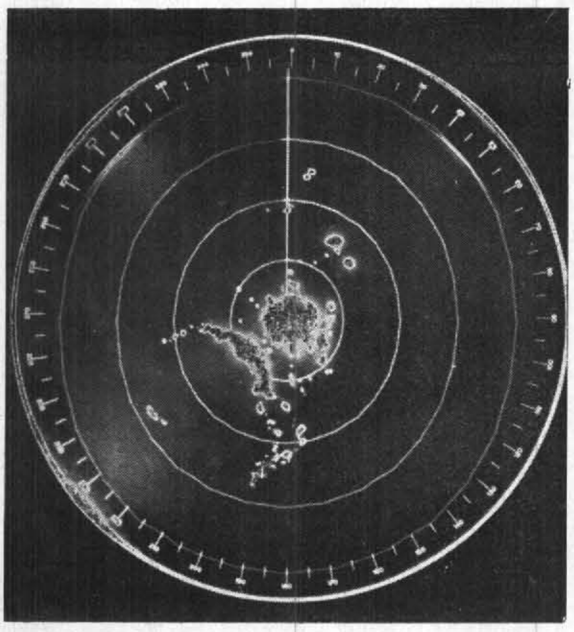

Fig. 2(c). 1 June 1976 at 1158 GMT

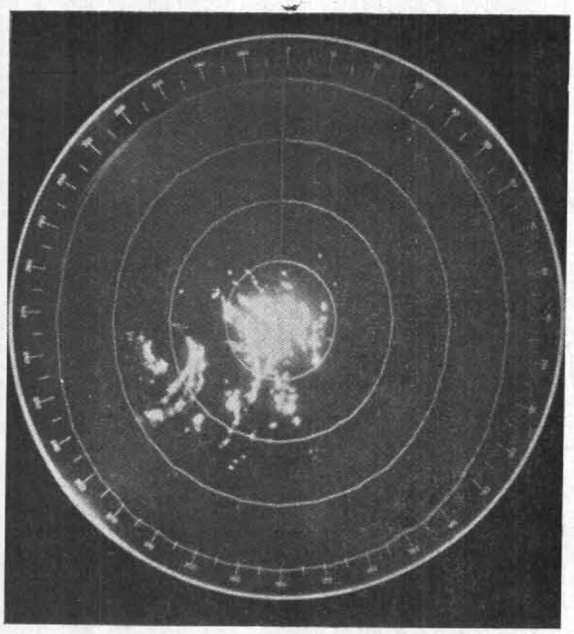

Fig. 2(d). 2 June 1976 at 0058 GMT

Radar photographs taken at Bombay on 1 and 2 June 1976

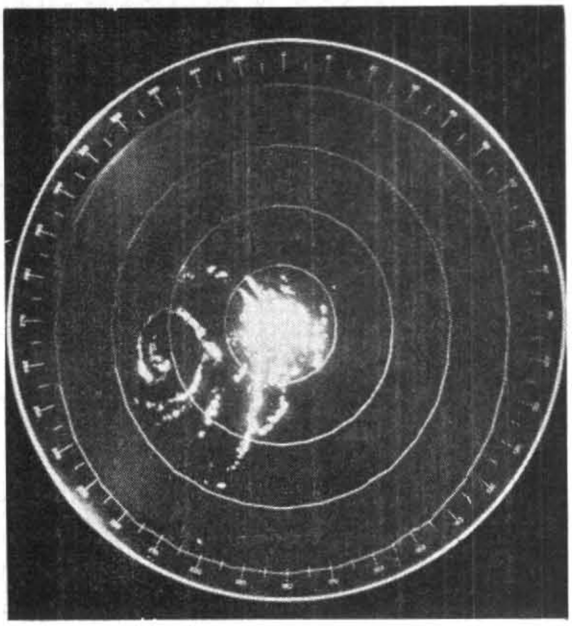

Fig. 2(e). 2 June 1976 at 0251 GMT

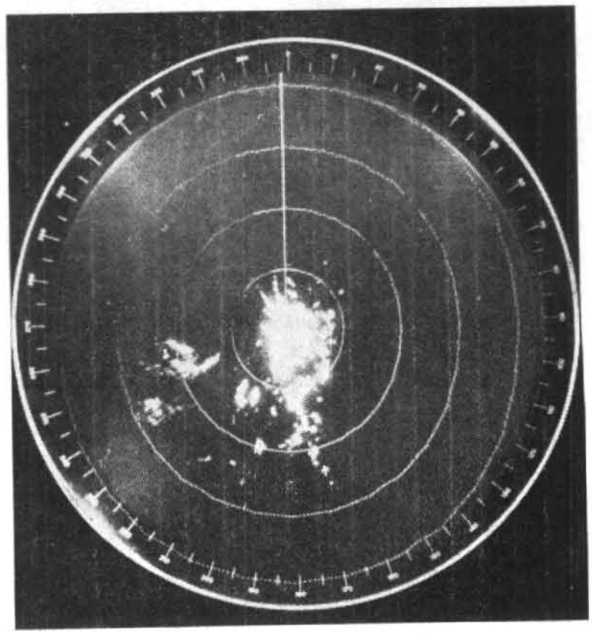

Fig. 2(f). 2 June 1976 at 0609 GMT

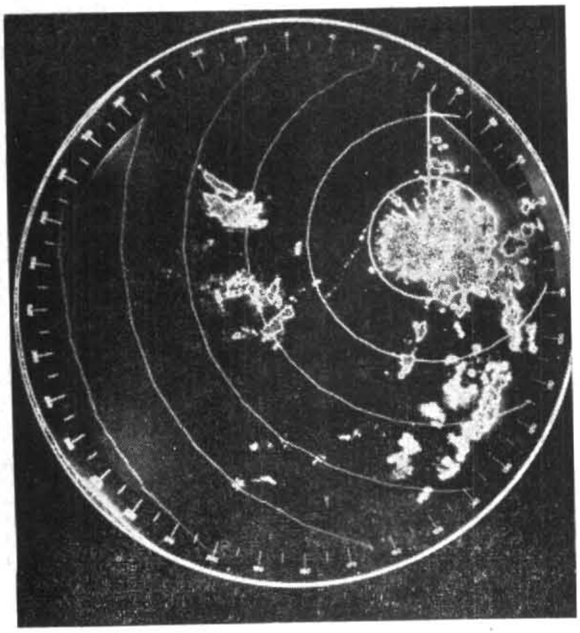

Fig. 2(g). 2 June 1976 at 1128 GMT

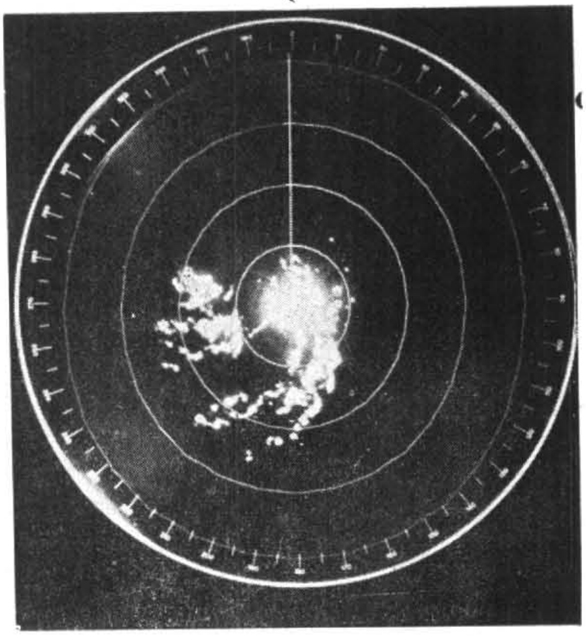

Fig. 2(h). 2 June 1976 at 1156 GMT

Radar photographs taken at Bombay on 2 June 1976

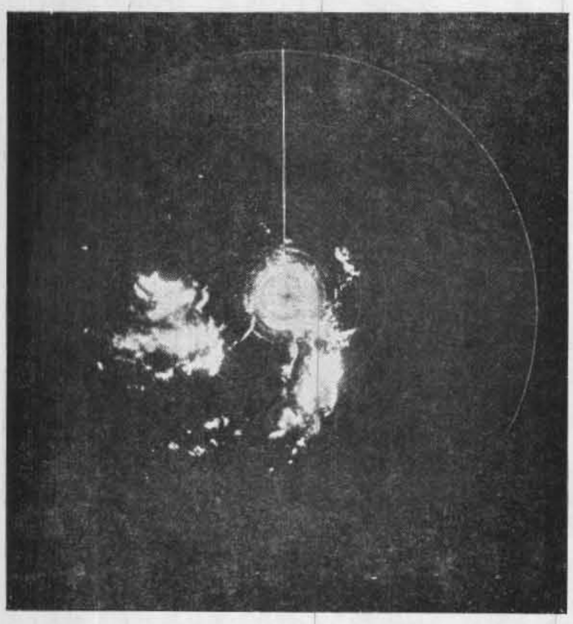

Fig. 2 (i). 2 June 1976 at 1200 GMT

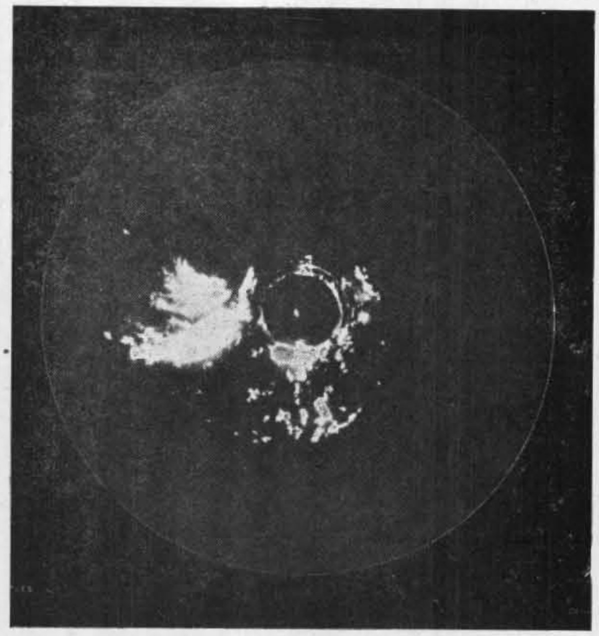

Fig. 2 (j). 2 June 1976 at 1500 GMT

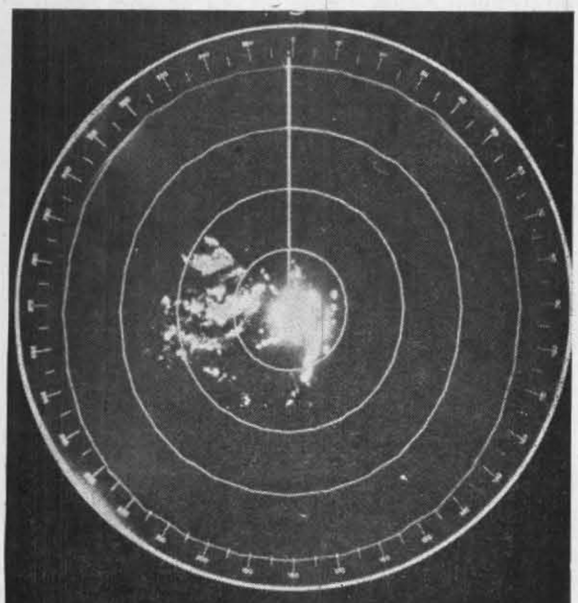

Fig. 2 (k). 2 June 1976 at 1830 GMT

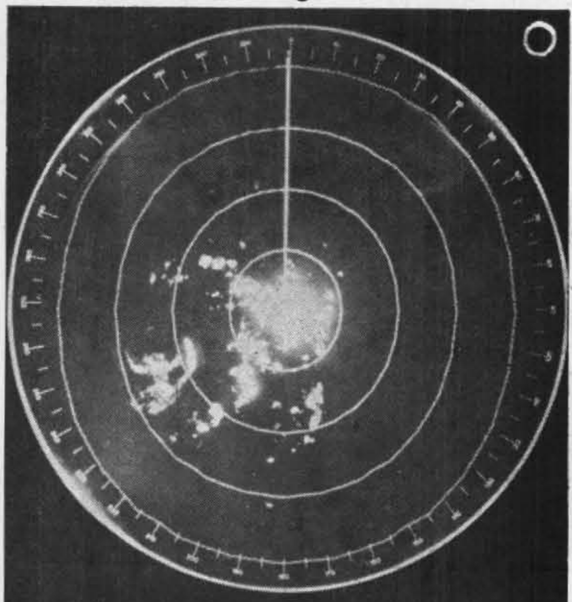

Fig. 2 (l). 1 June 1976 at 2233 GMT

Radar photographs taken at Bombay on 1 and 2 June 1976

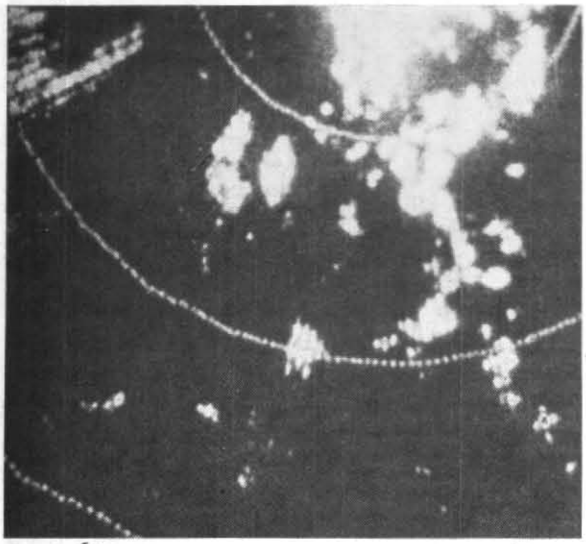

Fig. 2(m). 1 June 1976
(Enlargement of Fig. 2l)

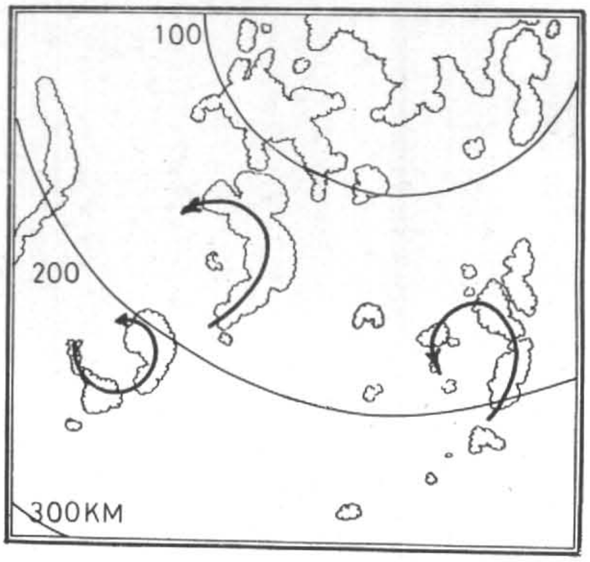

Fig. 2 (mi). Tracing of Fig. 2 (m)

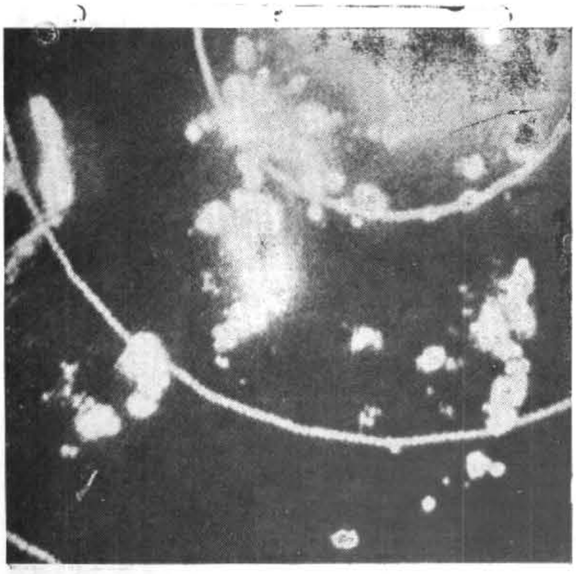

Fig. 2(n). 2 June 1976
(Enlargement of Fig. 2 f)

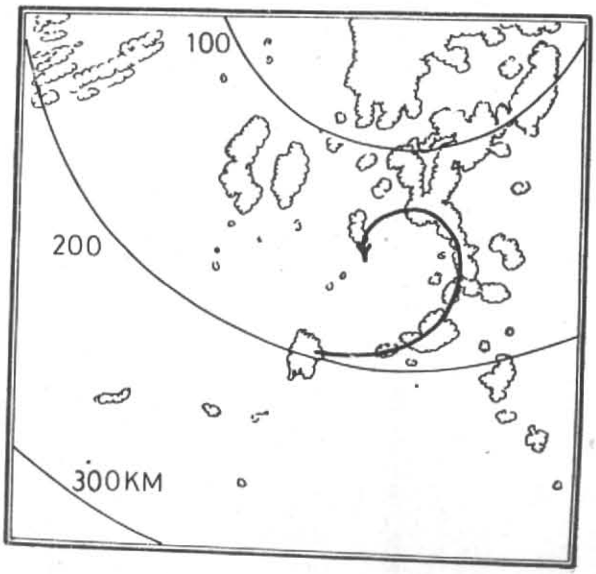

Fig. 2(ni). Tracing of Fig. 2(n)

Radar photographs taken at Bombay on 1 and 2 June 1976

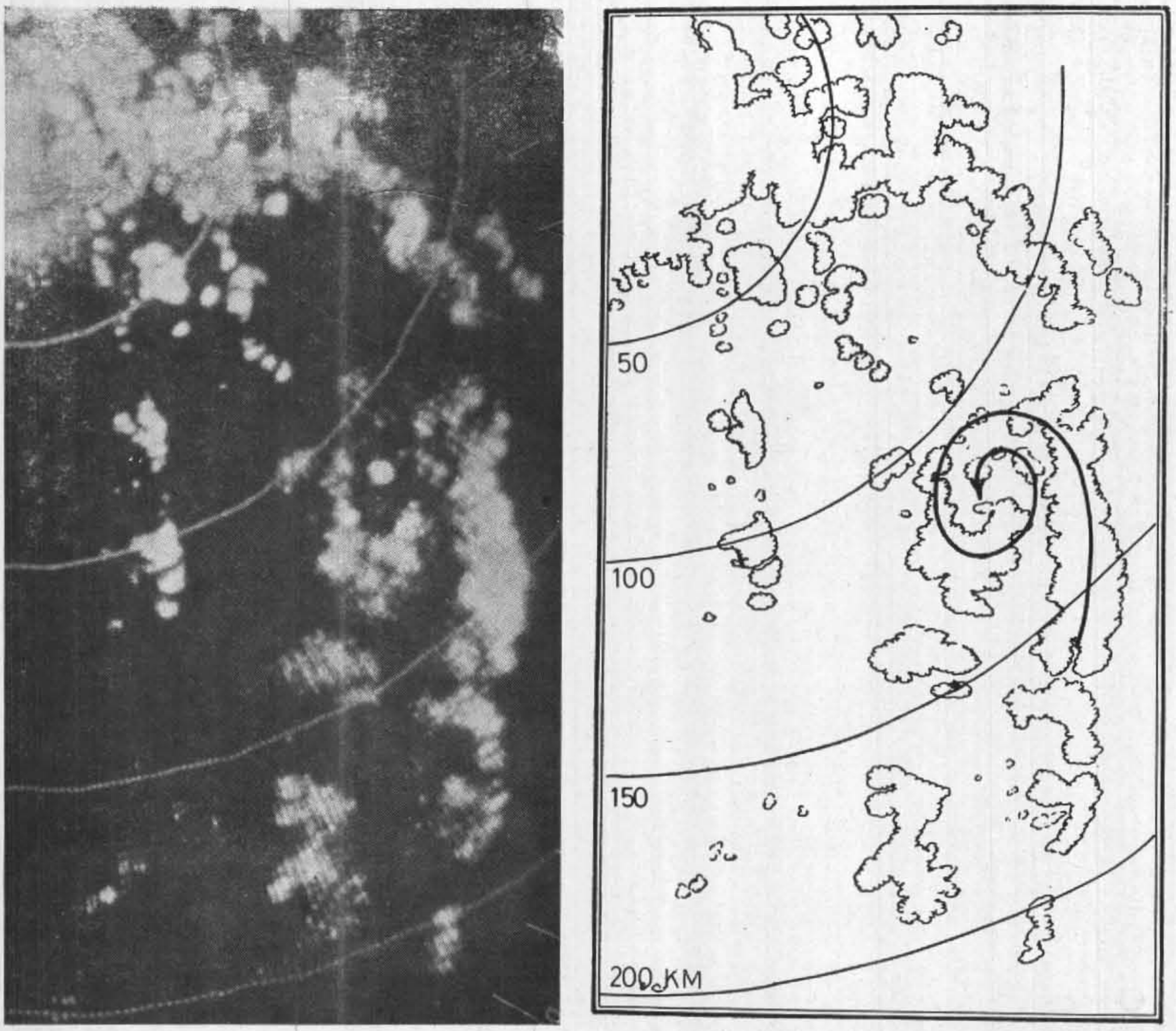

Fig. 2(p). Radar photograph taken at Bombay on 2 June 1976 and its tracing (Enlargement of Fig. 2g)

24-hr rainfall ending at 0300 GMT on 3rd at Harnai (205 mm) and that on 4th at Dahanu (146 mm) are examples in this respect. Such heavy rain could have been due only to some factor other than the storm itself. An examination of the radar photographs suggested the presence of small vortices on some occasions, on the right rear quadrant of the cyclone field. Three instances of such probable vortex formation are shown in Figs. 2(l), 2(m), 2(n) and 2 (p); the last three are enlargements of the relevant portions of the observations in Figs. 2(l), 2(f) and 2(g). The radar echoes forming the vortices are indicated on the tracings accompanying the Figs. 2(m), 2(n) and 2(p). The "vortices" were propagating to the ENE direction whereas the movement of the cyclonic storm itself was in a northerly direction.

TABLE 1

24-hr rainfall at coastal stations during the period 1 to 5 June 1976

Station	24-hr rainfall (mm) measured at 0300 GMT of				
	1st	2nd	3rd	4th	5th
Ratnagiri	8	75	24	34	44
Harnai	0	53	205	33	121
Alibag	0	47	95	1	41
Colaba	Tr	30	46	20	98
Santacruz	Tr	4	41	34	196
Dahanu	1	1	32	146	154
Surat	0	0	1	19	195

Such delineation of the vortices was not possible in the case of Dahanu as the zone of formation of these lies in the blind zone of the radar.

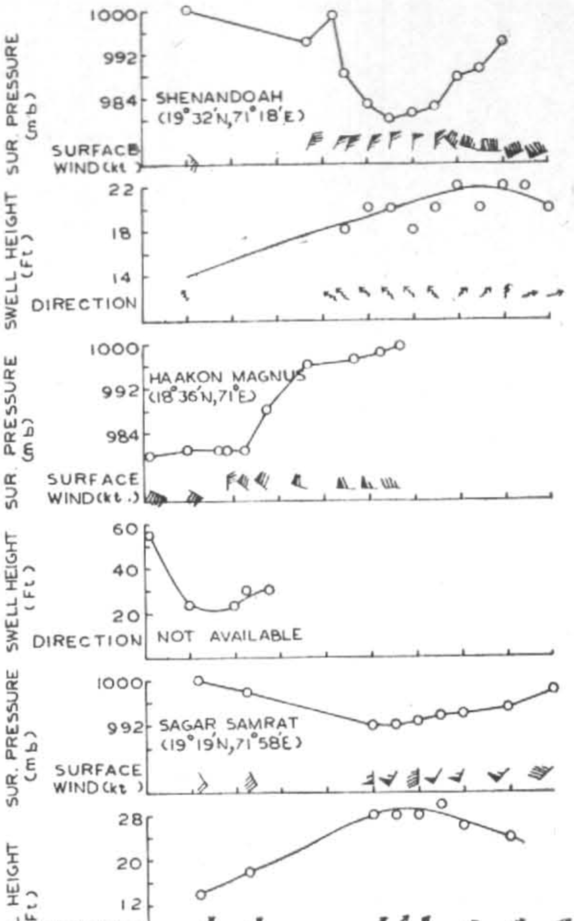

Fig. 3. Observations of ONGC ships of the cyclonic storm on 2 June 1976

3. Discussion

3.1. On both 1 and 2 June, the cyclonic storm showed signs of disorganization commencing from sometime in the early forenoon and attaining maximum disorganisation in the late afternoon. The organization was found to be prominent in the night/early mornings. The question arises whether the storm itself weakened during the daytime (particularly afternoons) and intensified during the night and morning hours, or the storm did not appreciably weaken but only the cloud bands become disorganized at certain times of the day.

In the case of this particular cyclonic storm we had an independent source of observation for checking the alternatives put forth. The oil rigs working for the Oil and Natural Gas Commission were kind enough to supply the observations as and when requested even though they were working under extremely difficult conditions. In fact the eye of the storm passed over one of the rigs. These were *Sagar Samrat*, *Haakon Magnus* and *Shenandoah* located at 19°19'N, 71°58'E; 18° 36'N, 71° E & 19° 32'N, 71° 18'E respectively. Their observations of surface pressure, wind and swell for the period 0800-2400 hr on 2 June are given in Fig. 3. These observations may be taken as fairly accurate as the ships are fitted with instruments for measurement of pressure and wind, the wave height being measured with reference to markings on the legs.

It may be seen from these observations that the storm remained at hurricane stage throughout 2 June which forms 50 per cent of the period under study. This confirms the second alternative

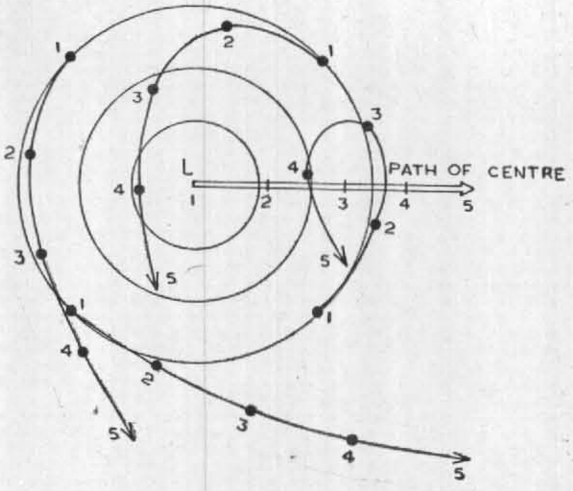

Fig. 4

proposed, *i.e.*, only the cloud bands around the storm became disorganized during a certain period of the day. This particular cyclonic storm moved close to and to the west of the coast. From this fact, the following tentative explanation can be proposed for the phenomenon observed. During day time, the land had high convective activity. The outflow from the thunderstorms on the coast should have been to the west as is evident from APT pictures of 1 and 2 June 1976, and also from the prevailing winds aloft. This probably caused some subsidence, within the storm area or suppressed the convection, inhibiting the growth and organization of the cloud bands during the particular period.

This explanation may also be verified by a study of the temperature field at the 200-mb level. Due to vigorous convection in the cyclone field, there should be a warm area over this region at the 200-mb level (Koteswaram 1956). During that part of the day when the growth and organization of the cloud bands is inhibited due to the reasons proposed as above, the normal warm area above the cyclone field would either be absent or not so prominent during the daytime but would be marked during the night and early morning. Confirmation of this may become possible with the introduction of aircraft reconnaissance of the cyclones, as a routine feature.

A simpler explanation is also possible. It is well known that the diurnal variation of monsoon rainfall is an indication of the preference for rain formation during early morning. In the case under study, there was a temporary advance of monsoon in the wake of the storm. Since appreciable quantities of monsoon air was drawn into the storm circulation, the normal characteristics of monsoon rainfall appear to have been manifested. This might have caused improved return of the radar echoes during late nights and early mornings. If this explanation is valid, then the diurnal variation should be found in the case of other storms where monsoon air is drawn into the circulation.

3.2. The propagation of the vortices which formed within right rear quadrant may be explained by the fact that the streamline and trajectory in a cyclone field are different, as expressed by the formula :

$$K_t = K_s \left(1 - \frac{C \cos r}{V} \right)$$

where K_t and K_s are the curvatures of the trajectory and streamline, C is the velocity with which the streamline pattern moves and V is the wind vector and r the angle between vectors V and C (Petterssen 1956). Diagrammatically it can be shown that moist air from the storm field is released from the right rear quadrant (Fig. 4). The storm was moving north and the trajectory of moist air parcels met the north-south coastline at an angle conducive to the formation of vortices. It is not possible to say whether the vortices moved bodily or propagated by a process of regeneration. It is well known that heavy rain occurs on the west coast of India associated with off-shore vortices (George 1956). Therefore these vortices were expected to produce heavy rain which they did. Table 2 gives the sequence of rainfall from south to north along the west coast. The locally heavy rainfall moved northward but lagged behind the storm as can be confirmed from the rainfall of Harnai, Alibag and Bombay. The best evidence for this is seen in the case of heavy rainfall at Harnai which corresponds to the passage of the vortex (arrow in Fig. 2 p).

4. Conclusions

4.1. Cyclones are defined on the basis of wind and pressure criteria. Theoretically, it is assumed that when a storm attains a severe cyclonic stage, the cloud bands around it should also be well organized. Under these circumstances it is assumed that the radar would show the intensity of the system by the organized and well defined cloud patterns. However, in the cyclone under study, though the cloud pattern underwent some disorganization during the day, the system as such satisfied the wind/pressure criteria for the severe cyclone and maintained itself as such, throughout the period under study.

The forecaster should, therefore, be cautious in interpreting the radar presentation even if the cloud bands are poorly organised temporarily and should not be misled into believing it as a sign of weakening of the system. It is also possible that when a cyclone with considerable monsoon air in the circulation forms during the day or late afternoon, it may not be observed on the radar as a well organized system for the above mentioned reason.

4.2. The passage of a secondary vortex over an observing station is similar to the passage of a cyclone of small intensity with reference to high winds, marked shift in wind direction, pressure fall and copious rainfall. In the absence of radar observation, the forecasters who have only the coastal observations to rely on, may be misled into believing that the storm had crossed the coast at that point when it is still over the sea area.

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