Multiple eyewall structure in an Arabian Sea cyclone

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A depression was formed in the south-east Arabian Sea on the afternoon of 16 May 1999. While moving initially north-west and later northwards it rapidly developed through several stages on 17 May and acquired a wind speed more than 100 knots on 18 May. Multiple concentric and somewhat symmetric eyewalls were seen in this cyclone on 19 May 1999 when the intensification process had already stopped. Development and consequences of multiple eyewalls in this cyclone in terms of inner core intensification, outer core strengthening and recurvature are discussed in this study.

THERE is a variety of cloud patterns associated with development of tropical cyclones[1,2]. These cloud patterns depend by and large on the nature of environmental flow patterns and their vertical wind shears. The most familiar pattern is curved band pattern observed in the satellite imagery or the rain band pattern seen in the Radar Plan Position Indicator (PPI) images. Banded structure of cloudiness and precipitation in a tropical cyclone is a rule rather than exception in a vast majority of cases though Gray[3] also lists cases of cyclones without much of banding organization. Occasionally the eye is seen surrounded by two or more cloud bands with clear lanes in between. This is the famous multiple eyewall structure encountered in intense cyclones. Willoughby[4] found that in these cyclones with maximum sustained wind speeds in excess of 45 m/sec (88 knots), a secondary eyewall often develops leading to a repetitive cycle of the eyewalls. Raghavan *et al.*[5,6] and Gupta and Mohanty[7] have reported double eyewalls in the Bay of Bengal cyclones using radar images. Kalsi *et al.*[8,9] have also shown double eyewalls through satellite images in cyclones in which maximum wind speed of 127 knots was estimated. Since the launch of INSAT satellites, no cyclone with double eyewall has been reported from the Arabian Sea. However, Colon[10] found from aircraft reconnaissance of an Arabian Sea cyclone, an eye with diameter of 12 nautical miles and an eyewall width of about 8 nautical miles. The central pressure was 947 hPa. The maximum wind at the 900 hPa level was 96 knots at 12 nautical miles radius. The wind decreased to 65 knots at 18 miles radius but peaked again to 95 knots at 32 mile radius. This was the first case of double eyewall ever reported in respect of the Arabian Sea cyclone. The second episode of double/multiple eyewalls encountered in the cyclone is under consideration.

There is no reconnaissance aircraft or any ground truth available for analysis of eyewall structure of May 1999 Arabian Sea cyclone. However satellite imagery (Figure 1 *a*) received from multi-purpose geostationary Indian National Satellite (INSAT) shows three eyewalls seen distinctly on the eastern side of the centre. On the western side, the outermost spiralling wall is merging with the next inner, i.e. second wall from the centre. Two circular and concentric walls stand out clearly with the inner and outer eyewalls having an average radius of about 10 and 40 km, respectively, at 0900 UTC of 19 May 1999. The eyewalls started forming in the forenoon of 19 May when moat between the eyewalls and even the eye at the centre was not clearly defined even in the visible imagery (Figure 1 *b*). Though these features are very well defined in the visible imagery at 0900 UTC on this day, they are still more or less obscured with cirrus in the infrared imagery. A somewhat similar scenario was seen in cyclones on 7 May 1990 and 28 April 1991 in the Bay of Bengal[9]. The eye was clearly seen but the lane between the eyewalls was covered with thick cirrus. The inner eyewall of the current cyclone thinned out later and sinking at the centre became more pronounced. The temperature of the warmest pixel in the eye rose from – 50°C at 10 UTC to – 24°C at 1700 UTC of 19 May. It again cooled down to – 41°C at 0300 UTC of 20 May. Thereafter it started warming when the temperature rose to – 6.5°C at 1400 UTC of 20 May, thus indicating most pronounced adiabatic warming. The alteration of the eye temperature defining pixel shows the interaction between the two eyewalls. When this pixel cools, the outer wall is supplanting two inner eyewalls which are probably collapsing at this time. The sinking is more pronounced in the area of the inner eyewall rather than at the centre of the eye which shows cooling. Later when the outer eyewall has replaced the inner eyewall after 03 UTC of 20 May, sinking is again pronounced at the centre, showing warming of the eye, and also possibly reintensification of the inner core. The dark area at the centre became darker and wider with stadium effect also seen (figure not shown). Though cloud tops in the eyewall however also warmed up, a careful tropical cyclone intensity analysis according to Dvorak's[2] algorithm shows that it remained more or less the same with sustained wind speed of about 102 knots. So far as PPI images from Cyclone Detector Radar (CDR) Bhuj are concerned, as the cyclone tracked northward towards the coastline its organization improved from widely scattered echoes observed before 1800 UTC of 19 May to well-developed partial eyewalls/ spirals seen at 2200 UTC of the same day. Hereafter a weak convective organization was seen in PPI images for next two hours. The organization further started improving at 0100 UTC of 20 May. Figure 2 *a* shows arcs in the west-south-western side with inner radar radius of not less than 30 km. Further, this structure weakened after two hours (Figure 2 *b*). Complete circular eyewall was not noticed in this case up to 0500 UTC of 20 May – the time up to which the radar observations are available.

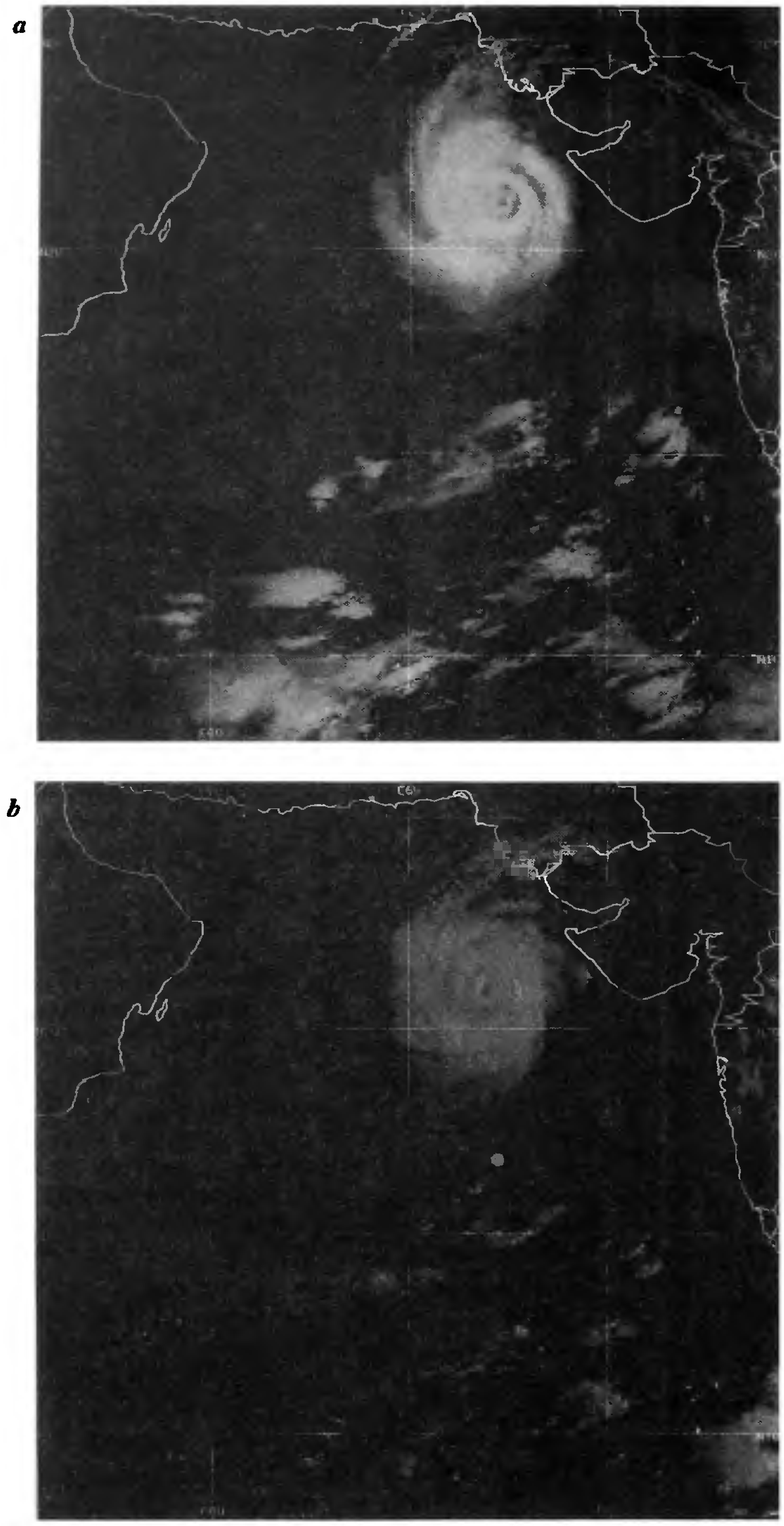
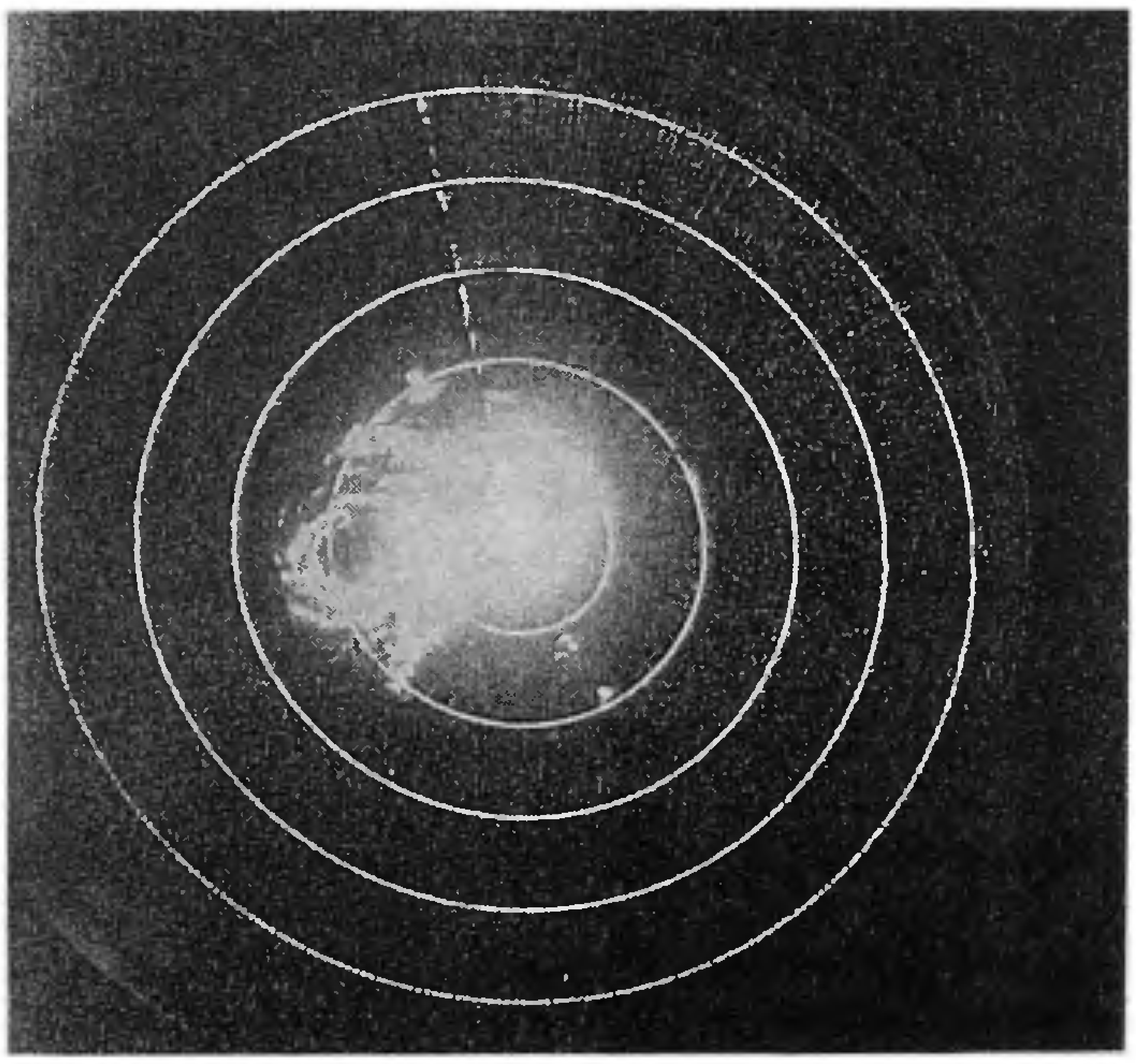


Figure 1. ***a***, 09 UTC INSAT visible image of cyclone showing multiple eyewall structure on 19 May 1999; ***b***, 04 UTC INSAT visible image of cyclone showing poorly defined eye on 19 May 1999.

The cyclone of May 1999 developed at the leading edge of equatorial westerly current, which was seen right from middle of April this year. Development was favoured in warm sea surface area where sea surface temperature hovered around normal by surges in the westerly current (not shown). Figure 3 shows the time evolution of this cyclone which was rather fast on 17 and 18 May. Kalsi *et al.*[9] showed that rapid deepening with pressure falls of more than 42 hPa occurred both in May 1990 and April 1991 cyclones of the Bay of Bengal on days when double eyewalls were seen. Multiple eyewalls developed in these two cyclones when they had maximum sustained wind speeds between 100 and 120 knots, i.e. when they were in their pre-super cyclonic storm stage that starts at 120 knots as per nomenclature recently introduced by India Meteorological Department. In this case the depression on 16 May deepened through several stages and became a very severe cyclonic storm at 21 UTC of 17 May. Though the pressure fall was quite significant and much larger in comparison to the fall normally seen in the first two days of development, the estimated central pressure remained flat at 950 hPa from 1200 UTC of 18 May onward, indicating that unlike two earlier cases in which rapid development was seen when multiple eyewalls developed, the intensification stopped in this case. Multiple eyewalls developed in this case also in the pre-super cyclonic storm stage. The maximum intensity of this cyclone has been operationally estimated to be *T* 5.5 corresponding to a wind speed of 102 knots as per the Dvorak's[2] algorithm, though there were signals of weakening of convective structure as seen in the satellite imagery and also in the radar PPI images in some of the hourly frames. There was warming and cooling of eye temperature and also cloud top temperatures in the eyewall. Mishra and Gupta's[11] scheme was applied to estimate the pressure defect at the centre using the satellite-derived intensity of the system. The estimated central pressure of the storm however remained more or less constant and did not show any change.

Figure 4 shows the track of this cyclone. Naliya area in western Kutch district has reported strong winds to the tune of 85 knots from southerly direction at a distance of nearly 100 km from the track of this cyclone. It may be added here that the radius of the maximum wind in the 9 June 1998 cyclone, which had the same inner core intensity, was less than 20 km at the time of landfall[12]. In the present case, relatively stronger wind of 85 knots at Naliya Airport indicates that it has a larger radius of maximum winds; however, precise data are not available. The eyewalls seen on 19 May merged the next day. Kalsi *et al.*[9] have reported earlier that merging of eyewalls in respect of the two cyclones of the Bay of Bengal was associated with strengthening of Outer Core Strength (OCS)[13]. Strengthening of OCS cannot be ruled out on the basis of reports of strengthening of winds at Naliya, Bhuj and Kandla. It may be of interest to add here that strengthening of winds at Naliya and in its neighbourhood was reported after the cyclone had moved north, crossing the latitude of Naliya. At this stage it was no doubt experiencing landfall conditions. This is consistent with weakening of convective structure observed at this time. But according to Weatherford and Gray[14], OCS could build up at this stage and this is what has actually been experienced between 2200 UTC of 19 May (time of crossing Naliya latitude) and 1400 UTC of 20 May when the cyclone was

a



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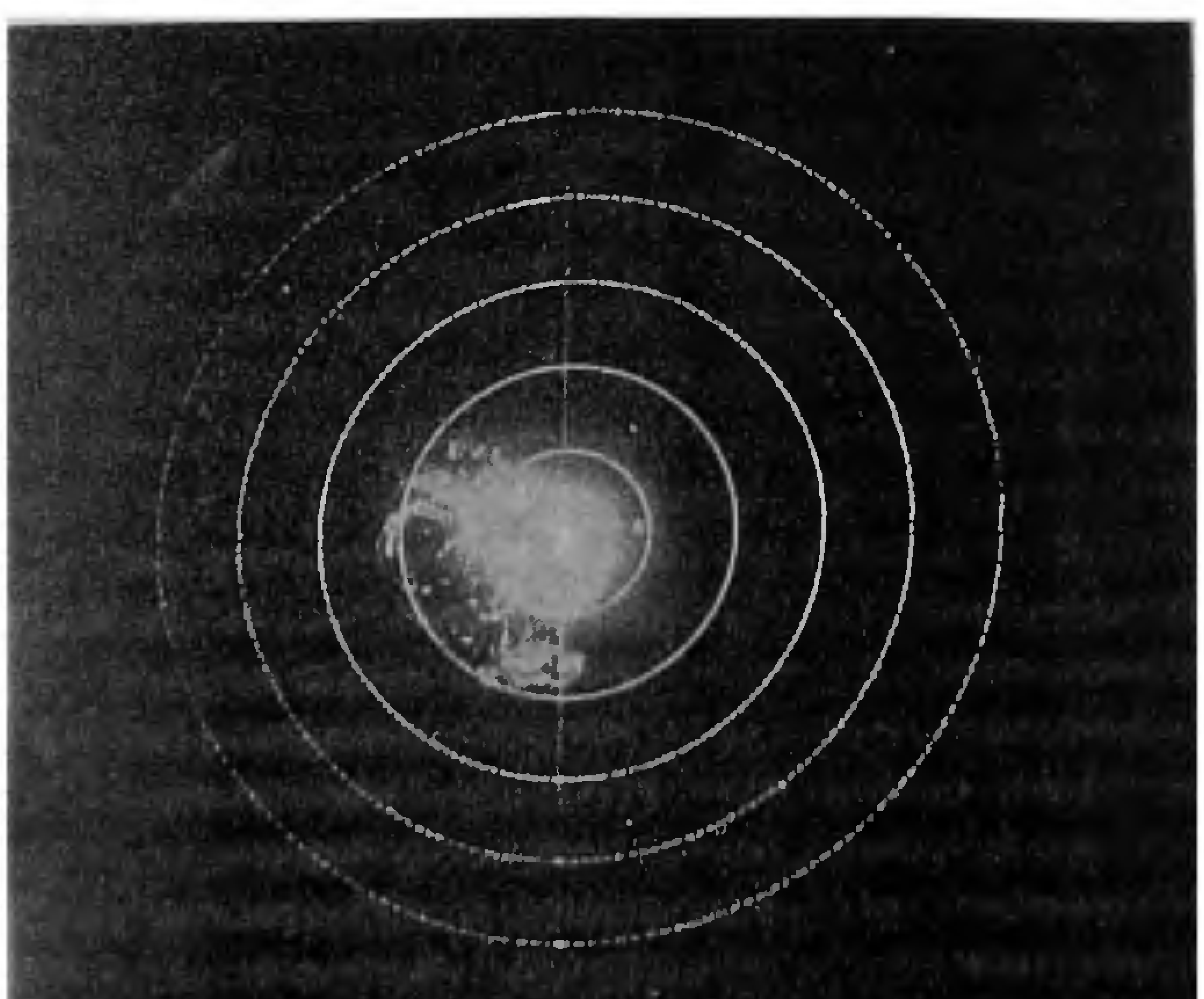

Figure 2. ***a***, 0049 UTC PPI image of CDR Bhuj showing eyewall ARCs on 20 May 1999; ***b***, 0235 UTC PPI image of CDR Bhuj showing weakening of the pattern on 20 May 1999.

over land over the south-eastern part of Sindh Province of Pakistan.

Raghavan[15] summarized studies on Radius of Maximum Reflectivity (RMR) which was related to radius of maximum winds. Raghavan *et al.*[6] defined RMR as the radial distance from the centre to the point of maximum reflectivity in the eyewall. No RMR was reported in respect of this cyclone. Its centre was more than 300 km to the south-west of Bhuj at 09 UTC of 19 May when multiple eyewalls were seen in the satellite imagery. Unfortunately the range was limited to 300 km even at the peak power of 455 kW. Spiral eyewall structure was seen in the radar PPI images. The bright spiral band around the eye had radius more than 30 km after 22 UTC of 19 May as discussed earlier. The inner eyewall experienced earlier and seen through satellite imagery was not captured in the PPI images.

Gupta and Mohanty[7] discussed the issue of recurvature in association with double eyewall episodes in tropical cyclones. As seen in the track, there does not seem to be any recurvature coming up in the course of this cyclone before landfall, but by that time the eyewalls had already got merged in this case. Whether the recurvature after landfall was due to the multiple eyewall episode of the previous day or due to some invisible short wave trough in the mid-latitude mid-tropospheric westerly flow (cloudiness was forced over western Himalayas, the Hindukush and Sulaiman Hills) is quite difficult to establish. It was a gigantic cyclone which controlled the position of the upper tropospheric ridge that shifted north along with the cyclone. It was steered by the strong southerly flow around the mid-tropospheric anticyclone over central India. When the cyclone weakened on account of land interaction, it apparently drifted to the north-east due to south-westerly flow in the middle and upper troposphere.

Gupta and Mohanty[7] also stated that intense tropical cyclones of the Bay of Bengal that exhibited double eyewalls acquired these characteristics when they came close to the coast (within 200–300 km). As indicated by Hawkins[16], land interaction might have had an important role in the development of multiple eyewall structure on 19 May 1998 in this cyclone that crossed close to the international border into Pakistan on 20 May 1999. It may be added here that this is the 3rd case of development of multiple/double eyewalls in the north Indian Ocean as seen in the satellite imagery after commencement of INSAT applications programme. In all the three cases, the diameter of dense convection with cloud tops cooler than – 70°C was more than 2°. In Kavali cyclone of 9 November 1989, in which estimated wind speed exceeded even 120 knots, the double/multiple eyewalls were not seen. But there was another cyclone (November 1988) with similar inner core intensity but much higher OCS[17], and associated with larger area dense convection which also did not show these characteristics. Willoughby[4] also found that three out of four hurricanes during 1983 to 1989 over the Atlantic

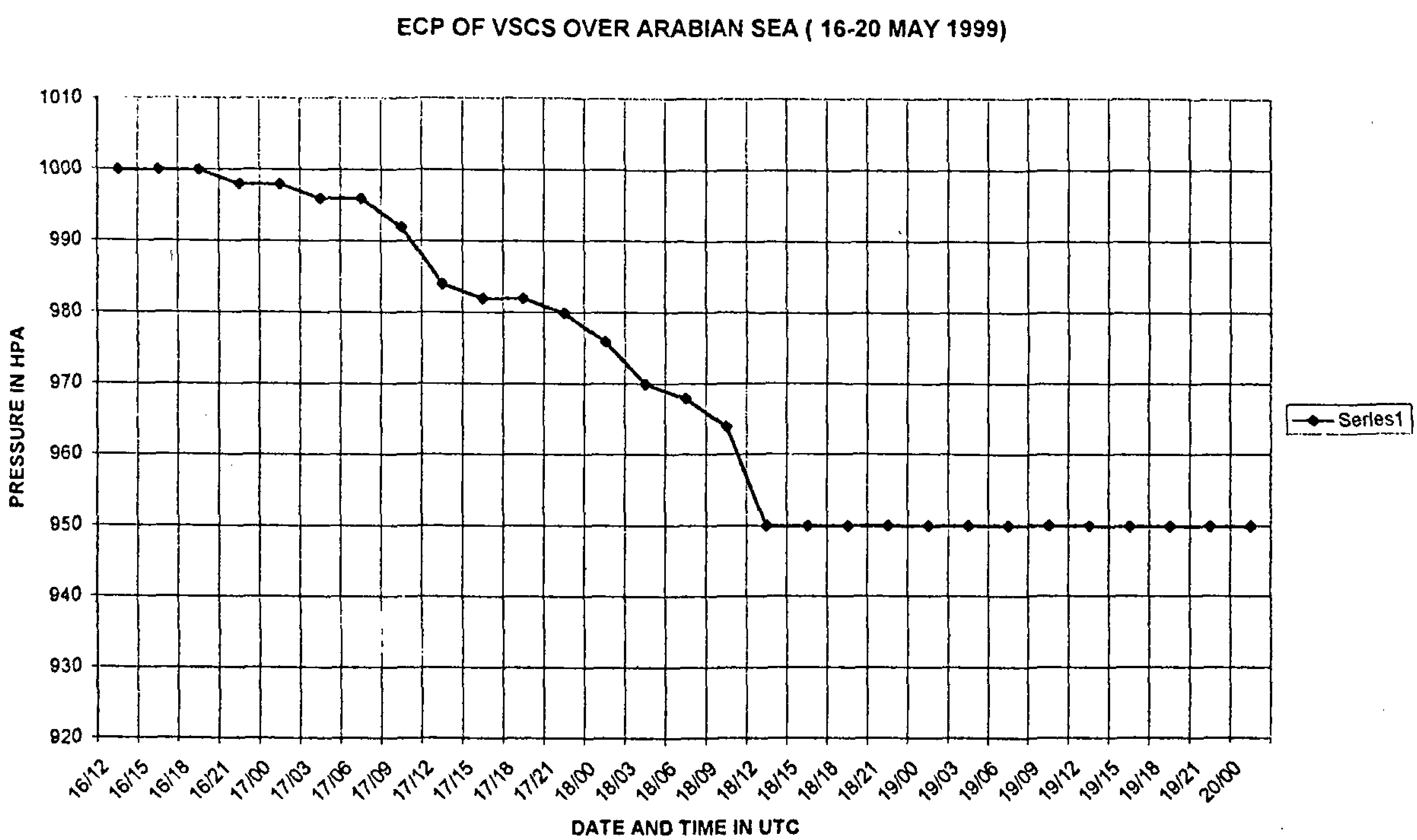

Figure 3. Estimated central pressure of cyclone during different phases of evolution.

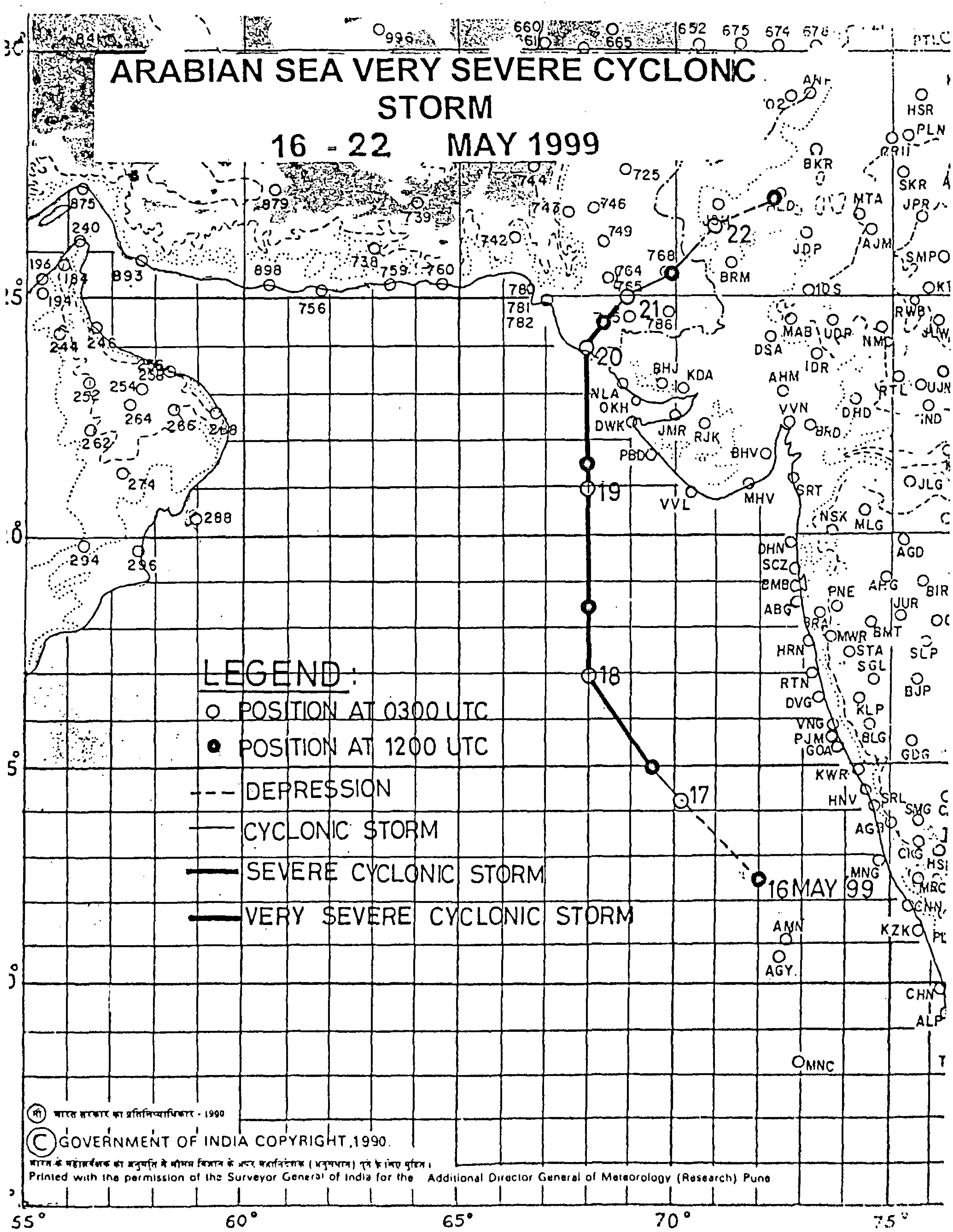

Figure 4. Track of very severe cyclonic storm.

developed double eyewalls when they came close to the landmass. Although the sample is admittedly biased towards the landfalling storms, there appears to be frequent coincidence of outer eyewalls with the landfall indicating an apparent relation of land-induced effects with the formation of a double eyewall.

Like the Machilipatnam cyclone of May 1990, this cyclone slowed down as it travelled towards the coast. It appears that along with the large area dense convection the cyclones which move rather slow, or slow down while racing towards the coast develop these characteristics. All the three cyclones with multiple eyewall structure showed these characteristics whereas others which did not acquire multiple eyewall structure behaved differently.

Multiple eyewalls developed on 19 May 1999 in the Arabian Sea cyclone before landfall after the intensification had ceased. They were associated with strengthening of outer core winds after the process of landfall had already started. These eyewalls developed in the pre-super cyclonic stage when the maximum sustained wind speed was about 102 knots. In the absence of any other plausible reason, land interaction seems to be the cause for development of multiple eyewalls in this cyclone.

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Snow characterization using SSM/I data

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Snow in the Himalayan region is a vital water resource for India. Most of the river systems of India are dependent on melting of snow during summer months, which gives substantial amount of water for agriculture and hydropower, and a boost to our development. But the changes in snow cover have direct relation to global climatic changes. It is expected that the surface and atmospheric temperatures may significantly change which may influence the snow cover over high altitude regions. Currently, much attention is being paid to the global warming trend due to the increase of greenhouse gases in the earth's atmosphere. The mapping of snow cover using optical sensors, however, suffers quite often with cloud problems. Such problems do not affect microwave remote sensing which has an added advantage of quantitative estimation of snow parameters and characterization of snow cover. In the present work, an attempt has been made to study the characteristics of brightness temperature of snow over Himalayan region using SSM/I data.

THE meteorological parameters from the ground, ocean and atmosphere have paramount importance in studying the earth's climate. The Special Sensors Microwave Imager (SSM/I) has been developed as a part of the Defence Meteorological Satellite Programme (DMSP) which was launched in 1987. Efforts have been made to characterize clouds, snow[1], surface temperature[2], rainfall over land[3], oceanic total perceptible water[4], cloud liquid water content[5], ocean surface wind speed[6], atmospheric water vapour over oceans[7], and sea ice[8]. The estimation of soil moisture and evapotranspiration fluxes from SSM/I data have also been carried out[9,10]. These studies have given an overall global picture of the brightness temperature, however, no effort has been made to explore or to use SSM/I data for the Indian region. In the past efforts have been made by Indian scientists to use microwave remote sensing data[11–14] recorded by microwave radiometer onboard *Bhaskara* satellite.

The SSM/I is on-board a sun-synchronous near polar orbiting satellite[15] (DMSP Block 5D–2 F8) since the end of June 1987. It has a seven-channels, four-frequencies radiometric system providing global observations at a constant incident angle of about 53°. The SSM/I is a conical scanning radiometer, which measures thermally emitted radiation by the earth at frequencies of 19, 22, 37 and 85 GHz. The brightness temperature (T_B) measurements have been observed for both horizontal and vertical

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