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Satellite-based monitoring and prediction of tropical cyclone intensity and movement

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सार — सिनॉप्टिक विश्लेषण और उष्णकटिबंधीय चक्रवातों के पूर्वानुमान से संबंधित आवश्यकताओं को पूरा करने की दिशा में मौसम विज्ञान उपग्रहों की क्षमताओं में काफी प्रगति हुई है। इस शोधपत्र में भारतीय समुद्रों में उष्णकटिबंधीय चक्रवातों की तीव्रता के आकलन और उनके पथ के पूर्वानुमान में उपग्रह आँकड़ो के प्रभाव के बारे में बताया गया है और इसमें उष्णकटिबंधीय चक्रवात तीव्रता विश्लेषण के कार्य के लिए व्यापक रूप से उपयोग में लाई जा रही डवोरक क्रिया विधि की समीक्षा भी की गई है।

अरब सागर और बंगाल की खाड़ी के उष्णकटिबंधीय चक्रवातों के विश्लेषण के लिए तीव्रता आकलन की डवोरक की स्कीम के व्यापक प्रयोग से इसकी बहुत सी सीमाओं और विषयनिष्ठता के तत्वों का पता चला है, जैसाकि उपग्रह से प्राप्त चित्रों में देखा गया है। इससे अन्य सागर बेसिनों के चक्रवातों की तरह बड़े पैमाने पर संरचनात्मक भिन्नता का भी आभास होता है।

चक्रवात के पथ का पता लगाने से संबंधित उपग्रह पर आधारित तकनीक में निम्नलिखित सम्मिलित हैं :

(*i*) उपग्रह का प्रयोग माध्यपवन प्रवाह (*ii*) उपग्रह चित्रों की अनुक्रम सक्रियता और मेघ प्रणाली की बाहरी गति का बहिर्वेशन (*iii*) जल वाष्प विलयन चैनल चित्रों में बाहरी नमीक्रम के मानीटरन में परिवर्तन

उष्णकटिबंधीय चक्रवात की तीव्रता के आकलन और उनके पथ के पूर्वानुमान से संबंधित उपग्रह पर आधारित तकनीकों से आपदा की चेतावनी देने में उल्लेखनीय प्रगति हुई जिससे जानमाल को बनाया जा सकता है ।

ABSTRACT. Capabilities of meteorological satellites have gone a long way in meeting requirements of synoptic analysis and forecasting of tropical cyclones. This paper shows the impact made by the satellite data in the intensity estimation and track prediction of tropical cyclones in the Indian Seas and also reviews the universally applied Dvorak algorithm for performing tropical cyclone intensity analysis.

Extensive use of Dvorak's intensity estimation scheme has revealed many of its limitations and elements of subjectivity in the analysis of tropical cyclones over the Arabian Sea and the Bay of Bengal, which, like cyclones in other ocean basins, also exhibit wide structural variability as seen in the satellite imagery.

Satellite-based cyclone tracking techniques include: (*i*) use of satellite — derived mean wind flow, (*ii*) animation of sequence of satellite images and extrapolation of the apparent motion of the cloud system and (*iii*) monitoring changes in the upper level moisture patterns in the water vapour absorption channel imagery.

Satellite-based techniques on tropical cyclone intensity estimation and track prediction have led to very significant improvement in disaster warning and consequent saving of life and property.

Key words — Satellite-based techniques, Intensity estimation, Track prediction, Wind fields.

1. Introduction

The advent of meteorological satellites in the sixties made an immediate global impact on the detection and monitoring of tropical cyclones and on their track prediction. Soon thereafter, the technique formulated by Dvorak (1975) for intensity estimation of tropical cyclones from satellite imagery gained widespread acceptance. It is now believed that many uncertainties in cyclone track fixation prevailed in the pre-satellite era, during which some tropical cyclones might have also just gone undetected. For example, the eastern North Pacific area had a pre-satellite climatology of less than 10 tropical storms in a year, but from 1968 to 1989, the average number of storms per year had gone upto 16.5 (Elsberry 1995). Over the Australian region, the number of cyclones was found to increase from 4 per year during 1910-40 to an average of 10 per year after 1960. While earlier tracks appear to be shorter in length and have an obvious proximity to coastal areas, satellite surveillance begins far out at sea and brings out details, such as, looping. Of course, the possibility of such variations being attributable to real changes on the decadal scale cannot be completely ruled out.

Over the north Indian Ocean, the decadal variations do not show any increase in the number of tropical cyclones attributable to satellite monitoring. On the contrary, the number of cyclonic disturbances, during the period 1981-89, was as low as 97 against a figure of 187 for the decade 1921-30 (Mandal 1991). However, Mandal's analysis shows that the frequency of severe cyclonic storms with a core of hurricane winds, during the year 1965 to 1989, is 2.5 times higher than the long period average taken over the years 1891 to 1989. This seems to suggest that the intensity estimations during the pre-satellite period could have been more conservative. It is also significant that all the seven known examples of looping cyclonic storms over the north Indian Ocean belong to recent years (1972-89), pointing to the difficulties which might have prevailed earlier while accepting such irregularities as real movement.

Satellite-based techniques for the estimation of the intensity of tropical cyclones and monitoring their development and movement underwent a rapid evaluation in step with advances in satellite technology. Initially, only one satellite image of a tropical cyclone could become available in a day. With later versions of the TIROS satellites, night-time observations with infrared sensors became possible. Subsequently, geostationary meteorological satellites, like GOES, GMS and Meteosat placed tropical cyclones under round-the-clock surveillance. Indian meteorologists have been privileged in this respect by having a succession of six geostationary satellites of the INSAT series, with meteorological payloads, located over the Indian Ocean since 1982. There are many other recent developments in the meteorological satellite scenario which may not have had an impact globally, but are sure to do so in the near future, as more and more satellites are equipped with water vapour imaging and microwave sensing capabilities. India's own INSAT-2E satellite, scheduled for launch by 1997 end, would have a 3- channel radiometer including a water vapour channel and a 3-band CCD array for 1 km resolution in the visible and near infrared imaging. It must be also mentioned that besides satellite imagery, derived quantitative products, such as, sea surface temperature, cloud motion winds, ocean surface winds, outgoing longwave radiation and large-scale precipitation estimates are also very useful in understanding the structure and behaviour of tropical cyclones.

This paper reviews contributions which satellites have made to our understanding of tropical cyclones, the status and limitations of various operational techniques currently in vogue and the future possibilities.

2. Intensity estimation

The technique for estimating the intensity of a tropical storm through satellite imagery is basically a pattern recognition process which assumes that certain characteristics or features of the cloud organisation are indications of the intensity. The features, however, may not always be clearly defined or they may appear differently or be uncharacteristic. Such a complexity can be dealt with through a set of systematic procedures, quantifiable and measurable cloud pattern descriptions and models of storm development with time, as was done by Dvorak (1984) in the technique which has become known after him and accepted worldwide.

Dvorak's model of cyclone development is built in terms of the so-called T-number (T = Tropical) which ranges from values of 1 to 8 in steps of 0.5, associated with increasing wind speed and decreasing sea level pressure (Table 1). On this scale, T1 to T2 indicate pre-storm situations and T

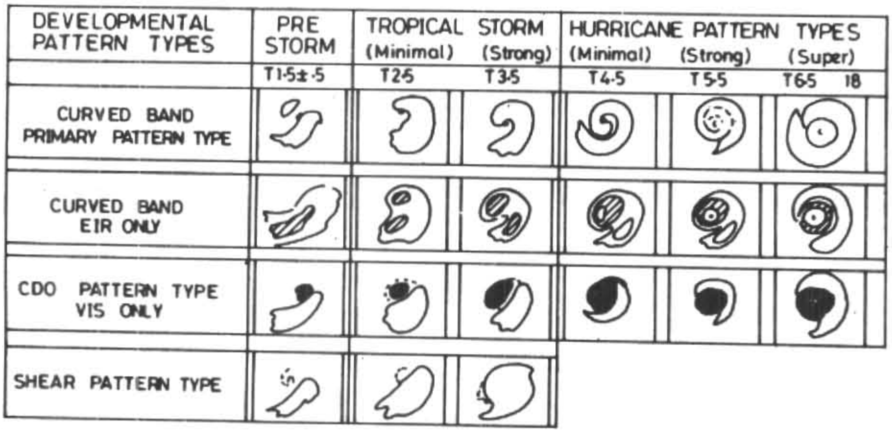

Fig. 1. Cloud pattern analogues in the tropical cyclone intensity analysis based on satellite imagery. Pattern changes from left to right are typical 24-hourly changes (Dvorak 1984)

TABLE 1

Intensity of tropical storms

Nomenclature in India	T-Number or CI-Number	Maximum wind speed (knots)	Minimum sea level pressure (hPa)		Pressure drop (ΔP) between central and peripheral pressure (hPa)
			Atlantic Ocean	NW Pacific Ocean	North Indian Ocean
Depression	1.0	25	—	—	—
	1.5	25	—	—	—
Deep depression	2.0	30	1009	1000	4.5
Cyclonic storm	2.5	35	1005	997	6.1
	3.0	45	1000	991	10.0
Severe cyclonic storm	3.5	55	994	984	15.0
SCS with core of hurricane winds	4.0	65	987	976	20.9
	4.5	77	979	966	29.4
	5.0	90	970	954	40.2
	5.5	102	960	941	51.6
	6.0	115	948	927	65.6
	6.5	127	935	914	90.0
	7.0	140	921	898	97.2
	7.5	155	906	879	119.1
	8.0	170	890	858	143.3

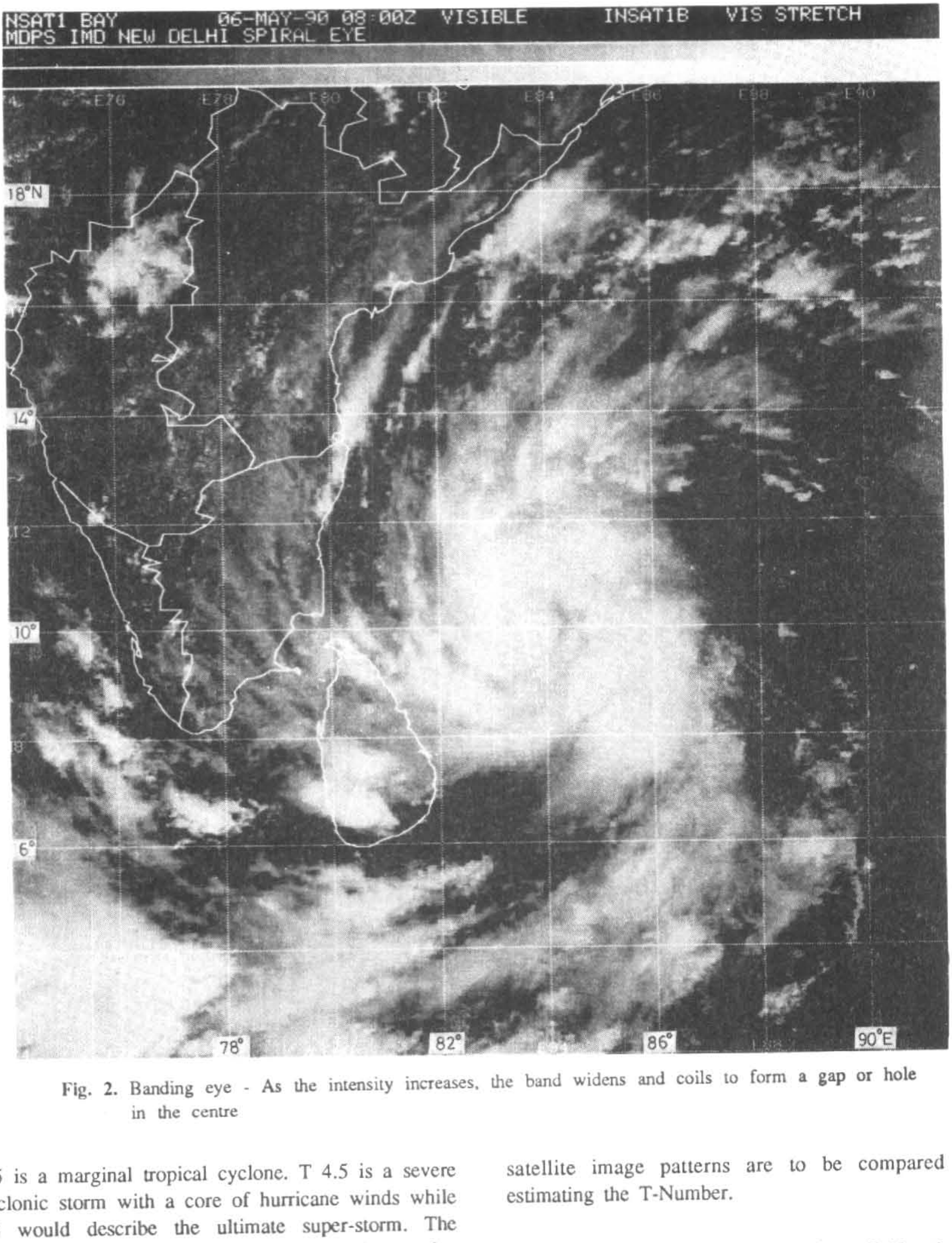

Fig. 2. Banding eye - As the intensity increases, the band widens and coils to form a gap or hole in the centre

2.5 is a marginal tropical cyclone. T 4.5 is a severe cyclonic storm with a core of hurricane winds while T8 would describe the ultimate super-storm. The T-Number would normally increase by 1 per day during intensification but departures from the model rate are possible.

Fig.1 shows the cloud pattern analogues corresponding to various situations, against which actual satellite image patterns are to be compared for estimating the T-Number.

Although infrared images are available during both night and day, their use is not without some additional difficulty. Firstly, infrared sensors generally have a poorer resolution than visible sensors. Secondly, thin cirrus clouds which are transparent to visible radiation, show up in infrared pictures

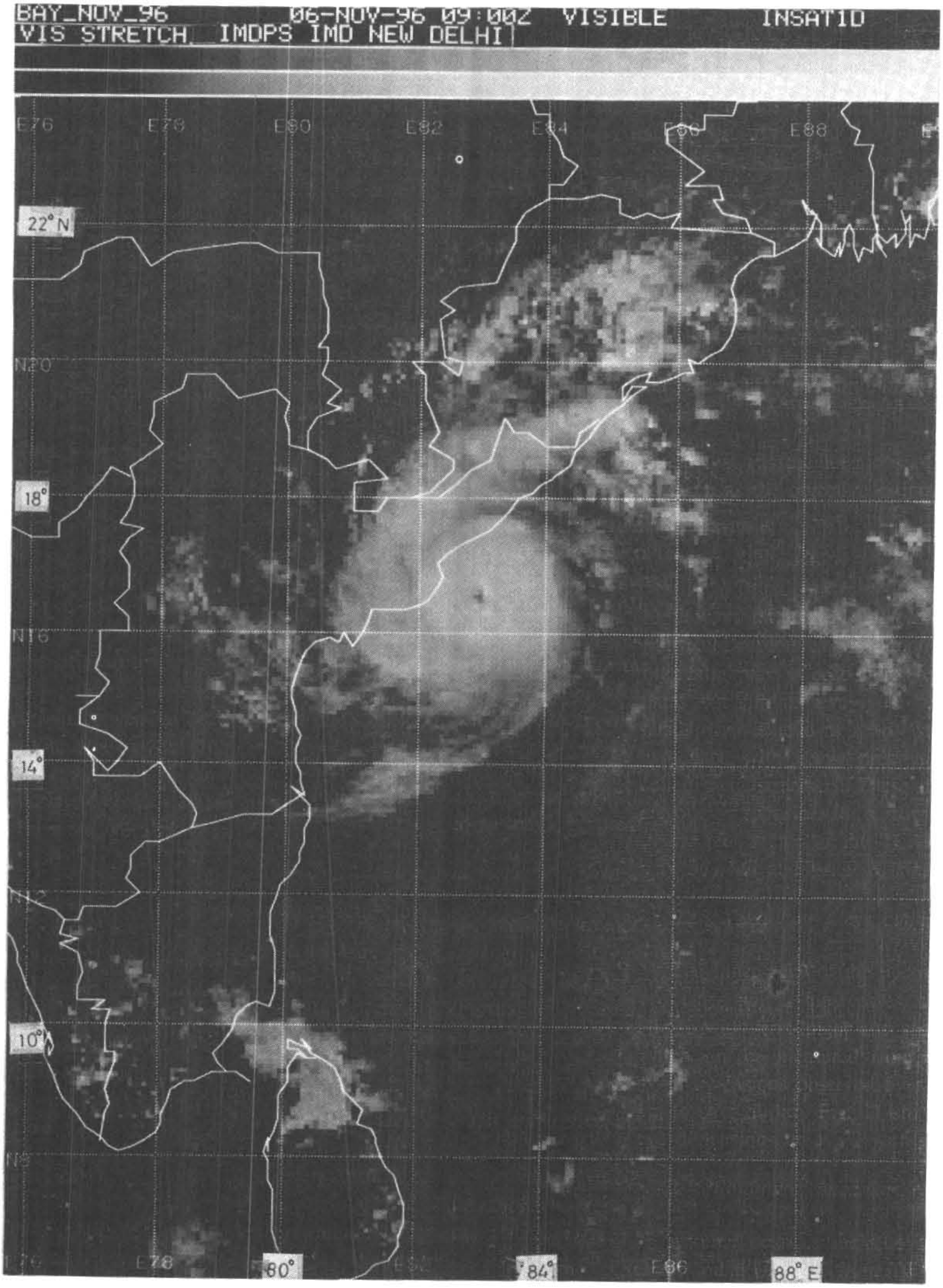

Fig. 3. Distinct eye - A distinct eye is formed at the centre of the CDO at a stage T4.5

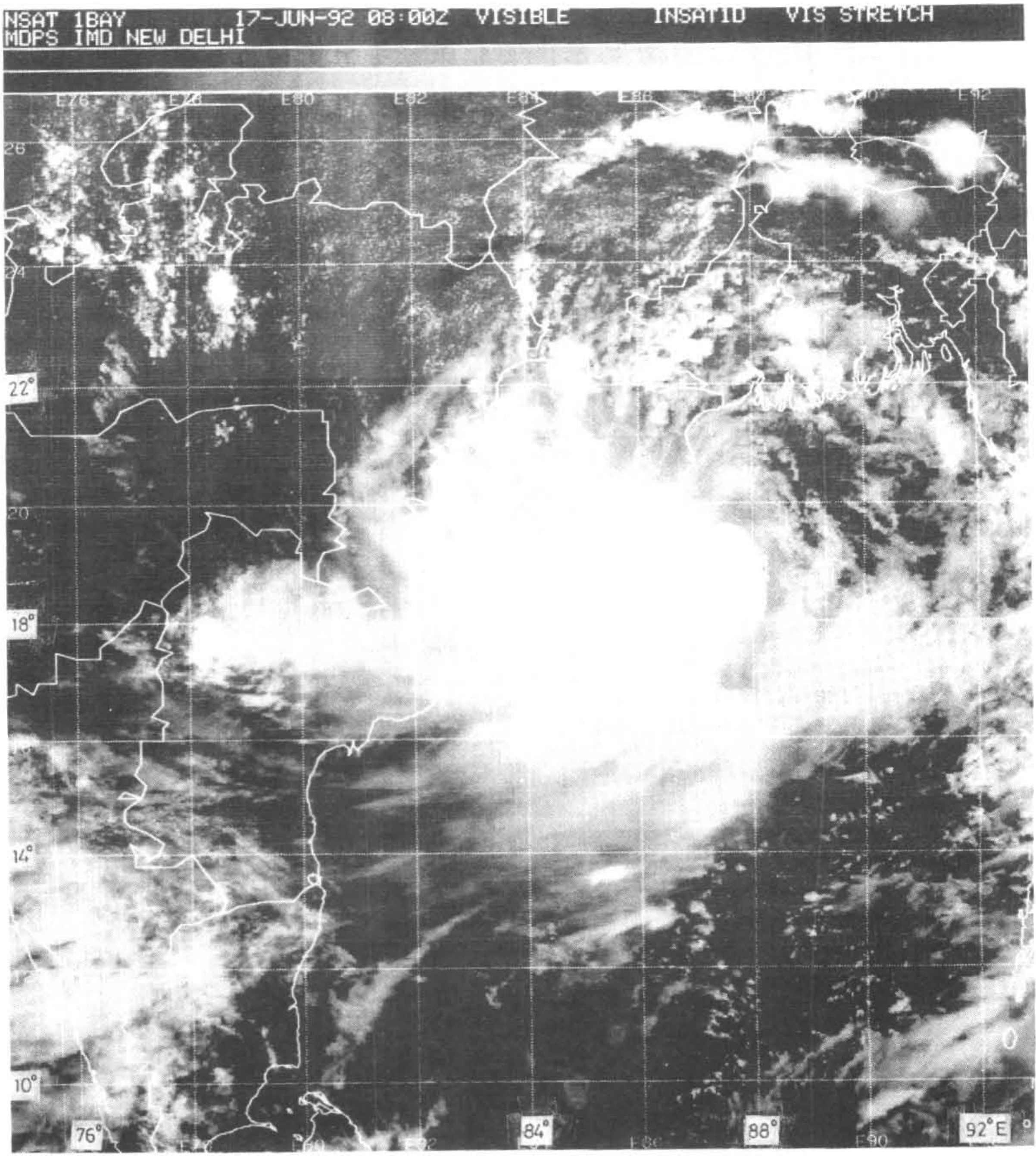

Fig. 4. INSAT picture of 17 June 1992 - In the shear pattern, the dense cloud mass appears to be distant from the centre defined by the cumulus lines

prominently, so that the cirrus shield blocks the lower level cloud features from the satellites view. Thirdly, the low cloud lines, which are clearly seen in visible pictures and are of help in locating the centre, are not noticeable in infrared imagery. However, the digital brightness temperature data, if used directly, can be of great value in quantitative analysis and digital image enhancement procedures. The infrared image can, thus, be made to display a number of gray shades, each one being assigned to a predetermined temperature range. The temperature of the eye, if seen, and that of the surrounding clouds, are also used as inputs to the intensity estimation algorithm, making it more objective than in the case of visible pictures. For hurricane patterns exhibiting an eye, the enhanced pictures also provide

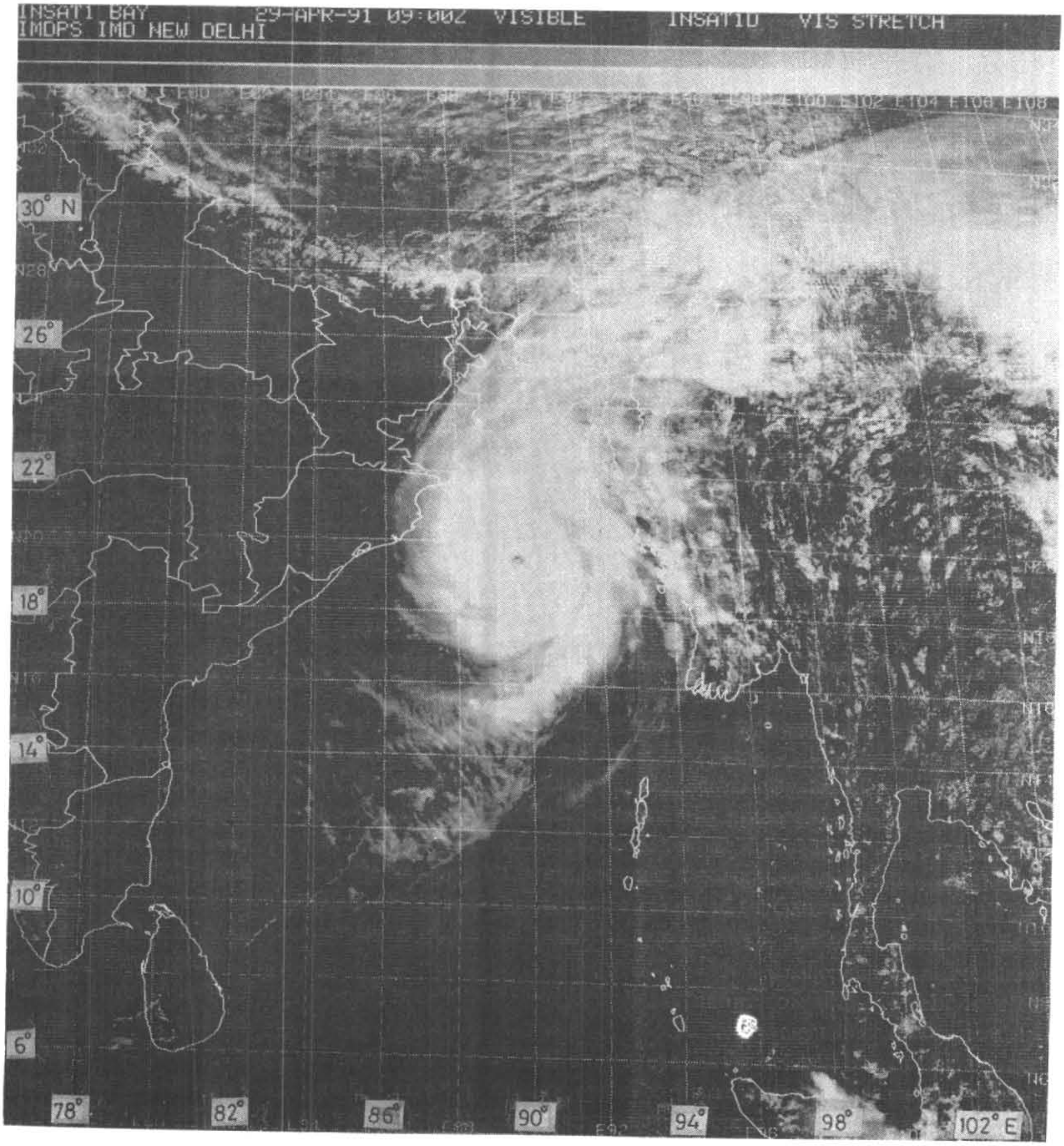

Fig. 5. INSAT VIS picture of 29 April 1991, 0900 UTC

a clearcut track of the storm movement.

The curved band pattern is very commonly observed in both visible and infrared satellite imagery in the development stage of a tropical cyclone. The intensity of the storm is determined from the extent to which the cloud band encircles the storm centre. At T 2.5, the cloud band may curve half-way around the centre. As the intensity increases, the band widens and coils to form a gap or hole in the centre (Fig. 2). In the Central Dense Overcast (CDO) pattern, a CDO area is formed within or over the curved cloud features defining the centre of the storm. A distinct 'eye' is formed at the centre of the CDO at a stage corresponding to T 4.5 (Fig. 3).

The curved cloud bands may sometimes get obliterated due to strong vertical wind shear. In such a case, the dense upper level clouds get separated from the low level circulation. In the shear pattern, the

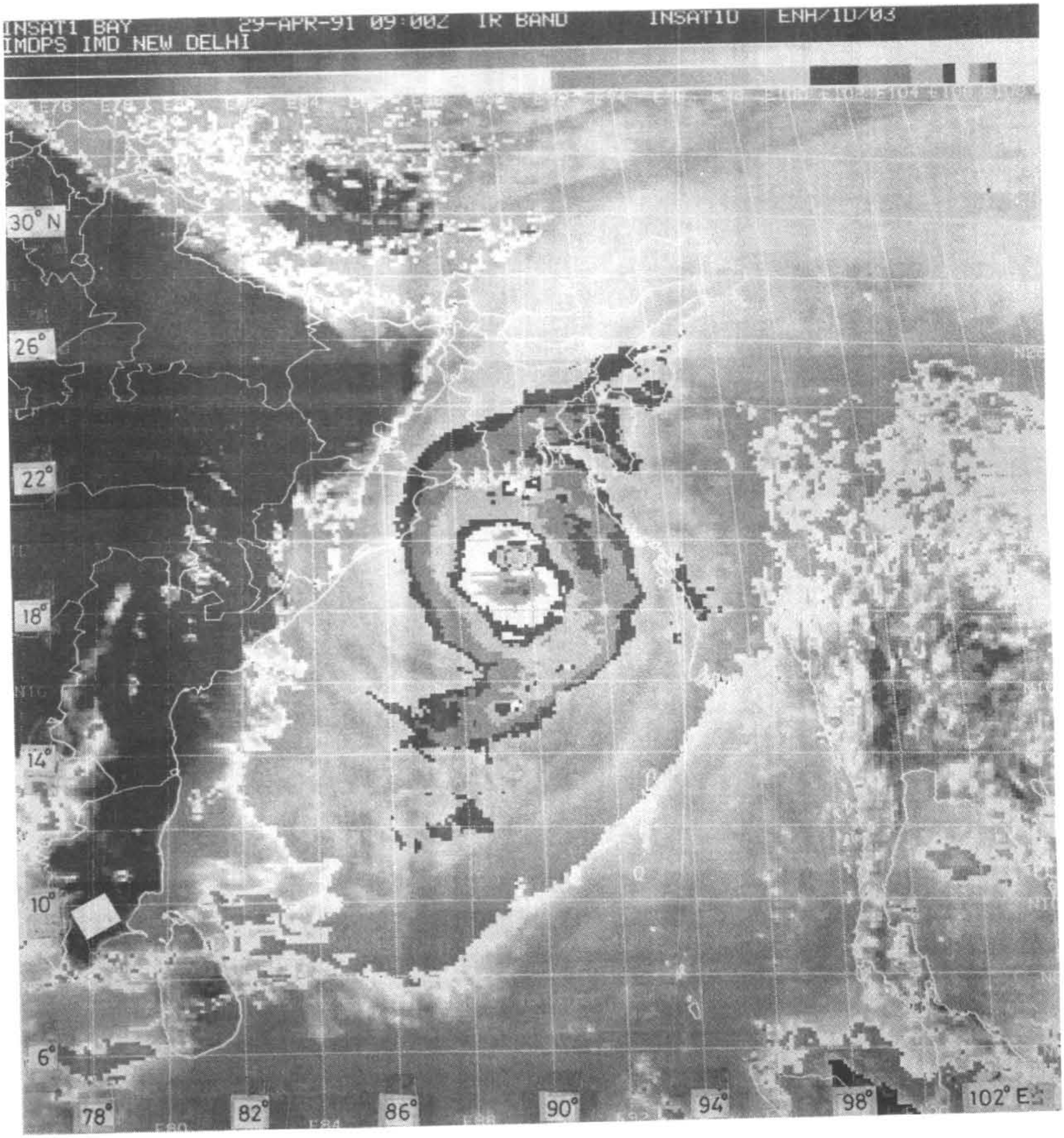

Fig. 6. INSAT IR picture of 29 April 1991, 0900 UTC

dense cloud mass appears to be distant from the centre defined by the cumulus lines (Fig. 4).

When the cyclone develops an eye embedded in the CDO, the intensity can be estimated from the size, shape and appearance of the eye and the smoothness of the CDO (Figs. 5 and 6). The use of enhanced infrared (IR) images and the brightness temperature contouring around the eye region are of additional help as mentioned earlier (Fig. 6).

Dvorak's scheme takes into account a climatological model of development of tropical cyclone in which, as already stated, the intensity increases at the rate of one T-Number per day. It calls for identification and measurement of Central and Banding Features, known as CF and BF, which together determine Data T-Number (DT). When the features are clear-cut, DT is measured from the cloud imagery. In case of unclear

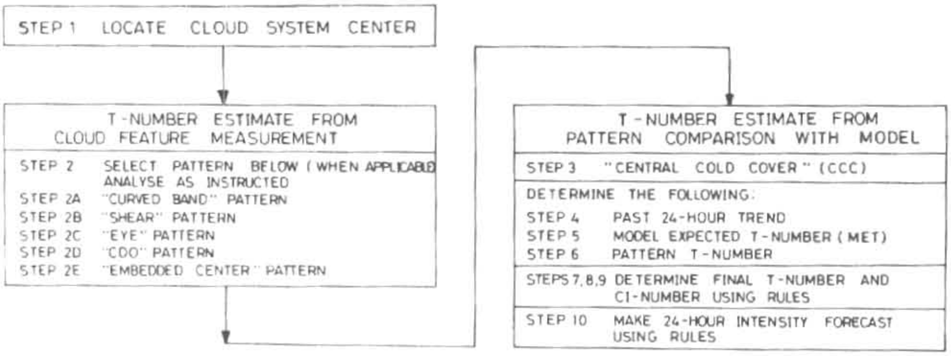

Fig. 7. Basic steps in Dvorak's intensity estimation technique

and poorly defined disturbances, the satellite observed pattern is compared with a set of patterns of known intensity to work out the instantaneous intensity of the cyclone. This gives the pattern T-Number known as PT. The technique also enables the satellite analyst to work out the Model Expected T-Number (MET) based on the trend in the overall rate of development of the cyclone. This provides powerful constraint to work out a consistent and reliable intensity estimate.

Dvorak's intensity estimation technique consists of ten basic steps (Fig. 7), beginning with locating the cloud system centre, and then analysing the central features and the banding features of the cloud pattern in the second step. Step 3 calls for identification of Convective Cold Cover (CCC) pattern in which a dense overcast obscures the centre of circulation. The development process is arrested in this case. 24-h trend is calculated by comparing the current with the 24-h past cloud picture in the 4th step. Using this trend, the MET is obtained in step 5. Next step involves estimation of PT by comparing the current picture with patterns of known intensity (Fig. 1). The last three steps are invoked to derive the final intensity by invoking constraints to hold T-Number within acceptable bounds.

When the storm begins to weaken, a current intensity (CI) number is used to indicate the intensity in place of the T-Number. The CI-Number is held higher than the T-Number for weakening storms, otherwise they are the same. This is done because indications of weakening may appear several hours in advance and may also not be sustained but be only temporary.

It is also possible to forecast the intensity of the storm over the next 24 hours by following the model curve, and with additional considerations of the upstream environment. It is necessary to consider whether the cyclone is entering or having an environment of strong vertical shear, stratocumulus clouds and southward-moving cirrus or approaching land. Cyclonically-curved bands forming in or entering the upstream area are unfavourable for further development.

Kalsi (1993) has discussed several time sequences of INSAT-1B images to illustrate how the genesis of a tropical cyclone can be detected by means of satellite imagery. Initially, there may not be a perceptible difference between developing and non-developing mesoscale cloud cluster over the ocean. However, the genesis phase is revealed by the relatively improved organisation of a random mesoscale convection. A large scale convective surge showing cyclonic circulation may also be seen to precede the genesis. The persistence of convection as a prelude to cyclogenesis was a feature common to many Bay of Bengal cyclones which later developed to hurricane stage.

Rao *et al.* (1989) made a detailed case study of a cyclonic storm in the Bay of Bengal in February 1987 and made a daily analysis of INSAT-derived Outgoing Longwave Radiation (OLR) and precipitation estimates. They inferred that persistent low values of OLR (100 watts/m^2) much below the expected seasonal value should be carefully watched as an advance indication of cyclogenesis.

Very few of the tropical vortices in the Bay of Bengal attain the intensity of hurricanes and a majority of them end up as marginal cyclones with a T-Number between 2.5 and 3.5 (Kalsi 1989). This particularly happens when the cyclogenesis proceeds in an area characterised by strongly sheared flow. The advection aloft of the heat and moisture from the vertical column over the vortex due to the strong shear displaces the CDO from the circulation centre defined by cumulus lines.

A severe cyclonic storm with a core of hurricane winds crossed the Andhra Pradesh coast near Machilipatnam on 9 May 1990. The cyclone had a fast rate of development and displayed certain unusual features of evolution, one of which was the double eyewall structure, which was clearly seen both in satellite and radar imagery. This is a signature of a "super-hurricane" (Kalsi *et al*. 1993). The double eye wall structure was observed by coastal radar for as long as 48 hours and underwent repetitive cycles of contraction and dissipation during this period (Raghavan 1993). During the Bangladesh cyclone of 29 April 1991, such a double eyewall structure was again seen on satellite imagery but there was no corroborative radar evidence (Kalsi *et al*. 1996). Both these cyclones intensified to T 6.5 and had a large area of overcast. Cyclones of comparable intensity but with smaller sized overcast have not shown such a structure.

Tropical cyclones over the Arabian Sea and the Bay of Bengal have exhibited wide structural variability from the model patterns of Dvorak. An analysis of past satellite imagery over the north Indian Ocean shows that there are commonly two main precipitation bands in a spiral configuration around the northwest and southern sectors of the tropical cyclone, which is not so for Atlantic storms (Mandal 1995). The most prominent bands are seen in the south-west quadrant coinciding with the inflow maxima, particularly in westward moving storms. However, in the case of recurving storms, cloud bands are also seen in the northeast quadrant. Diurnal variation of the cloud pattern has been observed, the inner core cloudiness being maximum around sunrise and minimum around sunset time.

Extensive use of Dvorak's intensity estimation scheme has brought to light many of its limitations and elements of subjectivity. Tropical cyclones undergoing rapid intensity changes tend to be underestimated. Basin-to-basin and storm-to-storm differences in storm behaviour and structure also get overlooked in this technique.

Velden (1989) and Velden *et al*. (1991) have derived upper tropospheric warm anomalies associated with tropical cyclones in the Atlantic and North Pacific, using satellite passive microwave radiometer data from NOAA / Microwave Sounding Unit (MSU). Due to resolution limitations (110 km) the microwave observations cannot fully resolve the temperature anomalies. However, the microwave techniques yield intensity estimates which are comparable in accuracy with Dvorak's technique, as borne out by aircraft reconnaissance observations. Either the 54.96 GHZ channel radiance anomaly (core minus environment) or the retrieved temperature anomaly at 25 hPa (core minus environment) can be determined from the microwave soundings, but the temperature anomaly has a better correlation with surface pressure anomalies, as determined from reconnaissance observations. Velden *et al*. (1991) developed regression equations between the 250 hPa temperature anomaly, pressure anomaly and maximum wind speed. The equations are, however, different for the Atlantic and North Pacific and may not hold good in other tropical cyclone basins. The standard errors in pacific basins are also higher than the Atlantic perhaps due to a larger proportion of higher intensity cases.

3. Track prediction

Velden *et al*. (1984) attempted to use VAS (VISSR Atmospheric Sounder) data from GOES satellites and TOVS (TIROS Operational Vertical Sounder) data from NOAA orbiting satellites in tropical cyclone applications. One of the aims was to use the satellite-derived mean layer wind as the steering current for forecasting hurricane movement. For this purpose microwave soundings from the NOAA satellites were combined with VAS soundings, low and high level cloud drift winds and middle level water vapour motion winds, to produce a deep layer (850 to 200 hPa) mean wind analysis. The various components of the data set complement each other, as the derivation of cloud motion is difficult in heavily clouded areas, while microwave radiances can penetrate the clouding. Velden *et al*. (1992) found that in the case of Hurricane Debby of September 1982 the satellite-derived mean wind flow was a fair approximation of the steering current for 72 hours.

In early years of satellite-based cyclone tracking, the commonly used track prediction method was to generate an animation sequence of satellite images and to extrapolate the apparent motion of the cloud system over the next 12 or 24 hours. This simplistic approach often failed as it could not envisage the possible recurvature of the storm. Considerations, such as, the angle and width of the cloud band affecting the cloud system and the size of the cyclone's canopy, were later introduced as factors related to storm recurvature.

After the water vapour absorption channel (6.7 μ band) imagery became available from operational meteorological satellites, changes in the upper level moisture patterns began to be used to forecast tropical cyclone motion (Dvorak 1984). In water vapour imagery, dark areas represent absence of moisture. Lighter gray shades indicate increased water vapour content in the upper troposphere. High (cold) clouds appear similar to those seen in thermal infrared images, while low (warm) clouds are not seen. The presence of a trough is usually noticeable in water vapour imagery as a curved moisture boundary on the eastern or forward side of the trough. It has darker shades behind and higher shades ahead of it. Two features of water vapour imagery were identified as indicators of recurvature for northeast Pacific hurricanes, *viz*., (*i*) a curved moisture band (CMB) observed about 10° latitude northeast of the cyclone and bowed cyclonically towards the cyclone and (*ii*) an increasingly northsouth orientation of the moisture cloud pattern of the cyclone. On the basis of these two developments, it became feasible to give a 24-hour forecast of recurvature.

Dvorak's (1984) study indicated that the water vapour imagery could be also used to forecast a westward turn in the track of the cyclone. Such storms were characterised by a drying (darkening) of the moisture pattern or cloud dissipation to the north prior to the westward turn. Subsequent work of Dvorak and Mogil (1994), with water vapour imagery of the Atlantic region, led to similar findings qualitatively. However, it became apparent that the CMB's approached cyclones at different speeds which could have a bearing on the forecast time of recurvature. Dvorak, therefore, prepared a monogram for this purpose based upon the distance between the CMB and the cyclone and the speed of approach of the CMB.

4. Wind fields associated with cyclones

Hurricane Rosa was the first hurricane to be observed at one-minute interval with rapid scan imagery provided by GOES-8 satellite of the U.S. on October 13, 1994. In the tropical storm season of 1995, more hurricanes have been observed in this manner by GOES-8 and GOES-9 satellites (Purdom 1996). With the help of such rapid scan observations, cloud drift winds can be derived from both cumulus and cirrus cloud motions. Detailed knowledge of the cyclone wind field is of great help in determining the storm intensity and distribution of gale force and higher winds. Conventional cloud motion wind derivations from half hourly image displacements are not capable of providing this information which is also important for creating tropical cyclone bogus data sets in numerical weather prediction (Onogi 1993).

While image animation techniques can give an idea of the synoptic wind field associated with a cyclone, a precise knowledge of the ocean surface winds is necessary for accurate prediction of storm surges. Many satellites now carry microwave payloads like scatterometers, synthetic aperture radars on altimeters. While the revisit frequency of these satellites is much lower than those of the operational meteorological satellites, it is possible to exploit the capability of the microwave sensors for deriving the wind parameters associated with a cyclone, in case the satellite track is close to it.

By means of a scatterometer, the ocean surface wind fields can be measured at finer resolutions over a limited area. Gohil and Gautam (1993) have suggested a method for deriving cyclone parameters from scatterometer-derived winds assuming a symmetric system. The methodology consists of identification of cyclone centre location and establishment of relationship between the radius and the intensity of the maximum winds from the observed wind field of the cyclone. The errors in the maximum winds are strongly dependent on the precise location of the centre which needs to be accurately monitored.

Spaceborne radar altimeters operate in the microwave frequency band and can see the ocean surface through the clouds. They provide specular values of back scattering coefficient of the ocean surface, from which wind speeds can be derived. In the case of a cyclone, the altimeter will show one or two peaks corresponding to the maximum surface winds. Raj Kumar *et al*. (1993) analysed Geosat altimeter data for 3 February 1987 over the Bay of Bengal, when the remnant of a tropical cyclone was existing as a deep depression. The estimated peak wind of 18 m/sec agreed well with INSAT estimates available for comparison. The distribution along the satellite track of wave height and wind speed could also be derived.

5. Concluding Remarks

The paper has described the impact of satellite-based techniques on tropical cyclone intensity estimation and track prediction. They have led to very significant improvement in disaster warning and consequent saving of lives and property. New developments in satellite technology would surely make it possible to further refine these techniques and to enable us to make more precise warnings in terms of landfall and cyclone damage potential.

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