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ADVANCES OF SPACE TECHNOLOGY IN TROPICAL CYCLONE RESEARCH

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ABSTRACT

Tropical Cyclone is the most devastating atmospheric phenomenon which forms over the warm tropical oceans. The observational network is scanty over these oceanic regions. As a result, it is not possible to monitor and analyze the dynamics and structure with the conventional observations. The satellite observations have filled up this gap and made it possible to track this devastating atmospheric phenomenon. The satellite observations are used for assessing useful physical parameters of tropical cyclones, which help prediction of their path and intensity. The tropical cyclone monitoring techniques using satellite observations made gradual advances with the improvement of the satellite technology and sensor systems with visible, near-infrared, infrared and passive and active microwave imaging sensors and vertical sounding instruments. Further, measurements of ocean and atmospheric parameters using the floating buoy in the oceanic areas and collection of the data through Data Collection System (DCS) onboard NOAA series of satellites enabled the scientists to make sea surface observations for studying tropical weather including the tropical cyclones. The radar scatterometers have been developed to estimate the surface wind and are in the process of improvement. Dvorak techniques made tremendous development since the early 1970s and is being improved with time. The Dvorak technique is used for computing the cyclone centre, assessment of pressure drop and maximum sustainable winds. This technique is fully automatic and provides T-number which is related to cyclone intensity. Further development of cyclone monitoring has been possible using Advance Microwave Sounding Unit (AMSU). Further advances of the tropical meteorological observations have been achieved through estimation of the cloud vector wind fields, wind field generation using active microwave scatterometers and rainfall measurements using infrared, microwave and radar observations. The measurement accuracy, spatial and spectral resolutions, sensor efficiency and analysis techniques are continuously being improved, which enables the weather scientists to assimilate the meteorological fields for initialization of numerical models for tropical cyclone observation and prediction. The ADT analysis for Bay of Bengal has been demonstrated for the tropical cyclone Sidr of 15 November, 2007.

Keywords: *Satellites, Visible and Infrared Imagery, Microwave Sensors, Tropical Cyclone, Dvorak Technique, T-number*

1. INTRODUCTION

The tropical cyclone is an atmospheric phenomenon with strong low pressure areas of horizontal dimension of around 500-1000 km and with central pressure drop ranging from 6-64 hPa and wind speed ranges from 62 km/hour to around 250 km/hour or more, where winds move anti-clockwise in the northern hemisphere and clockwise in the southern hemisphere. In the isobaric representation it looks like as shown in figure-1. From the figure it reveals that the tropical cyclones have closed and dense circular isobars. The tropical cyclone is one of the strongest and most disastrous meteorological phenomena of the tropics that form over the tropical warm tropical oceans with temperature above 26.5^{o} C within the 50 meter depth of the thermocline.

The meteorological networks are largely distributed over the land areas of the earth and to a lesser extent over the islands. The observations over the oceanic observations using conventional means are quite absent except those obtained from the commercial ships which are insufficient for mapping of the weather over the tropical oceans, not to speak of the monitoring of tropical cyclones which has the size of 500-1000 km. Besides, the well developed tropical cyclones have well defined core structure of radius 100-200 km radius. Thus, very dense observational networks are necessary to analyze the tropical cyclone structure and initialize the NWP models for better predictions. Only the observations from space (Air craft, Artificial Satellites and Shuttles) can provide measurements of the tropical weather as well as Sea Surface Temperature (SST) over the oceans. Thus the monitoring of the tropical cyclones which form over the warm tropical oceans are possible using the satellite observations using the polar orbiting and geostationary satellites with appropriate sensors.

It was completely out of our perception before the advent of the space technology that earth and atmosphere can be better viewed and analyzed from space observations. The first artificial satellite of the earth Sputnik demonstrated how beautifully the earth and the atmosphere could be observed from the space. Later-on the US Satellites TIROS (Television Infrared Observation Satellite) series started operation launched in 1960.TIROS was the first satellite that was capable of remote sensing of the Earth, enabling scientists to view the Earth from

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a new perspective. Thereafter, ESSA (Environmental Science Services Administration)satellites and the research satellites NIMBUS were launched, which began to operate in the polar orbits providing the Television pictures both in the visible and infrared channels in the form of hard copy images. In the 1970s the multispectral digital scanners / sensors were discovered. A good number of geostationary satellites such as GMS, GOES and METEOSATs were placed in the stationary orbit at an altitude of 38000 km from the surface to observe and monitor the weather systems of the globe. The sensors on board the satellites use the reflected solar radiation and outgoing long wave radiation (including microwave radiation) of the earth surface and atmosphere, especially the clouds in the bands situated within the atmospheric windows. For the visible and near-infrared radiations between 0.5-1.5 μm bands the atmosphere behaves as window allowing those radiations to pass freely through the atmosphere with very little absorption and scattering. Besides, the atmosphere behaves as window for the long wave radiations in range from 8.5-12.0μm. The GMS / MTSAT, METEOSAT-5 and GOES-1 are placed over in the western Pacific, Indian Ocean and Atlantic Ocean respectively, while the GOES-2 is placed over the eastern pacific. The TIRON-N series of satellites which have later been named as NOAA series started operation in 1978. The two orbital satellites would have covered an area twice, one in the noon and the other in the mid-night for a even numbered satellites and one in the morning and another in the evening for the odd numbered satellites. Thus two satellites, one even number and another odd number would cover an area 4 times daily at about 6 hours interval. Again a minimum 3 geostationary satellites can view the whole earth at one time and continuously monitor its environment. Table1 shows the list of some of the early satellites used for environmental monitoring especially for weather investigation (JPL, 2015).

Table1: Chronology of early satellite milestones and TC intensity papers (1957–84)

Year	Satellite	Comments
1957	Sputnik(USSR)	1st man-made Earth satellite
1958	Vanguard II	1st U.S. satellite
1959	Explorer	1st used for weather observation
1960	TIROS I	1st successful metsat (b)
1964	NIMBUS I	Daily day/night imagery
1965	TIROS IX	1st global view of clouds
1966	ESSA-1	Last use of TV (APT) (c)
1966	ATS-1	1st use of WEFAX (d)
1970	DAPP	Use of nighttime visible (e)
1970	ITOS-1	Use of scanning radiometers
1971	DMSP	High-resolution IS / IR (f)
1974	SMS-1	1st NOAA geostationary
1977	METEOSAT + GMS	Geostationary satellites (g)
1978	TIROS-N	1st polar orbiter with AVHRR

Note: The satellites are more acquainted with their abbreviated nomenclatures and details are not provided

2. SATELLITES AND SENSOR SYSTEMS FOR ENVIRONMENT MONITORING

Here we discuss the satellites and their sensor systems used for the weather monitoring and tropical cyclone tracking. Both polar orbiting and geostationary satellites are used for this purpose. The tropical cyclones are tracked right from their formation as tropical low pressure system, which gradually intensify due to large scale convergence of moisture which carries energy in the form of latent heat through the planetary boundary layer with the depth 1 km from the sea surface. Energy is also transported along the lower troposphere.

2.1 Basic principles of weather monitoring using various observing sensors

The earth, atmosphere and ocean parameters are measured by sensing the reflected solar radiation in the visible and near infrared solar radiations during the day and emitted long wave electromagnetic radiation from the target which travel thorough the atmosphere to the satellite sensors. Sometimes, the active microwave / RADAR signal which is transparent to the cloud cover are also used. The satellite sensors effectively map the cloud covers and rain bands associated with the tropical cyclones using the visible bands (0.4-0.7 μm (micro meter) and near-infrared (0.7-1.1 μm) bands of the electromagnetic spectrum. It uses the reflected solar radiation from the cloud tops to image the tropical cyclones. It also uses the far infrared radiation outgoing from the earth-atmosphere system.

The satellite imagery are interpreted based on the optical properties of the material body i.e., its reflectivity or albedo in the solar reflective bands and for far infrared (thermal) bands, the temperature obtained through inversion of the irradiated Blackbody temperature. Generally the thermal infrared sensors are selected within the range of λ from 8-15 μm because the atmosphere is a better window for the earth's thermal radiations in these wavelengths. The infrared channels are also useful to monitor the atmospheric water vapour, which is an important parameter of weather. Similarly, the microwave radiations emitted from the earth, ocean and atmosphere also work as the means of monitoring of the atmospheric features. In addition there are instruments on board the satellites which are capable for making the vertical sounding of the atmospheric temperature, moisture and ozone.

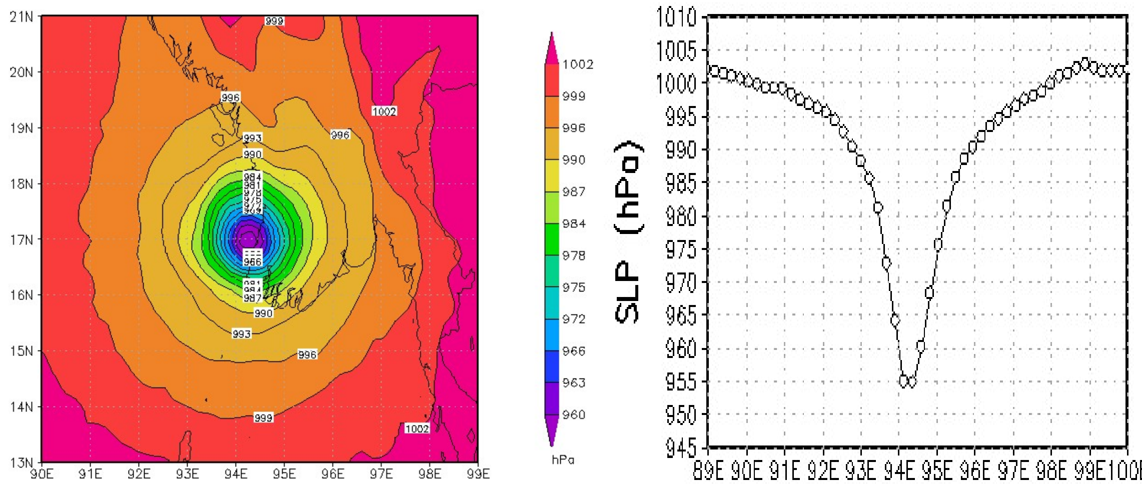

Figure 1: Distribution of SLP (hPa) at highest mature stage of cyclone Nargis at 0600 UTC of 2 May 2008 (left panel) and the horizontal east-west section of the pressure field (right panel)

2.2 The currently available environmental satellites

There are two types of environmental satellites based on the orbit:

1) Polar orbiting satellites, examples: NOAA series of satellites and Aqua/Terra Modis satellites.

2) Geostationary satellites placed on the equator at a height of around 35000km which has the orbital speed as that of the Earth, example: MTSAT, METEOSAT, GOES-, Kalpana Satellite, FY-series of Satellites.

The present NOAA series of satellites has an imaging sensor, namely Advanced Very High Resolution Radiometer (AVHRR), Advanced TIROS Operational Vertical Sounding (ATOVS) which has an infrared sensor and an advance microwave sounding unit (AMSU). The NOAA satellite has another instrument called Data Collection System (DCS) which is linked with the Data Collection Platforms placed over lands and Data Collection Floating Buoys placed over ocean surface. The DCP/Floating Buoys upload the environmental data to the polar orbiting satellites and the satellites transmit the data to the ground stations. The collected data are on atmospheric pressure, wind, humidity, SST, sea waves and salinity.

NOAA series of satellites have ended the missions and the last satellite of the series has already been put in the orbit in 2010. The next series of satellites NPOES has taken over the NOAA series soon.

Other satellites collecting the environmental data are: TRMM (Tropical Rainfall Monitoring Missions) using the rainfall radars on board the satellites.

Defense Meteorological Satellite Program (DMSP) polar orbiting satellites

Terra and Aqua Modis satellites: The satellites have 36 channel instruments providing land, ocean and atmospheric measurements. It also provides vertical profiles of temperature, water vapour mixing ratio and atmospheric ozone concentration.

Active Microwave / RADAR Satellites: Microwave scatterometer data providing the surface wind assessment of the tropical cyclones. The details of the currently operating environmental satellites are provided in Table2.

Table2: List of currently available satellites for environment monitoring

Satellite Orbit	Satellites	Type of data	Local Coverage	Products
Polar orbiting	DMSP F12-16 (Polar Orbiting)	SSM/I (non-functional), SSM/T-1 (non-functional), SSM/T-2	Twice a day for each satellite	Visual and infrared imagery available via stored data recovery through AFWA.
	TRMM (NASA Tropical Rainfall Measuring Mission)	85 and 37 GHz Microwave	Fluctuates from 30°N to 30°S Twice a day for each satellite	15 km resolution microwave coverage of the tropics from 30°S to 30°N. Microwave analysis of 85 and 37 GHz radiance composite passes. Brightness temperature products of the 85 and 37 GHz horizontal and vertical polarization.
	NOAA-17	HRPT (direct); AMSU-A; *AMSU-B (N-17); MHS (N-18);* HIRS	Twice a day	Cloud monitoring using visible, NIR and IR channels Vertical sounding of atmospheric temperature and mixing ratio of moisture.
	NOAA-18	AVHRR; GAC and LAC (recorded);	Twice a day for each satellite	1. 1 km resolution HRPT and Local Area Coverage (LAC) data. 4 km resolution APT; Vertical Soundings, etc.
	Terra/Aqua Modis	36 channel instruments	Twice a day for each satellite	Cloud monitoring, vertical sounding along with many other environmental and oceanic applications.
Geostationary Orbit	GOES-10 at 135°W GOES-11 *(on-orbit storage at 105°W)* GOES-12 at 75°W	Multispectral Imager 19 Channel Vertical Sounder 5 Channels for Imager 19 Channels for Vertical Sounder	Every 30 minutes Routine Scan Mode, Provides 3 sectors with prescribed coverage: Northern Hemisphere (NH) or Extended NH;	1, 2, 4, and 8 km resolution 2.4 km equivalent resolution IR 5.8 km water vapor sectors (4 km on GOES-12)
	METEOSAT-5, 6, 7 (Geostationary)	Multi-spectral Spin-Scan Radiometer	Full disk image every half hour	2.5 km resolution digital VIS imagery; 5 km resolution digital IR imagery. 3. 5 km water vapor imagery. Tropical storm monitoring and derivation of intensity.
	METEOSAT-8	Multi-spectral Spin-Scan Radiometer (SEVIRI) and High Resolution Visible (HRV)	Full disk image every 15 minutes. HRV: Sector scan to move with local noon.	1. 1 km resolution digital VIS imagery (HRV); 3 km resolution digital IR imagery, 3 km water vapor imagery. Tropical storm monitoring and derivation of intensity.

Note: The satellites are more acquainted with their abbreviated nomenclatures and details are not provided

3. TROPICAL CYCLONE STRUCTURE FROM SATELLITE

The tropical cyclones are observed by the satellite imaging sensors based on the characteristics of the distribution patterns, size and organization of cloud system in the visible and infrared channels. The visible images also show the textures of the clouds and the infrared channels show the cloud top temperature and altitudes of the clouds indicating the vertical development of the tropical cyclones. The cloud imagery shows the eye of the tropical cyclone for a well-developed system. The eye of the tropical cyclone is the clear near circular area of diameter of 20-80 km situated around its centre. The strongest wind is observed at the eye wall. The tropical cyclone has Central Dense Overcast (CDO) pattern around its eye with spiral cloud bands arranged around CDO. Figure 2 shows the structure of a tropical cyclone using visible and infrared imagery. The assessment of the centre of the cyclones is an important task. It is done quite accurately using the enhanced visible and infrared imagery. The imagery from all environmental satellites may be used; however, the half hourly or hourly images obtained from the geostationary satellites are used for monitoring of the system evolution and tracking of the path of its movement.

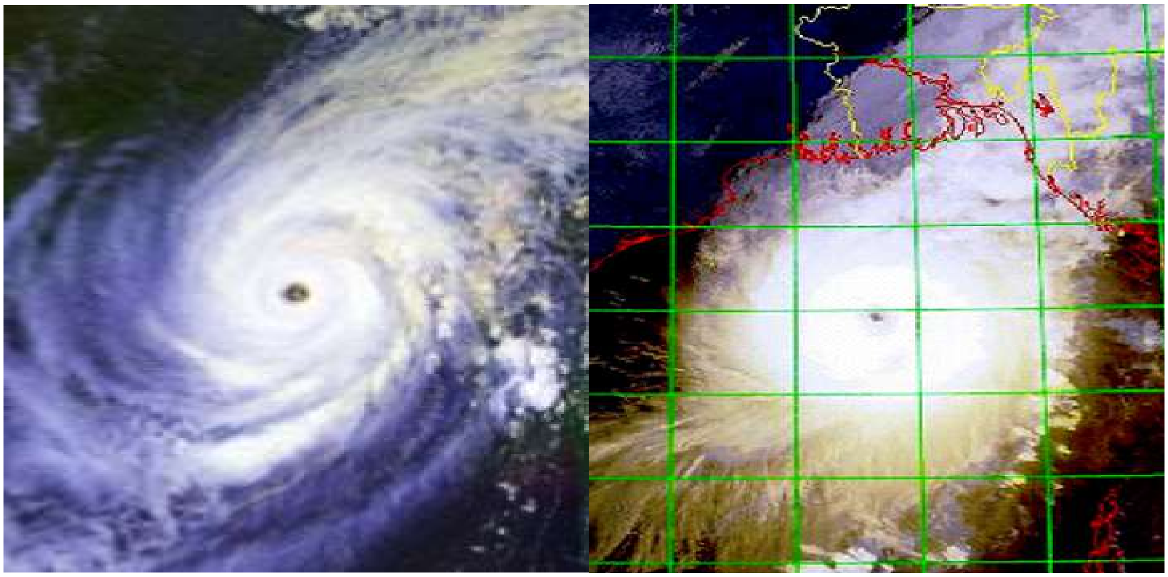

Figure 2: The Visible Image of Tropical Cyclone of 29 April, 1991(left panel) and Multi-spectral (visible andIR composite) Image of tropical cyclone CIDR, 15 November 2007 (right panel) of the Bay of Bengal

4. METHODS OF TROPICAL CYCLONE MONITORING

4.1 Dvorak Techniques

There are several techniques which are used for locating the centre and estimating the pressure drop and maximum sustainable wind speed of the tropical cyclones. The techniques of satellite applications for tropical cyclone monitoring were first developed by Dvorak about 35 years ago (Dvorak, 1975 and 1985), which has been successfully used for the past decades with time to time modifications. This technique is known as Dvorak Technique (DT) (Dvorak, 1973, 1975 and 1985). The Dvorak technique was initially based on fully manual interpretation of imagery (solar reflective and IR) based on the visual structure of different cloud patterns which are as follows:

- Identification of the system at the stage of genesis and locate the centre and to monitor if the system has intensified in the past 24 hours.
- Locating the centre of the system in the early stage of development becomes a challenging task as the system is not much organized; in such a case the geometric centre of all the cloud mass of the centre is taken as the centre.
- A shear pattern near the centre of the cloud appears in the formative stage.
- The clouds gradually organize in circular bands. The centre of curvature of the bands is taken as the centre of the system.
- As the system intensifies the CDO, eye and the banding patterns become more clearly visible. The eye centre is the centre of the cyclone at this stage.
- Study the eye pattern, the CDO pattern encircling the eye and banding features around CDO. These characteristics provide
- Sometimes the special enhancement of the IR image helps identify the eye, hence the centre which is warmer compared to its surroundings.
- The assessment of centre position and intensity are performed from time to tome to track the path of the cyclone and monitor the intensification process.

  Dvorak identified some numbers with the particular shape of the features and derived the so called T-number which is related with central pressure of the tropical cyclones and maximum sustainable wind (MSW) (Table-3). The details may be seen in the original works of Dvorak (1975,1984). Figure-3 shows the relation of T-numbers with the shape, size and eye pattern of the tropical cyclone. It is clearly seen from the figure that the more organized cloud system has higher T-number. The cyclones with broken eye pattern with well-defined circular banding features has T-number of around 4.5, while those with well-organized circular eye pattern has T-number higher than 4.5 (see the middle column). The rightmost column shows the tropical cyclones of equal strengths for the Bay of Bengal corresponding to those in the central column. Figure-3(b) shows the gradual development of tropical cyclones from development stage to mature stage.

Table 3: The wind–pressure and T-number relationship for the tropical cyclones of Atlantic and West Pacific Oceans

TI/CI number	MSW (Knots) 1 knots=1.82 km/hour	Atlantic MSLP (hPa) at the centre of the tropical cyclone	West Pacific MSLP (hPa) at the centre of the tropical cyclone
1.5 -2.0	25- 30	1009	1006
2.5	35	1005	1000
3.0	45	1000	991
3.5	55	994	984
4.0	65	987	976
4.5	77	979	966
5.0	90	970	954
5.5	102	960	941
6.0	115	948	927
6.5	127	935	914
7.0	140	921	898
7.5	155	906	879
8.0	170	890	858

Note: *MSW- Maximum Sustainable Wind; MSLP: Minimum Sea Level Pressure*

From the above discussions it comes out that the Dvorak technique was completely of subjective in nature; however the man machine interactive processing such as enhancing the image and fitting $\log_{10}$ spiral curve over the banding feature to identify the curvature and locating the centre of the system until the eye feature is detected. As observed by Dvorak the typical development rate is 1.0-1.5 T-number per day. Following continuous development the subjective technique gradually moved towards semi-objective and objective techniques.

4.2 T-number assessment from enhanced thermal imagery

In this semi-objective technique the warm eye temperature is determined and the coldest temperature surrounding in the central dense overcast at a radius of 55 km from the centre. In the nomogram as shown in Figure-4, two sets of values are obtained: one is for the warmest temperature of the eye and the other for the coldest temperature surrounding the center. The figure shows that the warm eye temperature is -10^{0}C. Then take the column with closest warmest temperature. The surrounding coldest temperature is found to be -72^{0}C and the row with coldest temperature is identified. The number next to it is 5.9. This row is intersects with the coldest column at the point, where the number is found to be 1.1; these two numbers are added to estimate T-number, which is 7.0. The nomogram is computerized as lookup tables for digital assessment of T-number. From Table-3 it can be seen that for the T-number of 7.0 the central pressure is around 900 hPa in the Pacific and the corresponding maximum sustainable wind is 140 knots (255 km/hour). Several modifications to this method have improved the intensity estimation results (Velden, 1989; Dvorak 1984):

1) The 55-km-radius ring can be well inside the coldest IR ring (eye wall convection) of Tropical Cyclones (TCs) with large eyes. The method was modified to compute an average IR temperature for a range of ring sizes (R = 25–125 km), which is used as the coldest.

2) In many situations, estimates fluctuate widely over a relatively short time, primarily due to localized or semidiurnal convective flare-ups. Averaging the computations (over 3–12 h) can produce more realistic intensity trends.

3) The original Dvorak (1984) digital IR table was amended to cover anomalous "cold" eyes or cases with no warmer "eye" pixels in the TC central overcast. In these events, the eye temperature is set equal to, or can even be colder than, the surrounding central overcast ring temperature.

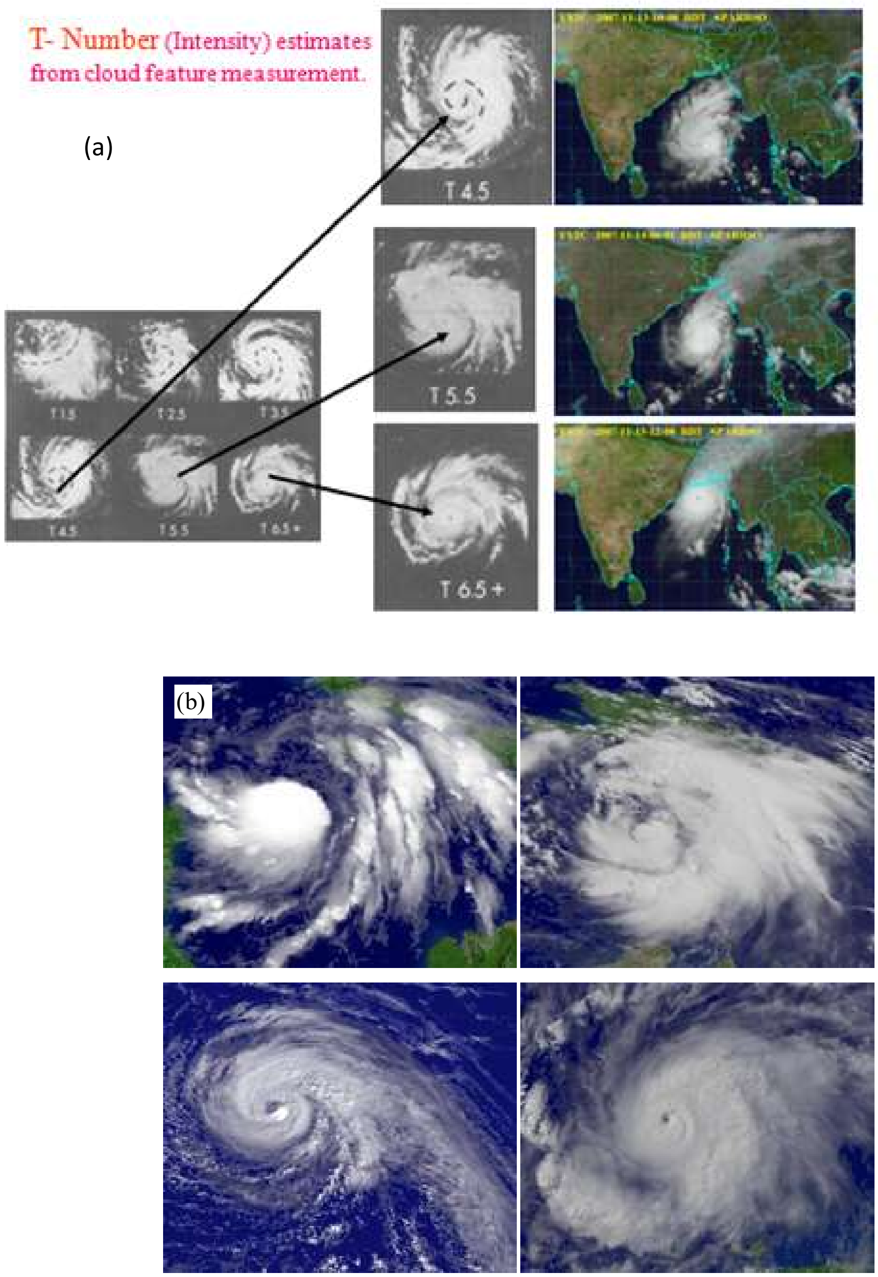

Figure3: The interpretation of the TCs for feature identification andassessment of T-number (a);Tropical Storm Wilma at T3.0 Tropical Storm Dennis at T4.0 Hurricane Jeanne at T5.0 Hurricane Emily at T6.0

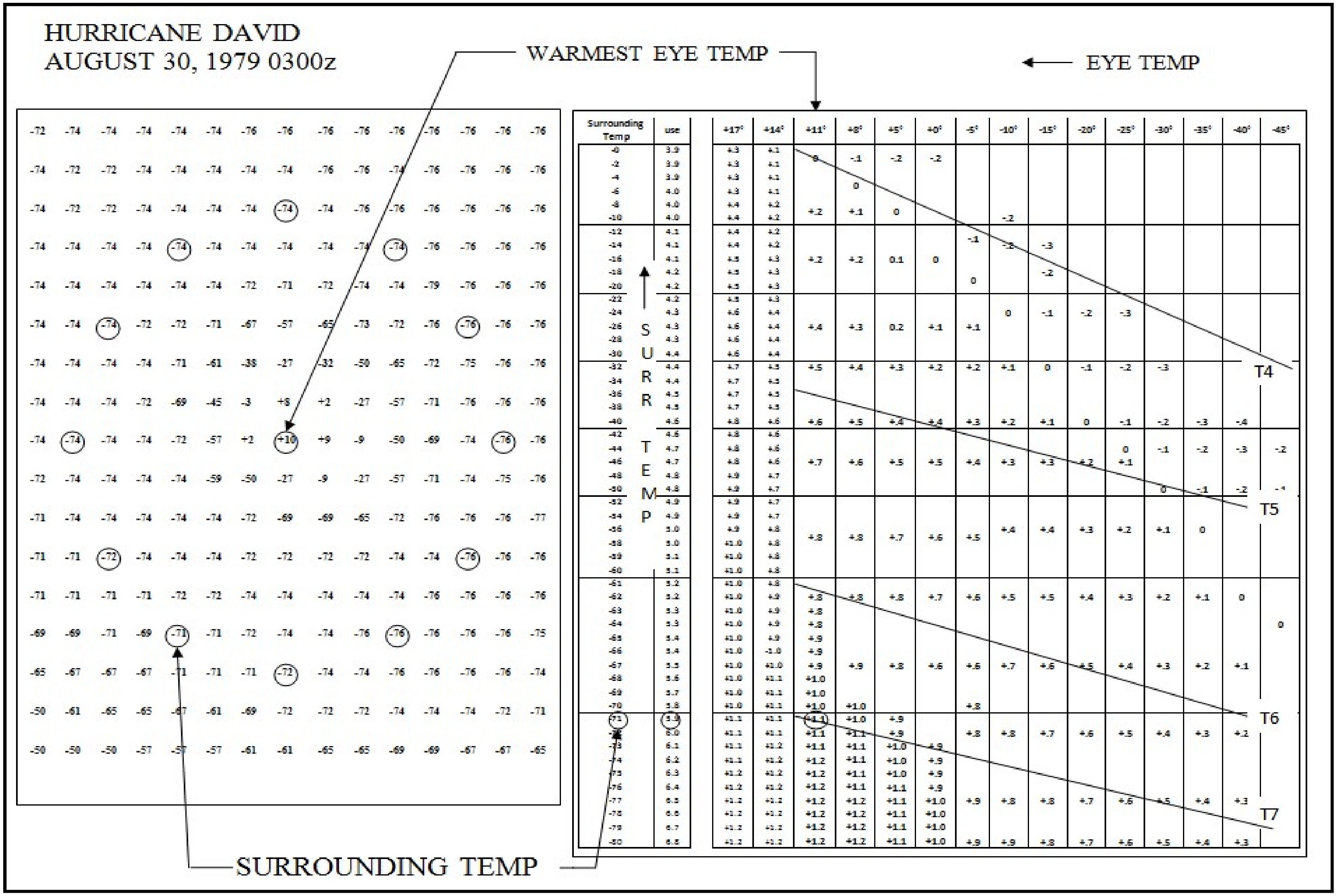

Figure 4: Methods of determining hurricane intensity from digital IR data. The coldest cloud temperature -71^{0}C contribute an intensity estimate of 5.9 to T value while warm eye adds 1.1 to the T-number totaling 7.

4.3 Advanced Dvorak Analysis

The Dvorak techniques are on continuous improvement where the data from many different satellites are used. The former Digital Dvorak method was not able to work in the situation where the eye was not there, but in this technique the T-number may be calculated even if the eye temperature is too low or lower than the surrounding temperature. In the 1990s the development of higher resolution data and increasing of the processing power the subjectivity were further reduced and the Objective Dvorak techniques (ODT) were evolved (Velden *et al.,* 1998), which began with a careful assessment of the Dvorak Digital (DD) algorithm. It was found that the DD performance was satisfactory only for well-organized TCs. Reasonably accurate intensity estimates were possible when the storm possessed an eye structure.

Thus, development continued and an advanced objective Dvorak Technique (AODT; Olander *et al.,* 2007) emerged. In the AODT, the manual determination of the centre and the banding feature are performed subjectively using the log 10 spiral and as soon as the eye is located the objective analysis takes over. Later-on an objective method was developed based on the estimation of the deepest temperature gradient within the lowest brightness circle. The most recent version of the objective algorithm progression is the advanced Dvorak technique (ADT). Unlike ODT and AODT, which attempt to mimic the subjective technique, the ADT research has focused on revising, digital IR thresholds and rules, and extending the method beyond the original application and constraints (Olander and Velden, 2007). The ADT, which has its heritage in Dvorak (1984, 1995), Velden *et al.* (1998), and Olander *et al.* (2004, 2013), is fully automated for real-time analysis. The historical evolution of the technique has been shown in figure-5.

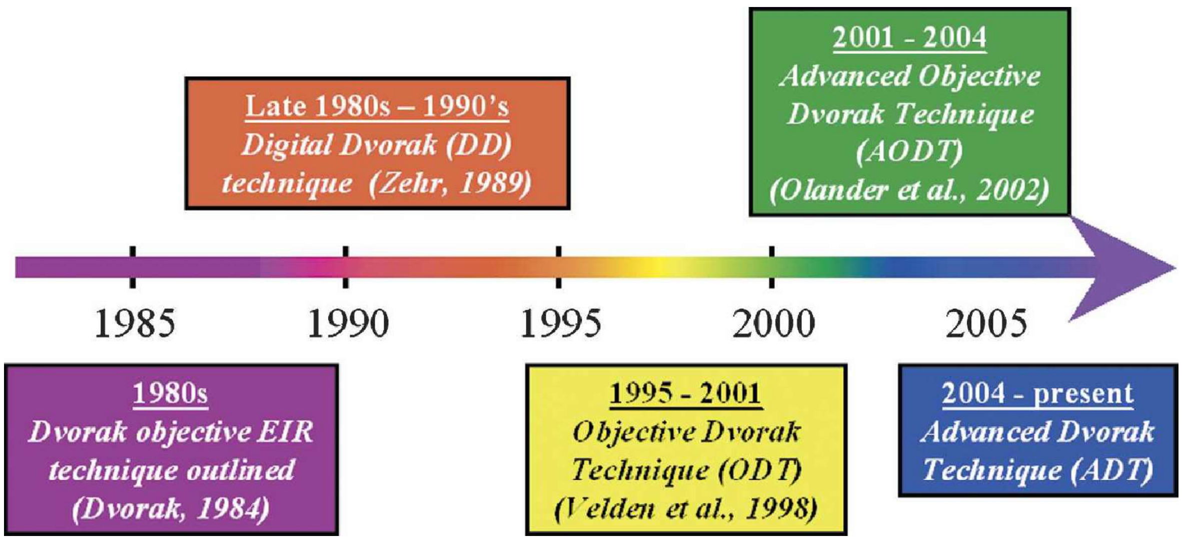

Figure 5: Progression of objective of Algorithms of Dvorak technique.

The ADT research efforts have focused on revising some of the digital IR thresholds and rules, and extending the method beyond the original application and constraints. The ADT is fully automated and provides forecasters with an objective tool as guidance in their real time TC analysis, and as a comparison to their subjective Dvorak estimates.

The high resolution (1 km) IR images from the AVHRR on NOAA satellites and the MODIS on NASA Terra and Aqua reveal features such as cyclonically curved thin cold cloud lines and transverse bands at hurricane cloud top as shown in Figure-6 are effectively used for analysis of tropical cyclone intensity and preparing future prediction using ADT (Hawkins *et al.,* 2006).
The ADT regression equations developed at CIMSS/University of Wisconsin—Madison, Madison, Wisconsin are shown as follows.

- Two separate regression equations are used in the ADT; one equation for the eye scene types and one equation for the cloud scene types. The equations yield intensity estimates in terms of T# values which can be converted to MSLP or Maximum Wind
- Eye scene T = 1.10 – 0.070*Tcloud + 0.011*ΔT – 0.015*Symcloud
- Cloud Scenes T = 2.60 – 0.020*Tcloud + 0.002*Dcdo – 0.030*Symcloud
- Tcloud : Cloud region average temperature (deg C)
- ΔT : Eye (max) – cloud (ave) region temperatures (deg C)

- Symcloud : Cloud region temperature symmetry (deg C)
- Dcdo : Cloud region CDO size (km)

The schematic description of the 4 variables of 2 regression equations has been shown in figure7.

The passive microwave imagery from satellites is found useful to investigate detail structure of tropical cyclone. Figure8 shows the tropical cyclone Diana by the microwave image which clearly shows the eye has inner eye wall and concentric bands of cloud showing outer eye wall. The image provides new knowledge about the eye structure with accurate measurements of its size.

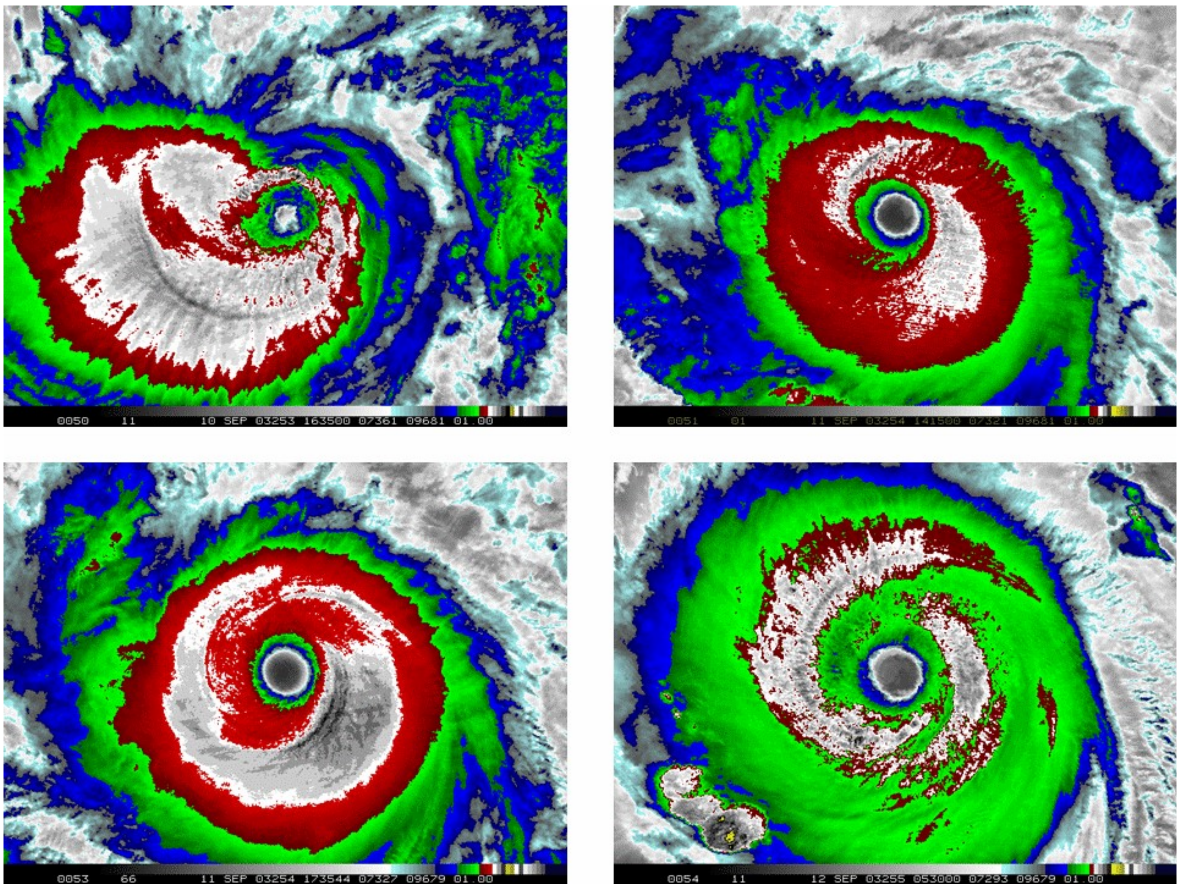

Figure 6: 1-km IR images of Hurricane Isabel, 10-12 September, 2003, from both MODIS andNOAA AVHRR showing various levels of enhancement

4.4 Application of satellite vertical sounding in tropical cyclone study

The vertical sounding data from TOVS, ATOVS and MSU and AMU sensors allows the retrieval of the vertical sounding of the atmospheric temperature. It is well known that the tropical cyclones are warm core systems with strong temperature anomaly in the upper troposphere. Le Marshal *et al.* (1996) showed that NOAA TOVS retrieved temperature anomaly (Tc-Tenv) of the upper troposphere (250 hPa) is correlated with Maximum Sustainable Wind (MSW) and central surface pressure anomaly. Besides, the geopotential height, temperature and humidity fields retrieved from the ATOVS plays important role in data assimilation for tropical cyclone prediction using NWP models. Goldberg (1999) studied the generation of retrieval products using AMSU-A sounding observations and validated with observations. The temperature field obtained through retrieval of temperature is also used to assess the thermal winds and pressure fields using the step by step integration of the hydrostatic equation considering the fact that the pressure at 50 hPa is constant.

The imagery from NOAA-14 MSU against NOAA-15 AMSU 55 GHz brightness temperature has been shown in Figure-9, which clearly depicts the advantage of the high resolution image in mapping of the warm core of the tropical cyclone with higher details (Kidder *et al.,* 2000). The red areas are the region of highest temperature and yellow indicate relatively cooler region of the surrounding the central warm core region. This observation clearly shows the warm core structure of the tropical cyclone. The vertical distribution of the temperature anomaly as derived from AMSU-A has been shown in Figure-10 (Stanely *et al*., 2000). The figure clearly demonstrates the cyclone's warm core with yellow to red tones, which is highly prominent between 200-300

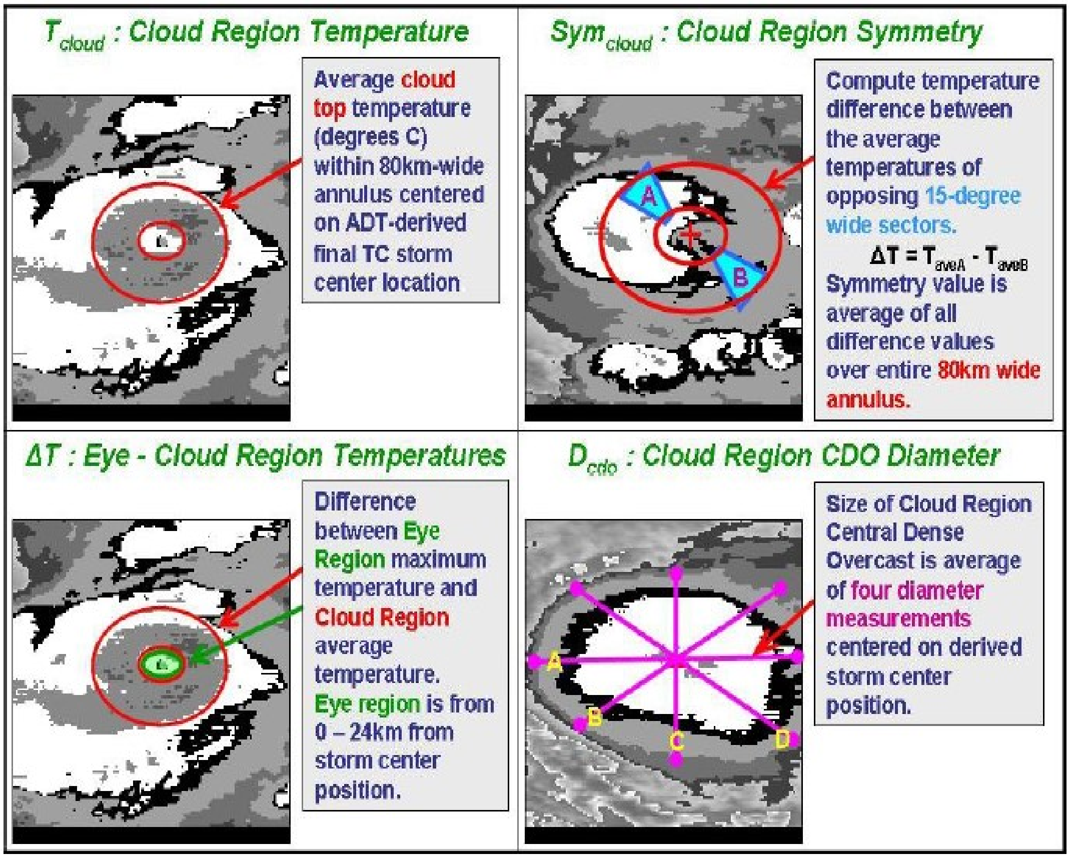

Figure 7: Schematic representation of 4 regression variables

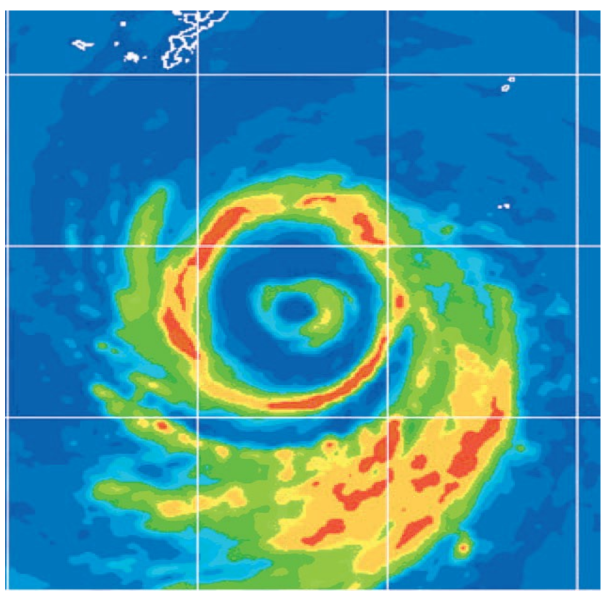

Figure 8: Example of concentric eye-walls in SSM/I (85 GH) imagery of Typhoon Diana (Source: Naval Research Laboratory TC Website) (Atlantic Hurricane of 16 September 1984)

hPa with maximum horizontal extent at 250 hPa. The warming of the core temperature is usually high for intense cyclone and low for weak cyclone. This property of tropical cyclone is useful in estimating the pressure drop and maximum sustainable wind. Several attempts have been made by a number of authors (for example, Kidder *et al.,* 1978 and 1980; Velden, 1989; Velden *et al.*, 1991) on this aspect using MSU data and the results were encouraging. AMSU-A, derived the central temperature anomalies for a number of tropical cyclones at different levels of intensities.

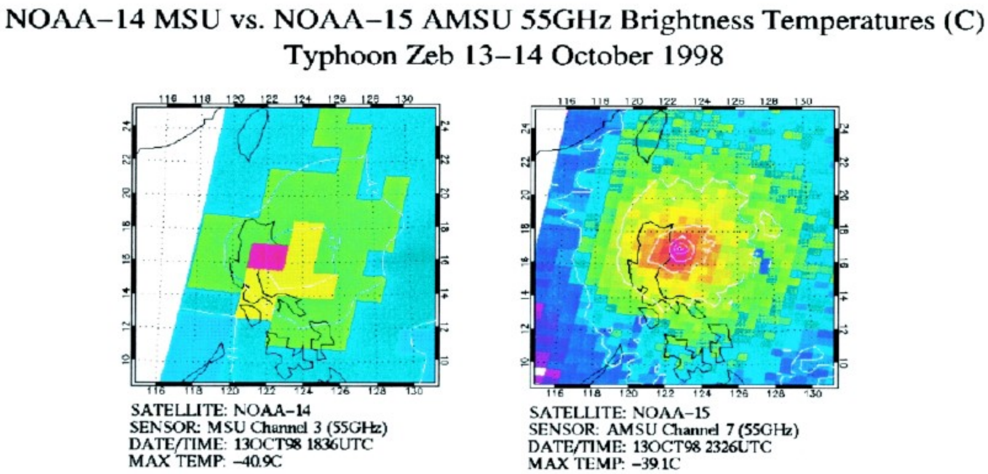

Figure 9: An illustration of the improvement in spatial resolution of the AMSU over the MSU for Typhoon Zeb (Kidder *et al.,* 2000).

The temperature anomalies have been plotted against the central pressure drop and maximum sustainable wind of the tropical cyclones in scatter-diagrams (Figure-11) which show good positive correlations of 0.86 and 0.84 respectively; this leads to the development of regression models relating the temperature anomalies with the strength of the tropical cyclones (maximum sustainable wind speed and central pressure drop) (Kidder *et al.,* 2000). These models indicate that wind speed of 19 kt and above and pressure drop of 13 hPa and higher are estimated using these empirical models.

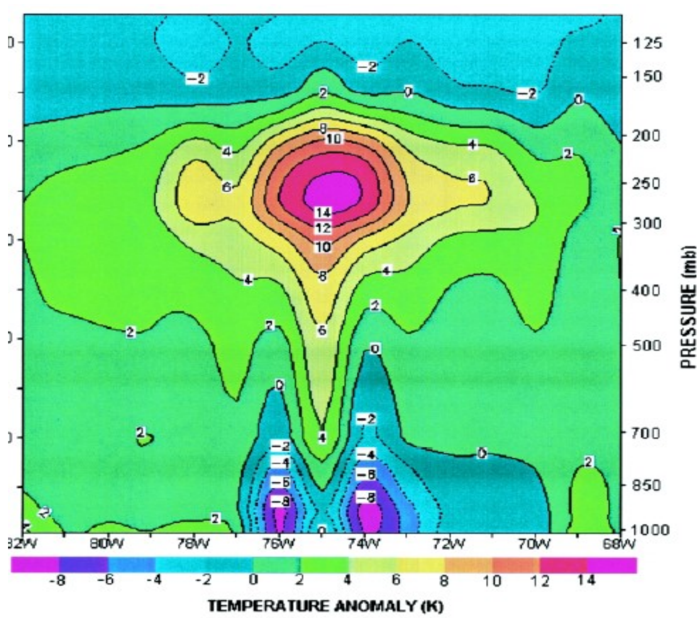

Figure 10: Vertical section of temperature anomaly retrieved from AMSU-A for Hurricane Floyed (14 September 1999, Kidder, 2000).

4.5 Assessment of cloud vector winds using geostationary satellites and scatterometer observation

The cloud vector winds are derived from the displacement of the individual clouds within 0.5 or 1.0 hour using the GMS observations. The vector winds are estimated all over the oceanic as well as land areas and are used in the data assimilation streams along with the satellite retrieved vertical sounding of temperature, moisture and derived parameters, DCS data collections and so on. Some examples of cloud vector winds are shown in Figure12.

The microwave scatterometer observations are also used to derive the surface winds. But this type of observation is not frequent. The microwave winds are compared with winds measured from oceanic Buoys and is shown in figure-13. The figure shows the scatter-plots of the winds from these two sources and it is found that the scatterometer data follow good relationship.

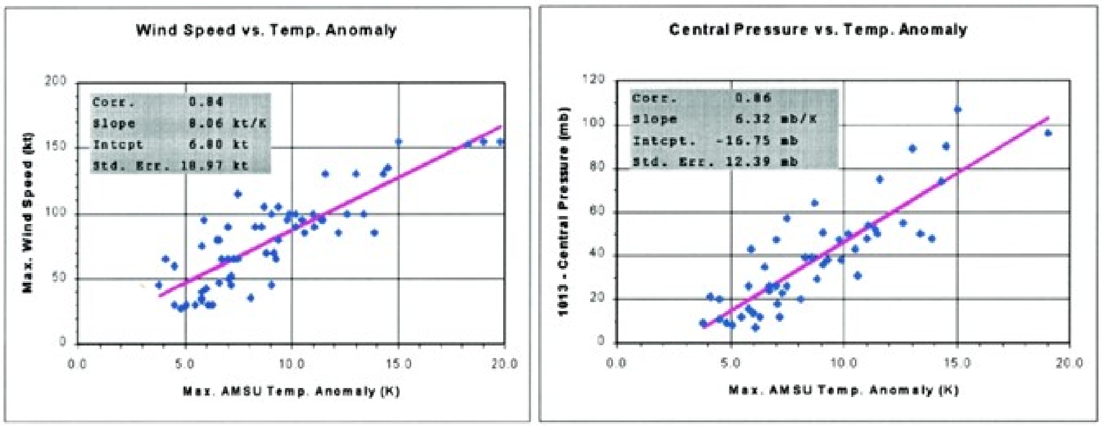

Figure 11: Scatter plots of maximum sustainable wind (MSW) and central pressure drop versus maximum retrieved AMSU temperature anomaly for Hurricanes Bonnie, Georges, and Mitch, and Typhoon Zeb [Kidder *et al.,* 2000).

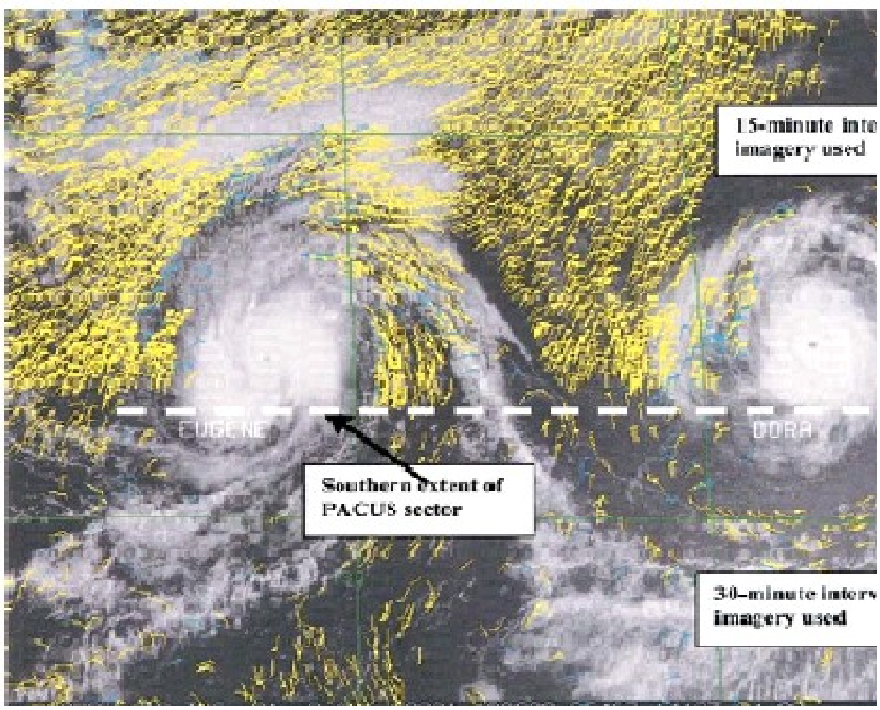

Figure 12: GOES-10 low-level cloud-drift winds (yellow: 800-950 hPa, cyan: 700 hPa around hurricane Dora and Eugine using 15 and 30 minutes interval visible imagery (Velden *et al.*, 2005).

5. DVORAK ANALYSIS OF TROPICAL CYCLONE OF BAY OF BENGAL

5.1 Study of Tropical Cyclone Sidr

The tropical cyclone Sidr formed in the south Bay as a weak low pressure system Depression on 9 November 2007 which intensified to cyclonic storm on 12 November 2007 in the Andaman Sea. The cyclone hit the coast of Bangladesh at eastern Sundarbans (Sharankhola of Bagerhat close to Patuakhali border). The track of the cyclone from 10-16 November 2007 is shown is Figure14.

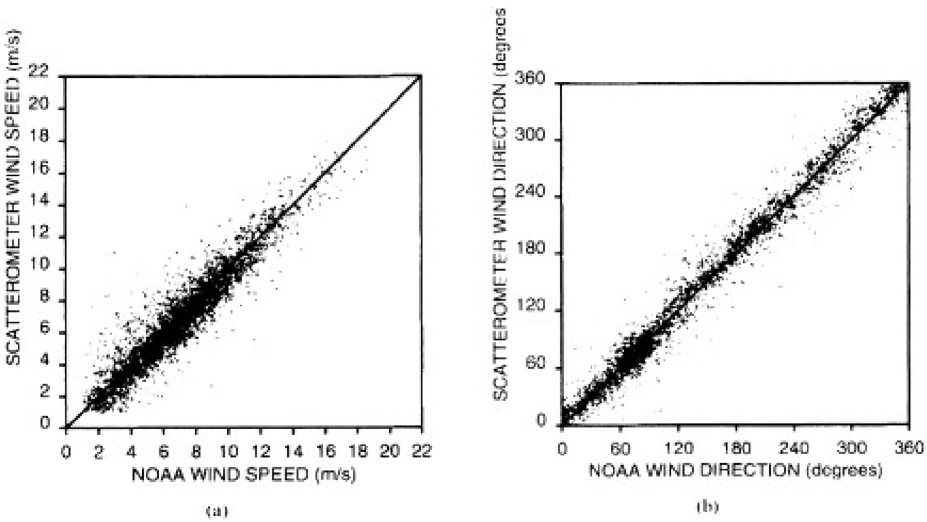

Figure 13: Comparison of the microwave scatterometer winds with that of floating buoy. (a) and the wind direction (b)

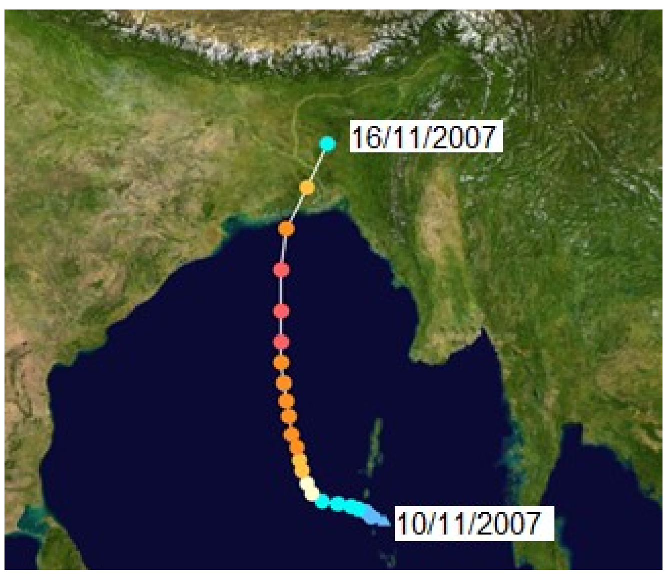

Figure 14: The track of the tropical cyclone Sidr from 10/11/2007 to 16/11/2007 derived using the NOAA and MTSAT imagery

Figure 15 shows the enhaned NOAA AVHRR IR (channel 4) image of 04:52 UTC of 15 November 2007. The image clearly shows the warm eye and cold overcast cloud around the eyewall. The horizontal color scalebar shows the temperature in ^{0} C. According to the figure, the pink areas within red shows that the dense overcast around the eye has the coldest temperature of -80 ^{0}C and the warm eye temperature is around -50 ^{0}C. Using the nomogram as presented in Figure-4, the T-number is estimated as 7.0 which indicates that the tropical cyclone Sidr has attained the speed of 255 km/hour and become a category-5 cyclone.

Meteosat7 IR images sourced from the CIMSS Tropical Cyclones site is shown in Figure 16. Category 4 intensity Tropical Cyclone Sidr as it moved northward across the Bay of Bengal on 14 November 2007.

The results of ADT analysis of Sidr based on AMSU and Satellite Consensus (SATCON) performed by CIMSS are shown as time function in Figure 17. At highest development, the cyclone Sidr attained the T-number of 7 on 15 November 2007 indicating the maximum sustainable wind speed of 255 km/hour.

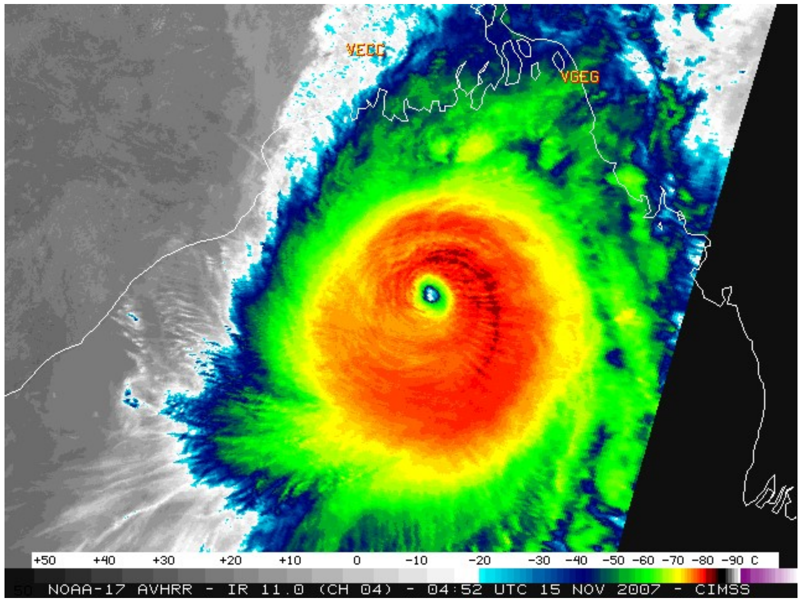

Figure 15: NOAA-17 AVHRR IR Image (Channel 4) of 04:52 UTC 15 November 2007 (Source:Cooperative Institute for Meteorological Satellite Studies (**CIMSS).**

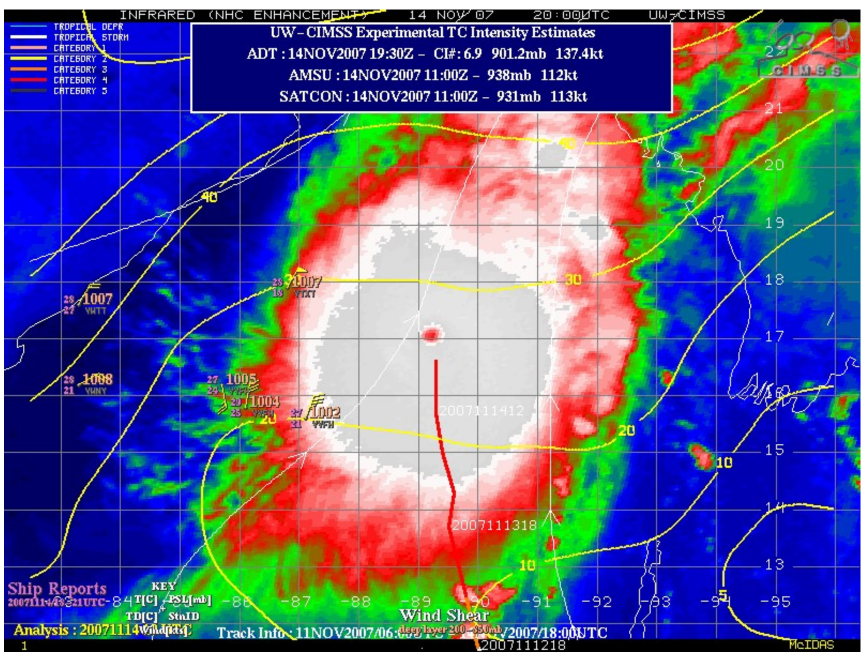

Figure 16: The enhanced IR image of SIDR of 15 November from GOES satellite for ADT analysis (Source: CIMSS archives). The yellow contours are vertical wind shear.

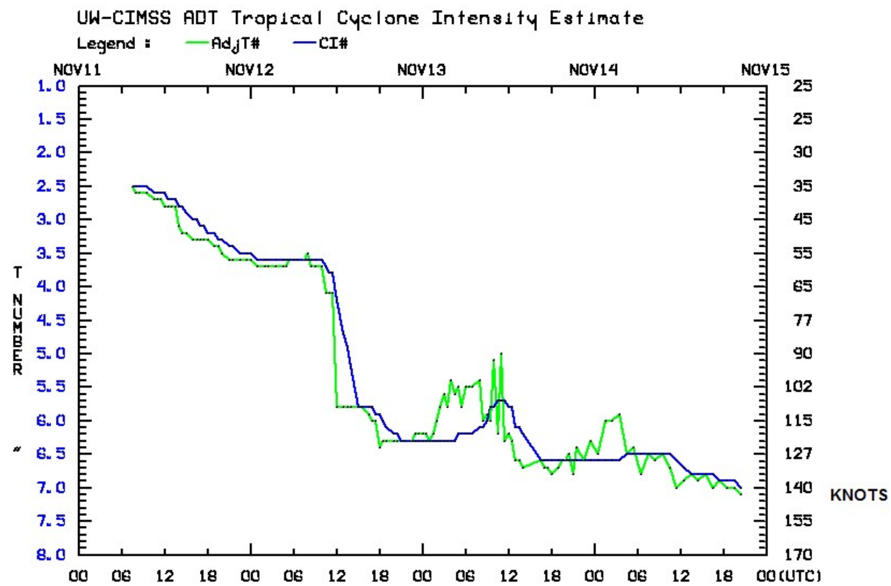

Figure 17: The temporal presentation of T-number as estimated by CIMSS ADT analysis of AMSU and Satellite Consensus (SATCON) [Source: CIMSS archives]

5. CONCLUSION

The satellite technology provides atmospheric weather observation over the earth, thus the vast oceanic and inaccessible land areas where the meteorological network is sparse are observed using the satellite data. The tropical cyclone formation, tracking the position and monitoring of the intensity are now performed using digital interpretation techniques of the real time IR images.

Further development has been achieved through the development of sensors capable of providing high resolution atmospheric soundings in NOAA and other satellites. The data from AMSU-A and B show the high resolution thermal and moisture fields also in the clouded areas.

The vertical temperature anomalies correlate well with intensity parameters and provide improved model of tropical cyclone intensity assessment. The satellite technology and algorithm of data analysis and interpretations are continuously being improved for refinement of the results and minimization of uncertainties.

The vertical thermal fields are used to derive the pressure fields which together with data transmitted from oceanic buoys, the satellite cloud vector winds and meteorological observations are used for global data assimilation system for initialization of NWP and other applications in aviation and agro-meteorology.

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