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Recent advances in observational support from space-based systems for tropical cyclones

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सार – पिछले चार दशकों से उष्णकटिबंधीय चक्रवातों (टी.सी.) के महत्वपूर्ण प्रेक्षण उपलब्ध कराने में मौसम विज्ञानिक उपग्रहों की क्षमताओं से सभी परिचित है। भू–स्थैतिक मौसम विज्ञानिक उपग्रहों से प्राप्त दृश्य, अवरक्त और जल वाष्प चैनलों से पृथ्वी के मेघाच्छादन के लगातार प्राप्त होने वाले चित्र और इन आँकड़ों से मात्रात्मक उत्पादों को तैयार करने की क्षमता सबसे महत्वपूर्ण है। मौसम विज्ञानिक उपग्रह अध्ययन सहकारी संस्थान (सी.आई.एम.एस.एस.) विस्कोंसिन यूनिवर्सिटी, यू.एस.ए. में पिछले कुछ वर्षों में किए गए अनुसंधान एवं विकास प्रयासों से उष्णकटिबंधीय चक्रवातों के स्वचालित विश्लेषण के लिए एक उन्नत ड्वोरक तकनीक (ए.डी.टी.) का विकास किया गया है। उत्तरी अटलांटिक और कैरिबियन सागर में आने वाले चक्रवातों के विश्लेषण के लिए इस तकनीक का प्रचालनात्मक उपयोग किया जा रहा है। जबकि भारतीय समुद्रों में परम्परागत ड्वोरक तकनीक (डी.टी.) बेहतर कार्य करती है तथापि हमारे क्षेत्र में इस समय प्रचालनात्मक आधार पर ए.डी.ए. का उपयोग इतना कारगर नहीं है।

सी.आई.एम.एस.एस. में पिछले कुछ वर्षों में अनुसंधान एवं विकास प्रयासों से उपग्रह के आँकड़ों से प्राप्त किए गए मात्रात्मक उत्पादों में भी काफी सुधार हुआ है। इन उत्पादों में निश्चित रूप में उष्णकटिबंधीय चक्रवातों के विश्लेषण में सुधार आया है और ये उष्णकटिबंधीय चक्रवातों की भावी गति दिशा का पूर्वानुमान करने के लिए महत्वपूर्ण सूचना उपलब्ध कराते हैं। भारतीय उपग्रहों के आँकड़ों से वर्तमान में प्रचालनात्मक उत्पादों की गुणवत्ता उपकरणों के अपरिष्कृत विभेदन पर आधारित है। अगले वर्ष (2013) से इनसैट श्रृंखला के नए उपग्रह से अधिक बेहतर गुणवत्ता के आँकड़ें उपलब्ध होने से उत्पादों की गुणवत्ता में और अधिक सुधार आने की अच्छी संभावना है। सूक्ष्म तरंग आधारित उपकरणों से प्राप्त आँकड़ें भी उष्णकटिबंधीय चक्रवात के विश्लेषण के लिए अतिरिक्त उपयोगी सूचना उपलब्ध कराते हैं। ऊपरी क्षोभमंडल में उष्ण कोर विसंगति उष्णकटिबंधीय चक्रवात की तीव्रता का उपयोगी सूचक है।

ABSTRACT. Capabilities of meteorological satellites to provide vital observations on Tropical Cyclones (TC) are well known since more than last four decades. Most important are the frequent pictures of earth's cloud cover in the visible, IR and water vapour channels obtained from Geostationary meteorological satellites together with the capability of generating a number of quantitative products from these data. R&D efforts of last several years at the Cooperative Institute of Meteorological Satellite Studies (CIMSS), Wisconsin University, USA have culminated into development of an Advanced Dvorak's Technique (ADT) for automatic analysis of Tropical Cyclones. It is in operational use for analysis of North Atlantic and Caribbean Sea cyclones. It has been used on experimental basis at Satellite Meteorology Center, IMD while the conventional Dvorak Technique (DT) works well over the Indian seas, experience of using ADT does not permit at present its use on operational basis over our region.

R&D efforts of last several years at CIMSS have also resulted in lot of improvements in the Quantitative products derived from the satellite data. These products have certainly improved the analysis of TC and have provided useful information for predicting the future intensity/movement of TCs. Quality of currently operational products from Indian satellite data is limited by the coarser resolution of the instruments. With the availability of much better quality of data from the new satellite of INSAT series from year (2013) onward there is a good possibility of making further improvements in the quality of products. Data obtained from microwave based instruments also provides useful additional information for TC analysis. The warm core anomaly in the upper troposphere is a useful indicator of the TC intensity.

Key words – ADT, Quantitative products, Warm core anomaly, INSAT-3D, Microwave instruments.

1. Introduction

Spaced-based platforms provide an ideal tool for observations of TC from an entirely different perspective which enables large areal coverage with sufficiently high spatial and temporal resolutions. The most important of all observations is the half hourly pictures of earth's cloud cover in different channels of electromagnetic spectrum obtained from imaging radiometers onboard geostationary meteorological satellites being operated by some countries of the world including India. These pictures provide reasonably good estimates of positions and intensity of the Tropical Cyclones using well known techniques of analysis (Dvorak, 1973, 1975, 1984). In addition, a large number of quantitative products are also derived from the digital data provided by these satellites. These products form very useful inputs for initialization of the Numerical Weather Prediction models being run by a number of centers world over. Assimilation of large amounts of non-conventional data obtained from space-based systems in the NWP models gives rise to much better capabilities for predicting the future tracks of the TC. Therefore, much better and reliable warnings can be issued which are more useful for disaster mitigation purposes. Additional data obtained from the passive and active microwave based payloads on board a number of satellites also form very important inputs for providing operational weather services related to cyclone warnings.

The main focus of this paper is to review the current state-of-art, particularly for the imaging radiometers and the sounders available on the geostationary and polar orbiting meteorological satellites and the types of data/products provided by them for cyclone tracking.

2. Analysis of cloud imagery data for location and intensity estimation of Tropical Cyclones

For operational tracking of the cyclones the analysis of cloud pictures is being done all over the world since more than last 30 years using the well known Dvorak's technique (Dvorak, 1975). An experienced analyst can estimate the intensity and location of the cyclone by analyzing the cloud patterns of the cyclonic storm using well established standard procedures. The Dvorak's Technique (DT) works quite well everywhere in the world and has been in use right from the early stages of reception of satellite cloud images at National Meteorological Services all over the world. In spite of its well proven suitability for operational use the technique has certain limitations and flaws. These are as follows:

- There is inherent subjectivity in storm center selection and scene type determination procedures.
- Learning to work with this technique in a real operational environment and understand its regional nuances and adjustments takes significant time to master.
- The technique was developed empirically without aid of computer analysis to determine statistical relationship between environmental parameters and intensity.

Mishra *et al.*, (1975) examined the applications of DT to the Tropical Storms and disturbances occurring in Indian seas. This study paved the way for operational use of DT in IMD. Subsequently further improvements were carried out from 1983 onwards after the availability of more frequent pictures from India's INSAT series of new satellites. Use of this technique has given fairly good results. Kalsi (2002) stated that DT has been the mainstay of operational analysis of TCs despite the well known problems of VIS and IR imagery that have continued to linger on. Using this technique Kalsi (2006) made a detailed study of the Orissa Super Cyclone (October, 1999) Kalsi *et al*., 2002 had analysed this cyclone using the Objective Dvorak Technique (ODT) algorithm originally developed by Dvorak (1984) and later modified by Zehr. Intensity estimates as per Velden *et al.,* (1998) were also incorporated. Recently, Mohapatra *et al.,* (2012) have provided an exhaustive review of Best track parameters of TC over the North Indian Ocean and have extensively delt with satellite observations.

Over the past several years several attempts have been made mainly at the Cooperative Institute of Meteorological Satellites Studies (CIMSS) of the University of Wisconsin (UW), USA to develop an Advanced Dvorak's Technique (ADT) to overcome the above mentioned problems with DT. As a result of persistent efforts (Velden *et al.*, 1998, Olander *et al*., 2002) of last 15 years or so by a team of scientistsat the UW-CIMSS, ADT has also now been fully developed. It is currently in operational use at the CIMSS-UW. A few other centers of the world are also working with this new technique on an experimental basis to start with main features of the ADT are:

- Use of objective storm center determination and cloud pattern determination logic removes subjective aspect for intensity estimate.
- It works well in all phases of Tropical Cyclone life cycle.

- Based on statistical analysis results obtained from more than 10 years of sample data of North Atlantic storms and significant samples of West and East Pacific storms covering entire spectrum of Tropical Cyclone intensities, regression based Intensity value estimates for various phases of Tropical cyclones have been derived.

Latest version of ADT software is 8.1.3 which is operational at UW-CIMSS and results obtained with this are quite good (Olander and Velden 2012). ADT has also been used on experimental basis at IMD for a few cyclones, but with an older version of the software. Experimental results show that ADT generally overestimates intensity approximately by one T number as compared to the conventional DT currently in operational use at IMD. This has been observed in all the four cyclones examined by IMD. Latest version of ADT software is yet to be installed at IMD.

A well known limitation of the ADT, and also in the DT, occurs during the strong Tropical Storm and/or weaker hurricane stage prior to the appearance of an eye feature in the IR imagery (Olander and Velden 2012). During this period of the storm life cycle a cirrus shield, known as Central Dense Overcast (CDO) typically obscures the forming eye feature. The ADT and DT have difficulty in determining the intensity of the Tropical Cyclone during this period due to the limited amount of information available in the IR imagery (CDO typically possesses a uniform temperature field which at best correlates marginally with actual storm intensity). Thus during the CDO period the ADT intensity estimates typically plateau until the eye features appear and the ADT intensity estimates increase. To remedy this limitation an externally-derived Tropical Cyclone Eye wall Organization Score (EOS) value is derived from Passive Microwave Imagery and passed into ADT. The EOS value measures the amount of eye wall convective uniformity and strength. The EOS value is then correlated to one of the two intensity estimate values 73 or 90 knots within ADT.

Olander and Velden (2009) had also introduced a multichannel differencing product which attempted to identify and quantify the convective vigor around the storm center (within 136 km radius from the storm center). This process subtracts the Brightness Temperature (BT) values of WV imagery from IR to identify regions where the WVBT values are warmer than the corresponding IRBT values (Schmetz *et al.*, 1991).

One major technical issue is navigation of KALPANA-1 images. ADT could not be introduced in IMD due to navigational problem of KALPANA-1 satellite which has at present very high orbit inclination. With the launch of next satellite of INSAT series (INSAT-3D) from year (2013) this problem will hopefully be sorted out.

2.1 *Use of water vapour imagery*

Dvorak (1984) had proposed that changes in upper level moisture, or water vapour (WV), patterns observed in 6.7 um satellite imagery could be used to forecast TC motion. Results of his studies indicated that a northwestward moving TC will turn northwards or northeastwards when two features are observed in WV imagery. One feature is a curved moisture boundary (CMB) observed about 10 degrees latitude northwest of the cyclone. The second feature involves the moisture/ cloud pattern of the cyclone showing an increase in the northward or northeastward direction giving the pattern a more north/south orientation. His study also found that a 24 hours forecast of a northward turn was feasible by monitoring the distance between the approaching CMB and the cyclone, and the change in the cyclone moisture pattern. Most of the cyclones in the sample turned northward or northeastwards 24 hours after the CMB approached within about 15 degree latitude of the cyclone and the cyclone's moisture pattern also indicated a turn. This simplistic approach was later modified to account for variations in the speed at which the CMB approached the cyclone. In one case study over the Indian region, Das and Meena, 2006 have studied the features associated with the curvature of TC Mala (24-29 April, 2006) as observed in Kalpana-1 satellite WV imagery. They observed that the cyclone had recurved when the CMB was located within 10 degrees in the northwestward direction of the cyclone.

3. Atmospheric Motion Vectors (AMVs) derived from satellite data and their use for cyclone tracking

One of the most important products derived by using the half hourly consecutive observations obtained from geostationary meteorological satellites is the AMVs at different levels of the atmosphere. These can be derived either by tracking the clouds or the water vapour features using the data obtained from the radiometers/sounders onboard the satellites. Additional data obtained in this manner supplements the conventional upper air observations obtained from Radiosondes. In fact, AMVs are the only upper air data available over the vast oceanic areas where there are no conventional observations. It is therefore very vital for tracking the movement of cyclones over the oceanic areas. As a result of persistent efforts by a number of scientists all over the world during last three decades, many significant developments have taken place in this field. Very good quality AMVs are now being generated by most of the satellite operators in the world. These are being routinely assimilated in the NWP models being run by almost all centers of the world. AMVs have made significant contributions in improving the initial conditions of the models. Initial analysis of the cyclones has also improved considerably by use of AMVs. Particularly over the Indian region the following products are being generated on a daily operational basis by the UW-CIMSS using the data transmitted by the METEOSAT-7 satellite of EUMETSAT located over the Arabian sea.

- Upper level and lower level winds derived by tracking clouds/water vapour.
- Upper level divergence and low level convergence.
- 850 hPa vorticity, wind shear and shear tendency.

These products have proved to be very useful for improving the cyclone analysis on an operational basis.

Based on R&D efforts for a number of years at CW-CIMSS Velden *et al.,* (1997) have reported results on improved quality of water vapour winds derived using GOES data over Pacific and Atlantic oceans. They have brought out characteristics of water vapour winds which are particularly important for cyclone tracking. The following characteristics were apparent in these winds:

- Coverage uniform and spatially coherent winds.
- Vertical distribution spread over 150-500 hPa.
- Large scale and synoptic features well represented.
- Smaller scale features (storm outflow and adjacent Environmental features) are well captured.

It has been reported (Velden *et al*., 1997) that these data can be useful in depicting upper level features and their evolution which play important role in TC formation and motion. In the vicinity of cyclones these data depict upper-level structure not captured in the global analysis. This information was very important for intensity forecast. The positive impact of GOES-8 derived winds on the Atlantic Tropical Cyclone track forecasts has been very nicely brought out in two papers (Velden *et al*., 1998, Part 1 and Goerss *et al*., 1998, Part 2). Apart from the use of conventional visible, infrared and water vapour channels to derive upper level winds by tracking clouds/water vapour, Velden *et al.,* (1997) have also reported that wind derivations at lower levels are possible using sounder channels of GOES instrument. Atmospheric sounder onboard GOES satellites includes two water vapour absorption bands (7.0 and 7.3 um). These channels can be employed as surrogate imagers to track water vapour features radiating from lower layers of the atmosphere. Good quality low level winds have been derived from these data for a particular cyclone which have proved to be very useful for improving the analysis.

Velden *et al.*, (2005) have reported results on a new low-level AMVs product focused particularly in the vicinity of TC .These are derived using shortwave infrared (SWIR) channel sensitive to emitted radiation in the 3.9 um window region. This channel is cleaner than 10.7 um IR channel because of less water vapour attenuation. It is therefore more sensitive to warmer (lower troposphere) temperatures. Hence, there is higher detectability rate of low-level tracers with this channel. It is not as sensitive as long wave Infrared (LWIR), to the cirrus clouds that may obscure low level tracers. Lot of low level winds have been derived with this SWIR channel. But these are limited only to the night time because of sensitivity of this channel to solar contamination. Use of this channel has given diurnally consistent AMVs in the low levels (600-900 hPa). By using a combination of visible and 3.9 um channels it is possible to get continuous coverage for low level winds. These are extrapolated to the surface to provide coverage in the periphery of the Tropical Cyclone (Dunion & Velden, 2002). Such surface adjusted AMVs improve estimation of 34 knot surface wind radii which is very important for issuing more reliable warnings. Due to non availability of 3.9 um channel on current INSAT/ KALPANA satellites of India it is not possible to derive this product with Indian satellites data. Next satellite of INSAT series will have this channel and will enable derivation of such winds from year (2013).

Some limited studies on the use of METEOSAT derive WV winds over the Indian region (Tyagi *et al.,* 2009 and Bhatia *et al*., 2008) have shown that water vapour winds provide good guidance for operational prediction of future tracks of TC and monsoon disturbances.

4. Use of microwave data for tropical cyclone analysis

Apart from the conventional satellite based observations of earth's cloud cover in the visible and infrared channels of e.m. spectrum, observations in the microwave channels also provide very useful additional data on Tropical Cyclones. Microwave radiation is sensitive to a wide variety of geophysical parameters such as Atmospheric Temperature and moisture, cloud liquid water, cloud ice and water, rain and surface wind speed.

A warm anomaly in data obtained from the Nimbus-6 Scanning Microwave Spectrometer over Typhoon June was first noticed by Rosenkranz *et al.,* (1978). It was subsequently shown by Kidder *et al.,* (1978) that the warm anomaly was the result of upper level warming over Tropical Storm that could be detected through the clouds by the microwave sounder. It was also shown that the magnitude of warm anomaly in the microwave data was related to the storm's central pressure and outer winds. Velden and Smith (1983), Velden (1989) and Velden *et al.,* (1991) used Brightness Temperatures and 250 hPa temperatures retrieved from Microwave Sounding Unit (MSU) data to estimate the intensity and central pressure of a large number of TC and found good agreement with aircraft and other methods. From the year 1998 an Advanced Microwave Sounding Unit (AMSU) onboard NOAA-15 Polar orbiting satellite provided much better quality of microwave data because of increased resolution, more number of channels and better radiometric accuracy. AMSU provided (Kidder *et al.,* 2000) exciting set of observations on TC from an entirely new perspective. Four major reasons for excitement with AMSU data were.

(*i*) It was the first instrument having potential to measure location and movement, thermal anomalies, wind speeds and rain rates of TC.

(*ii*) Clouds are nearly (but not completely) transparent to microwaves. AMSU, because of its better resolution, can measure above and even through Central Dense Overcast (CDO).

(*iii*) Because of significant improvements in spatial resolution, radiometric accuracy and number of channels, much better quality of data was obtained from AMSU.

(*iv*) Complements the more frequent observations of geostationary satellites to give complete description of TC.

Kidder *et al.,* (2000) have presented detailed results of their studies with AMSU data based on a number of storms. Five specific research and forecasting capabilities made possible with AMSU are Upper Tropospheric Temperature anomalies, TC intensity estimate, AMSU, AVHRR and GOES images, Gradient wind retrieval and estimation of TC Precipitation Potential.

Vertical cross section of temperature anomalies through a particular storm (Kidder *et al*., 2000) shows warm core of the hurricane centered at an elevation of about 10.7 km. Maximum warm core anomaly observed in one case is 16 degree K. Warm anomaly was also found to extend down upto lower troposphere inside the eye. These observations were found to be almost identical with the similar observations made with the Aircraft Reconnaissance data. Based on the study of a large number of storms it was found that surface wind speed can be estimated to within 19 knots (10m/sec) and central pressure can be estimated to within 13 hPa. AMSU data provided new insight into the internal structure of the cyclones with lot of potential for better analysis and forecasting. Subsequently, Demuth *et al.,* (2004) had used AMSU derived data from 1999-2001 for TC in the Atlantic and east Pacific basins to develop algorithms that provide objective estimates of 1 minute maximum sustained surface winds, minimum sea level pressure and the radii of 34, 50 and 64 kt winds in the NE, SE, SW and NW quadrants of TC. In a more recent paper Demuth *et al.,* (2006), have updated their earlier work to reflect larger data sets, improved statistical analysis technique and improved estimation through dependent variable transforms. Their developmental regression models resulted in mean absolute errors of 10.8 kt and 7.8 hPa for estimating maximum winds and minimum pressure respectively.

Singh *et al.,* (2003) have reported results of temperature retrievals over the Indian region using AMSU data from NOAA-16 satellite. They have also computed upper Tropospheric temperature anomaly for a particular storm. It was found that intensity is related to the strength of temperature anomaly. More recently, Mitra *et al.,* (2010) have reported results of a neural network approach for temperature retrievals from AMSU-A measurements and a case study with GONU cyclone. They have found a maximum anomaly of about 11 degree K and it is related to the intensity of the storm.

Kishtwal *et al.,* (2005) have reported results of development of an automatic method for intensity estimation of TC using multichannel observations from TRMM Microwave Imager (TMI). They have adopted a non-linear data fitting approach called Genetic Algorithm using data for the period 1998-2002 of storms over the Indian seas. Kalsi (2006) has also analysed Microwave images of Orissa Super cyclone. A compact eye was seen in the TRMM 85 H Ghz image on 28th October, 1999 which gives an impression of great strength.

5. Possible improvements in cyclone tracking after early 2013 launch of next satellite INSAT-3D

The next Indian satellite of INSAT series (INSAT-3D), currently scheduled for launch in the year 2013, will be an advanced version of INSAT Meteorological satellites with much better capabilities as compared to the currently operational meteorological satellites of INSAT series. It will have a six channel imager with a higher resolution of 1 km in visible channel and 4 km in the infrared channels. It will also have a 19 channel atmospheric sounder for obtaining temperature and humidity profiles over a large area around Indian subcontinent almost 8 times in a day. This new satellite will also have an onboard automatic image navigation and registration (INR) system which will provide much better accuracy of image navigation and registration as compared to the currently operational satellites which do not have this capability. This will, in turn, give rise to better tracking of cyclones with animated sequences of continuous images. The upper level winds derived by using data obtained from three sequential half-hourly images will also be of better quality as compared to those derived from currently operational satellites, particularly for cyclone tracking. This advanced satellite (INSAT 3D) will provide the following additional information/data, which will give rise to the significant improvements in our capability to locate cyclones and predict their future track.

(*i*) Availability of multichannel images with higher resolution will provide better quality of data on the structure of the cyclone. The frequent images during day time in visible channel with 1 km resolution will be useful for better clarity on structure of rain-bands and eye wall clouds. The 4 km resolution images in IR channels available all through the day will help in much better analysis of intensity of cyclone using automated techniques.

The new type of data as mentioned above, will also give rise to computation of more number of upper level winds and with a higher degree of accuracy which will be more useful for initializing the NWP models using non-conventional data sources from space based platforms.

(*ii*) The additional IR channels available in the sounder data can also be used for deriving winds at other levels not possible with the IR imagers, particularly in the lower level of the atmosphere useful for better cyclone analysis.

(*iii*) The availability of new 3.9 µm channel will enable derivation of low level CMVs in large numbers during night time, focused particularly in the vicinity of TC. These additional winds when used in combination of winds derived from visible channel data can provide continuous coverage of low level winds from satellite data. Such winds can also be extrapolated to the surface to provide coverage in the periphery of TCs (Dunion and Veldon, 2002). These surface adjusted AMVs help improving the estimation of 34 knot surface wind radii, an operationally useful parameter.

(*iv*) As a result of availability of (10.5-11.5 µm and 11.5-12.5 µm) split window channels in the IR imager with better resolutions (4 km) and higher radiometric resolution, it will be possible to derive Sea Surface Temperatures (SSTs) with higher accuracy.

6. Summary

Development of Advanced Dvorak's Technique for automatic analysis of cyclone intensity and determine its position objectively has reached the level of full maturity as a result of extensive work at UW-CIMSS over the last 15 years. Operational experience during last few years in the USA has shown that results are very good. There is a good match between ADT and conventional Dvorak's Technique (DT). ADT has been accepted for operational use with future GOES satellite (GOES-R) data. In India, however, lot more R&D work needs to be done at IMD/SAC to make ADT fully operational. R&D work also needs to be done to improve the quality of operational upper level winds being derived with INSAT/KALPANA satellites. With the operational availability of data from microwave based instruments at the three new stations (Delhi, Chennai and Guwahati) of IMD there is lot of scope for using AMSU data for improving cyclone analysis. Systematic R&D efforts are needed in order to make full use of existing capabilities at IMD. Launch of India's new satellite (INSAT-3D) with advanced payloads will certainly pave the way for much improved cyclone analysis from year (2013).

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