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Observational aspects including weather radar for tropical cyclone monitoring

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सार – भारत मौसम विज्ञान विभाग (आई. एम. डी.) के पूर्वानुमान प्रदर्शन परियचोजना (एफ. डी. पी.) के संदर्भ में की गई विभिन्न प्रेक्षणात्मक सुविधाओं और तकनीकों की समीक्षा की गई है। जिनका प्रयोग चक्रवात के पथ का पता लगाने और उष्णकटिबंधीय चक्रवातों को समझने के लिए किया जा सकता है। प्रौद्योगिकी के संबंध में किए गए प्रयासों के वास्तविक परीक्षण से प्रचालनात्मक संदर्भ में हमारे पूर्वानुमानों के निष्पादन का पता चलता है। इस संबंध में आवश्यक उपायों पर इस शोध–पत्र में विचार–विमर्श किया गया है।

ABSTRACT. In the context of the Forecast Demonstration Project (FDP) of the India Meteorological Department (IMD), a review is made of the various observational facilities and techniques which can be deployed, for the detection tracking and understanding of tropical cyclones. The real test of the efforts in terms of technology is the performance of our forecasts in an operational context. The paper discusses the steps needed in this regard.

Key words – Tropical cyclones, Phased array radars.

1. Introduction

India Meteorological Department (IMD) is running a Forecast Demonstration Project (FDP) aimed to demonstrate the ability of various numerical models to assess the genesis, intensification and movement of tropical cyclones over the north Indian ocean incorporating data from a variety of enhanced observations over the region. In this context a review is made of the various observational facilities and techniques which can be deployed, based on past experience in this country and abroad as well as recent technological developments.

2. Aircraft reconnaissance of tropical cyclones

Routine aircraft reconnaissance of Tropical Cyclones (TCs) affecting the Indian coasts, a long-standing dream of Indian meteorologists, now appears close to realisation. Aircraft observations over the Atlantic and Pacific have over the years contributed the most to our knowledge of TC structure and behaviour. Much of the knowledge of TC structure has come from airborne radar because of the possibility of flying close to where the action is. Fig. 1 shows a result of radar observation along with onboard instrumental data. Aircraft observation should enable better understanding of TCs in our region and lead to more effective forecasts and warnings. Important components to be included are *in situ* instrumentation for temperature, liquid water content etc., wind velocity measurements from the inertial navigation system and dropsondes. Doppler and perhaps Polarimetric Radar, with helical scan and configurations like pseudo-dual Doppler (Fig. 2) need to be deployed on board. Processing software is quite complex and needs to be robust. Disadvantages associated with airborne radar are - sea clutter, poor beam filling and attenuation; these limitations need to be recognised.

Aircraft reconnaissance is taxing in terms of resources and needs to be fully exploited. The possibility of mounting an instruments package when required and releasing the aircraft for other uses at other times needs to be explored. (Sheets R, personal discussion). Dropsonde observations would vastly enhance the tropical cyclone prediction capability.

3. Surface instrumentation

At the surface, traditionally we were dependent on hourly observations from manned coastal observatories and erratic reports from ships. The establishment of Automatic Weather Stations (AWS) over land [Fig. 3(a)] and data buoys over the ocean in the last few years

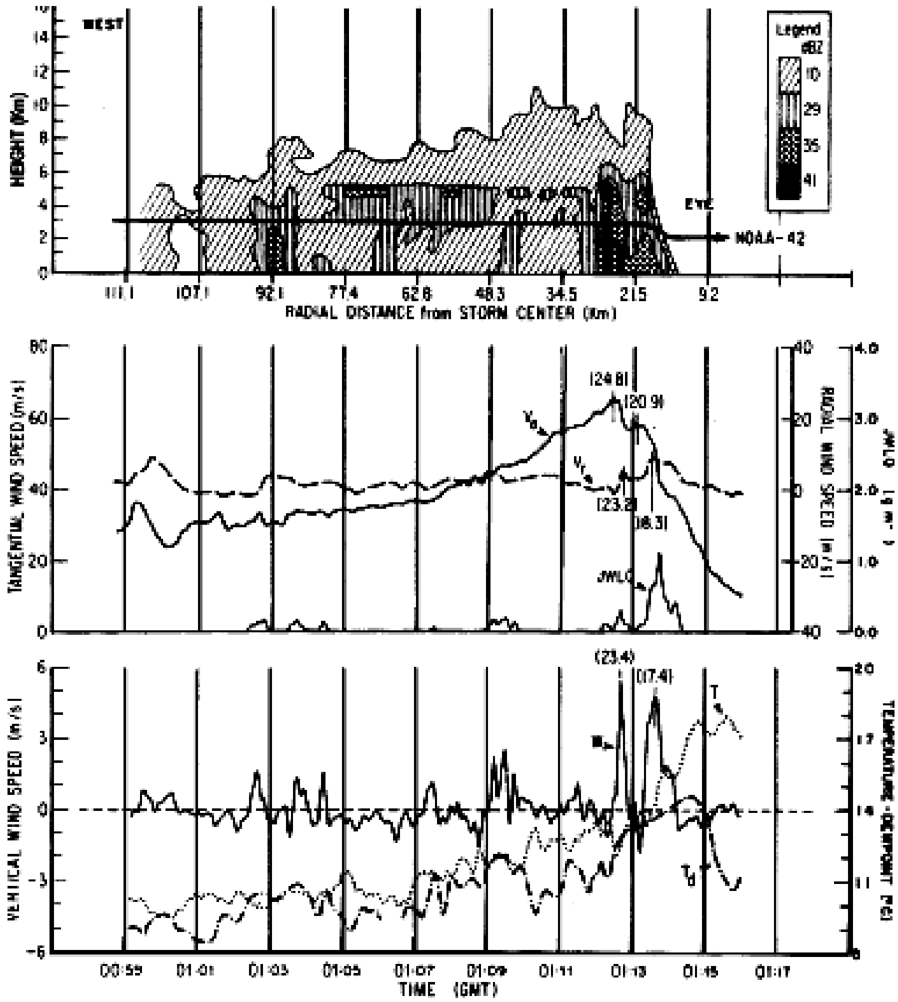
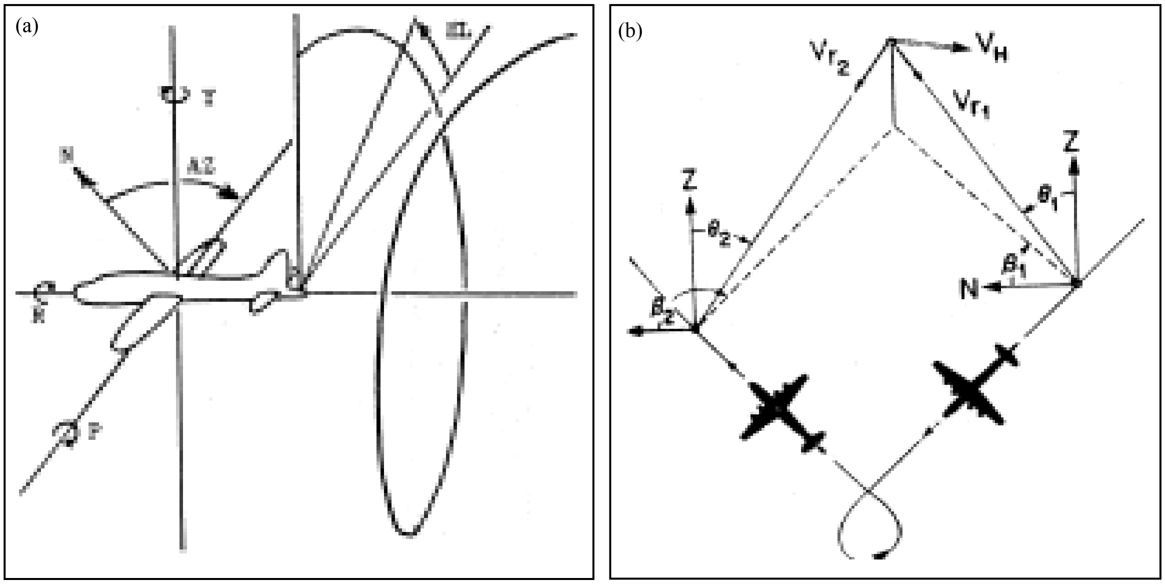


Fig. 1. Aircraft observation of tropical cyclone [From Jorgensen, 1984, *Courtesy* : American Meteorological Society (AMS)]. Profiles of radar reflectivity factor, tangential wind V_{θ}, radial wind V_r , cloud water content JWLQ, vertical wind W, temperature T and dew point T_d from Hurricane Anita. All wind data are relative to the moving storm. The aircraft flew from west of the centre inward to the eye. The radar reflectivity cross section was generated by compositing vertical rays from the tail radar at four samples per minute. Locations of the peaks of the horizontal and vertical wind are indicated in parentheses. Note that the position of the maximum tangential wind approximately coincides with the position of maximum reflectivity factor

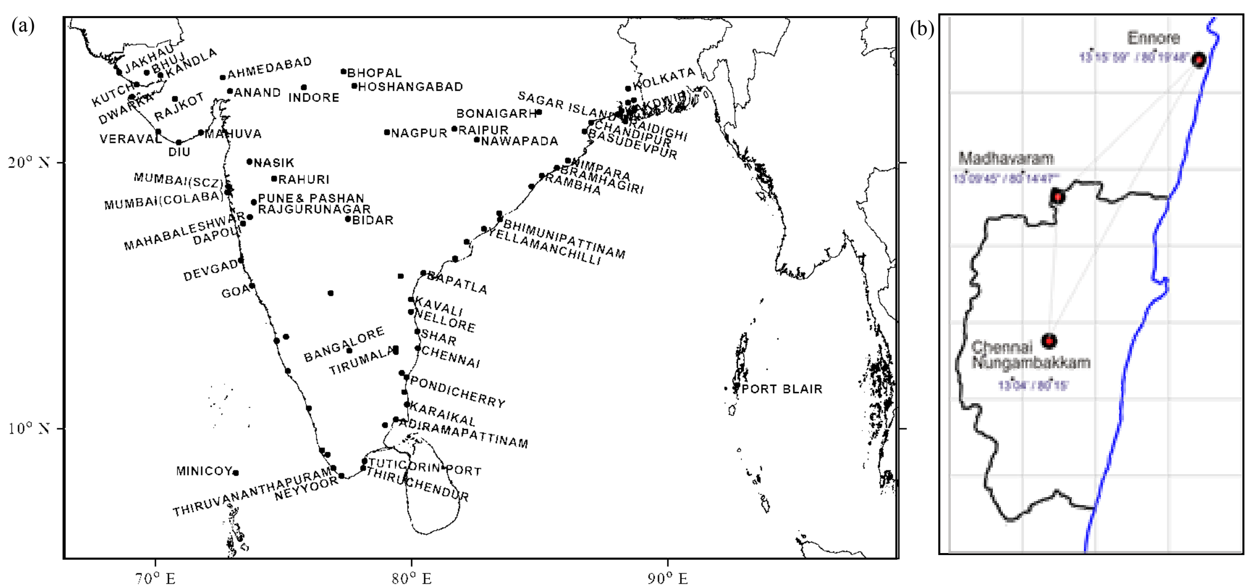
is a great step forward. Closely spaced AWS's [Fig. 3(b)] helped in determining landfall accurately in recent TCs, *e.g.*, Cyclone JAL, 2010 (Amudha and Raj, 2011).

4. Satellites

Geostationary satellites have been our mainstay in detecting systems at sea and estimating their intensity for nearly three decades. Several other features such as the water vapour channel and the cloud motion vector winds are of relevance to TCs. Polar orbiting data have been in use from earlier times. Though continuous coverage is not there numerous products are available. Indian Space Research Organiation (ISRO)'s Oceansat scatterometer data (Fig. 4) have been very useful in the case of the hurricane IRENE (August 2011) in the USA. ISRO has recently launched the Megha-Tropiques satellite having four payloads that would help estimate oceanic winds, rainfall, temperature and humidity profiles, total water vapour, cloud liquid water, cloud ice and several radiation budget parameters, all from a common platform. This



Figs. 2 (a&b). (a) Geometry of helical-scan airborne radar. (From Hildebrand *et al*. 1983, *Courtesy* : AMS Radar is mounted at the tail of the aircraft. The radar scans in a plane perpendicular to the track of the aircraft thus describing a helical scan as the aircraft moves forward. The axes marked R, P and Y are the Roll, Pitch and Yaw axes respectively. The AZimuth of the Pitch axis with respect to North (N) and the ELevation of the antenna are also shown". (b) Geometry of pseudo-dual-Doppler radar horizontal wind calculation. (From Jorgensen *et al*., 1983, *Courtesy* : AMS). The aircraft flies as shown and the observation of the same point from the two positions is treated as a dual-Doppler observation. β_1 β_2 are the azimuths with respect to North of the echo pattern from the two positions, θ_1 θ_2 are the elevations. Z represents the vertical and N is north. V_H is the horizontal wind velocity, V_{R1}, V_{R2} are the radial Doppler velocities as seen from the two positions"



Figs. 3 (a&b). (a) Network of automatic weather stations along the Indian coasts (*Courtesy* : IMD) and (b) AWSs around Chennai which helped accurate location of TC JAL

should help understanding TCs and their forecasting. The Tropical Rainfall Measuring Mission (TRMM) satellite data including the first space-borne weather radar have been widely used and we may look forward to the Global Precipitation Mission (GPM) expected to be launched in 2013.

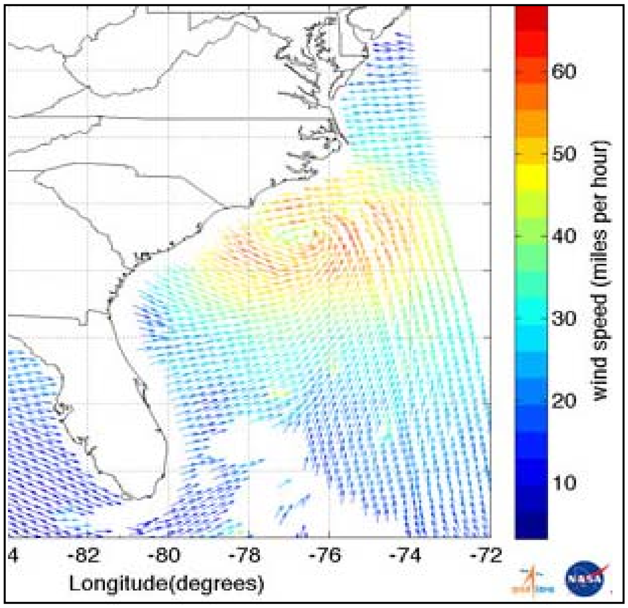


Fig. 4. Ocean-surface wind speeds and directions for Hurricane Irene six hours prior to the storm's landfall in North Carolina - OceanSat 2 image *Courtesy* : ISRO

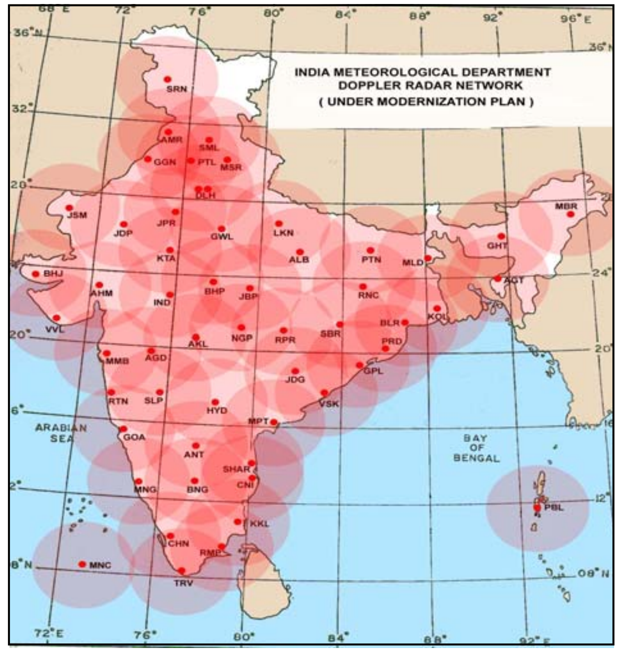


Fig. 6. Modernised radar Network of India Meteorological Department (*Courtesy* : IMD).

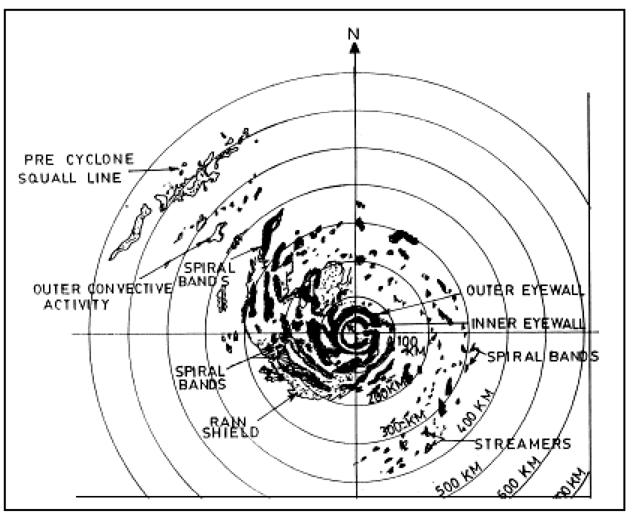


Fig. 5. Typical Horizontal structure of a well-developed tropical cyclone determined from radar observations. (From Raghavan 1985; *Courtesy* : WMO)

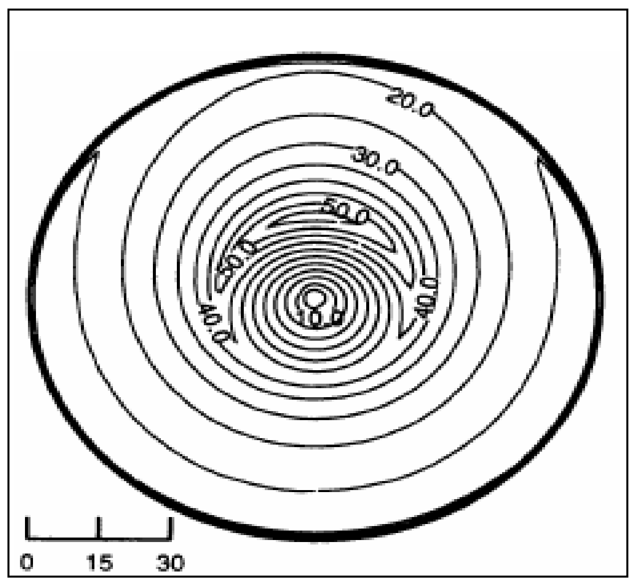


Fig. 7. The GBVTD-retrieved tangential winds for a vortex. (From Lee *et al*.,1999; *Courtesy* : American Meteorological Society)

5. Surface weather radars

In India, ground-based radar has contributed greatly to improved forecast of TCs over the past 40 years. Only non-Doppler analogue radars were available in the last century but using these, TC position determination, track extrapolation and mapping of rainfall distribution could be carried out. Considerable knowledge about cyclone structure (Fig. 5) and behaviour in well-developed as well as weak systems was built up. A concept of Radius of Maximum Reflectivity (RMR) was developed and used to provide inputs for storm surge forecasting (Raghavan, 1997 & 2003).

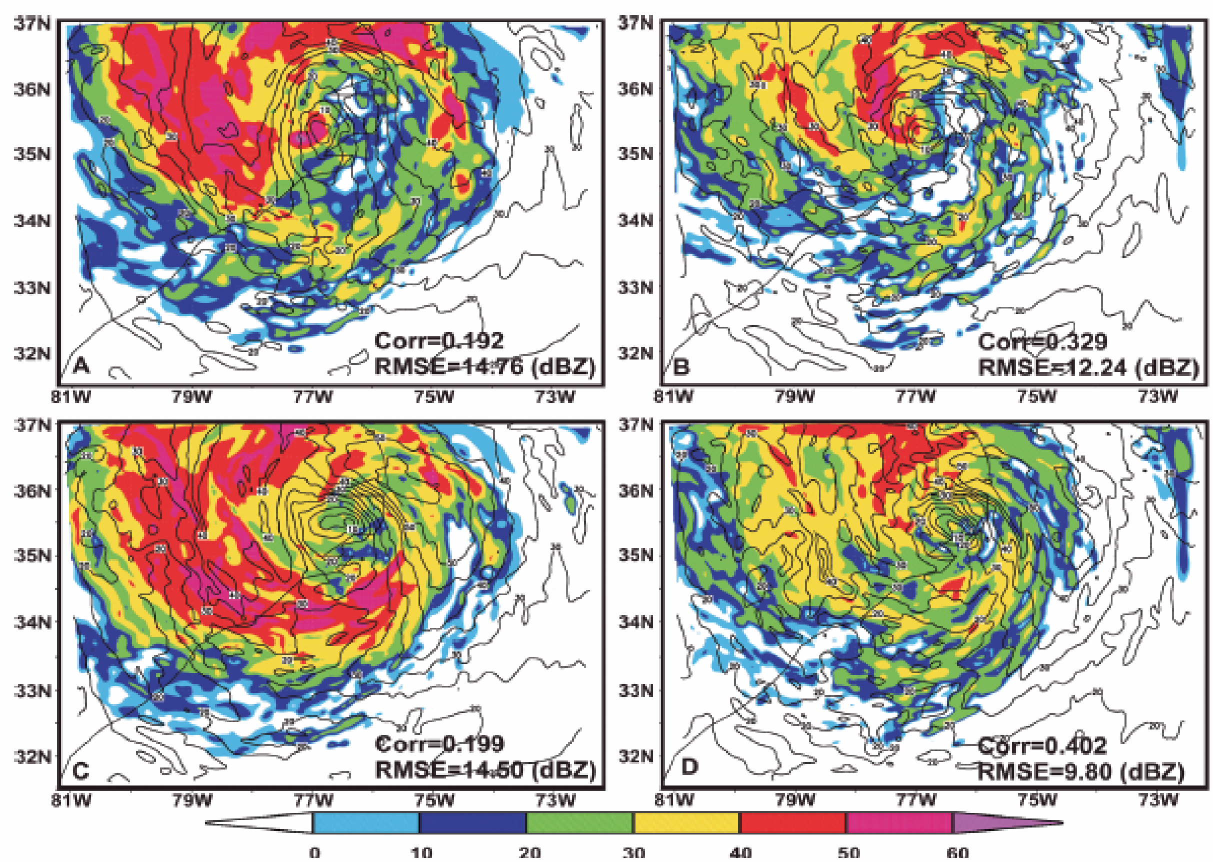


Fig. 8. Radar Data Assimilation in Hurricane Isabel (2004) Composite reflectivity (dBZ, shaded) and horizontal wind speed (m s^{-1}, contoured at 5 m s^{-1} intervals) at 2 km above the surface, from the model forecasts at 2 h after the data assimilation (valid for 1800 UTC) from (a) Control, (b) Z assimilation, (c) V_r assimilation, and (d) Z and V_r assimilation. The hurricane symbol indicates the approximate location of the observed hurricane centre. (*Courtesy* : American Meteorological Society)

6. Modernization of radar network

With the introduction of Doppler radars in the last 10 years we are able to get the wind field at close range and hopefully can determine maximum winds in TCs close to the coast. IMD is expanding the Doppler radar network (Fig. 6) and is likely to induct polarimetric radars. Mobile Radars which can be moved at short notice to areas of interest in TC situations as well as wind profilers are also being introduced. Clear air ST radars/wind profilers located not far from the coast have a great potential in the matter of understanding of structure of landfalling cyclones and modifications at landfall. There are prospects of establishment of more profilers in the near future. Other organisations too are setting up radars and profilers for operational or research purposes. Hopefully we may get a ship borne radar. Networking of radars to assemble a combined display from various radars is being organised (Arul Malar Kannan *et al*., 2011) but more needs to be done by way of integration of outputs of all sensors.

7. Radar data processing techniques

There are various processing techniques using radar data, *e.g.*, the Velocity-Track Display (VTD; Carbone and Marks 1989, Lee *et al*., 1994) algorithm (for airborne radar) which decomposes, by harmonic analysis, Doppler velocities on cylindrical rings into tangential, radial and mean cross-track components of the wind velocity. A Ground-Based version of Velocity Track Display (GBVTD) [Lee *et al*., (1993, 1999, 2000), Lee and Marks (2000)] maps winds around circles centred on the TC centre with a radar located away from the circle (Fig. 7). The technique can be used even when the radar does not directly see points of maximum velocity in the vortex and has been tested on a real TC.

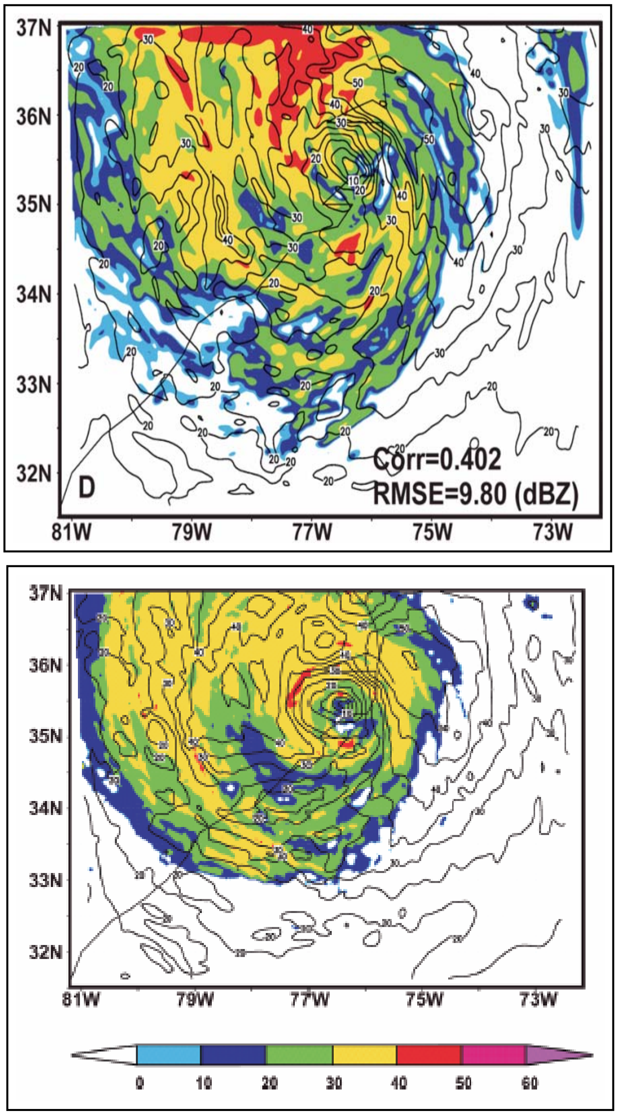


Fig. 9. Radar data Assimilation in Hurricane Isabel. Verification, Correlation coefficient and rms error of composite reflectivity forecasts verified against the observations. (*Courtesy* : American Meteorological Society)

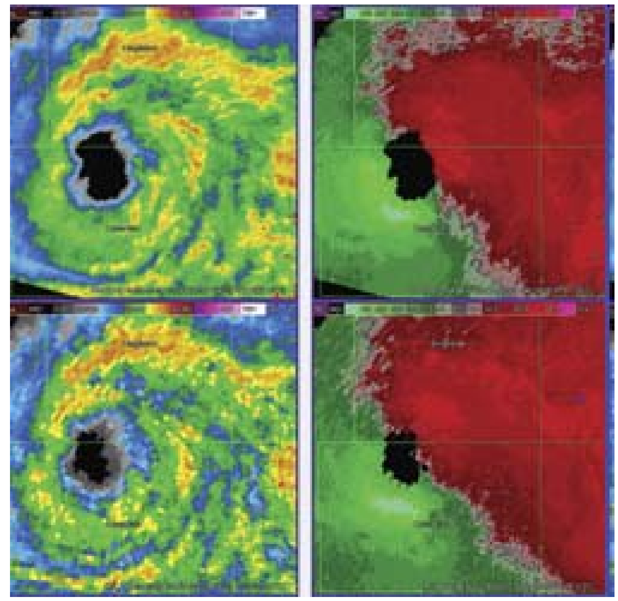


Fig. 10. Tropical Storm Erin rain bands and "eye" as captured by PAR. (*Photograph Courtesy* : National Severe Storms Laboratory, USA)

8. Radar data in numerical models

The most important recent advance is the direct assimilation of Doppler radar data in numerical models which has been taken up by several institutions in India. It has been demonstrated (Zhao and Jin, 2008) in the Atlantic hurricane Isabel (2004) that assimilation of reflectivity factor and Doppler radial velocity from 5 radars into a mesoscale Numerical Weather Prediction (NWP) model [US Navy's Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS)] improves TC intensity and structure analyses and forecasts significantly (Figs. 8 & 9). Krishnamurti *et al*., (2011) have developed a rain rate initialization for numerical models that utilises radar resolution rains. The major finding is that this radar resolution rain rate initialization is very powerful and can improve short range forecasts of heavy rains during rapid intensification and landfall of hurricanes.

Another example where new algorithms will be needed is the detection of tornadoes embedded in cyclones. Cases of such tornadoes are well-documented in the USA but we had no means of observing them in our region.

Several Indian researchers have adopted techniques for assimilation of Doppler radar data into mesoscale models for analysis and prediction of convective events and tropical cyclones (*e.g*., Abhilash *et al*., 2007, Das *et al*., 2006, Litta and Mohanty, 2010, Osuri *et al*., 2010, Pattanayak *et al*., 2010, Routray *et al*., 2010, Roy Bhowmick *et al*., 2011, Srivastava *et al*., 2010, 2010b).

We need to adopt all such techniques for operational use. Several Indian researchers in IMD, NCMRWF and IIT Delhi have also adopted with success, techniques for assimilation of radar data into mesoscale models for T.C. prediction.

9. Phased Array Radar

The deployment of Phased Array Radars (PAR) at a later stage may make the radars more versatile in continuous monitoring of tropical cyclones as very fast scan speeds and targeted observations (to locate the most severe weather) will be possible. Fig. 10 shows PAR observation of Tropical Storm Erin which re-intensified over land in Oklahoma near the National Weather Radar Testbed.

10. Real time integration of data

None of these observational platforms can be viewed in isolation. The real time integration of ground-based, aircraft-based and satellite data into NWP models needs to be pursued keeping in view the importance of human judgment. The Warning Decision Support System-Integrated Information (WDSS-II) developed at the US National Severe Storm Laboratory (Lakshmanan *et al.*, 2007) is a system of tools for the analysis, diagnosis and visualization of remotely sensed weather data from multiple sensors. Now several organisations have observational facilities as well as capability to run models. It is necessary that all concerned organisations in India collaborate effectively on a day-to-day basis and share their facilities, data and products.

11. Operational forecast performance

Besides all the technology, the real test is the performance of our forecasts in an operational context. Some lessons can be learnt from Hurricane IRENE which hit the US coast in August 2011. Many comments have been made that the intensity forecast was not good and that the weakening close to the coast produced an anticlimax and perhaps over-warning. Though some of the criticism was from the lay media it has to be taken seriously as these influence opinions. The criticism of over-warning does not seem justified. Intensity forecast is particularly difficult. The double eyewall feature (Raghavan 2003), seen on radar which was being commented upon (the eyewall replacement cycle) is an indicator of a severe TC but not a reliable predictor of intensity change.

This has implications for the continued support we can get from government for efforts such as the FDP to improve our understanding and forecast of tropical cyclones and for the creation of expensive facilities. The user is interested not in the phenomenon but its IMPACT. Operationally therefore it is important to put out warnings with graphics indicating the various possible scenarios and explaining the uncertainties, while keeping close liaison with disaster managers. This is being effectively done in the US where weather telecasters are qualified meteorologists.

In India we often give a "deterministic" type of forecast and keep changing it in the light of observations without explaining the background to the public. While this may be justified scientifically it projects a poor image of the Meteorological Service with a loss of credibility. It may be better to give a probabilistic forecast explaining the uncertainties and taking recipients into confidence. It is also necessary to create greater awareness of the importance of pro-active preparedness among administrators and ensure more funding for that rather than just for relief measures after the event (Raghavan and Rajesh, 2003).

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