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Outcomes and challenges of Forecast Demonstration Project (FDP) on landfalling cyclones over the Bay of Bengal

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सार – बंगाल की खाड़ी में उष्णकटिबंधीय तूफानों के मार्ग और उनकी तीव्रता के पूर्वानुमान तकनीक में सुधार लाने के लिए पूर्वानुमान निदर्शन परियोजना (एफ.डी.पी.) नामक एक कार्यक्रम तैयार किया गया है। एफ.डी.पी. कार्यक्रम का उद्देश्य, जिन क्षेत्रों से आँकड़े अव्यवस्थित रूप से प्राप्त होते हैं वहाँ उनके सवंर्धित प्रेक्षणों के साथ ही साथ उत्तरी हिन्द महासागर में चक्रवातों के उत्पन्न होने, उनके तीव्र होने और उनकी गति का आकलन करने के लिए विभिन्न सख्यात्मक मौसम पूर्वानुमान (एन. डब्ल्यू. पी.) निदर्शो की क्षमता का प्रदर्शन करना तथा विशेष रूप से बंगाल की खाड़ी से संबंधित वहीं उसी स्थान पर लिए गए मापों के आधार पर निदर्शो में सुधार करना है। एफ.डी.पी. कार्यक्रम तीन चरणों में निधारित किया गया है नामतः (*i*) प्री–पाइलट चरण (15 अक्तूबर से 30 नवंबर 2008, 2009), (*ii*) पाइलट चरण (15 अक्तूबर से 30 नवंबर 2010–2012) तथा (*iii*) अंतिम चरण (15 अक्तूबर से 30 नवंबर 2013–2014)। भारत, किराए के हवाई जहाज और ड्रॉपसौंदें प्रयोगों से 15 अक्तूबर से 30 नवंबर 2013–2014 के दौरान बंगाल की खाड़ी में बनने वाले चक्रवातों का हवाई जहाज के जरिए पता लगाने की योजना बना रहा है। इस उद्देश्य के पूर्ति के लिए (*i*) प्रेक्षणात्मक उन्नयन (*ii*) चक्रवात विश्लेषण और पूर्वानुमान प्रणाली का आधुनिकीकरण (*iii*) चक्रवात विश्लेषण और पूर्वानुमान प्रक्रिया (*iv*) चेतावनी उत्पादों को तैयार करना, उनका प्रस्तुतीकरण तथा प्रसरण (*v*) विश्वसनीयता उपाय और क्षमता निर्माण पर प्राथमिकता के आधार पर कार्य किए गए।

चक्रवात के प्रेक्षण, विश्लेषण और पूर्वानुमान में सुधार लाने के लिए विभिन्न कार्य प्रणालियाँ अपनाई गईं। वर्ष 2008–11 के दौरान एफ.डी.पी. अभियान के प्री–पाइलट और पाइलट चरणों में संयुक्त प्रेक्षणात्मक, संचारात्मक और एन.डब्ल्यू.पी. गतिविधियों में अनेक राष्ट्रीय संस्थानों ने भाग लिया। एफ.डी.पी. के पहले और उसके बाद की प्रेक्षणात्मक प्रणालियों की तुलना से क्षेत्र में रेडार, स्वचालित मौसम केन्द्र (ए. डब्ल्यू.एस.), उच्च पवन गति रिकॉडरों में महत्वपूर्ण सुधार का पता चला है। इस सुधार से मॉनीटरन और पूर्वानुमान में होने वाली त्रुटियों में कमी आई है। जी. एफ. एस. डब्ल्यू आर. एफ, एच. डब्ल्यू. आर. एफ. और असेम्बल पूर्वानुमान प्रणाली (ई. पी. एस.) के आरंभ होने से एन. डब्ल्यू. पी. निर्देशों के कार्य निष्पादन में वृद्धि हुई है। इस शोध पत्र में इस परियोजना की उपलब्धियों के महत्वपूर्ण लक्षणों सहित समस्याओं और संभावनाओं को प्रस्तुत किया गया है तथा उनकी विवेचना की गई है। चक्रवातों का हवाई जहाज द्वारा पता लगाने के लिए बार–बार किए गए प्रयासों के बावजूद यह कार्य अभी संभव नहीं हो सका है। वर्ष 2013–14 के दौरान भावी अभियान के समय यह एक मुख्य चुनौती होगी।

ABSTRACT. A programme has been evolved for improvement in prediction of track and intensity of tropical cyclones over the Bay of Bengal resulting in the Forecast Demonstration Project (FDP). FDP programme is aimed to demonstrate the ability of various Numerical Weather Prediction (NWP) models to assess the genesis, intensification and movement of cyclones over the north Indian ocean with enhanced observations over the data sparse region and to incorporate modification into the models which could be specific to the Bay of Bengal based on the in-situ measurements. FDP Programme is scheduled in three phases, *viz.*, (*i*) Pre-pilot phase (15 Oct - 30 Nov 2008, 2009, (*ii*) Pilot phase (15 Oct - 30 Nov, 2010-2012) and (*iii*) Final phase (15 Oct - 30 Nov, 2013-14). India is planning to take up aircraft probing of cyclones over the Bay of Bengal during 15 Oct - 30 Nov, 2013-14 with hired aircraft and dropsonde experiments. To accomplish the above objective, the initiative was carried out with priorities on (*i*) observational upgradation, (*ii*) modernisation of cyclone analysis and prediction system, (*iii*) cyclone analysis and forecasting procedure, (*iv*) warning products generation, presentation & dissemination, (*v*) confidence building measures and capacity building.

Various strategies were adopted for improvement of observation, analysis and prediction of cyclone. Several national institutions participated for joint observational, communicational & NWP activities during the pre-pilot and pilot phases of FDP campaign during 2008-11. The comparison of observational systems before and after FDP indicates a significant improvement in terms of Radar, Automatic Weather Station (AWS), high wind speed recorders over the region. It has resulted in reduction in monitoring and forecasting errors. The performance of NWP models have increased along with the introduction of NWP platforms like IMD GFS, WRF, HWRF and ensemble prediction system (EPS). Salient features of achievements along with the problems and prospects of this project are presented and discussed in this paper. With repeated attempts, the aircraft probing of cyclones could not be possible till now. It is a major challenge for the future campaign during 2013-14.

Key words – Tropical cyclone, Forecast Demonstration Project, Track, Intensity.

1. Introduction

During the past few years huge technological advancements have been achieved elsewhere in the world to observe the inner core of the cyclone. Accordingly a programme has been evolved for improvement in prediction of track and intensity of tropical cyclones (TCs) over the Bay of Bengal, resulting in planning of the Forecast Demonstration Project (FDP). FDP programme is aimed to demonstrate the ability of various Numerical Weather Predication (NWP) models to assess the genesis, intensification and movement of cyclones over the north Indian ocean with enhanced observations over the data sparse region and to incorporate modification into the models which could be specific to the Bay of Bengal based on the in-situ measurements and following the actual track through Satellite and Radar observations. There have been various attempts (Mohanty and Gupta, 1997; Gupta, 2006) to analyse dynamical aspects and NWP modeling of tropical cyclones. All these studies indicate that introduction of synthetic vortex and assimilation of satellite and radar data are essential for simulation of TC apart from proper initial and boundary conditions, high resolution and cumulus & boundary layer parameterization. The reviews by Rao (1997), Kelkar (1997), Raghavan (1997), Mohanty and Gupta (1997), Gupta (2006), Sikka (2006) and Chan (1997), with respects to synoptic, climatological, satellite, radar and NWP aspects of TCs are noteworthy.

FDP Programme is scheduled to be implemented in three phases, *viz*., (*i*) Pre- pilot phase (15 Oct - 30 Nov, 2008, 2009, (*ii*) Pilot phase (15 Oct - 30 Nov, 2010- 2012) and (*iii*) Final phase (15 Oct.- 30 Nov., 2013-14). India is planning to take up aircraft probing of cyclones over the Bay of Bengal during 15 Oct - 30 Nov, 2013-14 with hired aircraft and dropsonde experiments. India Meteorological Department (IMD) is the nodal agency for implementation of this project.

To accomplish the above objective, the initiative was carried out with following priorities.

(*i*) Observational upgradation,

(*ii*) Modernisation of cyclone analysis and prediction system,

(*iii*) Cyclone analysis and forecasting procedure,

(*iv*) Warning products generation, presentation & dissemination,

(*v*) Confidence building measures and capacity building.

Here, an attempt has been made to analyse the outcome and challenges of FDP programme carried out during 2008-2011. The study will be helpful to plan the future FDP campaigns. The implementation of FDP during 2008-2011 is presented in section 2. Outcomes and challenges are presented in section 3 and 4 respectively. The broad conclusions are presented in section 5.

2. Implementation of FDP during 2008-2010

Various strategies were adopted for improvement of observation, analysis and prediction of cyclone. Several national institutions participated for joint observational, communicational & NWP activities during the pre-pilot and pilot phases of FDP campaign during 2008-10. There were 23 days of intense observation period (IOP) in association with cyclonic disturbances (CDs) during 2008 & 2010 and no IOP during 2009, as there was no cyclonic disturbance (depressions and cyclones) during FDP period over the Bay of Bengal.

Enhanced observations during IOP helped in improved monitoring and prediction of CDs. The additional data was collected from Sagar Kanya cruise, enhanced Automatic Weather Station (AWS) network of the coast, high wind speed recorders (HWSRs), Doppler Weather Radars (DWRs), five activated buoy observations from the Bay of Bengal, Oceansat-II observations and microwave imagery products. The comparison of observational systems before and after FDP indicates a significant improvement in terms of Radar, AWS, high wind speed recorders over the region (Table 1). It has resulted in reduction in landfall point location error from 55 km to 25 km (Mohapatra *et al.*, 2011).

To ensure the availability of the data and forecast products from various national and international sources at Cyclone Warning Division, IMD, New Delhi, an institutional mechanism was developed in consultation with all the stake holders. A standard operation procedure

(i) Before initiative
(Isobaric analysis at mean sea level) at 1200 UTC of 28 April 2006)

(ii) After initiative
(Isobaric analysis and forecast at mean sea level during cyclone, Phet at 0000 UTC of 03 June 2010 based on ECMWF model)

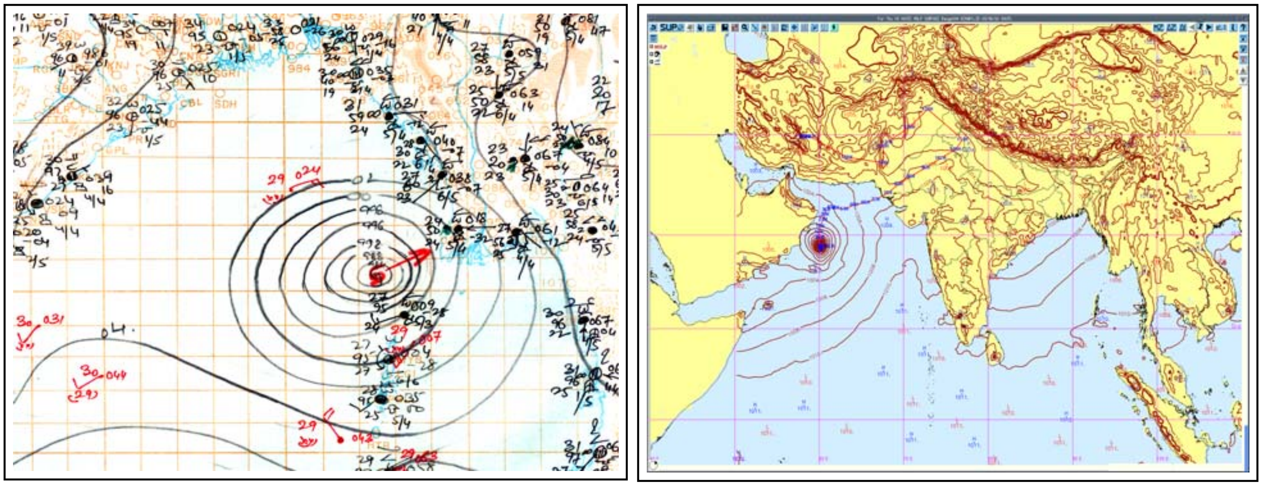

Fig. 1. Comparison of weather analysis products before and after the initiative

TABLE 1

Observatory network by end of 2007 and 2010

Observational system	Network by end of 2007	Network by end of 2010
Surface observatory network	559	559
Pilot balloon observatory network	62	62
Radiosonde/Radiowind Network	35	39
Buoy network	6	12
AWS network	125	524
HWSR	-	12
DWR	5	12

(SOP) has been prepared for monitoring and prediction of CDs and issue of warning. It includes the road map and check lists for this purpose.

The TC analysis, prediction and decision-making process was made by blending scientifically based conceptual models, dynamical & statistical models, meteorological datasets, technology and expertise. Conventional observational network, AWS, buoy & ship observations, cyclone detection radars and satellites were used for this purpose. A new weather analysis and forecasting system in a digital environment was used to plot and analyse different weather parameters, satellite, Radar and NWP model products. An integrated fully automated forecasting environment facility was thus set up for this purpose. The manual synoptic weather forecasting was replaced by hybrid systems in which synoptic method could be overlaid on NWP models supported by modern graphical and Geographical Information System (GIS) applications to produce

- High quality analyses
- Ensemble of forecasts from NWP models at different scales - global, regional and mesoscale
- Prediction of intensity and track of TC
- Specialized warning information to various sectors including Government and non-Government agencies.

The Tropical Cyclone Module (TCM) installed in this forecasting system has the facilities to serve the above purpose. The automation of the process has increased the efficiency of system, visibility of IMD and utility of warning products. For example, the mean sea level pressure analysis products before and after initiative are shown in Fig. 1. The improvements in monitoring and forecasting tools and techniques are shown in Table 2.

The TCM installed in this forecasting system has the following facilities:

- Analysis of all synoptic, satellite and NWP model products for genesis, intensity and track monitoring and prediction.

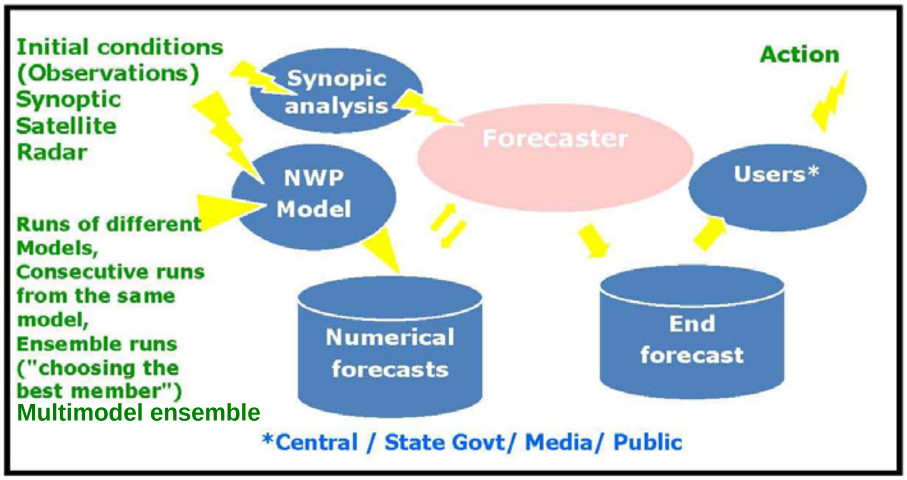

Fig. 2. Strategy adopted for cyclone analysis and forecasting

- Preparation of past and forecast tracks upto 120 hrs.
- Depiction of uncertainty in track forecast.
- Structure forecasting (Forecast of wind in different sectors of cyclone).

However, all the data are not still available in TCM through synergie system. For better monitoring and prediction, additional help is taken of FTP and websites to collect and analyse:

- Radar data and products from IMD's radar network and neighbouring countries.
- Satellite imageries and products from IMD and international centres.
- Data, analysis and forecast products from various national and international centres.

The strategy adopted for tropical cyclone analysis and forecasting is symbolically shown in Fig. 2.

3. Outcome of FDP-2008-2010

Salient features of achievements are described below.

3.1. *Cyclone track and intensity forecast*

For comparison, the 24 hr track forecast errors and the skill scores during the period 2003 to 2010 are shown in Figs. 3(a&b) The figures clearly indicate the gradual improvement in the cyclone forecast by IMD, as the error has decreased and the skill has increased. The average error was less than the long period average error for the cyclones over the north Indian Ocean (NIO). It is also very much comparable to the forecast errors over other Ocean basins including north Atlantic and Pacific Ocean basins. Considering the intensity forecast, the average 24 hrs wind forecast error (absolute error) has been about 12 knots (Table 3) for these cyclones.

Comparing the landfall forecast errors, [Regional Specialised Meteorological Centre (RSMC), New Delhi, 2009, 2010, 2011], the 24 hour mean error has been significantly less during last three years (2008-2010). It has come down to about 100 km as against the long period average error of about 150 km (Fig. 4).

The performance of NWP models have improved along with the introduction of NWP platforms like IMD Global Forecasting System (GFS), Weather Research & Forecast (WRF), Hurricane Weather Research & Forecast (HWRF) and Ensemble Prediction System (EPS). The mean track forecast errors of NWP models during 2010 are given in Table 4. The performance of multi-model ensemble (MME) prediction is reasonably good. The 48 hours track forecast errors by MME technique of IMD is about 200 km.

3.2. *Cyclone Warning Services*

The format and content of bulletins have been changed significantly as shown in Table 5. These changes have contributed to effective management of cyclone by disaster managers. The time of issue and frequency of

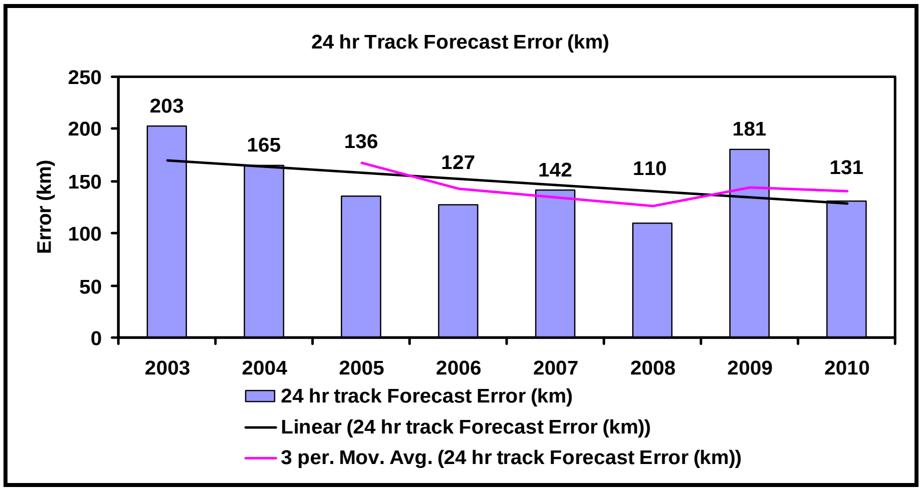

Fig. 3(a). 24 hr cyclone track forecast errors of IMD during 2003-2010

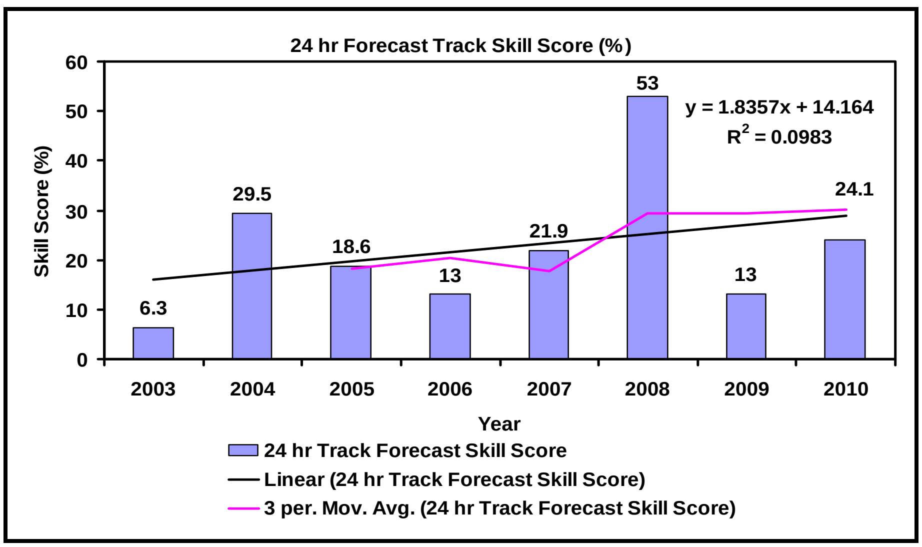

Fig. 3(b). 24 hr cyclone track forecast skill scores of IMD during 2003-2010

bulletins are standardized. The frequency of bulletin has also been increased along with the increase in number of users. The lead time of the forecast has been increased upto 72 hrs. The design of the bulletin has been revised with inclusion of prognostic and diagnostic features, observed and forecast track and intensity in tabular form and storm surge guidance for all member countries of World Meteorological Organisation/ Economic & Social Cooperation for Asia and the Pacific (WMO/ESCAP) Panel. The observed and forecast track and intensity of the cyclone were updated in cyclone page of IMD website time to time, based on the advisory bulletin issued by Cyclone Warning Division of IMD, New Delhi. The cone of uncertainty in the forecast has been introduced with effect from the cyclone, 'WARD' during December, 2009. It is helpful to the decision makers as it indicates the standard forecast errors in the forecast for different periods like 12, 24, 36, 48, 60 and 72 hrs. The examples of track and intensity forecasts issued by IMD are shown in Fig. 5. The radii of circles used to construct the cone of uncertainty are shown in Table 6.

The cyclone wind radii forecasts are generated in terms of the radii of 34 kts, 50 kts and 64 kts (1 kt = 0.52ms^{-1} or 1.85 kmph) winds in four geographical quadrants around the tropical cyclone (thereafter

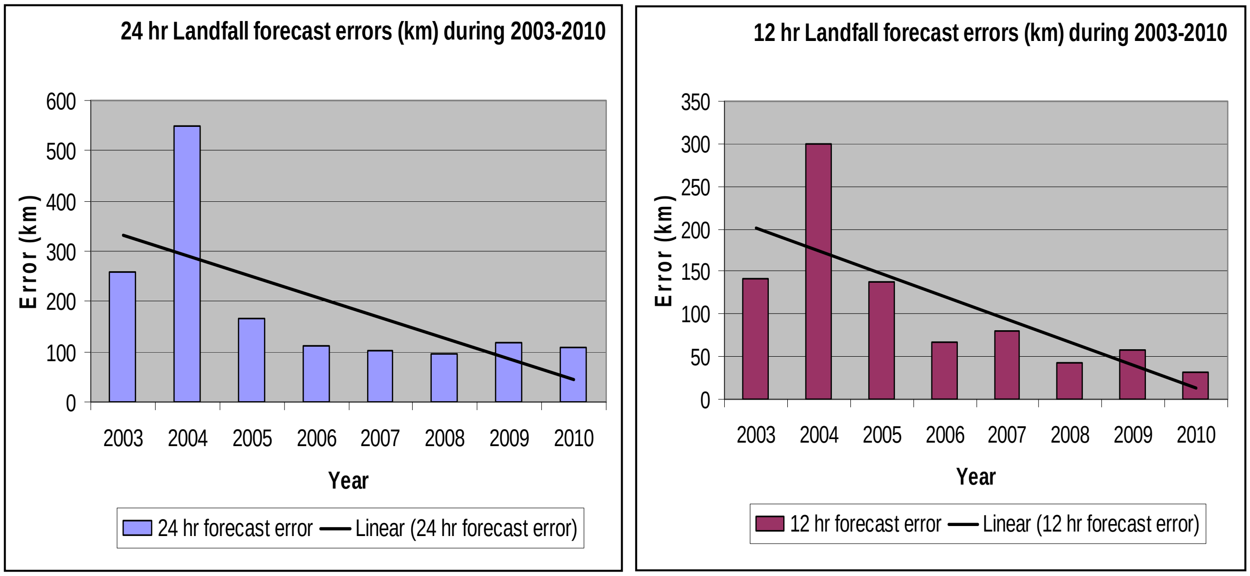

Fig. 4. Landfall forecast errors of IMD during 2003-2010

TABLE 2

Comparative analysis of tools and techniques by the end of 2007 and 2010

Parameters	Tools/technique by end of 2007	Additional tools/technique by end of 2010
Genesis	Synoptic, satellite (visible & IR imagery), NWP analysis of IMD GFS (T254), coarser resolution ECMWF, UKMO, NCEP, Quikscat, Ascat, AMV	Microwave imagery, Oceansat-II NWP analysis of IMD GFS(382) High resolution (25 km) ECMWF analysis
Location monitoring	Ship, Buoy, limited AWS, Quikscat, Ascat, AMV	Enhanced AWS network, GPS sonde, Buoy, Oceansat-II, microwave imagery
Intensity monitoring	Satellite (Visible and infrared imagery), Radar, Quikscat, Ascat, AMV, Buoy	Microwave imagery, enhanced DWR network, Buoy network, Oceansat-II,
Genesis forecast	Synoptic, satellite, radar, Low resolution NWP models	Microwave imagery, Dynamical statistical model, High resolution NWP models
Track forecast	Synoptic, satellite, radar, CLIPER, Limited NWP guidance (Coarser ECMWF, UKMET, NCMRWF (T80), LAM, MM5, QLM),	High resolution ECMWF, IMD GFS(382), Experimental (T574), NCEP GFS, ARP (Meteo-France), NCMRWF, MME, Experimental HWRF, WRF (ARW), WRF (NMM), modified CLIPER, ISRO GA technique
Strike probability	-	Strike probability based on EPS and super EPS
Intensity forecast	-	Dynamical statistical model
Rapid intensification	-	Dynamical statistical model

TABLE 3

Operational average intensity forecast error of 2010

Lead Period (hrs)	Intensity Error (knots)			No. of Observation verified
	Average	Absolute Average	RMS	
12	1.0	8.1	11.3	55
24	4.5	12.2	16.4	49
36	8.7	15.3	20.4	37
48	13.4	16.5	21.9	29
60	19.6	20.9	26.8	23
72	21.0	21.0	28.3	19

TABLE 4

Mean Track forecast errors of NWP models for cyclones during 2010

Average	12 hrs	24 hrs	36 hrs	48 hrs	60 hrs	72 hrs
ECMWF	54	71	102	170	202	246
NCEP-GFS	158	178	177	236	253	334
JMA	195	96	176	203	232	268
IMD-MM5	118	141	241	350	363	356
IMD-QLM	103	144	167	181	256	311
IMD-MME	72	104	140	205	190	244
IMD-T382	94	124	164	212	246	290
IMD-WRF-VAR	155	137	236	253	234	265

TABLE 5

Comparison of cyclone warning products and bulletins before and after the initiative

S. No.	Parameters	Bulletin issued before initiative (2007)	Bulletin issued after initiative (2010)
1	Date and time of issue of bulletin	Date only mentioned in the bulletin	Both date and time are mentioned
2	Current location, intensity	Yes	Yes
3	Past movement	Yes	Yes
4	Forecast validity period	Upto 24 hrs	Upto 72 hrs (+6, +12, +18, +24, +36, +48, +60 and +72 hrs)
5	Quality of forecast track and intensity	Qualitative	Quantitative
6	Landfall point and time	Qualitative	Quantitative with Lat./Long. of landfall and time
7	Prognostic and diagnostic features	Nil	Detailed features are explained in the Technical bulletin
8	Graphical presentation of observed and forecast track	No	Yes
9	Adverse weather (Heavy rain, Gale wind and storm surge)	Storm surge for Indian coast only	For coasts of all member countries of WMO/ESCAP Panel
10	Advice and action suggested	Yes	Yes, but more specific

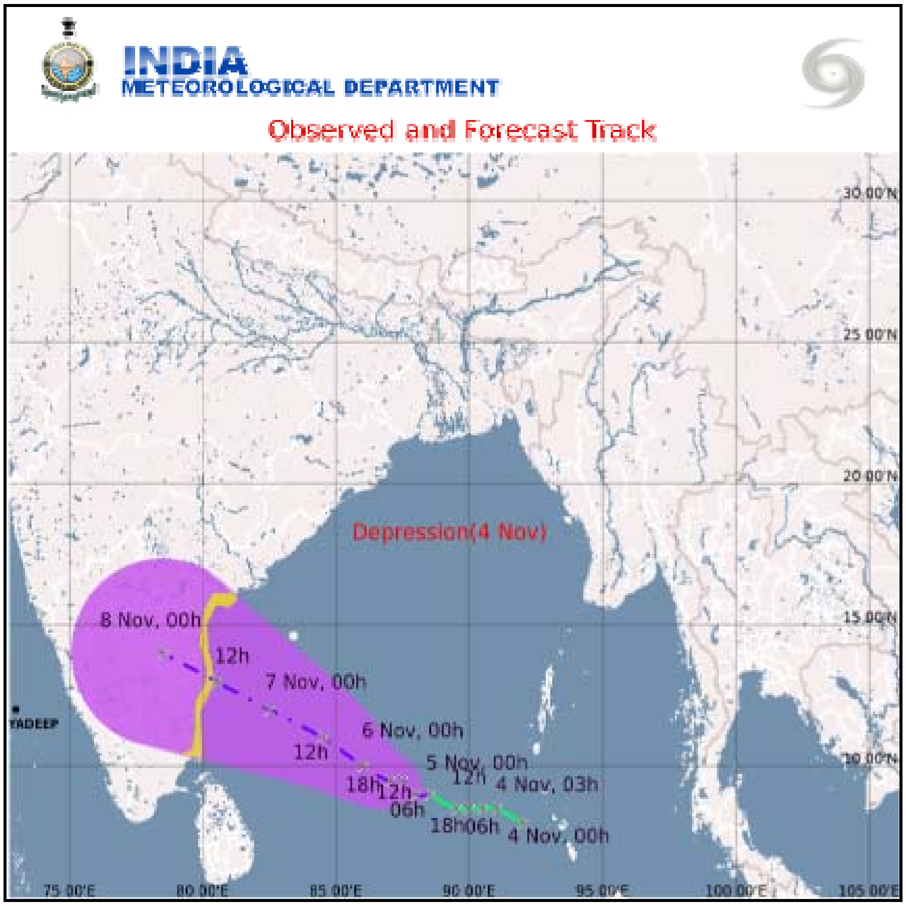

Fig. 5(a). A typical example of observed and forecast track of depression which later on became the severe cyclonic storm JAL

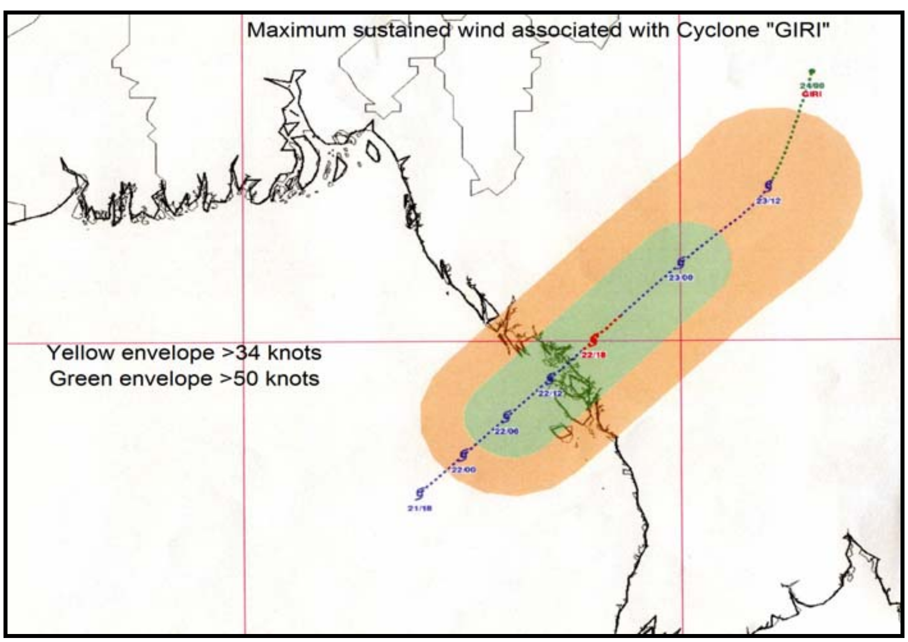

Fig. 5(b). A typical graphical presentation of cyclone wind forecast during cyclone, GIRI

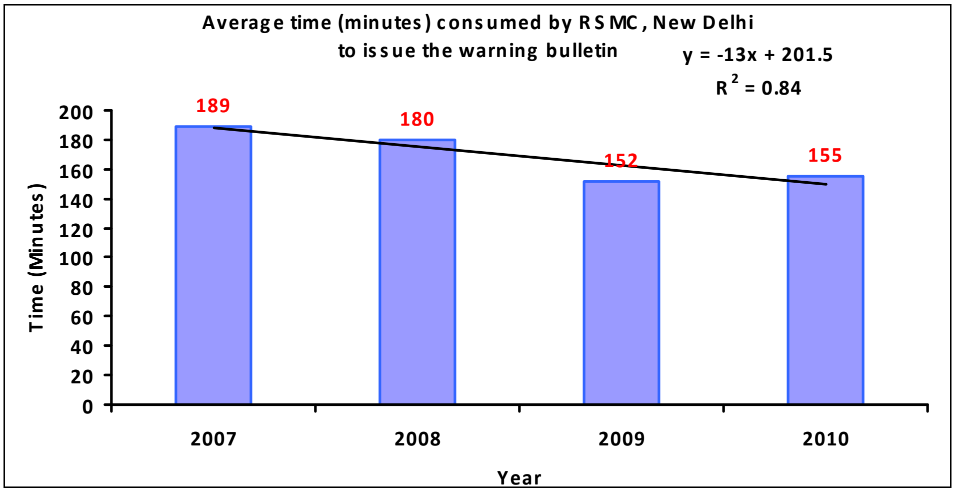

Fig. 6. Average time consumed by RSMC, New Delhi to issue cyclone warning bulletin since last three hourly synoptic observations

referred to individually as R34, R50 and R64 for 34kts, 50kts and 64kts wind thresholds respectively or collectively as wind radii in units of nautical miles [1nm = 1.85 km)]. These wind radii represent the maximum radial extent of winds reaching 34kts, 50kts and 64kts in each quadrant. The initial estimation and forecast of the wind radii of cyclone is rather subjective and strongly dependent on the data availability, climatology and analysis methods. The subjectivity and reliance on climatology is amplified in NIO in the absence of aircraft observations. However, recently with the advent of easily accessible remote sensing derived surface and near surface winds [*e.g*. OceanSat., Special Sensor Microwave Imager (SSMI), low level atmospheric motion vectors and Advanced Microwave Sounder Unit (AMSU) retrieval methods] and advances in real time data analysis capabilities, IMD introduced TC wind radii monitoring and prediction product in Oct, 2010. The initial wind radii estimates have become less subjective due to the tools and products mentioned above. While better initial estimates of R34, R50 and R64 are becoming available, forecasting these wind radii remains a difficult task. It is mainly because of the fact that we do not have any objective wind radii forecast methods and current NWP models fail to produce forecasts that are better than climatology (Knaff *et al.*, 2006, 2007, Knabb *et al.*, 2006).

The overall benefits due to improvement in cyclone warning bulletin contents after the initiative as compared to prior to initiative are shown in the Table 7. The improvement in time of delivery of cyclone warning bulletins to the disaster managers during 2007-2010 are shown in Fig. 6.

3.3. *Loss of lives due to cyclones*

The loss lives due to cyclone has reduced significantly due to many factors including improvement in early warning system of cyclone. Characteristics of two similar severe cyclones crossing Andhra Pradesh coast near Machhilipatnam in 2003 and 2010 are shown in Table 8 as example to compare the loss of human lives.

4. Challenges of FDP

With repeated attempt, the aircraft probing of cyclones could not be possible till now. It is a major challenge for FDP-2013-14. The FDP on landfalling cyclones over the Bay of Bengal with aircraft probing facility will help in minimising the error in monitoring and hence prediction of tropical cyclone track and intensity forecasts (Martin and Gray, 1993). In addition, this project will help in the following :

(a) Validation of Dvorak technique over the NIO.

(b) Validation of pressure-wind relationship in cyclones over the NIO.

(c) Understanding and prediction of structure of cyclones over the NIO.

TABLE 6

Radius of the circle based on standard error used to construct cone of uncertainty in cyclone track forecast

Forecast period (hrs)	Standard error (kms)
12	75
24	150
36	200
48	250
60	300
72	350

TABLE 7

Beneficiaries feedback of cyclone warning services before and after initiative

S. No.	Parameters	Beneficiaries feedback before initiative	Beneficiaries feedback after initiative (*e.g.* 2010)
1	Number of deaths	Higher	Less
2	Loss due to evacuation of people due to uncertainty in forecast	Higher	Less
3	Quality of warning presentation	Poor	Good
3	Appreciation by disaster management agencies	Limited	Appreciation by central & state Govt. agencies, and neighbouring countries
4	Number of warnees	Less, *e.g.* six in 2003-04 at national level	More, *e.g.* Fifteen in 2009-10 at national level
5	Number of visitors to cyclone page of IMD’s website	Less (No counter)	Significantly higher. Number of visitor during cyclone, PHET (June 2010) : 40, 000 (Approx.)

(d) Development/validation of wind conversion factor for converting 3-minute average wind to 1-minute average wind (used in Dvorak’s technique) and 10-min average wind (as required for preparation of standardised international best tracks archives).

(e) Reanalysis of best tracks with modified pressure-wind relationship, wind adjustment and modified Dvorak classification of intensity.

(f) Improvement/validation of performance of NWP models.

The other major challenges include (*i*) assimilation of regional data and development of suitable global and regional models for cyclone prediction with suitable modification of model physics, resolution and initial and boundary conditions (*ii*) development of ensemble prediction system based on IMD GFS and WRF models.

TABLE 8

Comparison of loss of human lives due to two similar cyclones crossing coast near Machilipatnam in 2003 and 2010

Cyclone period	17-21 May 2010	11-16 December 2003
Cyclone category	Severe cyclonic storm	Severe cyclonic storm
Point of landfall	South of Machhilipatnam	South of Machhilipatnam
Maximum wind at landfall	100 kmph	100 kmph
Landfall forecast error		
24 hr lead time	55 km	257 km
48 hr lead time	115 km	No forecast issued
72 hr lead time	207 km	No forecast issued
Loss of human lives	06	81

5. Conclusions

The FDP on landfalling cyclones over the Bay of Bengal has helped in improvement of monitoring, forecasting and warning of cyclones over the NIO. The observational network, tools and technologies, especially the NWP models have improved significantly during 2008-2010. As a result, the 24 hr forecast track error has reduced from 163 km during 2003-2007 to 141 km during 2008-2010. However, the main challenge of the FDP is still to be realised with the introduction of aircraft probing of cyclones and dropsonde experiments.

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