

Recent advancements in prediction of tropical cyclone track over north Indian Ocean basin

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सार – उष्णकटिबंधीय चक्रवात (TC) के पूर्वानुमान में सुधार लाना हमेशा से एक महत्वपूर्ण अनुसंधान क्षेत्र तथा मौसम विज्ञानियों के लिए चुनौतीपूर्ण कार्य रहा है क्योंकि यह मानव जीवन, संपत्ति और देशों की अर्थव्यवस्था पर बहुत अधिक प्रभाव डालता है। उष्णकटिबंधीय चक्रवातों के पूर्वानुमान में सुधार लाने के लिए विश्व भर के प्रचलनात्मक और अनुसंधान केंद्रों में मल्टी स्केल इंटरैक्शन के जरिए बेहतर ढंग से समझने का काम किया जा रहा है।

मोहंती और गुप्ता (1997) ने उत्तरी हिंद महासागर (NIO) बेसिन में उष्णकटिबंधीय चक्रवातों के मार्ग पूर्वानुमान के लिए अलग-अलग सांख्यिकीय और गत्यात्मक तरीकों को सविस्तार बताया है। वर्तमान समीक्षा लेख में संख्यात्मक मौसम पूर्वानुमान (NWP) विधियों पर जोर देते हुए अनुसंधान गतिविधियों पर ध्यान दिया गया है जिसके कारण पिछले दो दशकों में उत्तरी हिंद महासागर बेसिन में उष्णकटिबंधीय चक्रवातों के मार्ग का पूर्वानुमान देने में सुधार लाया जा सका है। इस शोध पत्र में NWP मॉडल के विकास और इन मॉडलों के द्वारा चक्रवातों की उत्पत्ति, भ्रमण और तूफान महोर्मियों पर चर्चा की गई है।

ABSTRACT. Improving the Tropical cyclone (TC) prediction is always an important research area and challenging task to the meteorologists since it poses a major impact on human life, properties and countries economy. The operational and research centers around the globe have been working to better understand the multiscale interactions involved to advance the TC predictions.

Mohanty and Gupta (1997) have elaborated different statistical and dynamical methods for the track prediction of TCs over the North Indian Ocean (NIO) basin. The present review article focuses on research activities with emphasis to numerical weather prediction (NWP) methods that led to advance the TC track prediction over the NIO basin in the last two decades. The evolution of NWP models and advancements in genesis, movement and storm surges by these models are discussed.

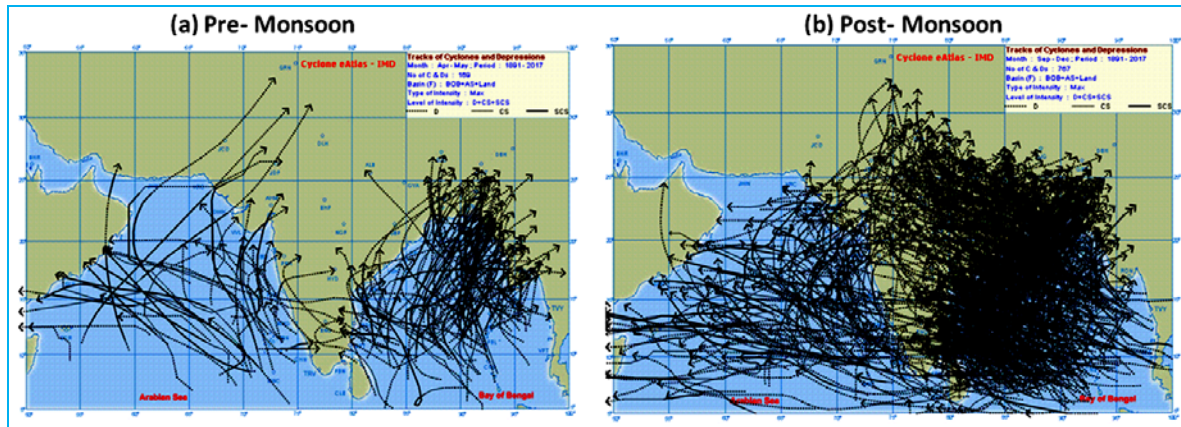
Key words – North Indian ocean, Tropical cyclones, Movement/track, Numerical weather prediction.

1. Introduction

The Tropical Cyclones (TCs) are termed differently in different parts of the globe. Over the Atlantic and Eastern Pacific, they are termed as ‘Hurricane’ and in western Pacific as ‘Typhoon’. In the North Indian Ocean (NIO) region, they are named as ‘Tropical Cyclone’. The NIO contributes 5-6 TCs every year (~7% of the world’s TCs) (Mohanty and Gupta, 1997). Though the percentage of frequency over the NIO basin is less relative to any other global basins, annual frequency rate is often stable with an average disparity of $\pm 7\%$. Every year, about 80 TCs causes an average number of 20,000 deaths and a total economic loss of \$6-7 billion (Mohanty *et al.*, 2015). Almost all the TCs form within 25° latitudes on both sides of the equator except in the equatorial region of 5° S to 5° N due to negligible Coriolis force.

The NIO basin comprised of Bay of Bengal (BoB) and Arabian Sea (AS), also commonly referred as Indian seas, is unique in its nature than any other global basins, as far as the genesis and season are concerned. Mohanty *et al.* (2011) suggest that the BoB and AS contributes ~76% and ~24%, respectively to the total number of TCs. In other ocean basins, TCs occur around late summer to early fall. However, the genesis of TCs over the NIO basin is very seasonal with primary maxima in post-monsoon season (October-December) and secondary maxima during pre-monsoon season (April-May) (Mohanty, 1997). The TCs over the NIO move usually the west, north-west and northward, sometimes, recurve towards north-east or east [Figs. 1(a&b)].

About 85% of the post-monsoon TCs move westward, out of which 30% is in October [Fig. 1(b)].



Figs. 1(a&b). Observed tracks of tropical cyclones over the NIO basin during 1891-2017 for (a) pre-monsoon season and (b) post-monsoon season

Northward moving TCs are also primarily seen in post-monsoon season. The northeastward moving / recurving TCs that cross Myanmar are common in the pre-monsoon season [Fig. 1(a)]. During the pre-monsoon season, inter tropical convergence zone (ITCZ) is located sufficiently over the open waters of the Indian seas which trigger low pressure system and its development into a stronger cyclone (Lee, 1989). As the storm gets intensified, it passes through several stages. Based on pressure drop and maximum sustainable surface wind, the World Meteorological Organization (WMO) classified the TCs over the NIO broadly into seven categories and is provided in Table 1.

2. Numerical prediction of tropical cyclones

The application of numerical models for tropical cyclones has certain difficulties. Firstly, tropical cyclones occur over data sparse tropical oceanic regions. This makes difficult to specify the initial state of the atmosphere accurately. Secondly, the region of high winds defining the tropical cyclone is small compared to synoptic scale systems and the present available observation network is not sufficient to represent such small scale systems in the meteorological analysis. There are limitations in the understanding of the dynamics of the tropical atmosphere and the interaction of the tropical cyclone with its surrounding environment. Some of these problems are partly solved with current advancements in the use of sophisticated numerical methods, advanced physics parameterizations, development of data assimilation methods, parallel computing techniques and so on. With the advent of high performance parallel computing techniques, it has become possible to use large area, multilevel, high resolution models. The implementation of multi-level nesting enabled to resolve the structure of tropical cyclones with a fine mesh grid

centered on the storm and the interaction of nested grid structures within a large grid which is used to represent the storm's changing environment. The limitation of initial conditions has been solved to some extent with the use of advanced data assimilation techniques with which all available observations can be incorporated to define the initial state.

A comprehensive review has been presented regarding the stepwise development in numerical weather prediction systems as well as statistical techniques by Mohanty and Gupta (1997). They have summarized that there has been significant progress in track prediction with the development of limited area models. Dedicated research towards improvement in resolution of global circulation models, improved parameterization schemes for presentation of physical processes and use of synthetic and non-conventional data for data assimilation is the key in achieving remarkable progress in the field of TC prediction. It has been realized that dense network of observation, better data assimilation and nudging methods, high resolution mesoscale models, better physical and micro-physical processes, land-ocean-atmosphere coupled systems, along with advancement in super-computing facility would deduct the uncertainty in forecast and help the community to predict TCs with reasonable accuracy at sufficient lead time. Till the first decade of 21st century, the improvements in the model (horizontal and vertical) resolutions and parameterizations of physical processes could improve the track forecast considerably (Goerss, 2006; Mohanty *et al.*, 2010, 2013; Osuri *et al.*, 2013), however, intensity prediction was still poor.

This dearth in cyclone intensity prediction can be solved for some magnitude by means of regional models. Continuous efforts have been made in the last two decades

to develop high resolution atmospheric models for tropical cyclone track predictions. Accurate numerical prediction of tropical cyclones is highly dependent on the quality of the initial state, resolving the in situ tropical cyclone circulation and the accurate representation of physical processes in the models. While large-scale flow determines the motion of the cyclones, the inner-core dynamics and its interaction with the environment determine the intensity of the system (Marks and Shay, 1998; Davis *et al.*, 2008). High resolution mesoscale models account for the asymmetric effects, interaction with the environment and to resolve the fine scale features associated with the tropical storms (Ley and Elsberry, 1976; Wang, 2001; Chen *et al.*, 1995; Kurihara and Bender, 1980; Liu *et al.*, 1997; Kurihara *et al.*, 1998; Aberson, 2001; Krishnamurti *et al.*, 2005 among several others). With the advancements in high performance computing and development of nested high resolution mesoscale models, the numerical forecasting of tropical cyclones has entered a new phase.

Under the modernization programme of IMD, several numerical models were introduced for 3-10 day predictions such as the IMD Global Forecast System (GFS), the WRF and HWRF system. Moreover, a few operational, research and academic institutes in India provide real-time forecast of TCs to IMD for its operational use, under the national programme, 'Forecast Demonstration Project of landfalling TCs (FDP-TC)' over BoB. In addition, the TC products from other global operational centers such as National Centers for Environmental Prediction (NCEP), European Centre for Medium Range Weather Forecast (ECMWF), the United Kingdom Meteorological Office (UKMO) and Japan Meteorological Agency (JMA) are available to forecasters. A single model ensemble prediction system (EPS) from various global models and multi-model ensembles (MME) was also introduced at IMD. Several studies were conducted to study the tropical cyclone evolution over the North Indian Ocean using advanced mesoscale models MM5, WRF-ARW and HWRF. They can be grouped in to different study categories namely physics sensitivity, resolution, initial conditions and impact due to data assimilation etc. Studies on TC simulations to physics sensitivity can be classified as dealing with physics sensitivity (Bhaskar Rao and Hari Prasad, 2006; Mandal *et al.*, 2004; Mandal and Mohanty, 2006; Trivedi *et al.*, 2006; Srinivas *et al.*, 2007; Deshpande *et al.*, 2010; Osuri *et al.*, 2012a ; Raju *et al.*, 2011; Mukhopadhyay *et al.*, 2011), on model grid resolution (BhaskarRao *et al.*, 2009, Osuri *et al.* 2013) and impact due to data assimilation (Singh *et al.*, 2008, 2012 a,b; Osuri *et al.*, 2012b, 2015; Routray *et al.* 2016; Srinivas *et al.*, 2010, 2012). A majority of these are case studies for few strong cyclones such as with Orissa Super

TABLE 1
Different stages of NIO cyclones and corresponding maximum wind defined by IMD

Category of system	Maximum sustained surface wind
Low Pressure Area (LPA)	< 17 knots
Depression (D)	17 - 27 knots
Deep Depression (DD)	28 - 33 knots
Cyclonic Storm (CS)	34 - 47 knots
Severe Cyclonic Storm (SCS)	48 - 63 knots
Very Severe Cyclonic Storm (VSCS)	64 - 89 knots
Extremely Severe Cyclonic Storm (ESCS)	90 - 119 knots
Super Cyclonic Storm (SuCS)	≥ 119 knots

Cyclone, GONU, SIDR etc. in the NIO region and vary with respect to model formulations, resolutions, physics etc. A prominent result of many physics sensitivity studies shows that while the convection schemes influence both intensity and motion of simulated storm, the PBL physics primarily influences the intensity. A common result reported by many studies is that the combination of MRF/YSU PBL and Kain-Fritsch convection schemes provided best simulations for track and intensity. Also it has been shown that the use of higher order PBL schemes based on prognostic TKE closure (Mellor and Yamada, 1982) give considerably higher intensity estimates than the first order non-local schemes based on eddy diffusivity approaches (YSU: Hong *et al.*, 2006). While some studies show that the microphysics (Wang, 2002) merely influences the morphology of the simulated storm, the others (Deshpande *et al.*, 2010; Mukhopadhyay *et al.*, 2011) show changes in intensity as well as vector position.

About data assimilation a good number of studies reported improvements in intensity and track forecasts of cyclones as for example using with multi-satellite data assimilation for Orissa Super Cyclone-1999, GONU-2007 and Mala-2006 using WRF (Singh *et al.*, 2011), with use of both conventional and satellite data in WRF for NISHA-2008 (Srinivas *et al.*, 2010), with satellite winds in WRF (Osuri *et al.*, 2012a) etc. Several impact studies of data assimilation were conducted on simulation of cyclones over the North Indian Ocean region (Roy Bhowmik 2003; Mukhopadhyay *et al.*, 2004; Sandeep *et al.*, 2006; among several others). Singh *et al.* (2008) reported that the assimilation of QuickSCAT and SSMI winds improve the position of the initial vortex, its strength leading to significant improvements in the intensity and track predictions for Orissa super cyclone. The Advanced Research WRF (ARW) model is one

among the widely used mesoscale models for weather predictions over the Indian region and indeed globally. Since 2007, the ARW model has been used for real-time TC forecasting over the NIO basin (Osuri *et al.*, 2012a, 2013). Substantial reduction in overall track (8-24%) and intensity (15-40%) forecast errors were observed when the model was used at a high resolution; in particular, there is a significant gain in predicting the re-curling nature of storms (Osuri *et al.*, 2013). This study highlighted the use of high resolution meso-scale models in prediction of track of the TCs over NIO. The 9 km horizontal grid spacing experiments have exhibited the least error in track position for all the forecast compared to the 18 and 27 km horizontal resolution experiments [Fig. 2(a)]. The error ranges from 106-329 km for forecast period of 24-72 hours, while 18 km and 27 km experiments ranges from 106-329 km and 113-375 km respectively for same forecast lengths. Osuri *et al.*, 2012a have discussed about the impact of satellite derived wind speed in prediction of TCs over NIO basin. In this study, an attempt is made to assess the impact of remotely sensed satellite-derived winds on initialization and simulation of TCs over the North Indian Ocean (NIO). For this purpose, four TCs over NIO basin comprises of 13 different cases, namely, Nargis, Gonu, 'Sidr' and Khai Muk, were considered. Two sets of numerical experiments, without (CNTL) and with satellite-derived wind data assimilation from QSCAT and SSM/I (SAT_WIND), are conducted using ARW model. The mean track errors from both the experiments are shown in Fig. 2(b). The results suggest that the CNTL runs have shown high track errors compared to the SAT_WIND runs. There is a mean improvement of 27%, 18% and 40% for 24, 48 and 72 hour forecast lengths. Osuri *et al.*, 2015 were studied the impact on TC prediction from assimilating DWR observations obtained from Kolkata and Chennai radars for four TCs over BoB basin. Fig. 2(c) displays the mean track error from with DWR and without DWR assimilation (CNTL). There is clear improvement has been achieved with the assimilation of DWR products in the high resolution meso-scale model. A significant error reduction has been observed after DWR assimilation.

The hurricane weather research and forecasting (HWRF) modeling system is a next generation non-hydrostatic hurricane model developed by NOAA and implemented as operational hurricane model by National Centre for Environmental Prediction (NCEP). Yeh *et al.* (2011) studied the real-time forecasts from an experimental version of HWRF called HWRF with two domains (27 and 9 km horizontal resolution) and is using slightly different physics for Atlantic hurricanes in 2008 considering a sample of 57 to 20 cases for 12 h to 120 h forecasts. The average track errors for 2008 hurricane season with HWRF/HWRF were found to range from

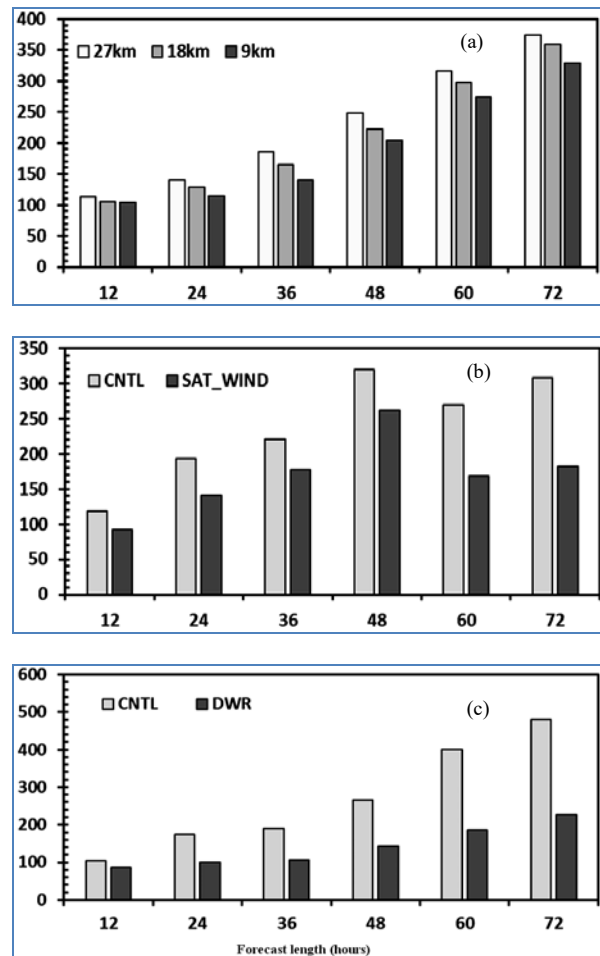
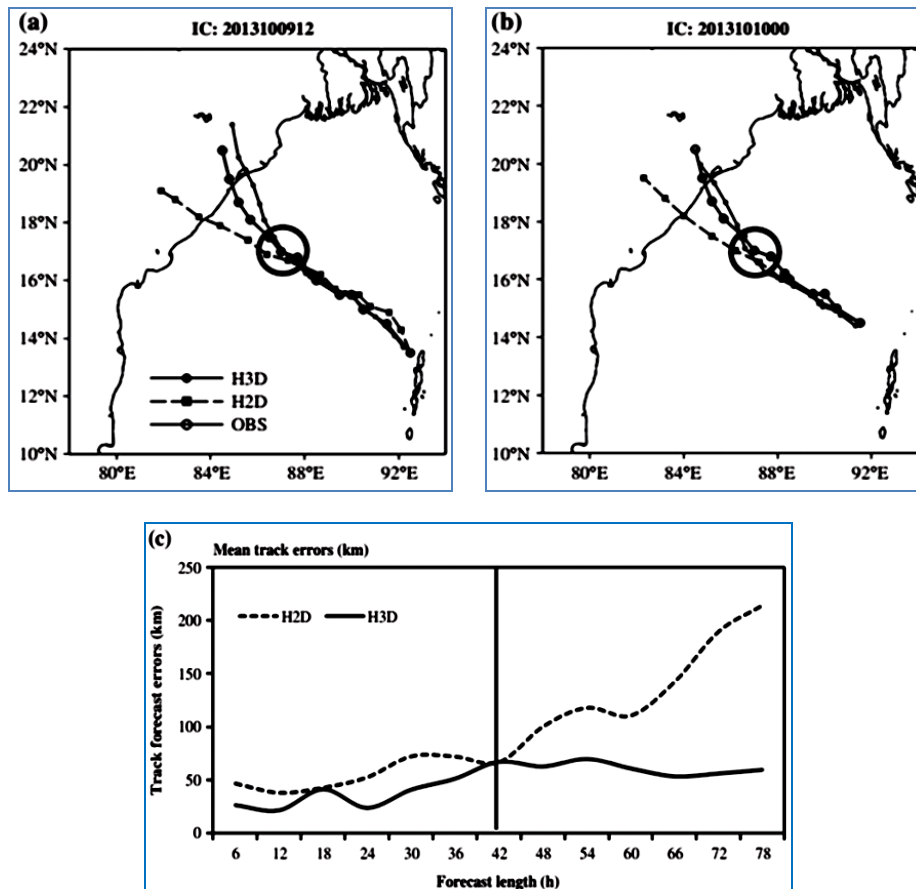


Fig. 2(a-c). Sensitivity of mean track errors of TCs over NIO basin to (a) horizontal resolution (Osuri *et al.*, 2013) and assimilation of (b) satellite derived winds (Osuri *et al.*, 2012a) and (c) DWR data (Osuri *et al.*, 2015)

37.5 /42.6 km at 12 hours to, 286.2/260.9 km at 120 hour forecasts and the corresponding mean intensity errors varied from 3.69/4.5 ms^{-1} at 12 hours to 11.6/12.7 ms^{-1} at 120 hours. Gopalakrishnan *et al.* (2012) evaluated the performance of the experimental high resolution HWRF for 87 cases of Atlantic tropical cyclones during the 2005, 2007 and 2009 hurricane seasons with two versions of horizontal resolutions (27-9 km and 9-3 km) using different initial conditions from the operational GFDL and HWRF models and with sensitivity tests for the model physics. It has been shown that the 9-3 km HWRF system using the GFDL initial conditions and the model physics similar to the operational version of HWRF provides the best results in terms of both track and intensity prediction. Mohapatra *et al.* (2012) have represented the best tracking procedure that helps in providing TC information during operational period at IMD. They have documented the details regarding the



Figs. 3(a-c). Predicted tracks from the H2D and H3D model configurations from initial conditions at 1200 UTC 9th October, 2013 along with the IMD observed best track. (b) Same as (a) but for initial conditions at 0000 UTC 10th October, 2013. (c) Mean track forecast errors (km) of six runs from both model versions. (Source: Osuri *et al.*, 2017)

observational network, monitoring technique, area of responsibility for monitoring for providing best information for all categories of TC, *i.e.*, climatology of genesis, location, intensity, movement and landfall. In 2012, operational version of HWRF at NCEP was made operationalized in IMD for prediction of TCs over NIO (Das *et al.*, 2015; Mohanty *et al.*, 2015). Das *et al.*, 2015 have shown the predictability of HWRF system over NIO and commented the deficient of HWRF in prediction of intensity prediction. Tropical Cyclone Phailin (2013) was predicted by three domain HWRF in terms of track, movement and intensity along with offline coupled surge prediction (Mohanty *et al.*, 2015; Osuri *et al.*, 2017). Osuri *et al.*, 2017 proved the credibility of HWRF system in predicting the track and rapid intensification of VSCS Phailin. In addition, they have highlighted the role of scale interactions in predicting the track and intensity changes. HWRF model was configured with two different setups, firstly two domains configured over NIO with 27 and 9 km horizontal grid spacing (called as H2D) and other with

three domains at 27, 9 and 3 km horizontal resolution (termed as H3D). The idea behind this is to resolve large and meso scale features in H2D setup, while Large, meso and vortex scale features will be resolved in H3D setup. Figs. 3(a&b), respectively, shows the simulated tracks for two initial conditions (1200 UTC 0900 and 0000 UTC 10 October, 2013) from H2D and H3D experiments along with the IMD best estimated track. From both cases, the system has altered its movement from north-westward to west-northwestward while moving towards land in H2D and made landfall over north of Visakhapatnam coast. The H3D simulations have shown landfall over Chilka (south Odisha coast), north of the observed location (Gopalpur) with least error in landfall position. Fig. 3(c) have shown the mean track error in km comprising of all 7 cases during the TC life span. The error statistics have been clearly showed the superiority in predicting tracks. The error ranges to a maximum of 200 km from H2D experiments, while H3D have exhibited less error and limited to a maximum of 96 km [Fig. 3(c)].

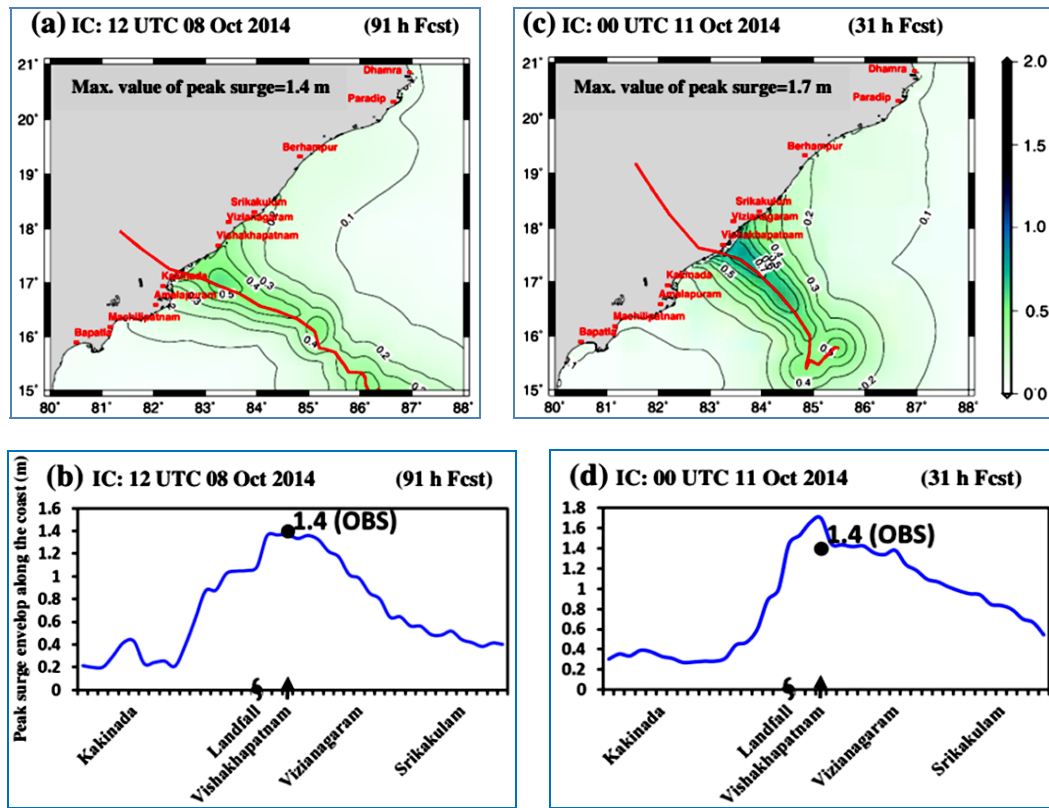
3. Coupled models in prediction of TCs

Although there is significant improvement in prediction of track of TCs in last few years, the intensity prediction still carries biases which sometime mislead the disaster authority to take necessary action during the calamity. Hence, the improved intensity prediction is a must to manage minimum loss. The atmospheric models used to predict the TCs (WRF and HWRF) have positive bias (overestimation of intensity) as they are unable to intake the ocean information underneath the TC during its forecast period. The large rotating system over the ocean churns the water which brings cool deeper water to surface thus inhibiting the warmth of sea surface temperature (SST). This diminishes the enthalpy flux exchange between the ocean and atmosphere which ultimately affects the TC intensity negatively. However, if the storm passes over a warmer SST or warm core eddy, the TC gets positive feedback from the ocean with enhancement of its intensity. If an oceanic meso-scale features exist in the storm path, the interaction becomes complex which should be included in the numerical prediction of the storm in order to improve the intensity forecast skill (Shay *et al.*, 2000; Jaimes and Shay, 2010; Lee and Chen, 2012). Thus, a modeling system equipped with both ocean and atmospheric models allowing exchange of ocean and atmospheric data for the forecast is required to implement for better prediction. Some numerical studies taking ocean-atmosphere coupled models explain various modulations from the formative stage to dissipative stage of the storm and thus improving the prediction skill (Chan *et al.*, 2001; Schade, 1998; Sandery *et al.*, 2010). Bender *et al.* (1993) taking coupled system of MMM (Moving Mesh Model): the atmospheric component and a primitive equation multilayer stratified model formulated in spherical coordinate system: ocean component, show slower-moving storms produce a progressively larger SST response and greater decrease of the total heat flux and hence a greater reduction in the tropical cyclone strength. Therefore, it is vital to take an account of ocean features for the precise prediction of tropical storms. For this, two-way interaction of atmosphere and ocean must be included in the numerical prediction system. A study by Srinivas *et al.* (2016) suggests that coupling of atmospheric model ARW and ocean model Price-Weller-Pinkel (3DPWP) for the prediction of TCs over NIO substantially improve the track and intensity forecasts. Although a number of climate coupled modeling systems are available, a few studies have been done to predict deterministically TC track and intensity using regional meso-scale coupled models. The high-resolution with the capability of telescoping moving grid, HWRF modeling system has the capability to be coupled with Princeton Ocean Model (POM) and Hybrid Coordinate Ocean Model (HYCOM).

This coupled system enabled as both operational and research purpose for Atlantic basin, presents better forecast skills than operational only-atmospheric component. The forecast skill and performance of HWRF-POM modeling system gives reasonably well prediction of storm intensity with proper simulation of evolving SST (Yablonsky *et al.*, 2014). However, HWRF-HYCOM system adopts a simple and comprehensive initial condition (IC) and boundary condition (BC) procedure providing a 3D estimation of the balanced ocean state with hurricane forcing, thus removing the need for separate ocean initialization for hurricane simulation (Kim *et al.*, 2013). The realistic representation of the air-sea exchange will improve the predictability of TCs, hence a comprehensive ocean-atmosphere HWRF modeling system needs to be established over NIO.

4. Storm surge prediction

With the advancement of numerical modeling, the storm surge associated with a TC which causes the maximum damage to life and property with coastal inundation, is predicted skillfully well in advance. The earliest attempt to have numerical storm surge prediction for the Indian Ocean basin was made by Das (1972). Ghosh (1977) adopted SPLASH model later known as Ghosh model, at IMD for storm surge prediction. Subsequent attempts have been made to improvise the prediction skill of the storm surge model over BoB and AS (Das *et al.*, 1974; Ghosh, 1977; Johns and Ali, 1980; Rao, 1982; Dube *et al.*, 1985a&b; Murty *et al.*, 1986; Flather and Khandekar, 1993). Three different numerical models with different model of representation of the coastlines of entire BoB are developed and tested for qualitative surge response (Johns *et al.*, 1981). Johns *et al.* (1983) presented a comparison between a sophisticated three dimensional numerical surge model with a turbulent energy closure scheme and a depth-averaged numerical approach using wind-stress forcing data of 1977 Andhra cyclone. The contemporary models for prediction of surges over NIO use two-dimensional finite-difference model developed at Indian Institute of Technology Delhi (IITD). The model description and numerical solution are explained in Das *et al.* (1983). The wind forcing to the model is calculated through Jelesnianski wind formulation (Jelesnianski and Taylor, 1973) which uses estimated pressure drop and radius of maximum wind. A community surge model; ADCIRC is also used for prediction of surge heights and inundation area (Luettich and Westerink, 2004). Recent improvement in storm surge is due to remarkable improvement in the prediction of track and intensity of the TCs accomplished in recent years, but not due to major implication of physical parameterization required for surge prediction. A lot of studies have established that the importance of accurate mesoscale



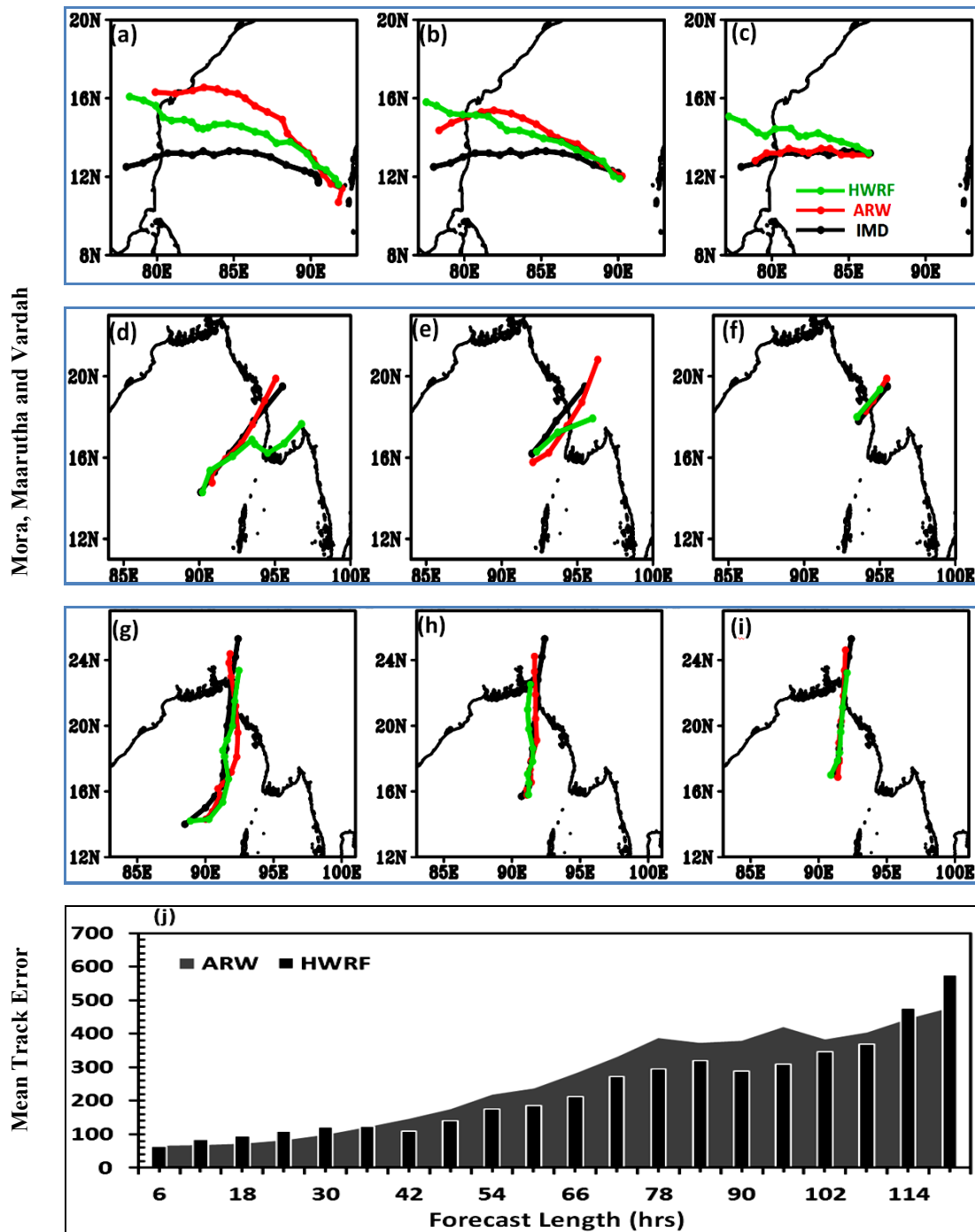
Figs. 4(a-d). Model predicted (a) surge height (m) and b peak surge envelope (m) along the coast at different locations with initial condition 1200 UTC 8th October, 2014 (91 h lead fcst). c, d are same as a, b, but with initial condition, 0000 UTC 11 October, 2014 (31 h lead fcst). The black dot in (b, d) is the observed peak surge from tide gauge at Vishakhapatnam. (Source: Nadimpalli *et al.*, 2016)

forcing estimation for surge model input (Dube, 2009; Pradhan, 2012). Different weather service centers around the globe use different models for different basins. National Weather Service (NWS) uses SLOSH model (Sea, Land, Overland Surge for Hurricane) for operational purpose to implement real time, imaginary: evacuation for mitigation, historical for validation purpose, probable and extra-tropical storm surge simulations. Mohanty *et al.*, 2015 were forecasted the storm surge associate with VSCS Phailin over south Odisha coast well in advance of 72 hours with inputs from high resolution meso-scale model output such as RMW, 10 m wind speed, pressure drop etc. Nadimpalli *et al.*, 2016 have shown the real time storm surge guidance from the one-way offline coupled with ARW model for VSCS Hudhud. They have pointed out the usefulness of dynamical storm surge models with inputs from ARW model. From Fig. 4(a), it is observed that the peak surge height of 1.4 m was forecasted on right side of the storm in advance of 91 h of landfall from IC 1200 UTC 8 October, 2014. The maximum surge height envelope along the Andhra Pradesh coast exhibited that the peak of 1.36 m surge is forecasted over Vishakhapatnam coast, *i.e.*, north of the TC landfall

position [Fig. 4(b)]. Similarly, the IC 0000 UTC 11 October, 2014 [Fig. 4(c)] also have shown the peak surge of 1.7 m to the north of the TC track and the station wise analyses indicate that the maximum surge of 1.7 m was at Vishakhapatnam [Fig. 4(d)].

5. Predictability of TC track and movement

The high resolution regional models WRF-ARW and HWRF, with the capability to predict the TCs with reasonably good accuracy, have been configured for operational purpose to predict the real time TCs over NIO in IMD, New Delhi. The models show high skill in predicting TCs over BoB as well as AS well in advance. ARW model is a fully compressible, non-hydrostatic primitive equation model that follows Arakawa C grid staggering and terrain-following vertical coordinates. The model is adaptable with a number of option for multiple nesting, use of boundary conditions, data assimilation and parameterization schemes for sub-grid scale processes (Osuri *et al.*, 2013). HWRF uses a non-hydrostatic mesoscale model (NMM) dynamic core with rotated latitude-longitude projection with E-grid staggering and



Figs. 5(a-j). (a-c) Predicted track of the TC Vardah from ARW (red) and HWRF (Green) along the IMD best estimation (Black) at different initial conditions, (d-f) & (g-i) are same as (a-c) but for the cyclonic systems, Maarutha and Mora respectively and (j) Mean track error in km for all the cases

51 hybrid (terrain following pressure sigma) vertical coordinates (Tallapragada *et al.*, 2015). The model comprises of three domains; a large parent domain and the capability of two moving telescopic nested domains following the vortex. This modeling system is based on

the combination of specifically designed physics schemes to best predict the hurricanes/TCs. It has been designed with the capability to couple the system with ocean and wave models too (Gopalakrishnan *et al.*, 2012; Tallapragada *et al.*, 2015). Under ‘Forecast Demonstration

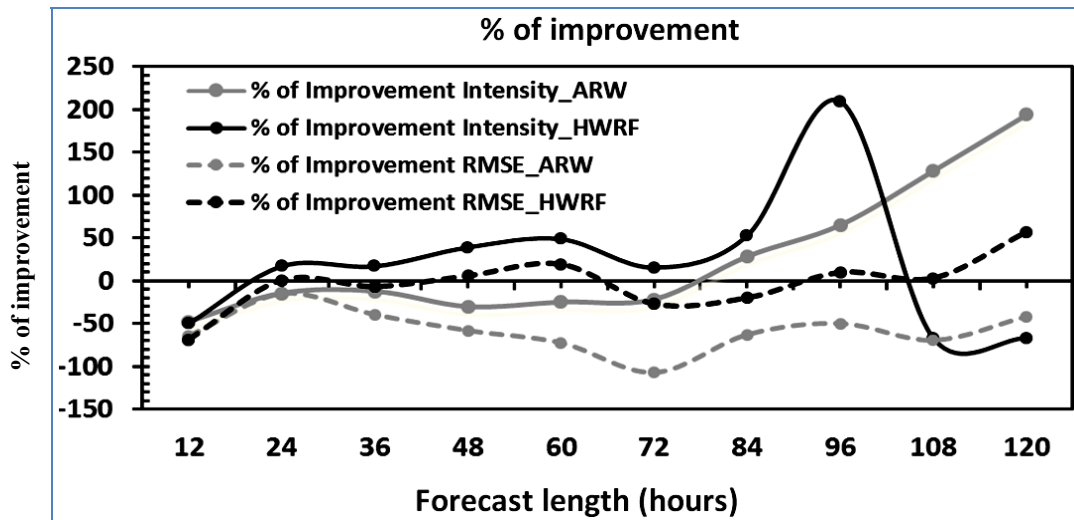
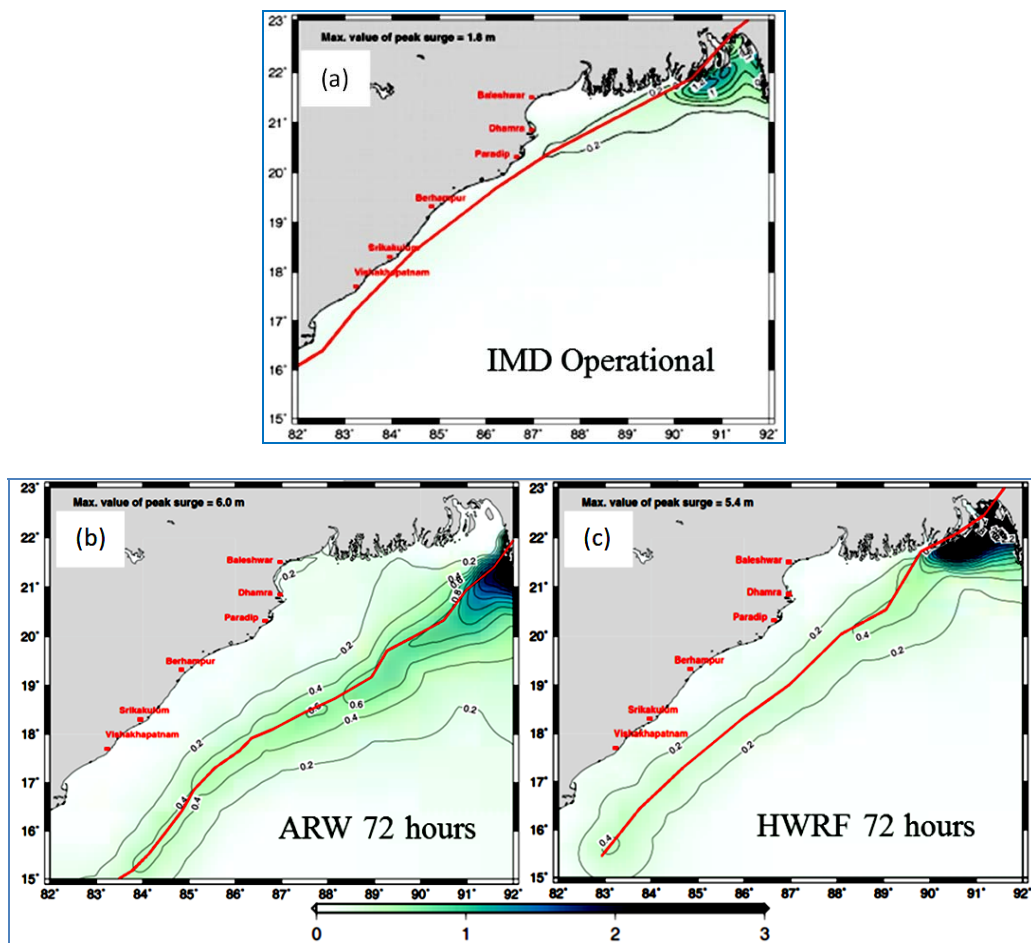


Fig. 6. Percentage of improvement in intensity error calculated using IMD official long term average



Figs. 7(a-c). Storm surge forecast Prediction using (a) IMD best track and intensity data named as IMD Operational, (b) 72 hours forecast data from meso-scale model ARW and (c) 72 hours forecast data from meso-scale model HWRF calculated through Ghosh model developed at IIT Delhi

TABLE 2
Mean intensity error in knots computed against IMD observations

S. No.	Forecast length	BIAS		RMSE	
		WRF	HWRf	WRF	HWRf
1.	12	5	7	15	17
2.	24	9	4	18	16
3.	36	10	4	22	18
4.	48	14	2	25	18
5.	60	16	1	25	16
6.	72	16	7	32	20
7.	84	13	9	30	23
8.	96	9	5	29	21
9.	108	-1	12	23	20
10.	120	-5	4	15	5

Project of landfalling TCs (FDP-TC) over BoB, Indian Institute of Technology, Bhubaneswar (IIT BBS) provides quasi-operational forecast on real time basis to IMD using both WRF and HWRf models, although the models are primarily used for research purpose. A quantitative analysis of the performance of both the models in predicting the track and intensity of TCs over NIO has been carried out taking 42 cases. The initial position and intensity predictions by the models are analyzed to verify the initial errors going to the model which ultimately magnifies the uncertainty errors during forecast. The configured models have been verified for the tracks of the TCs compared with IMD observed tracks over NIO. It has been broadly observed that WRF model shows better skill in predicting the overall track of the storm for most of the forecast periods. An example representing the track predictions from both the models compared with IMD observed track has been shown in Fig. 5 for three recent TCs; Vardah, Maarutha and Mora for 72, 48 and 24 hours forecast lead time. The track error calculation for all 42 cases considered gives a better idea of the track predictable skill of the models which is given in Fig. 5 (j). Interestingly, up to 36 hours of forecast, WRF model exhibits the less track error. In other hand, HWRf has been shown the reduced error in track prediction. The model performance for intensity prediction can be verified in terms of bias and RMSE which has been tabulated in Table 2. The bias and RMSE are given for each 12 hourly forecast for both the models. It is observed that except the very initial (12 hour forecast) and longer forecast (≥ 108 hour) periods, HWRf model consistently gives less bias and low RMSE value showing its greater efficiency in prediction of intensities. The performance of the model

predicted intensities are further verified against the IMD's long term operational errors in terms of the model skill (Fig. 6). Percentage of improvement in intensity is higher for HWRf for all forecast hour upto 96 hours. Percentage of improvement in root mean square error (RMSE) is also more for HWRf as compared to ARW for all the forecast hours. The highly capable meso-scale models; WRF-ARW and HWRf have helped in improved prediction of storm surges. Ghosh model/IITD model (Ghosh, 1977) for surge prediction is used taking pressure drop and radius of maximum wind information from ARW and HWRf models. An example of TC Roanu surge prediction from ARW and HWRf models compared with the prediction done from information provided by IMD during operational period using Ghosh model is shown in Figs. 7(a-c). The peak surge predicted from IMD operational method is 1.8 m whereas the peak surge from ARW is 6.0 m and from HWRf is 5.4 m. The observed surge height at Bangladesh coast is 2.0 m. More bias in ARW model leads to prediction of high surge as compared to HWRf.

6. Evolution of NWP models and reduction in the damage associated with TCs

In the Orissa super cyclone (1999) of BoB, about 130 lakhs of people were affected and ~10,000 people died. Similarly, more than 3300 deaths and about 2.5 millions of acres crop damage was recorded due to the VSCS Sidr (2007). The VSCS Nargis (2008) caused more than 1,38,000 deaths in Myanmar. This higher rate of death toll was mainly due to the failure in dissimulating the acute forecast well in advance.

The damage potential with specific emphasis to human deaths has been reduced significantly in recent years due to improved TC prediction in 4-5 days' advance. It could also provide ample time for effective disaster mitigation and management strategy. For example, VSCS Phailin (2013) which was the second most intense storm over NIO after 1999 super cyclone. Due to highly accurate prediction of Phailin in 4-5 days advance, a massive evacuation plans have been undertaken by the regional and national disaster management authorities, due to which the death toll is limited to two (Mohanty *et al.*, 2015). In the similar way, death toll is 46 in case of the VSCS Hudhud (2014) and is also attributed to the better forecast guidance (Nadimpalli *et al.*, 2016).

7. Conclusions

From the above results and discussions, the following broad conclusions are drawn:

- (i) There are large number of efforts made from last three decades to progress the prediction of TCs over NIO using various NWP models and assimilation techniques.
- (ii) Especially, high resolution meso-scale models (WRF and HWRF) have shown their credibility in predicting TC tracks when compared to the other global models.
- (iii) The HWRF model was efficacious in providing intensity forecast guidance well in advance. The mean error and RMSE of intensity (10 m maximum wind speed) up to 96 h forecast length is considerably less in HWRF predictions whereas ARW model not shown the same.
- (iv) The improvement in prediction of track and intensity has also led to improve in storm surge prediction well in advance of 3-4 days.
- (v) Further improvements can be achieved by the incorporation of improved land surface parameters, coupled modeling systems, advanced data assimilation, etc.

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