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RESEARCH ARTICLE

UNDERSTANDING THE RAPID ADVANCEMENTS IN THE FORECAST OF PATH OF TROPICAL CYCLONE OVER INDIAN OCEAN BASIN

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Abstract

Improving the forecast of Tropical cyclone (TC) is always an important research area and difficult task for the meteorologists since it poses a major impact on human life, properties and countries economy. The research and operational centers around the globe have been working to completely understand the multiscale interactions involved to advance the TC predictions. Mohanty and Gupta (1997) have elaborated different dynamical methods and statistical methods for the track prediction of TCs over the North Indian Ocean (NIO) basin. The review article focuses on activities related to research with more emphasis on numerical weather prediction (NWP) methods which led to advance the TC track prediction over the NIO basin in the last two decades. The growth of NWP models and advancements in the genesis, movement and storm surges by these models are discussed.

Key words: Indian ocean basin, Tropical cyclones, Forecast/prediction, Movement/track/path, Numerical weather prediction.

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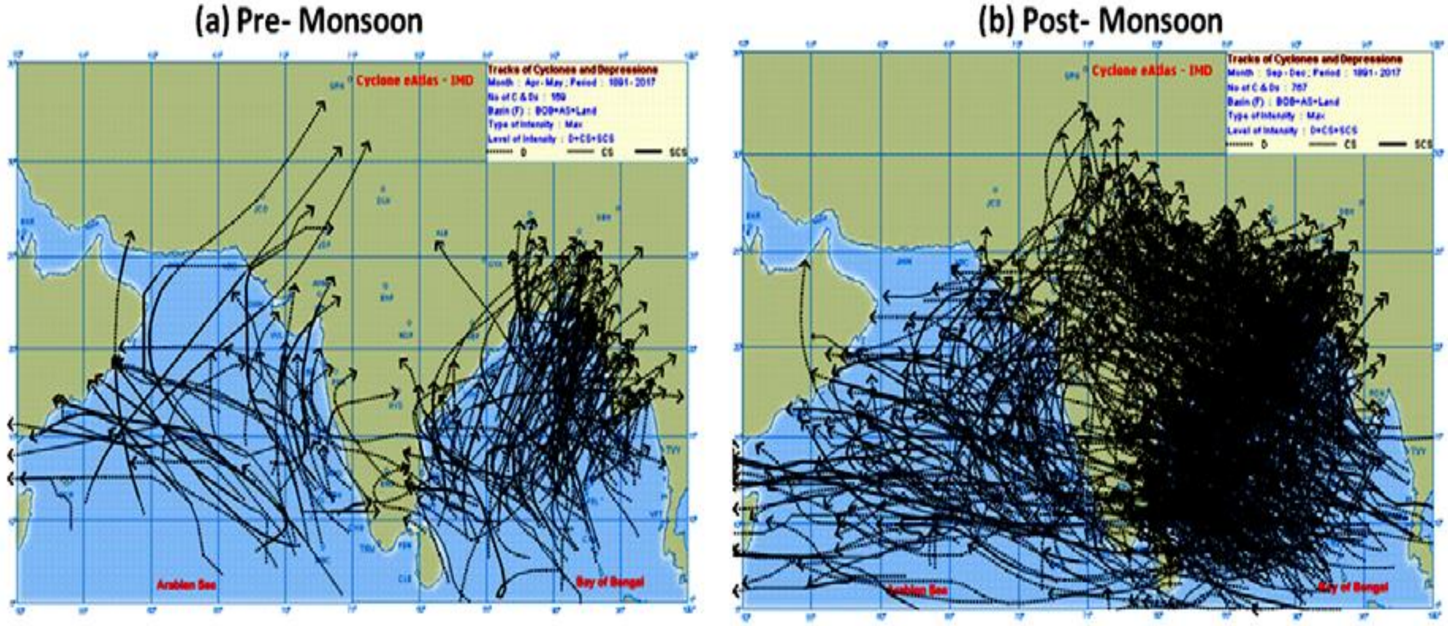
Introduction

The Tropical Cyclones (TCs) have different names in different parts of the globe. Over the Atlantic and Eastern Pacific, they are named as 'Hurricane' and in the western Pacific known as 'Typhoon'. In the North Indian Ocean (NIO) region, they are called as 'Tropical Cyclone'. The NIO contributes five to six TCs every year which is about

7% of the world's TCs (Mohanty and Gupta, 1997). Though the percentage of occurence of TCs over the NIO basin is less relative to any other global basins, annual frequency rate is often stable with an average disparity of ±7%. Every year, about 80 Tropical cyclones causes an average death of 20,000 in total and an averaged economic loss of $6-7 billion (Mohanty *et al.*, 2015).

Almost every 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 which includes Bay of Bengal (BoB) and Arabian Sea (AS), also commonly referred to as Indian seas, is unique in its nature than any other global basins, if genesis and season are concerned. Mohanty *et al.* (2011) suggest that the BoB and Arabian sea contributes about ~76% and ~24%, respectively to the total number of TCs.

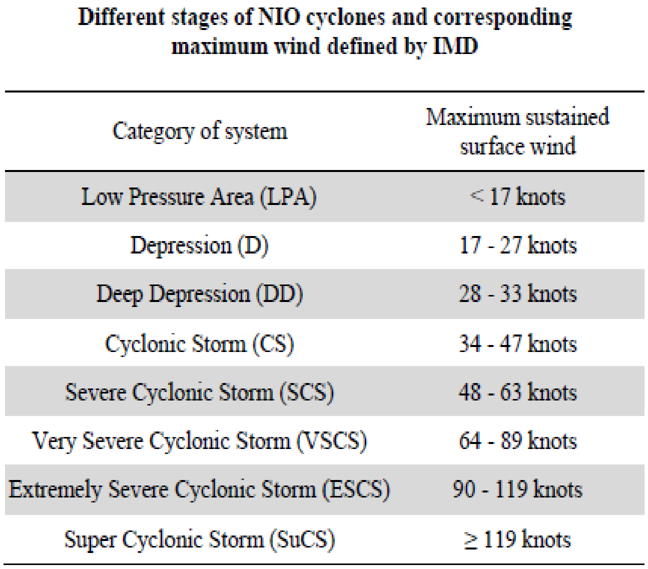
In other ocean basins, Tropical cyclones occur during late summer to early fall. Moreover, the generation of TCs across the NIO basin is very seasonal with primary maxima in the post-monsoon season (October- December) and secondary maxima during the pre-monsoon season (April-May) (Mohanty, 1997). The TCs over the NIO move usually the west, north-west and northward, sometimes it turns and move towards north-east or east [Figs. 1(a&b)]. About 85% of tropical cyclones which occur during post-monsoon season move westward, out of which 30% is in October [Fig. 1(b)].



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

Northward moving TCs are also primarily seen in the post-monsoon season. The north-eastward moving or recurving Tropical Cyclones 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 the low pressure system and its growth into a stronger cyclone (Lee, 1989).

When the storm gets intensified, it passes through the several stages. Based on most extreme manageable surface breeze and pressing factor drop, the World Meteorological Organization (WMO) ordered the TCs over the NIO bowl generally into seven classes which is given in the following 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

Materials and method

1. Numerical forecasting of tropical cyclones

The application of numerical models for tropical cyclones has certain difficulties. Firstly, the TCs occur over the data sparse tropical oceanic regions. This makes hard to indicate the underlying condition of the environment precisely. Secondly, the high winds regions which are 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 analysis done in meteorology.

There are some limitations in the understanding of the dynamics of the tropical atmosphere and the interconnection of the tropical cyclone with its surrounding environment. Some of these problems will be solved with current advancements in the use of sophisticated numerical methods, advanced parameterizations in physics, data development assimilation methods, parallel computing techniques and so on. With the arrival of high performance parallel computing techniques, now it has become possible to use large area, multilevel, high resolution models. The performance of multi-level nesting enabled to resolve the structure of TCs with a fine mesh grid centered on the storm and the interconnection of nested grid structures within a large grid which is used to denote the storm's changing environment. The limitations of initial conditions has now been solved to some extent with the use of new advanced data assimilation techniques with which all the available observations can now be incorporated to define the initial state.

A well explained 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 explained that there has been significant improvement in the track prediction with the advancements of limited area models. Dedicated research for the improvement in resolution of the global circulation models, improved parameterization schemes for the presentation of physical processes and the use of synthetic as well as non-conventional data for data assimilation is the key for achieving the remarkable progress in the field of TC forecasting. It has been observed that the dense network of observations, better data assimilation and nudging methods, high resolution meso-scale models, better physical and micro-physical processes, land-ocean-atmosphere coupled systems, along with development in the super-computing facility that would deduct the uncertainty in the forecast and help the community to predict TCs with good accuracy at sufficient lead time. Till the first decade of 21st century, the developments in the model (horizontal and vertical) resolutions and parameterizations of physical processes could improve the forecast of cyclone track considerably (Goerss, 2006; Mohanty *et al.*, 2010, 2013; Osuri *et al.*, 2013).

This dearth of cyclone intensity prediction can be solved for some magnitude by the help of regional models. Accurate numerical prediction of TCs is highly dependent on the quality of the initial state, resolving the in situ TC circulation and the exact representation of the physical processes in the models. While large-scale flow identifies the motion of the cyclones, the inner-core dynamics and its interaction with the environment calculate the intensity of the system (Marks and Shay, 1998; Davis *et al.*, 2008).

High resolution meso-scale models which account for the asymmetric effects, interconnection with the environment and to resolve the fine scale features related 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 improvements in high performance computing and development of the nested high resolution meso-scale models, the numerical forecasting of tropical cyclones has now entered a new phase. Under the modernization program of IMD, a few mathematical models were presented for around 3-multi day expectations, for example, the IMD Global Forecast System (GFS), the WRF and HWRF framework. Moreover, some of the operational, research and academic institutes in India provide real-time forecast of Tropical cyclones to IMD for its operational use, under the national programme, 'Forecast Demonstration Project of landfalling TCs (FDP-TC)' over the BoB. In addition to 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) which are available to the forecasters. A single ensemble model prediction system (EPS) from various global models and multi-model ensembles (MME) was also introduced at IMD. Too many researches have been conducted to study the TC evolution over the North Indian Ocean by using the advanced meso-scale 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 Tropical cyclone simulations to physics sensitivity can be categorised 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 the data assimilation (Singh *et al*., 2008, 2012 a,b; Osuri *et al*., 2012b, 2015; Routray *et al*. 2016; Srinivas *et al*., 2010, 2012).

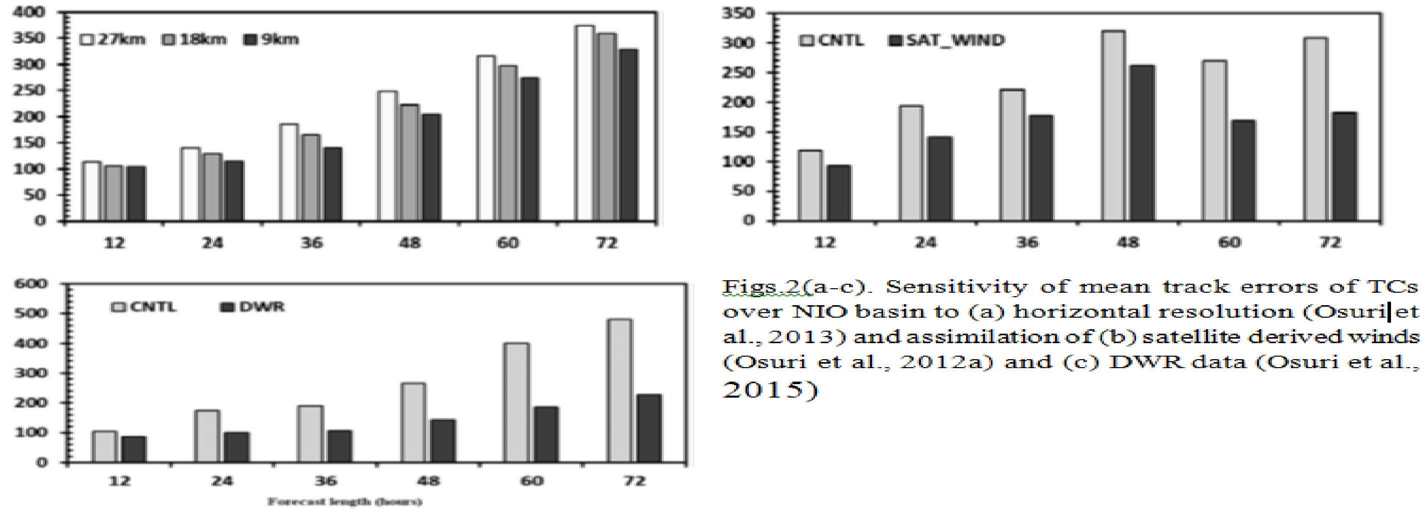
A prominent observation of many physics sensitivity studies shows that while the convection schemes influence both intensity and motion of the simulated storm, the PBL (Planetary Boundary Layer) physics primarily influences the intensity. A most common result reported by many studies is that the combination of MRF/YSU PBL and Kain-Fritsch convection schemes provides the best simulations for the track and intensity. Also it has been proved 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 upon the eddy diffusivity approaches YSU: Hong *et al*., 2006).

The Advanced Research WRF (ARW) model is one among the broadly used meso-scale models for weather predictions over the Indian region and indeed globally. Since 2007, the ARW model has been used for the real-time Tropical Cyclone forecasting over the NIO basin (Osuri *et al*., 2012a, 2013). Generous decrease in the general track (8-24%) and power (15-40%) figure mistakes were seen when the model was utilized at a high goal; specifically, there is a huge profit in predicting the re-curving behaviour of the storms (Osuri *et al*., 2013). This study shown the use of high resolution meso-scale models in prediction of the track of the TCs over NIO.

The 9 km horizontal grid spacing experiments have shown the least error in track position for all the forecast when compared with the 18 and 27 km horizontal resolution experiments [Fig. 2(a)]. The error now ranges from 106-329 km for the forecast period of 24 to 72 hours, while 18 km and 27 km experiments ranges from 106-329 km and 113-375 km respectively for the same forecast lengths. Osuri et al., 2012a have said that the effect of satellite determined breeze speed in forecast of Tropical twisters over the NIO bowl. In this research, an attempt which has been 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 reason, four Tropical cyclones over NIO basin comprises of 13 different cases, namely, Nargis, Gonu, 'Sidr' and Khai Muk, were considered.

Two arrangements of mathematical examinations, without (CNTL) and with satellite-got wind information digestion from QSCAT and SSM/I (SAT_WIND), are directed utilizing ARW model.The mean track errors from both the experiments are shown in Fig. 2(b). The results shown that the CNTL runs have shown high track errors as when compared to the SAT_WIND runs. There is an average improvement of 27%, 18% and 40% for 24, 48 and 72 hour forecast lengths.

Osuri et al., 2015 clarified the effect on TCs expectation from absorbing DWR perceptions acquired from Kolkata and Chennai radars for four TCs over Bay of Bengal bowl. Fig. 2(c) displays the mean track error from with DWR and without DWR assimilation (CNTL). There is clear development which has been achieved due to the assimilation of DWR products in the high resolution meso-scale model. A remarkable error reduction has been observed after DWR assimilation.



Figs.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)

The hurricane weather research and forecasting (HWRF) modelling system is a next generation non-hydrostatic hurricane model which has been developed by NOAA and implemented as operational hurricane model by National Centre for Environmental Prediction (NCEP). Yeh *et al*. (2011) examined shown the ongoing estimates from a test variant of HWRF called HWRFX with two of the areas (27 and 9 km level goal) and is utilizing somewhat different physics for Atlantic hurricanes in 2008 considering a sample of 57 to 20 cases for 12 h - 120 h forecasts. The average track errors for 2008 hurricane season with HWRF/HWRFX were found in the range from 37.5 /42.6 km at 12 hours to, 286.2/260.9 km at 120 hour forecasts and the corresponding average intensity errors changing from 3.69/4.5 m/s at 12 hours to 11.6/12.7 m/s at 120 hours.

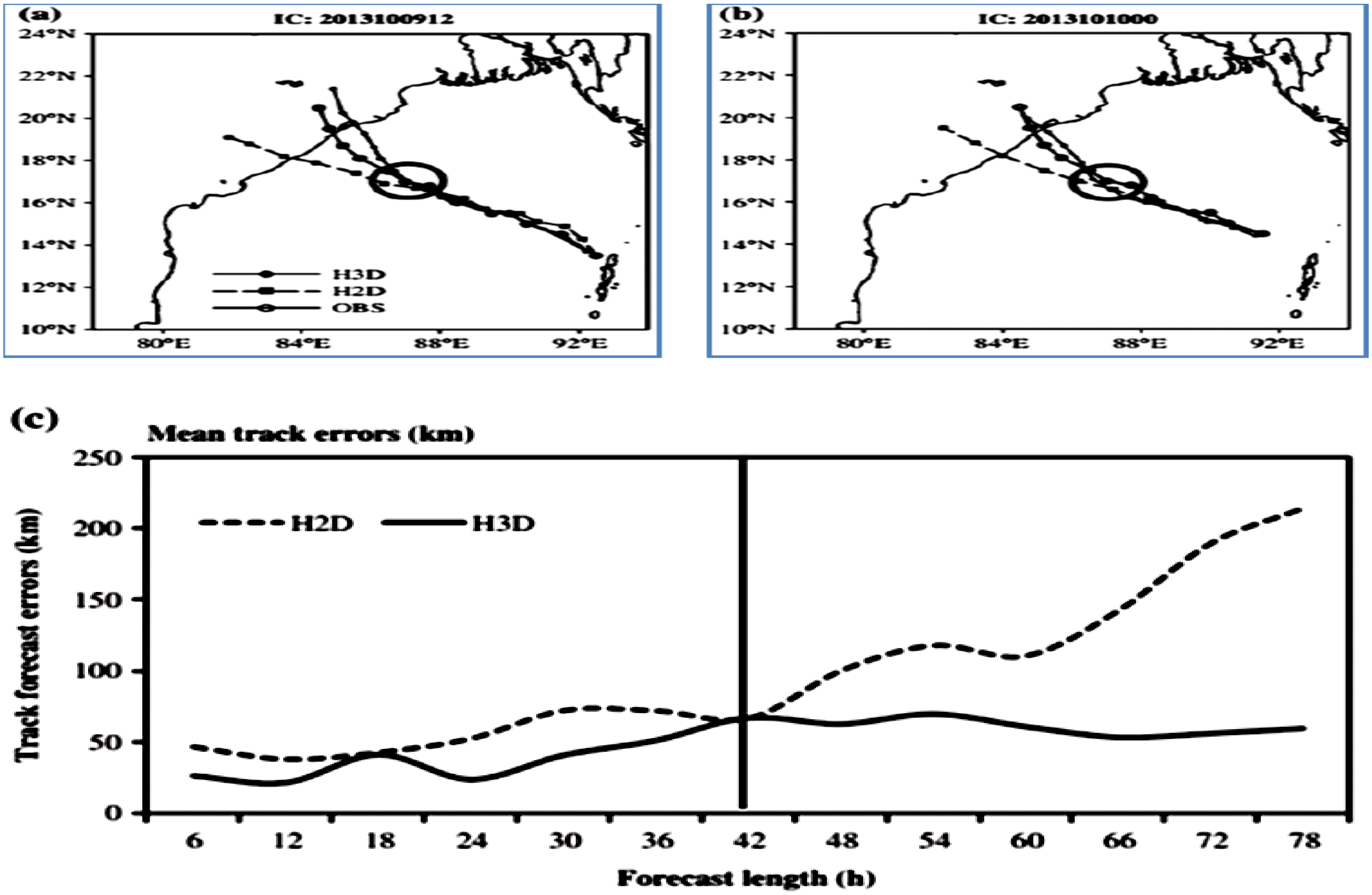
Gopalakrishnan *et al.* (2012) broke down and noticed the presentation of trial high goal HWRFX for 87 instances of Atlantic typhoons during the 2005, 2007 and 2009 storm seasons with two forms of horizontal resolutions (27-9 km and 9-3 km) using various initial conditions from the operational GFDL and HWRF models with the sensitivity tests for the model physics. It has been seen that the 9-3 km HWRFX framework utilizing the GFDL beginning conditions and the model material science which was like the functional variant of HWRF gives the best outcomes in terms of both path and intensity prediction.

Mohapatra *et al.* (2012) have shown the best tracking procedure which helps in providing Tropical Cyclone information during the operational period at IMD. They have listed the details regarding the observational network, monitoring technique, area of responsibility for checking and providing the best information for all categories of TCs, *i.e*., climatology of the genesis, location, intensity, movement and landfall. In

2012, operational version of HWRF at NCEP has been made functionalised in IMD for prediction of the TCs over NIO basin (Das *et al*., 2015; Mohanty *et al*., 2015).

Das *et al*., 2015 have shown and proved the predictability of HWRF system over NIO basin and told that lack of HWRF in prediction of intensity prediction. Tropical Cyclone Phailin (2013) has been forecasted 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 shown the proficiency of HWRF system in predicting the path and rapid intensification of VSCS Phailin. In addition, they told that the role of scale interactions in predicting the track and intensity changes.

The HWRF model have been 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 main intention is to resolve the large and meso-scale features in H2D setup, while Large, meso and vortex scale features will be resolved in the H3D setup. Figs. 3(a&b), respectively, shows the mimicked ways for two of the underlying conditions (1200 UTC 0900 and 0000 UTC 10 October, 2013) from H2D and H3D tries alongside the IMD best assessed track. From both of these cases examined, the framework has changed its development from north-toward the west to west-northwestward while moving towards land in H2D and made the landfall over the north of Visakhapatnam coast. The H3D reenactments have shown the landfall over Chilka (south Odisha coast), north of the noticed area (Gopalpur) with least blunder in the landfall position. Fig. 3(c) have shown that the mean track blunder in km containing every one of the 7 cases during the Tropical twister life range.The error statistics have been nicely showed the superiority in predicting the 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)].



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)

2. Coupled models with atmospheric and oceanic parameters included in prediction of TCs

However there is critical improvement in the guaging and expectation of track of TCs in most recent couple of years, the power forecast actually conveys blunders and predispositions which at some point deceive the disaster management authority to take necessary action during the time of calamity. Hence, the new improved intensity prediction is a must to manage minimum loss. The atmospheric models which are used to predict the Tropical cyclones (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(Sea Surface Temperature) or warm core eddy, the TCs gets positive feedback from the ocean with enhancement of its intensity. If any oceanic meso-scale features exist in the path of storm then the interconnection becomes complex which should be included in the numerical prediction of the storm in order to improve the skill of forecasting intensity (Shay *et al*., 2000; Lee and Chen, 2012; Jaimes and Shay, 2010). Thus, a modeling system equipped with both ocean and atmospheric models allowing the exchange of ocean and atmospheric data for the forecast is very much required to implement for better prediction. Some numerical studies taking ocean-atmosphere coupled models explain various types of modulations from the formation stage to dissipation stage of the storm and thus improving the prediction skill (Sandery *et al*., 2010; Chan *et al*., 2001; Schade, 1998).

Bender *et al*. (1993) took the coupled arrangement of MMM (Moving Mesh Model): the air segment and a crude condition multi-facet defined model planned in circular organize framework: sea part, show more slow moving storms produce a progressively larger SST response and significant 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 correct prediction of tropical storms. For this, two-way interconnection 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 enhance the track and intensity forecasts. However there are number of environment coupled displaying frameworks are accessible, a couple of studies have been done to foresee deterministically TCs way and force utilizing local meso-scale coupled models.The high-resolution with the capability of telescoping moving grid, HWRF modelling 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 good forecast skills than operational only-atmospheric component. The forecast skill and performance of HWRFPOM modeling system gives reasonably well prediction of the storm intensity with proper simulation of evolving the SST (Yablonsky *et al*., 2014).

Be that as it may, HWRF-HYCOM framework secure a straightforward and exhaustive introductory condition (IC) and limit condition (BC) strategy which gives a 3D assessment of the fair sea state with typhoon constraining, thus removing the need for separate ocean initialization for the 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 modelling system needs to be established over North Indian Ocean Basin.

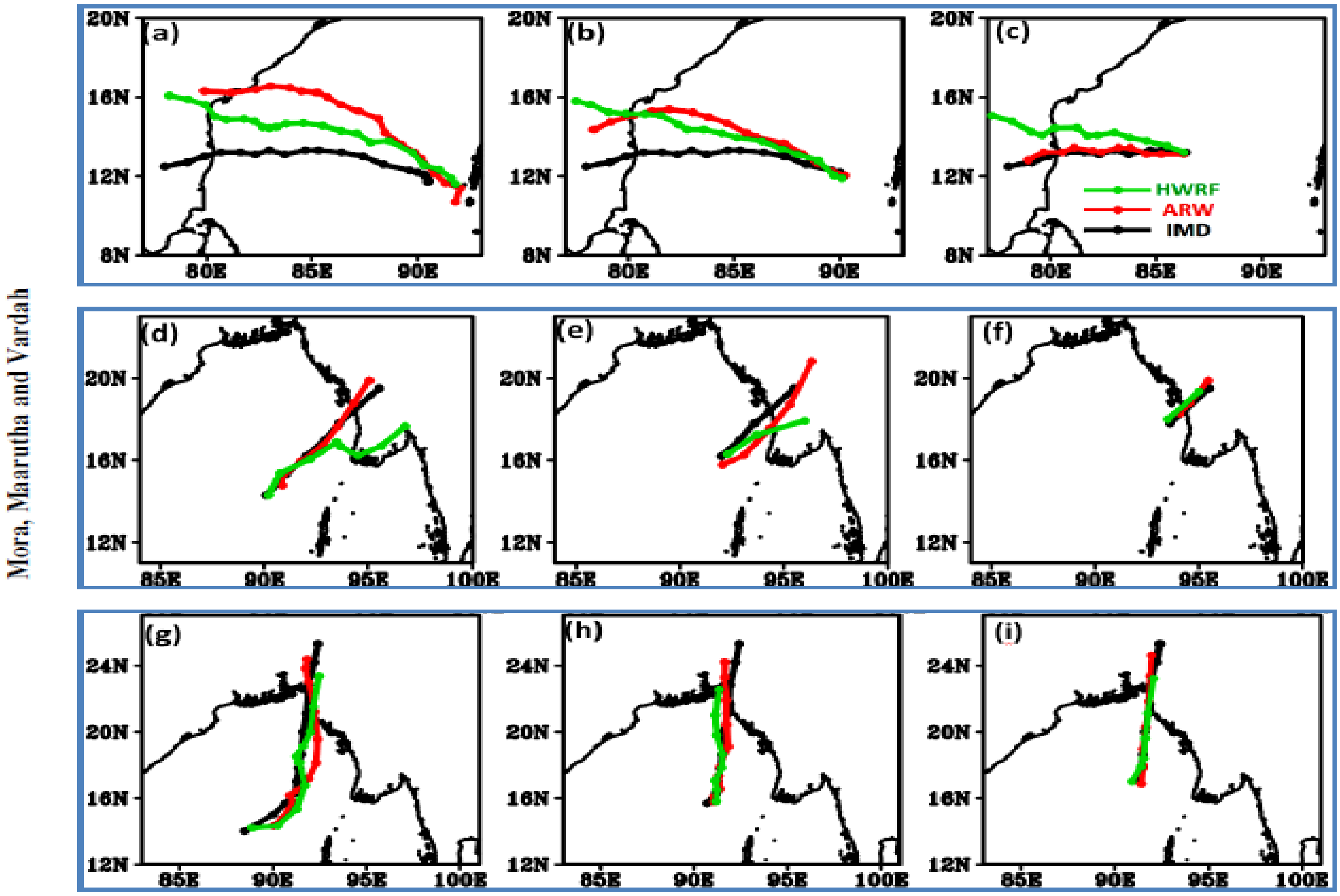
3. Predictability of Tropical Cyclone path and movement

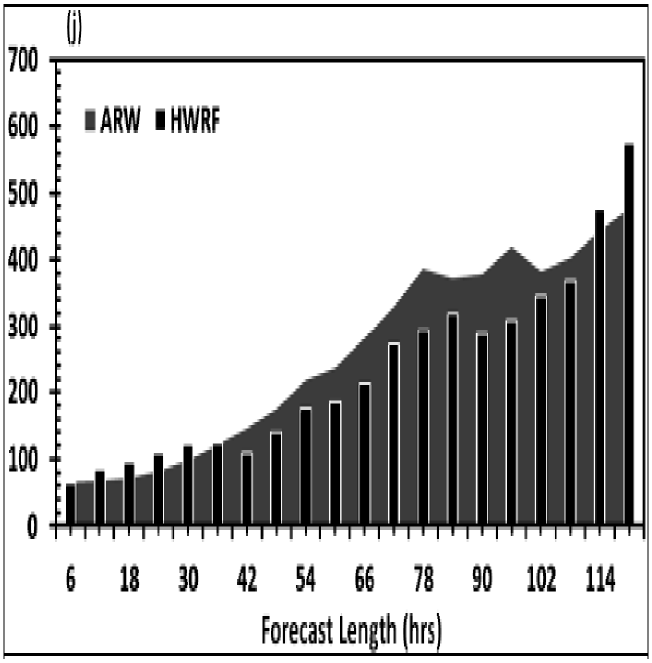
The high resolution regional models WRF-ARW and HWRF, with the ability to forecast the TCs with good accuracy, have been configured for the operational use to predict the real time Tropical cyclones over NIO basin in IMD, New Delhi. The models show their high skill in forecasting TCs over BoB as well 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 versatile with various choice for numerous settling, utilization of limit conditions, information absorption and definition plans for sub-framework scale measures (Osuri et al., 2013).

HWRF uses a non-hydrostatic meso-scale model (NMM) dynamic core with rotated latitude-longitude projection with the E-grid staggering and 51 hybrid (terrain following pressure sigma) vertical coordinates (Tallapragada et al., 2015). The model consists of three domains; a large parent domain and the capability of two moving telescopic nested domains following the vortex. This modeling system is completly based upon the combination of specifically designed physics schemes to predict the hurricanes/TCs accurately. It has been designed with the ability to couple the system with ocean and wave models too (Gopalakrishnan et al., 2012; Tallapragada et al., 2015).

Under the project ‘Forecast Demonstration Mean Track Project of landfalling TCs (FDP-TC)’ over BoB, Indian Institute of Technology, Bhubaneswar (IIT BBS) which provides quasi-operational forecast on real time basis to IMD using both WRF and HWRF models, though the models are primarily used for research purpose. A quantitative analysis of the performance of both the models in forecasting the path and intensity of TCs over NIO basin have 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 at last magnifies the uncertainty errors during forecast. The developed models have been checked for the tracks of the TCs contrasted and IMD noticed tracks over NIO bowl. It has been widely observed that WRF model shows better skill in predicting the overall track of the storm for most of the forecast periods.





Figs. 4(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 (Mohanty et al., 2019)

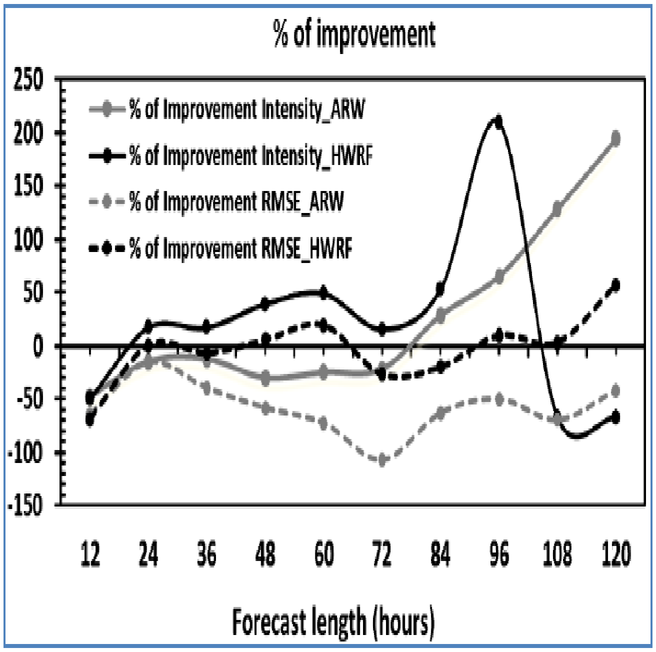


Fig. 5. Percentage of improvement in intensity error calculated using IMD official long term average (Mohanty et al., 2019)

An example which is representing the track predictions from both the models compared with the IMD observed track has been shown in Fig. 4 for three recent TCs; Vardah, Maarutha and Mora for 72, 48 and 24 hours forecast lead time. The track error evaluation and analysis for all 42 cases considered gives a better idea of the track predictable skill of the models which is given in Fig. 4 (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 performance of the model for intensity forecasting 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 has been 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 forecasted intensities which are further verified against the IMD's long term operational errors in terms of the model skill (Fig. 5). 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 flood forecast is utilized taking pressing factor drop and span of greatest breeze data 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 pinnacle flood anticipated from IMD functional technique is 1.8 m while the pinnacle flood 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 (Mohanty et al.,2019).

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

4. Evolution of Numerical Weather Prediction models and reduction in the damage related and associated with Tropical cyclones

In the Orissa super cyclone (1999) of Bay of Bengal, about 130 lakhs of people were affected and about ~10,000 people died. In the same manner, more than 3300 deaths and about 2.5 millions of acres damage to the crop 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 dissimilating the exact and accurate forecast well in advance.

The damage potential with specific emphasis to human deaths have been decreased significantly in recent years to due to the advanced and improved TC prediction in 4-5 days' advance. It could also provide ample time for the effective disaster mitigation and management strategy. For example, VSCS Phailin (2013) which was the second generally heartbreaking and extraordinary tempest over NIO bowl after 1999 super cyclone.

Due to highly accurate forecasting 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 decreased too much and is limited to two (Mohanty et al., 2015). In the same way, death toll reduced and is 46 in case of the VSCS Hudhud (2014) and is also attributed to the better forecast guidance (Nadimpalli et al., 2016).

Result and Discussion

From the above obsevations and discussions, broadly the following conclusions are drawn:

Large number of efforts have been made since last three decades to progress the prediction of Tropical cyclones across North Indian Ocean using various assimilation techniques and NWP models.

High resolution meso-scale models (WRF(Weather Research and Forcasting) and HWRF (Hurricane Weather Research and Forcasting)) have shown their proficiency in predicting paths of Tropical cyclones when compared to the other global models.

The HWRF model was efficient enough in providing intensity forecast guidance well in advance. The RMSE and Mean error of intensity (10 m maximum wind speed) up to 96 hour forecast is considerably less in HWRF predictions whereas ARW model was not showing the same result.

The improvement in forcasting of path and intensity of TCs has also led to improve the storm surge prediction well in advance of 3-4 days.

Further improvements can be achieved by the incorporation of improved land surface parameters, coupled modeling systems and advanced data assimilation.

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References

1. Aberson, S. D., 2001, "The ensemble of tropical cyclone track forecasting models in the North Atlantic Basin (1976-2000)",*Bull. Amer. Met. Soc.*, 82, 9, 1895-1904.
2. Bender, M. A., Ginis, I. and Kurihara, Y., 1993, "Numerical Simulations of Tropical Cyclone-Ocean Interaction with a high-resolution coupled model", *J. Geophy. Researh*., 98, 23245-23263.
3. Bhaskar Rao, D. V. and Hari Prasad, D., 2006, "Numerical prediction of the Orissa super cyclone: Sensitivity to the parameterization of convection, boundary layer and explicit moisture processes",*Mausam,* 57, 1, 61-78.
4. Bhaskar Rao, D. V., Hari Prasad, D. and Srinivas, D., 2009, "Impact of horizontal resolution and the advantages of the nested domains approach in the prediction of tropical cyclone intensification and movement", *Journal of Geophysical Research:Atmospheres,* D *(*114).
5. Chan, J. C. L., Duan, Y. and Shay, L. K., 2001, "Tropical cyclone intensity change from a simple ocean-atmosphere coupled model", *J. Atmos. Sci.*, 58, 154-172.
6. Chen, D. R., Yeh, T. C., Haung, K. N., Peng, M. S. and Chang, S. W.1995, "A new operational typhoon track prediction system at the central weather Bureau in Taiwan", Preprints 21st Conference on Hurricanes and Tropical Meteorology Society, Boston, 50-51.
7. Das, A. K., Rao, Y. R., Tallapragada, V., Zhang, Z., Bhowmik, S. R. and Sharma, A., 2015, "Evaluation of the Hurricane Weather Research and Forecasting (HWRF) model for tropical cyclone forecasts over the North Indian Ocean (NIO)", *Nat. Hazards,* 75, 1205-1221.
8. Das, P. K., 1972, "A prediction model for storm surges in the Bay of Bengal", *Nature,* 239, 211-213.
9. Das, P. K., Dube, S. K., Mohanty, U. C., Sinha, P. C. and Rao, A. D., 1983, "Numerical simulation of the surge generated by the June 1982 Orissa cyclone", *Mausam,* 34, 4, 359-366.
10. Das, P. K., Sinha, M. C. and Balasubrahmanyam, V., 1974, "Storm surges in the Bay of Bengal", *Quarterly Journal of the Royal Meteorological Society*, 100, 437-449.
11. Davis, C. A., Wang, W., Chen, S. S., Chen, Y., Corbosiero, K., DeMaria, M., Dudhia, J., Holland, G., Klemp, J. B., Michalakes, J. Reeves, H., Rotunno, R., Snyder, C. M., 2008, "Prediction of land falling hurricanes with the Advanced Hurricane WRF model", *Mon.Wea. Rev.*, 136, 1990-2005.
12. Deshpande, M., Pattnaik, S. and Salvekar, P. S., 2010, "Impact of physical parameterization schemes on numerical simulation of super cyclone Gonu", *Nat. Hazards*, 55, 211-231.
13. Dube, S. K., Jain, I., Rao, A. D. and Murty, T. S., 2009, "Storm surge modeling for the Bay of Bengal and Arabian Sea", *Nature Hazards*, 51, 3-27.
14. Dube, S. K., Sinha, P. C. and Roy, G. D., 1985b, "The numerical simulation of storm surges along the Bangladesh coast", *Dynamics of Atmospheres and Oceans*, 9, 121-133.
15. Dube, S. K., Sinha, P. C., Rao, A. D. and Rao, G. S., 1985a, "Numerical modelling of storm surges in the Arabian Sea: The problem and its Prediction", *Mausam*, 48, 283-304.
16. Flather, R. A. and Khandker, H., 1993, "The Storm Surge Problem and Possible Effects of Sea Level Changes on Coastal Flooding in the Bay of Bengal", *Climate and Sea Level Change:Observations, Projections and Implications*, Warrick, R. A., *et al*. (eds), 229-245, Cambridge: Cambridge University Press. p424.
17. Ghosh, S. K., 1977, "Prediction of storm surges on the east coast ofIndia", *Indian Journal of Meteorology and Geophysics*, 28, 157-168.
18. Goerss, J. S., 2006, "Prediction of tropical cyclone track forecast error for Hurricanes Katrina, Rita and Wilma", Preprints, 27th AMS Conference on Hurricanes and Tropical Meteorology,
19. Monterey, CA, *Amer. Meteor. Soc.*, 11A.1.

20. Gopalakrishnan, S. G., Goldenberg, S., Quirino, T., Zhang, X., Marks Jr., F., Yeh, K. S., Atlas, R. and Tallapragada, V., 2012, "Toward improving high-resolution numerical hurricane forecasting: Influence of model horizontal grid resolution, initialization and physics", *Weather and Forecasting*, 27, 3, 647-666.
21. Hong, S. Y., Noh, Y. and Dudhia, J., 2006, "A new vertical diffusion package with an explicit treatment of entrainment processes", *Mon. Wea. Rev.*, 134, 2318-2341. Jaimes, B. and Shay, L. K., 2010, "Near-inertial wave wake of hurricanes Katrina and Rita over mesoscale oceanic eddies",
22. *J. Phys. Ocean*., 40, 6, 1320-1337.
23. Jaimes, B., Shay, L. K. and Uhlhorn, E. W., 2015, "Enthalpy and Momentum Fluxes during Hurricane Earl Relative to Underlying Ocean Features", *Mon. Wea. Rev.*, 143, 1, 111-131.
24. Jelesnianski, C. P. and Taylor, A. D., 1973, "A preliminary view of storm surges before and after storm modifications", *NOAA Technical Memorandum ERL WMPO-3*, Washington, DC, 23-33.
25. Johns, B. and Ali, A., 1980, "The numerical modeling of storm surges in the Bay of Bengal", *Quarterly Journal of the Royal Meteorological Society*, 106, 1-18.
26. Johns, B. and Dube, S. K., Mohanty, U. C. and Sinha, P. C., 1981, "Numerical simulation of the surge generated by the 1977 Andhra cyclone", *Quart. J. R. Met. Soc*., 107, 919-934.
27. Johns, B. and Dube, S. K., Mohanty, U. C. and Sinha, P. C., 1983, "Simulation of storm surges using a three-dimensional numerical model: an application to the 1977 Andhra cyclone", *Quart. J. R. Met. Soc.*, 109, 211-224
28. Kim, H. S., Lozano, C., Thallapragada, V., Iredell, D., Sheinin, D., Tolman, H., Gerald, V. M. and Sims, J., 2013, "Performance of Ocean Simulations in the Coupled HWRF-HYCOM Model", *J. Atm. and Ocea. Tech.*, 31, 545-559.
29. Krishnamurty, T. N., Pattnaik, S., Stefenova, L., Vijaykumar, T. S. V., Mackey, B. P., O'shay, A. J. and Pasch, R. J., 2005, "On the hurricane intensity issue", *Mon Wea. Rev.*, 133, 1886-1912.
30. Kurihara, Y. and Bender, M. A., 1980, "Use of a movable nested mesh model for tracking a small vonex", *Mon. Wea. Rev.*, 108, 1792-1809.
31. Kurihara, Y., Tuleya, R. E. and Bender, M. A., 1998, "The GFDL hurricane prediction system and its performance in the 1995 hurricane season", *Mon. Wea. Rev.*, 126, 1306-1322.
32. Lee, C. S., 1989, "Observational analysis of tropical cyclogenesis in the western North Pacific Part I: Structural evolution of cloud clusters", *J. Atmos. Sci.*, 46, 2580-2598.
33. Lee, C. Y. and Chen, S. S., 2012, "Symmetric and asymmetric structures of hurricane boundary layer in coupled atmosphere-wave-ocean models and observations", *J. Atmos. Sci*., 69, 3576-3594.
34. Ley, G. W. and Elsberry, R. L., 1976, "Forecasts of typhoon Irma using a nested-grid model", *Mon. Wea. Rev.*, 104, 1154-1161.
35. Liu, Y., Zhang D. L. and Yau, M. K., 1997, "A multi-scale numerical simulation of hurricane Andrew 1992: Part I. Explicit simulation and verification*", Mon. Wea. Rev.*, 125, 3073-3093.
36. Luettich, R. A. and Westerink, J. J., 2004, "Formulation and numerical implementation of the 2D/3D ADCIRC finite element model version 44", XX (p74), R. Luettich.
37. Mandal, M. and Mohanty, U. C., 2006, "Numerical experiments for improvement in the mesoscale simulation of Orissa super cyclone", *Mausam*, 57, 1, 79-96.
38. Mandal, M., Mohanty, U. C. and Raman, S., 2004, "A study on the impact of parameterization of physical processes on prediction of tropical cyclones over the Bay of Bengal with NCAR/PSU mesoscale model", *Nat. Hazards*, 31, 2, 391-414.
39. Marks, F. D. and Shay, L. K., 1998, "Land falling tropical cyclones: Forecast problems and associated research opportunities", *Bull.Amer. Meteor. Soc.*, 79, 305-323.
40. Mellor, G. L. and Yamada, T., 1982, "Development of a turbulence closure model for geophysical fluid problems", *Rev. Geophys. Space Phys.*, 20, 4, 851-875.
41. Mohanty, U. C. and Gupta, A., 1997, "Deterministic methods for prediction of

tropical cyclone tracks”, *Mausam*, 48, 2, 257-272.

42. Mohanty, U. C., Osuri, K. K., Pattanayak, S. and Sinha, P., 2011, “An observational perspective of tropical cyclone activity over Indian seas in a warming environment”, *Natural Hazards*, DOI 10.1007/s11069-011-9810-z.

43. Mohanty, U. C., Osuri, K. K., Routray, A., Mohapatra, M. and Pattanayak, S., 2010, “Simulation of Bay of Bengal tropical cyclones with WRF model: Impact of initial and boundary conditions”, *Marine Geodesy*, 33, 4, 294-314.

44. Mohanty, U. C., Osuri, K. K., Tallapragada, V., Marks, F. D.,Pattanayak, S., Mohapatra, M., Gopalakrishnan, S. G. and Niyogi, D., 2015, “A Great Escape from the Bay of Bengal 'Super Sapphire-Phailin' Tropical Cyclone - A case of improved weather forecast and societal response for disaster mitigation”, *Earth Interactions*, 19, 17, 1-11.

45. Mohanty, U. C., Osuri, K. K. and Pattanayak, S., 2013, “A study on high resolution mesoscale modeling systems for simulation of tropical cyclones over the Bay of Bengal”, *Mausam*, 64, 117-134.

46. Mohapatra, M., Bandyopadhyay, B. K. and Tyagi, A., 2012, “Best track parameters of tropical cyclones over the North Indian Ocean: A review”, *Nat. Hazards*, 63, 1285-1317.

47. Mukhopadhyay, P., Sanjay, J., Cotton, W. R. and Singh, S. S., 2004, “Impact of surface meteorological observation on RAMS forecast of monsoon weather systems over the Indian region”, *Meteorol. Atmos. Phys.*, 90, 77-108.

48. Mukhopadhyay, P., Taraphdar, S. and Goswami, B. N., 2011, “Influence of moist processes on track and intensity forecast of cyclones over the North Indian Ocean”, *J. Geophys. Res.*, 116, D05116,1-21.

49. Murty, T. S., Flather, R. A. and Henry R. F., 1986, “The storm surge problem in the Bay of Bengal”, *Progress in Oceanography*, 16, 195-233.

50. Nadimpalli, R., Osuri, K. K., Pattanayak, S., Mohanty, U. C., Nageswararao, M. M. and Prasad, S. K., 2016, “Real-time prediction of movement, intensity and storm surge of very severe cyclonic storm Hudhud over Bay of Bengal using high-resolution dynamical model”, *Nat. Hazards*, 81, 1771-1795

51. Osuri, K. K., Mohanty, U. C., Routray, A. and Mohapatra, M., 2012b, “Impact of Satellite Derived Wind Data Assimilation on track, intensity and structure of tropical cyclones over North Indian

52. Ocean”, *Int. J. Remote Sens.*, 33, 5, 1627-1652. Osuri, K. K., Mohanty, U. C., Routray, A. and Niyogi, D., 2015, “Improved prediction of Bay of Bengal tropical cyclones through assimilation of Doppler weather radar observations”, *Monthly Weather Review*, 143, 11, 4533-4560.

53. Osuri, K. K., Mohanty, U. C., Routray, A., Kulkarni, M. A. and Mohapatra, M., 2012a, “Sensitivity of physical parameterization schemes of WRF model for the simulation of Indian seas tropical cyclones”, *Nat. Hazards*, 63, 3, 1337-1359.

54. Osuri, K. K., Mohanty, U. C., Routray, A., Mohapatra, M. and Niyogi, D., 2013, “Real-time Track Prediction of Tropical Cyclones over the North Indian Ocean using the ARW model”, *J. Appl. Meteorol. Climatol.*, 52, 11, 2476-2492.

55. Osuri, K. K., Nadimpalli, R., Mohanty, U. C. and Niyogi, D., 2017, “Prediction of rapid intensification of tropical cyclone Phailin over the Bay of Bengal using the HWRF modelling system”, *Q.J. R. Meteorol. Soc.*, 143, 678-690.

56. Pradhan, D., Mitra, A. and De, U. K., 2012, “Estimation of pressure drop and storm surge height associated to tropical cyclone using Doppler velocity”, *Indian Journal of Radio and Space Physics*, 41, 348-358.

57. Raju, P. V. S., Jayaraman, P. and Mohanty, U. C., 2011, “Sensitivity of physical parameterizations on prediction of tropical cyclone Nargis over the Bay of Bengal using WRF model”, *Meteo. Atm.Phy.*, 113, 125-137.

58. Rao, A. D., 1982, “Numerical storm surge prediction in India”, Ph.D. Thesis, IIT Delhi, New Delhi, p211.

59. Roy Bhowmik, S. K., 2003, “Prediction of monsoon rainfall with a nested grid mesoscale limited area model”, *Proc. Indian Acad.Sci. Earth Planet Sci.*, 112, 499-519.

60. Sandeep, S., Chandrasekhar, A. and Singh, D., 2006, "The impact of assimilation of AMSU data for the prediction of a tropical cyclone over India using a mesoscale model", *Int. J. Remote Sens.*, 27, 20, 4621-4653.
61. Sandery, P. A., Brassington, G. B., Craig, A. and Pugh, T., 2010, "Impacts of ocean-atmosphere coupling on tropical cyclone intensity change and ocean prediction in the Australian region",
62. *Mon. Wea. Rev.*, 138, 2074-2091.
63. Schade, L. R. and Emanuel, K., 1998, "The Ocean's Effect on the Intensity of Tropical Cyclones: Results from a Simple coupled Atmosphere-Ocean model", *J. Atmo. Sc.*, 56, 642-651.
64. Shay, L. K., Goni, G. J. and Black, P. G., 2000, "Effects of a warm oceanic feature on Hurricane Opal", *Mon. Wea. Rev.*, 128, 1366-1383.
65. Singh, Randhir, Kishtawal, C. M., Pal, P. K. and Joshi, P. C., 2012a, "Improved tropical cyclone forecasts over north Indian Ocean with direct assimilation of AMSU-A radiances", *Meteor. Atmos. Phys.*, 115, 1-2, 15-34.
66. Singh, Randhir, Kishtawal, C. M., Pal, P. K. and Joshi, P. C., 2011, "Assimilation of the multi satellite data into the WRF model for track and intensity simulation of the Indian Ocean tropical cyclones", *Meteor. Atmos. Phys.*, 111, 3-4, 103-119.
67. Singh, Randhir, Pal, P. K., Kishtawal, C. M. and Joshi, P. C., 2008, "The impact of variational assimilation of SSM/I and QuikSCAT Satellite observations on the Numerical Simulation of Indian Ocean Tropical Cyclones (2008)", *Wea. Forecasting*, 23, 460-476.
68. Singh, Randhir, Prashant, K. and Pal, P. K., 2012b, "Assimilation of Oceansat-2 Scatterometer-Derived Surface Winds in the Weather Research and Forecasting Model", *IEEE Trans.*
69. *Geosci. Remote Sens.*, 50, 4, 1015-1020.
70. Srinivas, C. V., Mohan, G. M., Naidu, C. V., Baskaran, R. and Venkatraman, B., 2016, "Impact of air-sea coupling on the simulation of tropical cyclones in the North Indian Ocean using a simple 3-D ocean model coupled to ARW", *J. of Geo. Res.Atmospheres*, 121, 16, 9400-9421.
71. Srinivas, C. V., Venkatesan, R., Bhaskar Rao, D. V. and Hariprasad D.,2007, "Numerical simulation of Andhra severe cyclone (2003): model sensitivity to boundary layer and convection parameterization", *Pure Appl. Geophys.*, 164, 1-23.
72. Srinivas, C. V., Yesubabu, V., Hari Prasad, K. B. R. R., Venkatraman, B. and Ramakrishna, S. S. V. S., 2012, "Numerical simulation of cyclonic storms FANOOS, NARGIS with assimilation of conventional and satellite observations using 3-DVAR", *Nat. Hazards*, 63, 2, 867-889.
73. Srinivas, C. V., Yesubabu, V., Venkatesan, R. and Ramakrishna, S. S. V. S., 2010, "Impact of assimilation of conventional and satellite meteorological observations on the numerical simulation of a Bay of Bengal Tropical Cyclone of November 2008 near Tamilnadu using WRF model", *Meteor. Atmos. Phys.*, 110, 19-44.
74. Tallapragada, V., Kieu, C., Trahan, S., Zhang, Z., Liu, Q., Wang, W. and Strahl, B., 2015, "Forecasting Tropical Cyclones in the Western North Pacific Basin Using the NCEP Operational HWRF: Real- Time Implementation in 2012", *Wea. and Forecasting*, 30, 5, 1355-1373.
75. Trivedi, D. K., Mukhopadhyay, P. and Vaidya, S. S., 2006, "Impact of physical parameterization schemes on the numerical simulation of Orissa super cyclone (1999)", *Mausam*, 57, 1, 97-110.
76. Wang, Y., 2001, "An explicit simulation of tropical cyclones with a triply nested movable mesh primitive equation model: TCM3. Part I. description of the model and control experiment", *Mon. Wea. Rev.*, 130, 3022-3036.
77. Wang, Y., 2002, "Vortex Rossby waves in a numerically simulated tropical cyclone. Part II: the role in tropical cyclone structure and intensity changes", *J. Atmos. Sci.*, 59, 1239-1262.
78. Yablonsky, R. M., Ginis, I., Thomas, B., Tallapragada, V., Sheinin, D. and Bernardet,

L., 2014, “Description and Analysis of the Ocean Component of NOAA’s Operational HurricaneWeather Research and Forecasting Model (HWRF)”, *J. Atmosph. And Ocean. Tech.*, 32, 144-163.

79. Yeh, K. S., Zhang, X., Gopalakrishnan, S., Aberson, S., Rogers, R., Marks, F. and Atlas, R., 2012, “Performance of the experimental HWRF in the 2008 hurricane season”, *Natural hazards*, 63, 3, 1439-1449.

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