MAUSAM, **72**, 1 (January 2021), 147-166

551.515.2 : 551.509.32 (267.6)

Comparative performance of HWRF model coupled with POM and HYCOM for tropical cyclones over North Indian Ocean

ANANDA KUMAR DAS, ARUN SHARMA, SUDHIR JOSEPH*,

AKHIL SRIVASTAVA and D. R. PATTANAIK

India Meteorological Department, Ministry of Earth Sciences, New Delhi – 110 003, India

**Indian National Centre for Ocean Information Services, MoES, Nizampet, Hyderabad – 500 090, India*

e mail : akuda.imd@gmail.com

सार – उच्च-रिज़ॉल्यूशन संख्यात्मक मौसम भविष्यवाणी (NWP) मॉडल में वायु-समुद्र की बातचीत का प्रदर्शन उष्णकटिबंधीय चक्रवात जैसी चरम घटना की भविष्यवाणी करने के लिए आवश्यक शर्त है। यह पहले से ही स्थापित है कि युग्मित मेसोस्केल मॉडल उत्तर हिंद महासागर (NIO) बेसिन और अन्य महासागर बेसिन के साथ-साथ उचित कौशल के साथ उष्णकटिबंधीय चक्रवातों के ट्रैक और तीव्रता का पूर्वानुमान लगाने में सक्षम हैं। तूफान का मौसम अनुसंधान और पूर्वानुमान (HWRF) मॉडल भारत के मौसम विभाग (IMD) द्वारा कई अन्य राष्ट्रीय मौसम विज्ञान और हाइड्रोलॉजिकल सेवाओं जैसे अन्य उष्णकटिबंधीय चक्रवातों के पूर्वानुमान के लिए प्रचालित होता है।

एचडब्ल्यूआरएफ मॉडलिंग सिस्टम के दो अलग-अलग युग्मित संस्करण जिनमें फ़ीचर आधारित प्रिंसटन ओशन मॉडल (पीओएम) और एडी-रेसोल्यूशन हाइब्रिड कोऑर्डिनेट ओशन मॉडल (HYCOM) हैं, जो कि TIO पर उष्णकटिबंधीय चक्रवातों के वास्तविक समय के पूर्वानुमान के लिए कार्यरत हैं। इस अध्ययन में, 2019 के दौरान सभी आठ चक्रवातों के लिए ट्रैक और तीव्रता की भविष्यवाणी करने में दो युग्मित वेरिएंट के बीच पूर्वानुमान कौशल की तुलना की गई है। परिणाम बताते हैं कि HYCOM के साथ मिलकर HWRF मॉडल द्वारा सभी चक्रवातों की ट्रैक भविष्यवाणी तुलनात्मक रूप से POM से बेहतर है। लेकिन दोनों युग्मित मॉडल की तीव्रता भविष्यवाणी कौशल सभी पूर्वानुमान घंटों के लिए किसी भी स्पष्ट श्रेष्ठता को चित्रित नहीं करते हैं। पीओएम कपलिंग के साथ एचडब्ल्यूआरएफ मॉडल की पूर्ण तीव्रता की त्रुटियां वायू चक्रवात को छोड़कर पूर्वानुमान के 60 घंटे तक के प्रारंभिक चरण के दौरान HYCOM की तुलना में बड़ी हैं। लेकिन, POM द्वारा प्रदर्शित तीव्रता में त्रुटियां HYCOM की तुलना में थोड़ी सी लंबी अवधि के लिए थोड़ी छोटी हैं, हालांकि दोनों मॉडल के लिए मानक विचलन बहुत बड़ा है और सत्यापित किए गए पूर्वानुमानों की संख्या भी कम है। 2020 के दो चक्रवातों के मामले में, HYCOM के साथ युग्मित वैरिएंट की क्षमता चक्रवात की पटरियों के पूर्वानुमान में POM से बेहतर है। तीव्रता की भविष्यवाणी के लिए दोनों मॉडल के कौशल को ध्यान में रखते हुए, यह स्पष्ट है कि अल्पकालिक कमजोर तूफानों के लिए युग्मित एचकॉम मॉडल का उपयोग लाभप्रद है लेकिन तीव्र और लंबे समय तक रहने वाले चक्रवात के लिए मॉडल के प्रदर्शन को लगातार लंबे समय तक बनाए नहीं रखा जाता है। । सतह के प्रवाह और समुद्र की सतह के तापमान का एक संक्षिप्त मूल्यांकन बताता है कि HYCOM POM की तुलना में बारी सतह के प्रवाह में अधिक यथार्थवादी महासागर की स्थिति को चित्रित करता है और इसलिए HYCOM के साथ HWRF का युग्मित संस्करण, दीप महासागर के ऊपर चक्रवात की भविष्यवाणी करते हुए POM के साथ संस्करण से बेहतर है।

ABSTRACT. The demonstration of air-sea interaction in the high-resolution numerical weather prediction (NWP) model is the necessary condition to predict the extreme event like tropical cyclone. It is already established that the coupled mesoscale models are capable of forecasting the track and intensity of tropical cyclones with reasonable skill over North Indian Ocean (NIO) basin and over other ocean basins as well. The Hurricane Weather Research and Forecasting (HWRF) model is consequently operational by India Meteorological Department (IMD) for the forecasting tropical cyclones like many other National Meteorological and Hydrological Services.

Two different coupled versions of HWRF modeling systems with feature based Princeton Ocean Model (POM) and eddy-resolving Hybrid Coordinate Ocean Model (HYCOM) are employed for the real-time forecasting of tropical cyclones over NIO. In this study, the comparison of forecast skills between two coupled variants in predicting track and intensity for all eight cyclones during 2019 has been carried out. The results show that the track prediction of all cyclones by HWRF model coupled with HYCOM is comparatively better than that with POM. But the intensity prediction skills of both coupled models do not portray any obvious superiority for all forecast hours. The absolute intensity errors of HWRF model with POM coupling are large compared to HYCOM during initial phase up to 60 hours of forecast except for Vayu cyclone. But, the errors in intensity exhibited by POM are a bit smaller compared to HYCOM for longer lead period.

However, the standard deviation is very large for both models and numbers of forecasts verified are also less. In case of two cyclones of 2020, the ability of coupled variant with HYCOM is superior to POM in forecasting the tracks of cyclones. Considering the skills of both the models for intensity prediction, it is clear that the use of coupled HCOM model for short-lived weaker storms is advantageous but the performance of the model is not consistently maintained with longer lead time for intense and long-lived cyclone. A brief assessment of surface fluxes and Sea Surface Temperature reveals that HYCOM portray more realistic ocean condition in turn surface fluxes compared to POM and therefore the coupled variant of HWRF with HYCOM is superior to the variant with POM while forecasting cyclones over deep Ocean.

Key words – Tropical cyclones, HWRF, POM, HYCOM.

1. Introduction

Timely and accurate prediction of track and intensity of a tropical cyclone (TC) is one of the many challenging problems in meteorology, but very important for many agencies engaged in disaster preparedness and mitigation. The forecasters of National Weather Service in many countries utilise the cyclone track and intensity forecasts generated by high resolution numerical models. But, representation of a TC adequately in the initial conditions (ICs) of high-resolution numerical weather prediction (NWP) models is a major problem due to lack of observations. The initial analysis is therefore relying on the first guess field from the global modelling systems. The ocean state in terms of sea surface temperature (SST) is abundantly utilized with static or time varying specified lower boundary conditions to the atmospheric model.

A few NWP centres employ ‘bogussing’ or vortex initialization procedure to reinforce a tropical cyclone vortex into the model atmospheric fields to reduce inadequacies in location, size, intensity and structure of the storm. There have been primarily three types of bogussing methods that were widely used in operational models, as summarized by Peng *et al*. (1993). The first is to bogus observational data before the objective analysis is carried out (Lord, 1991; Heming *et al*., 1995). In the second approach, a more complex vortex circulation defined by an analytical expression is added in initial field after the objective analysis but before the model initialization (Mathur, 1991; Prasad and Rama Rao, 2003). Finally, in the third kind of bogussing, a 'spin-up' vortex is generated by the same forecast model, instead of using an analytical one. The third kind has been utilized in the multiple nested tropical cyclone model of Geophysical Fluid Dynamics Laboratory, *i.e*., GFDL (Kurihara, 1995) and in the typhoon-Track Forecast System (TFS) of Central Weather Bureau (CWB) of Taiwan (Peng *et al*., 1993).

The vortex initialization is the most crucial part of Hurricane Weather Research and Forecasting (HWRF) model which provides opportunity to add more realistic structure of the storm and critical step towards better prediction of cyclone intensity and structure (Liu *et al*., 2000 and 2006). In this procedure, the vital observed information of the storm is utilized to correct and modify the background field from global forecasting system. The HWRF cycling system along with its data assimilation produces more representative and improved initial and boundary conditions for the model. The activities of Intensity Forecasting Experiment (IFEX) of National Oceanic and Atmospheric Administration (NOAA) established that the assimilation of airborne observations of the TC inner core contributed significant improvement in intensity forecasts of the high resolution mesoscale models (Rogers *et al*., 2012) which were utilized through the support of the NOAA Hurricane Forecast Improvement Program (HFIP). The improvement in the real-time performances of the model is also evaluated due to model upgrades (Tallapragada *et al*., 2014, 2016) in National Centers for Environmental Prediction (NCEP). A study by Das *et al*. (2014) stated that a significant improvement has been noticed in the HWRF forecasts of triple nested version from its double nested version. Osuri *et al*. (2017) in their study established the ability of the HWRF model in predicting rapid intensification of tropical cyclone Phailin. Nadimpalli *et al*. (2020) used HWRF along with Weather Research and Forecasting (WRF) mesoscale models for the forecasting of cyclones over Bay of Bengal in a quasi-operational mode and assessed their comparative skills. The impact of INSAT-3D/3DR radiance data assimilation to improve the skill of the model is established in a study by Nadimpalli (2020).

The role of sea surface temperature in modulating life cycle of tropical cyclones over BoB has been demonstrated clearly by Mohanty *et al*. (2019) with HWRF coupled modelling framework. A study (Kim *et al*., 2014) demonstrated the skill of the Hybrid Coordinate Ocean Model (HYCOM) in coupled atmosphere-ocean simulations in hurricane environments along with the feature-based Princeton Ocean Model (POM). The study also depicted the need of HWRF coupled with HYCOM to be well integrated into operational Real Time Ocean Forecast System (RTOFS) ocean models, ensuring a seamless acquisition of all the improvements of operational models to have the best representations of the ocean under hurricane conditions. Tallapragada *et al*. (2016) brought out the fact that the coupled version of the HWRF model performed well for North Pacific Basin.

A few studies simulated tropical cyclonic environment over North Indian Ocean basin with different coupled modeling systems. Samson *et al*. (2014) used a coupled modeling framework with NEMO Ocean and WRF atmospheric models and evaluated seasonal distributions of tropical cyclones, but failed to reproduce the strongest observed cyclone categories. In a study by Srinivas *et al*. (2016), the impact of air-sea coupling has been studied using a three-dimensional Price-Weller-Pinkel (3DPWP) ocean model coupled to the Advanced Research WRF, *i.e*., ARW model for six tropical storms in the North Indian Ocean and in general found that the ocean coupling in ARW leads to better track estimates besides improvements in intensity predictions. The simulation of a tropical cyclone Mora over BoB with a non-hydrostatic regional atmospheric model coupled to a regional ocean model (Agrawal *et al*., 2020) revealed that air–sea coupling made it possible to realistically capture ocean and atmospheric responses for storm genesis, changes within ocean subsurface layers and vertical structure of the upper ocean due to wind-generated mixing.

In their study, Osuri *et al*. (2013) predicted real-time tracks of 17 cyclones over NIO during a period of 4 years with nested ARW model and brought out the fact that the increase in resolution reduced the errors in track prediction. But real-time intensity prediction remained an outstanding issue. A thorough and continuous evaluation for different cyclonic storms over North Indian Ocean is needed to be carried out systematically with a real-time configuration of a coupled modeling system.

In the present study, the primary purpose of coupling a 3-D ocean model to HWRF is to create an accurate SST field for input into the atmospheric model during real-time integration of the coupled model. The SST field is subsequently used by the atmospheric model to calculate the surface heat and moisture fluxes from the ocean to the atmosphere. An uncoupled hurricane model with a static SST field is restricted by its inability which can contribute to a high-intensity bias (Bender and Ginis, 2000 and Bender *et al*., 2007).

In the present study, a comparative assessment has been performed with two sets different coupled variants of triple nested HWRF model. In the first system, the POM for Tropical Cyclones (POM-TC), a version of the three-dimensional primitive equation numerical ocean model was the ocean component whereas in the second arrangement the eddy resolving HYCOM ocean model has been exploited retaining the same atmospheric component of operational HWRF. All cyclones of 2019 have been considered for real-time prediction from their formation stages to landfalling/dissipating stages. The verification of HWRF model forecasts with both coupled model configurations has been carried out in the first part of the results and discussion section. Thereafter, in the last part of the discussion, specific characteristics of comparative performances of both coupled modeling systems have been thoroughly analysed and testified with two independent tropical cyclones of 2020, *e.g*., AMPHAN and NISARGA over Bay of Bengal (BoB) and Arabian Sea (AS) respectively.

2. Data and methodology

2.1. *HWRF modelling system in IMD*

This advanced hurricane prediction system HWRF was developed primarily at the NCEP's Environmental Modeling Center (EMC) in collaboration with other NOAA labs and the University of Rhode Island, taking advantage of the WRF model infrastructure developed at NCAR. HWRF is a state-of-the-art hurricane model that has the capability to address the intensity, structure and rainfall forecast problems. The HWRF model has been operational at NCEP since 2007. As a part of MoES-NOAA collaboration program, during the cyclone season of 2011, the HWRF modelling system with its double nested atmospheric component has been made operational in IMD to provide guidance for tropical cyclone track and intensity forecast at RSMC, New Delhi. In the year 2014, the triple nested version of the model has been implemented with its improved physics schemes. The ocean coupled version of HWRF model with POM-TC became operational during post-monsoon cyclone season of 2018. After thorough study and several experiments by the joint team of IMD and INCOIS (Indian National Centre for Ocean Information Services), the coupled HWRF model with HYCOM was made operational at NWP-Division of IMD since pre-monsoon cyclone season of 2019. Presently, the coupled HWRF system with both ocean models, *viz*., POM-TC and HYCOM was operational simultaneously and model guidance products were provided from both the variants.

2.1.1. *Atmospheric model*

The Hurricane Weather Research and Forecast system (HWRF) model is a primitive equation, non-hydrostatic coupled atmosphere-ocean model (Biswas *et al*., 2017). The atmospheric model employed with a parent and two moving nests domains at subsequent levels. The location of the parent and nests, as well as the relevant projection may vary from run to run and are dictated by the location of the storm, *i.e*., centre of the storm at the time of initialization. HWRF model uses a vortex initialization and relocation algorithm based on observed tropical cyclone position and intensity parameters. These

TABLE 1

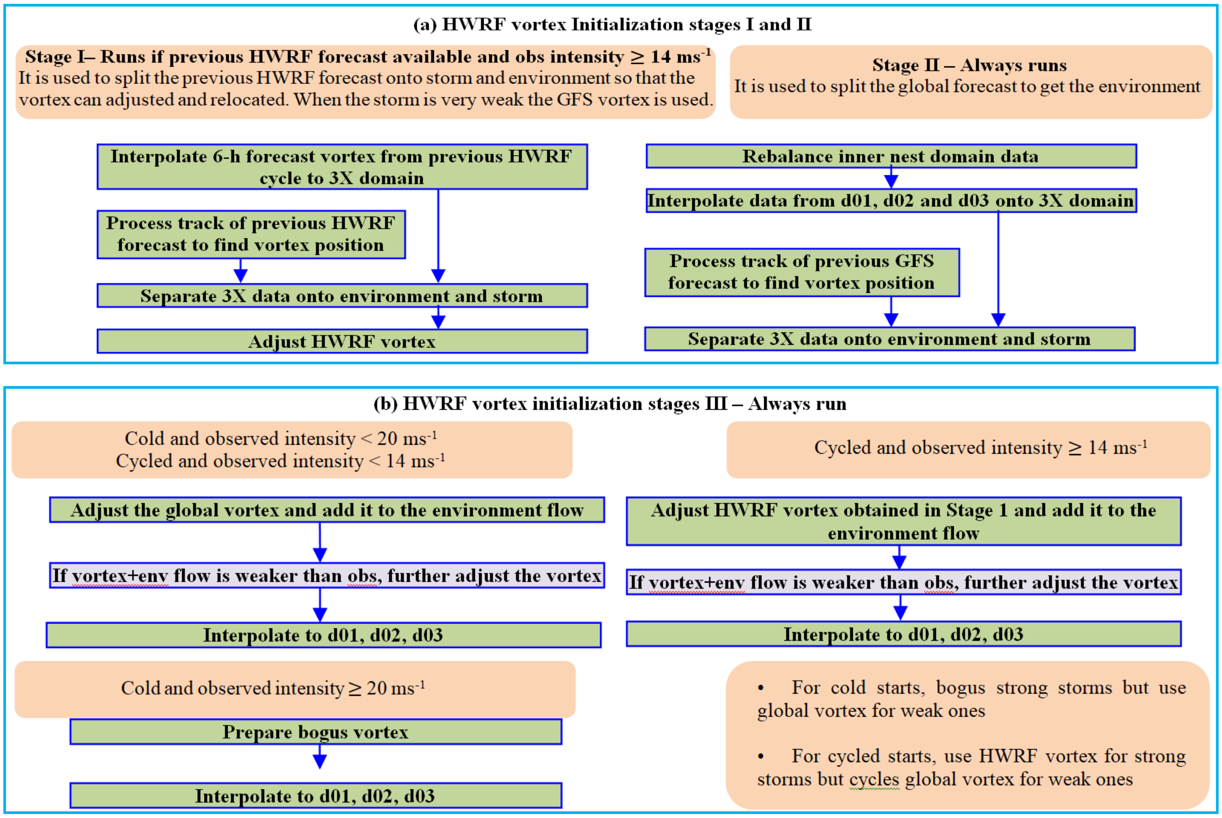
HWRF model configuration

Domain	
Horizontal co-ordinates	18 km: 80° × 80° at 0.135° (Fixed Parent domain) 6 km: 24°× 24° at 0.045° (Moving nest) 2 km: 7.1°× 7.1° at 0.015° (Moving inner-most nest)
Map Projection	Rotated Latitude and Longitude
Horizontal grid structure	Arakawa E – grid
Vertical co-ordinates	61 Hybrid levels (Sigma to pressure at 150 hPa)
Model top	10 hPa
Physics	
Microphysics	Ferrier-Aligo (FA) scheme - (Rogers *et al*., 2001; Aligo *et al*., 2014)
Radiation Scheme (Long-wave)	RRTMG scheme (Iacono *et al*., 2008; Thompson *et al*., 2014)
Radiation Scheme (Short-wave)	RRTMG scheme (Do)
Time between radiation calls	60
Surface layer physics	Modified GFDL scheme (Kwon *et al*., 2010; Powell *et al*., 2003 and Black *et al*., 2007)
Land-surface parameterization	Noah LSM (Chen and Dudhia, 2001; Mitchell, 2005)
Surface Flux Calculation	Monin-Obukhov (Sirutis and Miyakoda, 1990; Kurihara and Tuleya, 1974)
PBL parameterization (calls in every time step)	NCEP Global Forecast System scheme (Hong and Pan, 1996)
Cumulus parameterization schemes	Scale-aware Simplified Arakawa-Schubert scheme (Han and Pan, 2011; Biswas *et al*., 2014; Han *et al*., 2017)
Dynamics	
Dynamic option	NMM – Non-hydrostatic
Time Integration	Forward-backward scheme Implicit scheme (for sound waves)
Spatial differencing scheme	Adams-Bashforth scheme (horizontal) Crank-Nicholson scheme (vertical)
Vortex Initialization	(18 and 6 km) without any inner core observation

parameters in TCVital message are provided operationally by Cyclone Warning Division (CWD) of IMD for north Indian Ocean basin. Model initialization is comprised of both vortex improvement procedure and data assimilation. The IMD Global Forecast System (GFS) analysis is used to generate the initial conditions (ICs) for the hurricane model parent domain in the operational configuration. The different physical parameterizations used in the model are mainly the following: (*i*) microphysics, (*ii*) cumulus parameterization, (*iii*) surface layer, (*iv*) PBL (*v*) LSM and (*vi*) radiation. The details of domain and triple nest configuration which have been used for real-time forecasting by the model are given in Table 1. The scientific documentation of NCAR (National Center for Atmospheric Research), USA written by Biswas *et al*. (2018) provided the details of the HWRF model components along with physics formulation.

2.1.2. *Vortex initialization*

The operational initialization of cyclones in the HWRF model involves several steps to prepare the analysis at various scales. The environmental fields in the parent domain are derived from the GFS analysis and the fields in the nest domains are derived from 6-h forecasts from Global Data Assimilation System (GDAS), enhanced through the vortex relocation and HWRF Data Assimilation (HDAS). The vortex-scale fields are generated by inserting a vortex corrected using TCVital data, onto the large-scale fields. The vortex may originate from a GDAS 6-h forecast, from the previous HWRF 6-h forecast, or from a bogus calculation, depending on the storm intensity and on the availability of a previous HWRF forecast. Additionally, vortex-scale data assimilation is performed with conventional observations



Figs. 1(a&b). Simplified flow diagram for HWRF vortex initialization describing (a) the split of the HWRF forecast between vortex and environment, the split of the background fields between vortex and analysis and (b) the insertion of the corrected vortex in the environmental field

and satellite observations in the TC vortex area and its near environment. Finally, the analyses are interpolated onto outer domain and two inner domains to initialize the model. The steps involved in vortex correction process are partially represented in Figs. 1(a&b). The modification of the mesoscale hurricane vortex in the first-guess field is a critical aspect of the initialization problem. The vortex correction adjusts the vortex location, size and structure based on the TCVitals: (*i*) storm location (data used: storm center position); (*ii*) storm size (data used: radius of maximum surface wind speed, 34-kt wind radii and radius of the outmost closed isobar); and (*iii*) storm intensity in terms of maximum surface wind speed and, secondarily, the minimum Mean Sea Level Pressure (MSLP) also referred as Central mean Sea Level Pressure (CSLP). The storm size correction is followed by surface pressure, temperature and water vapour adjustments. Same way, there are also surface pressure, temperature and moisture adjustments after the intensity correction as well.

2.1.3. *Data assimilation*

The HDAS utilizes Grid point Statistical Interpolation (GSI) configured with 3DVAR assimilation technique to perform a one-way hybrid procedure to assimilate conventional observation along with a few satellite radiances collected in the local storm environment. The bogus vortex is primarily used to cold-start strong storms (observed intensity greater than or equal to 20 ms^{-1}) and to increase the storm intensity when the storm in the HWRF 6-h forecast is weaker than that of the observation. This procedure is in contrast with previous HWRF implementations, in which a bogus vortex was used in all cold starts. This change significantly improves the intensity forecasts in the first 1-3 cycles of a storm.

2.1.4. *Atmospheric boundary condition*

The boundary conditions to the model are prepared from the forecasts from GFS model of IMD. The lower boundary condition in terms of heat and moisture fluxes over land points and sea-ice points has been provided by the LSM (Land-Surface Model) within HWRF system. The prescribed dynamic interface is forced to be identical to the parent domain interpolated to the nest grid points are utilized to provide lateral boundary conditions to nests. The feedback from fine-resolution domain to coarse-

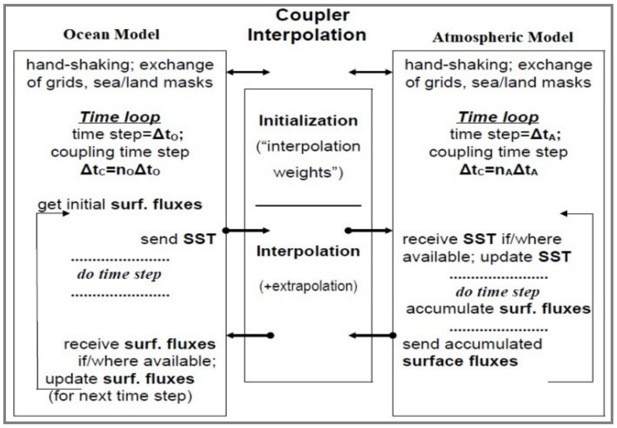


Fig. 2. The run-time data flow by the NCEP coupler

resolution domain is an important process for a hurricane forecast model because it reflects the multiple-scale physical interactions in the hurricane environment. The mass adjustment procedure and specialized approach are followed for the 2-way interactions between nests rather than using simple horizontal interpolation or direct modification of coarse-grid data by the finer resolution nests.

2.1.5. *Ocean coupling and ocean models*

IMD has two variants of Ocean coupled HWRF modelling system operationalized with the same atmospheric model component described earlier coupled with POM-TC and HYCOM (henceforth referred as coupled HPOM and HCOM models respectively) for track, intensity, rainfall and structure prediction of tropical cyclones over north Indian Ocean.

As a cyclone model coupled to an ocean model that does not account for fully 3-D ocean dynamics may only account for some of the hurricane-induced SST changes during model integration (Yablonsky and Ginis, 2009, 2013), within coupled framework of HPOM, 3-Dprimitive-equation numerical ocean model that has become widely known as the POM (Mellor, 2004) is implemented for real-time forecasting of cyclones. The POM is initialized with a realistic, 3-D temperature (T) and salinity (S) field and subsequently integrated to generate realistic ocean currents and incorporate the pre-existing cyclone-generated cold wake. The GDEM3 (Generalized Digital Environmental Model - V3.0) climatology data together with GFS model SST output are utilized to create the ocean initial conditions.

The HYCOM is also a 3-D primitive-equation numerical ocean model with specific configuration of vertical Hybrid Coordinate which is isopycnal in the open, interior and stratified ocean, while using a z-level coordinate in the mixed layer (Kim *et al*., 2014). It combines the advantages of isopycnic coordinates and z-level coordinates in a unique way to improve the simulations and supports several vertical mixing and diffusion schemes. The HCOM coupled system with moving nest has been set up at with oceanic initial and boundary conditions obtained from high resolution (1/16°) operational Indian Ocean HYCOM nested to a $1/4^{th}$ degree global HYCOM (RTOFS of INCOIS).

The NCEP coupler acts as an independent interface between the HWRF atmospheric component and the POM-TC or HYCOM ocean component (Fig. 2). During forecast integration of HWRF, the east-west and north-south momentum fluxes at the air sea interface ("wusurf" and "wvsurf" in Mellor, 2004) are passed from the atmosphere to the ocean, along with temperature flux ("wtsurf") and the shortwave radiation incident on the ocean surface ("swrad"). During forecast integration of POM-TC, the SST is passed from the ocean to the atmosphere. The configuration summary of both ocean models is described in Table 2.

2.2. *Cyclonic storms*

(*i*) *2019*

The year, 2019 was an exceptional year with respect to cyclonic activity over the North Indian Ocean (NIO) and witnessed 8 cyclones (3 over BoB and 5 over AS). Out of eight cyclones over the NIO in 2019, there were 5 land falling cyclones (namely Pabuk, Fani, Hikaa, Bulbul and Pawan) and others dissipated over sea (RSMC-New Delhi, 2020).

(*ii*) *2020*

During the pre-monsoon season of 2020, the NIO produced two prominent cyclonic storms of the year but with different characteristics. AMPHAN over BoB was a classic case super cyclone with clockwise recurving track and rapid intensification which made a landfall over Indian-Bangladesh coast as a very severe cyclonic storm. Whereas severe cyclone NISARGA over Arabian Sea was a short-lived storm with clockwise recurving track and crossed Maharashtra coast of India.

As per the cyclone manual published by IMD (2013), based on maximum sustained wind (MSW) speed, cyclonic disturbances in the NIO are classified as Depression (D, ≥ 17 knots), Cyclonic Storm (CS, ≥34 knots), Severe Cyclonic Storm (SCS, ≥48 knots), Very Severe Cyclonic Storm (VSCS, ≥64 knots) Extremely Severe Cyclonic Storm (ExSCS, ≥ 90 knots) and Super

TABLE 2

Comparison two ocean model configurations

	POM	HYCOM
Dynamics & domain Configurations	Hydrostatic, Free-Surface, Primitive Equations	
	1/12°	
	Domain size covering 83.2° of longitude and 37.5° of latitude	5° N-30° N / 43.2° E-100° E
	Rectangular Projection	Mercator Projection
	40 staggered vertical sigma levels; free surface (η)	41 vertical Hybrid isopycnal-Z levels
	Staggered Arakawa-C grid	
Mixing Physics	Mellor-Yamada 2.5 closure	KPP (K-Profile Parameterization)
Initialization	Monthly GDEM3 Climatology + daily NCEP SST + Feature Model	6 hourly HYCOM analysis from INCOIS-RTOFS
Lateral Boundary	Adjusted T/S fields	6 hourly 2D and 3D INCOIS-RTOFS forecasts
Numerical schemes	Split time steps; 2-D external and 3-D internal (pre-coupled initialization and forecast integration)	Leapfrog for the internal mode and a predictor corrector for the external mode
	Horizontal Explicit and vertical implicit	The advection scheme is fourth order and the gradient operator is numerically curl free

TABLE 3

List of cyclonic storms with description

S. No.	TC Name (basin) Classification	CSLP (hPa) & (MSW) in knots	Duration (D to D)	Landfall location and time	Areas affected
1.	Pabuk (BoB) CS	998 (45)	0000 UTC 04 - 0000 UTC 7 Jan, 2019	11.6° N / 92.7° E 1300 - 1500 UTC 6 Jan	Andaman and Nicobar Islands
2.	Fani (BoB) ESCS	932 (115)	0300 UTC 26 Apr - 1200 UTC 4 May, 2019	19.7° N/85.7° E 0230 - 0430 UTC 3 May	Nicobar Islands, Eastern India, Sumatra, Sri Lanka, Bangladesh, Bhutan
3.	Vayu (AS) VSCS	970 (80)	0000 UTC 10 - 1200 UTC 17 Jun, 2019	Weakened over ocean	Northern Maldives, India, South Pakistan, East Oman
4.	Hikaa (AS) VSCS	978 (75)	0300 UTC 22 - 0600 UTC 25 Sep, 2019	19.7° N/57.7° E 1400 - 1500 UTC 24 Sep	Western India, Oman, Saudi Arabia, Yemen
5.	Kyarr (AS) SuCS	922 (130)	0300 UTC 24 Oct - 1500 UTC 2 Nov, 2019	No landfall	Western India, Oman, Yemen, Somalia
6.	Maha (AS) ESCS	956 (100)	0000 UTC 30 Oct - 0900 UTC 7 Nov, 2019	No landfall	Southern and Western India, Oman, Maldives, Sri Lanka,
7.	Bulbul (BoB) VSCS	976 (75)	0000 UTC 5 - 0000 UTC 11 Nov, 2019	21.5° N/88.5° E 1500 - 1800 UTC 9 Nov	Andaman & Nicobar Islands, Eastern India, Myanmar, Bangladesh
8.	Pawan (AS) CS	998 (40)	1200 UTC 2 - 0300 UTC 7 Dec, 2019	7.4° N/49.6° E 0200 - 0300 UTC 7 Dec	Somalia
9.	Amphan (BoB) SuCS	920 (130)	0000 UTC 16 - 1200 UTC 21 May, 2020	21.6° N/88.3° E 1000 - 1200 UTC 20 May	Sri Lanka, India, Bangladesh, Bhutan
10.	Nisarga (AS) SCS	984 (60)	0000 UTC 1 - 0600 UTC 4 Jun, 2020	18.4° N/72.9° E 0700 - 0900 UTC 3 Jun	West India

Cyclonic Storm (≥ 120 knots). The detailed description of cyclones over NIO (with name, basin, intensity, duration from the formation as a Depression till dissipating Depression, landfall location and time along with the areas affected) considered during 2019 and 2020 for the study are described in Table 3.The observed tracks of all the cyclones considered in the present study are also shown in Fig. 3.

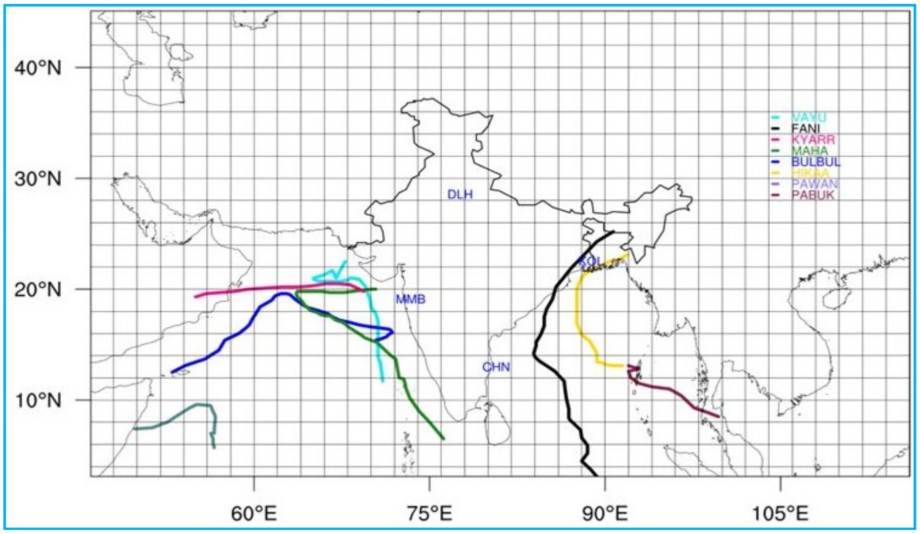


Fig. 3. Tracks of all forecasted eight cyclones of 2019 and two cyclones of 2020 over NIO

2.3. *Data*

Model forecasts : The coupled HPOM and HCOM models are run every 6 hours on real time basis in cyclic mode based on 0000, 0600, 1200, 1800 UTC initial conditions to provide track and intensity forecasts up to 126 hours. The forecast data are saved with 6 hour interval for further processing.

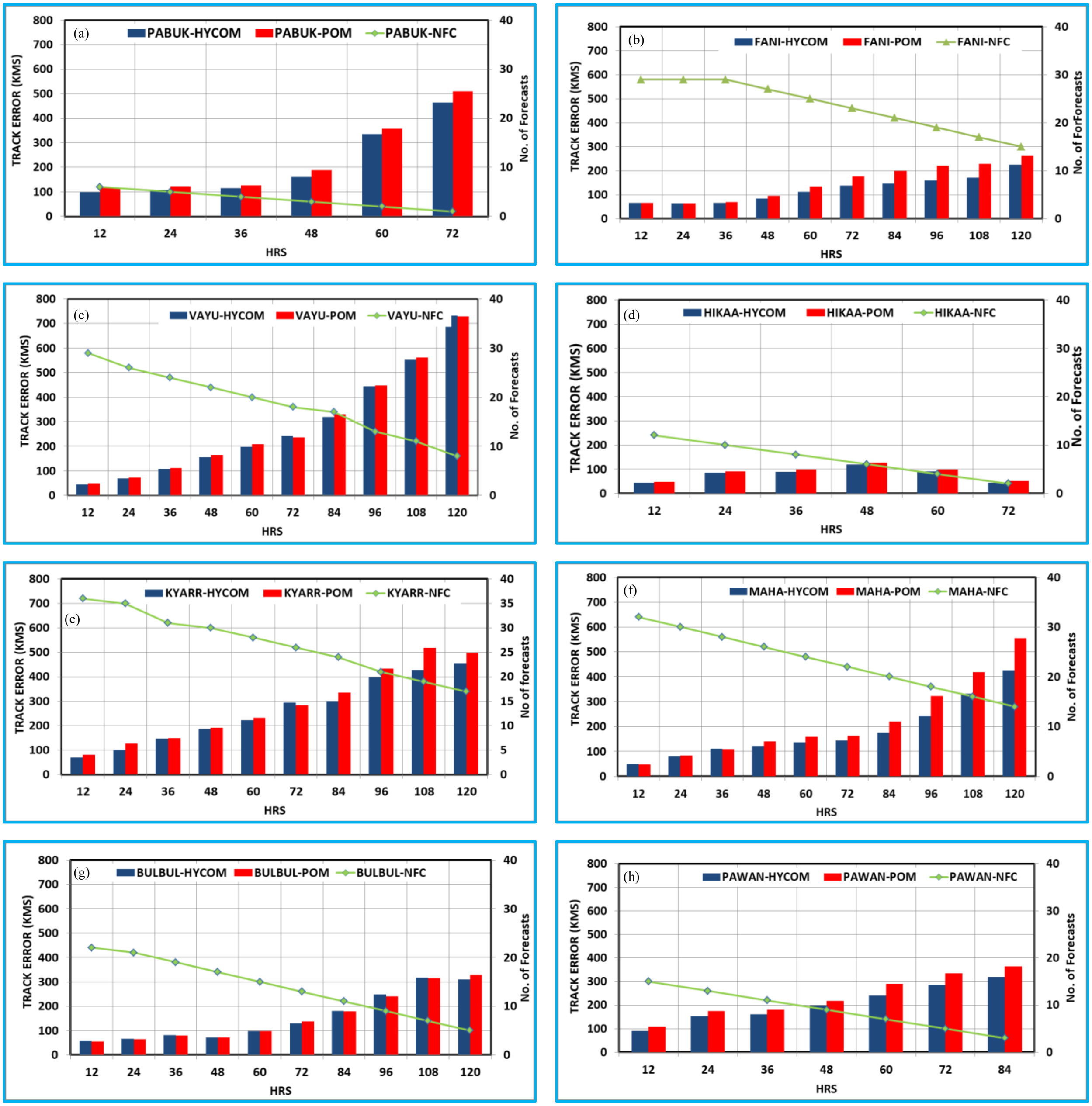
Vortex tracker : The Geophysical Fluid Dynamics Laboratory (GFDL) vortex tracker objectively analyzed HWRF model forecast data of the storm to provide an estimate of the vortex center position (latitude and longitude) along with other metrics [*e.g.*, intensity (maximum 10-m winds and minimum MSLP), structure (wind radii for 34, 50 and 64 knot thresholds in each quadrant), radius of the outermost closed isobar (ROCI) and optionally integrated kinetic energy (IKE), storm surge damage potential (SDP) and cyclone thermodynamic phase] for the duration of the forecast. The tracker requires the forecast to be on a cylindrical equidistant, latitude-longitude (Lat./Long.) grid and written preferably in GRIB (GRIB1 or GRIB2) format. The model fields used by the tracker are (*i*) relative vorticity at 10m, 850 hPa and 700 hPa, (*ii*) MSLP, (*iii*) geopotential height at 850 and 700 hPa, (*iv*) wind speed at 10 m, 850 hPa and700 hPa and (*v*) 200-500 hPa and 500-850 hPa thickness. The tracker code is able to function when certain input fields are missing or when certain alternate fields are provided instead of the primary fields. The output files of the tracker contain the vortex position, intensity and structure information in original (modified) Automated Tropical Cyclone Forecast (ATCF) format (available at https://www.nrlmry.navy.mil/ atcf_web/docs/ database/new/abdeck.txt).

2.4. *Verification*

In the current study, we evaluated the skill of both coupled versions of HWRF model in predicting TC tracks and intensity against the IMD best track data issued by the IMD (Mohapatra *et al*., 2012). The track forecasting skill of the model is evaluated in terms of mean absolute track error also known as direct position error (DPE), absolute along-track and cross-track errors hereafter mentioned as ATE and CTE respectively. The intensity errors have been computed in terms of the differences in MSW between forecasted & estimated best track values at each forecast hour.

3. Results and discussion

The first part of this section consists of overall validation of both coupled versions of HWRF model for all cyclonic storms individually during 2019. In the beginning of discussion, the model performance with track forecasting is considered in terms of DPE, ATE and CTE and subsequently intensity is taken up. An overall comparative skill analysis of both coupled variants of HWRF model has been carried out with a computation of consolidated average of all errors. In the second part of the discussion, the performances of both coupled models are thoroughly portrayed for two cyclones of 2020. As a detail investigation of all cyclones of 2019 was not within the limited scope of this study. The performances of both models for typically different two independent cyclones are examined to get an insight about analysis for the year 2019. A brief investigation has been carried out on a few specific parameters, *e.g.*, Sea Surface Temperature (SST), sensible heat flux and latent heat flux at the surface amid many forecast fields of two coupled model at the same forecast hour of each cyclone separately. A thorough



Figs. 4(a-h). Mean DPE (km) along with number of forecasts verified for both HCOM and HPOM coupled models during real-time forecasting of tropical cyclones over NIO (a) PABUK, (b) FANI, (c) VAYU, (d) HIKAA, (e) KYARR, (f) MAHA, (g) BULBUL and (h) PAWAN respectively in the year 2019

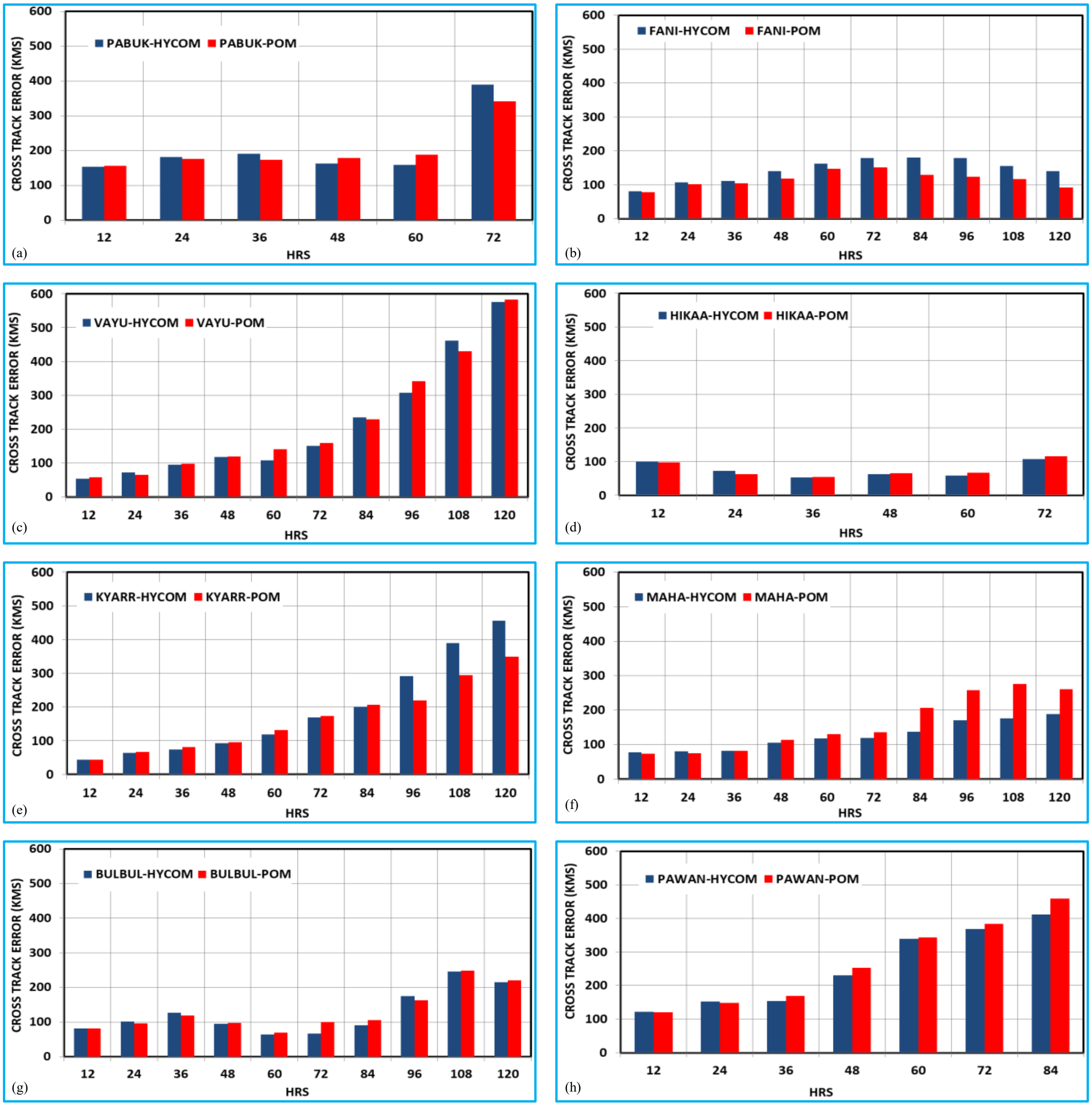
study on various specific characteristics parameters associated with air-ocean interaction has been omitted being out of the scope of the present research paper.

3.1. *Track and intensity prediction skill for all the cases of 2019*

Figs. 4(a-h) shows the direct position errors along with the number of forecast cycles verified for each cyclone separately. Subsequently, Figs. 5&6 are representing the ATE and CTE of all cases respectively maintaining the sequence of storms in different panels similar to Figs. 4(a-h). The track prediction skill for a few cyclones such as FANI, HIKAA, MAHA and BULBUL [Figs. 4(b, d, f & g)] is relatively better than other cyclones as the DPE is less than 200 kilometers up to a lead time of 84 hours, irrespective of the coupled ocean model. Although, the increasing track forecast errors of the models for longer

Figs. 5(a-h). Mean ATE (km) for both HCOM and HPOM coupled models during real-time forecasting of tropical cyclones over NIO (a) PABUK, (b) FANI, (c) VAYU, (d) HIKAA, (e) KYARR, (f) MAHA, (g) BULBUL and (h) PAWAN respectively in the year 2019

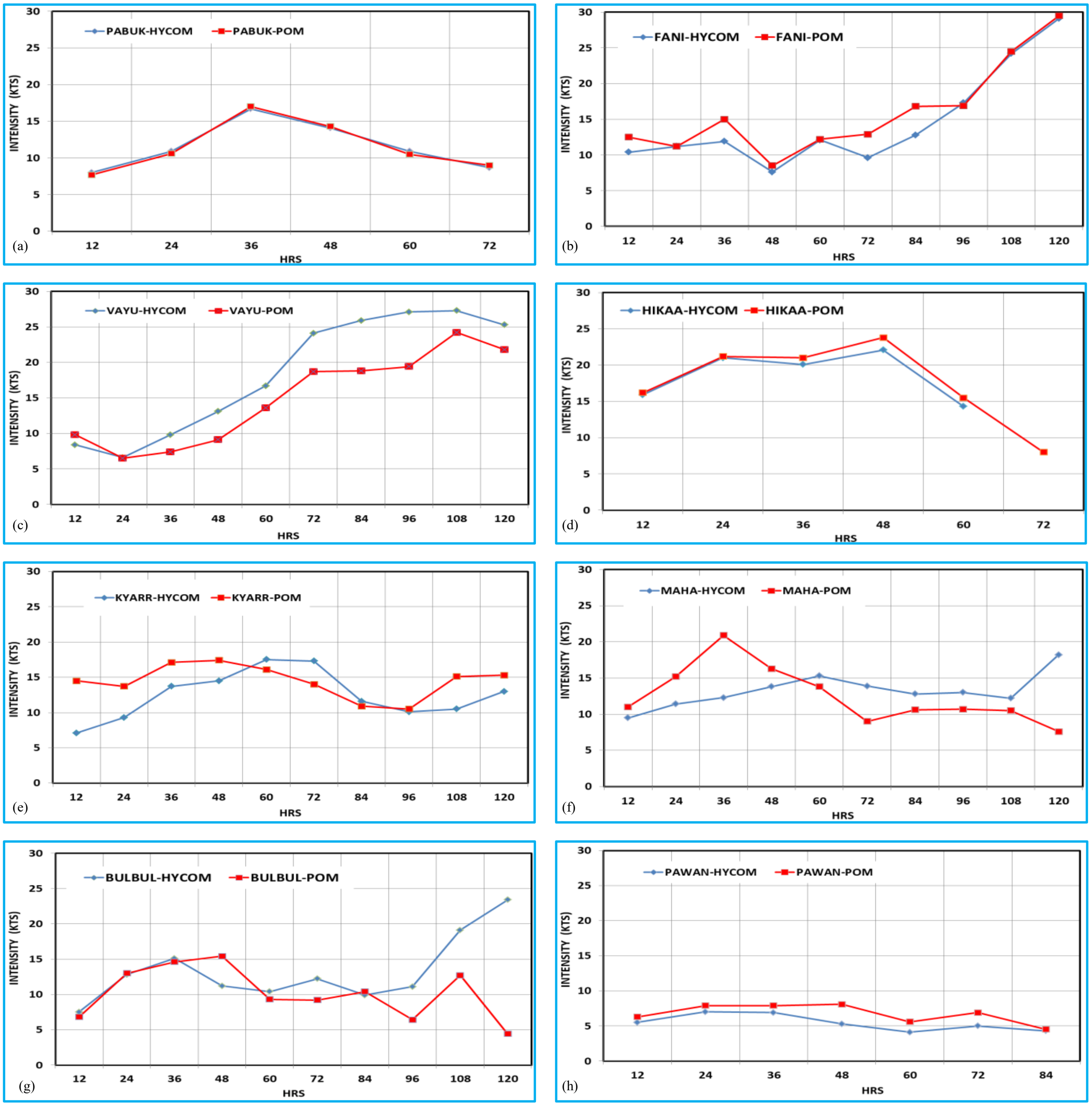
lead time are evident for the cyclones with recurving trajectory [*e.g.*, FANI, HIKAA, MAHA, BULBUL and PAWAN - Figs. 4(b, d, f, g & h)] in their lifetime, the track errors have modest values (DPE < 400 km, ATE and CTE ~ 200 km) at 5th day forecasts. It was also found that the track errors are even comparatively higher for cyclones [PABUK and KYARR - [Figs. 4(a&e)] with modest straight tracks. In case of VAYU cyclone which traced a typical track with multiple recurving segments, both versions of the model performed poorly with DPE more than 200 km even with a lead time of 2 days. The values of DPE for all cyclones depict that HCOM is comparatively a little better than HPOM. Although, the DPE for both variants of the model increases with lead time, both versions portray improved performance for the cyclones with longer lifetime (more number of forecast cycles verified) compared to short-lived cyclones (less number of forecast cycles). The joint analysis both the Figs. 5&6 bring out a fact that the ATEs of HCOM are smaller than the other coupled variant nearly for all forecast hours irrespective of cyclones (except



Figs. 6(a-h). Mean CTE (km) for both HCOM and HPOM coupled models during real-time forecasting of tropical cyclones over NIO (a) PABUK, (b) FANI, (c) VAYU, (d) HIKAA, (e) KYARR, (f) MAHA, (g) BULBUL and (h) PAWAN respectively in the year 2019

VAYU). The CTEs in Figs. 6(a-h) portray mixed scenario with respect to the comparison between two models for different cyclones. The values of ATEs in Fig. 5(a-h) are smaller than corresponding CTEs in Fig. 6(a-h) for each individual cyclone. Both coupled models' performances are comparable during initial hours (up to 36 hours) of track prediction as the error differences between them are very small.

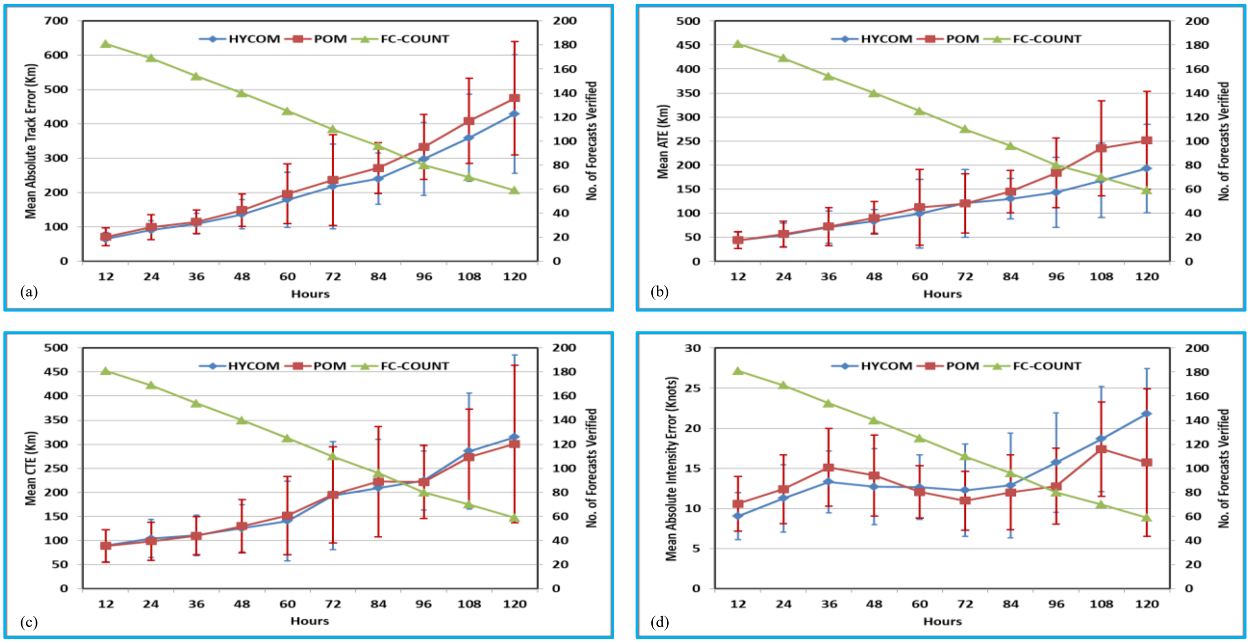
Figs. 7(a-h) show the mean absolute intensity error in the prediction of MSW of all cyclones. The relative positions of error lines in all panels corresponding to both coupled versions depict that the HCOM produced marginally better intensity prediction compared to POM up to 60 hours of forecast. In cases of cyclones with shorter life period [*e.g.*, PABUK, HIKAA and PAWAN - Figs. 7(a, d & h)], HCOM has superiority over HPOM. But for cyclones with long lifespan [FANI, KYARR, MAHA and BULBU - Figs. 7(b, e, f & g)], merely there is a transition around 60 hours of forecast wherefrom HPOM render a little improved skill compared to HCOM but with



Figs. 7(a-h). Mean absolute intensity errors (knots) for both HCOM and HPOM coupled models during real-time forecasting of tropical cyclones over NIO (a) PABUK, (b) FANI, (c) VAYU, (d) HIKAA, (e) KYARR, (f) MAHA, (g) BULBUL and (h) PAWAN respectively in the year 2019

less number of verified forecasts. Similar to track prediction the cyclone VAYU is an exception for poor real-time intensity prediction as well. Observing intensity error plots of different forecast hours for a few cyclones it is found that the both models show gradual growth in the error but the rate of growth diminishes and more often reverses and again rises thereafter with the increase of forecast hours. This may be attributed to the fact that the number of verified forecasts with longer lead time is less than initial hours. In addition, very often cyclones depict rapid intensification and rapid weakening after landfall. The performances of both models predicting intensity of weaker cyclones (*e.g*., PABUK, HIKAA, BULBUL and PAWAN) are very close whereas they differ for intense cyclones (KYARR, FANI, MAHA and VAYU).

The composite errors for track and intensity prediction for all cyclones of 2019 are plotted in Fig. 8. The four panels of Figs.8(a-d) represent average DPE, ATE, CTE and absolute intensity errors respectively. The



Figs. 8(a-d). The coupled HCOM and HPOM forecast errors with standard deviation for all tropical cyclones over NIO during 2019. (a) Mean absolute track error (KM), (b) Mean ATE (KM), (c) Mean CTE (KM) and (d) Mean intensity error (Knots)

error plots are accompanied with the total number of forecast cycle verified corresponding to each forecast hour. At the point of each forecast hour standard deviation of respective error is plotted as error bar. The generalized characteristics of track prediction errors discussed in previous paragraphs are mostly reiterated by the plots of Figs. 8(a-d) in a consolidated manner. The HCOM has a clear superiority in terms of track prediction after day 3 however this is not obvious for cross track errors. The spread of the error bars related to standard deviation shows that up to 60 hours both models show consistency in their track predictions. Although, both models show large values of standard deviation for track errors, the HCOM has comparatively a little less amount of inconsistency. On the other hand, intensity error graphs illustrate diversified view for different forecast duration. As discussed earlier, skill changeover amongst both models is noticeable beyond 60 hours of forecasts. The HCOM display authority during initial hours but HPOM show a clear advantage with longer lead time. Another fact also evident from the Fig. 8(d) is that both the models demonstrate a large variation in their intensity errors with comparatively larger values of standard deviations even from the initial forecast hours. In addition, one noticeable fact is the average absolute intensity error increases gradually from 10 knots at 12 hours to a value of 20 knots at 120 hours that implies twofold growth in 5 days although maximum upsurge (~75%) takes place between 84 and 120 hours (12.5 knots to 20 knots). A recent study by Dong *et al.* (2020) with three different models including coupled HWRF model employed operationally for hurricanes over Atlantic basin also demonstrated similar performance characteristics.

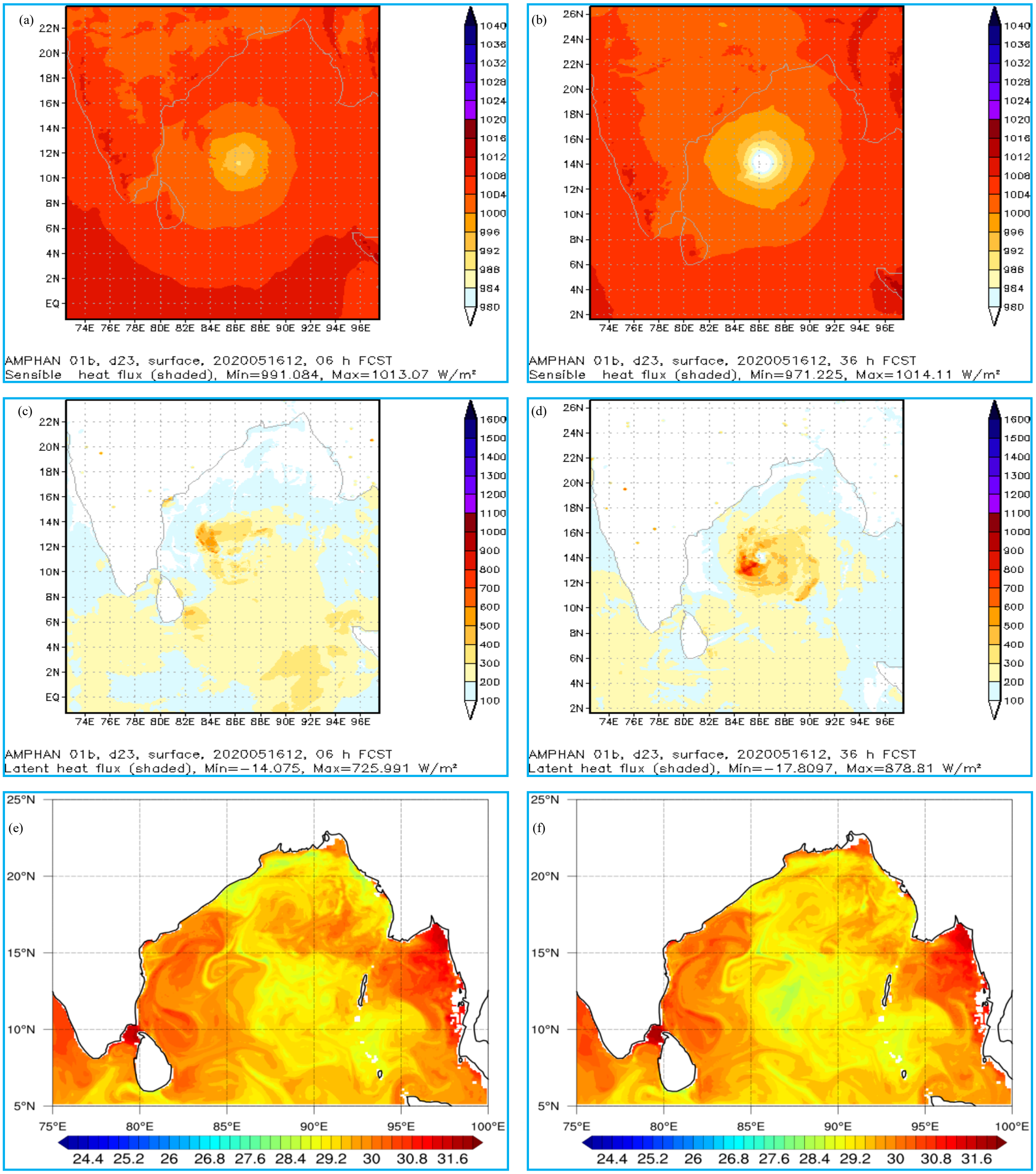
3.2. *Track and intensity prediction skill for two independent cases of 2020*

Figs. 9(a-h) described the comparative performances of both coupled models for two characteristically different and independent cyclones of 2020, *i.e.*, AMPHAN (suCS) and NISARGA (SCS). Three rows of the figure are showing mean plots of DPE, ATE, CTE and absolute intensity errors sequentially downwards. The left and right panels represent AMPHAN and NISARGA respectively. As both the cyclones were very different in their characteristics, the values and changes pattern of all errors for both coupled model with forecast hours are also very diverse in nature. The track errors are larger for AMPHAN but they are comparable in the forecast hours matching with the lifespan of NISARGA over sea. In case of NISARGA, two models have very small error differences with diversified nature of all three types of track errors (DPE, ATE and CTE). HCOM model demonstrate obvious supremacy over HPOM in the track prediction of AMPHAN but the contradictory performances are observed in forecasting intensity of the storm except during initial hours of forecast. However, the intensity prediction by HCOM is better than HPOM for NISARGA cyclone.

Figs. 9(a-h). Mean values of DPE, ATE, CTE (in Kilometers) and absolute intensity error (in Knots) of HPOM and HCOM forecasts in (a), (c), (e) & (g) for AMPHAN and in (b), (d), (f) & (h) for Nisarga respectively

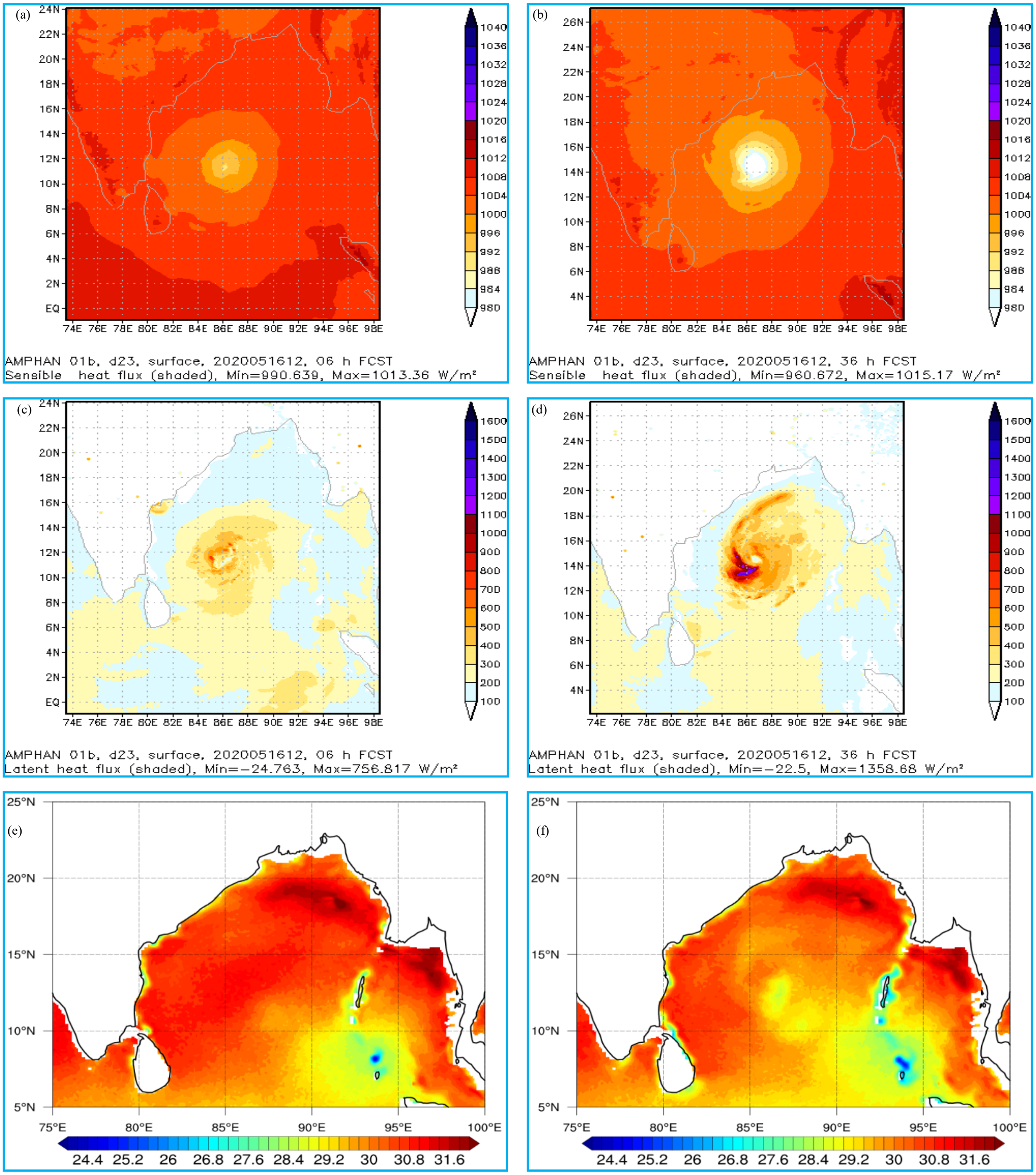
3.3. *Brief Analysis of a few surface parameters*

In Figs. 10(a-f), the transition from left to right panel of each row demonstrates the evolution of a surface parameter by HCOM model in the real-time forecasts of AMPHAN from 6^{th} to 36^{th} hour based on initial condition at 1200 UTC of 16^{th} May, 2020. The rows from top to bottom are sequentially displaying sensible heat flux, latent heat flux at the surface and SST. In the specified period of forecast the storm intensified and but moved slowly over central BoB. Corresponding changes in sensible heat flux are clearly seen in between Figs. 10(a&b) near storm location. The increase in latent heat flux from Figs. 10(c&d) around storm center due to further development of wall cloud region associated with storm intensification. The changes in SST field are very much visible as the advent of cold wakes along the rain swath of the cyclone took place during 30 hours.



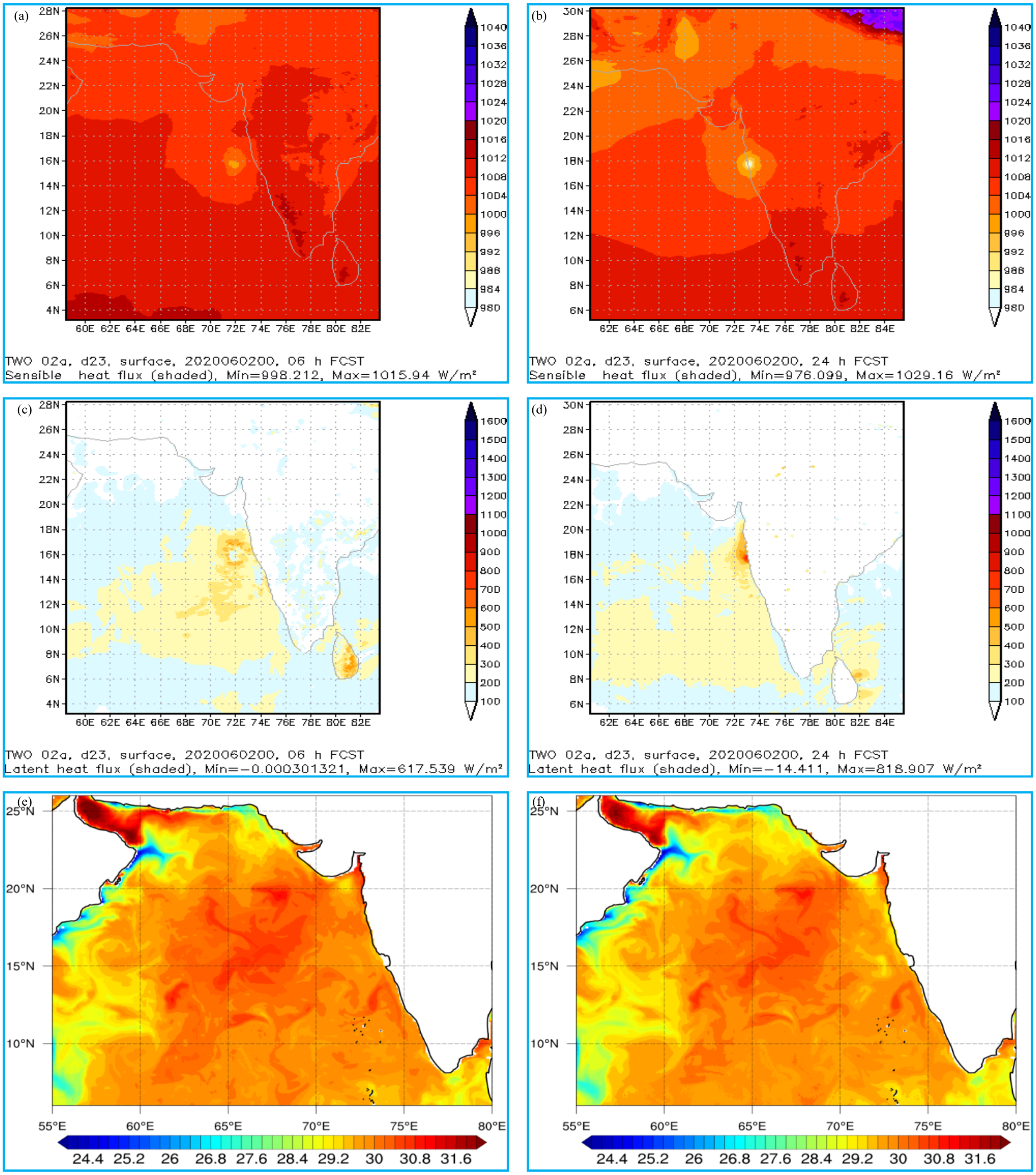
Figs. 10(a-f). (a) & (b) Sensible heat flux, (c) & (d) Latent heat flux and (e) & (f) Sea Surface Temperature for AMPHAN cyclone as forecasted by HCOM model at 6 and 36 hours respectively based on same initial condition at 1200 UTC of 16 May, 2020

Figs. 11(a-f) is similar to Figs. 10(a-f) but the evolutions of all surface parameters are attributed to HPOM model with its own initial conditions valid at same time. The oceanic feature portrayed by SST is very different from HCOM. Although, the evolution of ocean state such as appearance of cold region due to storm passage is also presented by the model, the distinctness of transformation over comparative Warm Ocean is missing. The sensible heat flux does not show prominent variation from HCOM model. On



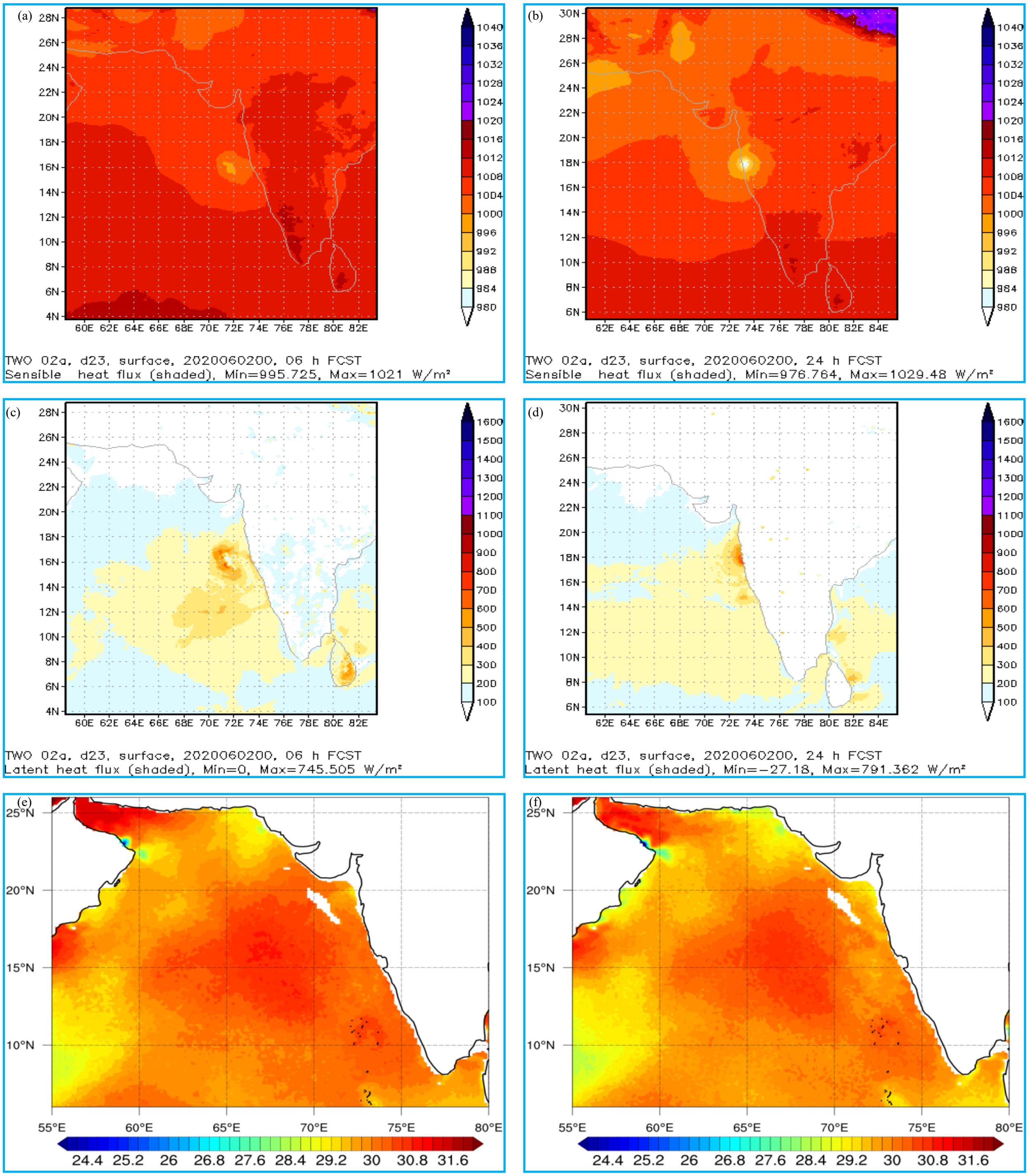
Figs. 11(a-f). (a) & (b) Sensible heat flux, (c) & (d) Latent heat flux and (e) & (f) Sea Surface Temperature for AMPHAN cyclone as forecasted by HPOM model at 6 and 36 hours respectively based on same initial condition at 1200 UTC of 16 May, 2020

the other hand, generation of latent heat flux at surface by POM is comparatively larger than HYCOM which may be due to higher SST in the model. The differences in surface fluxes of both models are due to the physical processes simulated based on different oceanic turbulent mixing, the ocean model grid spacing, the upper vertical layer discretization and the initial oceanic thermal state but also the air-sea flux formulations, which also depend upon the atmospheric model grid resolution (Kim *et al*., 2014).



Figs. 12(a-f). (a) & (b) Sensible heat flux, (c) & (d) Latent heat flux and (e) & (f) Sea Surface Temperature for NISARGA cyclone as forecasted by HCOM model at 6 and 36 hours respectively based on same initial condition at 1200 UTC of 16 May, 2020

The evolution of surface parameters of NISARGA cyclone by HCOM model from 6th to 24th hours of forecast is presented in Figs. 12(a-f) similar to Figs. 10(a-f) using its own oceanic and atmospheric initial conditions at 0000 UTC of 2nd June, 2020. In a similar fashion, HCOM displayed more convincing changes of surface parameters (verified with observations by compared to HPOM [Fig. 13(a-f)]. The specific surface features, *e.g.*, area of diminished sensible heat flux and enhanced latent heat flux associated with the progression of cyclonic storm



Figs. 13(a-f). (a) & (b) Sensible heat flux, (c) & (d) Latent heat flux and (e) & (f) Sea Surface Temperature for NISARGA cyclone as forecasted by HPOM model at 6 and 36 hours respectively based on same initial condition at 1200 UTC of 16 May, 2020

NISARGA are clearly visible. But the cold wakes due to fresh rain water caused by the cyclone is not clearly noticeable in both Figs. 12&13(a-f) associated to the forecast evolutions by HCOM and HPOM respectively.

4. Summary and conclusions

With both coupled versions of HWRF, the real-time forecasts of all cyclones demonstrated that the HCOM has an obvious benefit over HPOM in track prediction. But, a marginal advantage can only be found in case of intensity prediction. The improvement in the intensity prediction during initial hours of forecast is not maintained after 60 hours for intense cyclones with longer lifespan. It is also found that the growth of error in intensity prediction from its magnitude in the initial forecast period is much larger after day 4 onwards. The skills of both the models for short lived comparatively weaker storms (like NISARGA) are considerably better than intense long lived cyclones. The crispy analysis on the evolution of surface fluxes and SST although is not able to provide any explanation for intensity prediction issue, but established that the transformation of oceanic states and corresponding atmospheric response portrayed by the HCOM model is fairly convincing than HPOM. Considering this, it can be stated that the improvement in HCOM above comparatively simplistic coupling in HPOM, which can be attributed to the eddy-resolving ocean model along with realistic SST initialization with HYCOM (within RTOFS).

The issue with intensity prediction may be attributed to the fact that the intense cyclones like SuCS AMPHAN furnished different stages of intensification (rapid intensification or rapid weakening) within their lifespan. As the coupling is targeted to improve intensity prediction, the proper representation of air-sea interaction and its changes within a dynamic environment of an intense cyclonic storm within present coupled modelling framework needed to be improved. Further detail investigation of ocean evolution along with two-way feedback mechanism between air and ocean supported with observations is mandatory for the cyclones over NIO.

Acknowledgement

The authors are grateful for the support and encouragement by DGM, IMD, Director, INCOIS and Secretary, MoES towards the implementation of the high resolution coupled HWRF modelling system. MoES High Power Computing (HPC) facilities "Aaditya" located at IITM, Pune and "MIHIR" located at Noida and their support team are highly appreciated and acknowledged. National Centre for Environmental Prediction (NCEP), USA is acknowledged for sharing the latest version of coupled HWRF, tracker and for continuous support. The contents and views expressed in this research paper are the views of the authors and do not necessarily reflect the views of their organizations.

References

Agrawal, N., Pandey, V. K. and Kumar, P., 2020, "Numerical Simulation of Tropical Cyclone Mora Using a Regional Coupled Ocean-Atmospheric Model", *Pure Appl. Geophys.*, **177**, 5507-5521. https://doi.org/10.1007/s00024-020-02563-4.

Aligo, E., Ferrier, B., Carley, J., Rodgers, E., Pyle, M., Weiss, S. J. and Jirak, I. L., 2014, "Modified microphysics for use in high resolution NAM forecasts", 27 AMS Conference on Severe Local Storms.3-7 November, Madison, WI.

Bender, M. A. and Ginis, I., 2000, "Real case simulation of hurricane-ocean interaction using a high-resolution coupled model: Effects on hurricane intensity", *Mon. Wea. Rev.*, **128**, 917-946.

Bender, M. A., Ginis, I., Tuleya, R., Thomas, B. and Marchok, T., 2007, "The operational GFDL Coupled Hurricane-Ocean Prediction System and a summary of its performance", *Mon. Wea. Rev.*, **135**, 3965-3989.

Biswas, M. K., Abarca, S., Bernardet, L., Ginis, I., Grell, E., Iacono, M., Kalina, E., Liu, B., Liu, Q., Marchok, T., Mehra, A., Newman, K., Sippel, J., Tallapragada, V., Thomas, B., Wang, W., Winterbottom, H. and Zhang, Z., 2018, "Hurricane Weather Research and Forecasting (HWRF) Model : 2018 Scientific Documentation", available at https://dtcenter.org/HurrWRF/users/docs/index.php.

Biswas, M. K., Bernardet, L. and Dudhia, J., 2014, "Sensitivity of hurricane forecasts to cumulus parameterizations in the HWRF model", *Geophysical Research Letters*, **41**, 9113-9119. doi : 10.1002/2014GL062071.

Biswas, M. K., Bernardet, L., Abarca, S., Ginis, I., Grell, E., Kalina, E., Kwon, Y., Liu, B., Liu, Q.,Marchok, T., Mehra, A., Newman, K., Sheinin, D., Sippel, J., Subramanian, S., Tallapragada,V., Thomas, B., Tong, M., Trahan, S., Wang, W., Yablonsky, R., Zhang, X. and Zhang, Z., 2017, "Hurricane Weather Research and Forecasting (HWRF) Model : 2017 Scientific Documentation", NCAR Technical Note NCAR/TN-544+STR, doi: 10.5065/D6MK6BPR.

Black, P. G., D'Asaro, E. A.,Drennan, W. M., French, J. R., Sanford, T. B., Terrill, E. J., Niiler, P. P., Walsh, E. J. and Zhang, J., 2007, "Air-Sea Exchange in Hurricanes: Synthesis of Observations from the Coupled Boundary Layer Air-Sea Transfer Experiment", *Bull. Amer. Meteor. Soc.*, **88**, 357-374.

Chen, F. and Dudhia, J., 2001, "Coupling an advanced land surface–hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model description and implementation", *Mon. Wea. Rev.*, **129**, 569-585. doi : 10.1175/1520- 0493(2001) 129<0569:CAALSH>2.0.CO;2.

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)", *Natural Hazards*, **75**, 2, 1205-1221.

Dong, J., Liu, B., Zhang, Z., Wang, W., Mehra, A., Hazelton, A. T., Winterbottom, H. R., Zhu, L., Wu, K., Zhang, C., Tallapragada, V., Zhang, X., Gopalakrishnan, S. and Marks, F., 2020, "The Evaluation of Real-Time Hurricane Analysis and Forecast System (HAFS) Stand-Alone Regional (SAR) Model Performance for the 2019 Atlantic Hurricane Season", *Atmosphere*, **11**, 6, 617. doi : 10.3390/atmos11060617.

Han, J. and Pan, H. L., 2011, "Revision of Convection and Vertical Diffusion Schemes in the NCEP Global Forecast System", *Wea. Forecasting*, **26**, 520-533.

Han, J., Wang, W., Kwon, Y. C., Hong, S., Tallapragada, V. and Yang, F., 2017, "Updates in the NCEP GFS Cumulus Convection Schemes with Scale and Aerosol Awareness", *Weather and Forecasting*, **32**, 5, 2005-2017.

Heming, J. T., Chan, J. C. and Radford, A. M., 1995, "A new scheme for the initialisation of tropical cyclones in the UK Meteorological Office global model", *Meteor. Appl*., **2**, 171-184.

Hong, S. Y. and Pan, H. L., 1996, "Nonlocal Boundary Layer Vertical Diffusion in a Medium Range-Forecast Model", *Monthly Weather Review*, **124**, 2322-2339.

Iacono, M. J., Delamere, J. S., Mlawer, E. J., Shephard, M. W., Clough, S. A. and Collins, W. D., 2008, "Radiative forcing by long-lived greenhouse gases : Calculations with the AER radiative transfer models", *J. Geophys. Res*., **113**, D13103. doi : 10.1029/2008JD009944.

IMD, 2013, Cyclone Warning in India: Standard Operation Procedure; India Meteorological Department, New Delhi.

Kim, H., Lozano, C., Tallapragada, V., Iredell, D., Sheinin, D., Tolman, H. L., Gerald, V. M. and Sims, J., 2014, "Performance of Ocean Simulations in the Coupled HWRF-HYCOM Model", *Journal of Atmospheric and Oceanic Technology*, **31**, 2, 545-559.

Kurihara, Y., Bender, M. A.,Tuleya, R. E. and Ross, R., 1995, "Improvements in the GFDL Hurricane Prediction System", *Mon. Wea. Rev.***, 123**, 9, 2791-2801.

Kurihara, Yoshio and Tuleya, Robert., 1974, "Structure of a Tropical Cyclone Developed in a Three-Dimensional Numerical Simulation Model", *J. of Atmos. Sciences*, **31**, 893-919. doi : https://doi.org/10.1175/1520-0469(1974)031<0893:SOATCD> 2.0.CO;2.

Kwon Y. C. and Lord, S., Lapenta, B., Tallapragada, V., Liu, Q. and Zhang, Z., 2010, "Sensitivity of Air-Sea Exchange Coefficients (Cd and Ch) on Hurricane Intensity", 29th Conference on Hurricanes and Tropical Meteorology, 13C.1.

Liu, Q., Lord, S., Surgi, N., Zhu, Y., Wobus, R., Toth, Z. and Marchok, T., 2006, "Hurricane relocation in global ensemble forecast system", *Preprints,* 27thConf. On Hurricanes and Tropical Meteorology, Monterey, CA, *Amer. Meteor. Soc*., P5.13.

Liu, Q., Marchok, T., Pan, H.L., Bender, M. and Lord, S., 2000, "Improvements in Hurricane Initialization and Forecasting at NCEP with Global and Regional (GFDL) models", NCEP Office Note, p472.

Liu, Q., Surgi, N., Lord, S., Wu, W. S., Parrish, S., Gopalakrishnan, S., Waldrop, J. and Gamache, J., 2006a, "Hurricane Initialization in HWRF Model", Preprints, 27th Conference on Hurricanes and Tropical Meteorology.

Lord, S. J., 1991, "Abogussing system for vortex circulations in the National Meteorological Center Global Forecast Model", Preprints, 19th Conf. on Hurricane and Tropical Meteorology, Miami, FL, *Amer. Meteor. Soc*., 329-330.

Mathur, M. B., 1991, "The National Meteorological Center's Quasi-Lagrangian model for Hurricane Prediction", *Mon. Wea. Rev*., **119**, 6, 1419-1447.

Mellor, G. L., 2004, "Users guide for a three-dimensional, primitive equation, numerical ocean model", (June 2004 revision).Program in Atmos. and Ocean. Sci, Princeton University, p56.

Mitchell, K., 2005, "The community Noah Land Surface Model (LSM)", http://www.ral.ucar.edu/research/land/technology/lsm/noah/Noah_LSM_USERGUIDE_2.7.1.pdf.

Mohanty, S., Nadimpalli, R., Osuri, K. K., Pattanayak, S., Mohanty, U. C. and Sil, S., 2019, "Role of Sea Surface Temperature in Modulating Life Cycle of Tropical Cyclones over Bay of Bengal", *Tropical Cyclone Research and Review*, **8**, 2, 68-83.

Mohapatra, M., Bandopadhyay, B. K. and Tyagi, A., 2012, "Best track parameters of tropical cyclones over the North Indian Ocean : A review", *Nat. Hazards*, **63**, 3, 1285-1317.

Nadimpalli, R., Osuri, K. K., Mohanty, U. C., Das, A. K., Kumar, A., Sil, S. and Niyogi, D., 2020, "Forecasting tropical cyclones in the Bay of Bengal using quasi-operational WRF and HWRF modeling systems: an assessment study", *Meteorology and Atmospheric Physics*, **132**, 1, 1-17.

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", *Quarterly Journal of the Royal Meteorological Society*, **143**, 703, 678-690.

Osuri, Krishna K., Mohanty, U. C., Routray, A., Mohapatra, M. and Niyogi, Dev, 2013, "Real-Time Track Prediction of Tropical Cyclones over the North Indian Ocean Using the ARW Model", *Journal of Applied Meteorology and Climatology*, **52**, 11, 2476-2492, JSTOR, www.jstor.org/stable/26175917.

Peng, M. S., Jeng, B. F. and Chang, C. P., 1993, "Forecast of Typhoon motion in the vicinity of Taiwan during 1989-90 using a dynamical model", *Wea. Forecasting*, **8**, 309-325.

Powell, M. D., Vickery, P. J. and Reinhold, T. A., 2003, "Reduced drag coefficient for high wind speeds in tropical cyclones", *Nature*, **422**, 279-283.

Prasad, K. and Rama Rao, Y. V., 2003, "Cyclone track prediction by quasi-Lagrangian limited area model", *Meteol. Atmos. Phys*., **83**, 173-185.

Rogers, E., Black, T., Ferrier, B., Lin, Y., Parrish, D. and DiMego, G., 2001, "Changes to the NCEP Meso Eta Analysis and Forecast System: Increase in resolution, new cloud microphysics, modified precipitation assimilation, modified 3DVAR analysis", *Technical Procedures Bulletin*. http://www.emc.ncep.noaa.gov/mmb/mmbpll/eta12tpb/.

RSMC New Delhi, 2020, "Report on Cyclonic Disturbances over North Indian Ocean during 2019", Published by India Meteorological Department, No. MOES/IMD/RSMC-Tropical Cyclone Report No/01 (2020)/10 p424. http://www.rsmcnewdelhi.imd.gov.in/images/pdf/publications/annual-rsmc-report/rsmc-2019.pdf.

Samson, G., Masson, S., Lengaigne, M., Keerthi, M. G., Vialard, J., Pous, S., Madec, G., Jourdain, N. C., Jullien, S., Menkes, C. and Marchesiello, P., 2014, "The NOW regional coupled model: Application to the tropical Indian Ocean climate and tropical cyclone activity", *J. Adv. Model. Earth Syst.*, **6**, 700-722. doi : 10.1002/2014MS000324.

Sirutis, J. J. and Miyakoda, K., 1990, "Subgrid scale physics in 1-month forecasts. Part I: Experiment with four parameterization packages", *Mon. Wea. Rev.*, **118**, 5, 1043-1064.

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. Geophys. Res. Atmos.*, **121**, 9400-9421.doi:10.1002/2015JD024431.

Tallapragada, V., Kieu, C., Kwon, Y., Trahan, S., Liu, Q., Zhang, Z.and Kwon, I. H., 2014, "Evaluation of storm structure from the operational HWRF during 2012 implementation", *Monthly Weather Review*, **142**, 11, 4308-4325.

Tallapragada, V.,Kieu, C., Trahan, S., Liu, Q., Wang, W., Zhang, Z., Tong, M., Zhang, B., Zhu, L. and Strah, B., 2016, "Forecasting tropical cyclones in the western North Pacific basin using the NCEP operational HWRF Model : Model upgrades and evaluation of real-time performance in 2013", *Weather and Forecasting*, **31**, 3, 877-894.

Thompson, G., Bernardet, L., Biswas, M.and Holt, C., 2014, "Explicitly-Coupled Cloud Physics and Radiation Parameterizations and Subsequent Testing in HWRF", http://www.dtcenter.org/eval/hwrf_hdrf_hdgf/HFIP_GT2014Dec17.pdf.

Yablonsky, R. M. and Ginis, I., 2009, "Limitation of one-dimensional ocean models for coupled hurricane-ocean model forecasts", *Mon. Wea. Rev.*, **137**, 4410-4419.

Yablonsky, R. M. and Ginis, I., 2013, "Impact of a warm ocean eddy's circulation on hurricane-induced sea surface cooling with implications for hurricane intensity", *Mon. Wea. Rev.*, **141**, 997-1021.