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Study of the impact of high resolution ROMS-SST on the simulation of two intense tropical cyclones over Bay of Bengal using ARW modeling system

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सार – बंगाल की खाड़ी (BoB) के ऊपर विकसित दो तीव्र भ्रमिलों (फैलिन और हुदहुद) पर क्षेत्रीय महासागर प्रतिरूपण प्रणाली (ROMS) से प्राप्त उच्च-विभेदन समुद्री सतह ऊष्मामान (SST) के प्रभाव की जांच की गई। बंगाल की खाड़ी (BoB) पर उपलब्ध विभिन्न प्रेक्षणीय डेटासेट के साथ ROMS-SST का सत्यापन 0.90 से अधिक का यथोचित अच्छा सहसंबंध दर्शाता है। मूल माध्य वर्ग अंतर लगभग 0.40°C है। उन्नत मौसम अनुसंधान (ARW) मॉडल की निचली सीमा स्थिति के रूप में ROMS-SST को प्रेरित करने से TC फैलिन के लिए TC तीव्रता और वर्षा स्थान में सुधार हुआ। TC हुदहुद की तीव्रता में मामूली सुधार देखा गया है। फिर भी, नियंत्रण प्रयोग की तुलना में पवन संरचना और वर्षा स्थान की बेहतर प्रतिकृति के साथ, जो वैश्विक मॉडल आउटपुट से निम्न-विभेदन रेनॉल्ड्स- SST का उपयोग करता है। नियंत्रण प्रयोग की तुलना में ROMS प्रयोग में दोनों टीसी के लिए अवरक्त उपग्रह बिम्बावली से देखे गए गंभीर संवहन की प्रेक्षित संरचना के साथ गुप्त ऊष्मा प्रतिरूप का यह दक्षिण अवखण्ड क्षेत्र शिखर बेहतर मेल खाता है। हालाँकि, ROMS-SST प्रयोग के लिए मॉडल सिम्युलेटेड ट्रैक ने दोनों TC के लिए सभी प्रारंभिक स्थितियों के लिए TC ट्रैक में सुधार नहीं किया। वर्तमान प्रतिरूपण अध्ययन टीसी अनुकरण के लिए एक मेसोस्केल क्षेत्रीय महासागर प्रतिरूप द्वारा डाउनस्केल लिए गए उच्च विभेदन SST के उपयोग करता है।

ABSTRACT. Impact of high-resolution Sea Surface Temperature (SST) derived from the Regional Ocean Modeling System (ROMS) on two intense vortices (Phailin and Hudhud) developed over the Bay of Bengal (BoB) are investigated. The validation of ROMS-SST with various observational datasets available over BoB showed a reasonably good correlation of greater than 0.90. The root mean square difference is around 0.40° C. Instigating ROMS-SST as a lower boundary condition to the Advanced Weather Research (ARW) model improved the TC intensity and rainfall location for TC Phailin. A minor improvement is observed in the intensity of TC Hudhud. Still, with better replication of wind structure and rainfall location than the control experiment, which uses low-resolution Reynolds-SST from the global model output. This right sector peak of latent heat pattern matches better with the observed structure of deep convection observed from infrared satellite imagery for both TCs in the ROMS experiment as compared with the control experiment. However, the model simulated track for the ROMS-SST experiment did not improve the TC track for all the initial conditions for both the TCs. The present modeling study compliments the use of higher resolutions SST downscaled by a mesoscale regional ocean model for the TC simulations.

Key words – Phailin, Hudhud, Bay of Bengal (BoB), WRF, SST, ROMS, Tropical cyclones.

1. Introduction

Tropical cyclone (TC) remains one of the worst natural disasters globally. Among many ocean basins, the Bay of Bengal (BoB) is one of the potential regions for the formation of TCs (Gray, 1968). Its coast is especially highly vulnerable to TCs due to the large density in population, shallow bathymetry and almost funnel shape coastline. Accurate prediction of the intensity and landfall location of TCs well in advance will immensely help minimize heavy loss of life and property. During the last few decades, regional numerical models over BoB played a vital role in the real-time prediction of TCs (Srinivas *et al.*, 2013; Osuri *et al.*, 2012; 2013; 2017; Mohanty *et al.*, 2015; Das *et al.*, 2015; Nadimpalli *et al.*, 2016; 2019; 2020; 2021). Although from the past 30 years impressive strides have been made in the quality of TC track predictions, unfortunately, there has been no perceptible improvement in the skill of tropical cyclone intensity prediction. One of the crucial elements in the intensity evolution of the TC is its interactions with the upper ocean.

The Ocean serves as an energy feeder to the TC through the exchange of the enthalpy fluxes provided a finite-difference of enthalpy between the atmosphere and ocean interface (Palmen, 1948; Miller, 1958; Riehl, 1954), which helps in enhancing the convection. As the TC intensifies over the ocean, fluxes are enhanced due to the intense winds, which further augments TC intensity (Emmanuel, 1986); hence, TC's interactions with the ocean play a predominant role in its life cycle. Further, interactions of TC with different oceanic features have been studied in detail over all the basins. *e.g*., TCs over the Atlantic basin intensify as they pass through warm ocean features like warm eddies and currents (Shay *et al.*, 2000; Goni and Trinanes, 2003). Conversely, TC interactions with the cold-core eddy degrade TC intensity (Zhanhong Ma *et al.*, 2013). Thus, Sharp SST gradients over the ocean play an important role in the intensity evolution of the TC (Kaplan and DeMaria, 2003). Many modeling studies showed that an accurate representation of the SST fields could resolve the majority of the ocean features and improve the TC's intensity prediction (Schade and Emanuel, 1999; Bao *et al.*, 2000; Chen *et al.*, 2001; Wu *et al*., 2007). Over the Atlantic basin studies with high resolution coupled ocean and atmosphere model reported an improvement in the prediction of the TC intensity (Sanabia *et al*., 2013; Kim *et al*., 2014; Yablonsky *et al*., 2015), similarly few modeling studies over the pacific also reported the same (Sandery *et al*., 2010; Jullien *et al*., 2014).

Over the BoB, several numerical experiments are conducted using the Advanced Research version of the Weather Research and Forecasting (WRF) model to show its reliability in the real-time TC forecasts (Osuri *et al*., 2013; 2020). However, it is to be noted that most of these studies used SST fields obtained from Reynolds SST analysis (Chelton and Wentz, 2005). Reynolds SST consists of weekly averages on a global 1° × 1° grid. Few studies over BoB showed that with the use of high-resolution satellite-derived SST, the intensity evolution of the TC has improved significantly (Bongirwar *et al.*, 2011; Mandal *et al.*, 2007). This improvement was attributed to the high-resolution SST fields, which captured the sharp SST gradients. However, a three-day composite Tropical Rainfall Measuring Mission Microwave Imager (TMI) SST was used in these studies as a boundary condition. More details of TMI SST can be found in Bongirwar *et al*. (2011). One of the major drawbacks of the TMI SST is its inability to represent accurate SST fields at times of cloudy weather and the coastal regions. Over BoB air-sea coupling on tropical cyclone (TC) predictions are studied using a three-dimensional Price-Weller-Pinkel ocean model coupled to WRF improved the prediction of TCs over BoB, which is attributed to the realistic representation of the ocean state during the integration of the model (Srinivas *et al*., 2016). Hence, a higher resolution SST is needed over the BoB for realistic TC prediction.

Over the north Indian Ocean, a coupled WRF-Regional Ocean Modelling System (ROMS) model simulations showed an improvement in the Indian summer monsoon prediction due to the improved air-sea interactions over the ocean (Samala *et al.*, 2013). The scientific community widely uses ROMS for various applications (Sil and Chakraborty, 2011a; Sil *et al*., 2011b; 2014). The authors in the current study focus on studying the impacts of high-resolution climatological SST produced from ROMS (now called ROMS-SST) in the simulations of TCs using the WRF atmospheric model. In the current study, two intense TCs occurred over BoB in October 2013 and 2014, *i.e*., TC Phailin and TC Hudhud, respectively, are selected as case studies. The ROMS-SST with a horizontal resolution of 9 km is obtained from the climatological simulation by Sil and Chakraborty (2011a). They highlighted the capability of the ROMS in simulating the mesoscale oceanic features, which might significantly play an important role in the intensity evolution of TCs.

The broad objective of the present study is to investigate the impact of high-resolution ROMS-SST on the intensity evolution and track of two TCs over BoB. Before the simulations, ROMS-SST is validated with available observations. Later, the WRF model simulates two TCs, as stated earlier. The research and operational community over India obtained two different kinds of ocean boundary conditions from Reynolds-SST (defacto mode of running forecast models for predicting tropical cyclones Bay of Bengal (BoB) by the research and operational community over India) ROMS-SST is used. The paper is organized as follows. A short description of two TC cases considered for this study is discussed in section 2. Section 3 details the model, experimental design and data used in this study. Results are presented in section 4, followed by a summary and conclusions in the final 5th section.

2. Tropical cyclone cases selected for the study

Two cyclone cases in October 2013 and 2014, *i.e*., TC Phailin and TC Hudhud, have caused a devastating impact on the coastlines of Orissa and Andhra Pradesh in the current study. The selection of the two recent cases that occurred during the last decade enables a glimpse of the objectives of the current study.

2.1. *Phailin cyclone*

TC Phailin originated from a remnant cyclonic circulation from the south china sea. It laid as a low pressure on 6 October over the Tenasserim coast. It intensified into a well mark low pressure on 7 October over the north Andaman Sea, which later concentrated into a deep depression over the same region on 8 October. It moved west-northwestwards and intensified into a cyclonic storm on 9th-morning Indian standard time. Later, it intensified into a severe cyclonic storm and then rapidly intensified into a very severe cyclonic storm in the forenoon of 10 October. It crossed the Odisha coast and adjoined Andhra Pradesh coast near Gopalpur (Odisha) around 2230 hrs IST on 12 October, causing extremely heavy rainfall over Odisha leading to floods (Osuri *et al.*, 2017).

2.2. *Hudhud cyclone*

Cyclone Hudhud developed from a low-pressure area over the Tenasserium coast and adjoined the North Andaman Sea on 6th October, 2014, which further intensified into a depression on 7 October, 2014 over the Andaman Sea. On 8 October, it intensified into a cyclonic storm crossing the Andaman Islands. Later it moved northwestwards and intensified into a severe cyclonic storm (SCS) in the morning of 9th October IST and further into a very severe cyclonic storm (VSCS) in the afternoon of 10 October. It continued to intensify further and reached its peak intensity on the 12th morning with a sustained wind speed of 180 kmph crossing north Andhra Pradesh coast over Vishakhapatnam on 12 October. It caused heavy to extremely heavy rainfall over North Andhra Pradesh and south Odisha coast (Nadimpalli *et al.*, 2016).

3. Models, experimental setup and methodology

3.1. *Atmospheric model*

The current study uses the advanced weather research model WRF-ARW (hereafter ARW) model developed from the National Centre for Atmospheric research (NCAR). It consists of multiple dynamical cores, which helps use the model for operational and research needs. The ARW model is a non-hydrostatic, fully compressible mesoscale model based on the Eulerian solver. The model equations, physics and dynamics are described in (Dudhia, 2004 and Shamrock *et al*., 2005). Three velocity components (u,v,w), pressure perturbations (p'), temperature (T) and specific humidity (q) are the prognostic variables. The ARW model is integrated at a horizontal resolution of 9km with a single domain for all the simulations. The model setup is followed as given in Osuri *et al*., 2013.

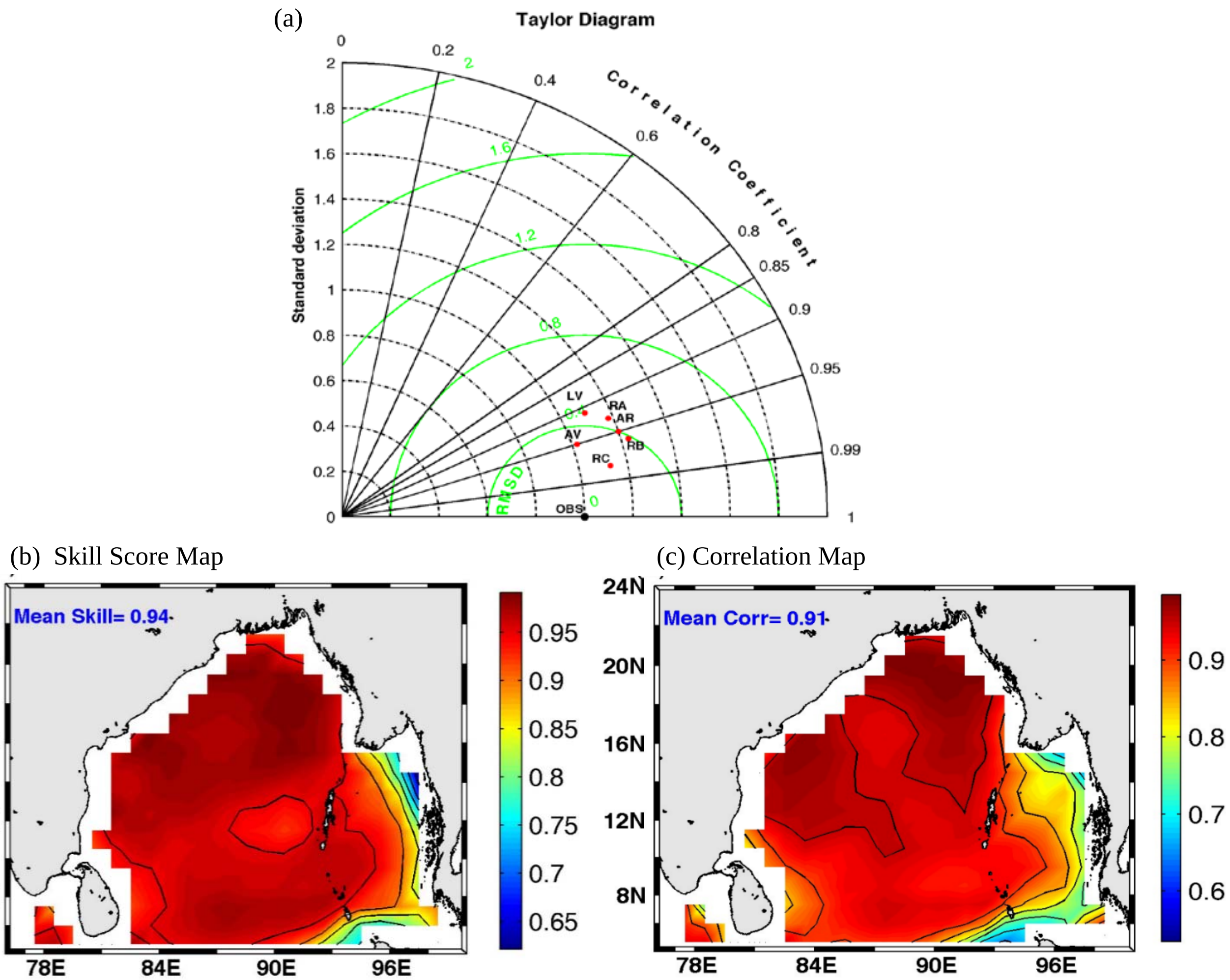
3.2. *Ocean model*

ROMS is a free-surface, terrain-following, primitive equation ocean model. The primitive equations are evaluated using boundary-fitted orthogonal, curvilinear coordinates on a staggered Arakawa C grid. The model is run at a 10 km resolution in an attempt to resolve fine structures of SST gradients. A complete description of the model setup and the methodology used to prepare the high-resolution climatological SST refer to Sil *et al*. (2011b).

3.3. *Data and experiments*

High-resolution ROMS-SST is validated with various available observational data sets such as World Ocean Atlas 2005 (WOA05 : https://www.ncei.noaa.gov/products/world-ocean-atlas), domain averaged SST from Argo (2003 – 2014 : https://incois.gov.in/argo/argo.jsp), AVHRR climatology (https://climatedataguide.ucar.edu/climate-data/sst-data-avhrr-pathfinder-v52-noaa-nodc) and SST derived from three RAMA buoy (2005 to 2014; https://incois.gov.in/portal/datainfo/rb.jsp) locations (A) 8° N, 90° E; (B) 12° N, 90° E, (C) 15° N, 90° E.

The WRF simulations are conducted for TC Phailin and Hudhud with integration using Reynolds SST and ROMS-SST. The forecast lead time of 96, 72 and 48 hours is chosen for the cyclone cases considering the real-time practice of cyclone forecast warning over the region (2-4 days before TC landfall). The simulations with Reynolds SST are referred to as control run (CNTL) and simulations with ROMS-SST are referred to as experimental runs (ROMS). TC Phailin is simulated from the initial conditions 0900 UTC, 1000 UTC & 1100 UTC and TC Hudhud is simulated with initial conditions from 0812 UTC, 0912 UTC & 1012 UTC. A set of two experiments with the three initial conditions are conducted for each TC and the results obtained are compared with the available observations. The initial atmospheric conditions are obtained from the real-time global analysis (GFS) available at 0.5° horizontal resolution. The TC intensity and track observations are obtained from the Indian meteorological department (IMD) and the same is



Figs. 1(a-c). (a) Taylor Diagram for SST comparison of model simulated SST with three RAMA moorings (RA, RB and RC), WOA2005 (LV), Argo (AR) and AVHRR (AV). The radial distances from the origin in a typical Taylor diagram represent the standard deviations, whereas the azimuthal positions show correlation coefficients. The distances between observation and model simulation represent model-observation root-mean-square errors, which measure differences in amplitude. (b) Skill Map and (c) Correlation map with respect to WOA 2005

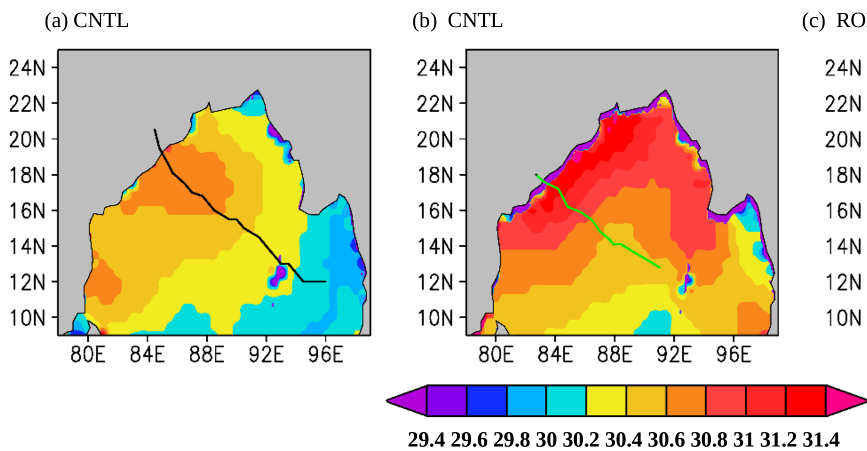
used for comparison with model simulations (https://www.rsmcnewdelhi.imd.gov.in/).The Satellite-based wind analysis (surface winds), which includes data sets from advanced satellite based wind analysis, cloud drift/IR/WV winds, Advanced-Scatterometer, IR-proxy winds and Scatterometer winds, is used as observation in comparing the model simulated winds. The preparation and details of the satellite based winds can be referred to with Bessho *et al.*, 2006 (https://rammb2.cira.colostate.edu/).

4. Results and discussion

The results obtained from the above mentioned numerical experiments are presented with the related observational facts. As the study's main objective is to access the impacts of the high-resolution SST derived from ROMS on TCs, the results presented here would primarily focus on the intensity (in terms of wind strength and precipitation) and storm tracks.

4.1. *Validation of ROMS climatological SST*

In order to summarize graphically on the agreement between the climatological SST obtained from the ROMS output with the observations, the authors use the Taylor diagram. The similarity between the ROMS-SST and observations is quantified in their correlation coefficients, their centered root-mean-square difference and the amplitude of their variations represented through their standard deviations. The correlations for the ROMS-SST are within 0.90 to 0.99 for all the observational data sets as shown in Fig. 1(a) with 99% significant with student *t*-test. The root mean square difference is around 0.4 °C,



Figs. 2(a-c). SST field along with the observed tracks for (a) Control run for TC Phailin valid for (b) Control run for TC Hudhud and (c) ROMS-SST for October. The black (green) line indicates the track of Phailin (Hudhud) TC

and the normalized standard deviation is slightly higher than unity, indicating the variability is almost similar for observations and model. From the above analysis represented in the Taylor diagram, it can be inferred that the climatological SST derived from the ROMS model agrees closely with the observations. The spatial comparison of the SST throughout the BoB is carried out on the same 1° × 1° grid of WOA 2005 which is considered as observation, the skill and correlation map is shown in Figs. 1(b&c), respectively. From Fig. 1(c), the ROMS-SST shows a mean correlation of about 0.91 throughout the BoB with 99% significance. The skill is shown in Fig. 1(b) also projects a skill greater than 0.94 for the ROMS-SST. The above results show that the ROMS-SST produces a realistic climatological pattern closer to observations. This SST, when used as a lower boundary condition for the simulation of TCs over BoB, might significantly provide a realistic ocean condition for the TC than compared with the Reynolds SST.

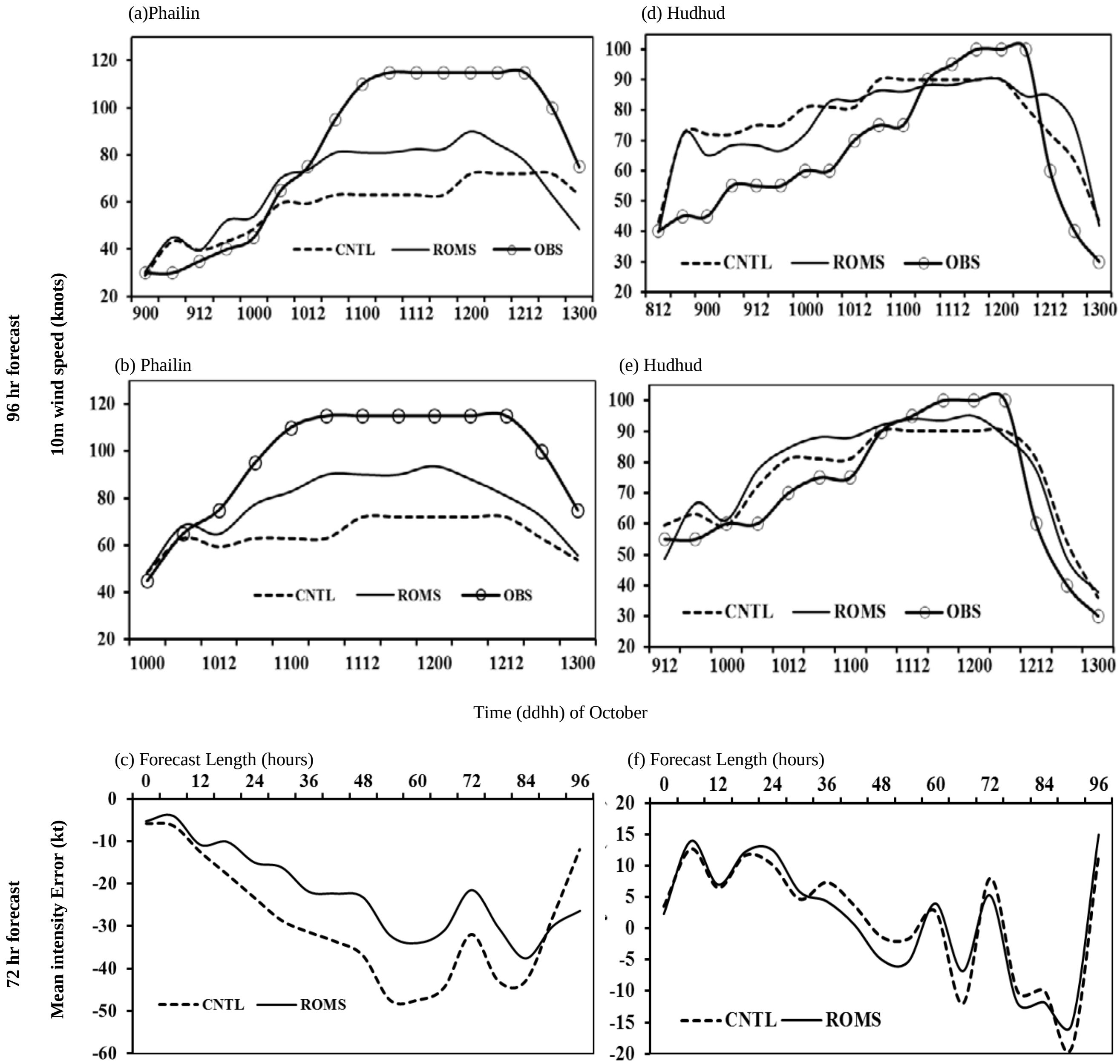
4.2. *Comparison of the SST fields*

Figs. 2(a-c) show the SST fields used in the simulations for TC Phailin and Hudhud along with their observed tracks. Fig. 2(a) represents the SST field in the control run for TC Phailin with initial condition 0900UTC along with Phailin TC observed track taken from IMD best observed tracks, while Fig. 2(b) represents the same for the TC Hudhud with initial condition 0812 UTC. Fig. 2(c) represents the climatological ROMS-SST for October used in the experiment for both the TC for all the initial conditions aforementioned in the data and methodology section. Comparing Fig. 2(c) with Figs. 2(a&b), it is clearly evident that the ROMS-SST is able to resolve the fine features in the SST field better compared with both the control runs, which exhibit smoothed out SST patterns. The gradients resolving capability for the ROMS-SST may be attributed to the outcome from high-resolution simulations while preparing the SST from ROMS (Sil *et al*., 2011b) when compared with the global model used for preparing Reynolds SST. However, it is noted that ROMS-SST used here gives us a higher spatial resolution. However, the temporal resolution compared with the control simulations is poor. However, the objective of the current study is to assess the impact of fine SST gradients resolved by the ocean model on TC simulations.

4.3. *Simulated Intensity*

4.3.1. *TC Phailin*

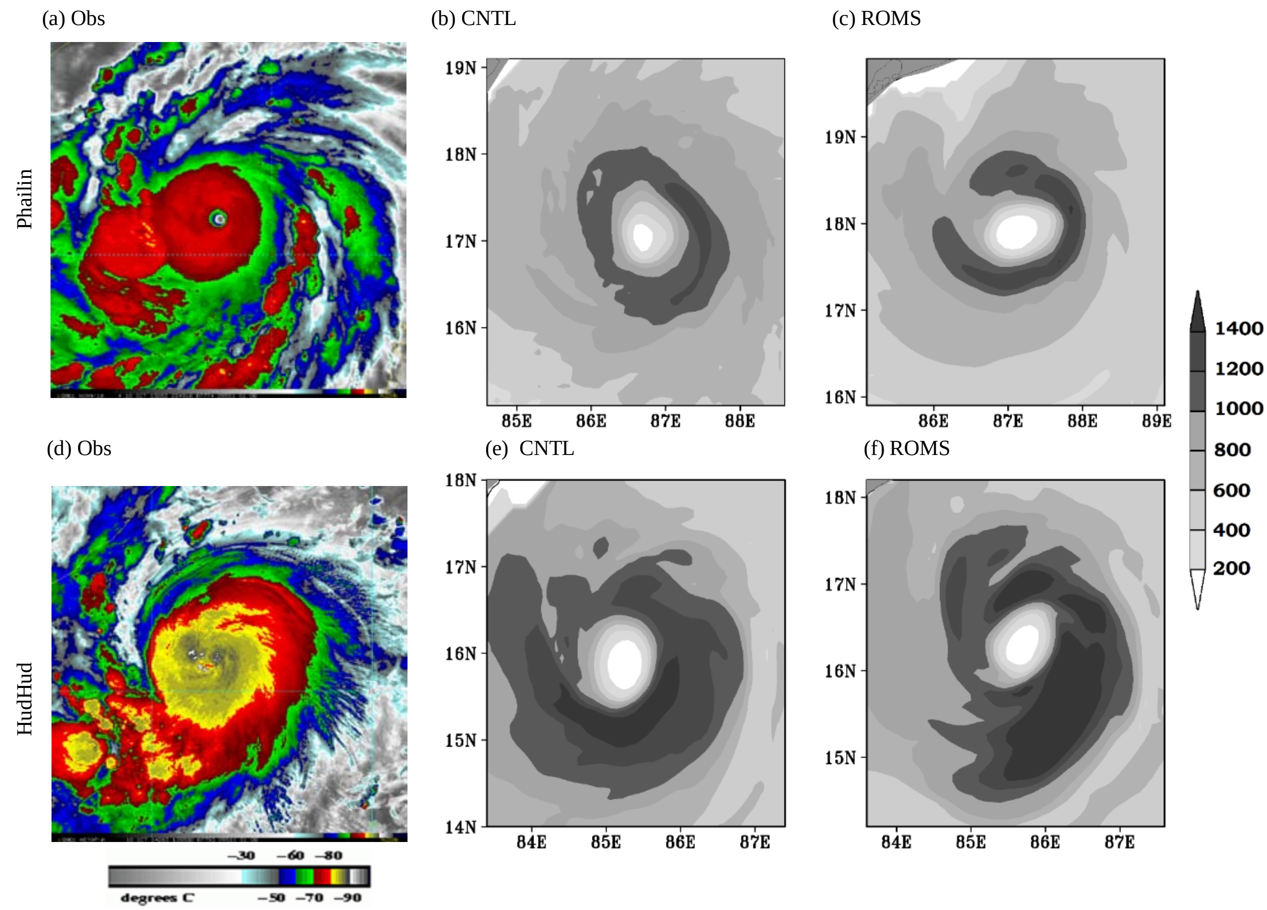
The intensity in terms of the model simulated maximum 10 m surface winds and the wind intensity errors calculated with IMD data considered as observations are shown in Figs. 3(a-f). Fig. 3(a) shows the time series evolution of the intensity of the TC for initial condition 0900 UTC. The simulated intensity in the ROMS is closer to the observations as compared with the CNTL, especially during the peak intensity period, *i.e.*, 1012 UTC to 1206 UTC. Similar results are observed for the other two initial conditions, *i.e.*, 1000 UTC [Fig. 3(b)] and 1100 UTC (figure not shown). The intensity errors calculated for all three simulations also prove that the intensity prediction in the ROMS simulation showed relatively less error than the CNTL run. The maximum error in the intensity in the CNTL run is about -45 knots, while the ROMS shows -35 knots. Phailin's peak intensity is captured in the ROMS with an underestimation of about 20 knots while CNTL showed an underestimation of 40 knots.



Figs. 3(a-f). Model predicted 10m wind speed (knots) from both CNTL and ROMS experiments at (a) 96 hour forecast, (b) 72 hour forecast along with IMD best analysis for TC Phailin and (c) mean intensity error from both the experiments. (d), (e) and (f) are same as (a), (b) and (c) respectively but for TC Hudhud

4.3.2. *TC Hudhud*

The model simulated intensity evolution for TC Hudhud in terms of 10 m surface windspeed and its associated intensity errors are shown in Fig. 3. The time series of the wind speed intensity for initial condition 0812 UTC indicates that both the CNTL and ROMS almost showed a similar intensity evolution; however, both the simulations could not produce realistic peak intensity of the TC [Fig. 3(b)]. For the initial condition 0912 UTC shown in Fig. 3(d). ROMS simulation slightly predicts peak intensity closer to the observation as compared with CNTL. It is to be noted that both the simulations are unable to capture the peak intensity shown in the observations. Fig. 3(f) shows the intensity error associated with all three initial conditions. It is seen that the ROMS and CNTL run are similar intensity errors for all the forecast lengths [Fig. 3(f)]. However, it is to be noted that ROMS run was able to capture a realistic peak intensity for the initial conditions 0900 UTC [Fig. 3(d)]

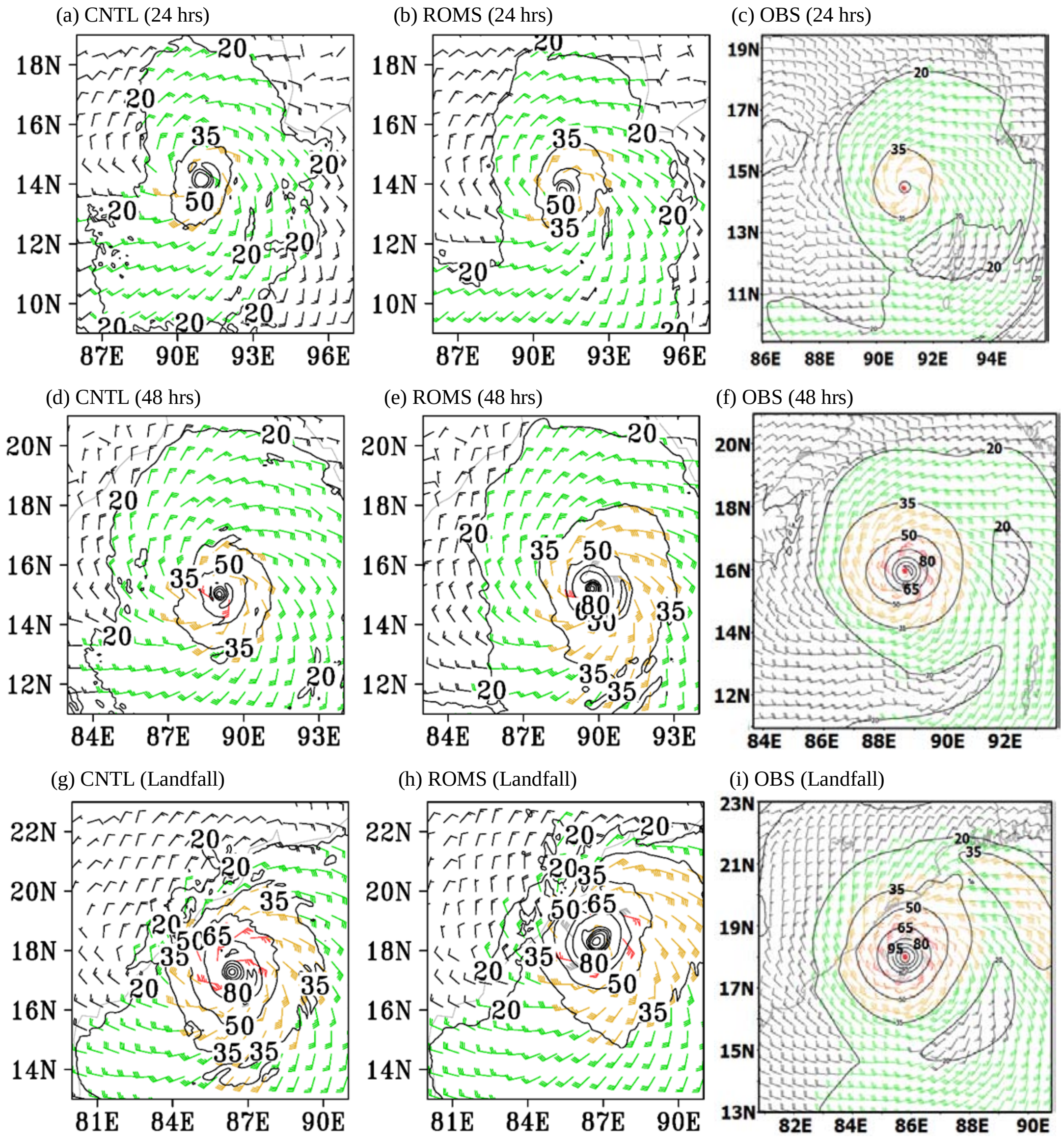


Figs 4(a-f). Enhanced infrared imagery from MODIS/AVHRR for (a) TC Phailin and (d) TC Hudhud along with model predicted latent heat flux (W/m^2) from both (a) CNTL and (b) ROMS experiments for TC Phailin (c) and (d) are same as (a) and (b) but for TC Hudhud

and 1012 UTC (figure not shown) compared with the CNTL run. However, the peak intensity is underestimated by both the simulations.

4.4. *Air-Sea Interaction*

From the theory of hurricanes (Emmanuel, 1986), it is well established that the latent heat released from the ocean plays a vital role in the intensification of TC. Hence it is worthwhile to investigate the latent heat flux at the peak intensity of the TC Figs. 4(a-f) represent the latent heat flux at peak intensity for the TC Phailin (IC: 0900 UTC) and TC Hudhud (IC : 0812 UTC) at 1100 UTC and 1200 UTC respectively. Figs. 4(a&b) show latent heat flux (W/m^2) for TC Phailin for CNTL and ROMS. It is observed that the ROMS experiment [Fig. 4(b)] shows a higher exchange of latent heat flux release compared with the CNTL [Fig. 4(a)] near the right side core of the TC. A similar result is established in the TC Hudhud in the ROMS experiment [Fig. 4(d)] compared with the CNTL [Fig. 4(c)]. According to the satellite imagery at peak intensity, it is evident that the height of clouds is maximum on the right side of the TC center, suggesting deeper convection on the right sector of TC. Both the simulations are able to capture the right sector peak in terms of latent heat flux. However, it is noted that the ROMS experiment inner core structures resemble well with the observation compared with the CNTL run. The improved inner core wind structure in the ROMS simulation may be attributed to the greater exchange of the latent heat flux in the right side of the TC, shown in Figs. 5(a-i) and Figs. 6(-i). The comparison of model simulated surface wind structure evolution of both the TCs with the available observations from the satellite derived winds are shown in Fig. 5 and Fig. 6 for TC Phailin (IC : 0900 UTC) and TC Hudhud (IC : 0812 UTC), respectively. Figs. 5(a&b) represent the surface winds for the CNTL and ROMS experiment after the 24 hrs integration of the model, while Fig. 5(c) illustrates the observed satellite winds. From the figures, it may be observed that the ROMS experiment replicates the realistic wind structure in the inner eyewall of the TC compared with the CNTL run. The maximum intensity of both the model runs remains the same, *i.e.*, 50 knts, but a major

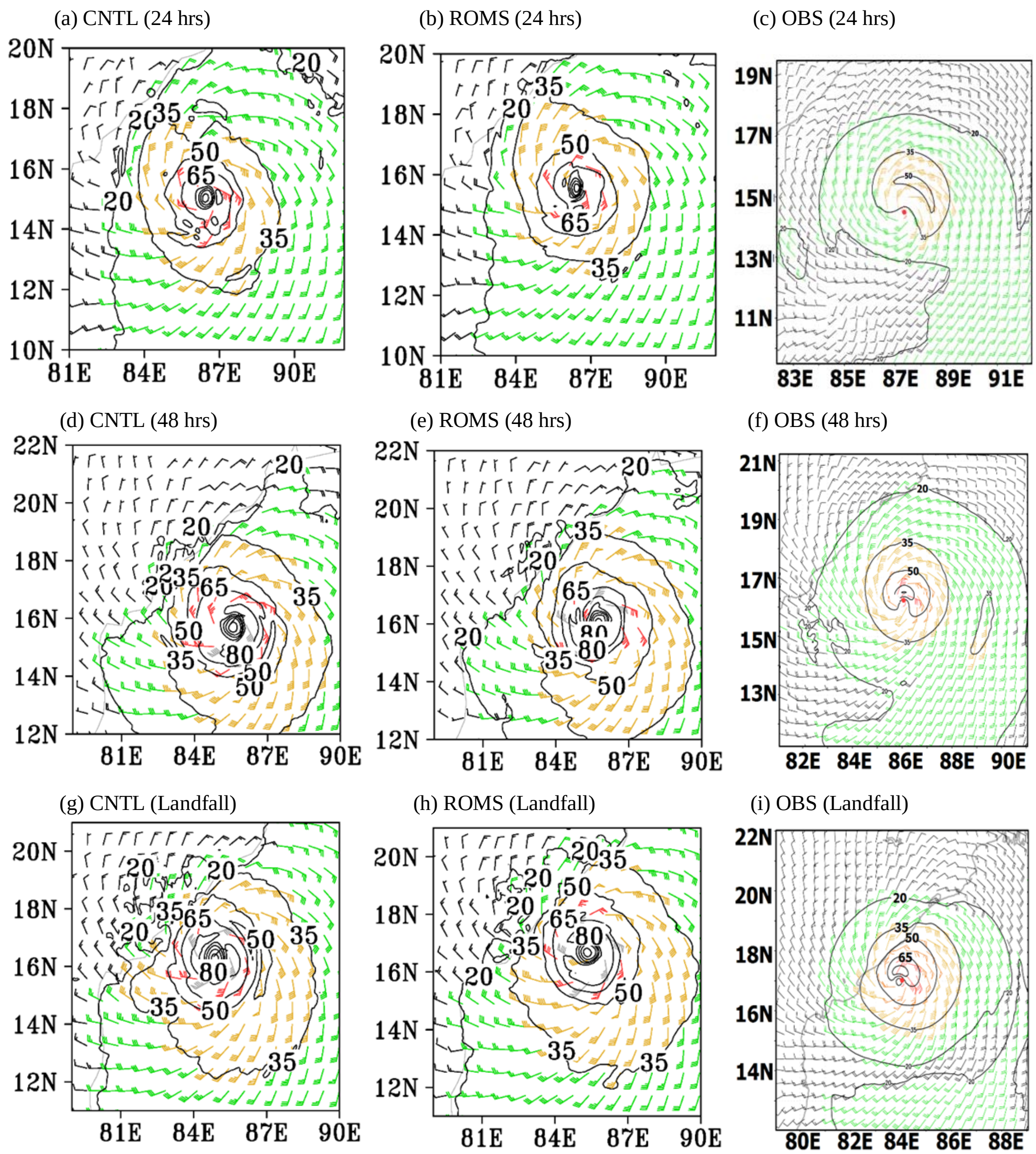


Figs. 5(a-i). Model predicted wind structure from both (a) CNTL and (b) ROMS experiments for TC Phailin along with Satellite derived wind structure at 24 hour forecast lead time. (d)- (f) and (g)-(i) are same as (a) and (b) but at 48 hour tome lead and landfall time

difference is noticed in the spatial extent of the inner core winds with the ROMS experiment closer to the structure seen in the satellite winds [Fig. 5(c)]. The same features in also observed after the 48hrs integration of the model [Figs. 5(d&e)] where ROMS produces realistic wind structure in the inner eyewall. It is also worth noticing that the ROMS experiment's peak intensity matches the observed satellite wind data [Fig. 5(f)]. The wind structure associated with the Phailin on the landfall day is also compared with the observations as it is significant for disaster management preparedness. From Figs. 5(g-i), the ROMS run produces a realistic wind structure pattern and peak winds compared with the CNTL, especially in the eyewall region. The wind structure is also verified for the TC Hudhud, as shown in Figs. 6(a-i). From Figs. 6(a-i), both the CNTL and ROMS simulations produce similar wind structures compared with the observations, but significant improvement in the wind structure is noticeable in the ROMS experiment compared with the CNTL in the inner core regions.

4.5. *Impact on winds, vertical velocity and temperature along the cross-section of TC*

In this section, the east-west cross-section of the horizontal wind (knots), vertical velocity (cm/s) and the



Figs. 6(a-i). Same as Fig. 5 but for TC Hudhud

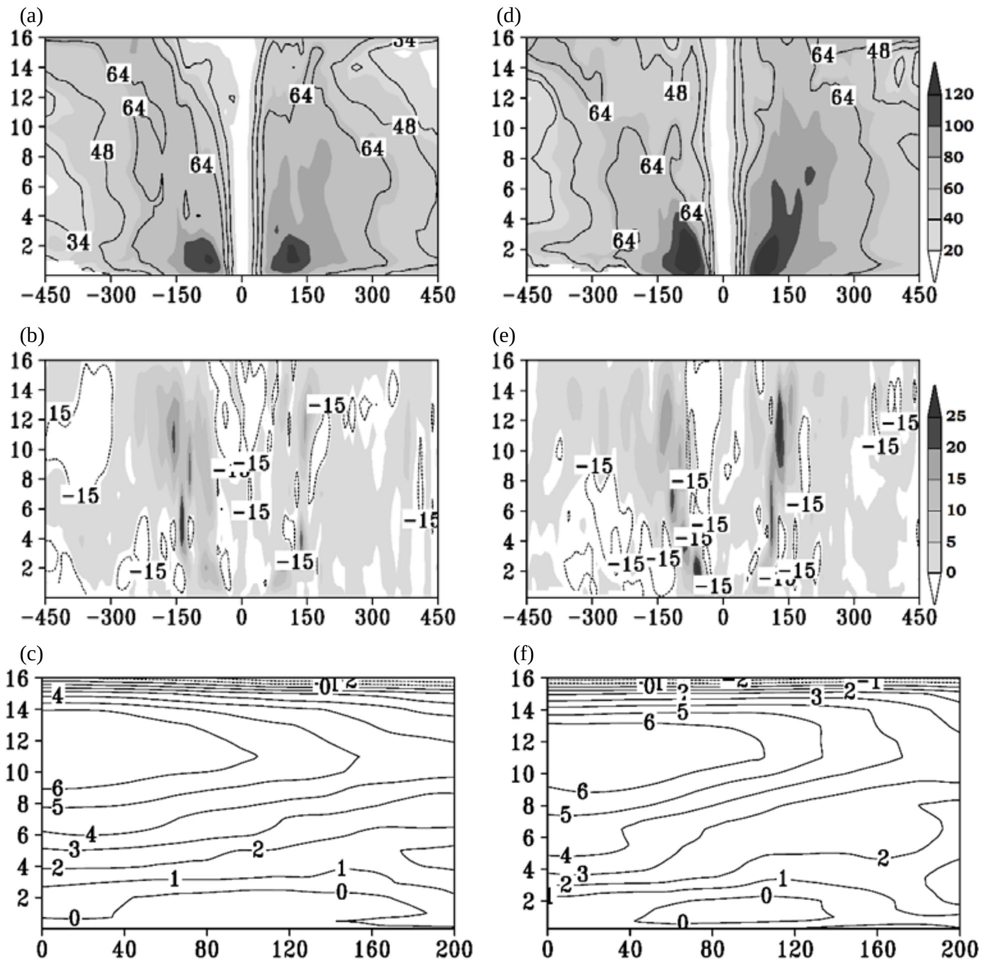
temperature anomaly (K) are presented. The cross-sections are obtained at reference latitudes that pass through the storm's center at their peak intensities.

4.5.1. *TC Phailin*

Figs. 7(a-f) represent the wind structure, vertical velocity and temperature anomaly of the model simulated runs for the TC Phailin, respectively. From Figs. 7(a&b), it can be inferred that the right sector peak horizontal wind speeds in the eye, eyewall and the outer structure of TC Phailin are captured in both CNTL and ROMS experiments. However, the ROMS experiment shows that the vertical structure in terms of wind distribution (>80 knts) has a greater depth extending up to 10 km. Comparing Figs. 7(a&b), which represents the vertical wind velocity structure for CNTL and ROMS experiments, stronger updrafts are visible in the ROMS experiments than in the CNTL run, which supports the convection seen from the satellite imagery. The temperature anomaly seen in both simulations is seen to be identical, but the ROMS experiment showed a large spatial temperature anomaly of 6 K.

4.5.2. *TC Hudhud*

Figs. 8(a-f) represent the same above mentioned parameters for both the model simulations for the TC Hudhud, respectively. Figs. 8(a&b) show that the eye, eyewall and outer structure are well simulated in both



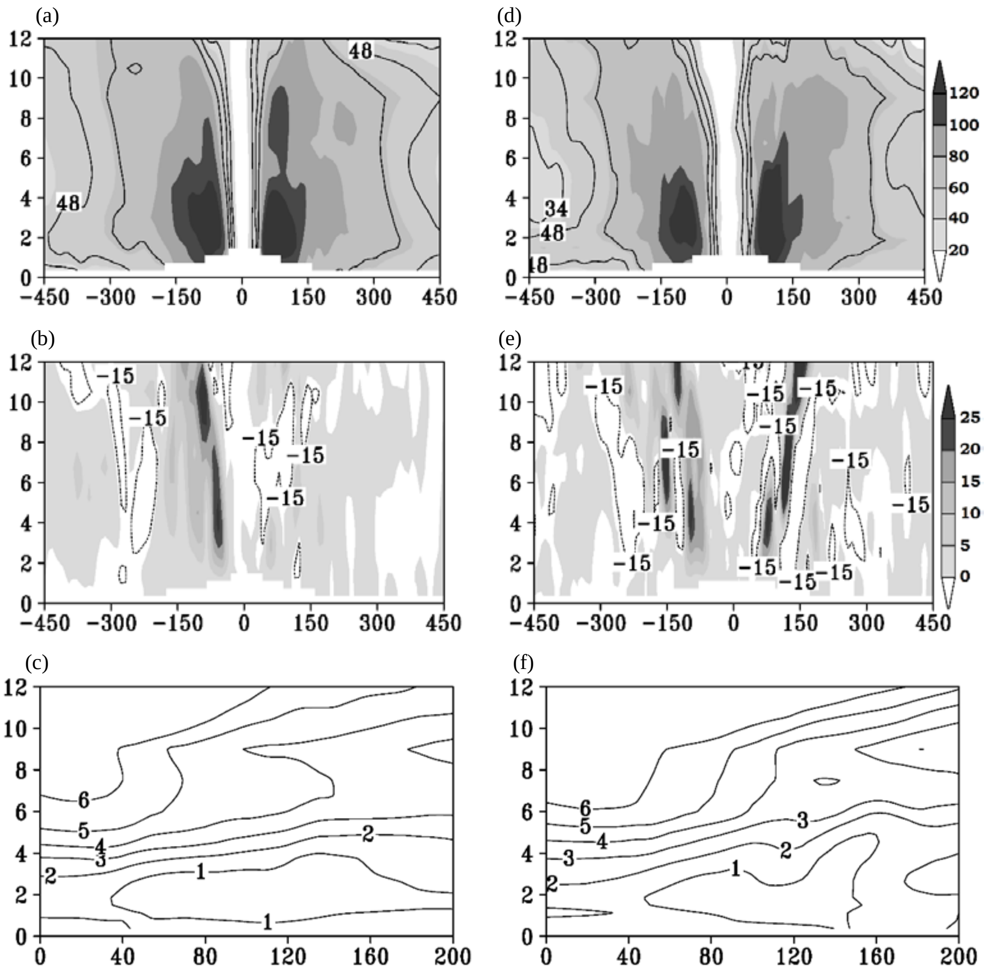
Figs. 7(a-f). East-west cross-section of (a) wind speed (knots), (b) vertical wind (cm s^{-1}) and (c) temperature anomaly (°C) for TC Phailin with CNTL run valid at peak observed time, 0000 UTC 12 October, 2014. (d-f) is also same as (a-c) but for ROMS run

CNTL and ROMS experiments. However, the vertical structure in terms of the maximum wind (>110knts) distribution reached higher altitudes in the ROMS experiment as compared with the CNTL experiment. However, the CNTL experiment shows the peak wind speed structure reaching higher latitudes compared with the ROMS experiment. It is to be noted that the ROMS experiment exhibited stronger winds of about 100knts on the right sector as well as the greater horizontal spatial extent of the storm compared with the CNTL run. Comparing Figs. 8(a&b) representing the vertical wind structure for CNTL and ROMS experiment respectively, stronger updrafts and associated downdrafts are visible in the ROMS experiments compared with the CNTL run, which supports the convection seen from the satellite imagery. The temperature anomaly seen in both the simulations is seen to be identical, but the ROMS experiment showed a temperature anomaly of 6° K at lower altitudes compared to the CNTL.

The above results on the distribution of winds, vertical velocity and the temperature anomaly warming indicate that the ROMS-SST impacts the size, strength and thermodynamic structure of both the TCs.

4.6. *Impact on the movement of TC*

The storm tracks of all 13 cases with the location of the MSLP centre obtained for both CNTL and ROMS experiment simulations and the IMD's best track are presented in Figs. 9(a-f). Figs. 9(a-c) shows that the TC movement for both the CNTL and ROMS experiment remains similar for all initial conditions. This is consistent with the previous results that the TC movement is less impacted with the SST when compared with the large-scale midlevel winds. Similar results are also found for the TC Hudhud [Figs. 9(d-f)], where no significant improvement in the storm track is noticed with the inclusion of the high-resolution ROMS-SST.



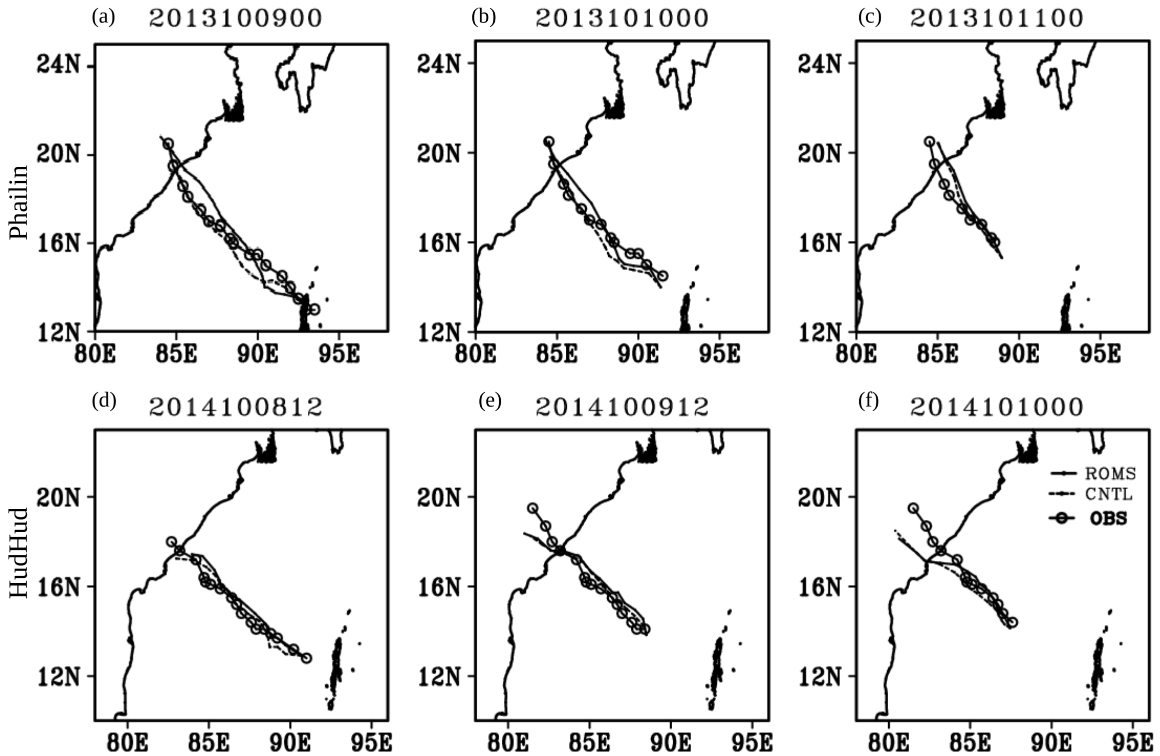
Figs. 8(a-f). East-west cross-section of (a) wind speed (knots), (b) vertical wind (cm s^{-1}) and (c) temperature anomaly (°C) for TC Hudhud with CNTL run valid at peak observed time, 0000 UTC 12 October, 2014. (d-f) is also same as (a-c) but for ROMS run

4.7. *Precipitation Prediction*

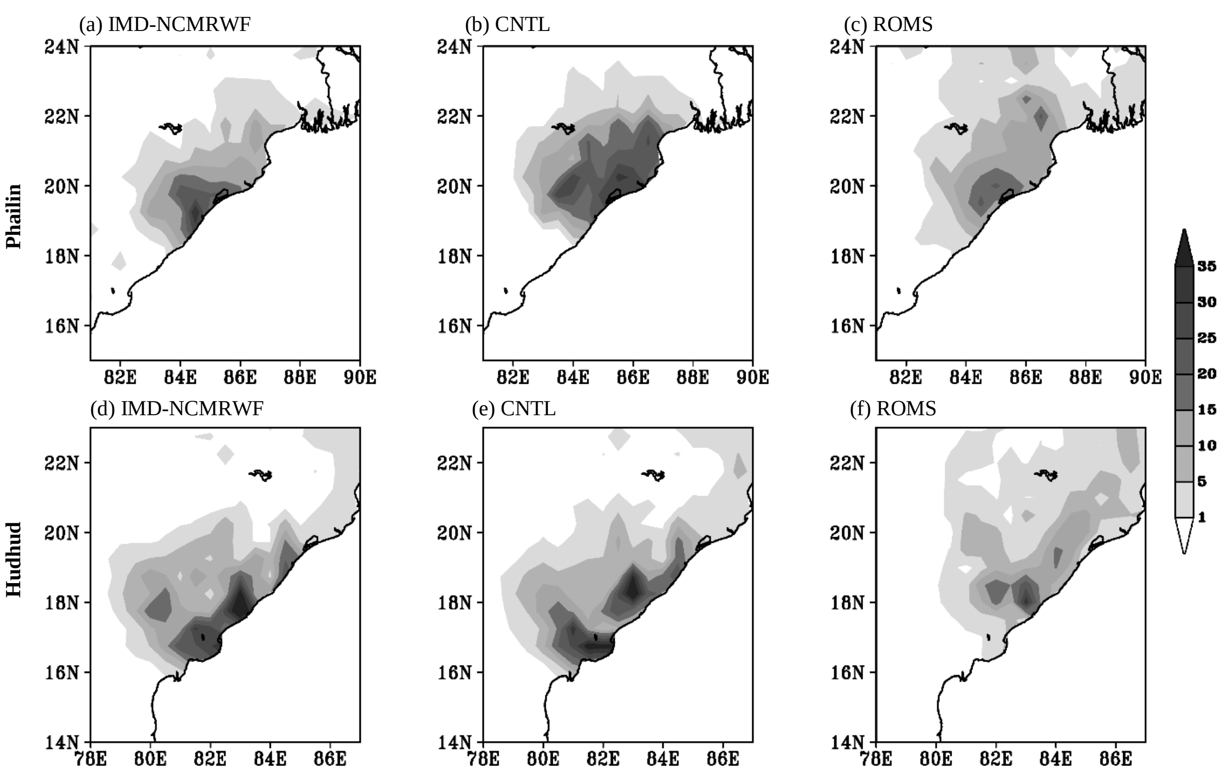
The model simulated rainfall model is shown along with the IMD rainfall data with a resolution of 0.5° × 0.5°. For the details of the preparation of the observed data, refer to Mitra *et al.*, 2009. The Observed 24-h accumulated precipitation (in mm) for TC Phailin and TC Hudhud is presented in Figs. 10(a-f). Figs. 10(a&b) represent the accumulated precipitation valid at 0300UTC on 12 October, 2013 for CNTL and ROMS run, respectively. Comparison of the model simulated rainfall with the observation [Fig. 10(c)] shows that both the simulations over predict the accumulated precipitation. However, it is interesting to note that the location of the rainfall in observation is well replicated in the ROMS run compared with the CNTL run. This improvement may be attributed to the realistic wind structure of the TC in the ROMS run compared with the CNTL run. For TC Hudhud, the same feature, *i.e.*, excess precipitation, is observed in both the simulations, while the location of the rainfall pattern is closely replicated in the ROMS [Fig. 10(e)] compared with the CNTL [Fig. 10(d)].

5. Summary and conclusions

The present study investigated the impact of high-resolution ROMS-SST in the numerical simulation of two intense TC, *i.e.*, Phailin and Hudhud, over the BoB. The ROMS-SST obtained from the ROMS mesoscale ocean model output is validated with the available observations. The Taylor diagram shows that the correlation of the ROMS-SST is near to 0.9-0.99 with all the observational data sets. The root mean square difference is around 0.4°C and the normalized standard deviation is slightly more significant than unity. The spatial comparison throughout the BoB domain shows a mean correlation of



Figs. 9(a-f). Model predicted tracks of VSCS Phailin (Top) and Hudhud (Bottom) with different initial conditions along with the IMD best track (solid line with open circle marked) from both the experiments CNTL (dashed) and ROMS (solid)



Figs. 10(a-f). Model predicted landfall day rainfall (cm) of VSCS Phailin (Top) and Hudhud (Bottom) with different initial conditions along with the IMD- NCMRWF merged rainfall analysis

0.91 throughout the maximum portion of the domain while the skill is about 0.94, suggesting that the ROMS model was able to replicate a realistic SST field.

Instigating ROMS-SST as a boundary condition to the WRF model improved the TC intensity, spatial structure and rainfall location for the TC Phailin, while a minor improvement is observed in the intensity of TC Hudhud and better replication of wind structure and rainfall location as compared with the CNTL. The latent heat released during the lifecycle of TC Phailin shows a more significant amount of flux release in the right sector eyewall of the TC. This enhanced latent flux might be associated with the improved wind structure in the ROMS simulation. Similar results are found in the TC Hudhud simulation. These results on the distribution of winds, vertical velocity and the temperature anomaly warming indicate that the ROMS-SST impacts the size, strength and thermodynamic structure of both the TCs. However, the model simulated track for the ROM-SST experiment did not improve the TC track for all the initial conditions for both the TCs. This shows that SST might not have a greater effect on the TC tracks. The present modeling study compliments the use of higher resolutions SST obtained from a mesoscale regional ocean model for the TC simulations.

Though the current study has a major limitation that usage of climatological ocean conditions in atmospheric model, this pays a path to the usage of high resolution ocean conditions in the model for the prediction of TCs in real time (Mohanty *et al*., 2019 and 2022).

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