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A study on high resolution mesoscale modeling systems for simulation of tropical cyclones over the Bay of Bengal

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सार – स्थल प्रवेश करने वाला उष्णकटिबंधीय चक्रवात (टी. सी.) प्राकृतिक आपदाओं में से एक है जिसकी वजह से बहुत तेज हवाएँ चलती है, मूसलाधार वर्षा होती है, इसके स्थल प्रवेश के स्थान से कई किलोमीटर तक बाढ़ आ जाती है और तूफानी समुद्री तरंगें मीलों तक तटवर्ती क्षेत्रों को प्रभावित करती हैं जिसके फलस्वरूप जानें चली जाती हैं और संपत्ति की क्षति होती है। यह आपदा बंगाल की खाड़ी (बी.ओ.बी.) से सटे क्षेत्रों में अधिक आती है। इसलिए भारत मौसम विज्ञान विभाग (आई. एम. डी.) ने उष्णकटिबंधीय चक्रवात का बेहतर पूर्वानुमान देने के लिए बंगाल की खाड़ी में बनने वाले उष्णकटिबंधीय चक्रवात की उत्पत्ति, उसकी तीव्रता और रचना की विस्तृत जानकारी प्राप्त करने के लिए 'फोरकास्ट डिमॉन्सट्रेशन प्रोजेक्ट (एफ.डी.पी.) ऑफ लेंडफॉलिंग साईकलोंस' नामक एक फील्ड परियोजना आरंभ की है। स्थल प्रवेश करने के लिए उष्णकटिबंधीय चक्रवातों ने अनुरूपण हेतु एफ.डी. पी. (2008–2011) के आरंभिक चरण में अत्याधुनिक मेसोस्केल मॉडुलन प्रणालियों जैसे – एडवांस रिसर्च वेदर रिसर्च एण्ड फॉरकास्टिग (ए. आर. डब्ल्यू.), डब्ल्यू. आर. एफ. (एन. एम. एम.) का अद्रवस्थैतिक मेसोस्केल मॉडल तथा हरीकेन वेदर रिसर्च एण्ड फॉरकास्टिग (एच. डब्ल्यू. आर. एफ.) आदि के व्यापक कार्यनिष्पादन को प्रस्तुत किया गया है। भिन्न – भिन्न मॉडुलन प्रणालियों का परस्पर तुलना करना इस शोध का आशय नहीं है। इस शोध पत्र में छः उष्णकटिबंधीय चक्रवातों नामतः रश्मि (2008), कैमुक (2008), निशा (2008), गिरी (2010), जल (2010) और थाणें (2011) को लिया गया है। यद्यपि इस शोध पत्र में उष्णकटिबंधीय चक्रवात के भिन्न – भिन्न पहलुओं जैसे – ट्रैक, तीव्रता, सरंचना और वर्षा के बारे में विस्तृत अध्ययन किया गया है। इस शोध पत्र में ट्रैक एवं तीव्रता के पूर्वानुमान तथा इससे संबंधित त्रुटियों के ऊपर मुख्य रूप से जोर दिया गया है।

इसके परिणाम से यह पता चला है कि उच्च विभेदन मेसोस्केल मॉडुलन प्रणालियाँ 72 घंटों तक उष्णकटिबंधीय चक्रवातों के पूर्वानुमान देने के लिए बेहतर मार्गदर्शन देती है। हालाँकि जब इन मॉडलों की शुरूआत अपरिष्कृत वियोजन भूमंडलीय विश्लेषण एवं पूर्वानुमान क्षेत्रों के साथ की गई तो इनमें ट्रैक एवं तीव्रता त्रुटियाँ अपेक्षाकृत अधिक पाई गई हैं। मॉडल के आरंभिक अवस्थाओं में अतिरिक्त स्थानीय प्रेक्षणों को समाहित करते हुए इन त्रुटियों को सार्थक रूप से कम किया जा सकता है। ट्रैक पूर्वानुमान त्रुटियों की गणना भारत मौसम विभाग के बेस्ट ट्रैक प्रेक्षणों के आधार पर की गई है। ए. आर. डब्ल्यू. प्रणाली में स्वांगीकरण प्रयोग के बिना पूर्वानुमान त्रुटियाँ 138, 135 एवं 182 कि. मी. पाई गई हैं। एफ.डी.पी.अवधि के दौरान सभी उपलब्ध प्रेक्षणों को मॉडल की आरंभिक अवस्था में सम्मिलित किए जाने पर त्रुटियों में 72, 99 एवं 126 कि.मी. की कमी क्रमशः 24, 48 एवं 72वें घंटे में पाई गई है और इससे लगभग 47 प्रतिशत का सुधार देखा गया है। एन.एम.एम. मॉडल के मामले में अस्वांगीकरण प्रयोग की तुलना में आँकड़ों के स्वांगीकरण प्रयोग से औसत ट्रैक त्रुटियाँ (30 उप स्थितियों पर आधारित) में लगभग 32 प्रतिशत, 22 प्रतिशत, 23 प्रतिशत, 28 प्रतिशत, 24 प्रतिशत एवं 16 प्रतिशत का सुधार क्रमशः 00, 24, 48, 72, 96 एवं 120 घंटे पर हुआ है। एच.डब्ल्यू.आर.एफ. मॉडल की आरंभिक स्थिति एवं सरंचना में महत्वपूर्ण रूप से सुधार इस लिए हुआ क्योंकि इसके वोरटेक्स–रिलोकेशन एवं आरंभिक प्रक्रियाओं में सुधार हुआ है। इसलिए इससे उष्णकटिबंधीय चक्रवात गिरी के तीव्र गति से आगे बढ़ने का आगामी घंटे में पूर्वानुमान दिया जा सका।

ABSTRACT. Landfalling tropical cyclone (TC) is one of the natural disasters producing extremely strong winds, torrential rains, floods influencing many kilometers from the point of landfall and storm surges that overwhelm miles of shores resulting loss of lives, and damages to properties. This disaster is higher in the regions covering Bay of Bengal (BoB). Therefore, the India Meteorological Department (IMD) initiated a field project, "Forecast Demonstration Project (FDP) of landfalling cyclones" over the BoB to acquire detailed understanding of genesis, intensity, and structure evolution of TCs so as for better TC forecasting. A comprehensive performance of state-of-the-art mesoscale modeling systems such as Advanced Research Weather Research and Forecasting (ARW), non-hydrostatic mesoscale model of WRF (NMM) and Hurricane Weather Research and Forecasting (HWRF) etc for the simulation of landfalling TCs during pilot phase of FDP (2008-2011) is presented. The study is not meant for the inter-comparison of different modeling systems. In the present study, six TCs namely Rashmi (2008), KhaiMuk (2008), Nisha (2008), Giri (2010), Jal (2010) and Thane (2011) are considered. Though different aspects of the TC such as track, intensity, structure and rainfall are studied in detail, this paper is mainly emphasized on the track and intensity prediction and associated errors.

Results indicates that the high resolution mesoscale modeling systems provide better guidance for TC forecast up to 72 hours. However, the track and intensity error is relatively more when these models are initialized with coarser resolution global analyses and forecast fields. This error can be significantly reduced with the assimilation of additional regional observations into model initial conditions. The track forecast errors are calculated with respect to IMD best track observations. In case of ARW system, the forecast errors are 138, 135 and 182 km from no-assimilation experiment. The assimilation of all available observations during FDP period into model initial condition decreases the errors 72, 99 and 126 km at 24, 48 and 72 hour, respectively with an improvement of about 47%. In case of NMM model, the mean (based on 30 sub-cases) track errors are improved by about 32%, 22%, 23%, 28%, 24% and 16% at 00, 24, 48, 72, 96 and 120 hrs, respectively with data assimilation experiments compared to no-assimilation experiment. The HWRF model improved the initial position and structure significantly because of its improved vortex-relocation and initialization procedures and hence captures the rapid intensification of the TC Giri in the subsequent forecast hour.

Key words - Tropical cyclones, Forecast demonstration project, Bay of Bengal, Mesoscale models, Track, Intensity.

1. Introduction

The tropical cyclones (TCs) over the Bay of Bengal (BoB) form primarily in post-monsoon season (October - December) and pre-monsoon season (April - May) unlike in the other ocean basins which occur around late summer to early fall. During this period, the monsoon trough is located sufficiently over the open water of the Indian seas which trigger low pressure system and its development into a mature cyclone (Lee *et al*., 1989). The occurrence of TCs over the BoB is more with the development of about 6 TCs per year about 10 % of global total (IMD, 2008). It contributes more than 75% to the total number of TCs over the NIO (Mohanty *et al*., 2011). The geographical structure of the BoB including shallow bathymetry, many river basins, poor socio-economic conditions and large population density along the east coast of India enhances the damage and loss of lives and properties due to TCs. Therefore, the India Meteorological Department (IMD) has been initiated a national program "Forecast Demonstration Project" for improving track, intensity and landfall of BoB cyclones since 2008.

Mohanty and Gupta (1997), Gupta (2006) discussed the limitations of statistical methods beyond 24 hours. However, high resolution mesoscale models could provide better guidance for TC forecast up to 72 hours. Pattanayak and Mohanty (2008) made a comparative study on the performance of both Mesoscale model version 5 (MM5) and Advanced Research Weather Research Forecasting (ARW) models in the simulation of tropical cyclones over Indian seas and demonstrated the superiority of the ARW model over MM5. ARW model is used extensively worldwide for the simulation of various weather events, such as heavy rainfall (Mohanty *et al*., 2011, Hong and Lee, 2009), monsoon depressions (Routray *et al*., 2010a) and tropical cyclones (Osuri *et al*., 2012a; Pattanaik and Ramarao, 2009; Davis *et al*., 2008). The model is also used to study the land surface processes (Niyogi *et al*., 2006). The Non-hydrostatic Mesoscale Model of WRF (NMM) is also skillful for prediction of TCS over different basins. Pattanayak and Mohanty (2010) uses NMM model in simulation of very severe TCs (*viz*., Gonu and Sidr) and demonstrate the capability of NMM model over NIO. Mohandas and Ashrit (2011) uses NMM model for prediction of tropical cyclones over Indian seas. Similarly, the very recent coupled system Hurricane Weather Research and Forecasting (HWRF) with improved moving nested grid and more complex adaptive grid models (Gopalakrishnan *et al*., 2002) showed significant skill for the prediction of TCs. The atmospheric component of HWRF modeling system is used to simulate very severe cyclonic storm Mala (2006) formed over BoB (Pattanayak *et al*., 2011). This study emphasizes capability of HWRF system in simulation of track, intensity and vertical structure of the cyclone Mala with reasonable accuracy.

The performance of high resolution mesoscale models highly depends on the quality of initial conditions. Moreover, the initial and boundary conditions for these models are derived from the global model analyses and forecast fields which are relatively coarser in resolution. Because of lack of sufficient conventional observations over the oceans where TCs form and evolve, the global analyses are ill-defined in representing the initial structure and position of the vortex. According to Mohanty *et al*. (2010), the initial vortex position error in global analyses is about 80 – 100 km and further contributes to more track forecast errors. The primary and important task is to reduce the errors in initial conditions. The quality of initial conditions can be improved with the mesoscale data assimilation of high dense observations. Several previous studies have demonstrated that the assimilation of sea surface and upper air satellite-derived winds near and around the centre of the storm can substantially improve the initial analyses of TCs and hence the prediction of track, intensity and structure (*e.g.*, Velden *et al*., 1998; Chen 2007; Pu *et al*., 2008; Osuri *et al*., 2012b). Further, the 3DVAR assimilation of DWR reflectivity and radial wind observations clearly showed improvements in the

TABLE 1

Brief description of ARW, NMM and HWRF modeling system

Model	ARW	NMM	HWRF
Dynamics	Nonhydrostatic	Nonhydrostatic	Nonhydrostatic
Horizontal grid system	Arakawa C-grid	Arakawa E-grid	Arakawa E-grid
Map projection	Mercator	Rotated lat-long	Rotated lat-long
Horizontal resolution	9 km	9 km	D1: 27 km, D2: 9 km
Vertical coordinate	Terrain following sigma vertical coordinates	Terrain following hybrid sigma-pressure vertical coordinates	Terrain following hybrid sigma-pressure vertical coordinates
Vertical levels	51	51	42
Cumulus convection	Kain-Fritsch	Simplified Arakawa Schubert	Simplified Arakawa Schubert
PBL parameterization	Yonsei University (YSU)	Yonsei University (YSU)	NCEP GFS
Land surface physics	Monin-Obukhov	NMM	NMM
Microphysics	WRF single-moment 3-class (WSM3)	Ferrier (new eta)	Ferrier (new eta)
Radiation	RRTM LW/ Goddard SW	GFDL LW/SW	GFDL LW/SW

TABLE 2

The background and analysis departures from the observations for 3 cases for zonal, meridional wind components and wind speed

IC	U wind		V wind		SSMI	
	O-B	O-A	O-B	O-A	O-B	O-A
2008111312	2.7631	1.4323	2.7145	1.5281	3.1723	1.5321
2008111400	2.6097	1.489	1.7236	1.6104	3.1043	2.1402
2008111412	2.6883	1.9494	2.2032	2.1602	3.1848	2.4468

simulation of mesoscale events (Gao *et al*., 1999; Xiao *et al*., 2005 & 2007). Routray *et al*. (2010b) also showed better simulation of intense convective systems influencing the large-scale Indian monsoonal flow and showed positive impact of DWR data on the prediction of the location, propagation and development of rain bands associated with the monsoon depressions over the BoB. Govindankutty *et al*. (2010) indicates the positive impact of DWR radial wind along with IMD global telecommunication system (GTS) data in the simulation of a TC.

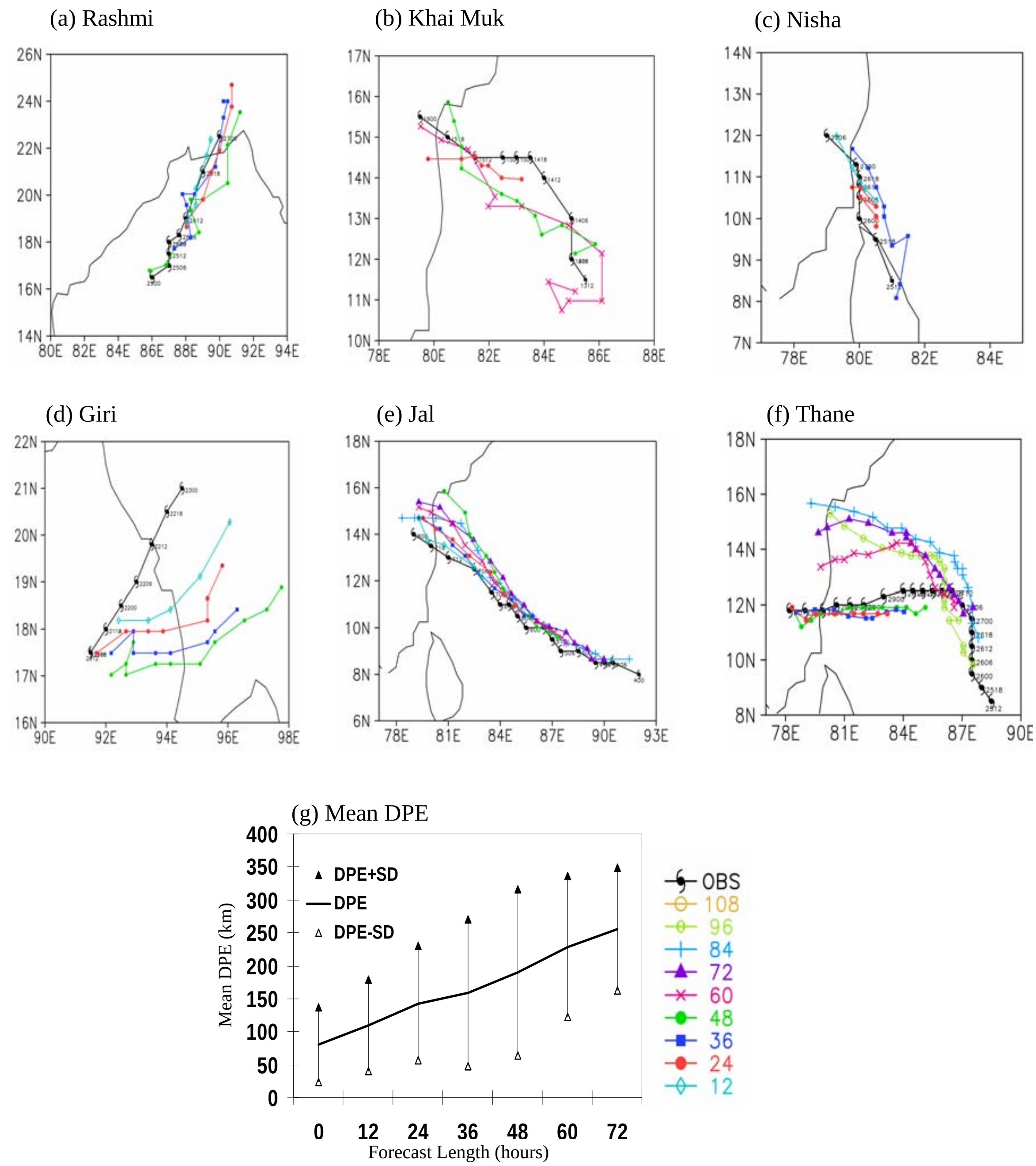
In the present study, the comprehensive performance of each of the modeling system [ARW, NMM and HWRF models] in track and intensity prediction of TCs occurred during FDP period (2008-2011) over the BoB is presented. Further, the impact of different sources of observations [such as satellite derived winds, DWR observations and GTS data] on the simulation of track and intensity of TCs are also demonstrated.

2. Models configuration

In this section, a brief description of both ARW, NMM and HWRF modeling systems are illustrated.

(a) *ARW model*

The single domain is fixed to 3° N - 28° N, 78° E - 103° E, centered at 15.5° N and 89.5° E for BoB TCs. The model runs at 27 km horizontal resolution for real-time TC predictions, while, 9 km resolution is used for the data impact studies such as assimilation of (*i*) satellite derived



Figs. 1(a-g). ARW model predicted tracks of TCs (a) Rashmi, (b) Khai Muk, (c) Nisha, (d) Giri, (e) Jal and (f) Thane (g) Mean direct position error (in km) and the range of the error (± standard deviation) up to 72 hour forecast length

sea surface winds (SAT experiment), (*ii*) observations collected during FDP (3DVAR experiments) and (*iii*) Doppler Weather Radar (DWR) data (DWR experiments). The model follows Arakawa C-grid staggering. ARW model is customized for the prediction of TCs over the BoB considering a number of cases and demonstrated that the combination of Kain-Fristch (KF) cumulus convection scheme and Yonsui university (YSU) planetary boundary layer (PBL) schemes, WRF single-moment 3-class (WSM3) microphysics scheme, Monin-

Obukhov surface scheme, thermal diffusion land-surface scheme and the Rapid Radiative Transfer Model (RRTM) for long wave and Goddard for short wave atmospheric radiation schemes provide relatively better track, intensity, structure of the inner core and hence the rainfall prediction (Osuri *et al*., 2012a).

(b) *NMM Model*

The WRF-NMM is a fully compressible, state-of-the-art, Eulerian non-hydrostatic model with a hydrostatic option (Janjic, 2001; 2003a; 2003b). The horizontal rotated latitude-longitude coordinate and the vertical terrain-following hybrid sigma-pressure coordinate system is used. The NMM model is integrated in a single domain with the horizontal resolution of 9 km covering the domain 3º N–28º N, 78º E–103º E for TCs over the BoB. The model has 51 levels up to the height of 30 km and the model top is fixed at 10 hPa. The model is integrated with time step of 20 sec, since WRF-NMM the maximum time step is 2.2 times of the model horizontal resolution. The optimum combination of the physical parameterization schemes (Pattanayak *et al*., 2012) in simulation of TCs over NIO is used in this study. The combination of Simplified Arakawa Schubert (SAS) cumulus convection, YSU PBL parameterization scheme, NMM land surface physics, Ferrier microphysics and the GFDL long wave/short wave radiation schemes is the optimum configuration for the simulation / prediction of tropical cyclones over NIO. The initial and lateral boundary conditions are provided from the NCEP / FNL (FiNaL) analysis (1° × 1° horizontal resolution). The FNL analyses come from NCEP's Global Data Assimilation System (GDAS, Kanamitsu 1989), which runs in 6-hr interval. GDAS system in the frame work of global spectral Medium Range Forecast (MRF) model is used to assimilate available observations. The full details, including the different types of observations that are going into the analyses system, can be obtained from the Data Documentation (National climatic data Center, 2002) for Data Set 6141B (NCEP Model Output-FNL archive data).

(c) *HWRF Model*

The HWRF is a fully compressible, state-of-the-art, non-hydrostatic model and the dynamics is similar to the NMM model described in section 2(b). The HWRF model is integrated in double domain with the horizontal resolution of 27 km and 9 km (D1: 27 for TCs over the BoB. The model has 42 vertical levels and the top of the model is fixed at 50 hPa. The combination of SAS cumulus convection, NCEP GFS PBL parameterization scheme, NMM land surface physics, Ferrier microphysics and the GFDL long wave/short wave radiation schemes is used.

The brief description of ARW, NMM and HWRF models are illustrated in Table 1.

3. Results and discussions

The performance of all the three models described above in prediction/simulation of track, intensity, structure and associated rainfall of landfalling TCs over the BoB is discussed, however, this study mainly focus on the performance of the model for the prediction track and intensity in terms of minimum central sea level pressure (CSLP; hPa) and 10-m maximum sustainable wind speed (MSW; m/s).

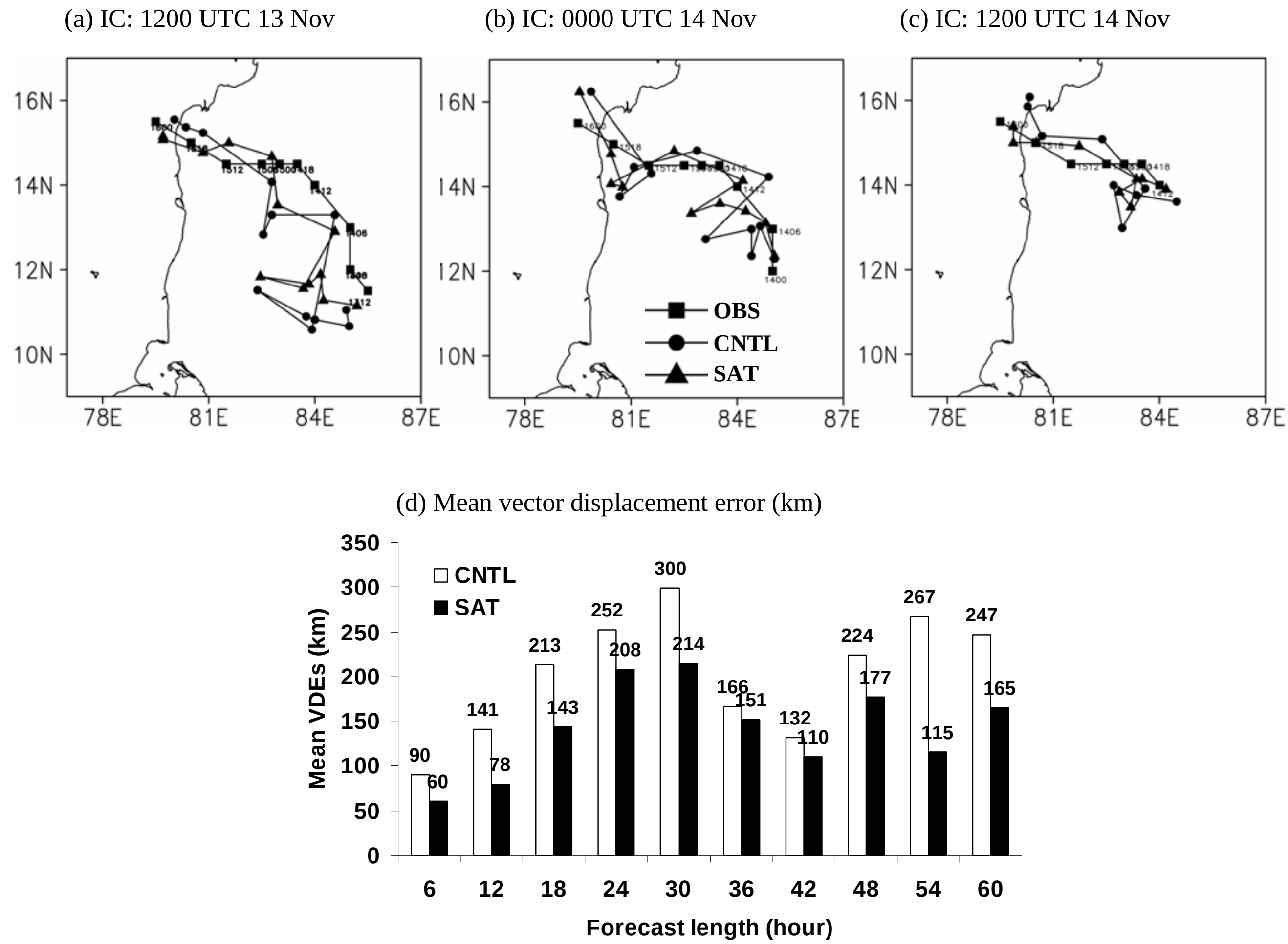
3.1. *Performance of ARW model*

In this section the performance of the ARW model in real-time prediction and data impact studies to improve the model performance is demonstrated.

(a) *Real-time prediction*

Figs. 1 (a-f) provides the ARW model predicted tracks for the BoB TCs, *viz*., Rashmi, KhaiMuk, Nisha, Giri, Jal and Thane in real-time basis (with 27 km horizontal resolution) at different initial times and mean direct position error (DPE) is given in Fig. 1(g). The initial vortex position error is about 80 km. Though the NCEP had vortex-relocation procedure for the BoB TCs, the large initial position error may be due to number of reasons: (*i*) poor data coverage near and around the vortex over the deep oceans where TCs form and develop (*ii*) NCEP does the relocation according to Joint Typhoon Warning Centre (JTWC) best track position. The average difference between IMD and JTWC best track positions is about 50-60 km (Falguni *et al*., 2004; Ahn *et al*., 2002 etc.). However, the error calculations are done with respect to IMD best track observations in this study. As the methodologies used by both agencies to obtain the best track differ with each other, the best track positions itself could vary with each other. (*iii*) Further, the global analyses are available at coarse resolution (about 0.5° × 0.5° or 1.0° × 1.0°) which could not provide right strength and circulations of the cyclone at the initial time. Recently, much research is going on to improve the initial vortex position and structure. The short-term TC forecast can be improved by using different techniques such as bogus data assimilation (Xiao *et al*., 2009), 3-dimensional variational data assimilation (Osuri *et al*. 2012b; Routray *et al*. 2010(a & b) etc.

The mean track forecast error from the ARW model varies from 110 km to 255 km for 12 to 72 hour forecast length. However, the range of mean DPE (*i.e*., actual



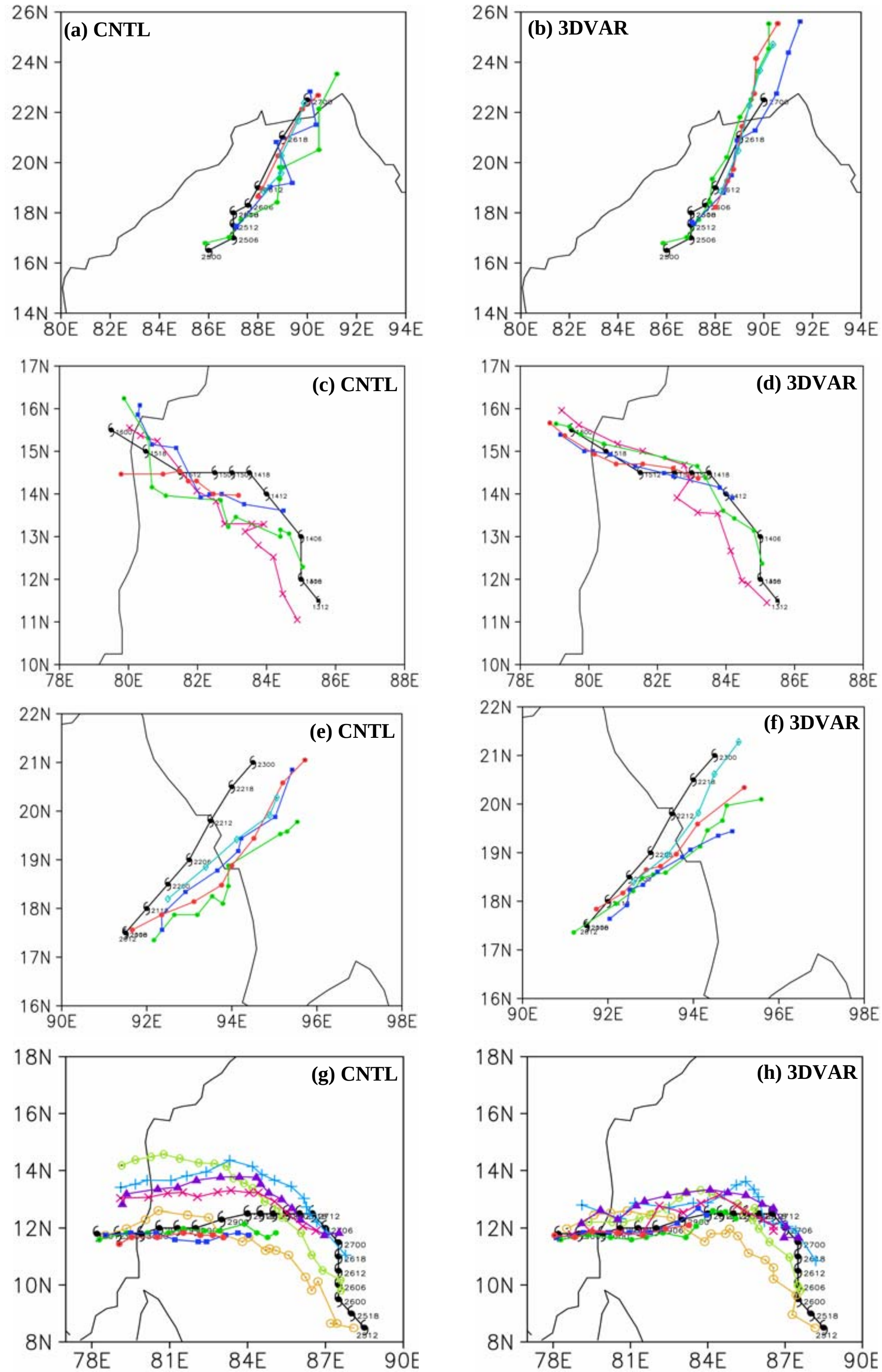
Figs. 2(a-d). Model simulated tracks of TC Khai Muk from CNTL and SAT experiments along with IMD best track at three initial times (a) 1200 UTC 13 (b) 0000 UTC 14 and (c) 1200 UTC 14 Nov 2008 and (d) Mean vector displacement errors (VDEs in km) in 6 hrs interval

value ± standard deviation) varies from as low as 40 km to as high as 350 km for the same forecast lengths. The analyses of systematic errors such as cross track (CT) errors state that the ARW model forecasts are biased to right side / eastward as the CT errors are increasingly positive with forecast length. The along track (AT) errors showed that the movement of model predicted TCs is slow as the AT errors are highly negative for all forecast intervals.

(b) *Impact of satellite derived sea surface winds on TC forecast*

The impact of satellite derived sea surface winds obtained from QSCAT and SSMI on initialization and simulation of TCs over NIO is presented in this section at 9 km model horizontal resolution. For this purpose, TC Khai Muk is simulated at 3 initial times, *i.e.*, at 1200 UTC 13 (Case-1), 0000 UTC 14 (Case-2) and 1200 UTC 14 (Case-3) November 2008. Two sets of numerical experiments, with and without satellite derived wind data assimilation are conducted: CNTL, in which FNL analyses are used as initial and boundary conditions and SAT, in which QSCAT and SSMI winds are assimilated in the model initial condition. The QSCAT observations assimilated in Case-1, Case-2 and Case-3 are 1026, 681 and 2946, while, the SSMI wind speed observations are 2561, 2096 and 1037 respectively.

The departures of SAT analyses and FNL analyses with respect to QSCAT and SSM/I observations is provided in Table 2 for 3 cases. The departure of SAT analysis (O – A) by the assimilation of satellite winds is less compared to that of global FNL background field (O - B), where O, B and A represent observation, background and modified analysis, respectively. With the



Figs. 3(a-h). Comparison of model simulated tracks from CNTL (first column) and 3DVAR (second column) for the cyclone Rashmi (1st row), Khai Muk (2nd row) and Giri (3rd row) and Thane (4th row) at different initial times during TC period. (Legends are same as in Figure 1)

TABLE 3

Mean DPE, CT and AT errors (in km) for CNTL and 3DVAR experiments up to 72 hour forecast length. In each box, top value is actual error and bottom value is the standard deviation

	CNTL			3DVAR		
	DPE (SD)	CT (SD)	AT (SD)	DPE (SD)	CT (SD)	AT (SD)
12	113 (60)	13 (83)	-83 (92)	59 (31)	35 (69)	-65 (77)
24	138 (70)	10 (105)	-121 (103)	72 (41)	7 (88)	-84 (108)
36	128 (74)	21 (97)	-134 (140)	89 (49)	3 (76)	-84 (126)
48	135 (69)	41 (115)	-134 (124)	99 (63)	3 (15)	-68 (119)
60	167 (74)	31 (24)	-98 (134)	109 (68)	24 (14)	-14 (112)
72	182 (47)	55 (106)	-72 (134)	126 (61)	-5 (50)	-18 (108)

assimilation of QSCAT winds, the mean departure of U-wind improves by 40%, and V-wind improves by 20% and the departure of wind speed improves by 35% with SSM/I winds. Overall, the assimilation of above satellite winds produced analysis that fit the QSCAT as well as SSM/I observations.

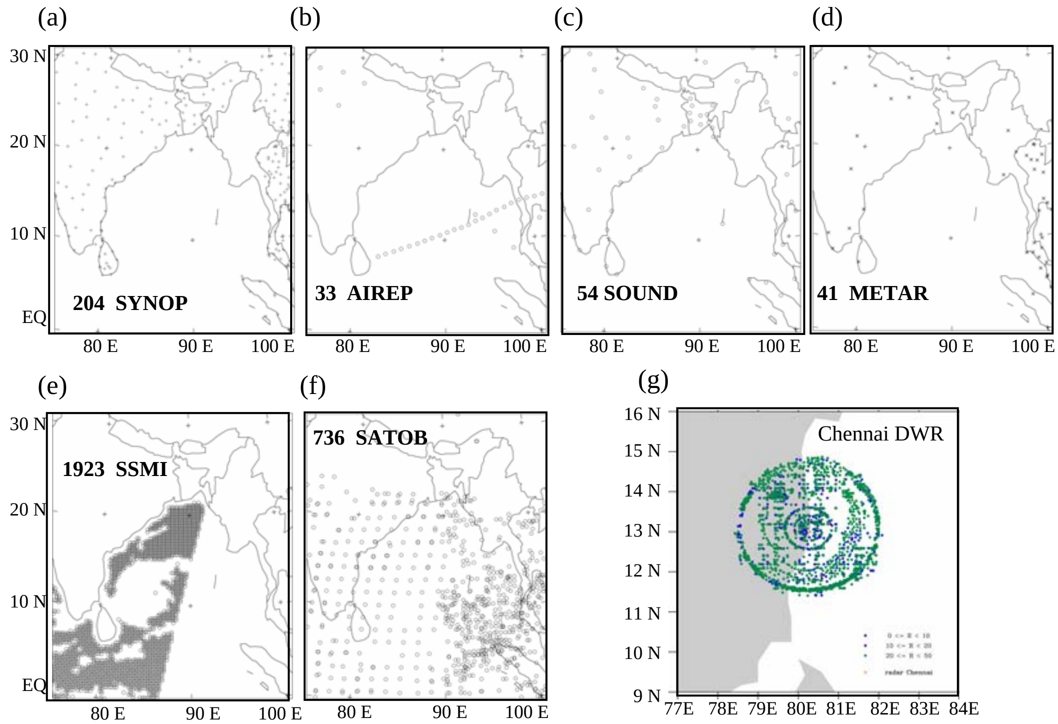
The assimilation of above mentioned data improved the initial vortex structure (not shown here) and therefore, the initial vortex position significantly improved in all the three cases. The initial vortex position errors with FNL analyses is about 83 km, 33 km and 68 km and after the assimilation sea surface winds, it is reduced to 51 km, 41 km and 22 km respectively with a mean improvement of about 37%. The large error in case-2 of SAT run may due to less coverage of QSCAT data around the vortex, though the SSM/I data is sufficiently ingested. Singh *et al*. (2008) showed that assimilation of QSCAT wind vectors reduces initial error significantly than the assimilation of SSM/I wind speed. So, it highlights the need for representation of inner core wind along with surrounding data. The SAT experiments improve intensity in all three cases significantly. According to IMD observations, the lowest CSLP is 994 hPa and maximum wind speed is 20 ms^{-1} for TC KhaiMuk. The CNTL experiments could not showed the realistic intensity (996, 1000, 1000 hPa and 18, 14, 14 ms^{-1} respectively for case-1, case-2 and case-3). The assimilation experiment improves the intensity prediction (995, 998, 998 hPa and 19, 17, 17 ms^{-1}, respectively).

The TC tracks of 3 cases with the location of CSLP centre from both CNTL and SAT simulations are analyzed and presented in Figs. 2 (a-c). Fig. 2 (d) gives the mean track error from 3 cases up to 60 hour forecast. The SAT experiment improves the track prediction for all the forecast length. The mean 12 hr, 24 hr, 36 hr and 48 hr forecast track errors (km) are 141, 252, 166 and 224 for CNTL experiment and 78, 208, 151 and 177 for SAT experiment respectively. Hence, there is an improvement of 44%, 17%, 9% and 21%, respectively with SAT assimilation experiment.

The three dimensional structure of the cyclone during peak intensity time is examined to understand the impact of sea surface winds. The assimilation experiment improved inner core structure of the cyclone in terms of depth of maximum winds, vorticity, updrafts and downdrafts structures. The SAT experiment retains the warmer core structure with well defined constant equitable potential temperature profiles extending through the depth of the entire troposphere which ultimately influences the intensity of the TCs also (Osuri *et al*., 2012b).

(c) *Impact of observational datasets collected during FDP*

During FDP, the IMD enhanced both temporal and spatial coverage of observational network. In this section, some experimental results are provided to show the impact of these additional observations on the prediction of TCs over the BoB. For this purpose, five cyclones *viz*., Rashmi (4 cases), KhaiMuk (4 cases), Nisha (3 cases), Giri (4 cases) and Thane (8 cases) during FDP period are considered and each cyclone is forecasted at different initial times with 9 km horizontal resolution. So, this analyses based on 23 cases. Two numerical experiments are conducted for each case (*i*) no-assimilation of additional data, known as CNTL in which initial and boundary conditions are obtained from GFS analyses and forecast fields (*ii*) assimilation of all available observations known as 3DVAR. The observational data includes automated weather stations (AWS), satellite derived winds, etc. with higher frequency. TC Jal is



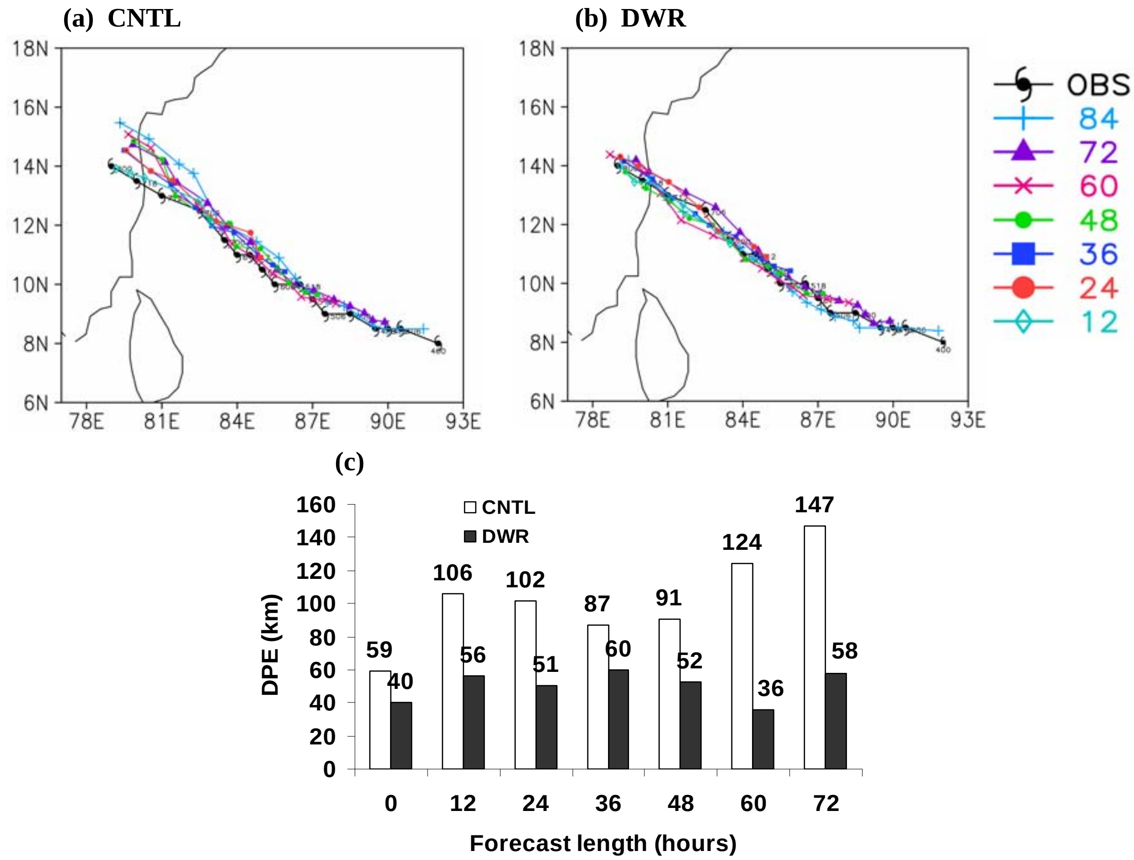
Figs. 4(a-g). Distribution of data that are assimilated into initial condition of TC Jal at 0000 UTC 6 Nov 2010 (a) SYNOP, (b) AIREP, (c) SOUND, (d) METAR, (e) SSMI, (f) SATOB, and (g) Chennai DWR respectively for TC Jal

presented in next section separately as the Doppler weather radar observations have been assimilated.

Figs. 3(a-h) shows the model simulated tracks from both the experiments at different initial times. The assimilation runs improve the track prediction and the significance of the assimilation of additional observations is demonstrated. The initial position error is considerably reduced from about 60 km (in CNTL experiment) to 42 km (in 3DVAR experiment) with a improvement of 30%. The spread of tracks in 3DVAR experiments is relatively smaller and the speed of the cyclone is enhanced than in CNTL experiment. To quantify this, the mean DPE, CT and AT errors (based on 23 cases) are presented in Table 3. The forecast DPEs are 138, 135 and 182 km from CNTL experiment while, the same are 72, 99 and 126 km at 24, 48 and 72 hour forecast lengths, respectively. The impact of these observations is significant up to 24 hour forecast with an improvement of 47%. The standard deviation is also less with 3DVAR runs showing the error range is less with more consistency. The CT errors are positive and AT errors are negative for both the experiments, *i.e.*, the forecasts are rightward/eastward biased with slow movement. However, comparing the magnitude, the 3DVAR errors are much smaller compared to those of CNTL. That means, the spread of the tracks is reduced and the speed of the cyclone is enhanced in 3DVAR experiment.

(d) *Impact of Doppler weather radar (DWR) observations*

Except the assimilation of additional DWR data, the other information like experimental setup, model configuration and physical parameterization schemes used for this section is same as in the previous section. The assimilation experiment is known as DWR experiment in which the DWR observations along with all other observations mentioned in previous section. Figs. 4(a-g) gives the distribution of the observations used in the assimilation system to prepare high resolution modified analyses at 0000 UTC 6 Nov 2010. The Chennai DWR data is used and the quality control is followed as presented in Routray *et al.* (2010b). Routray *et al.* (2010b) showed that the assimilation of DWR data can significantly improve the initial structure and position of the monsoon depressions over the BoB. Similar results are also found here, however, the structure is not presented here whereas the mean initial vortex position error is reduced from 59 km to 40 km. It is obvious that the reduction in initial position error of the cyclonic vortex leads to better track prediction (Holland 1984). The



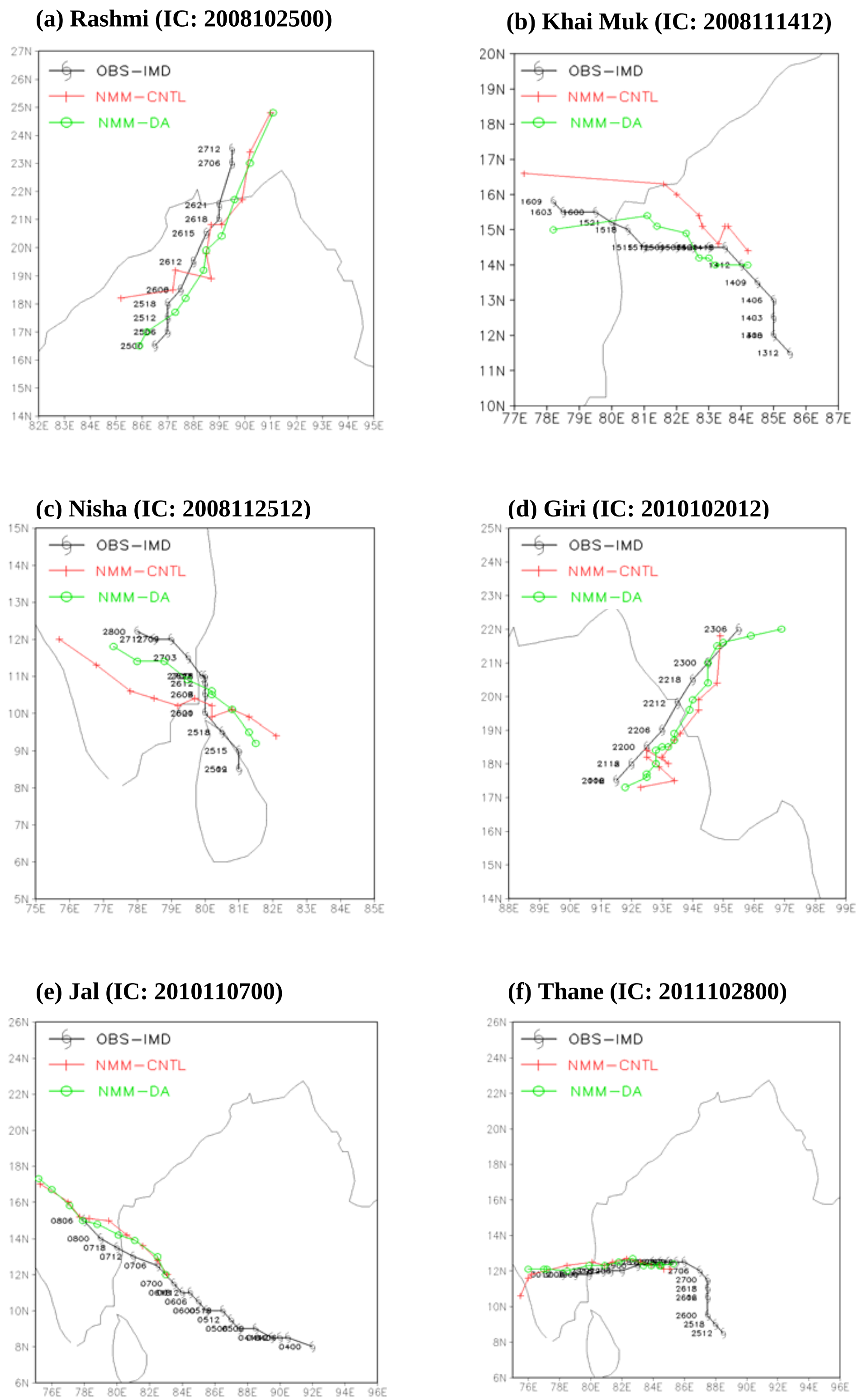
Figs. 5(a-c). Model simulated tracks from CNTL and DWR experiments along with IMD best track for TC Jal (a) CNTL and (b) DWR and (c) mean DPE of 7 cases in 12-hr interval. (Legends are same as in Figure 1)

model predicted tracks are presented in Figs. 5(a-c). The spread of the tracks in CNTL experiment are relatively larger, particularly at the landfall point, than those from DWR experiment. The (36, 24, 12 hour lead) landfall point errors from both CNTL and DWR experiments are (92, 89 36 km) and (33, 37, 22 km) respectively. The mean DPE of TC Jal is about 106, 102, 91, 147 km at 12, 24, 48 and 72 hour forecast lengths from CNTL experiment. However, it is about 56, 51, 52 and 58 km, respectively with DWR experiment. This large reduction in track errors may be attributed to the assimilation of high (temporal and spatial) resolution DWR observations. Though this study is based on only one case, the results are more encouraging and the individual impact of observations like AWS, DWR reflectivity and radial wind is under study with more number of cases.

3.2. *Performance of NMM model*

In this section the performance of NMM model in simulation of landfalling TCs over the BoB is illustrated. In this section, the post-monsoon TCs *viz*., Rashmi (2008), KhaiMuk (2008), Nisha (2008), Giri (2010), Jal (2010) and Thane (2011) are simulated at different initial times. A total of 30 cases (3 initial conditions for Rashmi; 4 initial conditions for KhaiMuk; 3 initial conditions for Nisha; 4 initial conditions for Giri; 7 initial conditions for Jal and 9 initial conditions for Thane) are considered. The numerical experiments are broadly categorized into two sets such as (*i*) control (CNTL) experiment with FNL as the initial and boundary condition and (*ii*) data assimilation (DA) experiment in which model initial back ground field is improved through assimilation of additional observations. These observations include SYNOP, SOUND, METAR, PILOT, BUOYS, AIREP, and QSCAT etc.

Figs. 6(a-f) represents the model simulated tracks from both CNTL and DA experiments along with best-fit track from IMD. Fig. 6 (a) presents the track of the cyclone Rashmi with initial condition of 0000 UTC 25 Oct 2008 with both CNTL and DA experiments and the IMD best-fit observation. The initial vortex position is improved and close to the actual realization in DA experiment than the CNTL simulation. Also, the subsequent forecasted track is improved in DA



Figs. 6(a-f). Model simulated tracks from both CNTL and DA experiments with NMM model along with best-fit track from IMD for (a) Rashmi, IC: 0000 UTC 25 Oct 2008, (b) Khai Muk, IC: 1200 UTC 14 Nov 2008, (c) Nisha, IC: 1200 UTC 25 Nov 2008, (d) Giri, IC: 1200 UTC 20 Oct 2010, (e) Jal, IC: 0000 UTC 07 Nov 2010 and (f) Thane, IC: 0000 UTC 28 Oct 2011

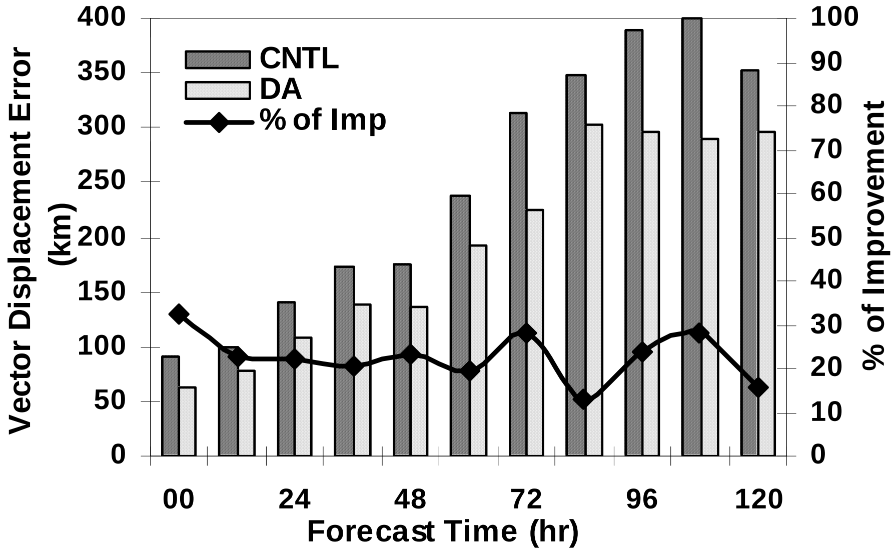


Fig. 7. Mean of vector displacement error (km) from both CNTL and DA experiments with NMM model along with the % of improvement in DA experiment than the CNTL simulation for all the 30 cases

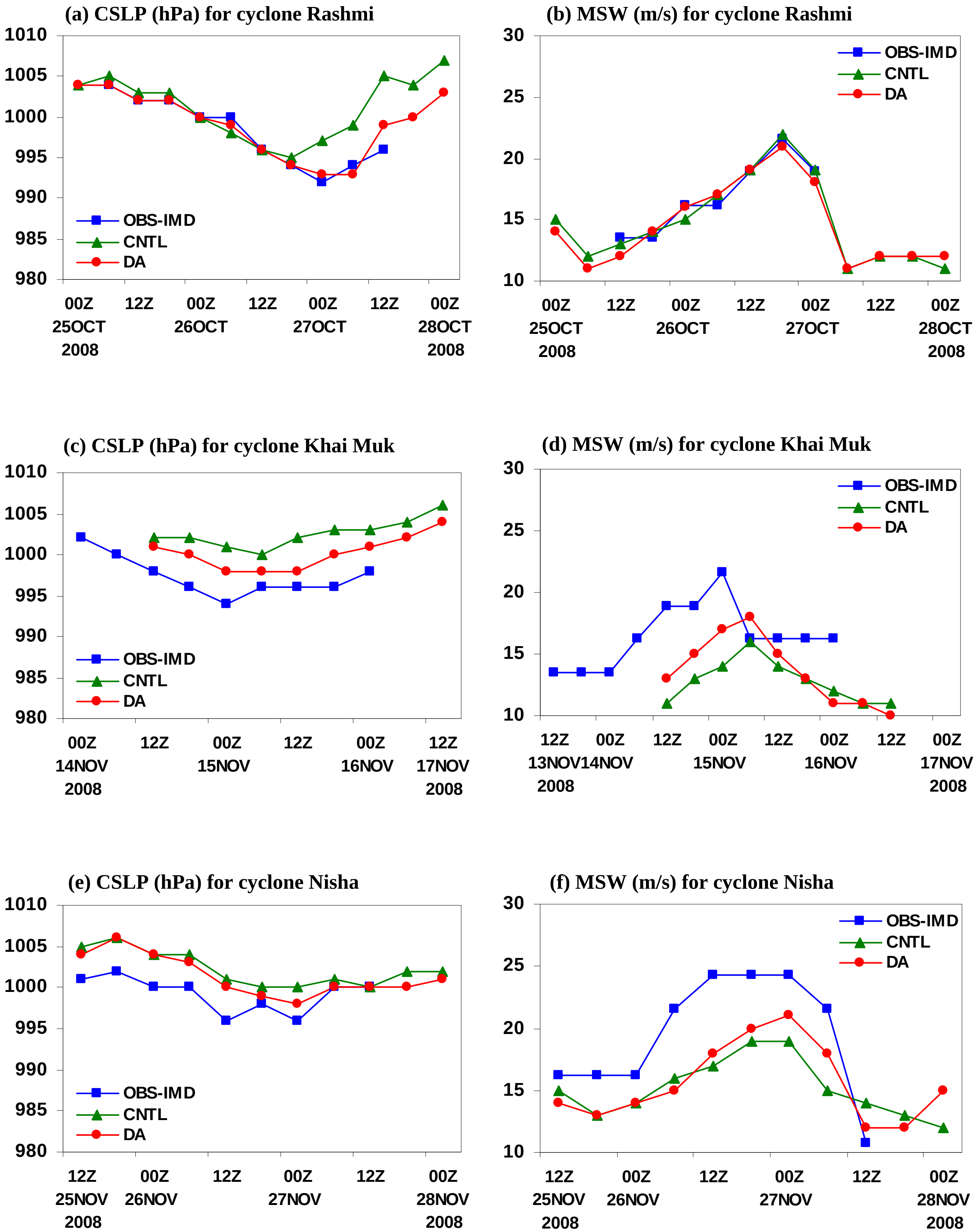
experiments. Similar results is noticed in all the other cases, *i.e.*, track simulation of Khai Muk with initial condition of 1200 UTC 14 Nov 2008 [Fig. 6(b)], Nisha with initial condition of 1200 UTC 25 Nov 2008 [Fig. 6 (c)], Giri with initial condition of 1200 UTC 20 Oct 2010 [Fig. 6(d)], Jal with initial condition of 0000 UTC 07 Nov 2010 [Fig. 6(e)] and Thane with initial condition of 0000 UTC 28 Oct 2011 [Fig. 6(f)].

The mean VDEs for all the 30 cases are also calculated and presented in Fig. 7. The mean improvement of 32%, 22%, 23%, 28%, 24% and 16% is noticed at 00, 24, 48, 72, 96 and 120 hrs respectively. Thus, it may be noted that the track position of the cyclones are improved in initial as well as forecast time of model integration. Comparing individual cases, DA runs an improvement of 44%, 10%, and 22% for Rashmi than the CNTL simulation at 00, 24 and 48 hrs, respectively. The mean improvement of 27%, 19%, 18% and 53% is calculated in KhaiMuk case with DA experiment than the CNTL simulation at 00, 24, 48 and 72 hrs of model integration, respectively. In case of Nisha, the mean improvement of 31%, 33% and 39% at 00, 24 and 48 hrs, respectively is evaluated. Similarly, in case of Giri, at the initial time the improvement of 54% is achieved in DA experiment. In case of Thane, both CNTL and DA experiments show higher VDE than all other cases because of its peculiar and rare movement.

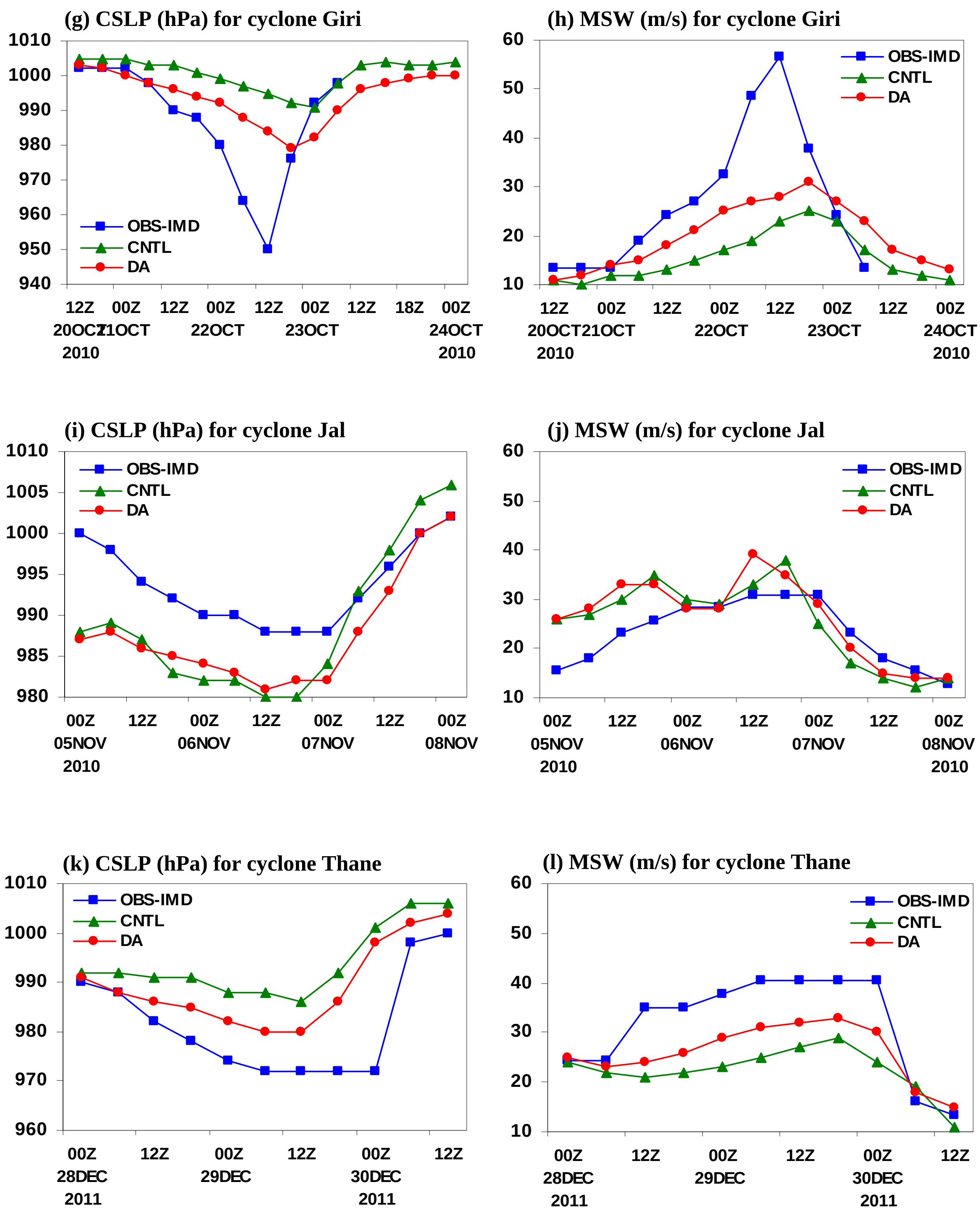
Figs. 8(a-l) illustrates the intensity forecast in terms of CSLP; hPa and MSW; m/s. Figs. 8(a&b) represents the CSLP (hPa) and MSW (m/s) for cyclone Rashmi with the IC of 0000 UTC 25 October 2008. The observed CSLP was 992 hPa valid at 0000 UTC 27 October 2008. The CNTL and DA experiments simulate 996 hPa and 993 hPa and the peak intense time is well captured by DA experiment. Figs. 8(c&d) provides the intensity prediction for cyclone KhaiMuk with the IC of 1200 UTC 14 November 2008. The observed CSLP was 994 hPa valid at 0000 UTC 15 November 2008. The CNTL and DA experiments simulate 1000 hPa and 998 hPa, respectively. Figs. 8 (e&f) represents the CSLP (hPa) and MSW (m/s) for cyclone Nisha. The observed CSLP was 996 hPa with MSW of 24 m/s valid at 0000 UTC 27 November 2008. The CNTL and DA experiments simulate peak intensity of 1000 and 998 hPa. The DA experiment simulates the wind speed of 21 m/s valid at 0000 UTC 27 November 2008. Figs. 8 (g&h) presents the CSLP (hPa) and MSW (m/s) for cyclone Giri. The observed CSLP was 950 hPa and MSW of 54 m/s valid at 1200 UTC 22 October 2010 and model could simulate the peak intensity of 991 and 982 hPa with CNTL and DA experiments valid at same time. The MSW of 25 and 31 m/s are simulated with CNTL and DA experiments, respectively. Similar type of results are found in TC Jal [Figs. 8 (i&j)] and Thane [Figs. 8 (k&l)].

3.3. *Performance of HWRF model*

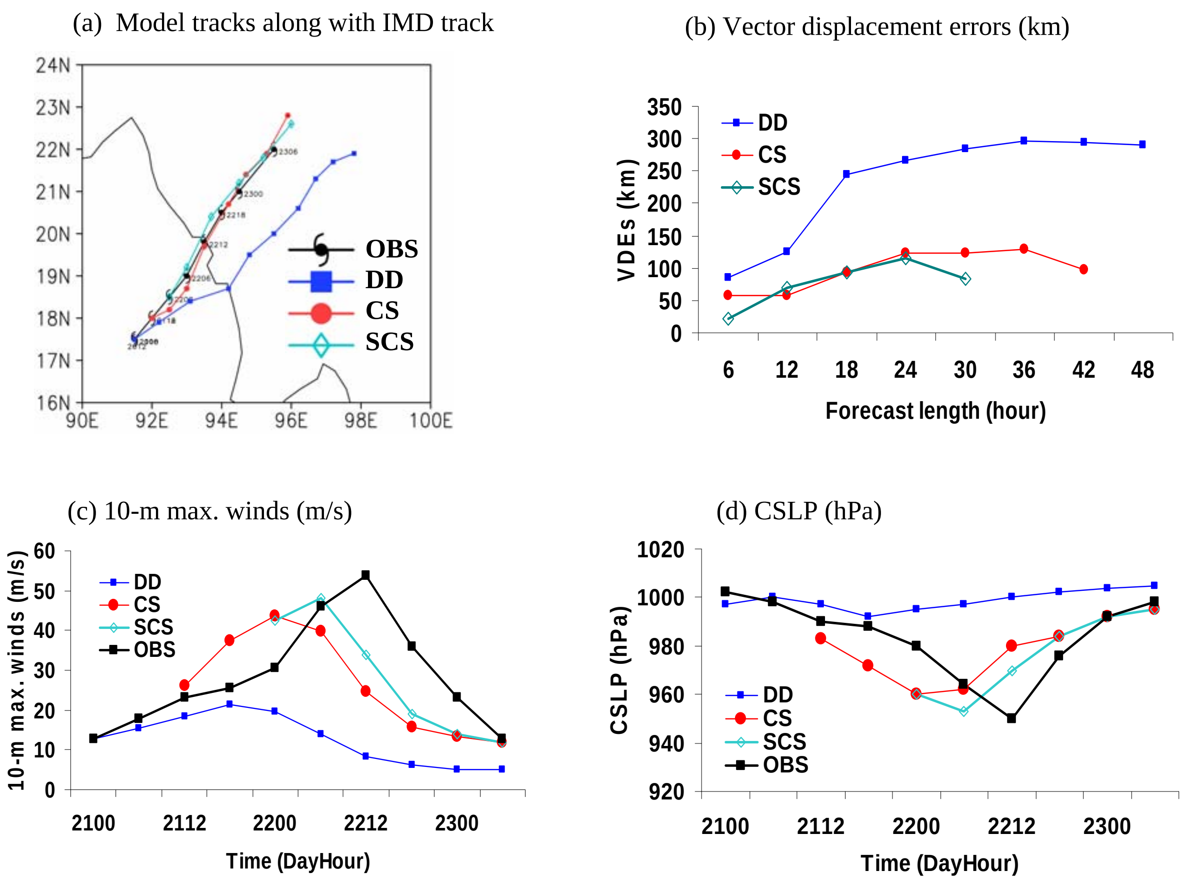
In this section, the performance of HWRF modeling system for the prediction of TC Giri is investigated as it is a rapid intensified cyclone just before the landfall. The model configuration and the physics employed are given


(a) CSLP (hPa) for cyclone Rashmi
1010
1005
1000
995
990
985
980
OBS-IMD
CNTL
DA
00Z 25OCT 2008
12Z
00Z 26OCT
12Z
00Z 27OCT
12Z
00Z 28OCT 2008
(b) MSW (m/s) for cyclone Rashmi
30
25
20
15
10
OBS-IMD
CNTL
DA
00Z 25OCT 2008
12Z
00Z 26OCT
12Z
00Z 27OCT
12Z
00Z 28OCT 2008
(c) CSLP (hPa) for cyclone Khai Muk
1010
1005
1000
995
990
985
980
OBS-IMD
CNTL
DA
00Z 14NOV 2008
12Z
00Z 15NOV
12Z
00Z 16NOV
12Z 17NOV 2008
(d) MSW (m/s) for cyclone Khai Muk
30
25
20
15
10
OBS-IMD
CNTL
DA
12Z 13NOV 2008
00Z 14NOV
12Z
00Z 15NOV
12Z
00Z 16NOV
12Z
00Z 17NOV 2008
(e) CSLP (hPa) for cyclone Nisha
1010
1005
1000
995
990
985
980
OBS-IMD
CNTL
DA
12Z 25NOV 2008
00Z 26NOV
12Z
00Z 27NOV
12Z
00Z 28NOV 2008
(f) MSW (m/s) for cyclone Nisha
30
25
20
15
10
OBS-IMD
CNTL
DA
12Z 25NOV 2008
00Z 26NOV
12Z
00Z 27NOV
12Z
00Z 28NOV 2008

Figs. 8(a-f).



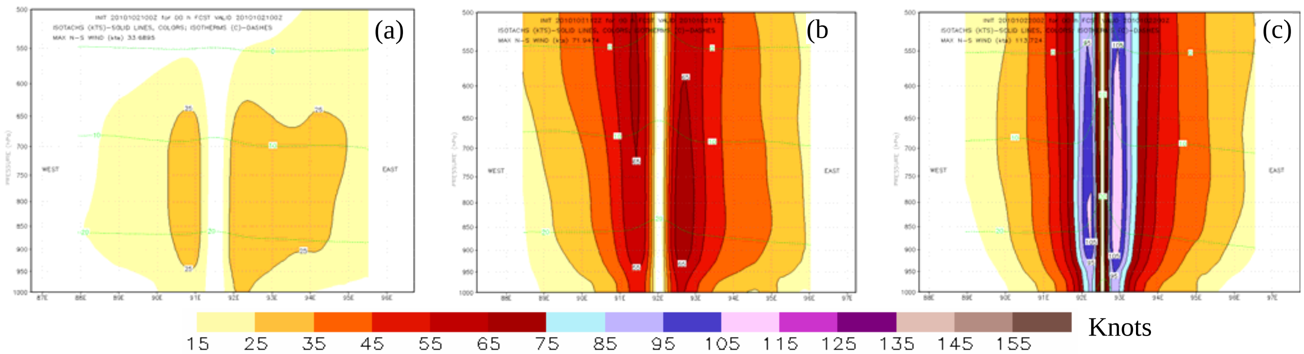
Figs. 8(a-l). Mean intensity forecast in terms of (a) CSLP (hPa) and (b) MSW (m/s) for Rashmi (IC: 2008102500); (c, d) is same as (a, b), but for cyclone Khai Muk (IC: 2008111412); (e, f) is same as (a, b), but for cyclone Nisha (IC: 2008112512); (g, h) is same as (a, b), but for cyclone Giri (IC: 2010102012); (i, j) is same as (a, b), but for cyclone Jal (IC: 2010110500); and (k, l) are same as (a, b) but for cyclone Thane (IC: 2011122800)



Figs. 9(a-d). HWRF predicted (a) tracks and (b) vector displacement error, km and intensity evolution in terms of (c) 10-m maximum winds, m/s (d) CSLP, hPa, for TC Giri at 3 stages of intensity. The forecast length decreases by 12 hours from DD to CS, CS and SCS *i.e.*, depression case has 48 hours forecast length, cyclonic storm case has 42 hours and SCS case has 36 hours forecast

in Table 1. HWRF uses two domains, *i.e.*, the outer static domain with 27 km and a movable 9 km nested domain. The size of the inner moving nest is 6° × 6° and follows the vortex. In this study, bogus vortex initialization, relocation and assimilation methods are used. For bogus vortex, TC position and intensity are taken from IMD observations and structure details (like radius of maximum winds and radius of outermost closed isobar) are taken from Joint Typhoon Warning Centre (JTWC). After creating the bogus vortex, depending up on the intensity of convection (shallow, medium or deep) associated with TC, the bogus vortex undergoes intensity and structure corrections in vortex initialization procedure. The vortex, in medium and deep convective TCs, receives the same vortex corrections mentioned above, while the vortex with shallow convection undergoes only two corrections *i.e.*, the vortex top is set to 700 hPa and the warm core structures are removed. TCs with deep convection, Grid Statistical Interpolation (GSI) system is used to assimilate large scale observations (upper-level, surface and satellite radiance data) to further improve the vortex. If the TC is not deep, data assimilation will not be used. The detailed information regarding the procedures can be found from HWRF scientific documentation by Gopalakrishnan *et al.* (2011). The TC Giri is initialized with HWRF model at three intensity stages *i.e.*, depression (DD), cyclonic storm (CS) and severe cyclonic storm (SCS) stages to predict the track, intensity and structure. According to NCEP TCvitals, Giri has shallow convection at DD stage, medium convection at CS and deep convection at SCS stage.

Figs. 9(a-d) provides the intensity evolution, track and associated errors for each experiment initialized at above mentioned three stages. The initial position error is zero as in all cases, vortex relocation is carried out. It is seen that, the experiment initialized from depression stage could not capture the intensity evolution, track movement even after the insertion of bogus vortex which results with large track errors of about 85 km to 295 km in 6 hour to



Figs. 10(a-c). HWRF initialized vortex at the initial time of each case (a) depression stage, 0000 UTC 21 Oct (b) cyclonic storm, 1200 UTC 21 Oct and (c) severe cyclonic storm, 000 0 UTC 22 Oct 2010

48 hour forecast lengths [Figs. 9 (a&b)]. The maximum intensity predicted in depression stage experiment is about 992 hPa (22 m/s) against the observed intensity of 950 hPa (54 m/s) [Figs. 9(c&d)]. This may be due to the fact that the TC Giri is a shallow vortex at depression stage and hence vortex is not improved [Fig. 10(a)] as there are no vortex intensity and size corrections, additional data assimilation, except the two above mentioned corrections. Hence, the intensity evolution is also poor compared to observation and other two experiments. Figs. 10(a-c) shows different vortex structures generated through different initialization procedures as mentioned above when TC Giri is at shallow (DD), medium (CS) and deep (SCS) convective stages. However, in the later two cases the results are very impressive having minimum errors in both intensity and track prediction because of improved initial structure. Though, data assimilation is not used in CS stage, it could capture the rapid intensification (wind increased about 18 m/s within 12 hours) before landfall and a maximum intensity of 40 m/s. Similar results are observed in the last case in which TC is initialized at SCS stage and capture the right peak intensity of 48 m/s [Figs. 9 (c&d)]. This may be due to the improved vortex initialization procedure at CS and both initialization and assimilation at SCS stages. It could also predict rapid dissipation after the landfall. The track errors are about 100 km in 6 hrs to 48 hrs forecast lengths [Figs. 9(a&b)] from both the CS and SCS initializations. These results show the importance of high resolution mesoscale data assimilation along with improved vortex initialization procedure for more realistic TC forecasts (as seen in CS and SCS stage initializations).

4. Conclusions

In view of the above results, the following broad conclusions can be drawn.

High resolution mesoscale modeling systems provide better guidance for TC forecast in real-time up to 72 hours. The track and intensity error is relatively more in real-time predictions using ARW model when initialized with global analyses and forecast fields without data assimilation. The mean track forecast error from ARW model in real-time predictions varies from 110 km to 255 km for 12 to 72 hrs forecast length. This error could significantly reduce with the assimilation of additional regional observations (like satellite derived winds, observations during FDP period and DWR observations) into model initial conditions. The assimilation of satellite derived winds into model initial condition could reduce the 24-, 48-, 72- and 96-hrs track forecast errors by 28%, 15%, 41% and 47%, respectively. Further, the gain in skill of the model after assimilation of all available FDP period observations is increased from 25% to 47% from the 12 to 72 hrs forecast as compared to CNTL (no assimilation) experiment.

Considering NMM model, the track and intensity errors are substantially improves in DA experiments than that of the CNTL experiments. The mean track error in WRF-NMM model based on the 30 cases varies from 91 km to 352 km in CNTL simulations for 00 hr to 120 hrs forecast length. At the same time, in case of DA experiments the mean track error for 00 hr to 120 hrs forecast length are ranges from 61 km to 297 km. The mean VDEs are improved of about 32%, 22%, 23%, 28%, 24% and 16% at 00, 24, 48, 72, 96 and 120 hrs respectively. The DA experiments significantly improve the intensity forecast as well in most of the cases. It may be noticed that the CSs provides less track and intensity error than the SCSs.

HWRF model with advanced capabilities like vortex relocation, initialization and data assimilation techniques showed impressive improvement for the prediction of TC Giri over the BoB. It could able to capture the rapid intensification and weakening of the system. Therefore, it can be a value-added model for the research and operational purposes.

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