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SIMULATION OF STRUCTURE, TRACK AND LANDFALL OF TROPICAL CYCLONE BIJLI USING WRF-ARW MODEL

K. M. ZAHIR RAYHUN, D. A. QUADIR[1], M. A. MANNAN CHOWDHURY, M. N. AHASAN[2] AND M.S. HAQUE[3]

Jahangirnagar University, Savar, Dhaka, Bangladesh

ABSTRACT

An attempt was made to simulate the structure, track, landfall and a few dynamical aspects of the tropical cyclone Bijli that formed over the Bay of Bengal using WRF-ARW model. WRF model was run in a single domain using KF cumulus parameterization schemes with WSM 3 micro physics and YSU planetary boundary layer scheme. The ARW model was run for 24, 48, 72 and 96 hrs to simulate structure, track and landfall of tropical cyclones Bijli. The different simulated parameters *viz.* minimum sea level pressure, maximum wind speed, convective available potential energy and relative vorticity have been studied. The results showed that the model is capable to forecast the formation of the first depression 60 - 78 hrs in advance. This indicates the high and unique predictive power of ARW model for predicting the tropical cyclone formation. The model generates a realistic structure of the tropical cyclones with high spatial details. This was possible due to the higher spatial resolution of the regional model. One of the outstanding findings of the study is that the model was successfully predicted the tracks, recurvature and probable areas and time of landfall of the selected tropical cyclone Bijli with high accuracy even in the 96 hrs predictions.

Key words: Tropical cyclone, Vorticity, Divergence, Vertical wind shear, Bay of Bengal

INTRODUCTION

The tropical cyclones (TCs) over the Bay of Bengal (BoB) form primarily in pre-monsoon season (March - May) and post-monsoon season (October - December) 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 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. Mohanty and Gupta (1997), Gupta (2006) discussed the limitations of statistical methods beyond 24

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[1] Uttara University, Mirpur, Dhaka, Bangladesh.
[2] SAARC Meteorological Research Centre (SMRC), Dhaka, Bangladesh.
[3] Govt. Ashek Mahmud College, Jamalpur, Bangladesh.

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*. 2010) and tropical cyclones (Osuri *et al*. 2012, Pattanaik and Ramarao 2009, Davis *et al*. 2008). The model is also used to study the land surface processes (Niyogi *et al*. 2006). 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 (Velden *et al*. 1998, Chen 2007, Pu *et al*. 2008, Osuri *et al*. 2012b).

In the present study, the comprehensive performance of WRF modeling system in structure, track and landfall prediction of a selected tropical cyclone Bijli over the Bay of Bengal is presented.

A convective cloud cluster developed over southeast Bay of Bengal and adjoining Andaman sea on 10 April, 2009. It persisted over the same region till 13 April, 2009 under its influence, a low pressure area formed over southeast Bay of Bengal on 13 April, 2009. It became a well marked low pressure area over the southeast and adjoining central Bay of Bengal at 0300 UTC of 14 April, 2009 with associated cyclonic circulation extending up to mid-tropospheric level. The well marked low pressure area concentrated into a depression and lay centred near lat. 12.5 0N and long. 88.50E at 0900 UTC of 14 April over southeast and adjoining central Bay of Bengal. It further intensified into a deep depression and lay centred over central and adjoining southeast Bay of Bengal near lat. 14.00N and long. 87.50E at 0600 UTC of 15 April, 2009. It intensified into a cyclonic storm Bijli and lay centred at 1200 UTC of 15 April over central and adjoining southeast Bay of Bengal near lat. 15°N and lon. 86.50°E. The system moved in a north-

northwesterly direction till 0900 UTC of 16 April and recurved thereafter towards north-northeast. The system moved northeastwards skirting the coast (it was lying around 100 km from Orissa coast at 0000 UTC of 17 April) from 17 April morning onwards, the system interacted with land surface also. As a result the system gradually weakened into a deep depression at 0900 UTC and into a depression at 1200 UTC of 17 April near at Bangladesh coast.

MODEL EXPERIMENTAL SETUP, DATA USED

To simulate a selected tropical cyclone Bijli a domain of dimension 10-30°N and 80-100°E was selected to cover the Bay of Bengal basin at 24 km horizontal resolution with 21 vertical sigma levels. Fig. 1 shows the horizontal domain of the model. The model domain consists of 93 × 99 grid points. Marcator map projection has been used.

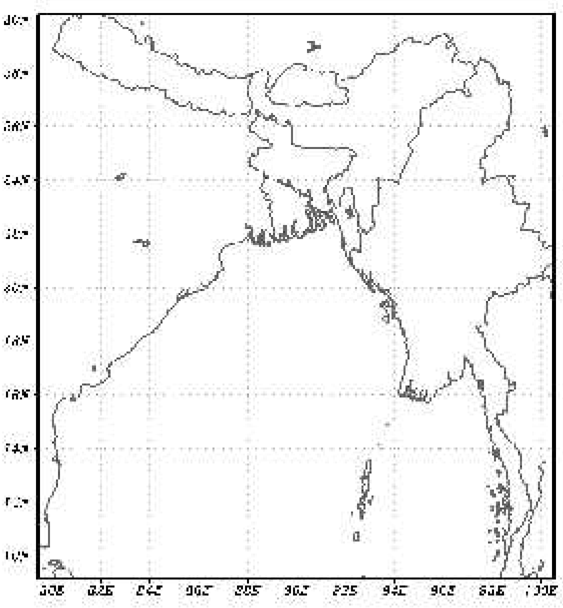

Fig. 1. WRF model domain setup.

Table 1. Selected parameterization schemes of different physics options.

Physics option	Selected parameterization schemes
Microphysics	WRF-single moment 3-class (WSM3)
Cumulus parameterizations	Kain-Fritch (KF) cumulus parameterization
Surface layer physics	Monin-Obukhov with Carslon-Bolan viscous sub-layer option
Land surface model	Noah 4-layer Land Surface Model (LSM)
Planetary boundary layer physics	Yonsei University scheme
Long wave radiation physics	Rapid Radiative Transfer Model (RRTM)
Short wave radiation physics	Dudhia schemes

The United States Geological Survey (USGS) terrain data at 30 sec interval were used to simulate the topographical features and land use/vegetation fields. The National Centre for Environment Prediction (NCEP) Final Reanalysis (FNL) data (1° × 1° resolution) was utilized as initial and lateral boundary conditions (LBCs) which are updated at six hourly intervals. The model results are compared with the IMD best track data to demonstrate the performance of the model.

METHODOLOGY

The ARW model was run for 24, 48, 72 and 96 hrs to simulate structure, track and landfall of tropical cyclones Bijli formed in the Bay of Bengal. The model was initialized with 0000, 0600, 1200 and 1800 UTC initial and boundary field from NCEP FNL. The model results are presented in the graphical and tabular forms and compared with the IMD best track data to demonstrate the performance of the modelling exercise.

The discussion in this section is mainly on the structure, track and landfall of selected tropical cyclone in terms of different parameters *viz.* minimum sea level pressure (MSLP), maximum wind speed (MWS), convective available potential energy (CAPE) and relative vorticity (ζ). These parameters are directly related to the intensity of tropical disturbances.

The distribution of model simulated surface pressure, winds, relative vorticity, temperature field, moisture fields and convective available potential energy were investigated for understanding the horizontal and vertical structure of the selected disturbances at their highest maturity stage.To study the tracks and landfall of the selected cyclonic systems the model was run for 24, 48, 72 and 96 hrs before the landfall time.

RESULTS AND DISCUSSION

The horizontal distribution of mean sea level pressure (MSLP) for the cyclone Bijli at its mature stage according to the model simulation at 0000 UTC of 18 April, 2009 has been shown in Fig. 2a. The Figure shows that the isobar has near circular arrangement around the cyclone centre. The contour interval is 1 hPa. Considering the outermost closed isobar, the system's horizontal size is estimated as 2 lon. (220 km) in the east-west direction and 2 lat. (220 km) in the north-south demonstrating some asymmetry of its circular shape in its horizontal structure having slight elongation in the east-west direction. Figure shows that the system is a strong one and it has organized core with pressure gradient.

The distribution of the sea level pressure of the cyclone Bijli along east-west section passing through its centre (18.9°N, 90°E) has been shown in Fig. 2b. The figure demonstrates that there is a strong pressure gradient. Model simulated system shows that the MSLP is of around 989 hPa.

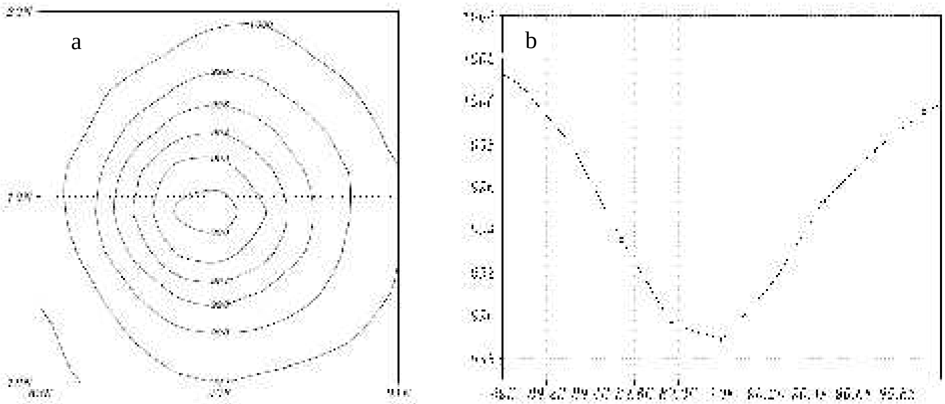

Fig. 2. (a) Distribution of model simulated MSLP (hPa) and (b) E-W sectional view of simulated MSLP at mature stage of cyclone Bijli at 0000 UTC of 18 April, 2009.

The distribution of surface wind of cyclone Bijli at 0000 UTC of 18 April, 2009 has been shown in Fig. 3(a). The figure shows that the wind field of the cyclone is highly asymmetric in the horizontal distribution. The figure also shows that the surface wind distribution is well organized indicating that it was a strong system. A strong wind band (wind speed >30 m/s) is found at a distance of around 25 km in the south of the system centre (18.9°N, 90°E) with elongation in east-west. It is noted that the strong wind is found in the south side of the system.

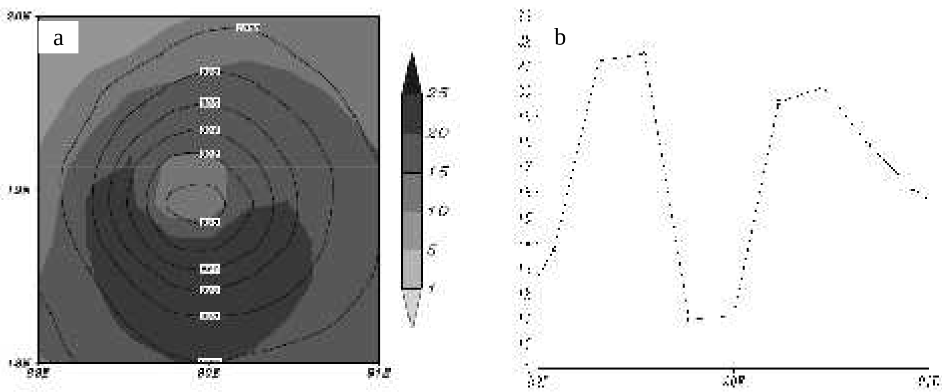

Fig. 3. (a) Distribution of model simulated surface wind (in left) and (b) north-south (N-S) sectional view of simulated surface wind (speed in m/s) at mature stage of cyclone Bijli at 0000 UTC of 18 April, 2009.

Fig. 3(b) shows the distribution of the surface wind of the cyclone Bijli along north-south section passing through its centre (18.9°N, 90°E). The figure demonstrates that a calm region is found at the eye of the system where wind speed is almost 10 m/s and maximum wind is found in the eye wall at the left side of the system centre.

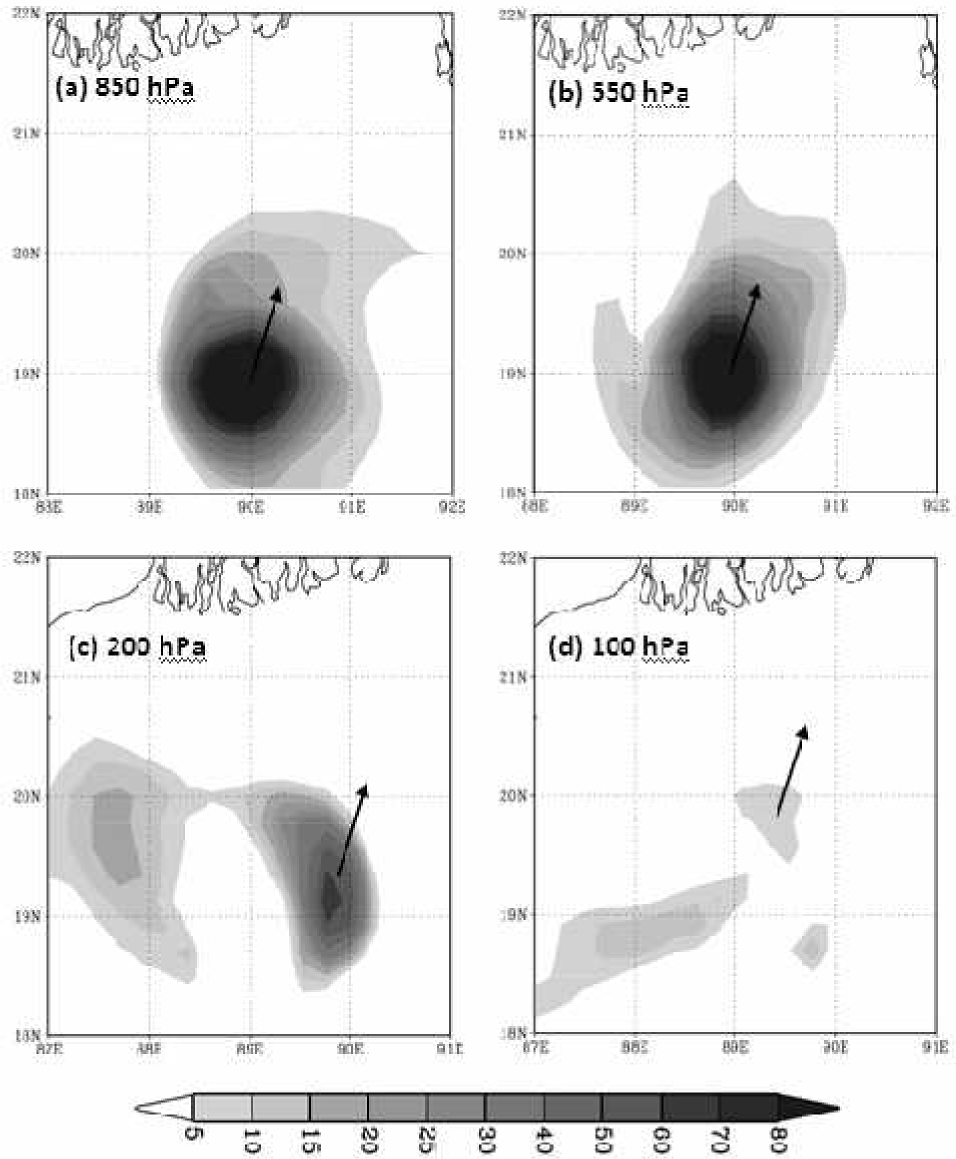

Fig. 4. Model simulated vorticity field at (a) 850 hPa, (b) 550 hPa, (c) 200 hPa, (d) 100 hPa level of cyclone Bijli at 0000 UTC of 18 April 2009 (Arrow indicates the simulated centre and direction of the system).

The horizontal distribution of the relative vorticity at 0000 UTC of 18 April, 2009 of cyclone Bijli at 850, 550, 200 and 100 hPa levels has been shown in the Fig. 6(a-d). According to the Fig. 6(a), it is seen that the vorticity is distributed with maximum value in the centre (18.9^{o}N 90^{o}E). The distribution maintains near circular pattern with some asymmetric features in the outer periphery. In 550 and 200 hPa, the strong vorticity is visible on the centre of the cyclonic system. In 100 hPa level the weak vorticity is found at the centre.

To study the tracks of selected tropical cyclones the model was run for 24, 48, 72 and 96 hrs before the landfall time. Table 2 summarizes the predicted average translational speed of selected tropical cyclone Bijli (2009) along with the corresponding observed speed. The observed average translational speed is calculated for respective model forecast hour (24, 48, 72 and 96 hrs) and also for full observed track. Observed full track average implies that the average translational speed of the Bay of Bengal cyclone is about 14 km/hr. Fig. 5 shows the time variation of model simulated and observed six hourly average translational speeds of the above cyclones. Table 2 and Fig. 5 demonstrate that in general the translational speed of the system increases as it intensifies and moves towards landfall position.

Table 2. Average translational speed of selected tropical cyclones.

Initial date/ time (UTC)	Forecast hours	Simulated average translational speed (km/hr)	Obs. translational speed (km/hr) [Respective forecast hours average]	Obs. translational SPEED (km/hr) [full track average]
13 April/1800	96	8.10	13.85	
14 April/1800	72	14	16.45	13.85
15 April/1800	48	15.9	19.5	
16 April/1800	24	19.58	26.72	

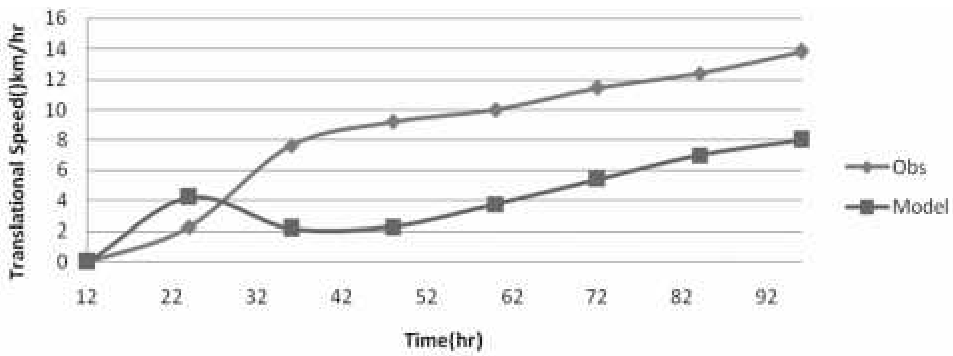

Fig. 5. Time variation of model simulated and observed 12 hourly average translational speed of cyclone Bijli beginning 1800 UTC of 13 April, 2009.

It is found from Table 2 that the simulated translational speed of Bijli is low compared with the actual speed of the system. Here 24 hrs forecasts speed is slightly less than the observed.

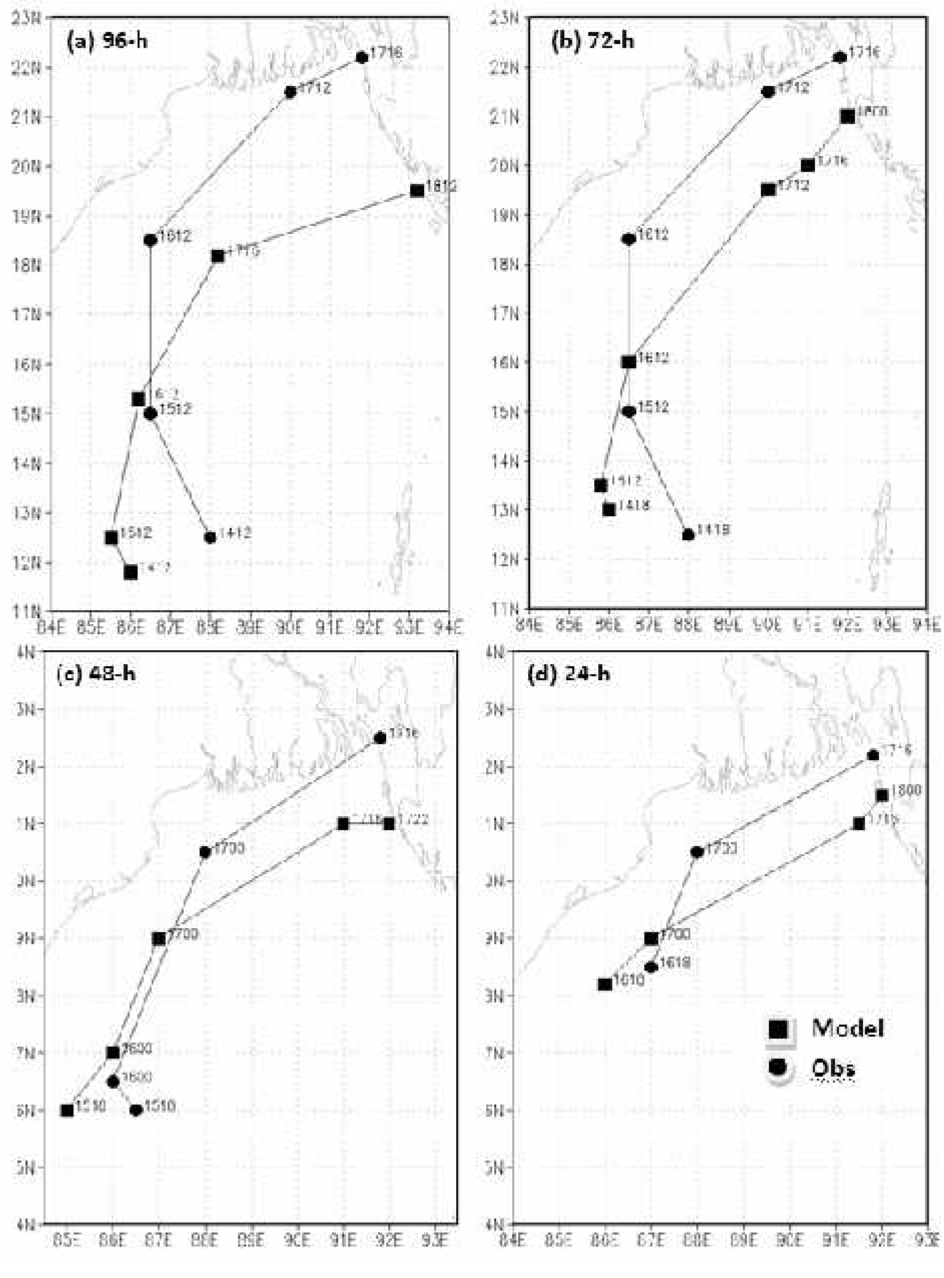

Fig. 6. Model simulated and observed track of cyclonic storm Bijli (2009), (a) 96 hrs forecast beginning 1800 UTC, 13 April, (b) 72 hrs forecast beginning 1800 UTC, 14 April, (c) 48 hrs forecast beginning 1800 UTC, 15 April and (d) 24 hrs forecast beginning 1800 UTC, 16 April.

Fig. 6 (a-d) shows 96, 72, 48 and 24 hrs forecasts track of cyclone Bijli (2009) beginning from 1800 UTC of 13, 14, 15 and 16 April, respectively. It reveals that model was capable to capture north-eastward movement in this case. The 96 and 72 hrs predicted track are almost same. Again 48 and 24 hrs are almost same but better than the previous two. It is found that the simulated landfall point of Bijli seems quite accurate with 48 and 24 hrs forecast based on 1800 UTC of 15 April and 16 April, respectively.

The model results produce an overall view that for weak system the predictions generate the direction of the motion very efficiently indicating the probable areas of the coast to be hit. However, the 24 and 48 hrs predictions show the better representation of the tracks, landfall position and landfall time.

As landfall of tropical cyclones is very important to the cyclone forecasters, the landfall position and time errors are investigated for evaluating the model performances. The results are presented in Table 3. It reveals that reducing the prediction hours with updated initial fields reduces the landfall errors. The tables show that most of the time the 24 and 48 hrs predictions exhibit low landfall position errors whereas 72 and 96 hrs predictions have comparatively high landfall position errors. There are variations in the landfall time errors. The 48 hrs predictions show low landfall time errors than that of 24, 72 and 96 hrs predictions for the selected cyclone Bijli.

It appears from the above discussion that the ARW model has high potential to forecast position and time of landfall of the Bay of Bengal cyclones with the certain amount of uncertainty. However, further studies on sensitivity experiments with model resolution, boundary layer formulation, model physics and cumulus parameterization schemes on track prediction are required for proper tuning of the model to improve the prediction accuracy and reduce landfall error. Landfall point and time error during cyclonic storm Bijli are shown in Table 3.

Table 3. Landfall point and time error during cyclonic storm Bijli.

Base date/ time (UTC)	Forecast hours	Landfall forecast		Actual landfall		Error	
		Position (Lat ^{0}N/ Lon ^{0}E)	Date/time(UTC)	Position (lat^{0}N / lon ^{0}E)	Date/time (UTC)	Difference of landfall point (km)	Time (hrs)
13/1800	96	19.5/93.2	18/1200	22.2/91.8	17/1600	337	20D
14/1800	72	21/92	18/0000	do	do	135	08D
15/1800	48	21/92.5	17/2200	do	do	154	06D
16/1800	24	21.5/92	18/0000	do	do	80	08D

D indicates delay of actual landfall time.

CONCLUSION

From the above findings the following conclusions are drawn:

(i) The formation of the first low pressure system 30 - 36 hrs ahead from its actual genesis without incorporation of any artificial vortex. It is also able to forecast the intensification of the system and is capable to predict the well-marked low 42 - 60 hrs before the formation. The model is capable to forecast the formation of the first depression 60 - 78 hrs in advance. This indicates the high and unique predictive power of ARW model for predicting the tropical cyclone formation.

(ii) The model generates a realistic structure of the tropical cyclones with high spatial details without use of any idealized vortex in the initial. This has been possible due to the higher spatial resolution of the regional model.

(iii) One of the important findings of the study is that the model has successfully predicted the tracks, recurvature and probable areas and time of landfall of the selected tropical cyclone Bijli with high accuracy even in the 72 hrs predictions.

The Bay of Bengal is a data sparse region, improvement of the meteorological network through deployment of fixed and floating data collection buoys over the Bay of Bengal will improve the initial field and thus the performance of the model will also improve.

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