

Research Article

Role of Four-Dimensional Data Assimilation on Track and Intensity of Severe Cyclonic Storms

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To examine the role of four dimensional data assimilation (FDDA) on prediction of two Severe Cyclonic Storm (Aila (May 23–26, 2009) and Jal (Nov 4–8, 2010)), four numerical experiments are performed using WRF-ARW model with three nested domains having two-way interaction and physical parameterization schemes as CPS-BMJ, MP-WSM6, and PBL-YSU. In each experiment, the model integration is started prior to the formation of depression and continued till the observed landfall. For the experiment without FDDA, NCEP-FNL data alone is used as initial and boundary conditions and for the experiments with FDDA, additional observations are used. In all the experiments, FDDA is considered only in the outer domain upto 24 hrs of integration and then the inner domain is introduced. The results are examined in terms of surface circulation, vorticity, CSLP, MSW, and surface track error. FDDA-produced surface circulation and vorticity showed well-organized structure. For the case of Aila, the surface track (maximum track error: 281 km) and landfall position ($88^{\circ}\text{E}/21.73^{\circ}\text{N}$) in FDDA experiment are predicted better than experiment without FDDA (track error: 445 km and landfall position $87.13^{\circ}\text{E}/20.37^{\circ}\text{N}$) whereas the landfall time experiment without FDDA is closer to observations (between 09 and 12 UTC of May 25) than that of experiment with FDDA (06 UTC of May 25). When CSLP and MSW are examined, the overall intensity is well predicted with FDDA experiment except near to the landfall time. For Jal cyclone, FDDA played significant role to improve the landfall position ($80.16^{\circ}\text{E}/13.67^{\circ}\text{N}$) with a time lead of ~10 hrs but other parameters remain more or less unchanged.

1. Introduction

In the last decade a total of 29 cyclones were formed in Bay of Bengal, 9 in premonsoon and 20 in postmonsoon, out of which 7 cyclones were very severe cyclonic storms (VSCS) and 6 cyclones were severe cyclonic storms (SCS). Most of these tropical cyclones formed over Bay of Bengal (BoB) region move generally in the north-west direction and cross the east coast of India. The east coast of India is known to be highly vulnerable to damage due to tropical cyclones because of the plain coastal terrain, developmental activity, and large population. Therefore it is desirable to have as much an accurate prediction as possible of the track and landfall of cyclones for effective implementation of the disaster management. Mesoscale numerical models based on well defined dynamical and physical processes have been increasingly used for the forecasting the movement and intensity of the storms.

The forecast performance of the mesoscale models critically depends on the quality of initial conditions. Typically, large scale global analyses provide the initial condition to the mesoscale models. These initial conditions have limitations, such as coarse resolution and inadequate representation of localized mesoscale features. Therefore, data assimilation techniques facilitate to combine all available past as well as current observations of the atmosphere to best define the initial state and thus to develop improved analyses (Kalnay [1]). Navon [2] has given a brief review of different data assimilation methods such as successive correction, optimum interpolation, and variational methods (3-DVAR, 4-DVAR) by highlighting their application in Numerical Weather Prediction (NWP) models. VinodKumar et al. [3] adopted four dimensional data assimilation (FDDA) and surface data assimilation to study tropical depressions over Bay of Bengal. The results suggested that improvement of monsoon

depression simulations over BoB was equivalent, or better than that of increasing the model resolution from 30 km to 10 km grid spacing. Xavier et al. [4] studied the effect of assimilated satellite and conventional data on the prediction of three monsoon depressions over India using analysis nudging with MM5 (5th generation NCAR/Penn State Mesoscale Model) and found a positive overall impact on the model performance. An analysis of the status and developments of the four-dimensional variational data assimilation for mesoscale/storm-scale applications has been provided by Park and Zupanski [5]. They presented the theoretical background and the practical issues of 4-DVAR in terms of high-resolution observations, nonlinearity and discontinuity problem, model error, errors from lateral boundary conditions, and so forth, with applications to both hydrostatic and nonhydrostatic models. One of the problems in numerical modeling of tropical cyclones is the lack of conventional observations over the oceanic regions where cyclones form and develop. Satellite observations provide a very useful data for understanding and simulation of tropical cyclones because of their high spatial coverage, repetition, and resolution. Leslie et al. [6] have shown that the track of a hurricane could be better simulated with assimilation of high temporal and spatial resolution GOES-satellite-derived wind vectors using FDDA nudging. Marshall et al. [7] using continuous assimilation procedures like nudging reported that the Scatterometer winds were able to reduce the initial position error of cyclone. Zhang et al. [8] have studied the individual impacts of a number of satellite data on winds, temperature profiles on the initialization and forecasting of the rapid weakening of Hurricane Lili 2002, using MM5. In addition to the large amount of satellite information, assimilation of dropwindsonde data deployed from surveillance aircrafts is of utmost importance in numerical forecast of tropical cyclones. A number of recent studies have reported positive impact of dropwindsonde observations on hurricane track and intensity forecasts using various models (Kim et al. [9]). Several studies on simulation of tropical cyclones with different data sources and different assimilation techniques are reported over North Indian Ocean region (e.g., Mukhopadhyay et al. [10], Sandeep et al. [11], Vinodkumar et al. [3]), and Srinivas et al. [12] did the simulation of BoB cyclone with FDDA technique using Weather Research & Forecasting (WRF) model and reported that the combination of land-based surface, upper-air observations with the satellite winds for assimilation produced better prediction than the assimilation with individual data sets). Similar studies are carried out by Srinivas et al. [13] for Jal cyclone over Bay of Bengal.

The objective of the present study is to investigate the role of FDDA analysis nudging on the track and intensity of two severe cyclonic storms Aila (May 23–26, 2009) and Jal (Nov 4–8, 2010) formed over the Bay of Bengal.

2. Brief Description of Severe Cyclonic Storms

2.1. Aila (May 23–26, 2009). According to RSMC [14], under the influence of increased low level convergence due to the onset of SW monsoon over Andaman Sea and adjoining south BoB on May 20, a low pressure area developed over

the southeast BoB on May 22 morning. Under favorable conditions, like warmer sea surface temperature (SST) and low vertical wind shear, it concentrated into depression and further into deep depression at 03 UTC of May 24 near 18°N/88.5°E. Continuing its northerly movement, on 12 UTC of May 24, it reached the cyclonic storm stage. With Central Sea Level Pressure (CSLP) of 974 hPa and Maximum Surface Winds (MWS) 29 m s⁻¹, it attained its severe cyclonic storm stage at 0600 UTC of May 25 over northwest BoB near 21.5°N/88.0°E close to Sagar Island. The system crossed West Bengal coast close to the east of Sagar Island between 0800 and 0900 UTC and immediately after landfall it had its maximum intensity with CSLP of 967 hPa and MSW as 31 m s⁻¹ (Figure 2(a)). Under the influence of cyclone Aila, widespread rain/thundershowers with scattered heavy to very heavy rainfall and isolated extremely heavy rainfall (≥25 cm) occurred over Orissa on May 25 and over West Bengal and Sikkim on May 25 and 26. The special features of the cyclone Aila are its northerly movement throughout its life period, and its rapid intensification just before the landfall. It maintained its cyclone intensity upto 15 hours after landfall.

2.2. Jal (Nov 4–8, 2010). A severe cyclone “Jal” over the BoB is the remnant of a depression which moved from the northwest Pacific Ocean to the BoB across Thailand. It concentrated into deep depression at 00 UTC of Nov 5 near 9.0°N/88.5°E and further intensified into severe cyclone at 2100 UTC of Nov 5, and lay centered around 10.0N/86E, with maximum intensity of CSLP 988 hPa and MSW 31 m s⁻¹ for 12 hrs from 12 UTC Nov 6. It weakened into a cyclonic storm at 0600 UTC of Nov 7 over southwest BoB about 250 km east-southeast of Chennai and further into a deep depression on 12 UTC of Nov 7 near 13.0°N/81°E. It crossed north Tamilnadu-south Andhra Pradesh coast, close to the north of Chennai near 13.3°N/80.3°E around 1600 UTC of Nov 7 (Figure 4(a)). It continued to move west-northwestwards, and further weakened into a depression at 0300 UTC and into a well marked low pressure area over Rayalseema and adjoining south interior Karnataka at 0600 UTC of Nov 8. Rainfall occurred at most places with heavy to very heavy fall at a few places over north Tamil Nadu, Puducherry, coastal Andhra Pradesh, Rayalseema, south Interior Karnataka, and coastal Karnataka. The salient feature of the cyclone Jal is that it weakened into deep depression over the sea before the landfall (RSMC [15]).

3. Model Description and Experimental Design

3.1. WRF Model. The non-hydrostatic fully compressible Advanced Research Weather Research and Forecasting (WRF-ARW) model developed by National Center for Atmospheric Research (NCAR) is suitable for a broad range of applications, such as idealized simulations, parameterization research, data-assimilation research, and real-time numerical weather prediction (NWP). In the present study, cumulus parameterization scheme (CPS) such as Betts-Miller-Janjic (BMJ), Microphysics Parameterization Scheme (MPS-WRF Single Moment (WSM) 6-class, and Planetary Boundary

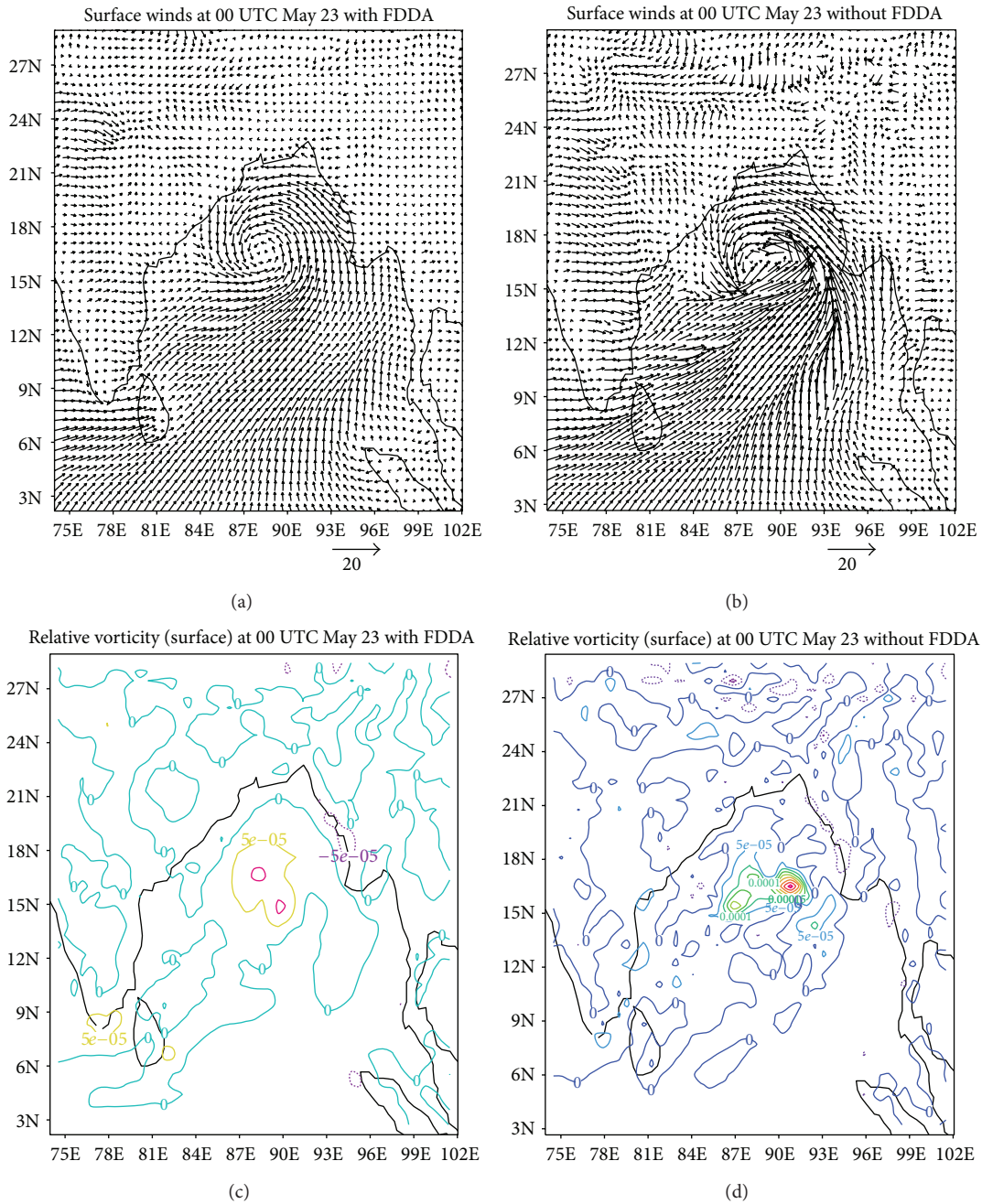


FIGURE 1: Upper panel: Surface winds at 00 UTC of May 23, 2009 (a) with FDDA and (b) without FDDA for Aila cyclone. Lower panel: surface relative vorticity at 00 UTC of May 23, 2009 (c) with FDDA (d) without FDDA for Aila cyclone.

Layer (PBL) scheme—Yonsei University (YSU) are considered and kept same for all the model runs.

The detailed descriptions of model formulation, horizontal and vertical discretization, and time integration schemes used are given in Skamarock et al. [16].

3.2. Experimental Design. WRF model version 3.2.1 with three nested domains (60, 20, and 6.6 km) having two-way interaction is used in the present study. The model topography for the 60, 20, and 6.6 km domain regions are obtained

from the USGS topography data at $10'$, $5'$, and $2'$ resolutions. Initial and boundary conditions are used from FNL (Final reanalysis) data of $1^\circ \times 1^\circ$ resolutions and Real Time Global (RTG) SST. For the experiments without FDDA, NCEP-FNL data alone is used as initial and boundary conditions and for the experiments with FDDA, additional observations (from NCEP ADP Global Upper Air and Surface data which include radiosondes, pilot balloons, aircraft, and satellite data) are used. In all the experiments, FDDA is considered only in the outer domain for a 24 h preforecast period and

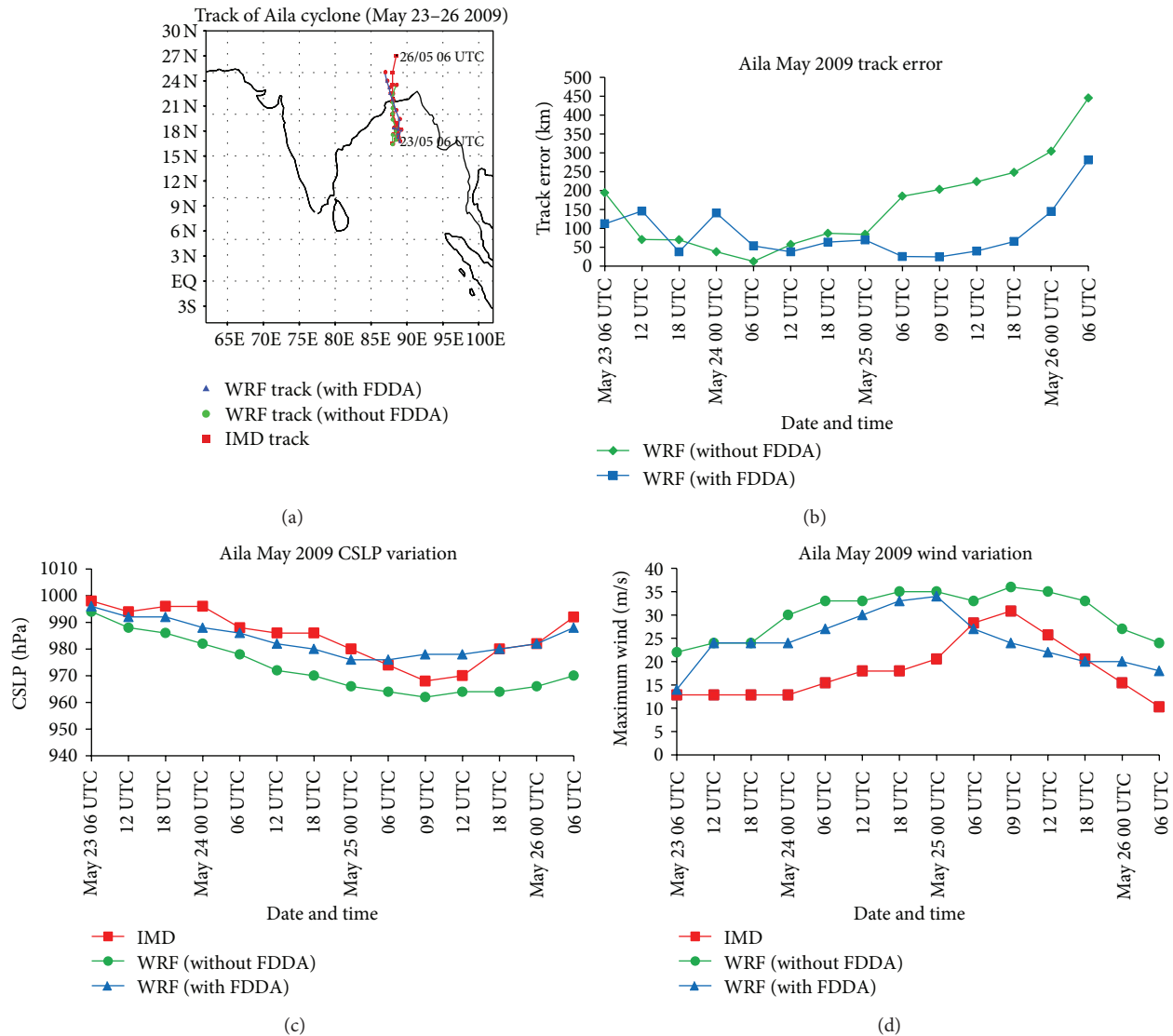


FIGURE 2: (a) Track of Aila cyclone, (b) variation of track error, (c) variation of CSLP, and (d) variation of maximum surface wind for Aila cyclone.

then the inner domain of 20 km is introduced. FDDA is a continuous data assimilation technique in which the model state is relaxed toward the observed state by augmenting some of the prognostic equations with forcing terms based on the difference between the observed state and the model state. Analysis nudging method is used in this work, in which the model solution is nudged toward time- and space-interpolated analyses using a point-by-point relaxation term (Stauffer and Seaman [17, 18], Stauffer et al. [19]).

4. Results and Discussion

The case of Aila (May 23–26, 2009) cyclone, during pre-monsoon period, is considered. The model integration is started from 00 UTC of May 22, 2009 which corresponds to the low pressure area state in the observation. In FDDA experiment, nudging technique is applied for a pre-forecast

period of 24 hrs and then the free forecast is observed. For other experiment, it is a control run without FDDA. After 24 hrs of model integration (at 00U TC of May 23, 2009), surface winds are observed for with and without FDDA experiments as shown in Figures 1(a) and 1(b). The surface winds are seen to be well organized for FDDA experiment whereas the circulation fields with wide area and with disturbed vortex are clearly seen in other experiment. The magnitude of winds is found to be larger for other experiment but it is reduced in FDDA experiment (Figures 1(a) and 1(b)). To see the wind fields in more detail, the surface relative vorticity fields are plotted at the same time in Figures 1(c) and 1(d). The decrease in the cyclonic vorticity values ($10e^{-5}$) is clearly seen when compared with the vorticity values ($35e^{-5}$) in other experiment. Also the maximum cyclonic vorticity center seems to be wider in other experiment. In short, the strength of relative vorticity is found

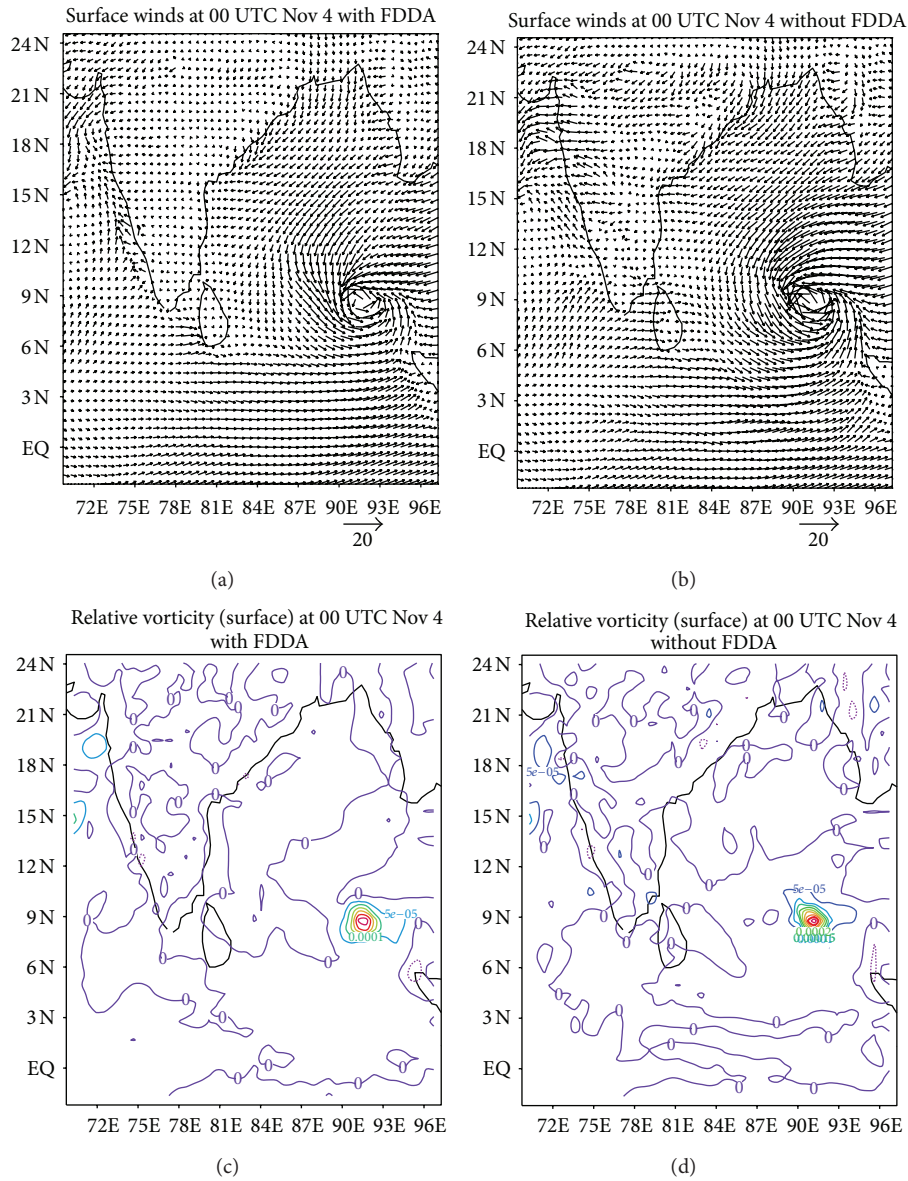


FIGURE 3: Upper panel: surface winds at 00 UTC of Nov 4 2010 (a) with FDDA and (b) without FDDA for Jal cyclone. Lower panel: surface relative vorticity at 00 UTC of Nov 4 2010 (c) with FDDA and (d) without FDDA for Jal cyclone.

to be weakened (Figures 1(c) and 1(d)). The observed and model simulated surface tracks are shown in Figure 2(a). Both the experiments show the overlapped track on the India Meteorological Department (IMD) observed track. In order to understand it quantitatively, the time evolution of track error for every 6 hrs is plotted in Figure 2(b). For without FDDA experiment, initially track error is found to be decreased with 12 km as its minimum value upto 06 UTC May 24 and thereafter it continuously increases and reaches ~450 km. In case of FDDA experiment, initially it appears that the track error is increasing upto 06 UTC May 24, but thereafter it is lower than 50 km. This indicates that the error in the landfall is low when FDDA technique is applied. The intercomparison between the different parameters for both cyclones is summarized in Table 1. As landfall position

and landfall time are very important for the mitigation purpose, for FDDA experiment landfall time is 2-3 hrs prior to the observed landfall and landfall position is found to be 25 km away from the observed position. This error in landfall time and position is more in other experiments. Similarly the intensity of Aila is represented by Central Sea Level Pressure (CSLP) and Maximum Surface Wind (MSW) and is shown in Figures 2(c) and 2(d). Simulated intensity (CSLP) is underestimated for FDDA experiment while it is overestimated for other experiments. Careful observation indicates that simulated intensity with FDDA experiment is very close to the observations over the oceanic region and it is underestimated thereafter. But MSW values are relatively closer to the observations for FDDA experiment. This change in the intensity values is maybe due to the modification

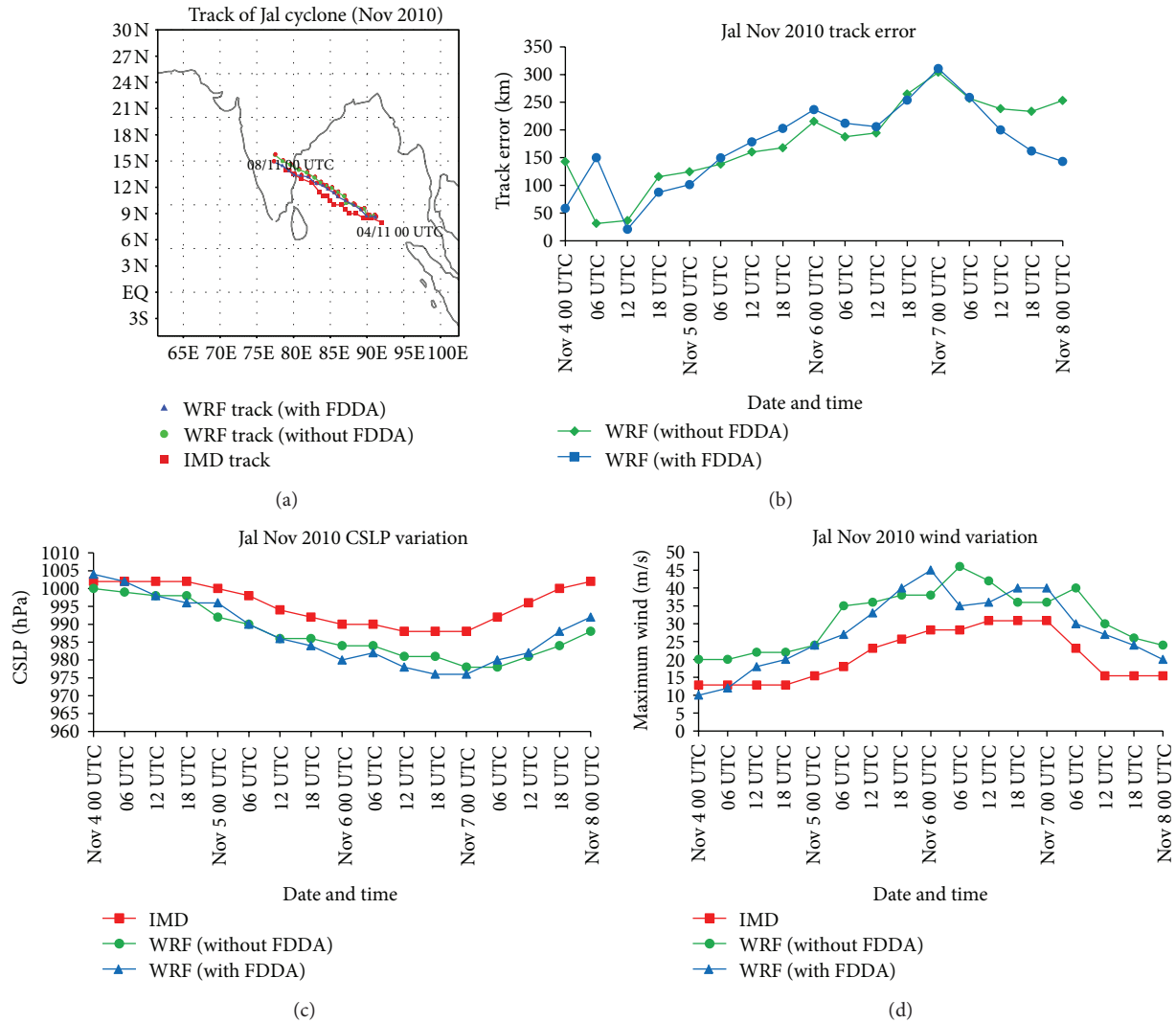


FIGURE 4: (a) Track of Jal cyclone, (b) variation of track error, (c) variation of CSLP, (d) variation of maximum surface wind for Jal cyclone.

TABLE 1: Comparison of observed parameters with simulated parameters for cyclone Aila and Jal.

Cyclone	Experiment	Landfall time	Landfall Position	CSLP (hPa)	MSW (m/s)
Aila	Observed (IMD)	08 and 09 UTC of May 25	88E/21.8N	968	30.84
	WRF with FDDA	06 UTC of May 25 2009	88E/21.73N	976	34
	Without FDDA	Bet. 9–12 UTC of May 25	87.13E/20.37N	962	36
Jal	Observed (IMD)	Near 16 UTC of Nov. 7	80.2E/13.3N	988	30.84
	WRF with FDDA	Near 06 UTC of Nov. 7	80.16E/13.67N	976	40
	Without FDDA	Bet. 6–12 UTC of Nov. 7	79.54E/14.6N	978	40

or change in the initial wind fields caused by the FDDA technique (Figures 1(a) and 1(b)).

In order to verify the results, another case of Post monsoon severe cyclone Jal (Nov 4–8, 2010) is considered. For Jal cyclone also two experiments—one with FDDA technique and another without FDDA—are carried out. The FDDA nudging is applied for pre-forecast period of 24 hrs (upto 00 UTC Nov 4) and then free forecast starts. The surface wind

fields after 24 hrs of integration, that is, at 00 UTC of Nov 4 are shown in Figures 3(a) and 3(b). For FDDA experiment, surface circulation is found to be well organized whereas the vortex is found to be narrow in other experiments. The magnitude of surface wind fields does not show remarkable change in both the experiments. But the slight reduction in the magnitude of relative vorticity is clearly depicted from Figures 3(c) and 3(d). The IMD observed surface track and

model simulated tracks are shown in Figure 4(a). Initially, tracks of both experiments are overlapped on each other and remain more or less at the same distance from the observed track. But when cyclone approaches towards the land, the track in FDDA experiment lies very close to the observed track. This can be clearly seen from the track error plot (Figure 4(b)). The track error is found to be reduced after simulated landfall for FDDA experiment. Landfall position is simulated accurately (track error ~ 37 km at the landfall point) with FDDA experiment when compared with other experiment. Both experiments show early landfall but landfall in case of experiment without FDDA is close to the observed landfall. When the intensity (CSLP and MSW) is compared with the observed intensity, it is overestimated in both experiments and remains more or less unchanged (Figures 4(c) and 4(d)). The very small change in the landfall position, landfall time, intensity, and the track error may be associated with the small changes in the initial fields especially in the wind fields.

5. Conclusions

The analysis nudging technique applied in the research work shows improvement in the wind fields and thus improved and well organized vortex for the pre-monsoon cyclone Aila and no remarkable improvement is noticed for the post monsoon cyclone Jal. The track, intensity, landfall position, and time for Aila are very close to the observations in the FDDA experiment. For Jal cyclone, FDDA played significant role to improve the landfall position ($80.16^\circ\text{E}/13.67^\circ\text{N}$) with a time lead of ~ 10 hrs but other parameters remain more or less unchanged. It needs to be verified with a greater number of pre- and post monsoon cyclone cases.

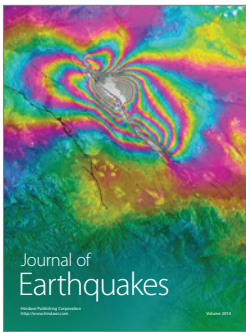
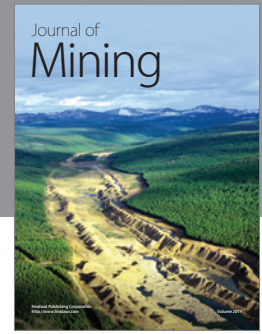
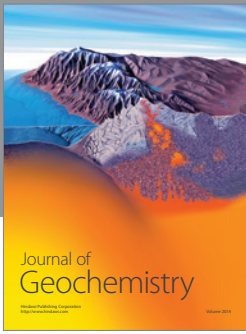
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