Article

Prediction of Bay of Bengal Extremely Severe Cyclonic Storm "Fani" Using Moving Nested Domain

Kuvar Satya Singh [1,2,*], Sridhara Nayak [3,*], Suman Maity [4], Hara Prasad Nayak [5] and Soma Dutta[6]

[1]Center for Disaster Mitigation and Management (CDMM), Vellore Institute of Technology, Vellore 632014, India; kuvarsatya.singh@vit.ac.in
[2]Department of Mathematics School of Advanced Sciences (SAS), Vellore Institute of Technology, Vellore 632014, India; kuvarsatya.singh@vit.ac.in
[3]Earth Science Center, Japan Meteorological Corporation Limited, Osaka 5300011, Japan; nayak.sridhara@n-kishou.co.jp
[4]Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokohama 236-0001, Japan; sumanmaity@jamstec.go.jp
[5]Department of Geography, University of California Los Angeles, CA, USA; hpnayak@ucla.edu
[6]Farmneed Agri Business Private Limited, Salt Lake 700091, India; soma.d@farmneed.com
* Correspondence: kuvarsatya.singh@vit.ac.in (K.S.S.); nayak.sridhara@n-kishou.co.jp (S. N.).

Abstract: The prediction of an extremely severe cyclonic storm (ESCS) is one of the challenging issues due to increasing intensity and its life period. In this study, an ESCS Fani that developed over Bay of Bengal region during 27 April - 4May, 2019 and made landfall over Odisha coast of India is investigated to forecast the storm track, intensity and structure. Two numerical experiments (changing two air-sea flux parameterization schemes; namely FLUX-1 and FLUX-2) are conducted with the Advanced Research version of the Weather Research and Forecasting (ARW-WRF) model by using a moving nest with fine horizontal resolution about 3 km. The high resolution (25 km) NCEP operational Global Forecast System (GFS) analysis and forecast datasets are used to derive the initial and boundary conditions, the ARW model initialized at 00 UTC 29 April 2019 and forecasted for 108 hours. The forecasted track and intensity of Fani is validated with available India Meteorological Department (IMD) best-fit track datasets. Result shows that the track, landfall (position and time) and intensity in terms of minimum sea level pressure (MSLP) and maximum surface wind (MSW) of the storm is well predicted in the moving nested domain of the WRF model using FLUX-1 experiment. The track forecast errors on day-1 to day-4 are ~ 47 km, 123 km, 96 km, and 27 km in FLUX-1 and ~54 km, 142 km, 152 km and 166 km in Flux-2 respectively. The intensity is better predicted in FLUX-1 during the first 60 h followed by FLUX -2 for the remaining period. The structure in terms of relative humidity, water vapor, maximum reflectivity and temperature anomaly of the storm is also discussed and compared with available satellite and Doppler Weather Radar observations.

Keywords: WRF model; Moving-nest; Fani; Bay of Bengal; Wind Speed

1. Introduction

The number of intense tropical cyclones has increased in different regions [1-3], and are expected to become much intense because of global warming [4-8]. The life-period and intensity in terms of maximum wind speed of the extremely severe cyclonic storms (ESCSs) over the Bay of Bengal region are increasing [9]. Several studies claimed that the Indian sub-continent is enormously vulnerable due to these intense tropical cyclones [10-13]. The risk over the coastal regions of the North Indian Ocean is also increasing due to increased population density. Hence, for socio-economic inferences, it is necessary and necessary to provide accurate forecasts for disaster preparedness. Also, the destructive potential due to intense cyclones becomes significantly higher when these intense tropical cyclones make landfall with higher intensity. Hence, the forecast accuracy of the intense cyclone is a necessity and challenging. However, in the past few decades a significant

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0536.v1

improvement has been observed in the forecast of intense tropical cyclones over the North Indian Ocean. This improvement due to the high-resolution atmospheric modeling system [14-16] with improved physical processes [17-20], advanced data assimilation techniques including good quality of observations [21-32]. Therefore, a modeling study is very important in a high resolution to forecast the intensity of the ESCS over Bay of Bengal region in an increasing intensity and life-period.

Several studies over the North Indian Ocean have brought attention to the prediction of tropical cyclones using atmospheric models in terms of the impact of model resolution, physical processes, and assimilation of different observations for the prediction of the track, intensity and structure of the intense storms in a static nested domain. Due to the availability of moving vortex platform in ARW-WRF model which reduces the computation cost during simulation, hence an extremely severe cyclonic storms which has a longer life period like a Fani cyclone that developed in 2019 with a period of more than 8 days need to be tested. Therefore, it is an important perspective to develop an understanding of the ARW-WRF model over the North Indian Ocean in a moving vortex platform for the forecast of ESCS. Therefore, an attempt has been made to study the forecast of track, intensity and structure at the high resolution of Fani. The study is systematized as follows: initially, it covers a brief description of Fani, the introduction section along with literature review. A brief model description along with data and methodology are presented in Section 3. The results from moving nested domain (finer domain 3 km horizontal resolution) of different experiments are presented in Section 4, and conclusions in the last section.

2. Case Study and Methodology

2.1. Brief description of cyclone Fani

Fani was a pre-monsoon storm that originated over the Bay of Bengal region in the last week of April 2019. The storm intensified into a cyclonic storm at 0600 UTC on 27 April 2019 and further intensity increased into a severe storm at 1200 UTC on 29 April with a minimum central pressure (MCP) of about 986 hPa and maximum surface wind (MSW) was about 55 knots. In the next 9 hours, the storm became a very severe cyclonic storm with MSW of about 65 knots. At 1200 UTC on 30 April the storm reached the stage of ESCS and Fani reached its maximum intensity with an MWS of about 115 knots. The storm crossed the Odisha coast near Puri between 0230 to 0430 UTC on 3rd May 2019. Then it continues to move towards West Bengal and weakens over Bangladesh and Central Assam. The observed track of the ESCS from the India Meteorological Department (IMD) was presented in Figure 1. The main salient features of Fani is as follows:

a. It was considered one of the longest (about 8 days 9 hours) tropical cyclones in the history of the North Indian Ocean [9] and the 10th most severe cyclone in the month of May in the last 52 years [33]. It developed near the equator, which is very rare over the north Indian Ocean.

b. The ESCS observed under rapid intensification (wind speed changes more than 30 knots within 24 h duration) during 30 April 2019 and Fani cyclone reached its maximum intensity in terms of MSW about 115 knots and MCP about 932 hPa whereas, the observed pressure drop was 66 hPa (Figure 2).

c. During the landfall the cyclone Fani was in the stage of ESCS (wind speed more than 90 knots) and hence caused heavy rainfall, strong winds leading to damage of structure over Odisha coast.

d. It affected about 89 fatalities, the projected economic loss was more than 8.1 billion US dollars and affected areas were Odisha, West Bengal, Andhra Pradesh, East India, and Bangladesh.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0536.v1

e. The cyclone Fani was considered one of the three worst storms in the past 150 years that made landfall to the Odisha coast with massive financial and social impact [34].

2.2. Data and Methodology

In the section, a brief overview of the Weather Research and Forecasting (WRF) modeling system, the dataset used for numerical experiments, and methodology are presented. In the study, the advanced core of WRF (ARW-WRF) model version 4.2.2 is used with the vortex following option available in the model. This option is more suitable for cyclone forecast if a well-organized cyclonic vortex is observed over the ocean. The ARW model can be used in a parallel computing environment, with wide applications of scientific problems with complex physical processes and having the flexibility of retaining spatial and temporal scales. The physical processes used in the study are Kain-Fritsch [35] for cumulus, the Lin [36] for microphysics, Yonsei University [37] for PBL scheme, Rapid Radiative Transfer Model RRTM [38] and Dudhia's scheme [39] for shortwave radiation. A model configuration such as the model domain, dynamics, horizontal resolution and other parameters in the modeling system used in the present study was adapted from previous study [28]. More details on the model configuration used in the study are shown in Table 1.

Table 1: WRF Model configuration used in the study

Dynamical core	Non-Hydrostatic, WRF-ARW (version 4.2)
Initial condition	GFS analysis (0.25º x 0.25º)
Lateral boundary conditions	GFS forecast (0.25º x 0.25º) 3 hourly
Model Resolution	15 km × 15 km (D1; fixed domain) and 3 km × 3 km (D2; moving nested domain)
Model time steps	75 seconds (D1) and 15 seconds (D2)
Vertical levels	51
Cumulus Parameterization	KF [used for outer domain only; 35]
Microphysics	Lin [36]
PBL scheme	YSU scheme [37]
Short and Long wave radiation	RRTM [38], Dudhia [39]
Surface layer	Noah Land Surface model [40]
Enthalpy Coefficient	**FLUX-1** experiment [Donelan Cd (drag coefficient for momentum) + constant Z_{0q} for alternative Ck (exchange coefficient for temp and moisture)] **FLUX-2** experiment [Donelan Cd + Garratt Ck] Garratt formulation, slightly different forms for heat and moisture.
Number of grids points	232×265 (D1) and 326×321 (D2)
Forecast length and initialization	4 days 12 hours, 0000 UTC of 29 April 2019
Vortex Interval	15 minutes
Track Level	850 hPa

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0536.v1

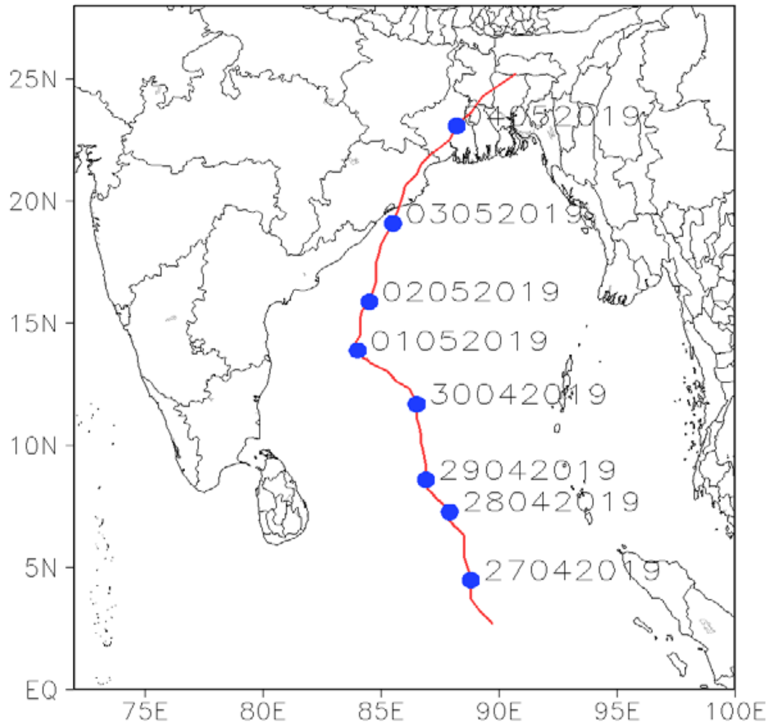


Figure 1: Life period of the cyclone FANI 2019 observed from IMD best-fit track.

In order to investigate the prediction skill of Fani, the model was initialized at 0000 UTC on 29 April 2019 and forecasted up to 1200 UTC on 03 May 2019. The initial and boundary conditions for model integration were derived from the NCEP-GFS analysis and forecast datasets at 0.25º x 0.25º resolution respectively and time-varying boundary conditions were updated at every 6 hours interval. The land information details are taken from the United States Geological Survey. Two nested domains 15 km and 3 km horizontal resolutions are used for simulations, where the second domain (finer domain) is considered as a moving nest (Figure 3). In the outer domain (15 km resolution) the cumulus convection activated and its 1/5th ratio for the inner domain (3 km resolution) the cumulus convection kept off. Two numerical experiments were accomplished by using two different air-sea flux parameterization schemes [two experiments using varying enthalpy coefficients by suggesting ISFTCFLX equals to 1 and 2, where experiments are referred to as FLUX-1, and FLUX-2, respectively] in the ARW model. These schemes specially designed for the application of cyclone forecast involving alternative Ck (exchange coefficient for temp and moisture), Cd (drag coefficient for momentum). Further, the model results were compared with the India Meteorological Department (IMD) best-fit track datasets, satellite observation and Doppler Weather Radar (DWR) and Visakhapatnam.

 doi:10.20944/preprints202208.0536.v1

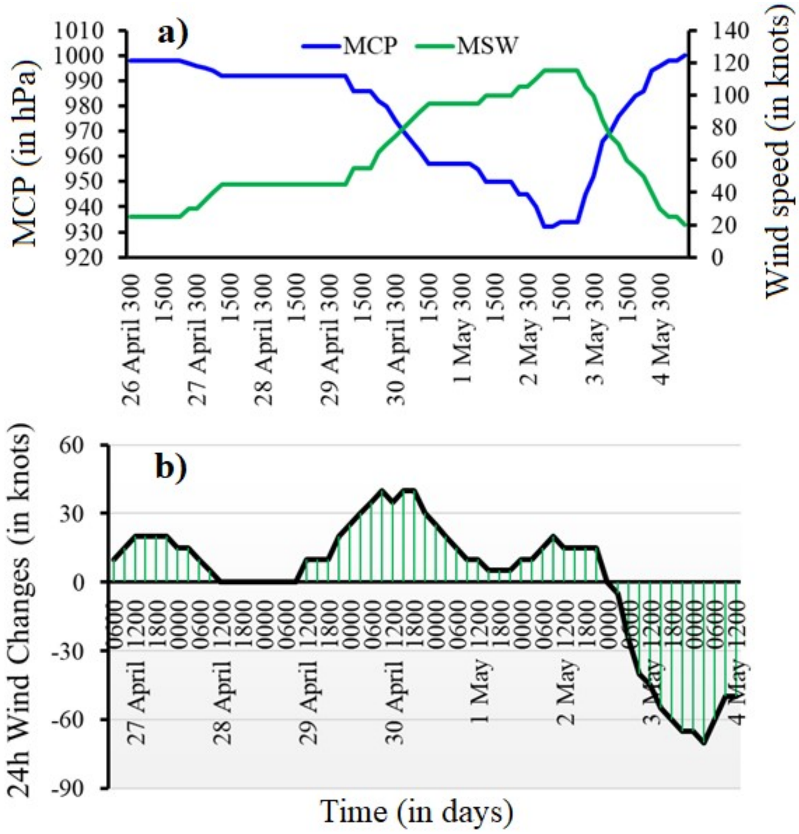


Figure 2: a) MCP and MSW of the ESCS FANI 2019 during their life-period and b) rapid intensification (RI; wind speed more than 30 knots within 24 hours) observed from IMD best-fit track.

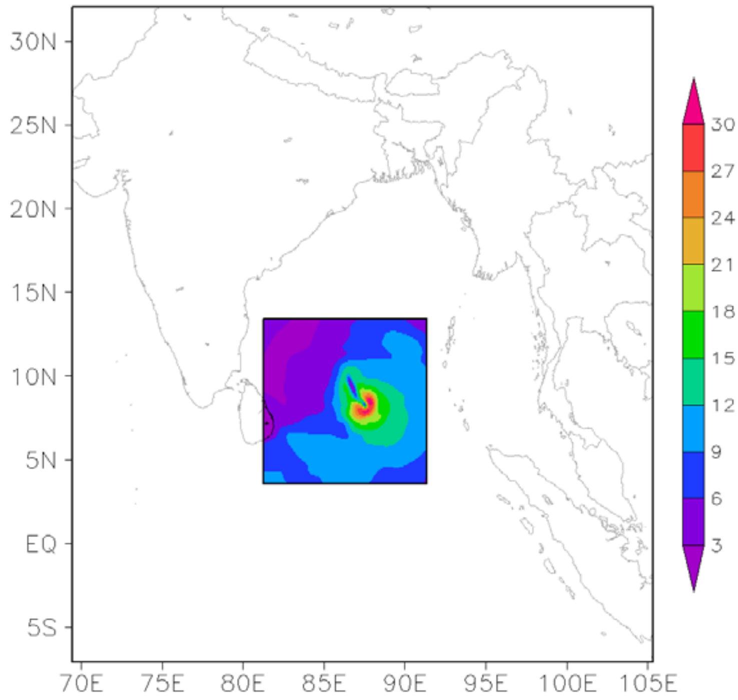


Figure 3: Double nested model domains (15 km and 3km) with inner domain is taken as moving nest, the shaded region shows the wind field (in m/s) during initialization at 0000 UTC on 29 April 2019.

 doi:10.20944/preprints202208.0536.v1

3. Results and Discussions

The impact of air-sea flux parameterization schemes on the ARW model for prediction of Fani 2019 over the Bay of Bengal region under moving nested domain platforms are analyzed. The study of the objective is to provide a better forecast of Fani in terms of track, intensity, and structure in a moving nested domain using a high-resolution model (3 km horizontal resolution). In the first section, the forecasted results from the experiments are compared with available IMD best-fit track datasets in terms of movement of the storm, maximum surface wind speed, minimum central pressure and landfall. In the second section, model forecasted results maximum reflectivity was compared with available Doppler weather radar (DWR) observations obtained from the IMD Visakhapatnam, relative humidity is compared with ERA-5 Global datasets, water vapor and temperature anomaly are compared with available satellite observations.

3.1. Forecast on track and intensity

The forecasted tracks of Fani using FLUX-1 and FLUX-2 experiments along with IMD best-fit track at every 3 hours intervals is presented in Figure 4 and their corresponding track errors is also presented in the section. It is apparent from the outcomes that the predicted storm track was comparatively better in FLUX-1 experiments as compared to FLUX-2 experiments. It is observed that movement of FLUX-1 experiment is comparable with IMD best-fit track and faster than FLUX-2 experiment. Whereas, on the third and fourth day the movement of Fani was slower in the FLUX-2 experiment. The calculated track errors at 24 h, 48 h, 72 h, and 96 h are 47 km, 123 km, 96 km, and 27 km in FLUX-1 experiment, whereas, this error was about 54 km, 142 km, 152 km and 166 km in FLUX-2 experiment respectively.

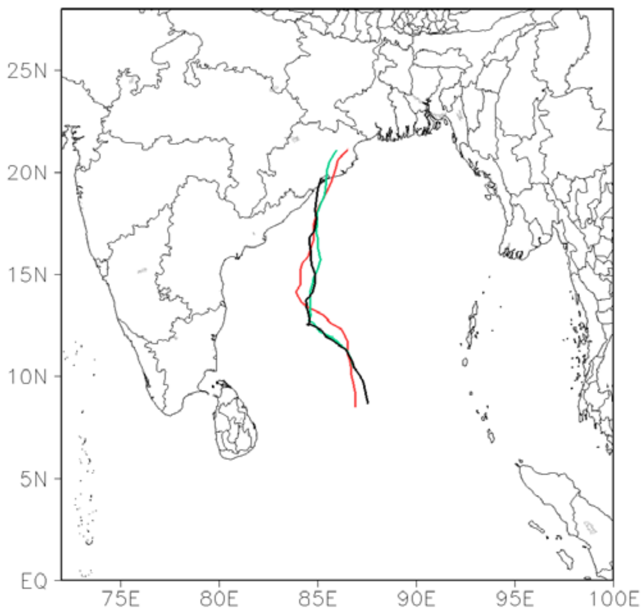


Figure 4: Model simulated tracks from FLUX-1 (green colour line), FLUX-2 (black colour line) experiments along with IMD best-fit track (red colour line) at every 3 hours intervals.

 doi:10.20944/preprints202208.0536.v1

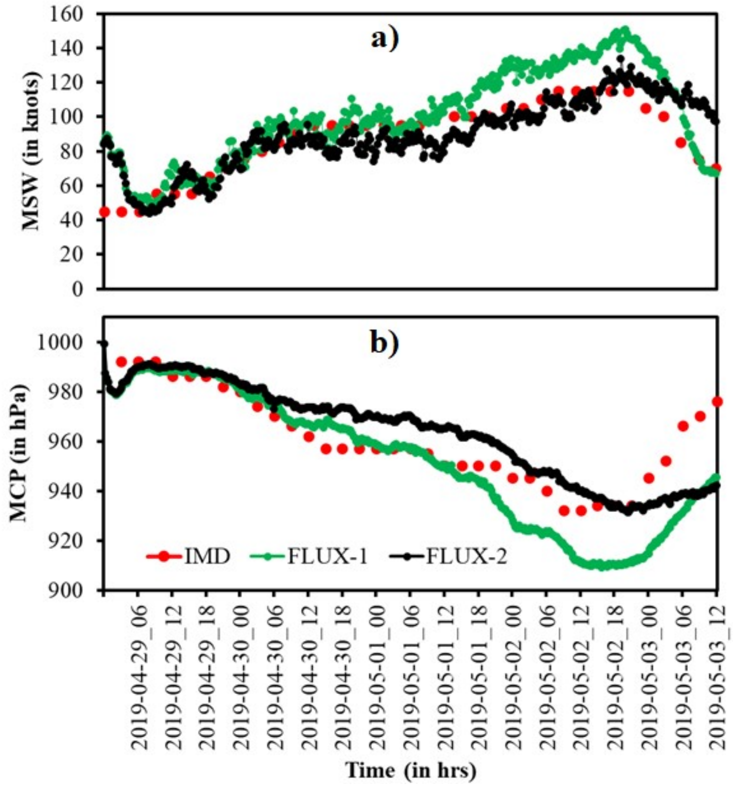


Figure 5: Model simulated intensity from FLUX-1 and FLUX-2 experiments in terms of MCP (in hPa) and MSW (in knots) along with IMD best-fit track dataset.

Based on model simulation results Fani crossed the coastal state of Odisha near Puri district at 0300 UTC on 3rd May 2019 in FLUX-1 experiment and 09 UTC on 3rd May 2019 in FLUX-2 experiment, whereas observations show that storm crossed Puri coast at 0300 UTC on 3rd May 2019. This suggests that landfall time of the storm exactly matches with the FLUX-1 experiment and having 6 hours delayed due to the slower movement of the storm in FLUX-2 experiment. It is also found that the landfall location error was about 37 km and 102 km towards the left of the observed track in FLUX-1 and FLUX-2 experiments respectively. Overall, it was concluded that the forecasted track of the storm Fani is well predicted in terms of movement and landfall (both in terms of time and location) in FLUX-1 experiment under the moving nested domain in a 3 km horizontal resolution compared to the FLUX-2 experiment.

The time evolution of intensity of Fani in terms of maximum surface wind speed (MSW) and minimum central pressure (MCP) obtained from simulations and IMD best-fit track is revealed in Figure 5. It is important to note that the model data was taken at every 15 minutes intervals and observation was taken at every 3 hourly intervals. From the figure it is noticed that the first 60 hours forecast was better in FLUX-1 experiment and after that intensity forecast was better in FLUX-2 experiment in terms of MCP and MSW. Whereas it was also found that intensification and dissipation pattern was well captured in FLUX-1 experiment as compared to the FLIX-2 experiment. The absolute intensity error in terms of MCP and MSW at every 12 hours interval is also calculated and presented in Figure 6. Results show that day-1 to day-4 the MCP error was about 1 hPa, 1 hPa, 17 hPa, and 30 hPa for FLUX-1 experiment and 3 hPa, 12 hPa, 9 hPa, and 11 hPa for FLUX-2 experiment respectively, whereas the MSW error was about 1 knot, 3 knots, 27 knots and 27 knots for FLUX-1 and 1 knot, 13 knots, 5 knots and 11 knots for FLUX-2. These results suggested that after 60 hours during intense stage in FLUX-1 experiment the predicted MCP and MSW are overestimated and hence indicated higher error in the simulation. It is also

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0536.v1

observed that the initial errors in MSW and MCP are more. These forecasted and initial errors need to improve through using other physical processes (PBL, microphysics, and cumulus) and data assimilation technique respectively under the moving nested platform.

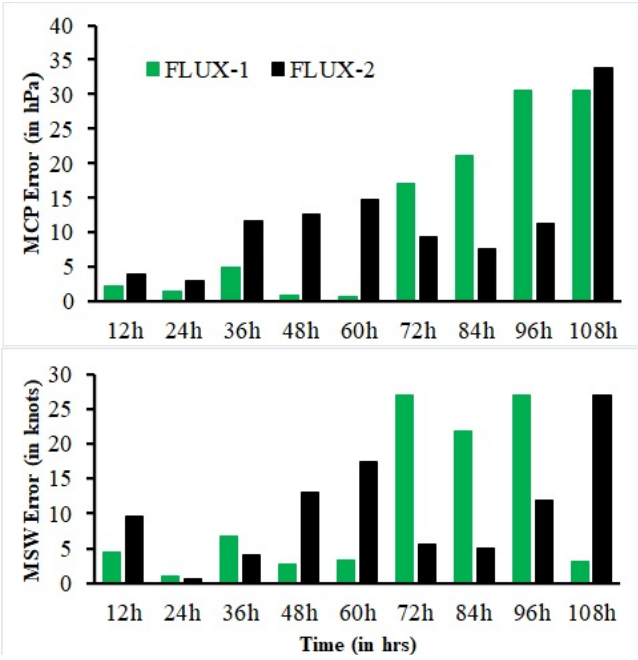


Figure 6: Simulated intensity errors from FLUX-1 and FLUX-2 experiments in terms of MCP (in hPa) and MSW (in knots).

3.2. Performance of model on forecast of Storm Structure

Time/height cross section of relative humidity (in %) obtained from model simulations using 15 km horizontal resolution (outer domain) is compared with ERA-5 reanalysis datasets with 25 km resolution (Figure 7) and is calculated area average between 78ºE to 93ºE and 2ºN to 24ºN in the active region. The simulated relative humidity from both experiments had a similar pattern during the entire simulation period with a minor difference in magnitude at different heights. The lower level humidity up to 900 hPa in both experiments well matches in terms of pattern but slightly higher magnitude in model forecast compared with ERA-5 reanalysis datasets. It is also observed that the simulated middle level relative humidity between 700 hPa to 500 hPa plays important role in the intensification of the storm [41-43] and well correlated with predicted intensity of the storm. Whereas the maximum relative humidity is observed in the simulations during 1200 UTC of 30 April to 1200 UTC of 2nd May 2019. During this time period a similar pattern was observed in ERA-5 datasets but in the lower level between 900 hPa to 600 hPa. The results from model simulations and previous studies suggested that the forecasted maximum intensity of the storm depends on the mid-level relative humidity. Figure 8 shows the structure of water vapor obtained from satellite observation and model simulated water vapor mixing ratios at 0000 UTC on 3rd May 2019. The structure in terms of the vortex and eye of the storm were simulated in the FLUX-1 and FLUX-2 experiments. The location of the centre in terms of the eye of Fani is slightly better predicted in the FLUX-1 experiment, and this was due to the better forecast of the track in the FLUX-1 experiment compared to the FLUX-2 experiment. Overall, it is concluded that the FLUX-1 experiment provides the better forecast of structure of Fani 2019 over the Bay of Bengal.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0536.v1

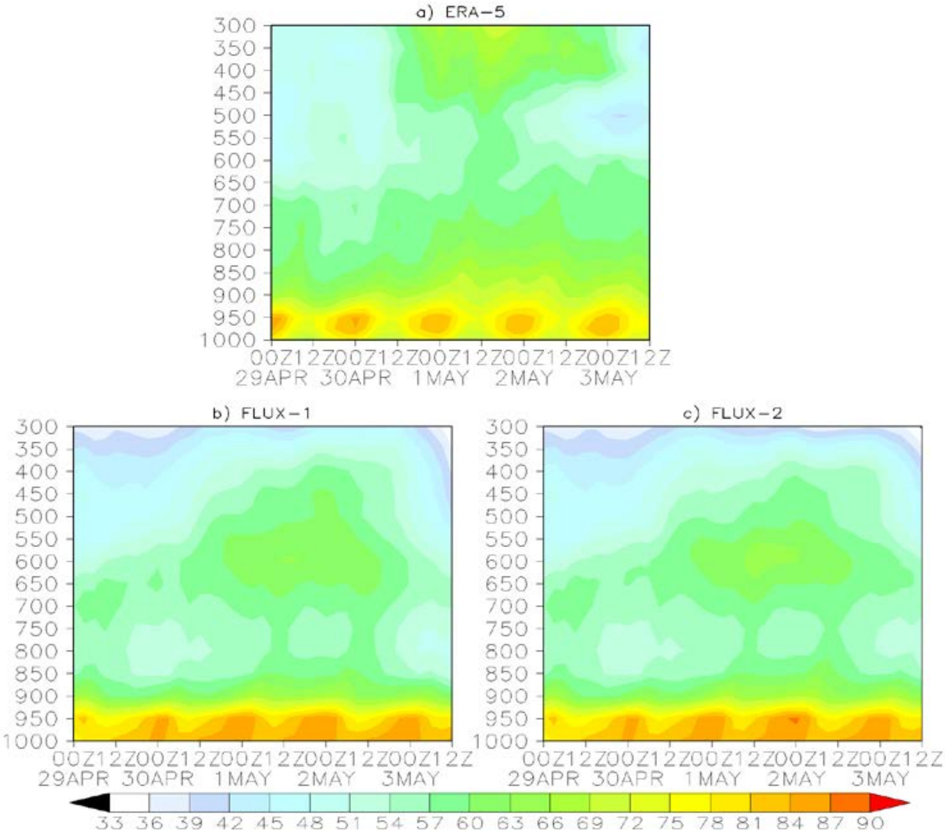
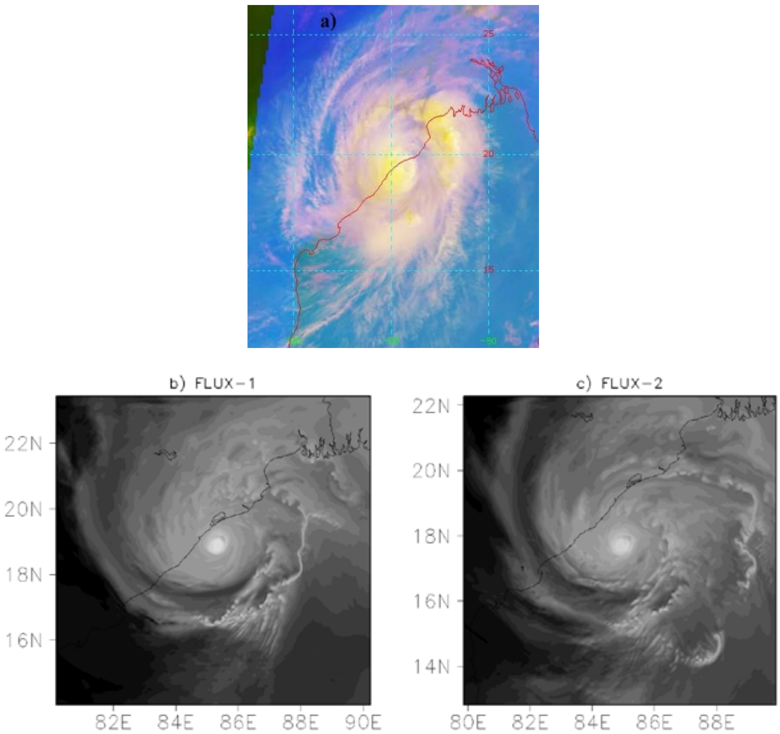


Figure 7: Area average relative humidity (in %) in the active region (longitude from 78ºE to 93ºE and latitude from 2ºN to 24ºN) obtained from a) ERA-5 reanalysis datasets b) FLUX-1 experiment and c) FLUX-2 experiment.



Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0536.v1

Figure 8: Structure of Water vapor content about 0000 UTC on 3rd May 2019 obtained from a) Satellite observation, b) FLUX-1 experiment and c) FLUX-2 experiment.

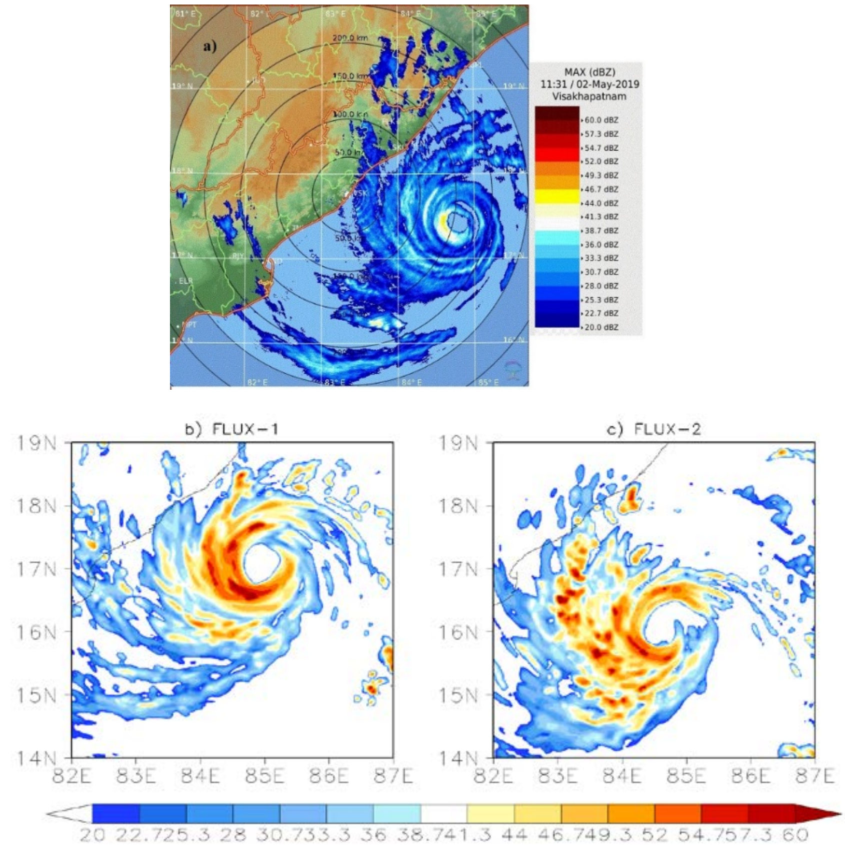


Figure 9: Maximum reflectivity (in dBZ) about 1130 UTC on 02 May 2019 obtained from a) Vishakhapatnam DWR, b) FLUX-1 and c) FLUX-2 experiment.

In Figure 9, the model simulated maximum reflectivity at 1130 UTC on 02 May 2019 from both experiments compared with Vishakhapatnam Doppler Weather Radar (DWR) at 1131 UTC on 02 May 2019. From the results it is observed that the spatial distribution of maximum reflectivity of the storm is better predicted in FLUX-1 experiments compared to the FLUX-2 experiment. But the magnitude of the reflectivity was over-predicted in both experiments compared to the observation. The maximum reflectivity from DWR observation is about 46.7 dBZ, whereas in the model forecast the maximum reflectivity was about 60 dBZ in both experiments. It is also noticed that the pattern of the structure of the storm vortex was better in the FLUX-1 experiment. Overall, the performance of the model with FLUX-1 experiment was quite good in prediction of reflectivity compared to FLUX-2, even though it was over-predicted in terms of distribution, and proved the model capability to predict the structure of the storm Fani.

Figure 10 shows the height cross section of temperature anomaly at 03 UTC on 02 May 2019 obtained from model simulations using experiment FLUX-1, FLUX-2 and satellite derived observations from https://rammb-data.cira.colostate.edu/tc_realtime [44]. The satellite derived observation indicated a strong positive temperature anomaly between 9 km to 15 km height with magnitude of 2ºC to 6ºC and the larger area in low-level having cold temperatures. The results from the both simulations suggested that the pattern of temperature anomaly is similar and the positive anomaly was obtained between 3-17 km height with a maximum magnitude about 8ºC and 7ºC in FLUX-1 and FLUX-2 experiments. Whereas in the observation the maximum anomaly was about 6ºC about at 12 km height and in the simulations the maximum anomaly was obtained at approximately 8.5

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 August 2022 doi:10.20944/preprints202208.0536.v1

km in both the experiments. In observation the spatial expansion of positive anomaly was more compared to the simulated anomaly but slightly better in FLUX-1 experiment compared to the FLUX-2 experiment.

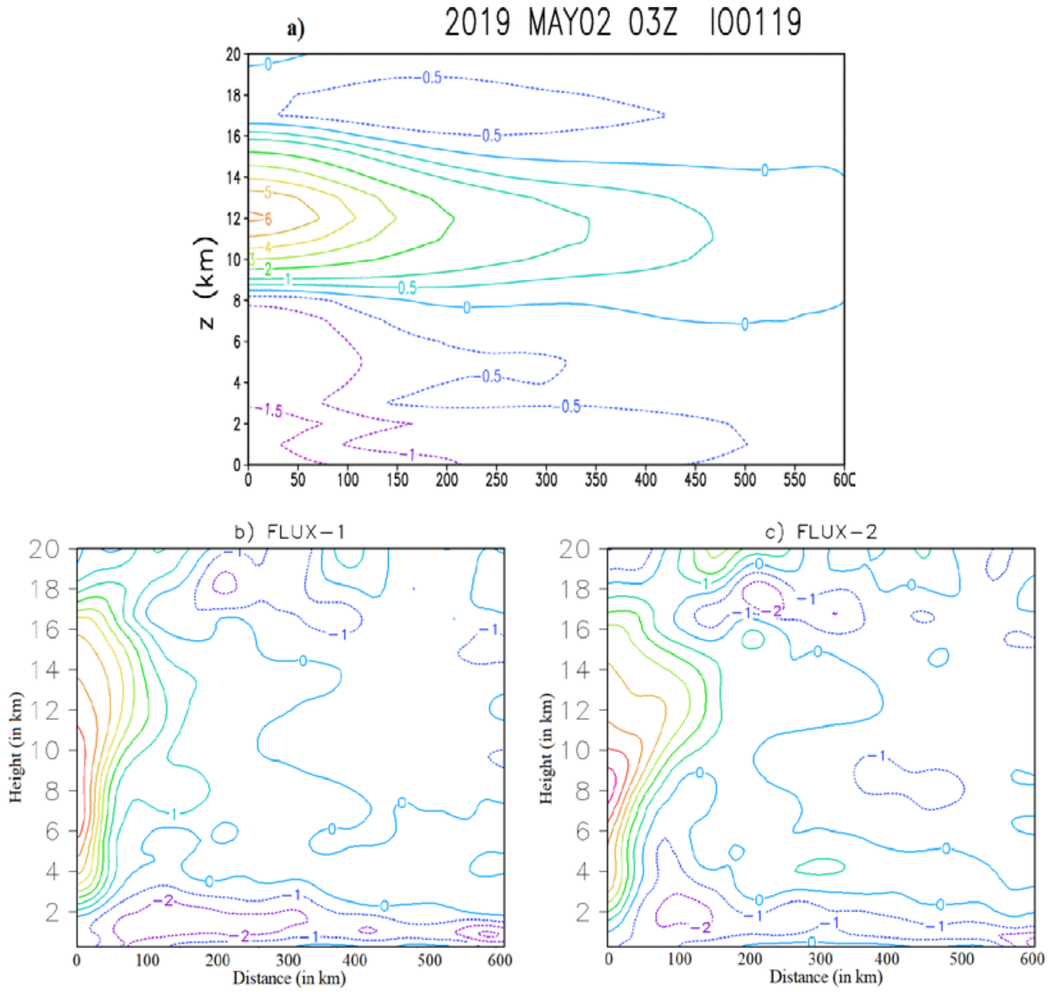


Figure 10: Temperature anomaly at 03 UTC on 02 May 2019 obtained from a) satellite observation, b) FLUX-1 experiment and c) FLUX-2 experiment.

4. Conclusions

The evaluation of model performance in the prediction of Fani was investigated using ARW model with 3 km horizontal resolution under a moving nested domain. The model towards the prediction of movement of the storm, intensity in terms of MCP and MSW, and structure in terms of relative humidity, temperature anomaly, maximum reflectivity and water vapor are critically assessed and the major findings can be brief as follows:

- The track of the storm Fani was well simulated by ARW model in moving nested domain by using 3 km horizontal resolution and the track errors on day-1 to day-4 are about 47 km, 123 km, 96 km, and 27 km in FLUX-1 experiment as compared to FLUX-2 experiment.
- The landfall (time and location) of Fani has significantly better predicted in the FLUX-1 experiment and the landfall time exactly matches with observation and location error was about 37 km.
- The FLUX-1 experiment provided a better forecast of rapid intensification and dissipation pattern with higher magnitude. First 60 h intensity forecast was better

 doi:10.20944/preprints202208.0536.v1

in the FLUX-1 experiment followed by the FLUX-2 experiment for the remaining period.

- The structure of the storm in terms of relative humidity, maximum reflectivity and temperature anomaly suggested that moving nested domain platforms is also good agreement to forecast Fani and needs to further improve.
- Overall, the results signify that the performance of the ARW model with FLUX-1 experiment was quit better in prediction of Fani cyclone compared to FLUX-2 experiment in a moving nested domain, even though it was over-predicted to the maximum intensity after 60 h forecast.
- More number of cases required to make the robust analysis over the Bay of Bengal and Arabian Sea for model evaluation and need further improvement in terms of rapid intensification and structure of the storms including data assimilation.

6. Limitation and future studies

The investigations presented here are the preliminary ideas using moving nested domain over the Bay of Bengal region, for similar modeling studies in future will be conducted with more number of cases over the North Indian Ocean. In addition, it is also important to test the model skill using moving nested domain in comparison with fixed domain.

Author Contributions: Conceptualization- K.S.S.; methodology - K.S.S.; software - K.S.S.; validation - K.S.S., S.M., S.N. and H.P.N.; formal analysis, K.S.S.; investigation, K.S.S., S.M., S.N. and H.P.N.; data curation, K.S.S.; writing—original draft preparation, K.S.S.; writing—review and editing, K.S.S., S.M., S.N., H.P.N. and S.D.; visualization, K.S.S., H.P.N., S.M., S.N. and S.D.; supervision, K.S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The India Meteorological Department best fit track data and CIRA https://rammb-data.cira.colostate.edu/tc_realtime data used for validation and are freely available.

Acknowledgements: The author sincerely acknowledges the financial support by the DST-SERB (Project file no. ECR/2018/001185). IMD and CIRA for providing the cyclone best-fit track datasets and satellite observations respectively. NCEP and NCAR for providing GFS analysis and forecast data sets, and WRF modeling system.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Webster PJ, Holland GJ, Curry JA, Chang HR 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science 309, 1844-1846
2. Balaji M, Chakraborty A, Mandal M 2018. Changes in tropical cyclone activity in North Indian Ocean during satellite era (1981–2014). International Journal Climatology 38(6), 2819-2837.
3. Albert, J., Krishnan, A., Bhaskaran, P.K. and Singh, K.S., 2021. Role and influence of key atmospheric parameters in large-scale environmental flow associated with tropical cyclogenesis and ENSO in the North Indian Ocean basin. Climate Dynamics, 1-18.
4. Nayak S and Takemi T. 2020. Robust responses of typhoon hazards in northern Japan to global warming climate: cases of landfalling typhoons in 2016. Meteorological Applications 27(5), e1954, doi: 10.1002/met.1954

5. Nayak S and Takemi T. 2020. Typhoon induced precipitation characterization over northern Japan: A case study for typhoons in 2016. Progress in Earth and Planetary Science 7, 39, doi: 10.1186/s40645-020-00347-x
6. Morimoto J, Aiba M, Furukawa F, Mishima Y, Yoshimura N, Nayak S, Takemi T, Haga C, Matsui T, Nakamura F. 2021. Risk assessment of forest disturbance by typhoons with heavy precipitation in northern Japan. Forest Ecology and Management 479, 118521, doi: 10.1016/j.foreco.2020.118521
7. Nayak S, and Takemi T. 2019. Dynamical downscaling of Typhoon Lionrock (2016) for assessing the resulting hazards under global warming. Journal of the Meteorological Society of Japan, 97(1), 69-88, doi: 10.2151/jmsj.2019-003
8. Nayak S and Takemi T. 2019. Quantitative estimations of hazards resulting from Typhoon Chanthu (2016) for assessing the impact in current and future climate. Hydrological Research Letters, 13(2), 20–27, doi: 10.3178/hrl.13.20.
9. Singh, K.S., Albert, J., Bhaskaran, P.K. and Alam, P., 2021. Assessment of extremely severe cyclonic storms over Bay of Bengal and performance evaluation of ARW model in the prediction of track and intensity. Theoretical and Applied Climatology, 143(3), 1181-1194.
10. Prasad, K. and Rao, Y.R., 2006. Simulation studies on cyclone track prediction by quasi-lagrangian model (QLM) in some historical and recent cases in the Bay of Bengal, using global re-analysis and forecast grid point data sets. SAARC Meteorological Research Centre.
11. Sudha Rani, N.N.V., Satyanarayana, A.N.V., Bhaskaran, P.K., 2015. Coastal vulnerability assessment studies over India: a review. Nat. Hazards 77 (1), 405-428.
12. Sahoo, B. and Bhaskaran, P.K., 2016. Assessment on historical cyclone tracks in the Bay of Bengal, east coast of India. International Journal of Climatology, 36(1), 95-109.
13. Albert, J. and Bhaskaran, P.K., 2020. Ocean heat content and its role in tropical cyclogenesis for the Bay of Bengal basin. Climate Dynamics, 55(11), 3343-3362.
14. Mohandas, S. and Ashrit, R., 2014. Sensitivity of different convective parameterization schemes on tropical cyclone prediction using a mesoscale model. Natural hazards, 73(2), 213-235.
15. Srinivas, C.V., Bhaskar Rao, D., Yesubabu, V., Baskaran, R. and Venkatraman, B., 2013. Tropical cyclone predictions over the Bay of Bengal using the high-resolution Advanced Research Weather Research and Forecasting (ARW) model. Quarterly Journal of the Royal Meteorological Society, 139(676), 1810-1825.
16. Steptoe, H., Savage, N.H., Sadri, S., Salmon, K., Maalick, Z. and Webster, S., 2021. Tropical cyclone simulations over Bangladesh at convection permitting 4.4 km & 1.5 km resolution. Scientific data, 8(1), 1-12.
17. Deshpande, M., Pattnaik, S. and Salvekar, P.S., 2010. Impact of physical parameterization schemes on numerical simulation of super cyclone Gonu. Natural Hazards, 55(2), 211-231.
18. Osuri, K.K., Mohanty, U.C., Routray, A., Kulkarni, M.A. and Mohapatra, M., 2012. Customization of WRF-ARW model with physical parameterization schemes for the simulation of tropical cyclones over North Indian Ocean. Natural Hazards, 63(3), 1337-1359.
19. Singh, K.S. and Mandal, M., 2014. Sensitivity of mesoscale simulation of Aila Cyclone to the parameterization of physical processes using WRF Model. In Monitoring and prediction of tropical cyclones in the Indian Ocean and climate change (pp. 300-308). Springer, Dordrecht.
20. Singh, K.S. and Bhaskaran, P.K., 2017. Impact of PBL and convection parameterization schemes for prediction of severe land-falling Bay of Bengal cyclones using WRF-ARW model. Journal of Atmospheric and Solar-Terrestrial Physics, 165, 10-24.
21. Vinodkumar, Chandrasekhar A, Alapaty K, Niyogi D 2008. The impacts of indirect soil moisture assimilation and direct surface temperature and humidity assimilation on a mesoscale model simulation of an Indian monsoon depression. J Appl Meteorol Climatol 47, 1393-1412.
22. Srinivas CV, Yesubabu V, Venkatesan R, Ramakrishna SS 2010. Impact of assimilation of conventional and satellite meteorological observations on the numerical simulation of a Bay of Bengal tropical cyclone of November 2008 near Tamilnadu using WRF model. Meteorol Atmos Phys 110, 19-44.
23. Rakesh V, Singh R, Pal PK, Joshi PC 2009. Impacts of satellite observed winds and total precipitable water on WRF short-range forecasts over the Indian region during the 2006 summer monsoon. Weather Forecast 24, 1706-1731.
24. Rakesh V, Singh R, Pal PK, Joshi PC 2011. Impact of satellite soundings on the simulation of heavy rainfall associated with tropical depressions. Nat Hazards 58, 945-980.
25. Osuri KK, Mohanty UC, Routray A, Mohapatra M 2012. The impact of satellite-derived wind data assimilation on track, intensity and structure of tropical cyclones over the North Indian Ocean. Int J Remote Sens 33(5), 1627-1652.

 doi:10.20944/preprints202208.0536.v1

26. Routray A, Mohanty UC, Osuri KK, Kar SC, Niyogi D, 2016. Impact of satellite radiance data on simulations of Bay of Bengal tropical cyclones using the WRF-3DVAR modeling system. IEEE Trans Geosci Remote Sens 54(4), 2285-2303.
27. Osuri KK, Nadimpalli R, Mohanty UC, Niyogi D, 2017. Prediction of rapid intensification of tropical cyclone Phailin over the Bay of Bengal using the HWRF modelling system. Q J R Meteorol Soc 143(703), 678-690.
28. Singh, K.S. and Bhaskaran, P.K., 2018. Impact of lateral boundary and initial conditions in the prediction of Bay of Bengal cyclones using WRF model and its 3D-VAR data assimilation system. Journal of Atmospheric and Solar-Terrestrial Physics, 175, 64-75.
29. Singh, K.S. and Bhaskaran, P.K., 2020. Prediction of land-falling Bay of Bengal cyclones during 2013 using the high resolution Weather Research and Forecasting model. Meteorological Applications, 27(1), p.e1850.
30. Nadimpalli, R., Srivastava, A., Prasad, V.S., Osuri, K.K., Das, A.K., Mohanty, U.C. and Niyogi, D., 2020. Impact of INSAT-3D/3DR radiance data assimilation in predicting tropical cyclone Titli over the Bay of Bengal. IEEE Transactions on Geoscience and Remote Sensing, 58(10), 6945-6957.
31. Singh, K.S. and Tyagi, B., 2019. Impact of data assimilation and air-sea flux parameterization schemes on the prediction of cyclone Phailin over the Bay of Bengal using the WRF-ARW model. Meteorological Applications, 26(1), 36-48.
32. Singh, K.S., Mandal, M. and Bhaskaran, P.K., 2019. Impact of radiance data assimilation on the prediction performance of cyclonic storm SIDR using WRF-3DVAR modelling system. Meteorology and Atmospheric Physics, 131(1), 11-28.
33. Kumar, S., Lal, P. and Kumar, A., 2020. Turbulence of tropical cyclone 'Fani' in the Bay of Bengal and Indian subcontinent. Natural Hazards, 103(1).
34. Chatterjee, S., 2020. Analytical Study of North Indian Oceanic Cyclonic Disturbances with Special Reference to Extremely Severe Cyclonic Storm Fani: Meteorological Variability, India's Preparedness with Terrible Aftermath. Natural Hazards and Earth System Sciences Discussions, 1-24.
35. Kain, J.S., 2004. The Kain–Fritsch convective parameterization: an update. Journal of applied meteorology, 43(1), 170-181.
36. Lin, Y.L., Farley, R.D. and Orville, H.D., 1983. Bulk parameterization of the snow field in a cloud model. Journal of Applied Meteorology and climatology, 22(6), 1065-1092.
37. Hong, S.Y., Noh, Y. and Dudhia, J., 2006. A new vertical diffusion package with an explicit treatment of entrainment processes. Monthly weather review, 134(9), 2318-2341.
38. Mlawer, E.J., Taubman, S.J., Brown, P.D., Iacono, M.J. and Clough, S.A., 1997. Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. Journal of Geophysical Research: Atmospheres, 102(D14), 16663-16682.
39. Dudhia, J., 1989. Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. Journal of Atmospheric Sciences, 46(20), 3077-3107.
40. Niu, G.Y., Yang, Z.L., Mitchell, K.E., Chen, F., Ek, M.B., Barlage, M., Kumar, A., Manning, K., Niyogi, D., Rosero, E. and Tewari, M., 2011. The community Noah land surface model with multi parameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. Journal of Geophysical Research: Atmospheres, 116(D12).
41. Kaplan, J., DeMaria, M. and Knaff, J.A., 2010. A revised tropical cyclone rapid intensification index for the Atlantic and eastern North Pacific basins. Weather and forecasting, 25(1), 220-241.
42. Shu, S., Ming, J. and Chi, P., 2012. Large-scale characteristics and probability of rapidly intensifying tropical cyclones in the western North Pacific basin. Weather and forecasting, 27(2), 411-423.
43. Wang, Y., Rao, Y., Tan, Z.M. and Schönemann, D., 2015. A statistical analysis of the effects of vertical wind shear on tropical cyclone intensity change over the western North Pacific. Monthly Weather Review, 143(9), 3434-3453.
44. Demuth, J.L., DeMaria, M., Knaff, J.A. and Vonder Haar, T.H., 2004. Evaluation of Advanced Microwave Sounding Unit tropical-cyclone intensity and size estimation algorithms. Journal of Applied Meteorology, 43(2), 282-296.