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Track and Landfall Characteristics of Very Severe Cyclonic Storm Fani over the Bay of Bengal using WRF Model

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Abstract

An attempt has been made to assess the capability of the Weather Research and Forecasting (WRF) model in simulating the track and landfall characteristics of Tropical Cyclone (TC) Fani (25th April – 05th May 2019) over the Bay of Bengal (BoB). WRF model has conducted on a single domain of 10 km horizontal resolution using Global Data Assimilation System (GDAS) data (0.25°×0.25°). The model predicted outcomes show auspicious agreement with the observed datasets of the Bangladesh Meteorological Department (BMD) and India Meteorological Department (IMD). It is found that the diminished lead time of the model run plays a crucial role in delivering good consistency with the minimum forecast uncertainty. A strong correlation between the track and intensity forecast deviations has also been determined. According to the results, the model simulation which captures the minimum deviation in the intensity forecast also ensures better track prediction of the system. The feasibility of the track and landfall forecast by the model even up to 27 hr advance is reasonably well. Finally, it can be decided that the model is capable to predict the cyclonic storm Fani precisely and it can be chosen confidently for future events over the BoB.

Keywords: tropical cyclone, WRF, intensity, track, vertical wind shear, SST, Bay of Bengal

I. Introduction

Tropical Cyclones (TCs) are one of the most damaging natural disasters in the coastal parts of the Indian subcontinent. The landfall of a TC is defined as the point where the storm's eye passes over the coastal areas and the track is characterized as the relatively small zone over the seas and oceans where storm moves in response to the dominant winds. The key periods for TC formation regularly over the BoB are the pre-monsoon season (March-May) and post-monsoon season (October-December). During these seasons, the monsoon channel is located over the Indian Ocean, which promotes low-pressure systems and their development into a stable cyclone system[1]. The BoB is responsible for around 7% of the total yearly universal number of TCs[2].

The most dangerous areas are those where a TC makes landfall. Lives and property in the coastal regions of the Indian subcontinents are extremely miserable as a result of TC landfalling events. These low-lying coastal states' civilization is deeply concerned about their current and future livelihood challenges. Proper storm forecasting might help to diminish the loss of lives and property over the region.

Numerous research approaches have been taken into consideration in the field of weather forecasting over the last two decades using the Numerical Weather Prediction (NWP) model. Sousounis et al.[3] performed a comparative study using WRF, ETA, MM5, and RUC models for severe precipitation events. They concluded that the WRF model is capable of producing physically realistic fine-scale formations than any other operational prediction models. Deshpande et al.[4] analyzed the Odisha super cyclone and found that the intensity and track of the TC are sensitive to the cumulus parameterization schemes used in the model. They also suggested that the KF2 scheme has captured the rapid intensification phase successfully than all other cumulus parameterization systems in forecasting. Depending on 65 sensitivity analysis of five Severe Cyclonic Storms (SCS), Srinivas et al.[5] found that the combination of Kain–Fritsch (KF) convection, LIN explicit microphysics schemes, Yonsei University (YSU) planetary boundary layer, and NOAH land surface schemes represent better forecast for track and intensity prediction.

According to Chan[6], dynamic factors such as vertical shear are considerably more significant than thermodynamic parameters for interpreting variations in TC intensity over climatic time periods. The formation and intensification activities of TC are adversely affected by the relatively higher vertical wind shear values between (200 and 850) hPa levels[7,8]. The Sea Surface Temperature (SST) and maximum potential intensity of TCs between (1981-2000) were examined by Kotal et al.[9] and they indicated that the maximum intensity of TC increases with increasing temperature. The dominance of climate change increased with SST, and rising sea levels are all likely to increase cyclone activity. The impact of warmer weather may also influence more severe storms[10]. TC patterns are altering due to climate change and their strength is increasing in terms of wind speed[11]. The frequency of intense storms (significantly higher than 115 knots) almost doubled between the period (1990-2004), which is strongly linked to SST[12].

As the frequency of such intense storms over the BoB basin increases in the current warming trend and it appears to be a major concern to the Indian subcontinent. It is important to predict the progression of TCs using NWP models in order to minimize the significant damage to lives and properties. The competency of the WRF model in forecasting the track and landfall features of the Very Severe Cyclonic Storm (VSCS) Fani over the BoB is evaluated in the current study. It is expected that this study will have a major impact on future TC forecasting over the BoB.

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II. Event Description

The VSCS Fani was the strongest TC to strike the Indian state of Odisha since the Odisha cyclone (1999). On the morning of 25th April, at 0300 UTC, cyclone Fani developed from a well-marked Low-Pressure Area (LPA) over the northern side of the Equatorial Indian Ocean (EIO) and the adjacent southeast BoB near latitude 2.70°N and longitude 88.70°E[13]. Under subsidiary conditions, the system condensed into a Depression (D) in the same areas at 0300 UTC on 26th April. In the morning and midday of April 27, it proceeded nearly northeast and strengthened into a Deep Depression (DD) and subsequently concentrated into a Cyclonic Storm (CS), Fani, over the identical regions. Moving north-northwestwards, it extended into a severe cyclonic storm across the central portion of south BoB in the evening of April 29th. Furthermore, from the early morning until the evening of 30thApril, the storm intensified from VSCS to Extremely Severe Cyclonic Storm (ESCS) over west-central and surrounding southwest BoB[13]. It proceeded to recurve north-northeastwards from the very early morning of 01st May. After becoming more intensified, the system reaches its maximum intensity of 115 kts at 0900 UTC of 02nd May. On May 03rd, it crossed the Odisha coast near Puri between 0230 UTC and 0430 UTC (latitude 19.75°N and longitude 85.70°E). Moving north-northeastwards, it deteriorated into a DD over Bangladesh and adjacent Gangetic West Bengal at 0300 UTC on May 04. The lifespan (D to D) of the system was 204 hr. The track length of the storm was 3030 km which was one of the longest tracks over the BoB[13].

III. Model Description, Data, and Methodology

The Weather Research and Forecasting (WRF) model[14] is an atmospheric NWP model that is designed to meet the needs of atmospheric research as well as operational forecasting. The WRF model is arguably the world's most widely used NWP model due to its combination of various physics schemes and proficiency for a variety of applications among various numerical operational models that are directly accessible for atmospheric simulation and meteorological research. This next-generation numerical operational model is generally utilized due to its higher-order numerical accuracy and scalar conservation qualities. The WRF-ARW (Advanced Research WRF) and WRF-NMM (Nonhydrostatic Mesoscale Model) solver are the two dynamic solvers of the WRF model. The WRF-ARW solver has been primarily promoted at NCAR, whereas the WRF-NMM solver has been improved at NCEP. These solvers are capable of delivering a wide variety of atmospheric applications at scales ranging from meters to thousands of kilometers. The ARW method integrates the ARW dynamics solver with several WRF system components to provide a simulation[14]. The ARW dynamic core of the WRF model (WRF-ARW) version 4.0.3 has been conducted during this study.

The National Center for Environmental Prediction (NCEP) FNL (Final) operational global analysis and forecast data (0.25°×0.25°) grids from the GDAS, which are assembled operationally every six hr, have been used as both initial and lateral boundary conditions in the current research. Estimated Central Pressure (ECP), MSWS, track, and landfall position data from the IMD report[13] have been used to validate to the model's findings. The observed maximum and minimum temperatures, relative humidity, and rainfall datasets of BMD has been used to evaluate the model's simulation capabilities.

The WRF model has run on a single 10 km horizontal resolution domain for 204, 156, 108, 84, 60, and 36 hr based on initial conditions of 0000 UTC of April 26th, 28th, 30th, 01st May, 02nd May, and 1800 UTC of May 2nd, 2019 to simulate the track and landfall features of VSCS Fani over the BoB. The center point of the domain for track pattern and landfall events simulation was set as (14°N, 87°E). The model domain was partitioned into (300×300) grid points in the west-east and north-south directions, whereas the vertical structure was 38 unequal spaced sigma (dimensionless pressure) levels. The map projection that has been applied in this study is Mercator. Kain-Fritsch (new Eta) scheme for cumulus parameterization[15] and Kessler scheme for microphysics, Revised MM5 scheme for the surface layer physics, Yonsei University (YSU) scheme for the planetary boundary layer, Unified Noah LS scheme for the land-surface model, Dudhia scheme for the short-wave radiation, and the RRTM scheme for the longwave radiation are the physics parameterization schemes that have been applied in the current research.

IV. Results and Discussions

Mean Sea Level Pressure and Wind Distribution Analysis

The distribution of Mean Sea Level Pressure (MSLP) of the VSCS Fani (at the time of model simulated landfall event) study has presented in (**Fig. 1.** (**a-f**)) respectively at 1200 UTC of 04th May, 0200 UTC of 04th May, and (0800, 0700, 0300, and 0600) UTC of 03rd May 2019, based on the initial conditions of 0000 UTC of 26th April, 28th April, 30th April, 01st May, 02nd May, and 1800 UTC of 02nd May 2019. The model forecasted a steady decrease in MSLP over time until it reached its peak intensity, and then a gradual increase before the system made landfall. It is also predicted that the system's core is circled by multiple isobar shapes. Those isobars have strengthened significantly over time due to high-pressure gradient and the system center moved towards India's south-eastern portions 21.37°N and 89.37°E; 21.61°N and 88.6°E; 19.88°N and 86.23°E; 19.86°N and 86.14°E; 19.80°N and 85.97°E; 19.62°N and 85.55°E is the model predicted landfall position of the simulated system based on 204, 156, 108, 84, 60 and 42 hr model run respectively.

The corresponding landfall places are the adjoining area of Sundarbans, the attached area of Sundarbans, Puri, Konark (Odisha), Puri, and Brahmagiri (Odisha) of India. At the moment of landfall, the central pressure of the system is found as (940, 950, 956, 962, 969, and 960) hPa, respectively. The outcomes indicate that for the different initial condition-based models run the position of the system center, landfall location, and minimal MSLP has varied slightly. A comparison between the ECP of IMD[13] and the simulated Minimum Central Pressure (MCP) (**Fig. 3**, (**a1**, **b1**, **c1**, **d1**, **e1**, **f1**)) reveals that prior to landing, the simulated MCP exhibits an identical pattern with a comparably severe intensity than the determined ECP, and after landfalling events, the observed ECP rises relatively fast in comparison to the simulated MCP.

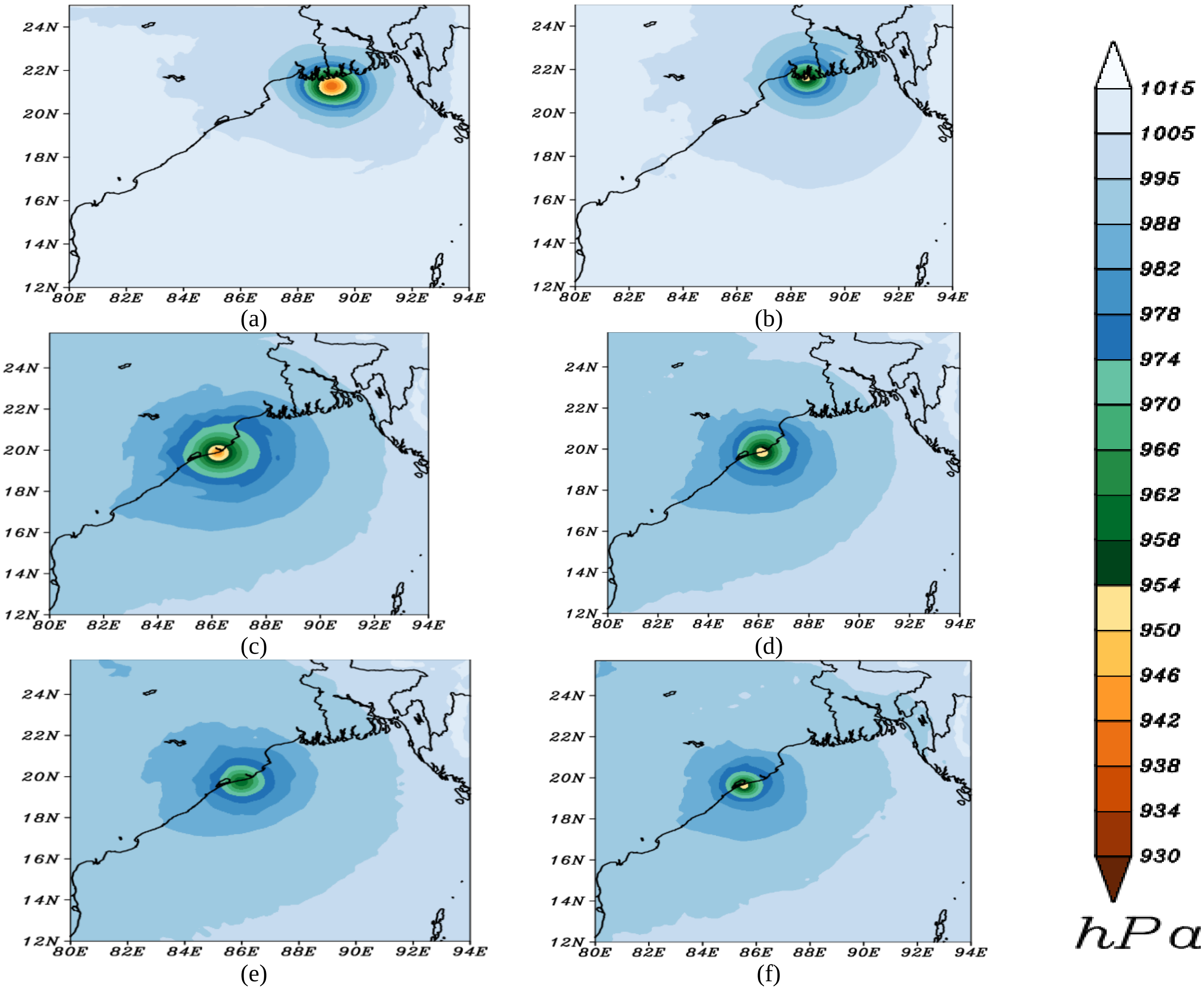

Fig. 1. The distribution of MSLP (hPa) based on (**a**) 0000 UTC of 26th April valid for 1200 UTC of 04th May (**b**) 0000 UTC of 28th April valid for 0200 UTC of 04th May (**c**) 0000 UTC of 30th April valid for 0800 UTC of 03rd May (**d**) 0000 UTC of 01st May valid for 0700 UTC of 03rd May (**e**) 0000 UTC of 02nd May valid for 0300 UTC of 03rd May (**f**) 1800 UTC of 02nd May valid for 0600 UTC of 03rd May 2019 respectively.

The model forecasted wind flow at various pressure levels has been assessed in the present study. Over the coastlines of Odisha/Puri and surrounding areas, a cyclonic circulation with a well-structured convergence zone has been found up to 500 hPa level which indicating a deep inflow of wind to the lower level over the mentioned regions. The maximum wind speed is ascertained in the eyewall of the system center and it is about (55, 40, 65, 50, 55, and 60) (m s^{-1}) at the model predicted landfall time for 42, 60, 84, 108, 156 and 204 hr model run respectively. Though a convergence zone is detected up to 500 hPa level, a divergence zone of scattered cyclonic circulation is found at 200 hPa level. A considerable westerly flow is captured well enough in the northern portion of the system center which is convenient to the eastward movement of the system and immensely important for the system degradation.

Fig. 3 (**a2**, **b2**, **c2**, **d2**, **e2**, **f2**) provides a comparison between the MSWS values determined by the model and the IMD report. The comparisons demonstrate that the forecasted MSWS is overestimated compared to the observations. The estimated results at the landfall time are very analogous to the observations, which is a good indication of the model. The model further captured the MSWS changes successfully. The reduction of lead time model run provides comparatively better acceptable results. It can be mentioned that the selection of the initial condition and duration of the model run plays a vital role in MSWS prediction.

Temperature and Vertical Wind Shear Analysis

The distribution of the vertical wind shear is analyzed using the zonal component of velocity between (200-900) hPa and (500-900) hPa levels. The changing patterns of vertical wind shear among the prementioned levels has depicted in **Fig. 3** (**a2**, **b2**, **c2**, **d2**, **e2**, **f2**). The rising tendency of vertical wind shear is found at the initial phages of the system in case of both simulations based up to 28th April which clearly illustrates the pernicious situation for the system's intensification. Afterward, the vertical wind shear's increasing tendency declines, the situation becomes suitable, and the system's attained its maximum strength. Consistent values/ increasing tendency with minimum oscillations in vertical wind shear values is found for 84, 60, and 42 hr model simulation and this resultant vertical wind shear may be responsible for the quick degradation of the system. Finally, it can be concluded that the model has captured the vertical wind shear distribution well enough.

The temperature of the sea surface has a significant influence on the development of TCs. From the model predicted temperature study at a 2-meter height, the temperature around the system's center is determined to be approximately (25-32)°C which was sufficiently convenient to achieve its intensity. It is also forecasted that temperature diminishes up to (18–24)°C after the cyclone had passed its landfall location due to severe rainfall. The system degrades its category with the resultant temperature diminishment and comes to an end with time.

A comparison has been made between the simulated maximum and minimum temperatures with the observed datasets at various stations of Bangladesh. The comparison explicitly reveals that the predicted maximum temperature underestimates the observed results (the Figure has not given) and by contrast, the forecasted minimum temperature overestimates the determined results (**Fig. 2** (**a-f**)). Finally, it could be revealed that the WRF model can forecast the temperature distribution fairly well even though it has some errors.

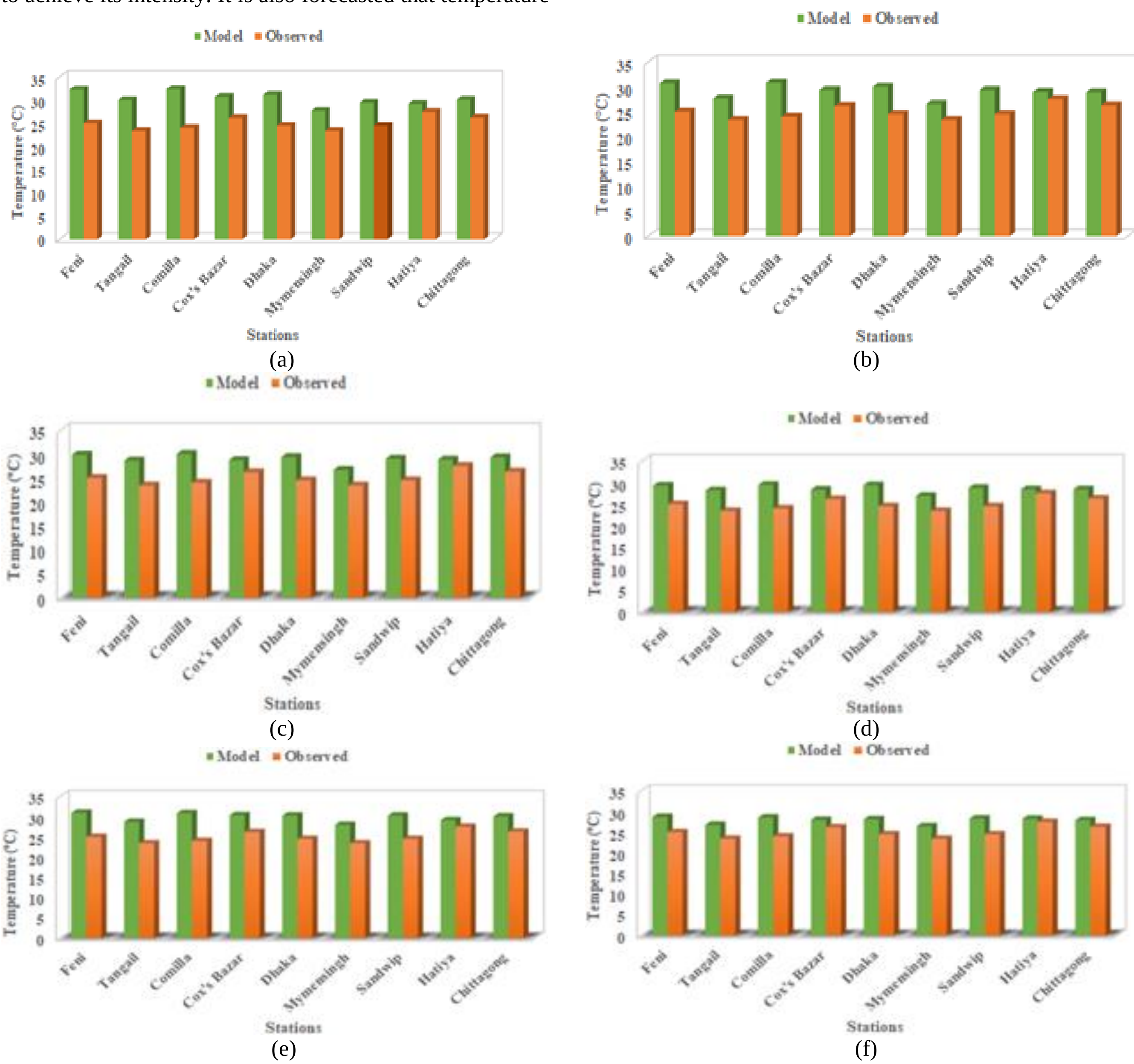

Fig. 2. Comparison of model forecasted minimum temperature (°C) at 2-meter height with the observed results at different stations on 04th May based on (**a**) 0000 UTC of 26th April (**b**) 0000 UTC of 28th April (**c**) 0000 UTC of 30th April (**d**) 0000 UTC of 01st May (**e**) 0000 UTC of 02nd May (**f**) 1800 UTC of 02nd May respectively.

Analysis of Horizontal and Vertical Profile of Relative Humidity

The model forecasted horizontal and vertical cross-section of the Relative Humidity (RH) distributions is analyzed. A strong southwesterly flow full of enormous moisture (≥80 %) in the northern direction is predicted from the model simulated RH analysis at a 2-meter height. The predicted system's eyewall is the proprietor of the maximum amount of RH whereas comparatively smaller RH (≤75 %) is forecasted at the system center. The vertical cross-section of RH profile along 21.37°N, 21.61°N, 19.88°N, 19.86°N, 19.80°N, 19.62°N at the model forecasted landfall time for 204, 156, 108, 84, 60, and 42 hr model simulation is analyzed. Analyzing the model forecasted vertical cross-section of RH distribution, it can be determined that the RH simply on top of the center is noticeably less (≤70%) than its surrounding regions between (550 – 200) hPa levels. It can be also revealed that the RH is vertically prolonged to a level of (90-100) % up to 100 hPa level. This availability of predicted moisture plays a significant role for the development of severe convective activities associated with the cyclone. The model simulated RH outcomes show auspicious agreement with the observed RH data at different stations of BMD.

Track Pattern Analysis

The predicted track of VSCS Fani for all lead time model run based on initial conditions at 0000 UTC of 26thApril, 28th April, 30th April, 01st May, 02nd May, and 1800 UTC of 02nd May is represented alongside the observed track in **Fig. 3** (**a3**, **b3**, **c3**, **d3**, **e3**, **f3**). The center position has taken to sketch the track of the chosen system. It is found that all the forecasted tracks show identical signatures with the observed track. The cyclone is moving much faster than the predicted tracks based on the initial conditions up to 28th April. The model has forecasted the curvature and direction of movement up to 204 hr in advance which is evidence of good competency of the model, although it has a significant eastward deviation. Changing/adjusting the initial condition and reducing lead time in simulation, the predicted track is very similar to the observed track.

According to the results of the

Table 1 study, track prediction errors are linked to the model predicted MSLP and MSWS distributions. The MSLP values predicted by the model are positively correlated with the track forecast error, while the MSWS values predicted by the model are negatively correlated with the track forecast deviation, indicating a deep relationship between track and intensity forecast. Considering the MCC relationship, it can be concluded that the more intense a system be, the less likely it is to generate error in the track prediction.

Based on the study of the findings (

Table 1), it can be shown that errors in the track forecast, SLP, and MSWS prediction are all strongly correlated. The model simulated MSLP and MSWS errors are positively correlated with track forecast error. Particularly, MCC between MSWS and track forecast errors (MCC=0.512) are stronger than MCC between MSLP and track forecast errors (MCC=0.271). Inspection of MCC among MSLP, MSWS, and track forecast error can provide a good notion about the track forecast deviation. As a result, it can be concluded that the model simulation that predicts a lower deviation in the intensity prediction also predicts a relatively better track of the system.

An analysis has also been performed to explain the connection between track and vertical wind shear prediction. The model has predicted a well-matched track for model simulation for 42 and 60 hr. Taking the specified outcome into consideration, it is also found that the corresponding vertical wind shear values are in a consistent/rising trend with minimal oscillation. This stable/rising pattern of vertical wind shear values perhaps played a vital role within the eastward track movement.

Mean and Standard Deviation (SD) for the predicted track forecast errors has been calculated for 6 initial conditions-based model run (**Table 3**). The average and SD of the errors are found (205.17, 123.3, 75.67, 52.26, 40.15, and 93.98) km and (102.34, 65.1, 67.43, 34.75, 23.83, and 96.2) which indicates that relatively reduced lead time model run has simulated the system's track with comparatively smaller deviation. The simulated result based on 1800 UTC on 02nd May is somewhat unusual in terms of analyzed results due to the fact that the system degrades much faster than the simulation. In this case, the simulation capability for landfall position prediction is satisfactory but the speed of the system has not captured very well.

V. Analysis of Landfall Forecast Errors

The landfall position and time prediction are the important issues for cyclone forecasting. The subsequent **Table 2** and **Table 3** includes overview of the simulated outcomes of the landfall position, time prediction, and corresponding error analysis for different initial conditions-based model run.

Variation in the landfalling position and time prediction has been noticed for the distinct lead-time model run. Reduced lead time model run ensures a more precise forecast of landfall timing and location. The model's simulated outcome based on 0000 UTC of 02nd May predicts the same landfall time as the actual landfall time. Considering the error analysis, it can be determined that landfall prediction based on 0000 UTC of 02nd May (27 hr prior to the observed landfall time) is significantly better than any other simulations and the corresponding landfall forecast error is only in place, 30.48 km.

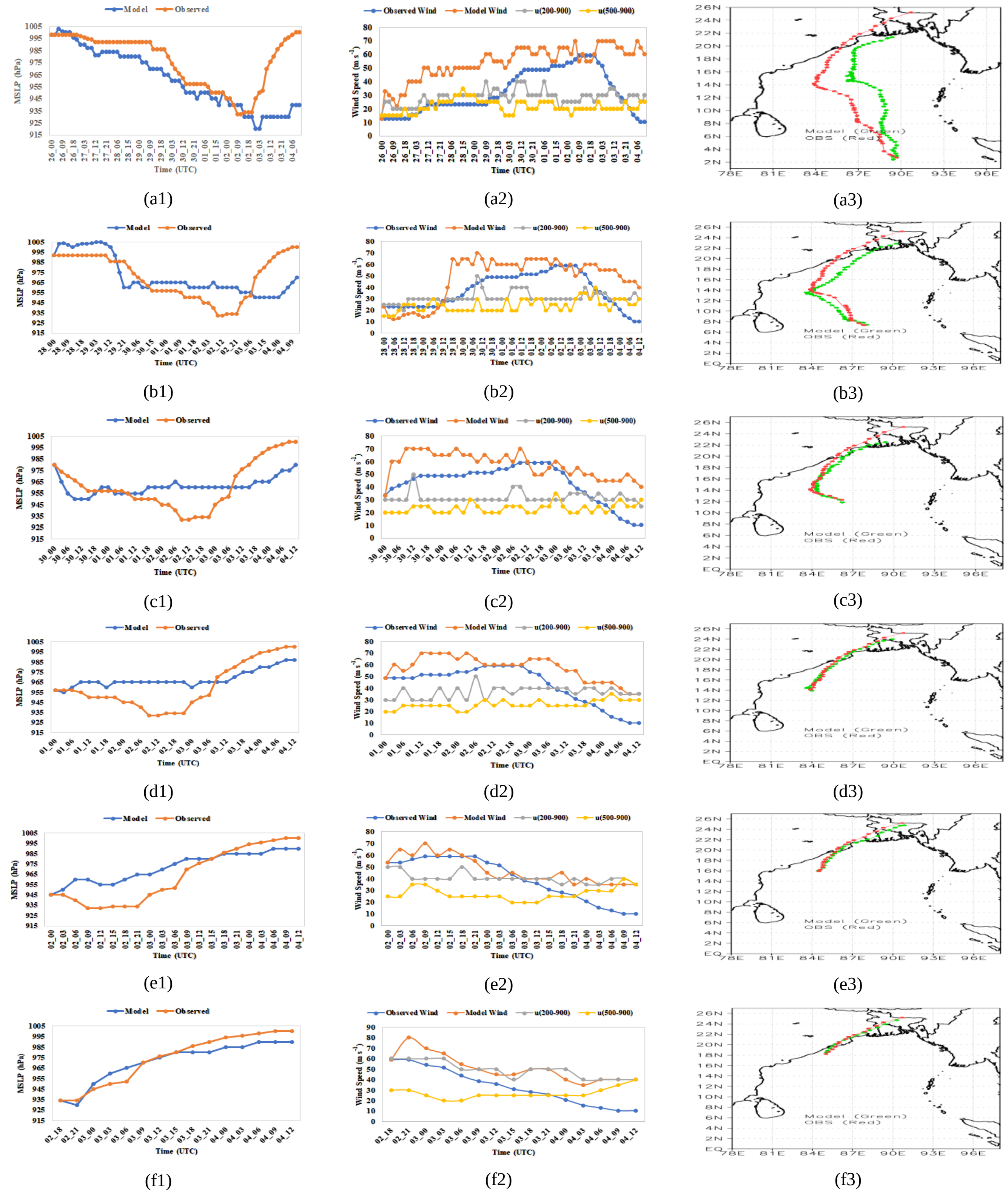

Fig. 3. Comparison of model simulated MSLP (**a1, b1, c1, d1, e1, f1**), MSWS (**a2, b2, c2, d2, e2, f2**), track pattern (**a3, b3, c3, d3, e3, f3**) and vertical wind shear distribution of zonal component of velocity between (200-900) and (500-900) hPa levels (**a2, b2, c2, d2, e2, f2**) based on 0000 UTC of 26th April, 28th April, 30th April, 01st May, 02nd May and 1800 UTC of 02nd May respectively.

Table 1. Mean correlation coefficient analysis.

	MCC between track and SLP forecast error	MCC between track and MSWS forecast error	MCC between SLP and MSWS forecast error	MCC between track error and SLP forecast	MCC between track error and MSWS forecast	MCC between SLP and MSWS forecast
MCC	0.271	0.512	0.186	0.268	-0.210	-0.853

∗MCC represents Mean Correlation Coefficient

Table 2. Landfall location and time errors of VSCS Fani.

Base Date/ Time (UTC)	Forecast Hours	Landfall Forecast		Observed Landfall		Forecast Error	
		Position (Lat °N/ Lon °E)	Date/Time (UTC)	Position (Lat °N/Lon °E)	Date/ Time(UTC)	Distance (km)	Time (hr)
26th April /0000	204	21.37/89.37	04th May/1200	19.75 /85.7	03rd May /0300	445	33D
28th April /0000	156	21.61/88.6	04th May/0200			382.4	23D
30th April /0000	108	19.88/86.23	03rd May/0800			60.57	5D
01st May /0000	84	19.86/86.14	03rd May/0700			50.34	4D
02nd May /0000	60	19.80/85.97	03rd May/0300			30.48	0D
02nd May/1800	42	19.62/85.55	03rd May/0700			22	3D

*D represents delay

Table 3. Model forecasted SLP, MSWS and Track error analysis.

Base Date/ Time (UTC)	Forecast hours	SLP forecast error		MSWS forecast error		Track forecast error	
		Average (hPa)	SD	Average ($m\ s^{-1}$)	SD	Average (km)	SD
26th April /0000	204	15.93	17.91	21.79	12.10	205.17	102.34
28th April /0000	156	16.43	11.19	14.18	10.28	123.2	65.1
30th April /0000	108	14.54	9.38	15.53	9.19	75.67	67.43
01st May /0000	84	15.83	9.08	14.48	9.04	52.26	34.75
02nd May /0000	60	13.57	9.7	10	8.24	40.15	23.83
02nd May/1800	42	6.46	4.52	17.87	8.25	93.98	96.2

∗SD represents Standard Deviation

VI. Conclusion

The main objective of the ongoing research is to assess the capability of the WRF-ARW model in simulating the track and landfall events of VSCS Fani. The following conclusions can be revealed from the above-mentioned assessments:

1. The reduction of lead time model run shows relatively better agreement with the observed intensity outcomes. The selection of the initial condition and duration of the model run plays a significant role in intensity prediction. The predicted maximum intensity is determined as 920 hPa and 70 $m\ s^{-1}$ based on 0000 UTC of 26th April model run.

2. The model can simulate the RH and temperature distribution good enough with negligible errors.

3. Consistency/rising aptitude in vertical wind shear values has captured very well at the system's farewell phase, which may be one of the significant reasons for the quick degradation of the cyclone.

4. Identical/ the rising tendency of vertical wind shear ($\geq$20m s^{-1}) values with insignificant/minimum oscillation can play a dominating role in eastward track movement over the specified region. For observing track movement, the effects of vertical wind shear between (500-900) hPa levels can be comparatively higher than (200-900) hPa levels.

5. The diminishment of lead time model run and correction of the initial condition ensures better outcomes in track prediction with insignificant time and position errors. Positive results in predicting the system's curvature and direction during the 204 hr model run can be a good sign for the model.

6. 850 hPa is the identified level along with the vertical pressure coordinate system where MSWS prevails almost all time.

7. Track forecast errors are closely correlated with the intensity prediction. A positive correlation between track and intensity forecast errors has found. The WRF model run which forecasts minimum deviation in the intensity prediction also forecasts the better track of the system.

8. The capability of the WRF model for landfall forecasting up to 27 hour in advance of the actual landfall can be considered standard.

Based on the preceding discussion, it can be decided that the WRF model can forecast most of the characteristics of cyclonic storm Fani precisely and it can be chosen confidently for future events over the BoB.

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