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A Data-Driven Approach to Tropical Cyclone Track Prediction with GFS Data

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Abstract

Tropical cyclones (TCs) are powerful weather phenomena that are infamous for their catastrophic effects when they make landfall along coastal areas. The Bay of Bengal (BOB), which is located in the northeastern Indian Ocean, has come to be known as a breeding ground for some of the deadliest and most devastating TCs in the world. The BOB's increased sea surface temperatures, which encourage cyclonic activity, especially during the pre-monsoon and post-monsoon seasons, are chiefly to blame for this reputation. Many atmospheric factors, such as low-level winds, relative vorticity, vertical wind shear, humidity levels in various tropospheric layers, and mid-tropospheric thermal instability, affect the development of TCs. To reduce the possibility of property damage and human casualties, precise TC track and intensity projections are crucial. Invaluable techniques for comprehending TC origin, trajectories, and intensities have arisen, including numerical weather prediction (NWP) models and dynamical statistical models. Forecasting cyclone formation, strength, paths, and specifics of landfall are crucial tasks for organisations like the India Meteorological Department (IMD) and the Joint Typhoon Warning Centre (JTWC) in the United States. The current goal of international TC research is to improve the accuracy of TC track predictions by utilising physical parameterizations, synthetic data, and other data sources. The National Centre for Atmospheric Research (NCAR) developed the Advanced Research Weather Research and Forecasting (ARW-WRF) mesoscale model, which has proven exceptional capabilities in producing fine-scale atmospheric structures and increasing forecasting accuracy.

Keywords: *Tropical cyclones, Numerical weather prediction, Planetary boundary layer, FNL data etc.*

Introduction:

When they make landfall along coastal regions, tropical cyclones (TCs), which are powerful meteorological occurrences that are characterised by torrential downpours, hurricane-force winds, and catastrophic effects, cause havoc. Some of the world's worst and deadly TCs are known to breed in the Bay of Bengal (BOB), which is located in the northeastern corner of the Indian Ocean. This infamous reputation is largely due to the BOB's elevated sea surface temperatures, which fuel increased cyclonic activity, particularly in the months before and after the monsoon season. The BOB emerges as a highly dynamic zone for TC production, in striking contrast to the Arabian Sea. The significant latent heat content of the area makes the post-monsoon TCs that arise here particularly dangerous. As a result, the local air conditions are crucial in the development of cyclonic systems over these warm oceanic seas.

The development of cyclones is controlled by a number of atmospheric variables, including low-level winds, relative vorticity, vertical wind shear, elevated relative humidity at low and middle tropospheric levels, and mid-tropospheric thermal instability. To reduce the loss of life and property during these natural disasters, precise forecasts of TC paths and intensities must be combined with prompt warnings to at-risk communities.

With a relative degree of effectiveness in predicting these parameters, numerical weather prediction (NWP) models and dynamical statistical models have become important tools for understanding TC origin, track, and intensity. The Joint Typhoon Warning Centre (JTWC) in the United States and the India Meteorological Department (IMD) in India both play crucial roles in predicting cyclone formation, strength, courses, and even the specific time and place of landfall [2]. At the moment, improving the accuracy of tropical storm track prediction is the focus of international TC research. This collaborative effort aims to use physical parameterizations, synthetic data, and both conventional and non-traditional data to their fullest potential. [1-3].

The Advanced Research Weather Research and Forecasting (ARW-WRF, hereafter referred to as WRF) mesoscale model, created by the National Centre for Atmospheric Research (NCAR), has emerged as a standout performer among the variety of models created for cyclone prediction, each outfitted with unique microphysics schemes. Especially noteworthy is that the WRF model excels at producing fine-scale atmospheric structures, improving its forecasting skills [8].

We set off on a voyage of TC track simulation using the WRF model within the constraints of this section, including three layered domains and a variety of cyclone prediction (CP) and model physics (MP) variables. Our major goal is to identify the most precise track predictions and investigate how different model domain resolutions affect TC track simulations. In order to do this, we use the NCEP FNL data from the National Centres for Environmental Prediction to generate initial and boundary conditions for the ARW model runs. Notably, other studies have indicated that TC track forecasts benefit more from initial circumstances driven by FNL data, showing lower initial position errors than initial conditions based on GFS [4–7]. Additionally, our analysis shows that domain resolution and parameterization approaches like cumulus (CPS), planetary boundary layer (PBL), and microphysics (MPS) have a significant impact on the predictions of TC track and intensity within the mesoscale WRF model [5]. The prediction of tropical cyclones is also significantly impacted by radiation parameterization systems [6].

Data and Methodology:

The mesoscale Advanced Research Weather Research and Forecasting (ARW) Version 3.6.1 model created by the National Centre for Atmospheric Research (NCAR) was used in the study's cyclone simulations [9]. These simulations used numerical weather prediction (NWP) techniques, a systematic method of weather forecasting that makes use of fundamental governing equations, various numerical methods, parameterization schemes, distinct domains, and meticulous initialization and boundary conditions.

Model Selection: The mainstay of the study's cyclone simulations was the ARW mesoscale model, which is famous for its aptitude in simulating meteorological phenomena.

Terrain and Topographical Data: The study used terrain and topographical data from the Moderate Resolution Imaging Spectroradiometer (MODIS) into the WRF Pre-processing System (WPS) to increase the accuracy of simulations across various geographical scales. These data were carefully applied to domains 1, 2, and 3 to ensure that the underlying terrain was accurately represented.

Data Sources:

FNL Data: The Operational Global Analysis data also known as FNL data from the National Centres for Environmental Prediction (NCEP) were heavily utilised in the study. These priceless datasets, which contain gridded data at a spatial resolution of 1 degree by 1 degree, were produced by the Global Data Assimilation System (GDAS). The Global Telecommunication System (GTS), as well as different meteorological and satellite systems, are just a few of the data sources that are used to provide FNL data, which is operationally created at six-hour intervals. Notably, as compared to the Global Forecast System (GFS) statistics, FNL data give a more complete set of observational data. It's vital to note that the GFS system operates ahead of the most pressing forecast requirements and that the startup of the model uses the previous 6-hour FNL data.

Data Parameters: The FNL data span 26 pressure levels in the surface boundary layer and a wide range of meteorological factors. Sea level pressure, geo-potential height, surface pressure, sea surface temperature, temperature, ice cover, relative humidity, soil characteristics, u-wind (east-west component of wind), v-wind (north-south component of wind), vorticity, ozone concentration, and vertical motion are among the parameters that make up the essential components of the atmospheric state.

WRF Model Domain Configuration: The WRF Pre-processing System (WPS) was set up to create the necessary domains in order to simulate tropical storms using the FNL data. Figure 1's visual representation of the details of this domain configuration demonstrates how the model accurately covers the relevant temporal and geographical scales needed for thorough cyclone investigation. In conclusion, our approach combines the strength of the ARW mesoscale model with topography information from MODIS and a wealth of observational data from the FNL dataset. This integrated strategy serves as the basis for the study's thorough investigation and precise cyclone prediction.

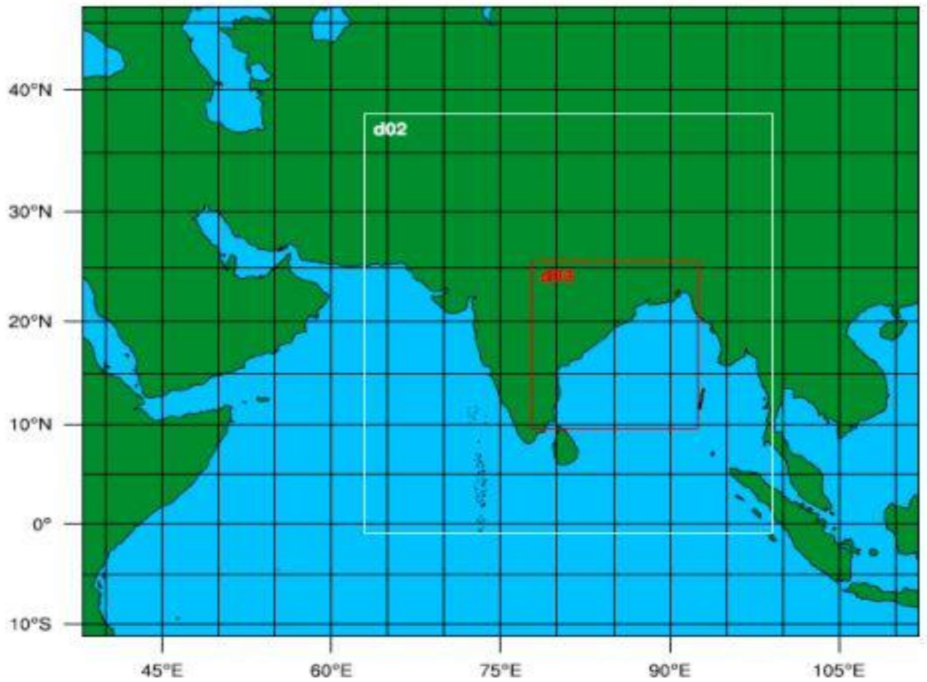

Fig 1: WPS Domain Setup for Tropical Cyclone Simulation Utilizing FNL Data

To properly determine the track position of each of the three tropical cyclones (TC) simulated in this study, the model's output was gathered every six hours. This time clarity made it possible to follow the TC's progress and supplied insightful data for study.

Microphysics Parameterization Schemes: To improve the accuracy of the simulations, the Weather Research and Forecasting (WRF) model used a variety of Microphysics Parameterization Schemes. These models are essential for simulating cloud functions and precipitation in the TC system. Table 1 lists the specific Microphysics Parameterization Schemes used in the WRF model.

Table 1: Microphysics Parameterization Schemes Employed in WRF Model Simulations Using FNL Data

S. No.	Name of the MPS Parameterization	Acronym
1	WRF Single Moment 5-class scheme (mp option=4)	WSM5
2	Lin et al. scheme (mp option=2)	LIN
3	Kessler scheme (mp option=1)	KS
4	WRF Single Moment 3-class simple ice scheme (mp option=3)	WSM3
5	Thompson graupel scheme 2 moment (mp option=8)	THOM2

This study's primary beginning and boundary conditions were from the UCAR & NCAR Research Data Archive [9]. The NCEP FNL (Final) Operational Global Analysis datasets, which are operationally prepared at intervals of six hours and are gridded at a resolution of 1 degree by 1 degree, were used to generate these conditions.

Figure 2 explains the research process used for the WRF modelling system, in particular the flowchart for simulating utilising FNL data. Notably, our research shows that the FNL data performed better at predicting tropical cyclone tracks than both the GFS and NCMRWF datasets [10, 11]. This highlights the value of using FNL data for better track predictions when considering tropical cyclone models.

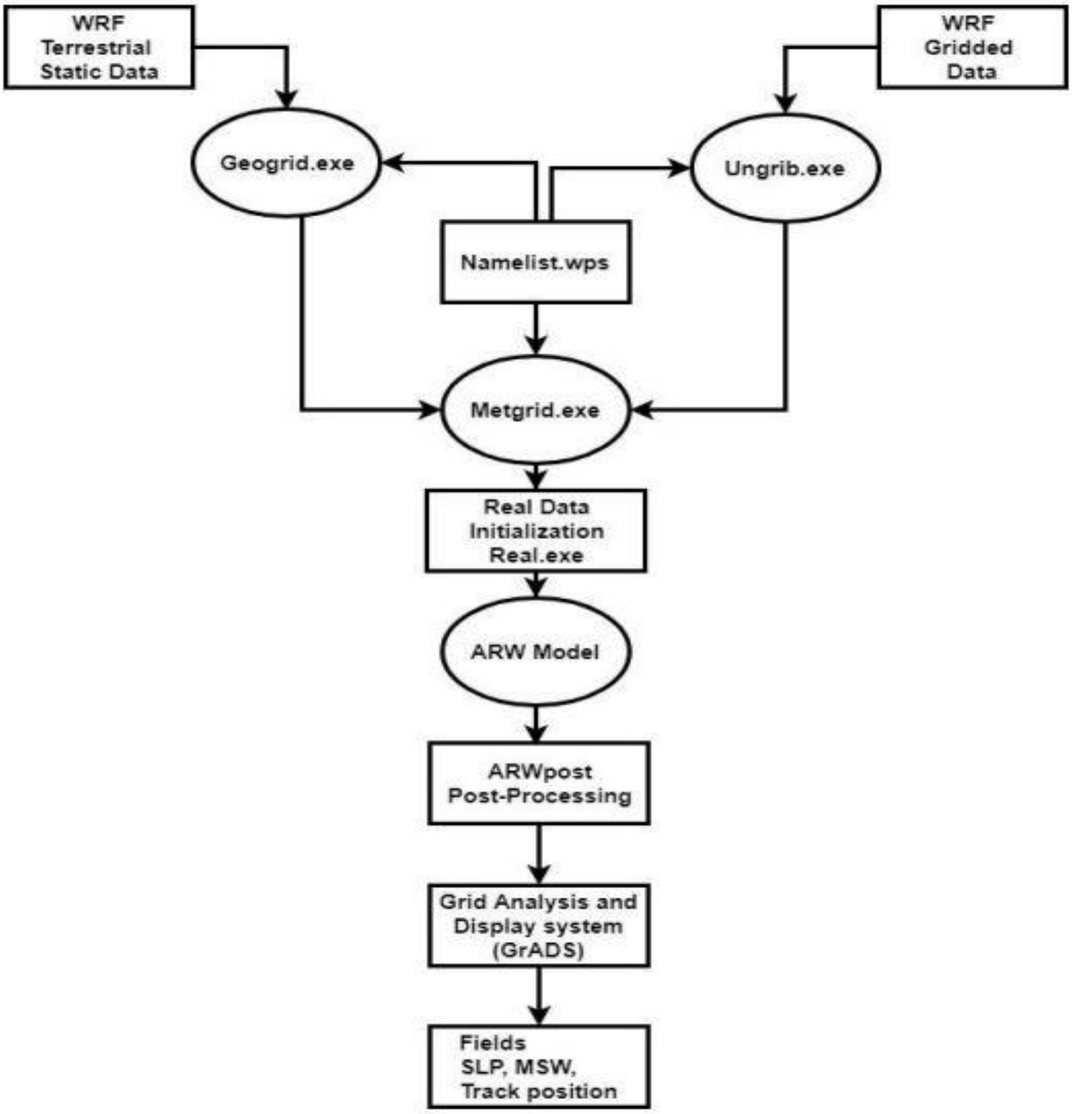

Fig 2: Flowchart of the WRF Modeling System for FNL Data Simulations

Table 2 lists the many Cumulus Parameterization Schemes used in the WRF model. Dynamics and domain requirements of the WRF Model

Table 2: Cumulus Parameterization Schemes Employed in WRF Model Simulations Using FNL Data

S. No.	CPS Parameterization Scheme	Acronym
1	Grell-Devenyi ensemble scheme (cu option=3)	GD
2	Kain-Fritsch (new Eta) scheme (cu option=1)	KF
3	Grell-3D ensemble scheme (cu option=5)	G3D
4	Betts-Miller-Janjic scheme (cu option=2)	BMJ
5	No Cumulus Scheme (cu option=0)	Ncu
6	Simplified Arakawa-Schubert scheme (cu option=4)	SAS

Enhancing Tropical Cyclone Track Prediction

This study used detailed simulations of the Hudhud, Phailin, and Laila cyclones to improve the ability to predict the trajectory of tropical cyclones. Finding the best Microphysics Parameterization Schemes (MPS) and Cumulus Parameterization Schemes (CPS) for precise track prediction was the main goal. Results from domain-3 simulations, which included a total of 24 thorough experiments, were predominantly used in the analysis.

The Yonsei University (YSU) planetary boundary layer (PBL) design was maintained throughout all simulations [12–14]. The YSU PBL scheme's superior performance in forecasting factors linked to tropical cyclones, such as wind patterns, pressure systems, and cloud fractions, supported the decision to use it. When compared to other PBL systems that are currently available, it also demonstrated superior realism in capturing horizontal divergence, vector track locations, and vorticity [15].

The simulated tracks of the tropical storm Hudhud were presented in Figure 3 to evaluate the performance of various MPS and CPS parameterization schemes, and Figure 4 shows the track errors related to different parameterization methods for Hudhud and Phailin.

The Grid Analysis and Display System (GrADS) was used to visualise and analyse the results of the WRF model. This tool made it easier to compare the outputs of the WRF model with the observed tracks supplied by the India Meteorological Department (IMD) at the same time.

The haversine formula was used to calculate the track error for the Hudhud tropical cyclone with regard to various CPS and MPS parameterization methods [20]. This method was used to calculate the great circle distance between different latitude and longitude points on the surface of the Earth, offering a reliable indicator of the accuracy of track predictions.

$$x = sin^{2\frac{\Delta\varphi}{2}} + cos\varphi * cos\varphi * sin^{2\frac{\Delta\lambda}{2}} \quad (1)$$

$$y = 2 * tan^{-1}\frac{\bar{x}}{\overline{\overline{1-x}}} \quad (2)$$

$$D = R * y \quad (3)$$

$$\Delta\varphi = \varphi_{JTWy} - \varphi_{wrf} \quad (4)$$

$$\Delta\lambda = \lambda_{JTWy} - \lambda_{wrf} \quad (5)$$

The haversine formula was used to get the track error (D), which takes into consideration latitude, longitude, and the Earth's mean radius (R), which is approximately 6,371 km. Radians are used to measure all angles.

Table 3: List of Simulated Tropical Cyclones Utilizing FNL Data

S. No	Name of the Cyclone	Start Date and Time (UTC)	End Date and Time (UTC)	Model Run Time (hours)
1	HUDHUD	08/10/2014 0000	13/10/2014 1200	132
2	PHAILIN	10/10/2013 1200	13/10/2013 1200	72

Hudhud Cyclone Track Simulations

On October 8th, 2014, at 0000 UTC, the simulations for the tropical storm Hudhud started using lateral boundary conditions. These simulations ran for a total of 132 hours, ending on October 13th, 2014, at 1200 UTC. The Hudhud cyclone's simulated path is shown in Figure 3 using several Cumulus Parameterization Schemes (CPS) and Microphysics Parameterization Schemes (MPS).

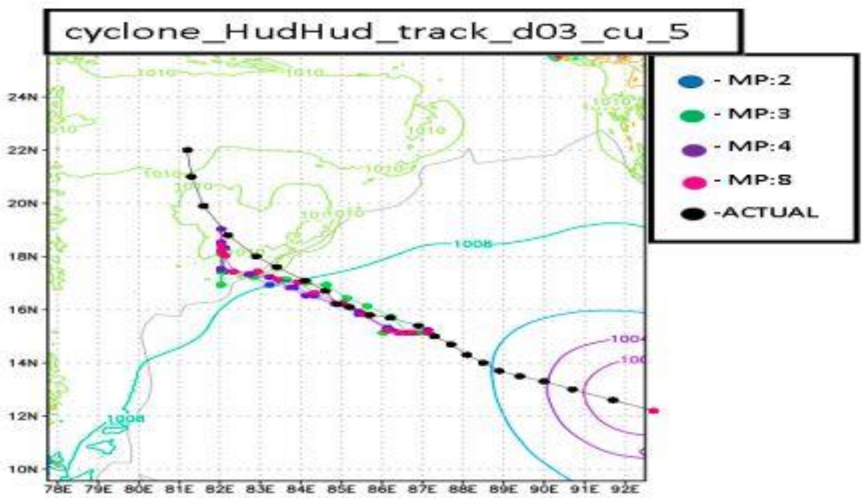

Fig 3: Hudhud Track Simulations with Different Microphysics and Cumulus Parameterization Schemes (CPS: Grell 3D Ensemble scheme - cu option=5)

Phailin Cyclone Track Simulations

On October 10, 2013, at 1200 UTC, simulations for the Phailin tropical cyclone were started, including lateral boundary conditions. These simulations ran for a total of 72 hours, ending on October 13th, 2013, at 1200 UTC. The simulated path of the Phailin cyclone under different Cumulus Parameterization Schemes (CPS) and Microphysics Parameterization Schemes (MPS) is shown in Figure 7. Additionally, Figure 8 shows the track error analysis for the Phailin tropical cyclone taking into account several Cumulus Parameterization (CP) and Microphysics Parameterization (MP) schemes. It is important to highlight that while the ideal mix of physics parameterization schemes may optimise the forecast of cyclone tracks, it may not always be appropriate for the prediction of cyclone intensities. The findings highlight how vulnerable tropical cyclone course and intensity are to microphysics parameterization approaches [16–19].

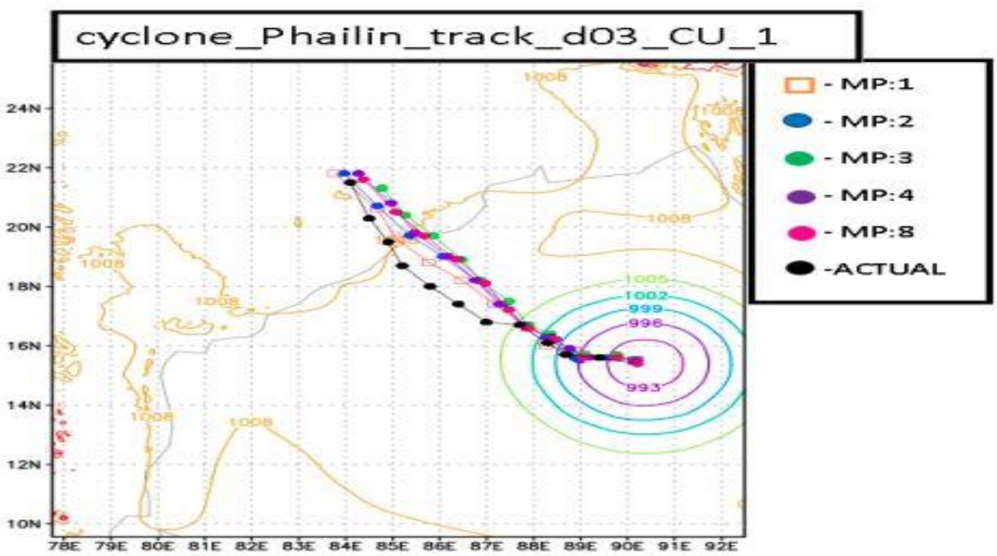

Fig 4: Phailin Track Simlations with Different Microphysics and Cumulus Parameterization Schemes (CPS: Kain-Fritsch (KF) scheme - cu option=1)

Results and Discussions

Figures 5 and 6 show, respectively, the simulated track of the Hudhud cyclone and the accompanying track error analysis for several microphysics parameterization approaches. The Planetary Boundary Layer (PBL) scheme remained constant at YSU, whereas the Cumulus Parameterization Scheme (CPS) was continually set to the G3D scheme during the whole WRF model simulations.

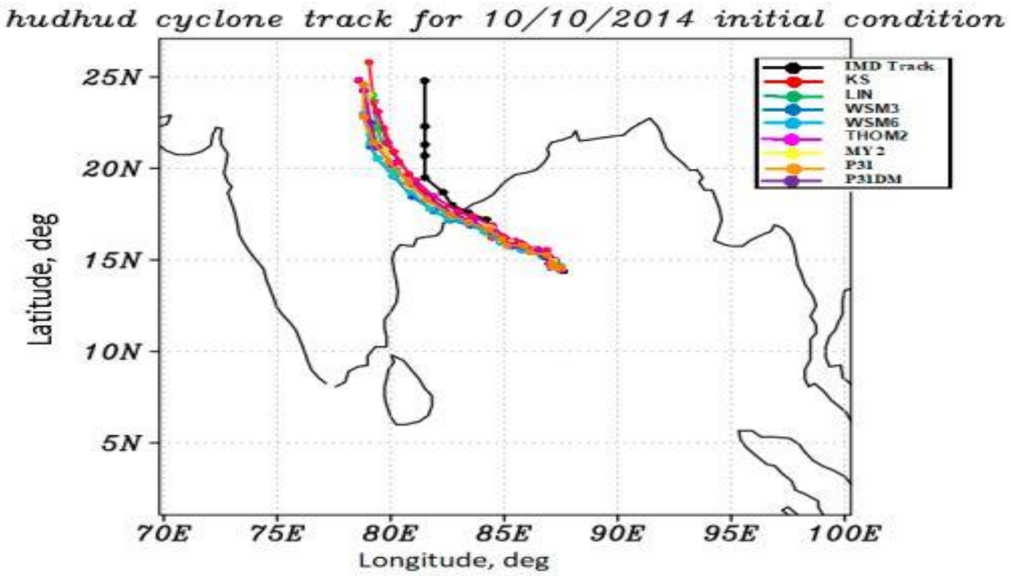

Fig 5: Hudhud Tropical Cyclone Track with Various Microphysics Parameterization Schemes (MPS) and Fixed Cumulus Parameterization Scheme (CPS: G3D)

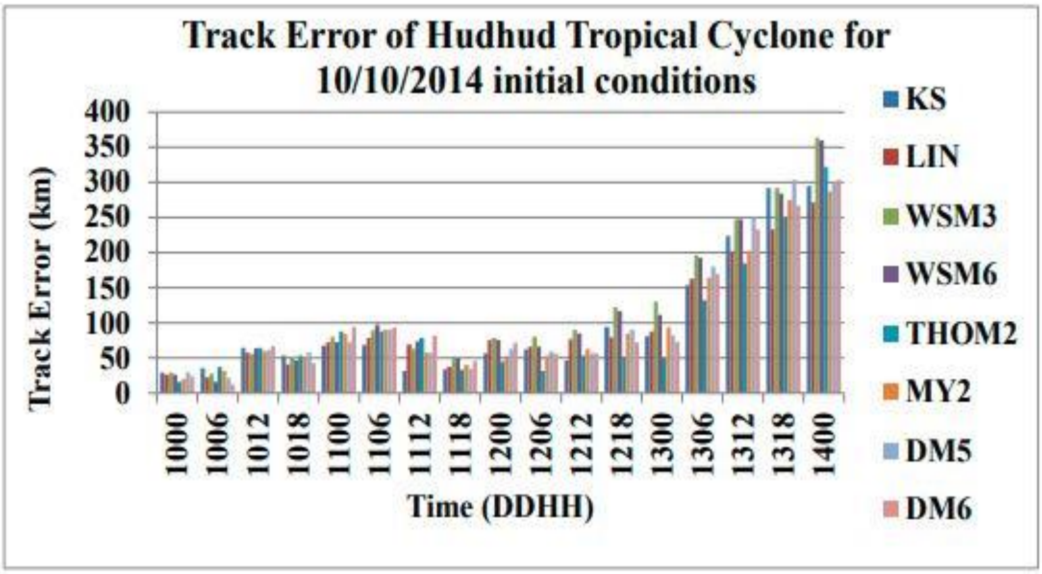

Fig 6: Hudhud Tropical Cyclone Track Error for Initial Conditions on October 10, 2014

All of the models showed increased accuracy in predicting the Hudhud Tropical Cyclone's initial track position on October 10, 2014, at 0000 UTC. Up until the cyclone made landfall, the model's track prediction held true. The model's track forecasts started to diverge more from the actual track seen by the India Meteorological Department (IMD) after landfall, though. Figure 6 shows the Root Mean Square Error (RMSE) for the Hudhud Tropical Cyclone's track as a quantitative indicator of the model's track forecast precision.

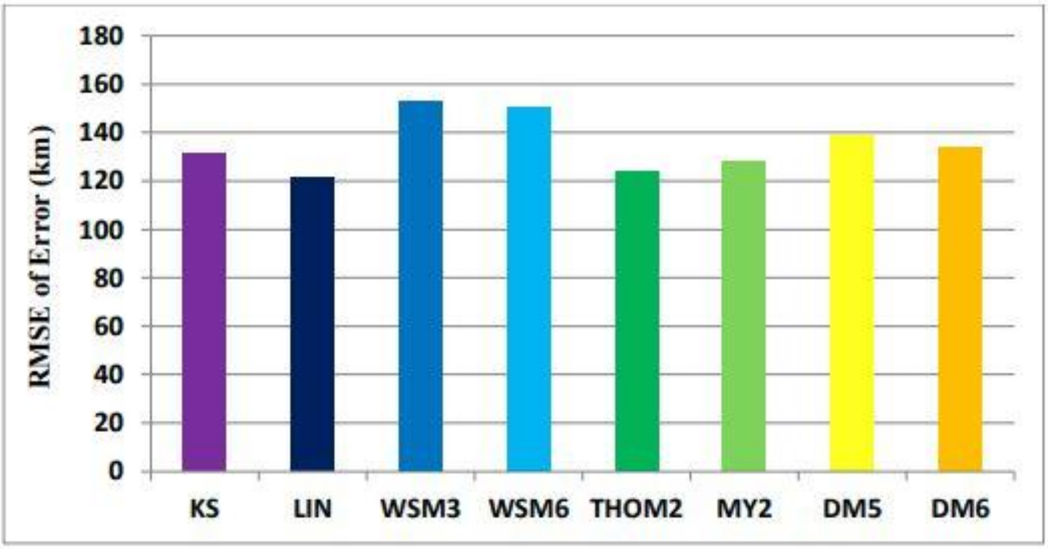

Fig 7: Root Mean Square Error (RMSE) of Hudhud Tropical Cyclone Track Error Using GFS Data

Tropical Cyclone Phailin had a devastating impact on the state of Odisha, causing extensive damage and fatalities. Tropical Cyclone Phailin's origins can be linked to an initial region of low pressure that existed over the Andaman Sea in the Bay of Bengal at the beginning of October 2013. It developed into a powerful cyclonic storm over time. On October 12, 2014, Phailin made landfall close to the town of Gopalpur along the coast of Odisha. With and without Sea Surface Temperature (SST) updates, the WRF model was used to better comprehend and forecast Phailin's trajectory. Figure 8 depicts the forecast trajectories for Tropical Cyclone Phailin in both scenarios. The track error analysis for Phailin with and without SST updates is also shown on Figure 9. These comparisons provide insightful information on how SST updates affect the precision of track predictions.

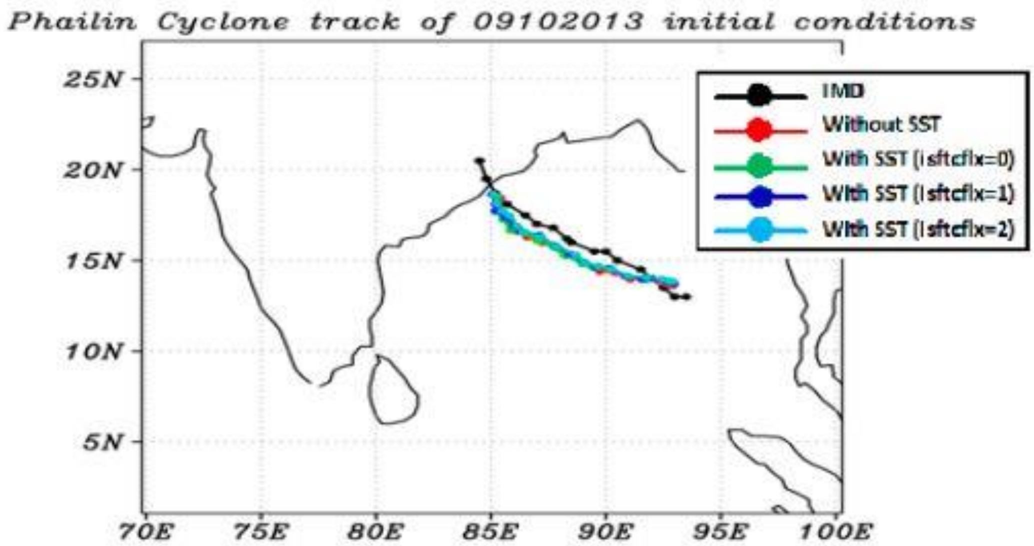

Fig 8: Phailin Cyclone Track Simulation with Sea Surface Temperature (SST) Update

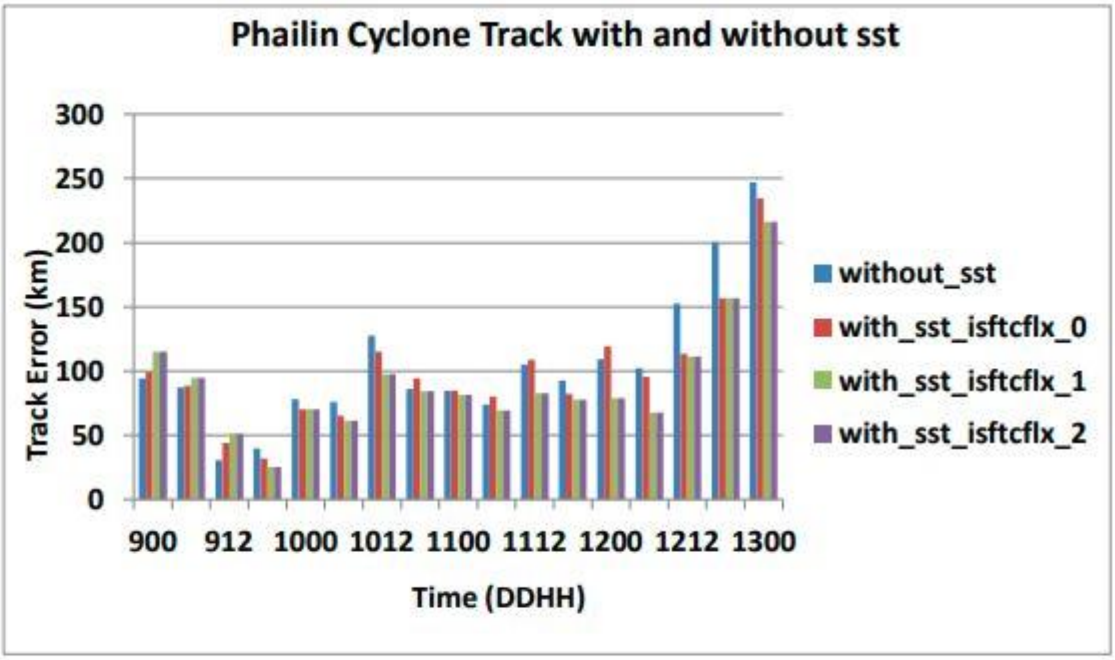

Fig 9: Phailin Cyclone Track Error Comparison with and without Sea Surface Temperature (SST) Update

Tropical Cyclone Vardah track simulations were subjected to a Root Mean Square Error (RMSE) analysis both with and without Sea Surface Temperature (SST) updates running on the WRF model. Figure 9 shows the outcomes of these RMSE track comparisons.

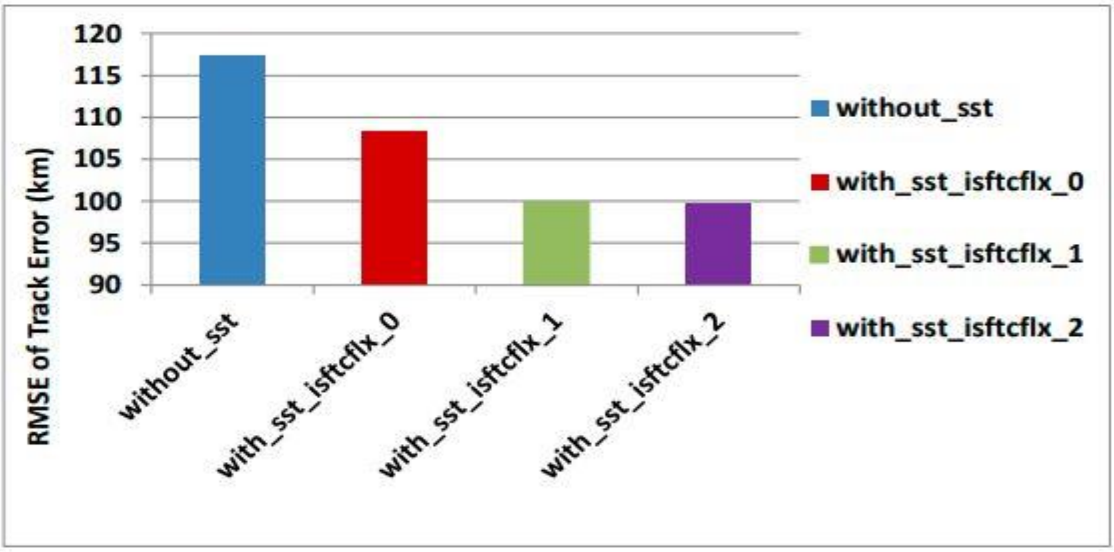

Fig 10: Root Mean Square Error (RMSE) of Phailin Tropical Cyclone Track with and without Sea Surface Temperature (SST) Update Compared to IMD

Conclusion

As a result of our thorough examination of the Hudhud and Phailin cyclones, as well as our investigation of multiple parameterization schemes and SST updates, we now have a more nuanced understanding of tropical cyclone track forecasts. We have seen how several elements interact and how this affects the precision of predictions. Initial track estimates were optimistic, particularly when supported by SST data, but discrepancies after impact point to the need for further study and model improvement. Our study adds to the larger initiatives targeted at boosting preparedness and response strategies to lessen the destructive effects of these natural disasters. These efforts are ultimately aimed at improving our capacity to anticipate tropical storm tracks. Combining ensemble-based forecasting with remote sensing technologies These efforts will ultimately strengthen our preparedness and response capabilities to lessen the terrible effects of these natural catastrophes. They will also contribute to larger initiatives targeted at improving our capacity to predict the paths of tropical cyclones.

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