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Performance of land surface schemes on simulation of land falling tropical cyclones over Bay of Bengal using ARW model

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सार — वर्तमान अध्ययन में उष्णकटिबंधीय चक्रवातों (TC) की प्रमुख विशेषताओं - मार्ग, औसत समुद्र स्तर दबाव (MSLP), अधिकतम निरंतर हवा (MSW) और वर्षा के अनुकरण पर भूमि सतह मॉडल (LSM) भौतिकी के प्रदर्शन को शामिल किया गया है। 12 दिसंबर 2016 को चेन्नई के पास तमिलनाडु तट को पार करने वाले प्रचण्ड चक्रवाती तूफान (SCS) 'वरदा' और अत्यंत प्रचण्ड चक्रवाती तूफान (ESCS) 'फानी' जो 03 मई 2019 को पुरी के करीब ओडिशा तट को पार करने वाले तूफान के लिए चार LSM योजनाओं – तापीय विसरण, नोह, RUC और नोह-MP के प्रभाव का मूल्यांकन किया गया है।

इस उद्देश्य के लिए, बंगाल की खाड़ी वाले 9 किमी क्षैतिज विभेदन के एकल डोमेन के साथ उन्नत मौसम अनुसंधान और पूर्वानुमान (एआरडब्ल्यू) मॉडलको आकार दिया गया है। मॉडल एकीकरण की प्रारंभिक और पार्श्व सीमा पस्थितियाँ राष्ट्रीय पर्यावरण पूर्वानुमान केंद्र (NCEP) अंतिम विश्लेषण (FNL) से ली गई हैं। मॉडल अनुकरणीय मार्ग को दोनों मामलों के लिए भारत मौसम विज्ञान विभाग (IMD) द्वारा देखे गए मार्ग से सत्यापित किया गया है। थल प्रवेश स्थान पर मॉडल सिम्युलेटेड अधिकतम निरंतर हवा (MSW) और न्यूनतम समुद्र स्तर दबाव (MSLP) को पांचवीं पीढ़ी के ECMWF पुन: विश्लेषण (ERA5) उत्पादों के IMD के सर्वोत्तम अनुमान के साथ मान्य किया गया है। इसकी पुष्टि के लिए दोनों चक्रवातों से जुड़ी वर्षा की तुलना ERA5 और वैश्विक वर्षा मापन (GPM) वर्षा से की गई है।

टीसी वरदा और फानी का मार्ग सभी चार भूमि सतह योजनाओं के साथ अच्छी तरह से अनुकरणीय है, जिसमें सिस्टम काथल प्रवेश और थल प्रवेश के समय में उचित सटीकता है। एकीकृत नोह LSM योजना के लिए अलोंग ट्रैक एरर (ATE) और क्रॉस ट्रैक एरर (CTE) न्यूनतम हैं। एकीकृत नोह योजना से थल प्रवेश स्थिति त्रुटि (केवल लगभग 2 किमी) में काफी सुधार हुआ है। वर्षा के पूर्वानुमान के मामले में, LSM दोनों प्रणालियों के थल प्रवेश के दौरान वर्षा का अधिक अनुमान लगाते हैं। यह भी देखा गया है कि तट की तुलना में अंतर्देशीय क्षेत्र की ओर अधिक आकलन किया गया है। सभी चार LSM में से, RUC से वर्षा का अनुमान थल प्रवेश के दौरान GPM और ERA5 वर्षा अनुमान के सबसे करीब है। इसके अलावा, RUC योजना अन्य मानकीकरण योजनाओं की तुलना में सिस्टम के थल प्रवेश के दौरान MSLP और MSW के संदर्भ में चक्रवातों को तेज करती है।

ABSTRACT. The present study encompasses the performance of Land Surface Model (LSM) physics on simulation of Tropical Cyclones (TCs) key characteristics - track, mean sea level pressure (MSLP), maximum sustained wind (MSW) and rainfall. The impact of four LSM schemes - Thermal Diffusion, Noah, RUC and Noah-MP, is evaluated for the simulation of Severe Cyclonic Storm (SCS) 'Vardah' that crossed Tamil Nadu coast, near Chennai on 12 December, 2016 and Extremely Severe Cyclonic Storms (ESCS) 'Fani' that crossed Odisha coast, close to Puri on 03 May, 2019.

For this purpose, the Advanced Weather Research and Forecasting (ARW) model, configured with a single domain of 9 km horizontal resolution covering the Bay of Bengalis considered. The initial and lateral boundary conditions to the model integration are taken from National Centers for Environmental Prediction (NCEP) Final Analysis (FNL). The model simulated track is verified with India Meteorological Department (IMD) observed track for both the cases. The model simulated MSW and MSLP at the landfall location is validated with IMD best estimation along with fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis (ERA5) products. The rainfall associated with both the cyclones are compared with ERA5 and Global Precipitation Measurement (GPM) rainfall for its validation.

The track of TCs Vardah and Fani are well simulated with all the four land surface schemes with reasonable accuracy in landfall position and time of landfall of the systems. The Along Track Error (ATE) and Cross Track Error (CTE) are minimal for the unified Noah LSM scheme. The landfall position error (about 2 km only) is significantly improved with the unified Noah scheme. In case of rainfall forecast, LSMs tend to overestimate the rainfall during landfall of both systems. It is also noticed that overestimation is more towards inland than on the coast. Out of all four LSMs, rainfall estimation from the RUC is closest to the GPM and ERA5 rainfall estimates during landfall. In addition to this, RUC scheme intensifies the cyclones in terms of MSLP and MSW during the landfall of the system as compared to the other parameterization schemes.

Key words – Land falling Tropical Cyclone, ARW, Land Surface Models, Track Error, CTE, ATE.

1. Introduction

The representation of land surface processes in climate simulations poses one of the largest uncertainties, as there is a lack of observations to calibrate or constrain them. Different land surface schemes use quite different parameterizations to describe the complex hydrological, bio-geophysical and bio-geochemical processes. Even when applied with the same parameter settings and the same atmospheric forcing, different land surface schemes can still give significantly different surface fluxes. These surface fluxes are the essential input for enthalpy and moisture equations in the numerical modeling. The land surface schemes are also responsible for the model predicted surface parameters such as dew point and low-level cloudiness. Further, the surface conditions are responsible to provide adequate feedback mechanisms for the other physical processes in the atmosphere - low level cloudiness influences the surface radiative balance, sensible heat and latent heat fluxes influence the boundary layer exchanges and hence the moist convective processes in the atmosphere. Therefore, it is very important to study the effect of different land surface schemes on simulations of atmospheric extremes such as tropical cyclones, heavy rainfall etc. and associated key characteristics.

Numerous studies have discussed cyclone characteristics through diagnostics and Weather Research and Forecasting (WRF) modeling studies (Mohanty and Gupta, 1997; Gupta, 2006; Routray *et al*., 2016a; Osuri *et al*., 2011, 2012; Mohanty *et al*., 2004, 2010; Nasrol *et al*., 2012; Parker *et al*., 2014; Biswadip, 2014; Chauhan *et al*., 2018). Several researchers have studied the role of sub-surface and surface properties in near-surface meteorology and PBL development (Betts *et al*., 1996; Raupach, 2000; Maxwell *et al*., 2007). Alapaty *et al*. (1997) showed that soil moisture is an important surface parameter that regulates the atmospheric surface energy balance and thus has significant impacts on the vertical distribution of turbulent heat fluxes and the boundary layer structure. Several studies have also examined the role of the PBL scheme in WRF model (Storm and Basu, 2010; Draxl *et al*., 2012) as the PBL characteristics and their impacts on the triggering convection are strongly influenced by the partitioning of available radiation energy into sensible and latent heat, which itself is determined by soil moisture. The studies on impact of land surface processes for diverse weather extremes using different modelling framework such as MM5, WRF, HWRF etc. are available (Singh *et al*., 2007; Thomas *et al*., 2014; Zu-Heng *et al*., 2014; Zhang *et al*., 2019; 2021, Reddy *et al*., 2020; Nellipudi *et al*., 2022 etc). Singh *et al*. (2007) studied the influence of different land surface processes on Indian summer monsoon circulation using MM5 model and suggests that Noah scheme is performing better than other parameterization schemes in terms of distribution of precipitation and associated monsoon characteristics. There are a few studies that have specifically looked at how different land surface parameterization impacts the forecasting of various cyclone parameters (Zhang *et al*., 2019; 2021, Jin *et al*., 2010; Nellipudi *et al*., 2022). Zhang *et al*. (2019) used the Hurricane WRF (HWRF) model to investigate the features of pre-landfall tropical storm over Atlantic, and highlights the importance and uncertainty of soil moisture in numerical modelling of landfalling hurricanes during and its further evolution after the landfall processes. Further, Zhang *et al*. (2021) studied the land surface diurnal effects on asymmetric structure of tropical storm and suggests the model simulated storm with the Slab land-surface scheme is stronger, with faster eastward movement and presenting more asymmetric structures than that with the Noah land-surface scheme. Nellipudi *et al*. (2022) studied the impact of the moisture and land surface processes for the cyclone Yemyin using the Advanced Research WRF (ARW) model and suggests that RUC scheme gives significant results for intensification of the cyclone. However, time to time the land surface models incorporate new processes

TABLE 1

Summary of TCs Vardah and Fani used in the study

S. No.	Cyclone Name	Landfall Time (UTC)	Duration of the System	Simulation Dates
1.	FANI (ESCS)	Crossed Odisha coast, close to Puri between 0230 to 0430 UTC on 03 May 2019	26 April 2019 to 04 May 2019	Start_date=2019-05-01_00 UTC End_date=2019-05-04_18 UTC
2.	VARDAH (VSCS)	The VSCS crossed the north Tamil Nadu coast, near Chennai from 0950 - 1150 hrs UTC on 12 December 2016	06 - 13 December 2016	Start_date=2016-12-10_00 UTC End_date=2016-12-13_09 UTC

like increase of soil layer, distinct rainfall-snowfall partitioning, snow albedo treatment, vegetation treatment, and surface data in the scheme which are not available in other schemes previously. It is very much essential to carry out the sensitivity studies time to time with modified version of the land surface schemes.

Therefore, the present study focused on the impact of land surface processes on simulation of key characteristics of land-falling tropical cyclones (TCs) over Bay of Bengal using ARW model with four Land Surface Models (LSMs) - Thermal Diffusion, Noah, RUC and Noah-MP. This study analyzed the features of very severe cyclonic storm (VSCS) Vardah and extremely severe cyclonic storm (ESCS) Fani covering the extreme ends of the east coast of India. The Vardah cyclone made landfall in Tamil Nadu and cyclone Fani moved further north and made landfall in Odisha. The study corroborates the findings of Nellipudi *et al*. (2022) and will provide positive feedback to the modelling community in selecting the physical parameterization schemes for their research and further development.

1.1. *Numerical experiments*

Eight numerical simulations are conducted for the above-mentioned cyclones using the ARW model. The ARW model is initialized with Final Analysis (FNL) data sets of National Centers for Environmental Prediction (NCEP) (https://rda.ucar.edu/datasets/ds083.2/) available at horizontal resolution of 1.0° × 1.0° latitude-longitude grid at 6-hr interval. The model topography, vegetation and land use are taken from United States Geological Survey (USGS) Global datasets at 30sec horizontal resolution. These datasets are downloaded from the website(https://www2.mmm.ucar.edu/wrf/users/download/get_sources_wps_geog.html).

Table 1 summarizes the experimental set-up with specifying the name, landfall time and the details on model initialization. The observed storm intensity and track position is taken from the India Meteorological Department (IMD) report of respective cyclones for comparison of the model results.

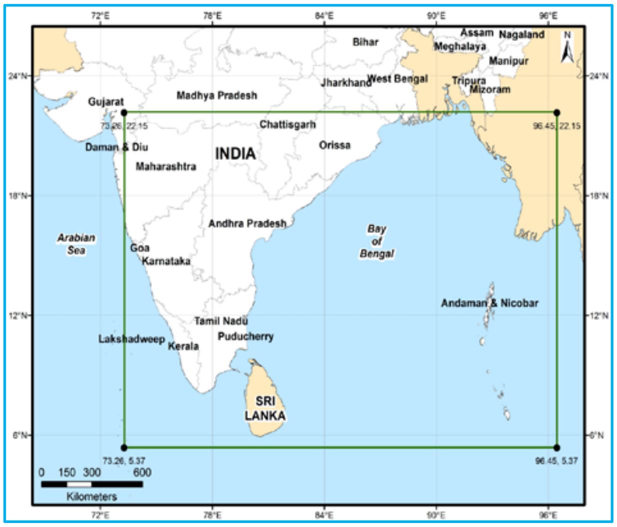


Fig. 1. WRF Model domain used for the present study

2. Methodology and study area

In the present study, the ARW model is configured with 9-km horizontal resolution with the grid dimension of 280 × 210 points in east-west and north-south direction and covering the entire Bay as shown Fig. 1. In order to better represent the large-scale flow which influences the regional-scale circulations, the model domain is considered from (96.45° E, 22.15° N) over Myanmar to (96.45° E, 5.37° N) beyond Andaman and Nicobar Islands in the East and (73.26° E, 22.15° N) over Gujarat to (73.26° E, 5.37° N) beyond Lakshadweep Islands in Arabian Sea in the West. The impact of four LSM schemes, *viz*., Thermal Diffusion, Noah, RUC and Noah-MP on simulation of key characteristics - track, rainfall, maximum sustained wind (MSW) and Mean Sea Level Pressure (MSLP) are analysed.

TABLE 2

Model configuration used in the present study

Model Physics	Parameters common to all experiments
Cumulus Parameterization	Kain-Fritsch (new Eta) scheme
PBL	YSU scheme
Surface Layer Parameterization	Monin Obukhov scheme
Cloud Microphysics	Ferrier (new Eta)
Long Wave Radiation	Rapid Radiative Transfer Model (RRTM)
Short Wave Radiation	Dudhia Scheme
Land Surface Processes	1(Thermal diffusion scheme), 2(Unified Noah land-surface model), 3(RUC land-surface model), 4(Noah-MP land-surface model)
Model Dynamics	
Time Integration	3rd order Runga-Kutta time integration
Time Filtering	Robert's Method
Vertical Differencing	Arakawa's Energy Conserving Scheme
Spatial difference scheme	6th order centered difference
Horizontal Diffusion	2nd order over Quasi-pressure, surface, scale selective
Horizontal grid	Arakawa C-grid

2.1. *Brief description of the ARW model*

The ARW model version v3.8.1 is developed with the collaborative efforts of National Center for Atmospheric Research (NCAR), NCEP, the Earth System Research Laboratory, the U.S. Air Force, the Naval Research Laboratory, the University of Oklahoma and the Federal Aviation Administration (FAA). The model physics includes non-hydrostatic, fully compressible equations, and a set of analytical variables including geo-potential, the wind in three dimensions, perturbation measures such as pressure, surface pressure and turbulent kinetic energy. The model also includes prognostic scalars such as cloud water, water vapour mixing ratio etc. The model dynamics have the terrain following hydrostatic-pressure in the vertical coordinate, Arakawa C-grid for the horizontal staggering, third-order Runge-Kutta scheme for time integration. The model supports two-way nesting, spatial discretization and various number of physical parameterization schemes.

In addition to this, the optimum combination of model physics such as Yonsei University (YSU) planetary boundary layer scheme (Hong *et al*., 2006), Kain-Fritsch (new Eta) cumulus convection scheme (Kain 2004), Purde Lin explicit moisture scheme (Lin *et al*., 1983), Ferrier (new Eta) microphysics, Rapid Radiative Transfer Model (RRTM) longwave radiation (Mlawer *et al*., 1997) and Dudhia (1989) scheme for short wave radiation are considered in the present study from the Johari *et al*., (2020). The details of model physics and dynamics employed in the experiments are summarized in Table 2.

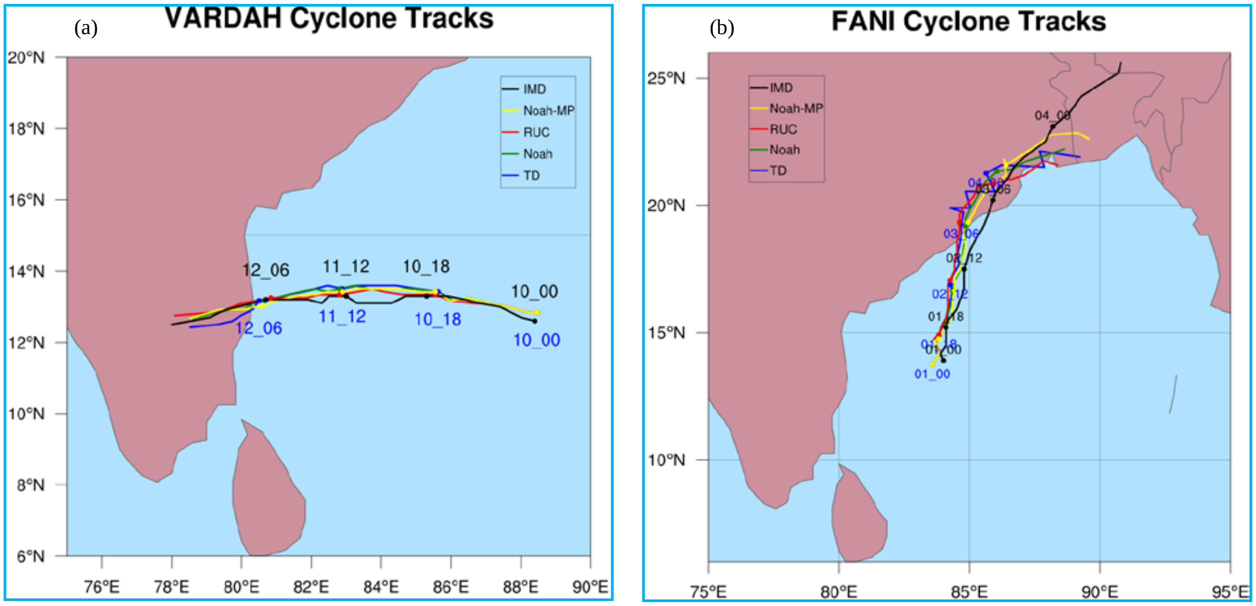
2.2. *Land Surface Model Descriptions*

Thermal Diffusion (TD)

It is the most basic LSM that uses 1-D equations to calculate surface heat fluxes. The soil temperature and moisture are profiled across five soil layers (Blackadar 1978). Temperature profiles are assumed to be linear across the five layers of soil whereas moisture is assumed to be fixed for a specific land use and season-dependent constant value combination. It does not consider explicit vegetation effect and any other soil variables except temperature.

NCEP, OSU, Air Force and Office of Hydrology (NOAH)

The community NOAH LSM is one of the most complex LSMs and was developed through a



Figs. 2(a&b). ARW model simulated tracks along with the IMD observed track for cyclone (a) Vardah and (b) Fani

collaboration of public and private institutions, under the leadership of NCEP (Chen *et al.*, 1996). The scheme predicts soil moisture and temperature at 4 layers going up to 2m, as well as canopy moisture at one layer and water-equivalent snow depth. The upper 1m of soil serves as the root zone depth, and the lower 1m of soil serves as a reservoir with gravity drainage. The scheme defines vegetation using monthly estimates of albedo and the fraction of green vegetation cover. Evapotranspiration takes into account both the physics of water flow through soil and plants and photosynthesis as it is modelled by the Ball-Berry equation.

Rapid Update Cycle (RUC)

It is an advance LSM than the TD scheme. The scheme accurately characterizes soil parameters up to 6-9 soil levels with default parameterization upto a depth of 300 cm. The scheme implemented a well-characterized snow and soil phase change physics (Smirnova *et al.*, 1997). The basic approach is to characterize evapotranspiration from the canopy. The estimation of fluxes from Canopy is implemented using the same equations that are used to compute the transfer of heat and moisture from soil with some adjustments.

NOAH-Multi-parameterization (Noah-MP)

NOAH-MP LSM is a multi-parameterization variation of NOAH LSM. The users can tune the model for dominant processes, either maximize or reduce complexity (Niu *et al.*, 2011). Some of the key enhancements include three options for modeling transpiration due to changes in soil moisture, two options to model conductance through soil matric potential and three levels of complexity for modeling radiation transfer through canopy.

3. Results and discussion

The performance of the land surface schemes in simulation of key characteristics of the TCs Vardah and Fani are analyzed and presented in this section.

The analysis involves the formation, intensification and movement of TCs with model simulation and its validation with IMD observed rainfall, the rainfall observation from Global Precipitation Measurement (GPM) 3B IMERG data, which is available at 0.1° × 0.1° horizontal resolution and temporal resolution of 30 min (Huffman *et al.*, 2014) and 3-hourly rainfall data sets from fifth generation ECMWF Re-analysis (ERA5) obtained from Copernicus Climate Change Service (C3S) at 0.25° × 0.25° resolution (C3S, 2017; Hersbach *et al.*, 2020). The impact of the four LSMs is analysed during and after the landfall of the system and the proficiency of the land surface schemes for TCs landfall processes are evaluated.

3.1. *Simulation of the Cyclone Track*

Fig. 2(a) represents the model simulated track with all the four experiments, initialized at 0000 UTC 10 December, 2016 along with the IMD estimation for the

TABLE 3

Observed and the ARW model simulated landfall location and time and the error associated with model simulations for all the four land surface schemes

Experiments	Initial Conditions of TCs	Landfall Point (°N/°E)		Landfall Time (UTC)		Forecast Error	
		ARW Forecast	Actual IMD	ARW Forecast	Actual IMD	LPE* (km)	LTE* (hrs)
Cyclone Vardah - period 10th to 13th December, 2016							
TD	IC = 10122016	12.7˚N/80.79˚E	13.13˚N/80.3˚E	12/0900	12/1030	20.1	-1.5
Noah	IC = 10122016	12.9˚N/80.81˚E	13.13˚N/80.3˚E	12/0900	12/1030	2.4	-1.5
RUC	IC = 10122016	13.1˚N/81.1˚E	13.13˚N/80.3˚E	12/0800	12/1030	14.2	-2.5
Noah-MP	IC = 10122016	13˚N/80.3˚E	13.13˚N/80.3˚E	12/1000	12/1030	16.3	-0.5
Cyclone Fani - period 1st to 4th May, 2019							
TD	IC = 01052019	18.52˚N/84.72˚E	19.75˚N/85.7˚E	03/0200	03/0330	129.6	-1.5
Noah	IC = 01052019	18.67˚N/84.78˚E	19.75˚N/85.7˚E	03/0430	03/0330	128.5	+1
RUC	IC = 01052019	18.44˚N/84.61˚E	19.75˚N/85.7˚E	03/0000	03/0330	131.9	-3.5
Noah-MP	IC = 01052019	18.49˚N/84.89˚E	19.75˚N/85.7˚E	03/0300	03/0330	122	-0.5

SCS Vardah. The IMD observed track for the cyclone Vardah is referred from (https://rsmcnewdelhi.imd.gov.in/uploads/report/26/26_af079d_vardah.pdf). It may be noticed that the model could simulate the track of Vardah in all the four experiments that well matched with that of the observed track. Fig. 2(b) shows the tracks of the VSCS Fani as simulated in all the four experiments as well as the IMD observed track. The IMD observed track for cyclone Fani is referred from (https://rsmcnewdelhi.imd.gov.in/uploads/report/26/26_7122ae_Preliminary%20Report%20on%20ESCS%20FANI_15082020.pdf). The model simulated track from all the four schemes closely followed the observed track throughout the life-span of the TC. It may be noticed that all four schemes are very close to each other over the Ocean, however, difference in the tracks is noticed during and after the landfall of the system. This is mainly attributed due to the variation in flux estimation and difference in number of surface layers among the land surface parameterization schemes. In addition to this, the variability in surface roughness and moisture extent plays a crucial role on the track of the cyclone. The impact of the land surface models for the landfalling TCs is demonstrated in Routray *et al*. (2023) and similar results are observed in the present study.

Table 3 shows the model simulated landfall point and time error associated with four LSM experiments for tropical cyclones Vardah and Fani. The error table clearly shows that for both the cyclones, the experiment with NOAH-MP land surface Scheme performed better in terms of landfall time and closer to the IMD observation. However, none of the LSM models consistently performs well in simulation of landfall location. In the case of the Fani cyclone, NOAH-MP LSM simulated landfall location and time was closer to observation as compared to other models. Similarly, in the case of the Vardah cyclone the unified NOAH LSM simulated landfall location was closer to observation as compared to other experiments. The +ve and -ve sign in the landfall time error (LTE) corresponds to the delay and early landfall of the system, respectively.

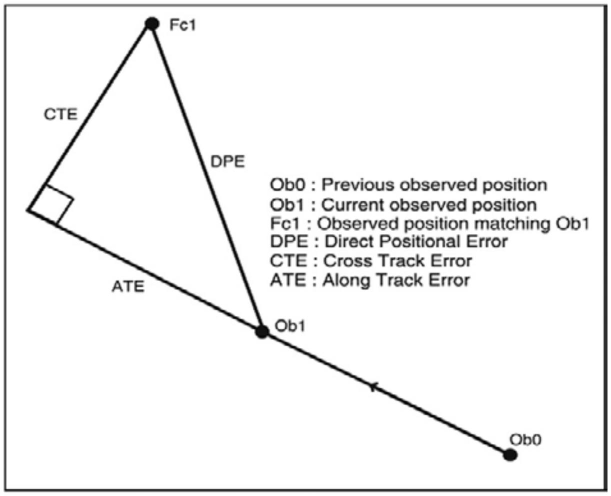
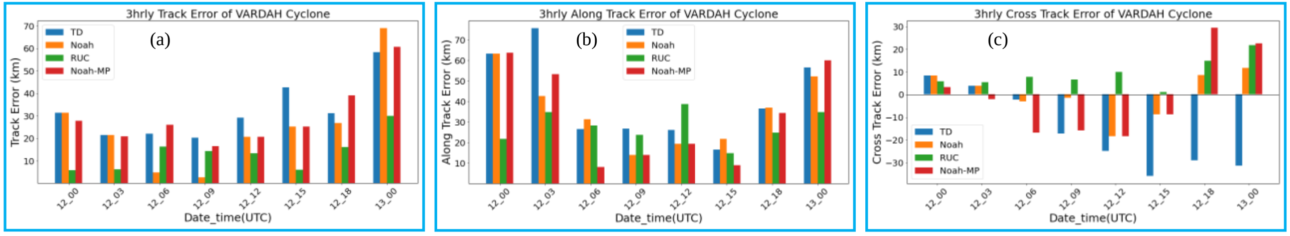


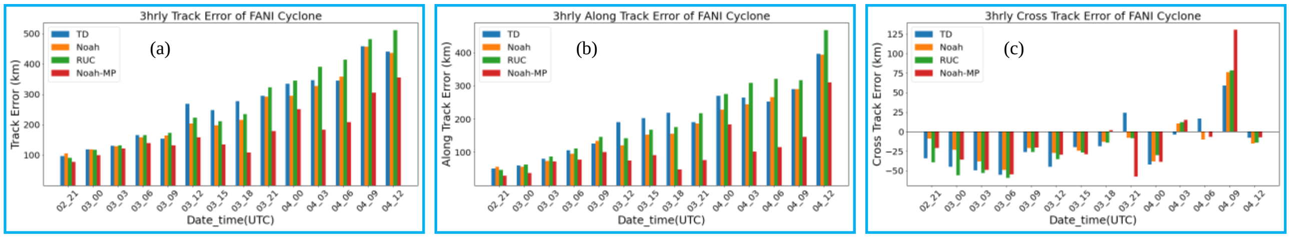
Fig. 3. Schematic representation on model predicted track errors in terms of Direct Positional Error (DPE), Along Track Error (ATE) and Cross Track Error (CTE) (Source: Heming 2016)

The error in the model simulated track is analyzed in terms of Direct Positional Error (DPE), Along Track Error (ATE) and Cross Track Error (CTE). The positive

Direct Positional Error Along Track Error Cross Track Error



Vardah



Fani

Figs. 4(a-c). (a) Direct Positional Error (km), (b) Along Track Error (km) and (c) Cross Track Error (km) associated with cyclones Vardah and Fani w.r.t. the IMD observed track positions

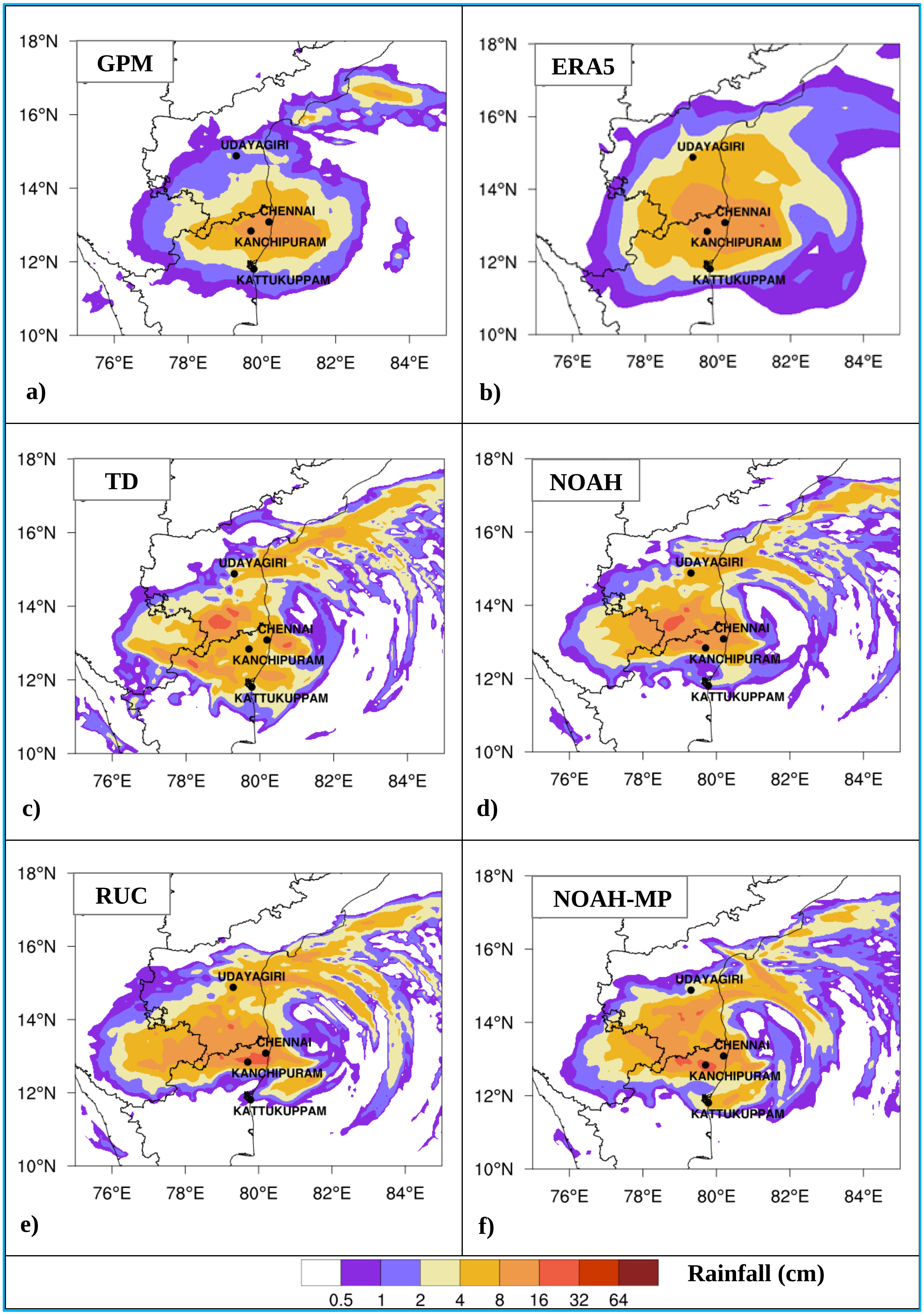
(negative) values of ATE indicate that the forecasted TC position lies ahead (behind) as compared to the observed track position, *i.e*., the faster (slower) forecast movement than in observation, whereas positive (negative) values of CTE indicate that the forecasted track is to the right (left) of the observed track. The CTE represents the spatial spread of the model simulated tracks, whereas ATE measures the perpendicular distance of the observed track position from the forecast track position. The schematic representation of DPE, ATE and CTE are described in Heming (2016) and same has been presented in Fig. 3. The DPE (km), ATE (km) and CTE (km) are calculated with respect to the corresponding IMD observed track locations and presented in x Fig. 3. The upper panel demonstrates the error associated with the Vardah cyclone. It may be noticed that the unified Noah scheme produces less DPE and ATE as compared to other land surface schemes. The CTE from the Noah scheme produces positive error throughout the model integration, whereas, the RUC and Noah MP schemes provide negative error initially over the ocean and positive error afterwards. The Thermal diffusion scheme provides higher CTE than any other schemes.

Analysing the ATE (Fig. 4), it is observed that values for all simulations are mostly positive. This indicates that the forecasted track moves slower as compared to the observed track. The CTE (Fig. 4) values for Vardah are positive throughout for Scheme 3 (RUC LSM) whereas other schemes turn negative immediately after landfall, which indicates that all schemes except scheme3 (RUC) turn left to the observed track immediately after landfall. Though, scheme 1 (TD) stays negative 12 hours after landfall, other schemes give positive CTE after landfall. The CTE has been mostly negative for Fani for all simulations (Fig. 4) and it also goes positive for short duration after landfall. Another observation is that all LSMs behave the same; either the simulated track from all LSMs is to the left or to the right of the observed track. This implies that the average ARW forecast track lies to the left of the observed track for nearly all the simulations. This may be interpreted as a bias shown by the ARW model to predict westward movement of the TC over the domain considered. It is also observed that the CTE values are smaller as compared to ATE values for all the forecast lengths. This indicates that the spread of the forecasted track relative to the observed track is less as compared to the distance by which the simulation is ahead of the observed. Also, mostly negative CTE values are also indicative of cyclones considered are not straight moving cyclones.

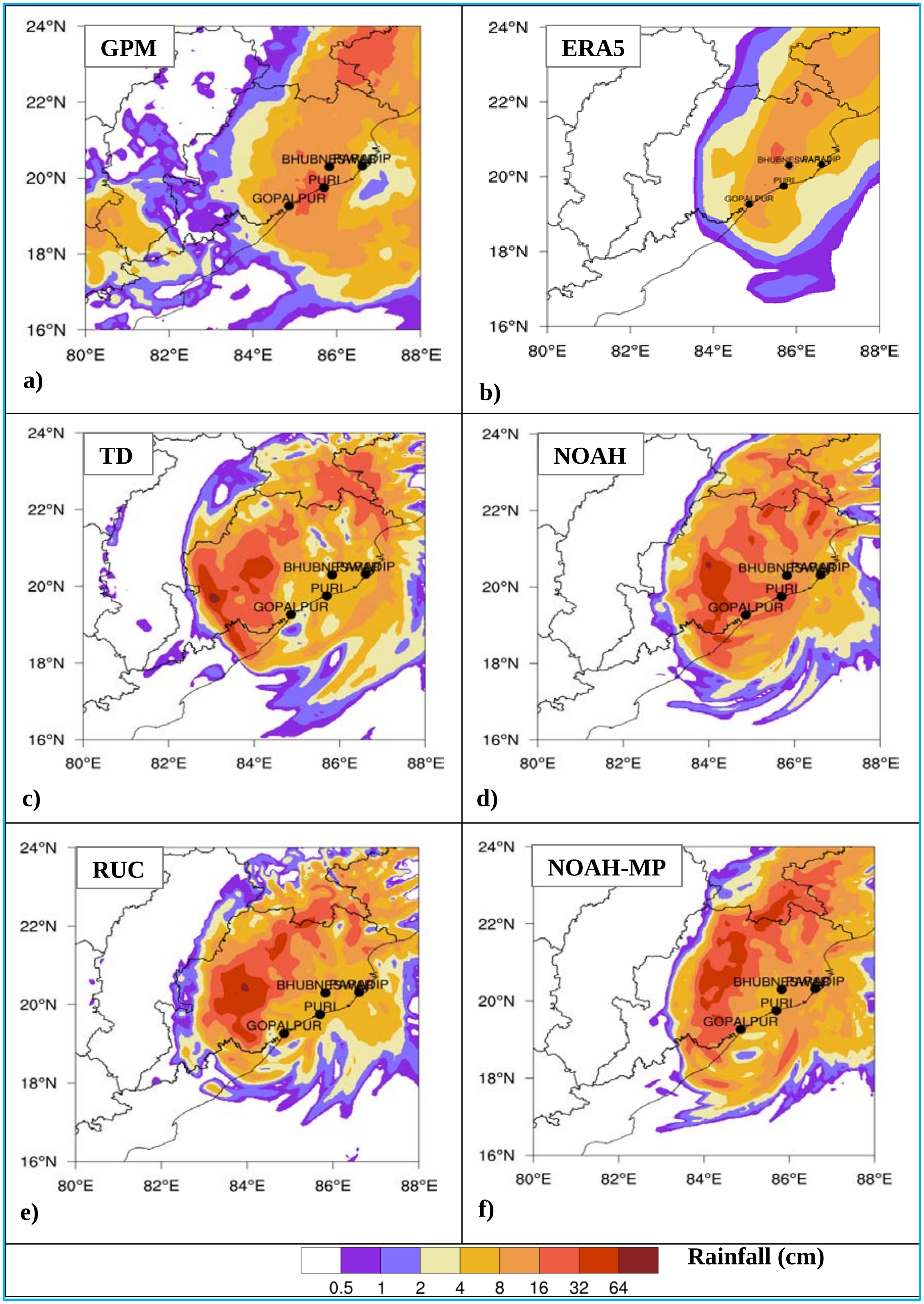
The landfall point and time error are also calculated w.r.t. the observed landfall position and time and presented in Table 3. It is noticed that the unified Noah LSM predicts the landfall error of about 2.4 km for Vardah, which is closest to the observed landfall location. However, in case of Fani the Noah-MP is providing smallest landfall point and time error.

3.2. *Rainfall analysis*

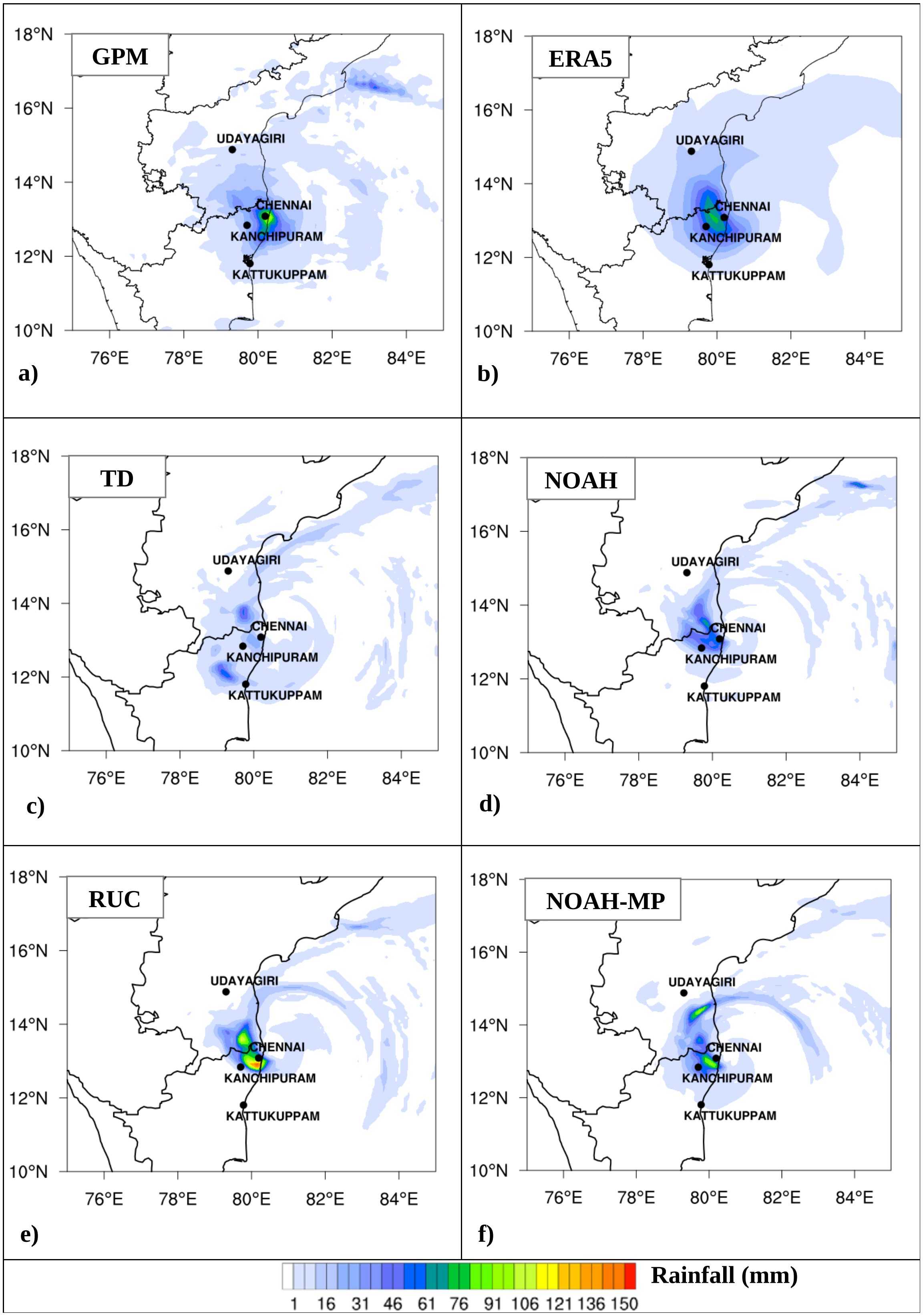
The model simulated accumulated rainfall is analysed and compared with GPM and ERA5 rainfall



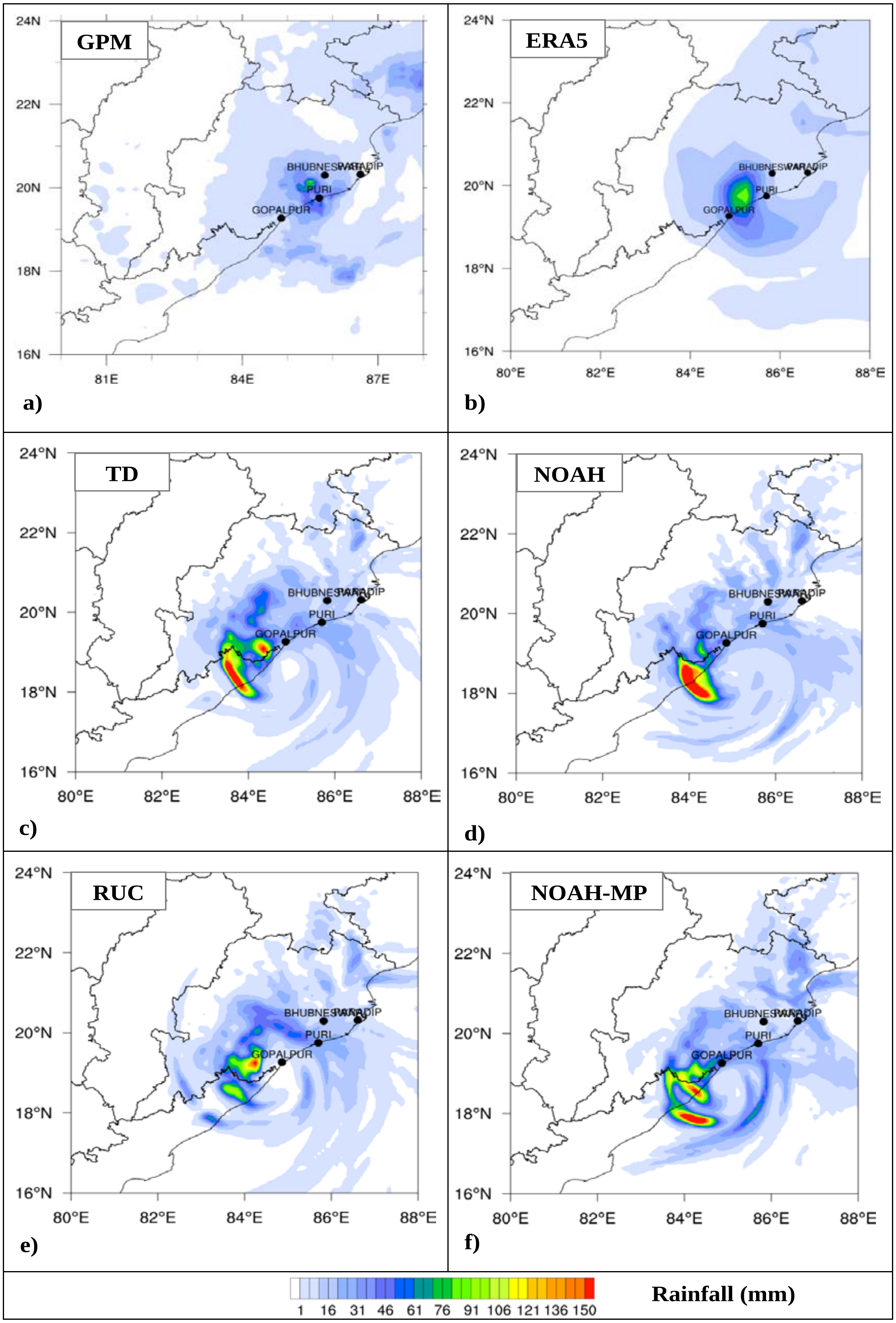
Figs. 5(a-f). Spatial distribution of ARW model simulated daily accumulated rainfall (cm) with different land surface parameterization schemes along with rainfall estimates from GPM and ERA5 re-analysis for cyclone Vardah



Figs. 6(a-f). Spatial distribution of ARW model simulated daily accumulated rainfall (cm) with different land surface parameterization schemes along with rainfall estimates from GPM and ERA5 re-analysis for cyclone Fani



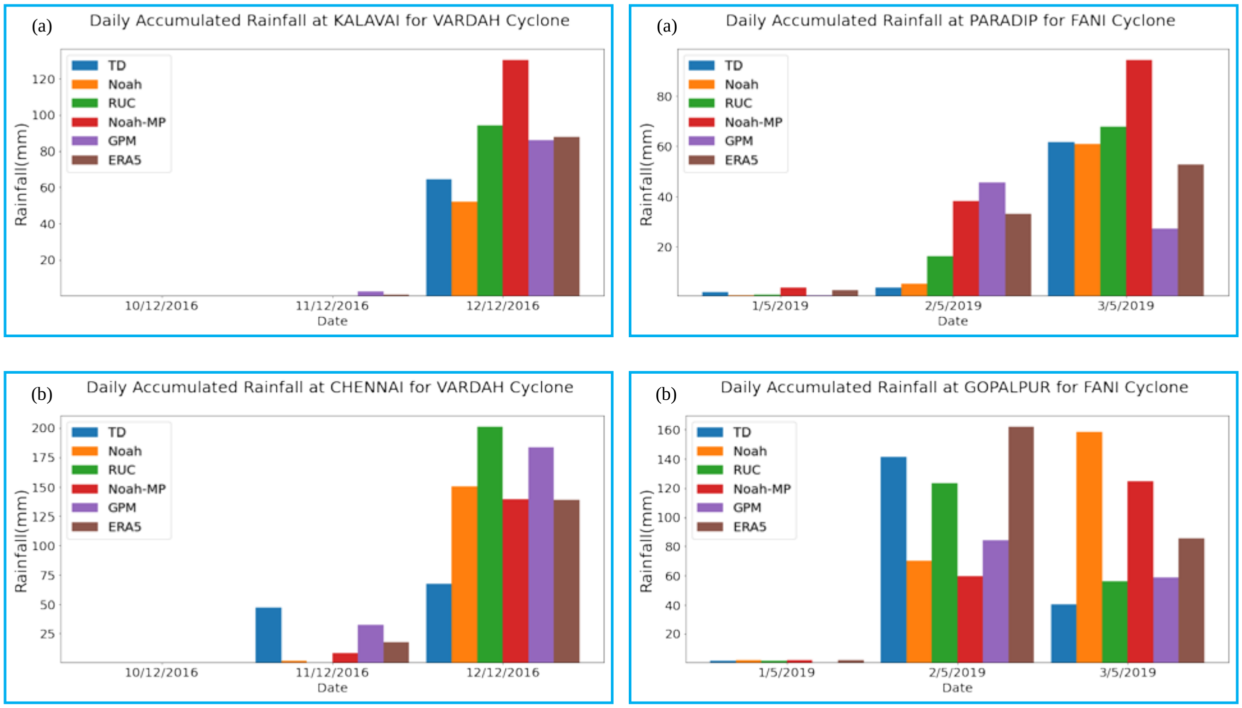
Figs. 7(a-f). Spatial distribution of ARW model simulated 3-hourly accumulated rainfall (mm) with different land surface parameterization schemes along with rainfall estimates from GPM and ERA5 re-analysis for cyclone Vardah



Figs. 8(a-f). Spatial distribution of ARW model simulated 3-hourly accumulated rainfall (mm) with different land surface parameterization schemes along with rainfall estimates from GPM and ERA5 re-analysis for cyclone Fani

Daily Accumulated Rainfall for Vardah Cyclone

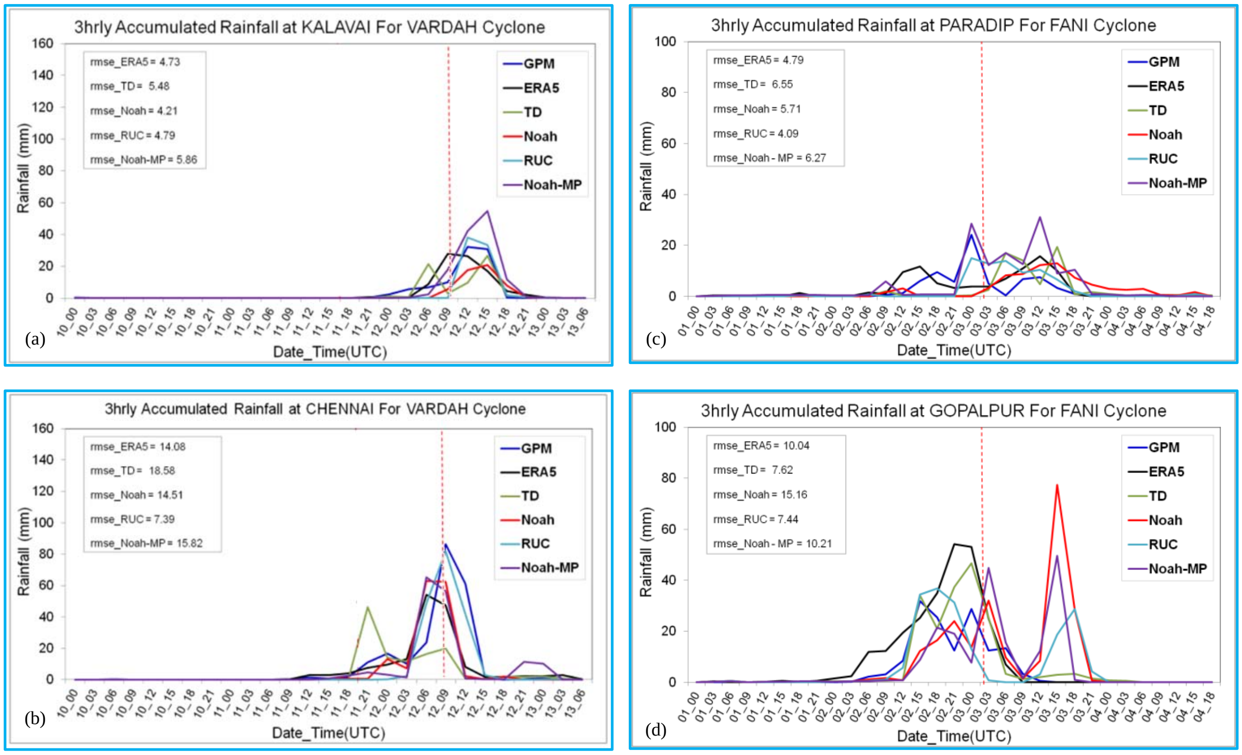
Daily Accumulated Rainfall for Fani Cyclone



Figs. 9(a&b). Validation of daily accumulated rainfall (mm) at Kalavai and Chennai for cyclone Vardah and at Paradip and Gopalpur for cyclone Fani along with GPM and ERA5 data sets

Three hourly Accumulated Rainfall for Vardah Cyclone

Three hourly Accumulated Rainfall for Fani Cyclone



Figs. 10(a-d). Model Simulated three-hourly accumulated rainfall (mm) and its validation with GPM and ERA5 observation and re-analysis, respectively estimates and presented in this section. Fig. 5 represents the spatial distribution of 24 hrs accumulated rainfall for TC Vardah valid for 12th December, 2016, the landfall day of the system, which indicates that all the schemes have well captured the overall rainfall amount, and apparently comparable with GPM and ERA5 estimated rainfall. However, some small pockets of heavy rainfall are seen in model simulations with all the land surface parameterization schemes. Fig. 6 represents the spatial distribution of 24 hrs accumulated rainfall for cyclone Fani valid for 3rd May, 2019. In case of Fani, all the LSMs overestimate the rainfall amount, and the maximum rainfall is more away from the coast. Along the coast, scheme 3 (RUC) aligns very well with GPM and ERA5, followed by scheme 4 (Noah MP). The model simulated 3 hrs accumulated rainfall is also analysed at the landfall time for both the cases and compared with GPM and ERA5 estimated rainfall. Fig. 7 represents the spatial distribution of 3 hourly accumulated rainfall valid at 0900 UTC on 12 December, 2016, the landfall time for cyclone Vardah. The RUC scheme is overestimating the rainfall amount on the land region than any other schemes. Fig. 8 presents the rainfall distribution valid at 0600 UTC 03 May, 2019 for cyclone Fani. The Noah-MP is overestimating the rainfall amount; however, RUC is showing reasonable rainfall and comparable with GPM and ERA5 estimated rainfall.

The model simulated accumulated rainfall is analysed at stations nearby to the landfall location and compared with the GPM and ERA5 data sets. In case of Vardah, 7 nearby stations such as Chennai, Kalavai, Kanchipuram, Kattukuppam, Udayagiri, Atmakur and Tiruvallur are considered. In case of Fani, 5 nearby stations such as Puri, Gopalpur, Bhubaneswar, Paradip and Balasore are considered and analysed. However, rainfall over two stations for each cyclone such as Kalavai and Chennai are presented for Vardah cyclone and Paradip and Gopalpur are considered for Fani cyclone. Fig. 9 demonstrates the model simulated 24 hrs accumulated rainfall at the above-mentioned stations along with the corresponding rainfall values from GPM and ERA5. It is noticed that the model simulated daily accumulated rainfall with the RUC scheme for both Vardah (12 December, 2016) and Fani (03 May, 2019) cyclones are reasonably comparable with the GPM rainfall than other land surface schemes. However, there are significant differences between GPM and ERA5 estimated daily accumulated rainfall values. It is also noted that at majority of the stations, the Noah-MP model overestimated the daily accumulated rainfall in both the cyclones.

Fig. 10 demonstrates the model simulated 3 hourly accumulated rainfall at two stations (mentioned above) for each case and corresponding rainfall estimates from GPM and ERA5, at the landfall time of Vardah and Fani cyclones. The vertical dashed line (red colour) in the figure represents the landfall time of the cyclone. In both the cases, it is observed that the model simulated 3 hourly accumulated rainfall with the RUC land surface scheme matched closely with the GPM rainfall estimates during the closed hours of landfall of systems. It is also noted that the Noah MP land surface scheme over estimates the rainfall forecast for both the cyclones. Fig. 11 and Fig. 12 presents the mean of daily accumulated rainfall estimates across all the stations for TCs Vardah and Fani, respectively. From the figures, it is very evident that scheme 3 (RUC) shows the closest match with both GPM as well as ERA5 daily accumulated mean rainfall values. In the case of the Vardah cyclone, the mean ofall stations for scheme 4 (Noah MP) is also highest, indicating overestimation by the model. Also, in the case of Fani, scheme 4 (Noah MP) overestimated as compared to scheme 3 (RUC). Overall, the rainfall analysis suggests that RUC is best scheme among the all and followed by Noah-MP. The results corroborate the finding of Nellipudi *et al.* (2022).

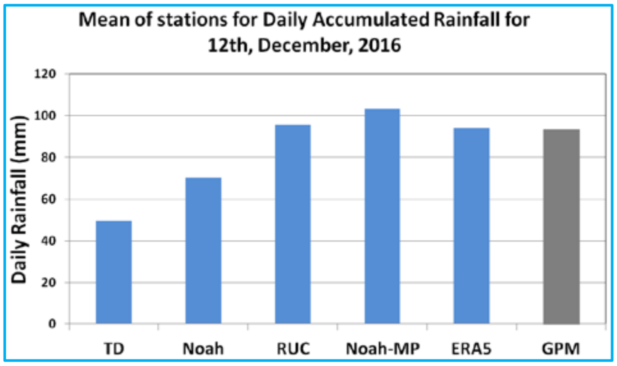


Fig. 11. Mean of daily accumulated rainfall for all stations for cyclone Vardah

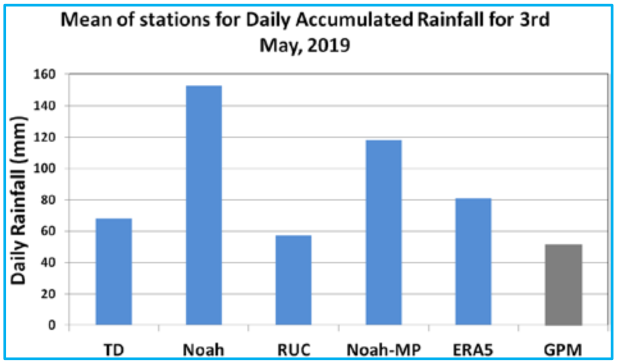
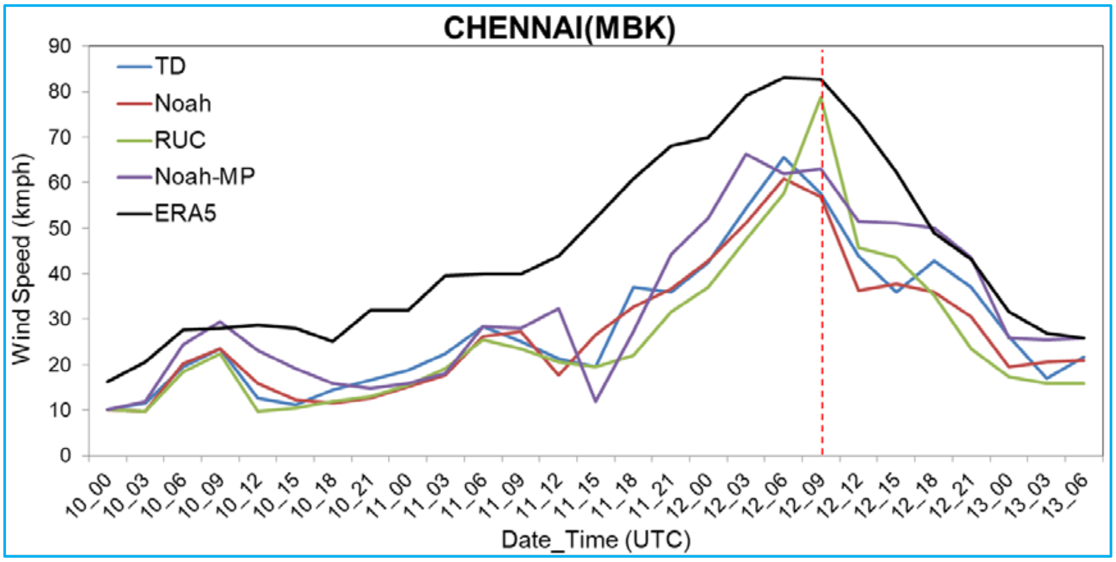


Fig. 12. Mean of daily accumulated rainfall for all stations for cyclone Fani

Station/(Lat./Long.)	Wind Speed (kmph) at 0900 UTC 12 December 2016 (Just Before the landfall of the system)					
	IMD	TD	Noah	RUC	Noah-MP	ERA5
Chennai (MBK)/ (12.98 N/80.18 E)	111	58	57	79	63	83



Station/(Lat./Long.)	Lowest MSLP (hPa) and at 0900 UTC (IMD value at 1000 UTC					
	IMD	TD	Noah	RUC	Noah-MP	ERA5
Chennai (MBK)/ (12.98 N/80.18 E)	975	993.8	994.1	990.5	992.9	1007.3

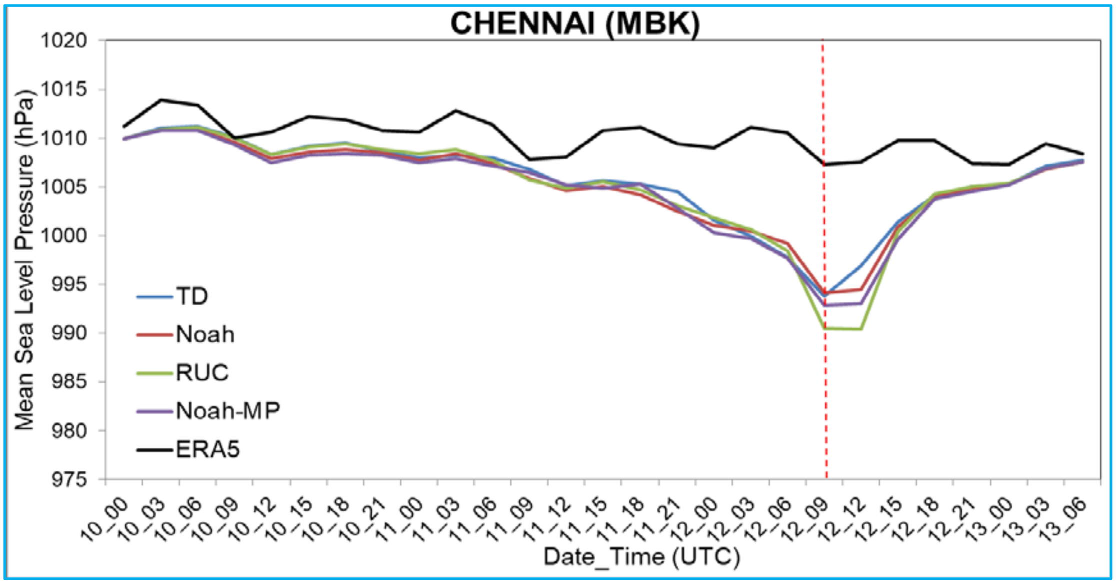
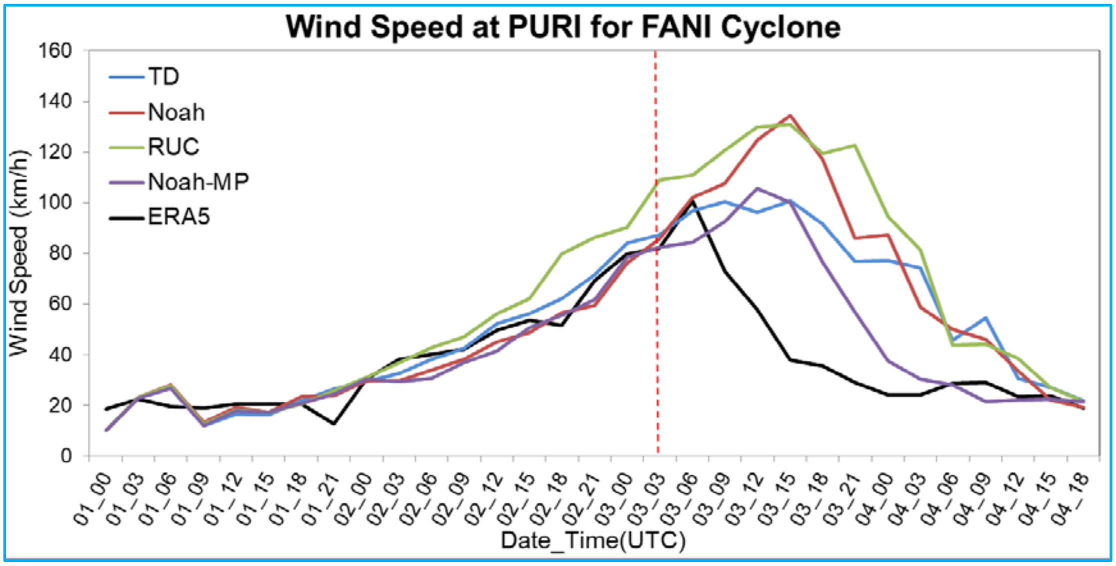


Fig. 13. Validation of ARW model simulated wind speed (kmph) and mean sea level pressure (hPa) with IMD observation at Chennai for cyclone Vardah

3.3. *Maximum Sustained Wind and Mean Sea Level Pressure*

The intensity of the cyclone is analyzed in terms of MSW and MSLP at the landfall time of the cyclones. The model simulated 3 hourly MSW and MSLP are compared with ERA5 estimated values. Also, the model simulated results are compared with India Meteorological Department (IMD) observed MSW and MSLP at Chennai just before the landfall of the system. Fig. 13 shows the comparison of MSW and estimated

LSM Models	Wind Speed (kmph) at landfall time (0400 UTC 03 May)			WRF model simulated maximum wind speed (kmph)
	Simulated	IMD	ERA5	
TD	91.98	175-185	91.44	100.8 (1500 UTC 03May)
Noah	93.78			134.28 (1500 UTC 03May)
RUC	109.8			130.68 (1500 UTC 03May)
Noah-MP	83.34			100.08 (1200 UTC 03May)



LSM Models	MSLP (hPa) at landfall time (0400 UTC 03 May)			WRF model simulated minimum MSLP (hPa)
	Simulated	IMD	ERA5	
TD	989.65	959	984.45	987.4 (1200 UTC 03 May)
Noah	990.3			977.7 (1200 UTC 03 May)
RUC	989.25			984.3 (1200 UTC 03 May)
Noah-MP	989.35			983.5 (0900 UTC 03 May)

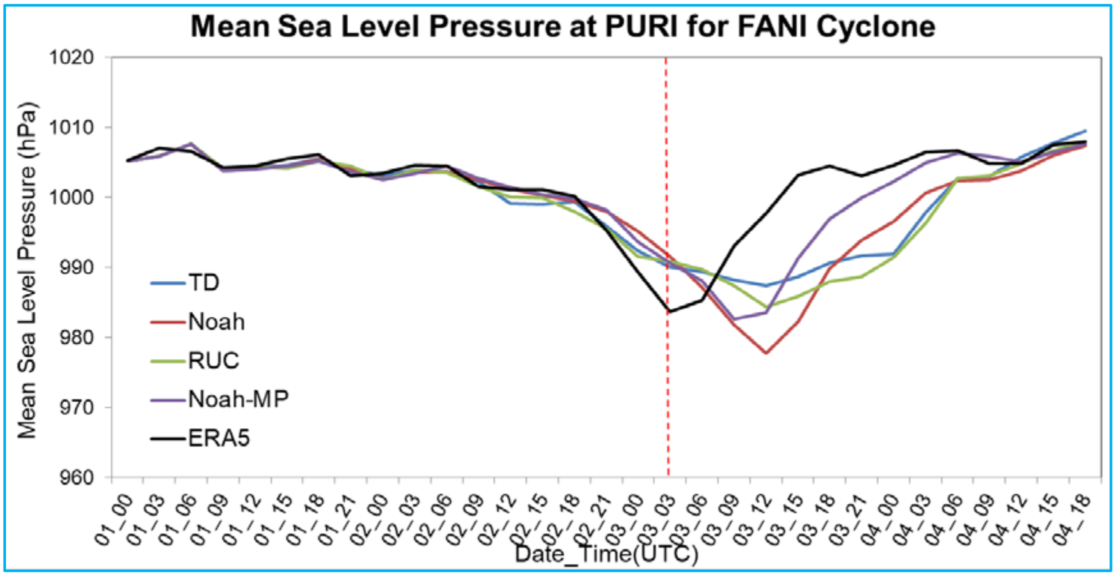


Fig. 14. Validation of ARW model simulated wind speed (kmph) and mean sea level pressure (hPa) with IMD observation at Puri for cyclone Fani

MSLP for cyclone Vardah at Chennai. It is noticed that the RUC scheme could well simulate the MSW at Chennai which is closest with IMD observed MSW and with ERA5. In case of MSLP, the ERA5 does not show any signature of intensification and decay process. However, the model could reasonably simulate the MSLP value with all the four schemes, though it slightly underestimates than that of IMD observed MSLP at Chennai. Fig. 14 demonstrates the MSW and MSLP at Puri, the landfall location for cyclone Fani. It is seen that though RUC does not perform well as of the cyclone Vardah, but it is the best among other land surface schemes, while the sustained wind speeds are the closest to both IMD observed as well as the ERA5 estimates and the maximum winds and minimum MSLP values occur with 9 hours delay. Also, it is seen that the maximum intensity in Noah-MP scheme occurred 3 hours before that of RUC.

4. Conclusions

The present study demonstrates the role of land surface processes in simulation of key characteristics of tropical cyclones using WRF model.

The track of TCs Vardah and Fani are well simulated with all the four land surface schemes with reasonable accuracy at landfall position and time of landfall of systems. All the LSMs perform in a similar way in terms of simulating cyclone tracks that move ahead and to the left of the observed cyclone tracks. There is a systematic bias in the cross-track error from all four LSM schemes, which shows the ARW forecast track lies to the left of the observed track for nearly all the simulations.The ATE and CTE is minimal for the unified Noah LSM scheme. The landfall position (about 2 km only) is significantly improved with the unified Noah scheme.

It is observed that, all the four land surface schemes tend to overestimate the rainfall simulation during the landfall, which corroborates the findings of Jin *et al*. (2010). It is also noticed that overestimation on the land is more than the coast. Out of all four land surface models, rainfall estimation during landfall from the RUC is closest to the GPM and ERA5 rainfall estimates. It is also seen that the RUC scheme intensifying the cyclones in terms of minimum MSLP while moving close to landfall as well as after landfall. The overall analysis suggests that Noah-MP presents least error in the movement of the system while the RUC scheme gives significantly better result for intensification.

The current study uses Land use and Land cover from the global source, United States Geological Survey (USGS). So, in order to better understand the feedback of the sophisticated land surface processes to high resolution Land Use Land Cover, the future study will consider the updated version of Land use and Land cover data over the Indian region from the Indian Space Research Organization (ISRO). Since land surface models use radiative forcing from the radiation schemes, the sensitivity study of radiation physics along with the updated Land use and Land cover should be studied.

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