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Impact of Physics Parameterization Schemes in the Simulation of Laila Cyclone Using the Advanced Mesoscale Weather Research and Forecasting Model

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Abstract

The severe Tropical Cyclone Laila caused extensive damage and loss of life in southeastern India during May 2010. The cyclone developed from a low-pressure system that formed under the influence of an upper-air cyclonic circulation in the Bay of Bengal and intensified into a Severe Cyclonic Storm. The cyclone reached its peak intensity with a minimum central pressure of 974 mbar and reached the maximum sustained wind speed of 120 km/h (64.8 Knots). The cyclone crossed the Andhra Pradesh coast near Bapatla between 1100 and 1200 UTC on May 20. In this present study, the sensitivity of numerical simulations of tropical cyclone Laila to physics parameterizations is carried out with a view to determining the best set of physics options for prediction of cyclones originating in the north Indian Ocean. The latent heat released in the clouds plays very important role in intensifying or strengthening of Tropical cyclones and the latent heat release is mainly dependent on the cloud microphysical and dynamical properties. Three nested domains are considered for WRF model simulation. The resolution of domain-1, domain-2, and domain-3 are 45 km, 15km, and 5 km respectively. The results from the domain-3 are considered for analyzing and comparing the results. Model simulation outputs are compared with corresponding observation data. The simulated track and intensity of tropical cyclone Laila are compared with the real-time data provided by the Joint Typhoon Warning Centre (JTWC). WRF model Simulations are performed using different convective cumulus parameterization (CU) and microphysics parameterization (MP) schemes. The main purpose of the present study is to find the best suitable combination of MP and CU schemes for the simulation of an accurate track of severe tropical cyclone Laila over the Bay of Bengal. It was observed that in the mesoscale model the track and intensity prediction skill predominantly depends on CU and MP parameterization schemes.

Keywords: Laila, WRF Model, physics parameterizations, Cyclone track, Track error

INTRODUCTION

The Very Severe Cyclonic Storm Laila developed from a low-pressure area over North Indian Ocean late on 17th May 2010 and intensified into Cyclone Strom on 18th May and further intensified into a Very Severe Cyclonic Storm (VSCS) in the early morning of 19th May. It continued to intensify while moving north-west direction and reached maximum intensity with a maximum sustained wind speed (MSW) of 120 kmph over the Bay of Bengal of Andhra Pradesh coast on 20th May 2010. It crossed south Andhra Pradesh coast near Bapatla 16.0°N 80.6°E between 1100 and 1200 UTC on 20th May. At the time of landfall on 20th the estimated central pressure was 974 hPa (JTWC 2010) and the estimated maximum sustained surface wind speed was about 70 Knots. It caused very heavy to extremely heavy rainfall over South Andhra Pradesh. Ongole received heavy rain of 32 cm on May 20 and 142 mm on May 21in Andhra Pradesh. On May 21, in 24 hours kothapatnam received rainfall of 258 mm, Maddipadu received rainfall of 510 mm and Addanki received the highest rainfall of 522 mm [1].

The numerical weather prediction (NWP) and dynamical statistical models provided good guidance with respect to its genesis, track, and intensity. The India Meteorological Department (IMD) and the Joint Typhoon Warning Centre (JTWC), USA predicted the genesis, intensity, track, point and time of landfall 5 days in advance. Cyclones developed over warm oceans and under the influence of steering forces cyclone move towards the land [2]. In recent years Indian Meteorological Department adopted various strategies and decision-making process to improve the prediction of tropical cyclones [5]. Different simulation experiments are conducted to examine the performance of the high-resolution Advanced Research Weather Research and forecasting model for tropical cyclone prediction over the Bay of Bengal (BOB) region of the northern Indian Ocean (NIO) [11]. Several experiments conducted to study the impacts of cloud microphysical processes on hurricane track, intensity, precipitation and thermodynamic vertical structural characteristics of hurricane

inner core [7]. Orography and level of nesting also influence the sensitivity of tropical cyclones prediction [4]. The factors influence the cyclogenesis is an increase in sea surface temperature, large Coriolis force, high low-level relative vorticity, moisture in the middle troposphere, weak vertical wind shear, and convective instability. The BOB region of NIO is the high potential zone for the cyclogenesis, with an annual frequency of about five cyclones [10]. Several simulation studies conducted to evaluate Tropical Cyclones with respect to resolution, initial conditions, physics sensitivity and impact of data assimilation [8][12][13][14]. It is considered to be very important to examine the synoptic features of cyclone with different microphysics schemes using Advanced Research Weather Research and Forecasting (ARW-WRF, hereafter WRF) mesoscale model [3][9] developed at National Center for Atmospheric Research (NCAR), because of its superior performance in generating fine-scale atmospheric structures as well as its better forecast skill [6].

DATA AND METHODOLOGY

Numerical Weather Prediction (NWP) model used in cyclone simulation is the Advanced Research WRF (ARW) v 3.6.1 mesoscale model developed by NCAR. NWP is a method of weather forecasting that uses governing equations, different numerical methods, parameterization schemes, different domains and Initial and boundary conditions. The MODIS based terrain topographical data have been used for domain-1, domain-2, and domain-3 in the WRF Preprocessing system (WPS).

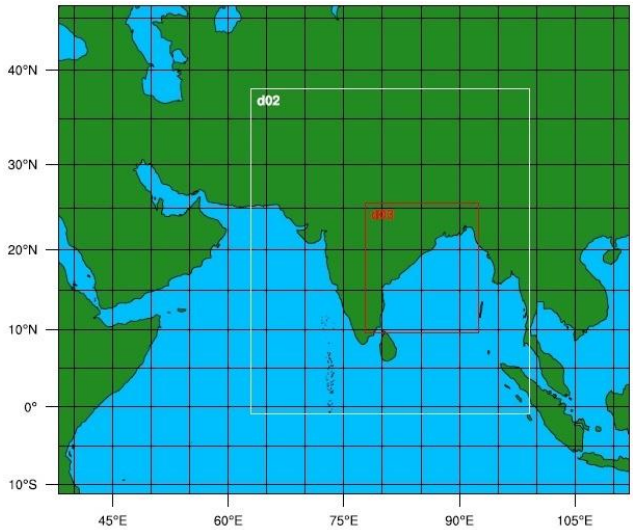


Figure 1: WPS domain configuration used in simulation

The Initial and boundary conditions are obtained from the UCAR & NCAR Research Data Archive http://rda.ucar.edu/datasets/ds083.2/index.html#sfol-wl-/data/ds083.2?g=2. These NCEP FNL (Final) Operational Global Analysis data are on 1-degree by 1-degree grids prepared operationally every six hours. For all the three TC simulations the model output is generated for every six hours were taken into consideration for track position.

Table 1: List of MP and CU used in WRF simulations

Model Microphysics(mp) parameterization schemes		
1	Kessler scheme (mp option=1)	**KS**
2	Lin et al. scheme (mp option=2)	**LIN**
3	WRF Single Moment 3-class simple ice scheme (mp option=3)	**WSM3**
4	WRF Single Moment 5-class scheme (mp option=4)	**WSM5**
5	Thompson graupel scheme 2 moment (mp option=8)	**THOM2**
Model Cumulus-physics(CU) parameterization schemes		
1	Kain-Fritsch(new Eta) scheme (cu Option=1)	**KF**
2	Betts-Miller-Janjic scheme (cu Option=2)	**BMJ**
3	Grell-Devenyi ensemble scheme (cu option=3)	**GD**
4	Old Simplified Arakawa–Schubert Scheme (cu option=4)	**SAS**
5	Grell-3D ensemble scheme (cu option=5)	**G3D**
Planetary Boundary Layer (PBL)		
1	Yonsei University Scheme	**YSU**

The WPS domain configuration is generated using NCL (NCAR Command Language). The CU and MP parameterization schemes used in the present simulation to investigate the track of the tropical cyclones were listed in Table 1. WRF Model dynamics and domain details are listed in Table 2 and the HPC Cluster details are given in Table 3.

Table 2: WRF Model dynamics and domain details

Dynamics	
Equation Non	**hydrostatic**
Time integration scheme	**Third-order Runge-Kutta scheme**
Horizontal grid type	**Arakawa-C grid**
Domain	
Map projection	**Mercator projection**
Central point of the domain	**75ºE, 20ºN**
No. of domains	**3**
No. of vertical layers	**27**
Horizontal grid distance	**45 km , 15 km & 5 km for domain 1, 2 & 3 respectively**
Time step	**180 sec, 30 sec & 10 sec for domain 1, 2 &3 respectively**
No. of grid points	**173 (EW), 148 (SN) in domain-1**
	253 (EW), 295 (SN) in domain-2
	310 (EW), 355 (SN) in domain-3

Table 3: HPC Cluster Specifications

HPC Cluster Specifications	
Master nodes	**Fujitsu PRIMERGY RX200 S8 Servers (02)**
Compute Nodes	**Fujitsu PRIMERGY RX200 S8 (08)**
Compute Nodes (MIC nodes)	**Fujitsu PRIMERGY CX400 S2 (02)**
Communication with all internal cluster	**D Link 24 port Gigabit ports with the manageable Ethernet switch**
Fast Interconnects	**Mellanox 18 port switch (01)**
I/O display	**KVM 16port switch (01)**
Fujitsu DX 60 Storage	**40 TB**

RESULTS AND DISCUSSIONS

The initial state and representation of the physical process in the model decide the accuracy of numerical prediction of tropical cyclones. The Simulations for the Laila cyclone were carried out in order to determine the best MP and CU parameterization scheme for track and intensity prediction. Results from domain-3, considered for the analysis of tropical cyclone Laila. In all the simulation experiments the planetary boundary layer (PBL) scheme is fixed to Yonsei-University (YSU) scheme [9]. The simulated track of Laila cyclone with different MP and CU parameterization schemes are plotted using Grid Analysis and Display System (GrADS) for visualization of the wrf model output. GrADS an interactive desktop tool used for the analysis and display of satellite remote sensing data. GrADS support different data formats and data models. GrADS can handle regular, non-linearly spaced, Gaussian resolution grids. GrADS allow graphically overlay of different data sets with the correct time and spatial registration. The wrf model output and the JTWC observed track were compared concurrently. Track error is calculated using haversine formula. The track error for Laila TC for different CU and MP is plotted in Figure 5.

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

$$c = 2 * \tan^{-1}\left(\frac{\sqrt{a}}{\sqrt{(1-a)}}\right) \quad (2)$$

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

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

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

Where D is Track error, φ is latitude, λ is longitude, R is earth's radius (mean radius = 6,371km) and the angles are in radians.

CYCLONE TRACK SIMULATION

Laila TC Simulations were initiated on 18th May 2010, 0000 UTC with lateral boundary condition and were carried up to 21st May 2010, 1800 UTC. The model was run up to 90hr and the simulated track of Laila cyclone with different MP and CU parameterization schemes are plotted. The Laila cyclone with different CU and fixed MP parameterization Thompson graupel scheme 2 moment (mp=8) are plotted in the Figure 2. The Laila cyclone with different MP schemes and no CU parameterization scheme (cu=0) are plotted in the Figure 4. The Laila cyclone with different MP schemes and CU parameterization Kain-Fritsch (new Eta) scheme (cu=1) are plotted in the Figure 3.

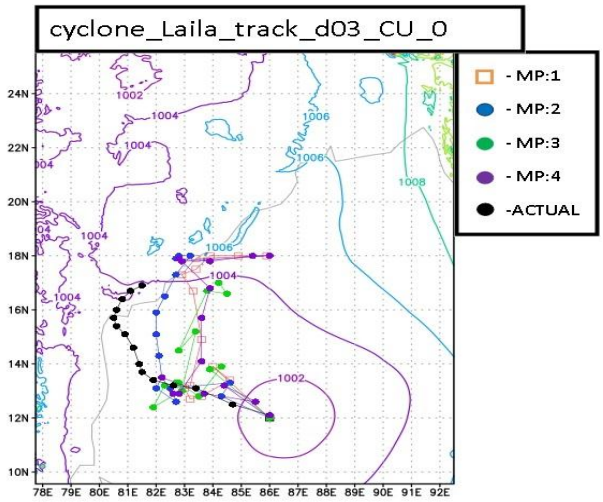


Figure 2: Laila track simulations with different MP schemes and without Convection scheme (cu=0)

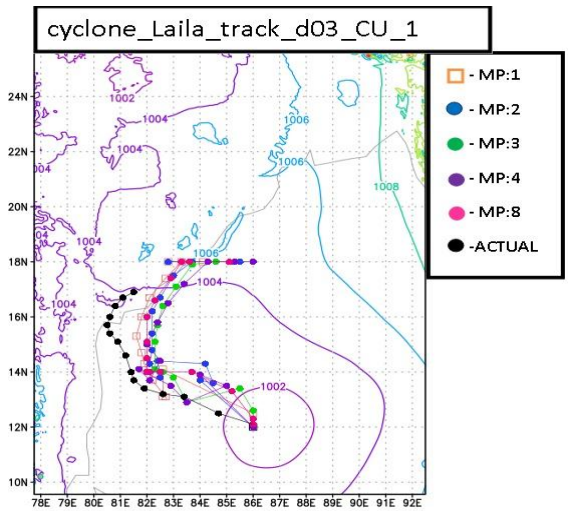


Figure 3: Laila track simulations with different MP schemes and CU fixed to Kain-Fritsch (new Eta) scheme (cu=1))

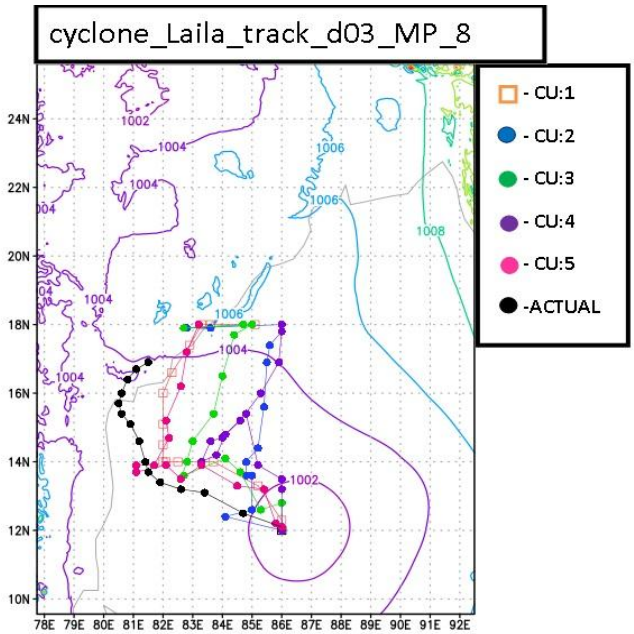


Figure 4: Laila track simulations with different CU schemes & MP fixed to Thompson graupel scheme 2 moment (mp=8)

The RMSE of Tracks in Figure 5 indicates that the Thompson graupel scheme (THOM2) with Grell-3D ensemble scheme (G3D) produces the relatively small track error compared to other schemes. The maximum track error is 413.62 km for THOMS with BMJ schemes.

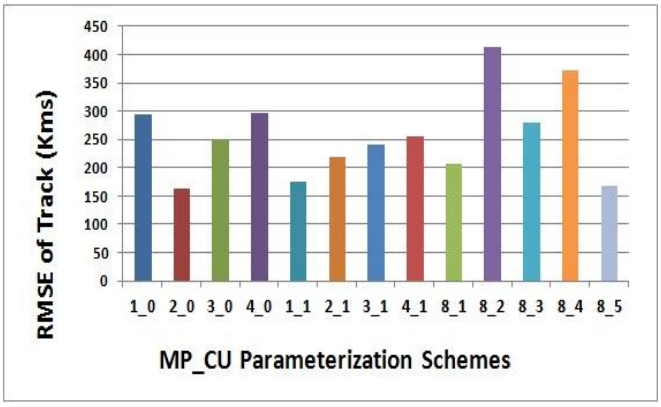


Figure 5: RMSE of track compared with JTWC

The track error of Laila TC simulations for different mp schemes and CU parameterization Grell-3D ensemble scheme (cu=5) are plotted in the Figure 6. The results suggest that for early warning (96-hr) of cyclones the track simulations by THOM2 with G3D schemes is very close to the observed track.

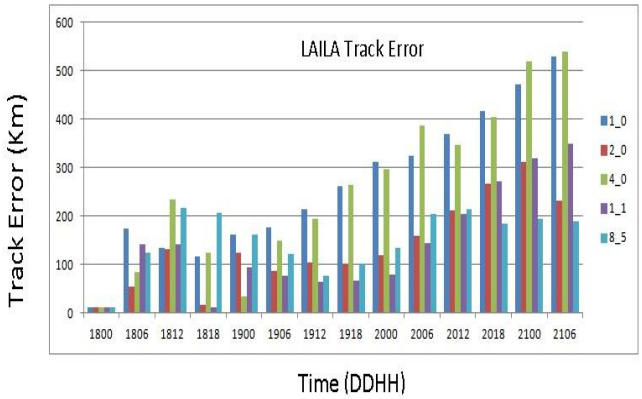


Figure 6: Track error for Laila TC simulations

CENTRAL SEA LEVEL PRESSURE

Time variation of model-simulated central sea level pressure (CSLP) with JTWC observations for Laila TC in hPa is plotted in Figure 7. All the schemes predict the same CSLP at 0000 UTC on 18 May and continue up to 0006 UTC on 18 May. All the schemes well simulated the initial position of the storm. Only the THOM2 with G3D scheme predicts the CSLP of 980 hPa from 0012 UTC on 21 May to 0018 UTC on 21 May which is same as the observed value and the others underestimates the CSLP of Laila cyclone.

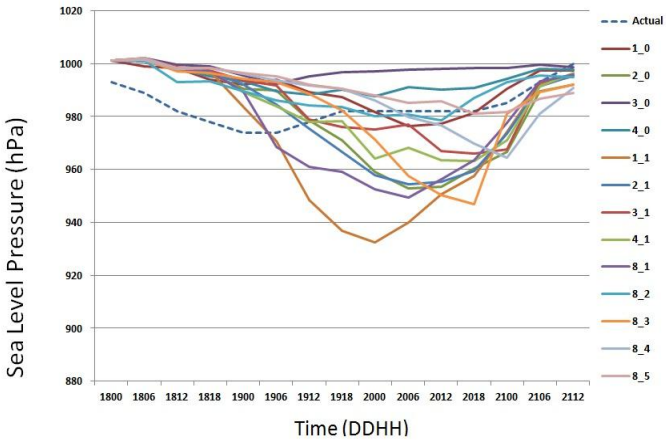


Figure 7: Time variation of model CSLP with JTWC in (hPa)

MAXIMUM SUSTAINED WIND

Figure 8 shows the 10-m MSW speed along with JTWC observation. At 0000 UTC on 18 May all the schemes under estimated the MSW speed of 21.38 knots and the actual JTWC observation MSW speed is 38 knots. When the storm attains the VSCS intensity level the MSW speed of 75 knots is over estimated by THOM2 & KF and KS & KF schemes while all other schemes under estimated the MSW speed. After the landfall all the schemes over estimated the MSW speed.

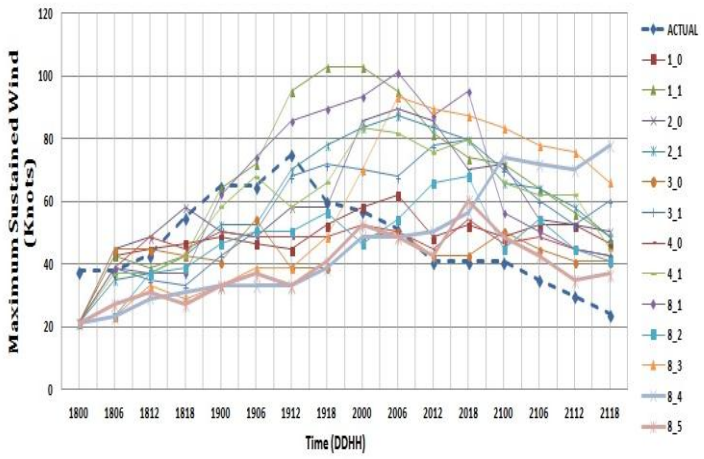
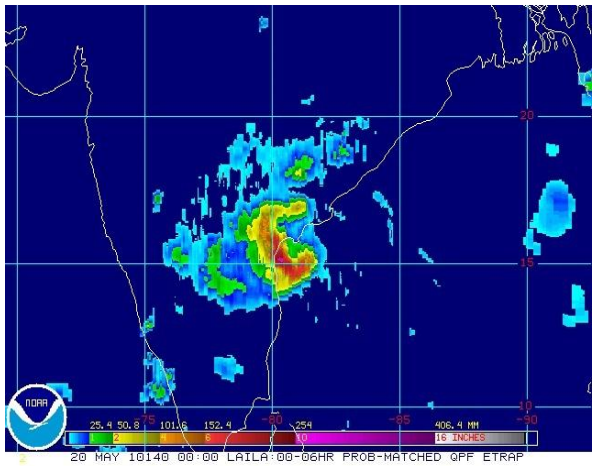


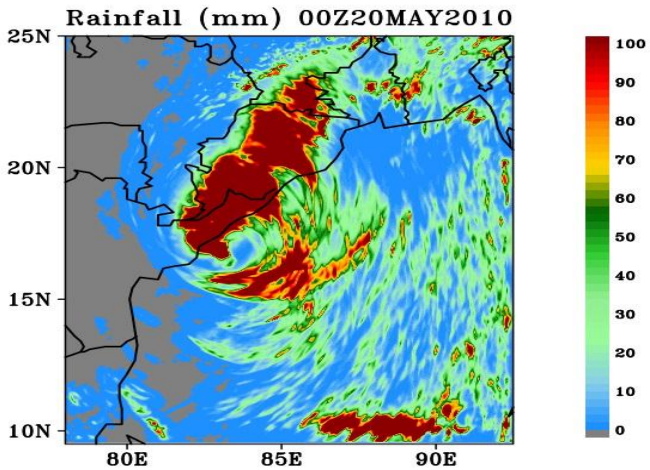
Figure 8: Time variation of model surface wind with JTWC in (Knots)

PRECIPITATION

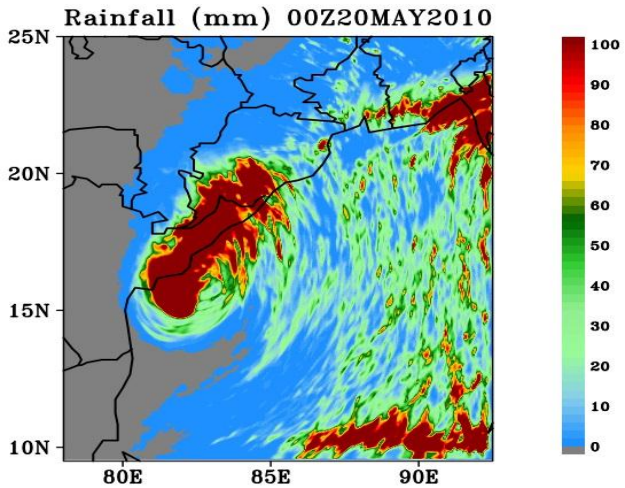
Figure 9 shows the 24-hour accumulated precipitation on 20th May, 2010 by different micro physics parameterization schemes along with Satellite observation. Precipitation is one of the important parameter to be simulated accurately by the wrf model. Before the landfall (on 18 and 19 May) rainfall is confined mainly over the ocean. East and West Godavari districts received heavy rainfall and 62.7 mm average rainfall recorded in West Godavari district in Andhra Pradesh



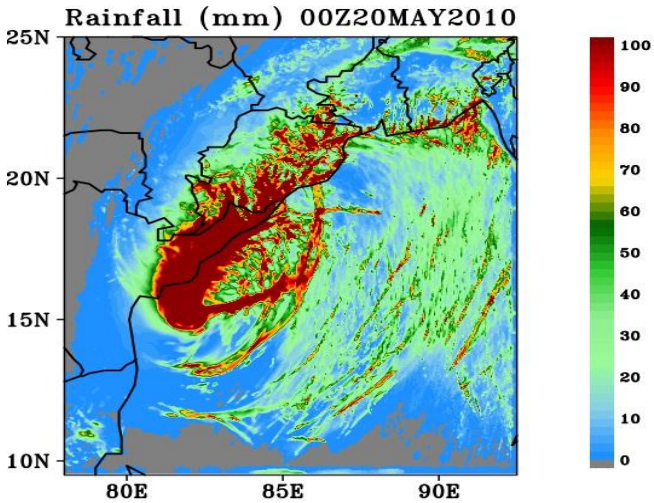
TRMM



Kessler scheme (KS) with cu=0



Lin et al. scheme (LIN) with cu=0



THOM2_KF

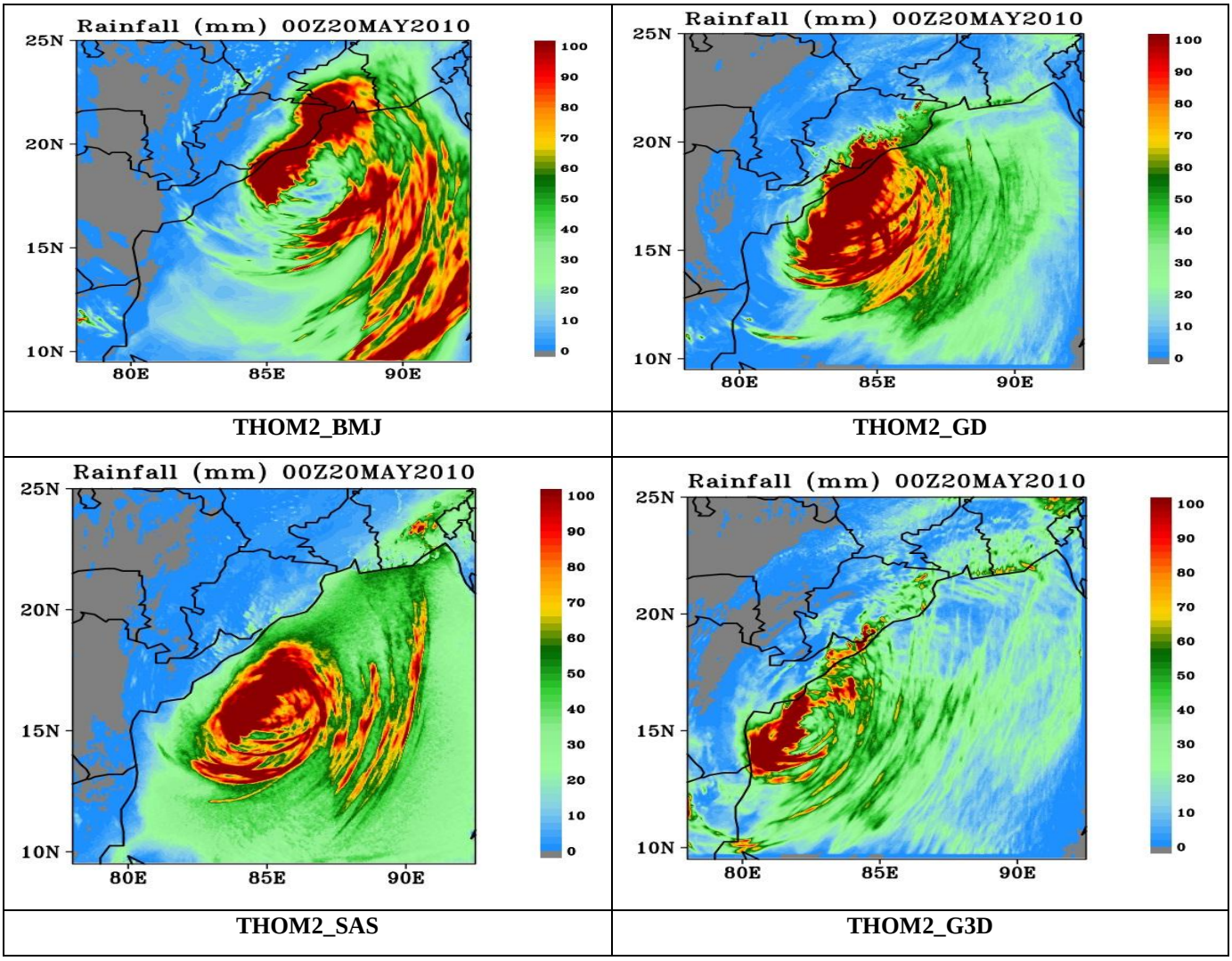


Figure 9: 24-hour accumulated rainfall by different schemes along with TRMM observation.

Figure 10 and Figure 11 shows time series of the 24 hour cumulative precipitation and time averaged three hourly precipitation over Ongole (latitude 15.5057° N and longitude 80.0499° E), Andhra Pradesh, India. All microphysics parameterization schemes underestimate the precipitation as compared to TRMM data. Only THOM2 with G3D schemes compared to other schemes best estimated the precipitation.

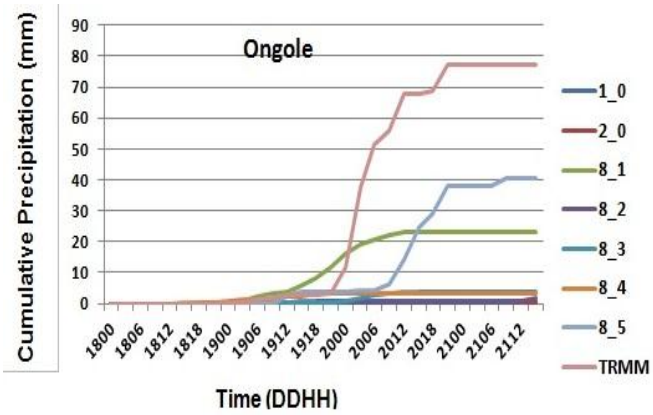


Figure 10: Cumulative Precipitation

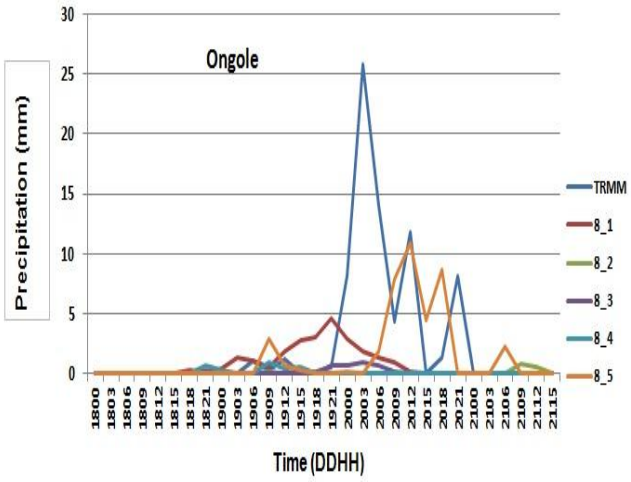


Figure 11: Time averaged three hourly Precipitation

CONCLUSION

The sensitivity analyses of model performances have mainly focused on model physics, and initial conditions. The analysis associated with inner domain-3 is considered. In this paper, Laila cyclone is simulated over the coast of Bay of Bengal and presented the best possible combination of microphysics and cumulus physics. For Laila TC simulations THOM2 microphysics scheme in combination G3D cumulus scheme gives out the best results which closely matches with the JTWC track and intensity. The track error for this combination is the minimum of all the other combinations

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