

Impact of physics parameterization and 3DVAR data assimilation on prediction of tropical cyclones in the Bay of Bengal region

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Abstract This study focuses on the sensitivity of tropical cyclones (TCs) simulations to physics parametrization scheme for TCs in the Bay of Bengal (BOB). The goal of this study was to arrive at the optimum set of schemes for the BOB region to increase forecast skill. Four TCs, namely Khaimuk, Laila, Jal and Thane have been simulated through the weather research and forecasting (WRF) model with all the physics parametrization schemes available in WRF, and the optimum set of schemes is arrived at. The analysis shows the cumulus, microphysics and planetary boundary layer parameterizations exert a very significant influence on the TC simulations than land surface, short-wave radiation and long-wave radiation parameterizations. With this optimum set of physics schemes, the impact of assimilation of National Centers for Environmental Prediction Automatic Data Processing upper air observations data in the TC simulations has been studied by using three-dimensional variational (3DVAR) data assimilation technique. The control run (without assimilation) and the 3DVAR-simulated tracks and maximum sustained wind speed have been compared with the Joint Typhoon Warning Center observed tracks and wind data. The model-simulated precipitation is validated with Tropical Rainfall Measuring Mission 2A12 surface rain rate and 3B42 daily accumulated rain data. Bias score and equitable threat score have been evaluated for both instantaneous rain rate and 72-h accumulated rain.

Keywords Tropical cyclones · WRF · 3DVAR · Sensitivity study · Bay of Bengal

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1 Introduction

Prediction of TC track and intensity is very essential to give prior warning to people with a view to mitigate loss of life and property. Lately, mesoscale weather models and computing facilities available have increased prediction skill considerably. Even so, numerical weather prediction (NWP) models get their initial (IC) and boundary (BC) conditions from a low-resolution global forecast system (GFS) and are interpolated into the model domain of interest, and thereafter the basic conservation and momentum equations with specified physics parameterization schemes and time step are solved. The uncertainties in the ICs, physics parameterization schemes and limitations in numerical techniques like truncation and discretization errors and round-off errors from the computation are the major causes of reduced forecast skill in NWP models. While numerical and round-off errors can be reduced only to certain extent, it is possible to reduce the uncertainty in the physics schemes and the ICs through the sensitivity studies and data assimilation techniques.

The NWP models have different physics parameterization schemes to represent the atmospheric processes, but these schemes have been developed by different groups with different assumptions and are region specific. Sensitivity studies are a rational way to determine the best set of physics parameterization schemes for a specific region and reduce the uncertainties in subgrid-scale process.

Srinivas et al. (2007) simulated the Andhra severe cyclone (2003) using the fifth-generation Penn State/National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) with four PBL parametrization schemes, namely Blackadar (BL), Mellor–Yamada (MY), medium-range forecast (MRF) and Burk–Thomson (BT), and two convective parametrization schemes, namely Grell (GR) and Kain Fritsch 2 (KF2). All the PBL experiments underpredicted the intensity. The error in 72-h simulation was 206 km for MRF, 289 km for MY, 310 km for BL and 432 km for BT. The MRF thus predicts the track with reasonable accuracy. The 72-h track error in convective studies was 63 km for the KF2 scheme and 63 km for the GR. From the above studies, they concluded that a combination of KF2 and MRF gives better prediction.

Raju et al. (2011) analyzed the severe cyclone Nargis by using WRF with 11 different combinations of CU, PBL and MP parameterization schemes. They inferred that the convective process is a very important factor in the prediction of track and intensity of the cyclone. They indicated the Kain Fritsch (KF) scheme is able to represent the subgrid-scale feature of updraft and downdraft processes better than other convective schemes, namely Betts–Miller–Janjic (BMJ) and Grell–Devenyi (GD). They finally concluded that the combination of KF, Yonsei University scheme (YSU) and Ferrier schemes gives best results with an average track error of 64 km and MSWS error of about 11.7 m/s.

Osuri et al. (2012a) studied the influence of the CU and PBL processes on five different cyclones over the BOB by using the WRF model. They observed that these processes play a significant role in the genesis and intensification of tropical cyclones and concluded that the combination of KF and YSU gives better prediction.

Deshpande et al. (2010) studied the impact of CU and MP parametrization on the simulation of the Orissa super cyclone in terms of track and intensity prediction by using MM5. They tested three different cumulus schemes, namely GR, BMJ and KF2, and four microphysics parametrization, namely mixed phase, Goddard microphysics with Graupel (GG), Reisner Graupel (RG) and Schultz (SC). From the studies, they concluded that the CU and MP parametrization schemes have more impact on the track and intensity

prediction and the combination of KF2 in CU, mixed phase schemes in MP and MY from PBL gives better prediction.

Srinivas et al. (2013) conducted sensitivity studies on five different cyclones over BOB through 65 numerical experiments with combinations of CU, PBL, MP and LS parameterizations. From the sensitivity studies, they concluded that the combinations of KF, YSU, LIN and NOAH schemes simulate the cyclones close to observations. They also analyzed 21 cyclones in the same region with the best set of physics schemes arrived at from their study and observed that the best set of schemes overestimated the intensity of cyclone with the mean error ranging from 1 to 22 m/s corresponding to 24- and 72-h simulations and the mean track errors are 244 km at 48-h and 250 km at 72-h simulations.

Rao and Prasad (2007) simulated the Orissa super cyclone with different convective and PBL schemes by using MM5 model. They concluded that the combinations of MY from PBL and KF2 from CU give better simulations in terms of track. The model-predicted precipitation also gave good agreement with observations.

Chandrasekar and Balaji (2012) conducted sensitivity studies of cyclone Jal to physics schemes and arrived at the best set of physical parameterizations for both track and intensity prediction by using the WRF. They concluded that (1) the best schemes arrived for the track overpredict the intensity of the same cyclone and (2) the results differ, when the grid size and number of nesting are changed. According to them, the performance of physics schemes depends on the grid resolutions and number of nesting and the best schemes arrived from any sensitivity study will give the best results only when the same model configuration is used. Furthermore, they indicated that the CU, PBL and MP parameterizations play a crucial role in TC simulations.

Srinivas et al. (2012) simulated two TCs, viz. Fanoos and Nargis in the region of BOB with and without 3DVAR assimilation. They conducted the following three experiments: (1) control run initialized with 0.5° GFS data, (2) assimilation of conventional surface and upper air observations, and (3) assimilation of Quikscat scatterometer (QSCAT) surface wind speed and direction. They concluded that assimilation has a negative impact in terms of track and intensity when assimilating conventional observations, largely because most of the conventional data are located in the land. They also mentioned that assimilation gives positive impact in terms of track and intensity when the QSCAT surface wind speed and direction are assimilated into the model. They reasoned that this is due to the fact that assimilation reduces the initial vortex position error and corrects the wind direction.

Osuri et al. (2012b) studied the impact of assimilation of satellite-derived wind data on the track, intensity and structure of TCs over the north Indian Ocean. They analyzed four TCs, namely Nargis, Gonu, Sidr and Khaimuk with and without 3DVAR assimilation. They used QSCAT and Special Sensor Microwave/Imager (SSM/I) data for the assimilation and concluded that the assimilation of surface wind gives positive impact on the track simulation and improves the initial position of cyclone near 34 %; furthermore, 72-h mean error of track simulation improved by 41 %, and the landfall prediction improved by 32 %. The assimilation improved the intensity prediction between 10 and 20 %. They also concluded that assimilation also improves precipitation with the equitable threat score (ETS) being 0.2 up to a rainfall threshold of 90 mm, when 24-h accumulated rainfall simulations are compared with TRMM-observed rainfall.

Singh et al. (2008) used 3DVAR and assimilated QSCAT and SSM/I surface wind data for simulating the Orissa super cyclone. They concluded that the surface wind data assimilation increases the sea-air heat flux in the initial stages of the cyclone and it helps improve the intensity prediction. The wind vector from the QSCAT and SSM/I reduces the

Table 1 Model physics parameterization schemes

Cumulus (CU)
1. Kain Fritsch (new Eta) scheme (KF)
2. Betts–Miller–Janjic scheme (BMJ)
3. Grell–Devenyi ensemble scheme (GD)
4. New Grell scheme (GRELL)
Microphysics (MP)
1. Kessler scheme (KS)
2. Lin et al. scheme (LIN)
3. WRF Single Moment 3 class simple ice scheme (WSM3)
4. WRF Single Moment 5 class scheme (WSM5)
5. Ferrier (new Eta) microphysics (FERRIER)
6. WRF Single Moment 6 class Graupel scheme (WSM6)
7. Goddard GCE scheme (GODDARD)
8. Thompson Graupel scheme 2 moment (THOM2)
9. Morrison 2-moment scheme (MORRISON)
10. Double moment, 5 class scheme (DM5)
11. Double moment, 6 class scheme (DM6)
12. Thompson scheme (THOMP)
Planetary boundary layer (PBL)
1. Yonsei University scheme (YSM)
2. Mellor–Yamada–Janjic (Eta) TKE scheme (MYJ)
3. Quasi-Normal Scale Elimination (QNSE)
4. Mellor–Yamada–Nakanishi Niino 2.5 level TKE (MYNN2.5)
5. Mellor–Yamada–Nakanishi Niino 3 level TKE (MYNN3)
6. Asymmetrical Convective Model version 2 (ACM2)
7. Bougeault and Lacarrere (BOULAC)
Surface layer physics (SL)
1. Monin Obukhov scheme (MON)
2. Monin Obukhov (Janjic Eta) scheme (JAN)
3. Quasi-Normal Scale Elimination (QNSE_ SF)
4. Mellor–Yamada–Nakanishi Niino scheme (MYNN_ SF)
5. PleimXu scheme (PLEIM_ SF)
Land surface physics (LS)
1. Thermal diffusion scheme (TD)
2. Unified Noah land surface model (NLS)
3. Rapid Update Cycle land surface model (RUC)
4. PleimXu scheme (PLEIM)
Short-wave radiation (SWR)
1. Dudhia scheme (DS)
2. Goddard short wave (GSW)
3. Rapid Radiative Transfer Model for Global (RRTMG)
Long-wave radiation (LWR)
1. Rapid Radiative Transfer Model (RRTM)
2. Rapid Radiative Transfer Model for Global (RRTMG)

initial errors in the wind direction in the cyclonic region and thus reduces the mean track error in the simulation.

Singh et al. (2011) studied the impact of the QSCAT sea surface winds and SSM/I-derived total precipitable water (TPW), and Meteosat-7-derived atmospheric motion vectors (AMVs) in the track and intensity simulation of four TCs over the north Indian Ocean. They concluded that assimilation of (1) QSCAT surface wind gives positive impact on both track and intensity prediction and (2) SSM/I and AMVs gave negative impact in three cyclones out of four.

From the above studies, it is clear different sets of physics parameterization schemes are used for simulating TCs even within the region of BOB and the performance of these physics schemes mainly depends on the grid resolution and the number of nesting. So, in the first part of this study we try to determine the optimum physics schemes for the region of BOB for the specific grid resolution and number of nesting through sensitivity studies. For doing this, four TCs in the region of BOB, viz. Khaimuk, Laila, Jal and Thane have been analyzed.

The second part of the study focuses on the impact of the assimilation of NCEP ADP upper air data in TC simulations by using the 3DVAR assimilation technique. These three TCs, viz. Laila, Jal and Thane are simulated with and without assimilation, and the results are compared with the observations. The optimum physics schemes arrived from the sensitivity studies have been used in the assimilation studies (Table 1).

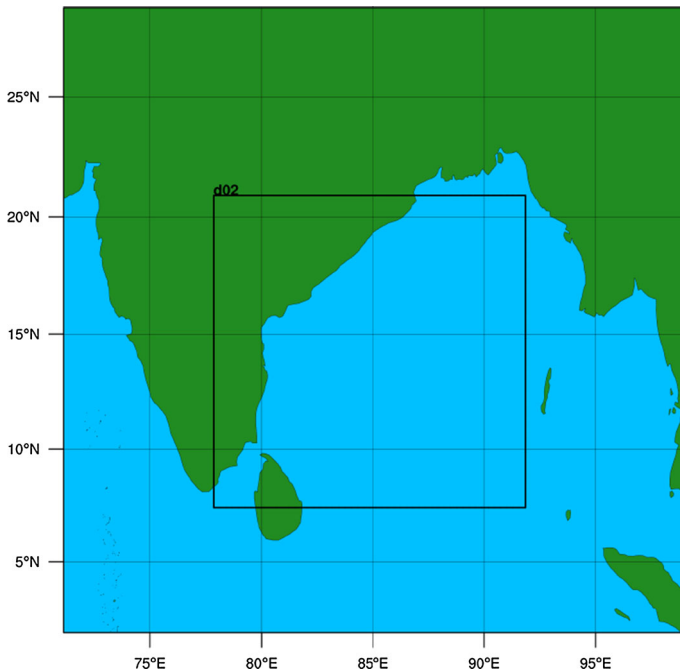


Fig. 1 Model domain used in the present study

2 Model domain and dynamic options

The WRF has been used for simulating the TCs. The physics schemes and dynamic options are detailed in the model technical note (Skamarock 2008), and the governing equations and the numerical technique used in the models are described in Skamarock and Klemp (2008). Figure 1 shows the model domain, and Table 2 lists the number of nesting, grid resolutions and dynamic options used in this study.

3 Data used

The United States Geological Survey (USGS) 30'' resolution topographical data have been used in the WRF preprocessing system (WPS). The GFS 0.5° resolution model forecast data from the NCEP have been used for generating the initial and boundary conditions. The JTWC-observed track and wind data have been taken to be the truth for validating the simulated tracks and MSWS. The NCEP ADP upper air observational data have been used in the 3DVAR assimilation. These data sets have the variables of pressure, geopotential height, air temperature, dew point temperature, wind direction and speed available from 1000 hpa to 10 hpa level. They include radiosondes, satellite data from the National Environmental Satellite Data and Information Service (NESDIS) and aircraft reports from the Global Telecommunications System (GTS). The TRMM 2A12 surface rain rate and 3B42 daily accumulated rain data have been used to validate the model-simulated precipitation.

4 Data assimilation methodology

Data assimilation is an optimization technique to improve the initial conditions by combining the available high-resolution observation data and model background data (GFS initial conditions) through iterative methods. The 3DVAR assimilation technique is a

Table 2 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
Central point of the domain	85 E, 15 N
No of domains	2
No of vertical layers	27 Sigma levels
Horizontal grid distance	30 km in domain 1 and 10 km in domain 2
Time step	90 s
No of grid points	101 in both (E–W) and (N–S) in domain 1 151 in both (E–W) and (N–S) in domain 2

calculus-based method and minimizes the error through minimizing J , Eq. 1 given below. J is frequently referred to as the objective function. In 3DVAR, the conjugate gradient method is used for minimizing the objective function. Details of the techniques are available in Barker et al. (2004).

$$J_x = J^b + J^o = (x - x^b)^T B^{-1} (x - x^b) + (y^o - Hx)^T R^{-1} (y^o - Hx) \quad (1)$$

where

- x = vector of analysis variables (n -dimensional)
- x_b = vector of background variables (n)
- y_o = observation vector (m -dimensional)
- B = background error covariances matrix ($n \times n$)
- R = observation error covariances matrix ($m \times m$)
- H = observation operator
- J^b = error in the back ground(n)
- J^o = error in the observations(n)
- J_x = total error(n).

5 Synoptic history of cyclones

5.1 Khaimuk

TC Khaimuk began as a low pressure in the southeast BOB and on November 13, 2008, the low pressure moved toward north Tamilnadu. On the next day, i.e., 14 November, morning it intensified into a deep depression and was expected to cross north Tamilnadu or south Andhra Pradesh. The system was named as Khaimuk by Indian Meteorological Department (IMD) on 15 November after the system became a cyclonic storm and had its land fall over south Andhra Pradesh. The GFS data for 2008 November 14 06 UTC (Coordinated Universal Time) have been used for providing ICs and BCs, and the simulations were carried out for 42 h up to 12 UTC on November 16, 2008.

5.2 Laila

Cyclone Laila formed as a depression in BOB at May 17, 09 UTC. After 3 h, it became a deep depression with a maximum sustained wind speed of 15.2 m/s. The system further developed as a tropical cyclonic storm on 17 May and moved west. The convection increased throughout the day, and the system intensified into a severe cyclonic storm on 19 May and hit the Andhra Pradesh coast on 20 May. For this TC, 72-h simulations have been done with the 2010 May 18 00 UTC as ICs.

5.3 Jal

Jal developed from a low pressure area in the South China Sea and organized into a tropical depression on October 28. The system further strengthened on November 04 18 UTC, and the JTWC declared it as a tropical storm with a maximum wind speed of 19.16 m/s. Later the storm moved west, gained energy from the warm waters and strengthened again as a category 1 storm on November 06 00 UTC and continued till November 07 06 UTC as a

category 1 storm. The system weakened and became a deep depression after its landfall near Chennai at 18 UTC on November 07. The GFS data for 18 UTC, November 4, 2010, have been used as ICs, and simulations were run up to 72 h.

5.4 Thane

Thane was the strongest tropical cyclone of the year 2011 in the region of north Indian Ocean. Initially, it developed as a tropical disturbance in the west of Indonesia. The system gradually developed and attained the tropical depression states on 25 December, and the next day, it further developed into a tropical storm. On 28 December, the system became a very severe cyclonic storm and moved toward the Tamilnadu and Andhra Pradesh coasts and made landfall over the Tamilnadu coastal area between Cuddalore and Puducherry in the early hours of December 30, 2011. For Thane, simulations are done for 72 h starting from 00 UTC on December 27, 2011.

6 Experimental design

In the sensitivity study, the WRF model has been run for the various physics schemes in a particular parameterization and the simulated tracks have been compared with the JTWC observation tracks. The physics schemes have been chosen based on the minimum RMSE

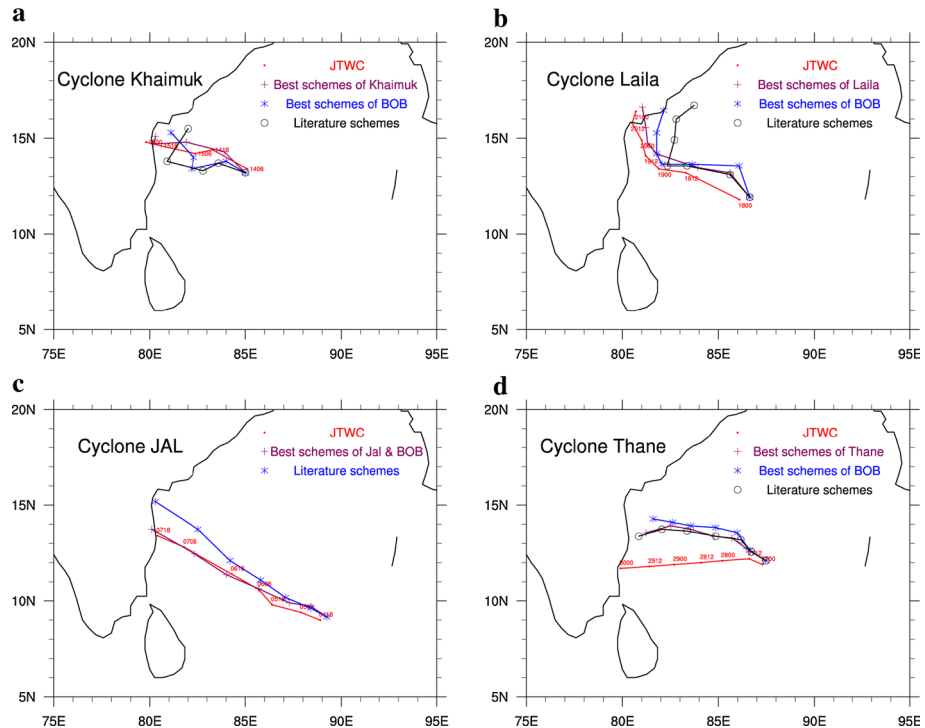


Fig. 2 Comparison of simulated track propagation with the best, optimum and literature physics schemes **a** Khaimuk, **b** Laila, **c** Jal, **d** Thane

between simulated and JTWC tracks. The experiment and selection procedure of physics schemes are based on the procedure followed by Chandrasekar and Balaji (2012). For each cyclone, totally 24 experiments were conducted and the optimum physics parameterization schemes for BOB have been arrived at through these sensitivity experiments for these cyclones with minimum RMSE as the performance metric. The set of physics schemes arrived at by Srinivas et al. (2013) based on the sensitivity studies in the region of BOB is considered as the literature physics schemes. The four cyclones are also simulated with this literature scheme, and the results are compared with the individual best and optimum physics schemes simulation for all cyclones.

For assimilation, the WRF has been initialized with GFS before 6 h of all the actual ICs which are used in the control run. WRF simulations at the end of six hours have been used as the first guess or the back ground, and a three-hour time window has been set in the 3DVAR. The default NCEP global background error covariances matrices (*B*) are used in this study. The *B* estimated with the difference between 24- and 48-h GFS forecast with T170 resolution valid for the same time for 357 cases distributed over a period of one year and the NMC method (Parrish and Derber 1992) are used to estimate the error covariances statistics.

7 Results and discussion

7.1 Sensitivity experiments

A series of systematic experiments with various physics schemes have been conducted for the above-mentioned cyclones. The physics schemes have been chosen based on the minimum track error between JTWC-observed track data and the simulated track. Figure 2a–d shows the track propagation of four cyclone simulations with the best schemes arrived from the respective sensitivity experiments of the cyclones. All the cyclones propagate westerly, as expected. Table 3 lists the track error and relative mean square error (RMSE) between the observed and simulated track for four cyclones. In the case of cyclone Khaimuk, the initial error in the cyclone position is 28 km and the landfall error is 44 km. The total 42-h RMSE of simulations with the best schemes is only 63 km. In the case of cyclone Laila, the 72-h total RMSE in the track simulation is 127 km and the landfall error is only 44 km. The best physics scheme from the Jal cyclone simulates the cyclone with a relatively smaller error, with the total 72-h RMSE of track prediction being only 48 km and the landfall error being 50 km even though the initial position error is 43 km. Cyclone Thane gives poor simulation results, and even with the best set of schemes, the RMSE in

Table 3 Track error in the individual best physics scheme

Time (hr)	0	6	12	18	24	30	36	42	48	54	60	66	72	RMSE (km)
Khaimuk	28	154	61	46	42	82	45	44						63
Laila	61	163	256	249	225	177	65	32	39	147	85	102	44	127
Jal	43	25	66	94	99	62	4	19	31	36	70	25	50	48
Thane	29	77	50	51	127	159	168	168	211	226	208	213	186	144

The bold values represent error at the time of landfall

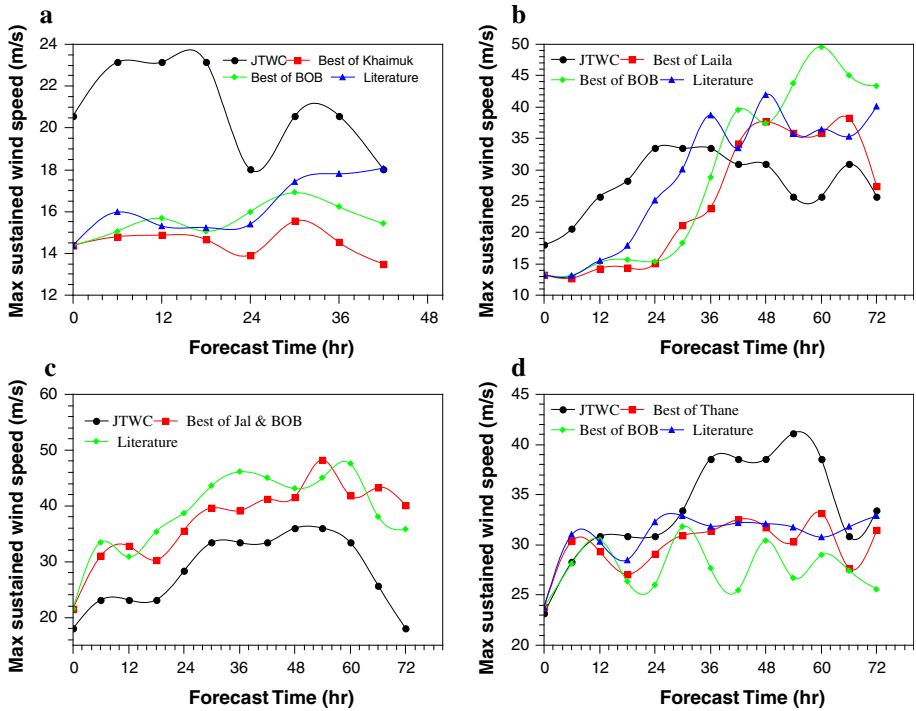


Fig. 3 Time series of simulated maximum sustained wind speed with the best, optimum and literature physics schemes **a** Khaimuk, **b** Laila, **c** Jal, **d** Thane

Table 4 Error in the maximum sustained wind speed in the individual best physics schemes

Time (h)	0	6	12	18	24	30	36	42	48	54	60	66	72	RMSE (m/s)
Khaimuk	6	8	8	8	4	5	6	5						6
Laila	5	8	11	14	18	12	10	3	7	10	10	7	2	9
Jal	4	8	10	7	7	6	6	8	6	12	8	18	22	9
Thane	1	2	2	4	2	2	7	6	7	11	5	3	2	4

The bold values represent error at the time of landfall

track prediction is 144 km and the landfall error is 186 km even though the initial position error was only 29 km.

Figure 3a–d shows the time series MSWS (m/s) of all simulated cyclones, and Table 4 lists the error between the JTWC-observed and model-simulated wind and the total RMSE in wind simulations. Overall, the wind prediction in all the cases seems to be done with better skill in terms of the total RMSE. The maximum RMSE value is 9 m/s in the case of cyclone Laila and Jal, whereas for Khaimuk and Thane, it is only 6 and 4 m/s, respectively. The maximum winds are simulated well at the time of landfall for three cyclones, and the errors are 5, 2 and 2 m/s for the cyclones Khaimuk, Laila and Thane, respectively, but for cyclone Jal, it is 22 m/s.

Table 5 Best schemes arrived at from the individual cyclone sensitivity study

Schemes	Cyclone			
	Khaimuk	Laila	Jal	Thane
CU	GRELL	KF	KF	KF
MP	FERRIER	WSM3	FERRIER	LIN
PBL	MYNN3	MYJ	MYNN2.5	MYNN2.5
SL	MYNN_SF	JAN	MYNN_SF	MYNN_SF
LS	TD	TD	TD	TD
SWR	DS	DS	DS	DS
LWR	RRTMG	RRTM	RRTM	RRTM

7.2 Optimum physics scheme for BOB

From the sensitivity studies for the above four cyclones in the BOB, it can be inferred that the best set of physics scheme in each cyclone is not the same. However, there are some schemes common to all the cases. So, it clear that it is possible to arrive at an optimum combination of physics schemes for the region of BOB. Table 5 lists the individual best physics schemes of four cyclones. The optimum physics schemes have been chosen based on better predictions for at least two or more than two cyclone cases from a particular parameterization.

7.2.1 Sensitivity of CU

From Table 5, it is seen that the KF scheme from the CU parameterization gives good results for cyclones Laila, Jal and Thane, but in the case of Khaimuk, the GRELL scheme gives better results. So, the KF scheme has been considered as the optimum scheme in CU parameterization.

7.2.2 Sensitivity of MP

For MP parameterization, the FERRIER scheme gives better results for Khaimuk and Jal, while WSM3 and LIN give better results for Laila and Thane, respectively. Hence, the FERRIER scheme has been chosen for the region of BOB.

7.2.3 Sensitivity of PBL

The MYNN2.5 scheme from PBL gives good results for Jal and Thane. Cyclone Khaimuk and Laila are simulated well with MYNN3 and MYJ, respectively. The MYNN2.5 scheme has been taken as the optimum scheme from the PBL parameterization.

7.2.4 Sensitivity of other parameterizations

From Table 5, it is seen that there is no significant variation in the results in respect of the other physics parameterization schemes. The MYNN_SF scheme from SL parameterization, TD scheme from LS, DS scheme from SWR and RRTM from LWR give good results

for all the cyclones considered. The results clearly indicate that the tropical cyclone predictions are more sensitive to CU, MP and PBL parameterization than the others.

From the detailed sensitivity studies, the optimum set of physics schemes have been arrived at for the region of BOB and its performance is compared with the best schemes arrived from the individual cyclone cases and the literature physics schemes. Table 6 lists the optimum set of physics scheme for the region of BOB and the literature physics schemes. The optimum physics scheme is similar to the individual best scheme arrived for the case of cyclone Jal.

Figures 2 and 3 show the track propagation and MSWS of all the cyclones simulated with the best, optimum and literature physics schemes. Tables 7 and 8 list the track error between JTWC track data and simulated tracks with the optimum and literature physics schemes. Tables 9 and 10 list the MSWS error between the JTWC-observed wind and simulated MSWS for the optimum and literature physics schemes. From the tables, it is clear that both the optimum and literature physics schemes do not simulate the cyclones as good as the individual best scheme arrived from the particular cyclones studies.

Table 11 lists the landfall error and RMSE for the cases of Laila, Jal and Thane, and the RMSE for the 72-h track simulation for the best, optimum and literature schemes. The average errors in landfall are 93, 185 and 251 km in case of best, optimum and the literature schemes, respectively. The average of the RMSE is 106 km for the best scheme and 136 km in the case of optimum physics scheme, and for the literature schemes, it is 151 km. Table 12 gives the average error in the MSWS at the time of landfall. This is 9 and 16 m/s in the case of best and optimum, respectively, and 11 m/s in the case of literature schemes. The average RMSE is 7, 6 and 8 m/s for the best, optimum and literature physics schemes, respectively.

From the results, it is clear that the optimum physics schemes simulate the TCs in BOB better than the literature physics in terms of track and intensity with this specific model configuration. Furthermore, it is seen that the optimum set is worse off compared to the individual best scheme, but the latter cannot give any guidance for simulation of future cyclones. Under these conditions, the optimum set arrived in these schemes is recommended for track and intensity predictions of TCs in the BOB.

7.3 Impact of assimilation

The NCEP ADP upper air observational data have been assimilated into WRF model by using 3DVAR assimilation technique as explained earlier, and the optimum physics

Table 6 Optimum physics schemes for BOB and the literature schemes

	Optimum scheme for BOB	Literature schemes
CU	Kain Fritsch (new Eta) scheme	Kain Fritsch (new Eta) scheme
MP	Ferrier (new Eta) microphysics	Lin et al. scheme
PBL	Mellor–Yamada–Nakanishi Niino 2.5 level	Yonsei University scheme
SL	Mellor–Yamada–Nakanishi Niino scheme	Monin Obukhov scheme
LS	Thermal diffusion scheme	Unified Noah land surface model
SWR	Dudhia scheme	Dudhia scheme
LWR	Rapid Radiative Transfer Model	Rapid Radiative Transfer Model

Table 7 Track error in the optimum physics schemes for BOB

Time (h)	0	6	12	18	24	30	36	42	48	54	60	66	72	RMSE (km)
Khaimuk	28	170	102	63	93	72	204	156						111
Laila	61	154	310	285	196	126	108	82	117	221	154	165	161	165
Jal	43	25	66	94	99	62	4	19	31	36	70	25	50	48
Thane	29	87	50	78	183	201	220	231	243	265	289	321	343	195

Table 8 Track error in the literature physics schemes

Time (h)	0	6	12	18	24	30	36	42	48	54	60	66	72	RMSE (km)
Khaimuk	28	168	83	133	111	228	93	251						137
Laila	61	154	256	227	164	116	140	159	190	315	257	309	339	207
Jal	43	18	62	85	88	73	56	72	79	110	132	168	199	91
Thane	29	81	42	61	162	159	174	204	208	226	227	224	214	155

Table 9 Error in the maximum sustained wind speed in the optimum physics schemes for BOB

Time (h)	0	6	12	18	24	30	36	42	48	54	60	66	72	RMSE (m/s)
Khaimuk	6	8	7	8	2	4	4	3						5
Laila	5	7	10	13	18	15	5	9	7	18	24	14	18	12
Jal	4	8	10	7	7	6	6	8	6	12	8	18	22	9
Thane	1	0	0	5	5	2	11	13	8	14	10	3	8	6

Table 10 Error in the maximum sustained wind speed in the literature physics schemes

Time (h)	0	6	12	18	24	30	36	42	48	54	60	66	72	RMSE (m/s)
Khaimuk	6	7	8	8	3	3	3	0						5
Laila	5	8	10	10	8	3	5	3	11	10	11	4	14	8
Jal	4	10	8	12	10	10	13	12	7	9	14	12	18	11
Thane	1	3	1	2	1	1	7	6	6	9	8	1	1	4

schemes arrived from the sensitivity studies have been used in the study. The ADP data have been preprocessed before assimilation through 3DVAR observation preprocessor (OBSPROC). The OBSPROC will remove the data out of the model domain and in a way does some quality control. Figure 4a–c shows the locations of ADP satellite data after the

Table 11 Landfall (km) error and RMSE (km) in track simulation with the best, optimum and literature physics schemes

scheme	Laila		Jal		Thane		Average	
	Landfall	RMSE	Landfall	RMSE	Landfall	RMSE	Landfall	RMSE
Best	44	127	50	48	186	144	93	106
Optimum	161	165	50	48	343	195	185	136
Literature	339	207	199	91	214	155	251	151

Table 12 Landfall (m/s) error and RMSE (m/s) in maximum sustained wind speed simulation with the best, optimum and literature physics schemes

scheme	Laila		Jal		Thane		Average	
	Landfall	RMSE	Landfall	RMSE	Landfall	RMSE	Landfall	RMSE
Best	2	9	22	9	2	4	9	7
Optimum	18	2	22	9	8	6	16	6
Literature	14	8	18	11	1	4	11	8

quality control, and it seems that dense quality data are in the edge of the model domain (90 E–95 E). Laila, Jal and Thane cyclones have been simulated with 3DVAR assimilation, and the results are compared with the control run simulation and JTWC observations. Figure 5a–c shows the propagation of simulated track for control run and 3DVAR assimilated along with JTWC-observed track. Table 13 lists the track error and the RMSE in the control run and 3DVAR simulations for the all three cyclones. It is worth mentioning that in the case of Laila, the initial error in the position of the cyclone is only 61 km for the control run, but after assimilation, it became 142 km and the 72-h forecast error in the simulation with assimilation is 185 km. However, this error is only 44 km in case of the control run. The total RMSE is nearly 40 % large for the 3DVAR simulation than the control simulation. Hence, assimilation gives a negative impact on track simulations in the case of cyclone Laila. For Jal, the assimilation reduces the initial position error from 43 to 39 km and it gives good results up to first 30-h simulation; after that, it starts deviating from the observations and gives large error compared to the control run. The 72-h forecast error is 50 km in the control run, but it is 99 km in 3DVAR simulation and also the total RMSE is 21 % larger than control run simulations. In the case of cyclone Thane, the initial position error is larger in 3DVAR, but it gives better results than control run in terms of 72-h forecast and RMSE. The error in the 72-h forecast is 253 km in the control run, but it is only 135 km with the use of 3DVAR and also the total RMSE is 18 % smaller than the control run. So, data assimilation gives mixed results.

Figure 6a–c shows the time series of the MSWS of control, 3DVAR simulations and JTWC observation. Table 14 lists the error in the wind forecast of control and 3DVAR simulations. It can be inferred that 3DVAR gives better results in the case of cyclone Laila. The 72-h MSWS error is only 4 m/s in 3DVAR, but it is 14 m/s in the control run. The total RMSE of MSWS is small in 3DVAR compared to the control run. The results from

Fig. 4 NCEP ADP upper air observations used in the 3DVAR assimilation **a** Laila, **b** Jal, **c** Thane

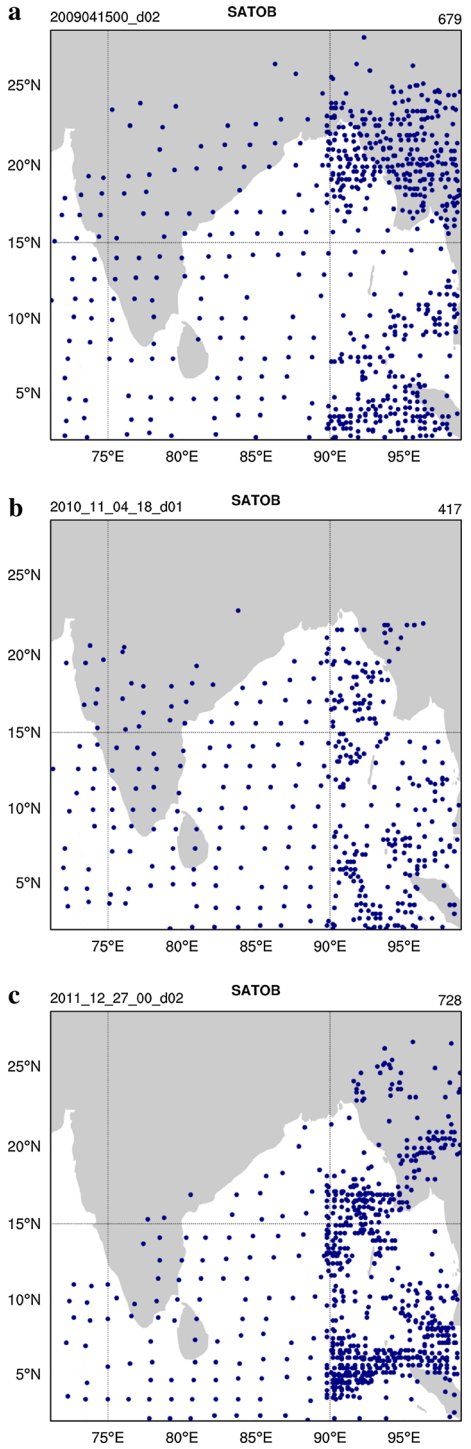


Fig. 5 Comparison of track propagation for control run and 3DVAR simulations **a** Laila, **b** Jal, **c** Thane

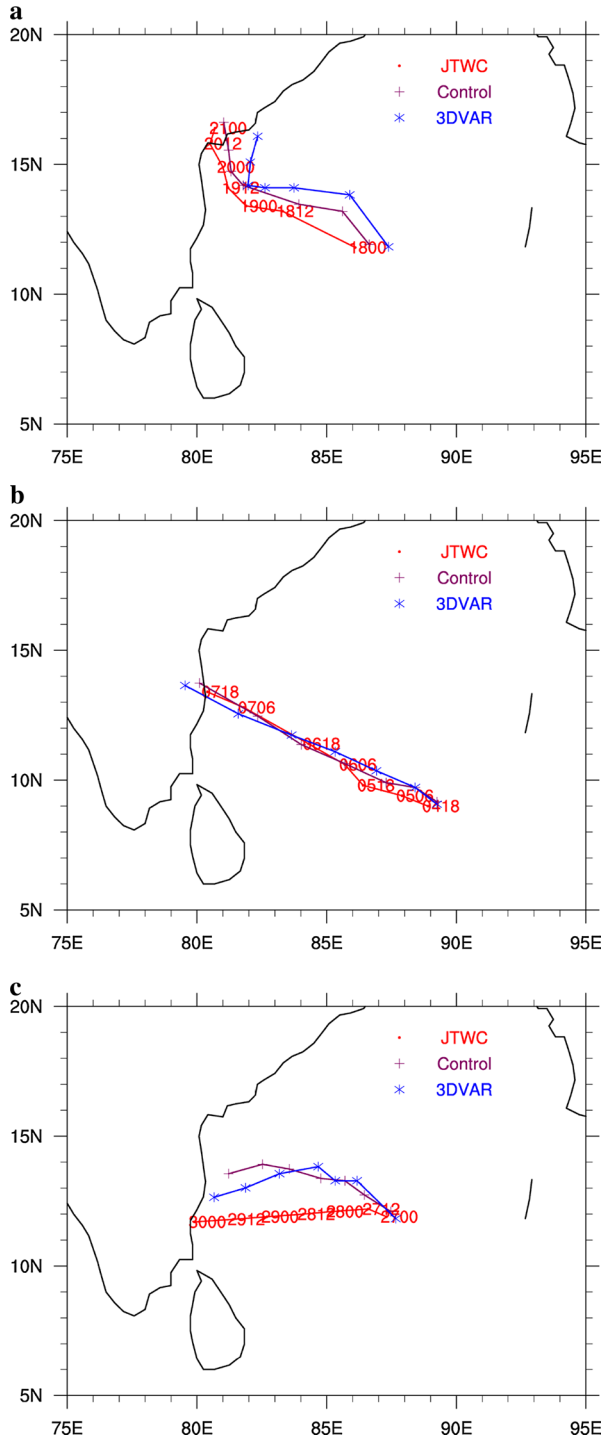


Table 13 Track error for control run and 3DVAR simulation

Time (h)	0	6	12	18	24	30	36	42	48	54	60	66	72	RMSE (km)
Laila(Ctrl)	61	163	256	249	225	177	65	32	39	147	85	102	44	127
Laila(3DVAR)	142	231	296	298	219	182	158	90	133	263	190	184	185	208
Jal(Ctrl)	43	25	66	94	99	62	4	19	31	36	70	25	50	48
Jal(3DVAR)	39	21	66	89	84	43	69	55	82	43	35	68	99	61
Thane(Ctrl)	29	81	62	69	143	137	170	209	225	233	266	264	253	165
Thane(3DVAR)	41	41	130	119	132	125	213	164	192	159	144	146	135	134

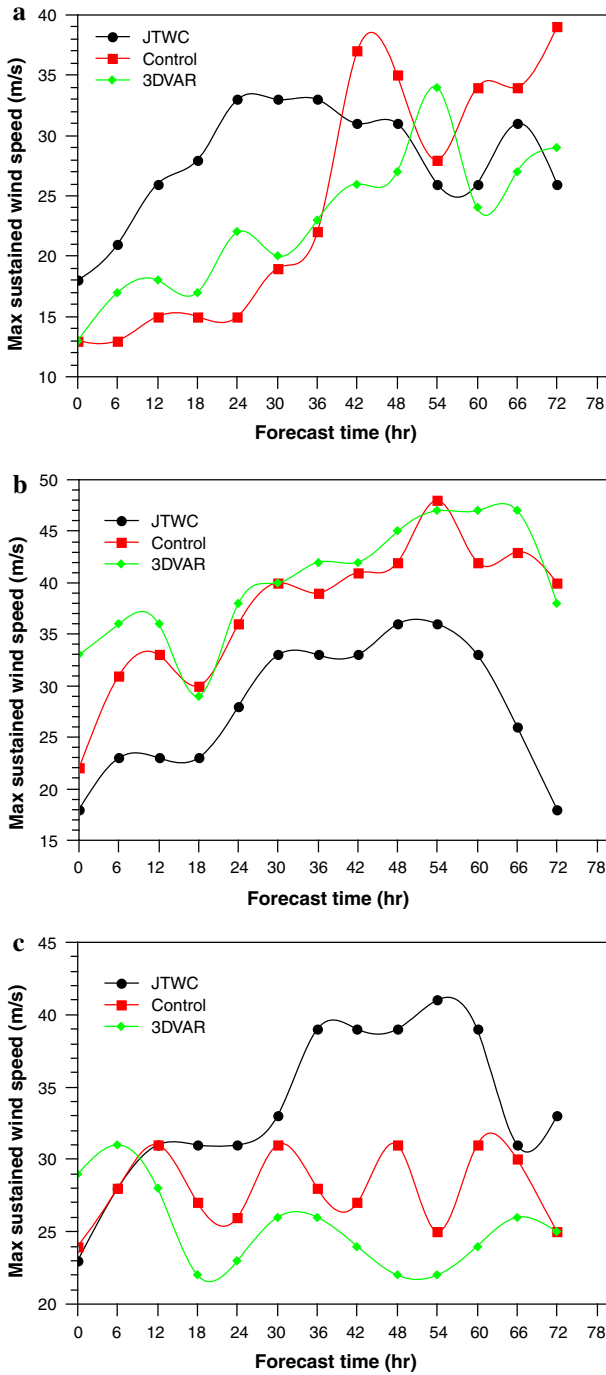


Fig. 6 Comparison of maximum sustained wind speed for control run and 3DVAR simulations **a** Laila, **b** Jal, **c** Thane

Table 14 Error in the maximum sustained wind speed in the control run and 3DVAR simulation

Time (h)	0	6	12	18	24	30	36	42	48	54	60	66	72	RMSE (m/s)
Laila(Ctrl)	5	8	11	13	18	14	11	6	4	3	8	3	14	9
Laila(3DVAR)	5	4	8	11	11	14	11	5	4	8	2	4	4	7
Jal(Ctrl)	4	8	10	7	7	6	6	8	6	12	8	18	22	9
Jal(3DVAR)	15	13	13	6	10	6	8	8	9	11	13	21	20	12
Thane(Ctrl)	1	0	0	4	5	2	11	12	8	16	8	1	8	6
Thane(3DVAR)	6	3	3	9	8	7	13	14	16	20	14	5	9	10

3DVAR have larger error in wind speed for the case of cyclone Jal than those from the control run. The initial error in wind after assimilation is 15 m/s, but is only 4 m/s in the control run, and the total RMSE in 3DVAR is 25 % larger than in the control run. Simulations with 3DVAR in the case of cyclone Thane show a larger error in terms of initial and RMSE. The initial error in the assimilation is 6 m/s, but it is 1 m/s in the control run and also the error in the RMSE is 40 % larger than in the control run.

Table 15 lists the landfall error and total 72-h RMSE of all cyclone simulations and average of them for the both control and 3DVAR track simulations. It seen that the average landfall error in the control run simulations is 116 km and it is 140 km in 3DVAR. The average RMSE is 113 km in the control run, but in 3DVAR, it is about 134 km and 16 % larger than in the control run. Table 16 gives the average landfall and RMSE of MSWS simulations for both the control and 3DVAR, and it can be inferred that the 3DVAR simulations have RMSE 20 % larger than control run on the average.

Figures 7, 8 and 9 show a comparison of TRMM 2A12 surface rain rate data, WRF control and 3DVAR-simulated surface rain rate in different time periods for the cases of cyclones Laila, Jal and Thane, respectively. The figures show that WRF is able to capture the circulation pattern in the all the cyclones. Furthermore, the precipitation patterns look similar to the TRMM 2A12 pattern, but the position of the system varies in all cases. The WRF 72-h accumulated rain (mm) has also been quantitatively validated with TRMM 3B42 daily accumulated rain (mm) data through the BS and ETS as followed by Gandin and Murphy (1992). The corresponding TRMM 3B42 daily data for all the cyclone days have been collected. This is based on 24-h accumulated rainfall, and so all the data have been combined to get 72-h accumulated rainfall for every cyclone. The 72-h accumulated rainfall for all the cyclones from WRF model has been estimated and collocated with the TRMM grid pixels. The statistical skills in the prediction can be estimated through the

Table 15 Landfall error (km) and RMSE (km) in track simulation for control run and 3DVAR simulation

Scheme	Laila		Jal		Thane		Average	
	Landfall	RMSE	Landfall	RMSE	Landfall	RMSE	Landfall	RMSE
Control	44	127	50	48	253	165	116	113
3DVAR	185	208	99	61	135	134	140	134

Table 16 Landfall error (m/s) and RMSE (m/s) in the maximum sustained wind speed simulation for control run and 3DVAR simulation

Scheme	Laila		Jal		Thane		Average	
	Landfall	RMSE	Landfall	RMSE	Landfall	RMSE	Landfall	RMSE
Control	4	9	22	9	8	6	15	8
3DVAR	4	7	20	12	9	10	11	10

contingency table shown in Figure 10. Mathematically, BS and ETS are given in Eqs. 2 and 3.

$$BS = \frac{\text{total forecast events}}{\text{total observed events}} = \frac{H + F}{H + M} \tag{2}$$

$$ETS = \frac{H - H_{\text{random}}}{H + M + F - H_{\text{random}}} \tag{3}$$

where

$$H_{\text{random}} = \frac{(\text{total forecast events}) \times (\text{total observed events})}{N} = \frac{(H + F) \times (H + M)}{N}$$

- H = Correct prediction of rain occurrence(Hit)
- F = Precipitation of rain for which no rain occurrence, (False alarms)
- M = Rain occurrence which not predicted, (Misses)
- Z = Correct forecast of no rain (correct rejection)
- N = Sample size ($H + F + M + Z$).

BS is this ratio of frequency of total forecast rain events to frequency of observed rain events, and a value of $BS = 1$ indicates perfect forecast and that means prediction is unbiased. If $BS < 1$, it means underprediction, and $BS > 1$ means overprediction. $BS = 0$ refers to no skill, and BS can vary from 0 to ∞ . The ETS gives an estimation of the fraction of correct prediction of rain occurrence (hits), adjusted for hits associated with random chance H_{random} . An ETS of 1 indicates perfect skill, and $ETS \leq 0$ means that prediction has no skill. ETS varies between $-\frac{1}{3}$ and 1.

Figure 11 shows the BS and ETS histograms for 72-h accumulated rainfall for the control run and 3DVAR simulations for Laila, Jal and Thane, respectively. It also shows the average BS and ETS over all three cyclones. From the histograms, we have the following observations.

1. For Laila, WRF overpredicts rain and control run returns better values of BS and ETS than 3DVAR.
2. For Jal, 3DVAR returns better estimates than control run.
3. For Thane, both WRF and 3DVAR return low estimates.

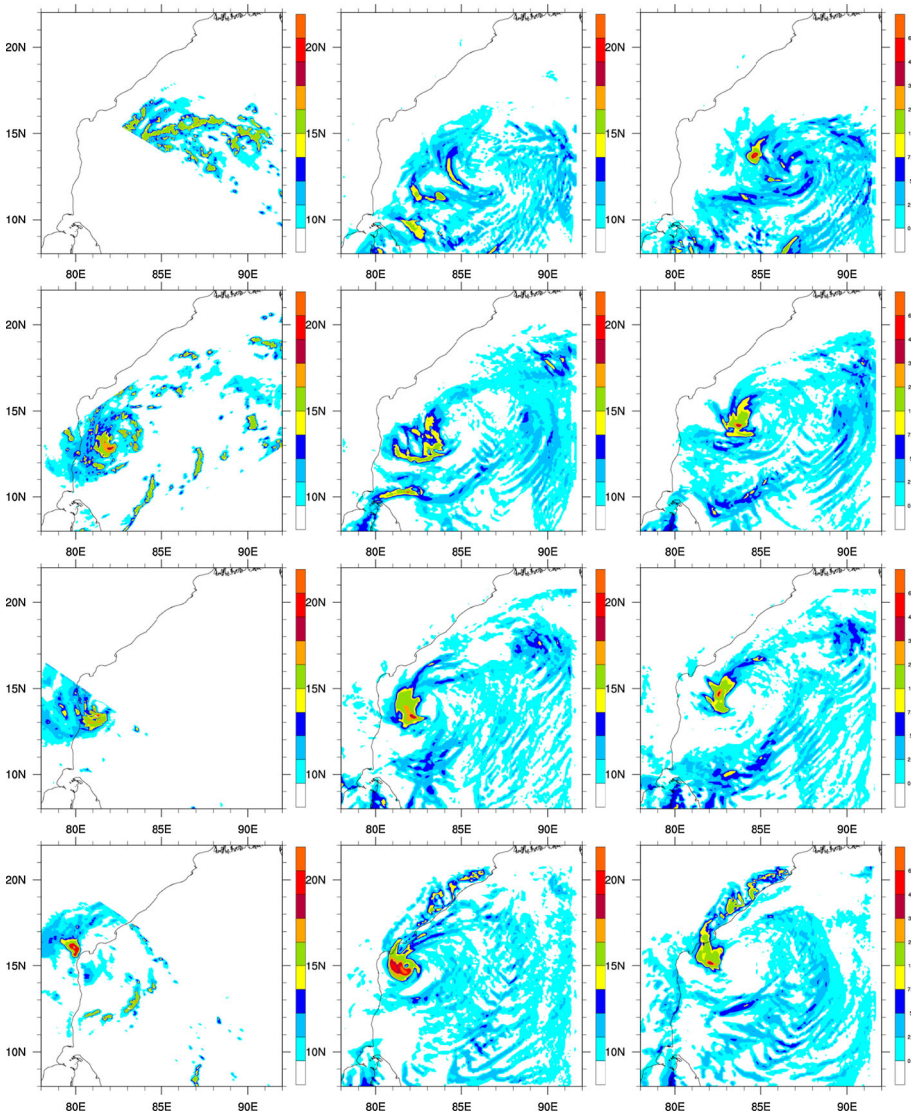


Fig. 7 Surface rainfall (mm/h) for cyclone Laila. TRMM 2A12 (*left column*), WRF control (*middle column*), WRF 3DVAR simulation (*right column*)

Based on the above observations, it is seen that 3DVAR and WRF can give good rainfall prediction in the case of medium rain (60–160 mm accumulated rain) for these cyclone cases. In future, more studies are required to arrive at more broader and general conclusions.

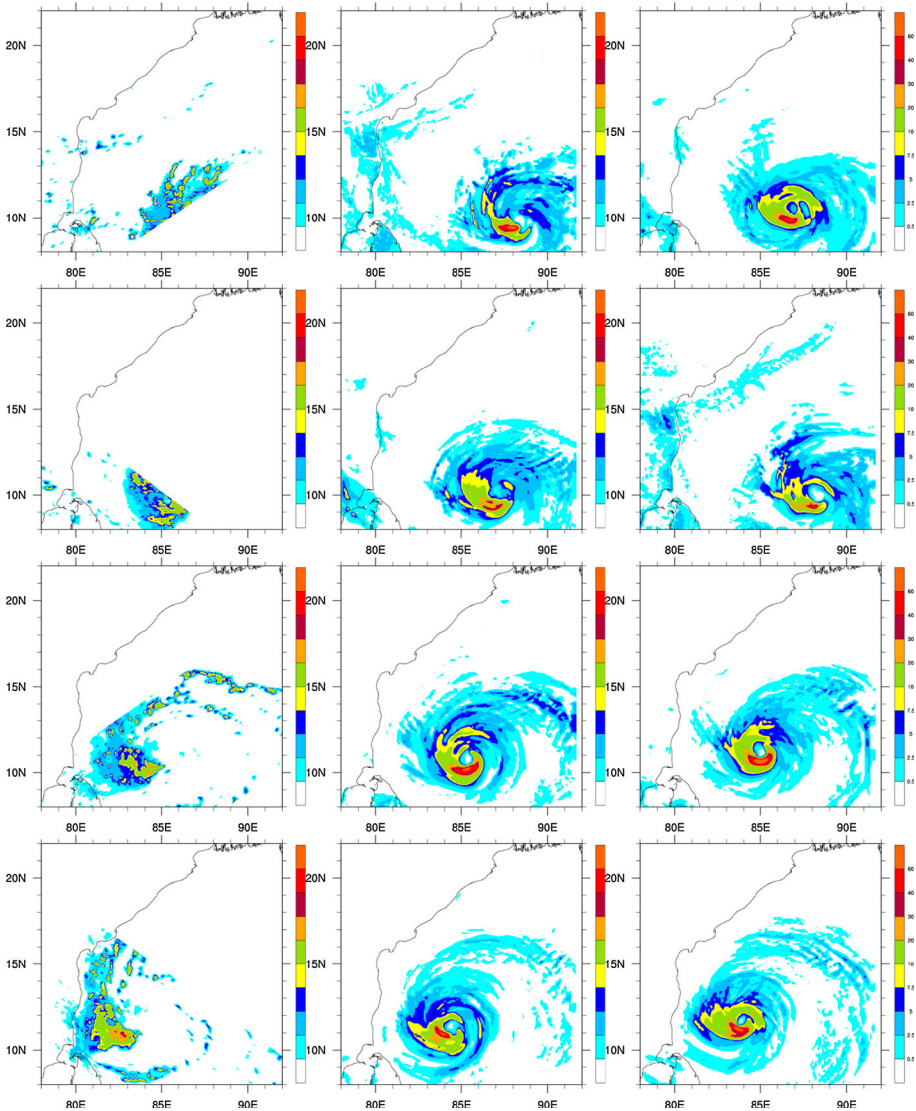


Fig. 8 Surface rainfall (mm/h) for cyclone Jal. TRMM 2A12 (*left column*), WRF control (*middle column*), WRF 3DVAR simulation (*right column*)

8 Conclusions

Sensitivity studies were conducted with four westward cyclonic cases in the BOB. The results show that the prediction of TC with considerable accuracy is possible if the correct physics parameterization schemes are chosen. However, the results clearly show that best scheme for one cyclone is not suitable for the other. So, it is difficult to fix a single set of physics schemes without compromising on the accuracy. Furthermore, track predictions are more sensitive to CU, MP and PBL schemes as opposed to other parameterization

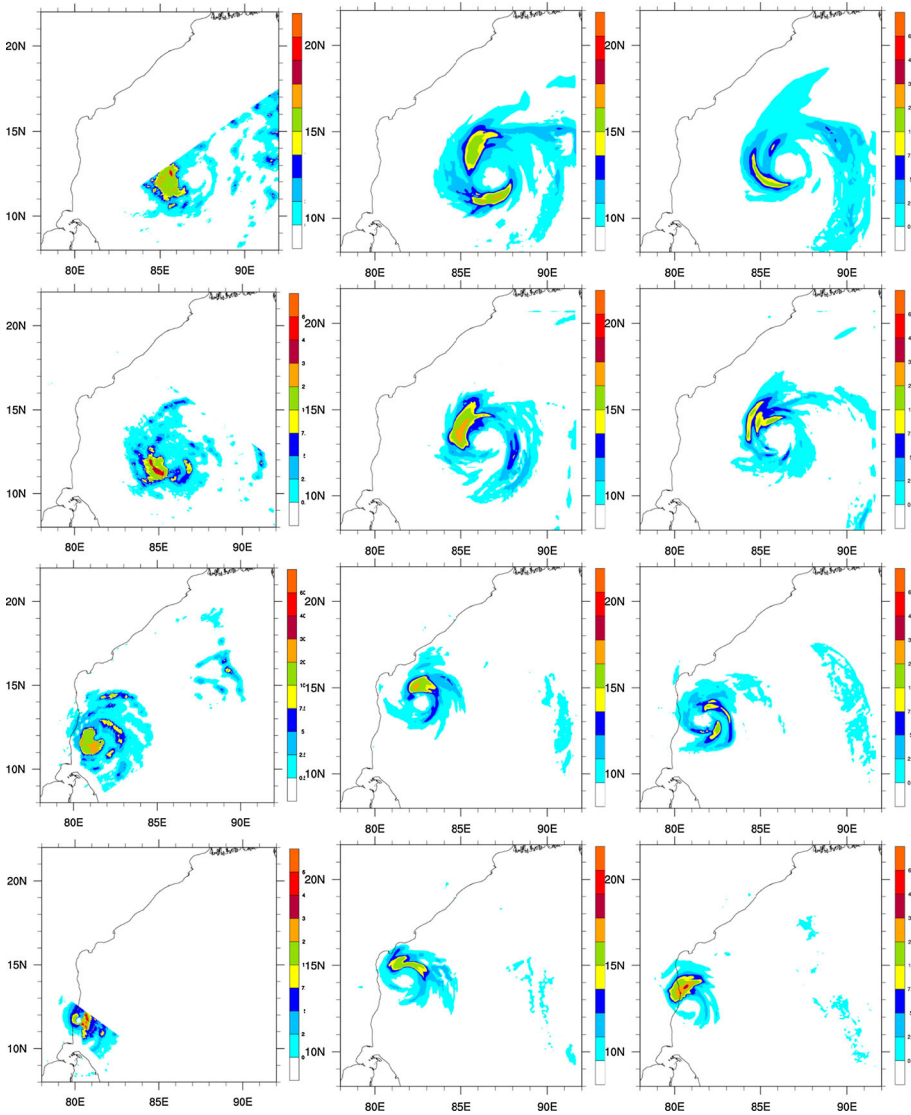


Fig. 9 Surface rainfall (mm/h) for cyclone Thane. TRMM 2A12 (*left column*), WRF control (*middle column*), WRF 3DVAR simulation (*right column*)

Fig. 10 Contingency table

		Observation		
		YES	NO	
Model	YES	H	F	H + F
	NO	M	Z	M + Z
		H + M	F + Z	N

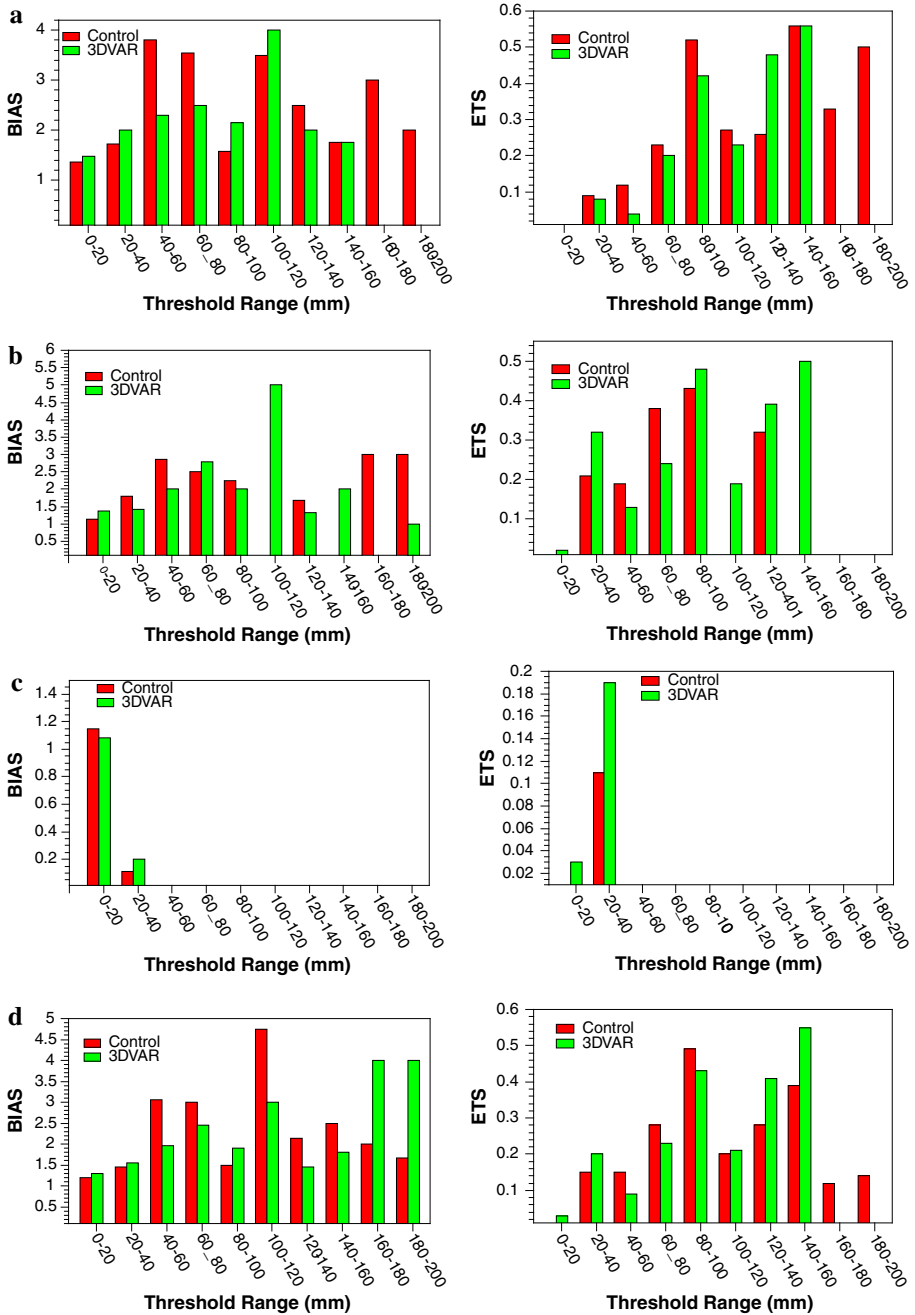


Fig. 11 Bias score and ETS for both control run and 3DVAR **a** Laila, **b** Jal, **c** Thane, **d** average for all the cyclones

schemes. From the sensitivity studies of four cyclones, an optimum set of physics parameterization schemes has been arrived at for the region BOB. This optimum set gives better performance compared to the literature and is recommended for use in forecasting TCs in the BOB region.

With the optimum physics schemes, the impact of assimilation of NCEP ADP upper air observation data on TC prediction has been analyzed through 3DVAR, and the results are mixed in respect of forecast of track, intensity and both instantaneous and accumulated rainfall simulations. The rainfall validation shows both WRF and 3DVAR have good statistics skill scores in the range of medium rain (60–160 mm accumulated rain).

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