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Simulation of tropical cyclones over the Bay of Bengal during 1999-2013 : Impact of physical parameterization schemes

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सार – उष्णकटिबंधीय चक्रवात (TC) सबसे विनाशकारी और घातक मौसम की घटनाओं में से एक है और यह जानमाल के नुकसान का कारण बनता है। बंगाल की खाड़ी (BoB) चक्रवाती तूफानों के लिए एक संभावित ऊर्जावान क्षेत्र है, जो चक्रवाती तूफानों की वैश्विक वार्षिक कुल संख्या का लगभग 6% है। जानमाल और संपत्तियों को नुकसान से बचाने के लिए इन तूफानों का सटीक पूर्वानुमान आवश्यक है। इस संबंध में, उष्णकटिबंधीय चक्रवात (TC) के मार्ग और तीव्रता के पूर्वानुमान से जुड़ी त्रुटियों में कमी आपदा प्रबंधन के लिए अधिक विश्वसनीय जानकारी का प्रसार करने के लिए एक महत्वपूर्ण पहलू है। वर्तमान अध्ययन में 1999-2013 के दौरान बंगाल की खाड़ी (BoB) में उष्णकटिबंधीय चक्रवात (TC) के मार्ग और तीव्रता के सिमुलेशन के लिए उन्नत अनुसंधान मौसम अनुसंधान और पूर्वानुमान (WRF-ARW) मॉडल के प्रदर्शन की जांच की गई है । WRF-ARW मॉडल के विभिन्न सूक्ष्म भौतिक प्राचल (MP), कपासी प्राचलीकरण (CP) और भूमंडलीय परिसीमा स्तर (PBL) योजनाओं का उपयोग करके 38-चक्रवातों (1999-2013 के दौरान) के संख्यात्मक सिमुलेशन किए गए। 11 संयोजनों का उपयोग करके कुल 1133 सिमुलेशन किए गए जिसमें चार सूक्ष्म भौतिक प्राचलों (MPs) [Lin *et al*. (LIN Ferrier (new Eta) (FERR), WSM 6 स्तरीय योजना ग्रौपेल योजना (WSM6) और थॉम्पसन (THOMP)], चार CPs [Kain-Fritsch (KF), Betts-Miller-Janjic (BMJ), Grell-Devenyi (GD) New Grell Scheme (NG)], और तीन PBLs [Yonsei यूनिवर्सिटी स्कीम (YSU), Mellor-Yamada- Janjic (Eta) TKE (MYJ) और असममित संवहन मॉडल संस्करण 2 (ACM2)] की पहचान करने के लिए बंगाल की खाड़ी (BoB) में उष्णकटिबंधीय चक्रवातों (TCs) के मार्ग और तीव्रता का पूर्वानुमान करने के लिए इन योजनाओं का सबसे अच्छा तार्किक संयोजन किया गया है। CP और PBL योजनाओं के सर्वश्रेष्ठ संयोजन ने MP योजनाओं की तुलना में चक्रवातों की तीव्रता और मार्ग के सिमुलेशन को प्रभावित किया। इसके अलावा, विभिन्न प्रारंभिक स्थितियों वाले तीव्र तूफानों का सिमुलेशन किया गया और सुझाव दिया गया कि KF + LIN + YSU के संयोजन ने बंगाल की खाड़ी (BoB) में 72 घंटे के लिए तूफानों के बेहतर सिमुलेशन प्रदान किए, और यह देखा गया कि 1999 से 2013 के चक्रवातों में मार्ग त्रुटि कम हुई । इससे यह स्पष्ट होता है कि WRF-ARW मॉडल की प्रारंभिक शर्तें और मानकीकरण योजना में सुधार हुआ है। यह अध्ययन चक्रवात चेतावनी केंद्रों , आपदा प्रबंधन केंद्रों , वास्तविक समय की शासन प्रणाली और शोधकर्ताओं को चक्रवात की घटनाओं के दौरान तटीय समुदाय के लिए बेहतर प्रबंधन प्रदान करने के लिए बहुत उपयोगी है।

ABSTRACT. Tropical Cyclone (TC) is one of the most devastating and deadly weather phenomena and causes loss of life and property. The Bay of Bengal (BoB) is a potentially energetic region for the development of cyclonic storms, accounting about 6% of the global annual total number of cyclonic storms. Accurate prediction of these storms is essential to avoid loss of lives and damage to properties. In this regard, the reduction of errors associated with the track and intensity forecast of the TCs is an important aspect to disseminate more reliable information to the disaster management. The present study examined the performance of Advanced Research Weather Research and Forecasting (WRF-ARW) model for the simulation of track and intensity of TCs over BoB during 1999-2013. The numerical simulations were carried out for 38-cyclones (during 1999-2013) using different microphysical parameterization (MP), cumulus parameterization (CP) and planetary boundary layer (PBL) schemes of the WRF-ARW model. The total 1133 simulations were performed by using 11 combinations with four MPs [Lin *et al*. (LIN), Ferrier (new Eta) (FERR), WSM 6-class Scheme graupel scheme (WSM6) and Thompson (THOMP)], four CPs [Kain-Fritsch (KF), Betts-Miller-Janjic (BMJ), Grell-Devenyi (GD) and New Grell Scheme (NG)] and three PBLs (Yonsei University scheme (YSU), Mellor-Yamada-Janjic (Eta) TKE (MYJ) and Asymmetrical Convective Model version 2 (ACM2)] to identify the best logical combination of these schemes to predict the track and intensity of TCs over BoB. The best combination of CP and PBL schemes were more influenced the simulations of intensity and track of the cyclones compared to the MP schemes. Further, the simulations were conducted for intense storms with different initial conditions and suggested that the combination of KF + LIN + YSU provided better simulations of the storms for 72h over the BoB and also observed the decreased track error from 1999 to 2013 cyclones. This clearly indicated that the improvement in the initial conditions and parameterization schemes of the WRF-ARW model. This study is very useful for the cyclone warning centers, disaster management centers, real-time governance system and researchers to provide better management for coastal community during the cyclone events.

Key words – WRF-ARW, Cumulus, microphysical, planetary boundary layer, Cyclones.

1. Introduction

Tropical cyclones (TCs) are known for the devastation and innumerable damage to lives and infrastructure of the coastal region of the country. The Pacific, Atlantic and Indian Oceans are the major Oceans, experience the formation of the cyclonic storms every year (Singh *et al*., 2016). In the North Indian Ocean (NIO), about 6-7% of the world's total TC formation takes place over the BoB region and are being three times more prone compared to Arabian Sea (Gupta 2006). Most of the TCs developed over the BoB made landfall at different coastal area of India, Myanmar and Bangladesh. Storms developed over the east coast of India and Bangladesh are extremely deep and intense and have high rainfall rates (Hirose and Nakamura 2002). Therefore, the forecast of landfall time and location of these storms are very essential by using advanced numerical weather prediction (NWP) models to make emergency response and to save the lives and property.

Several researchers have used the Advanced NWP models (Mesoscale Model (MM5) and Weather Research and Forecasting (WRF)) for the prediction of cyclones in different regions (Prater and Evans, 2002; Yang and Ching, 2005; Fovell and Su, 2007; Srinivas *et al*., 2007; Li and Pu, 2009; Loh *et al*., 2010; Raju *et al.*, 2011; Singh and Mandal 2015; Singh and Bhaskaran 2018). Prater and Evans (2002) reported that the Kain-Fritsch (KF) scheme provided better forecasts of the storm Irene (1999). Yang and Ching (2005) revealed that the Medium-Range Forecast Model (MRF) of planetary boundary layer (PBL) and Grell-Devenyi (GD) of cumulus parameterization (CP) combined with the Goddard Graupel of microphysical parameterization (MP) scheme showed the best performance to predict the typhoon Toraji (2001). Fovell and Su (2007) studied the sensitivity of Hurricane Rita and reported that the combination of MP and CP played an important role in the prediction of the track and landfall location of the Hurricane Rita. Li and Pu (2009) stated that the intensity of hurricane EMLY was very sensitive to the choice of CP schemes compared to PBL schemes. Reddy *et al*. (2014) showed that the selection of CP and MP schemes are vital for the simulation of the track and intensity of the cyclone JAL.

In the context of the Indian subcontinent, several researchers used NWP models such as MM5 and WRF models for the prediction of track and intensity of cyclones over NIO (Rao and Bhaskar Rao 2003; Mohanty *et al*. 2004; Sathi Devi *et al*. 2006; Bhaskar Rao and Hari Prasad, 2007; Srinivas *et al*., 2007; Mukhopadhyay *et al*., 2011; Raju *et al*., 2011; Deshpande et al., 2012; Reddy *et al*., 2014; Singh and Mandal 2014, Mandal *et al*., 2016; Singh and Tyagi 2018). Mukhopadhyay *et al*. (2011) studied the impact of moist processes on Gonu and Sidr storms over NIO and reported the moist convection produces a better forecast. Raju *et al*., (2011) highlighted that the CP schemes controlled the intensity and MP schemes influenced the track of cyclone NARGIS. Krishna *et al.* (2012) studied the model sensitivity for the cyclones over the NIO and suggested that the combination of YSU of PBL and KF of CP scheme simulated less track and intensity errors. However, Pattanayak *et al*. (2012) showed that the CP schemes influenced the movement and the PBL schemes controlled the intensity of the cyclone NARGIS. Chandrasekar and Balaji (2012) studied JAL TC using different physical processes and revealed that forecasts were more sensitive to the physical processes of CP schemes. Reddy *et al*. (2014) revealed that the simulated track and intensity of cyclone JAL were sensitive to the choice of CP schemes rather than MP schemes of the model. Singh and Bhaskaran (2017) studied the prediction of severe cyclonic storms over the BoB region and suggested that the simulations were sensitive to the parameterization of convective and PBL schemes.

Several researchers have studied the importance of physical parameterization schemes on the prediction of track and intensity of TCs. These studies explored the simulated track and intensity of the cyclones at different resolutions of the domain and with different initial/boundary conditions. However, the best set of physical parameterization schemes for one region could not be suitable for other region. Therefore, the sensitivity studies are the most essential to identify the best logical combination of physical schemes to predict the track and intensity of the cyclones over a particular region. The literature clearly showed that, most of the sensitivity studies were focused on either a cyclone or a few of the cyclones to predict the track and intensity over the BoB region using the best logical combination of physical schemes. The present study focused on the investigation of the best logical combination of physical parameterization schemes such as CP, MP and PBL to predict the track and intensity of cyclones which were developed over the BoB during 1999-2013 (*i.e.*, over the

TABLE 1

The best set of CP, PBL and MP schemes in the simulation of track and intensity for the cyclones developed between 1999 and 2013. (*Note* : K-KF, B-BMJ, G-GD, N-NG, Y-YSU, M-MYJ, L-LIN, F-FERR, W-WSM6, T-THOMP and a-All)

Case	Cyclone Name	Initial condition (0000 UTC)	Duration	Track error			Intensity			Best set of combination	
				CP	PBL	MP	CP	PBL	MP	Track	Intensity
01	991025	25-10-1999	6days	K	Y	F	K	Y	F	K+Y+F	K+Y+F
02	000327	27-03-2000	4days	B	Y	W	G	M	W	B+Y+W	G+M+W
03	001015	15-10-2000	5days	N	Y/M	F	G	M	F	N+M+F	G+M+F
04	001025	25-10-2000	4days	B/a	Y	T/a	N/G	M	T	B+Y+T	N+M+T
05	001126	26-11-2000	5days	K/N	M	F/a	K	Y	W/F	K+M+F	K+Y+W
06	001223	23-12-2000	6days	G/a	M	L/a	K	Y	L/a	N+M+L	K+Y+L
07	011014	14-10-2001	3days	K	M/Y	L/ a	N/G	Y/M	L/a	K+M+L	N+Y+L
08	021110	10-11-2002	3days	K	Y	L/a	K	Y	W/a	K+Y+L	K+Y+W
09	021123	23-11-2002	6days	N/G	Y/M	F/a	N/G	M/Y	L/a	N+Y+F	G+Y+L N+M+L
10	021221	21-12-2002	5days	B	Y	L	N	M	L	B+Y+L N+M+L	N+M+L
11	030510	10-05-2003	7days	K/N	Y/M	L	G/B	Y/M	L	N+M+L	B+M+L
12	031213	13-12-2003	3days	K	Y	L/a	K	Y	L/a	K+Y+L	K+Y+L
13	040516	16-05-2004	4days	B/K	Y	L	K	Y	L	B+Y+L	K+Y+L
14	HIBARU	13-01-2005	5days	K/a	Y	L	K/a	Y	L	K+Y+L	K+Y+L
15	PYARR	17-09-2005	5days	G/B	M	F/T	N/G	Y	L	G+M+F	N+Y+L
16	BAAZ	28-11-2005	5days	a/K	M	F				K+Y/M+F	
17	FANOOS	06-12-2005	5days	K	M	F	G	Y	L	K+Y/M+F	G+Y+L
18	MALA	25-04-2006	5days	N	M	F	N	A	T	N+M+F	N+A+T/L
19	OGNI	28-10-2006	3days	K	Y	T	K	Y/M	T	K+A+L	K+M+L
20	AKASI	13-05-2007	3days	K/a	Y/a	W/a	B	Y	L	K+Y+W	B+Y+L
21	SIDR	11-11-2007	5days	K	Y	T	K	M	a	K+Y+T/L	K+M+L
22	NARGIS	28-04-2008	6days	N	Y	F	N	A	T	N+Y+F/L	N+A+T
23	RASHMI	25-10-2008	3days	B	Y	L	K	Y	W	B+Y+L	B+A+L K+Y+W
24	KHAIMUK	13-11-2008	4days	B	Y	L	K	Y	L	B+Y+L	K+Y+L B+A+L
25	NISHA	24-11-2008	3days	K	Y	W	N	Y	L	K+Y+W	N+Y+F
26	BIJLI	14-04-2009	4days	K	Y	T	B	Y	a	K+Y+T	B+Y+a
27	AILA	23-05-2009	4days	B	Y/A	L	B/K	Y/M	L/F	B+Y+L B+A+L	N/B+Y/A+L K+M+F
28	WARD	10-12-2009	5days	K	Y	L/W	K	M	F	K+Y+L	K+M+F
29	LAILA	17-05-2010	5days	N/K	M	F	K	M	a	K+M+F	K+M+a
30	GIRI	20-10-2010	4days	G	Y	W	K	Y	W	G+Y+W	K+A+W
31	JAL	03-11-2010	5days	K	Y	L/F	B	Y	L	K+Y+L/F	B+Y+L
32	THANE	25-12-2011	6days	G/N	Y	W	K	Y	W	G+Y+W	K+Y+W
33	NILAM	28-10-2012	5days	K/N	Y/M	L/a	G	Y	L/a	K+Y+L	G+Y+L
34	VIYARU	11-05-2013	6days	G	Y	T	G	M	T	G+Y+T	G+M+T
35	PHAILIN	08-10-2013	6days	B	Y	F	K	M	F	B/K+Y+F	K+M+F
36	HELEN	19-11-2013	4days	K	Y	T/a	K	Y	T/a	K+Y+T	K+Y+T
37	LEHAR	23-11-2013	6days	N	M	L	N	M	L	N+M+L	N+M+L
38	MADI	07-12-2013	6days	K	M	W	K	M	W	K+M+W	K+M+W

period of 15 years) using the WRF-ARW model with a horizontal resolution of 27 km. Considering the limitations of computational facilities and more number of experiments, the model simulations have been conducted at a horizontal resolution of 27 km with rational scientific approach to predict the minimal error in track and intensity of the tropical cyclones.

2. Cyclone cases, methodology and datasets

2.1. *Details of cyclone cases*

In this study, simulation of the track and intensity of 38 TCs formed over the BoB region during 1999-2013 are investigated. Based on India Meteorological Department (IMD) report, the storms are classified based on wind speed (WS) into different categories, namely: cyclonic storm (CS) (WS between 34-47 knots), severe cyclonic storms (SCS) (WS between 48-60 knots) and very severe cyclonic storms (VSCS) (WS more than 60 knots). The names of cyclones are given as per the IMD report for those cyclones formed over the BoB since 2005. However, the cyclones formed over BoB before 2005 have given the name as per their genesis date. Among these 38 cyclonic systems, 19 cyclones are classified as CS, 6 as SCSs and 12 as VSCS.

2.2. *Methodology and datasets*

The WRF-ARW model (Skamarock *et al*. 2008) is used for the simulation of storms track and intensity over the BoB during 1999-2013. The simulations were conducted with four MP schemes such as LIN, FERR, WSM6 and THOMP, four convective parameterization schemes (CP) such as KF, BMJ, GD and NG and three PBL such as YSU, MYJ and ACM2 of the WRF-ARW model for different initial conditions at 27 km horizontal resolution. In this study, the model configured with Long wave radiation scheme, Short wave radiation scheme and Land surface scheme such as Rapid Radiative Transport Model (RRTM) scheme, Dudhia scheme and Noah land surface model, respectively. Initial and boundary conditions for 38 storms during 1999-2013 are obtained from NCEP FNL data at 1° × 1° horizontal resolution for every 6-h interval. Finally, the simulated results (track and intensity) of the storms are validated using the IMD best fit track observations.

3. Results and discussion

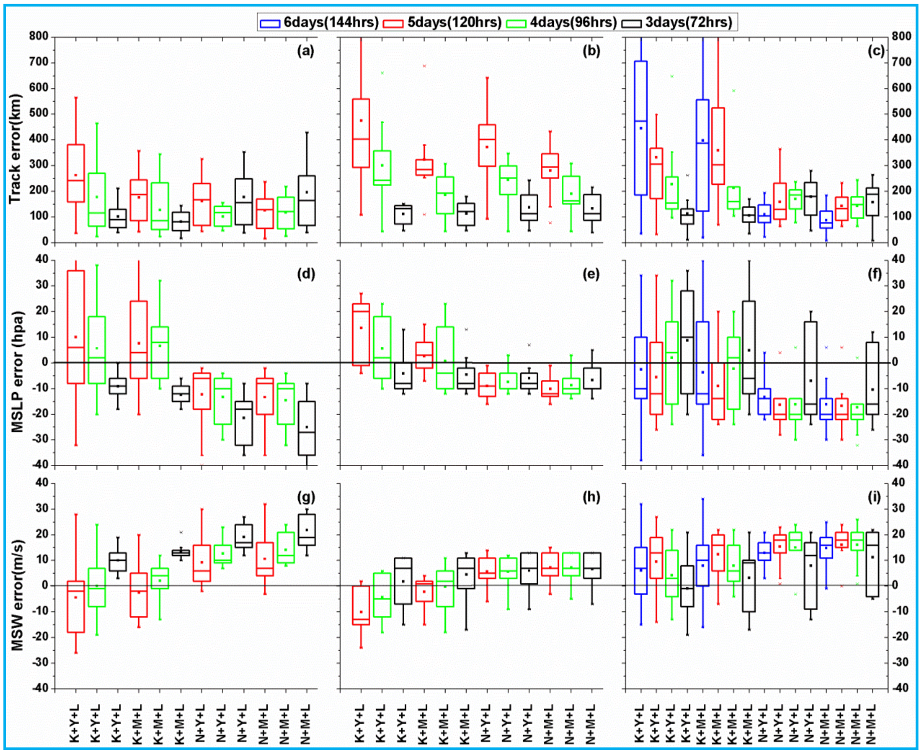
3.1. *Performance of physical parameterization schemes*

To understand the influence of physical parameterization schemes on the track and intensity prediction, the model simulations (from genesis to weakening stage) were carried out using different physical parameterization schemes for different tropical cyclones during 1999-2013. The model simulations are carried out for all the cyclones formed between 1999 and 2013 with different CPs with LIN MP and YSU PBL schemes. Thereafter, simulations are carried out with different PBL schemes with the best set of CP and LIN MP. Finally, different MPs with the best set of CP and PBL schemes. It is clear that the CP and PBL schemes play a major role in the prediction of the track and intensity of the cyclones compared to MP schemes. However, the MP schemes have a significant influence on the intensity compared to storm track. Table 1 shows the best logical combination of physical parameterization schemes for the prediction of the track and intensity of all the cyclones. It concluded that the results showed the logical combinations of CP, PBL and MP schemes of the simulated track and intensity were different for different cyclones. However, the best set of CP, PBL and MP schemes were identified from predictions of minimal error in the track and intensity of the tropical cyclones. Further, in the subsequence sections, the model performance was investigated the physical parameterization schemes with different initial conditions.

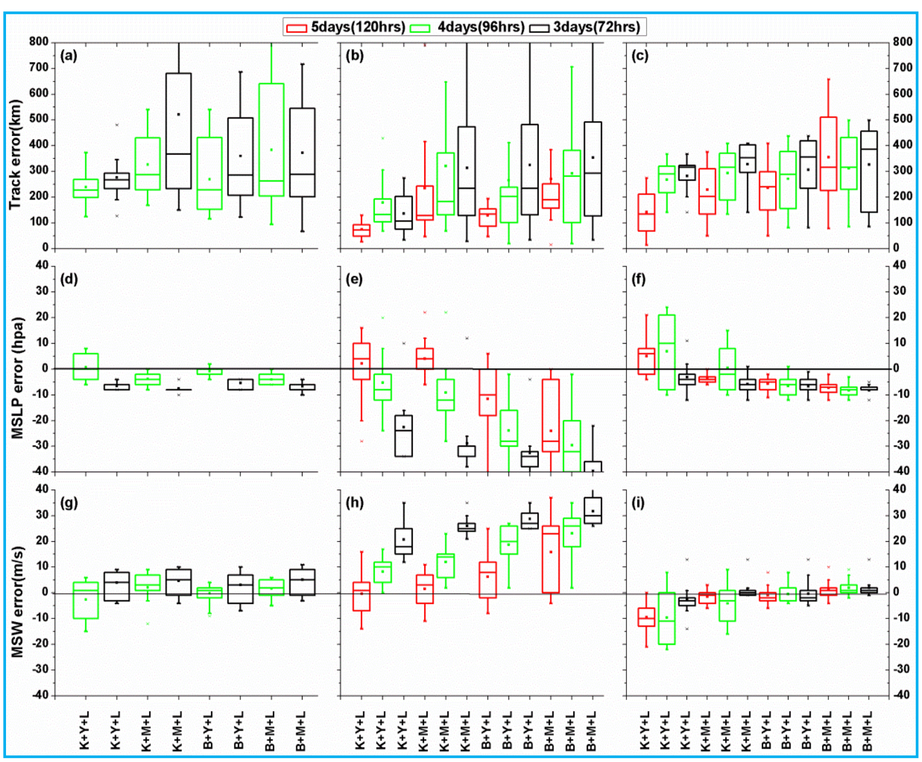
3.2. *Performance of physical parameterization schemes at different initial conditions (ICs)*

Model simulations were carried out using different initial conditions for different class of tropical cyclones such as MALA (VSCS), NARGIS (VSCS), BIJLI (CS), LAILA (SCS), SIDR (VSCS) and WARD (CS). Out of these six cyclones, four cyclones (MALA, NARGIS, BIJLI and LAILA) formed during pre-monsoon and the other two cyclones (SIDR and WARD) formed during post-monsoon season. The results of model simulations suggested that combination of NG+MYJ for MALA, NG+YSU for NARGIS, BMJ+YSU for BIJLI, KF+MYJ for LAILA, KF+YSU for SIDR and WARD provided better prediction. All these combinations with four MPSs, model simulated the better tracks for the six cyclones when compared with the observed track in most of the cases (Table 1).

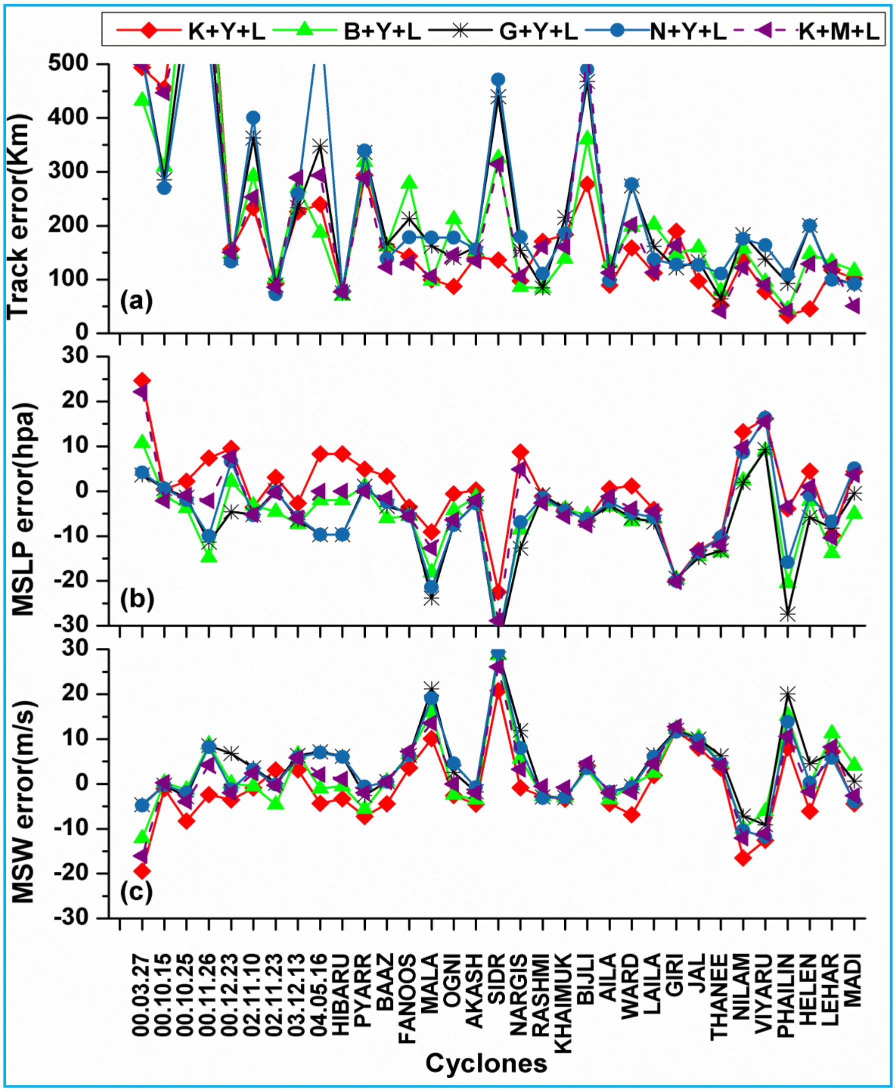
In this section, the six storms, MALA, NARGIS, LAILA, BIJLI, SIDR and WARD are simulated with the best combination as mentioned above with the BMJ, KF and NG of CP schemes, YSU and MYJ of PBL schemes and Lin MP scheme to predict the track and intensity using different initial conditions. Box and Whisker plots of simulated track error for all the simulations at different ICs are shown in Figs. 1(a-c) and 2(a-c). The horizontal line in the box represents the median value and the bubble represents the mean value. The boxes represent data between the first and third quartiles and the whiskers show



Figs. 1(a-i). Box and whisker plot of horizontal track (km), MSLP (hPa) and MSW (m/s) errors respectively for (a), (d) & (g) MALA, (b), (e) & (h) LAILA and (c), (f) & (i) NARGIS



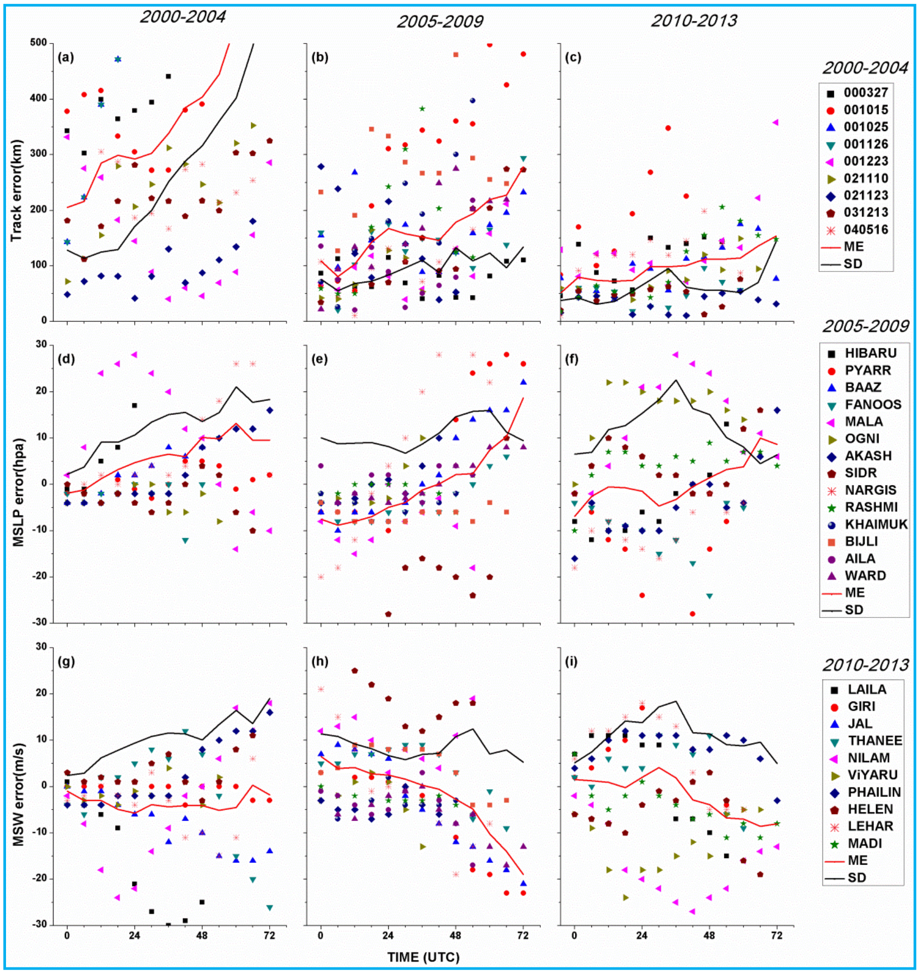
Figs. 2(a-i). Box and whisker plot of horizontal track (km), MSLP (hPa) and MSW (m/s) errors respectively for (a), (d) & (g) BIJLI, (b), (e) & (h) SIDR and (c), (f) & (i) WARD



Figs. 3(a-c). Mean deviation of (a) horizontal track (km), (b) MSLP (hPa) and (c) MSW (m/s) errors for 33 cyclones

percentile of error between 12.5 and 87.5. Simulated track error of MALA, LAILA cyclones was minimum with NG+MYJ schemes for 96 h and 120 h forecasts respectively. However, the combination of KF+YSU schemes showed minimum track error for 72 h simulations [Figs. 1(a&b)]. The median value increased from 72 h to 120 h simulations using KF scheme for both the cyclones MALA and LAILA. Similarly, NARGIS cyclone is simulated with minimum track error using a combination of NG+MYJ schemes for 96 h, 120 h and 144 h simulations. The median value of the track error decreased with a KF scheme from 72 h to 120 h simulations [Fig. 1(c)]. For cyclone BIJLI, the track errors are minimum with KF+YSU combination for 72 h and 96 h simulations. The median value of track error is minimum with KF+YSU combination for 72 h and BMJ+YSU for 96 h simulation [Fig. 2(a)]. The track error is minimum for cyclones SIDR [Fig. 7(b)] and WARD (Figure 2c) with the combinations of KF+YSU schemes of all initial conditions. The median track error increased from 72 h to 120 h simulations using both KF and NG schemes. It can be concluded here that the model experiments showed better track simulation for the combination KF+YSU schemes at 72 h simulation for all the initial and boundary conditions.

The intensity of a storm can be measured in terms of minimum sea level pressure (MSLP) and maximum surface wind speed (MSW). Figs. 1(d-i) and 2(d-i) show the box plot distribution of errors in MSLP (d-f) and MSW (g-i). Here, the positive (negative) values represent over (under) prediction of the simulated MSLP and MSW



Figs. 4(a-i). Time series of horizontal track error (km) along with their mean and standard deviation for the cyclones between (a) 2000 and 2004, (b) 2005 and 2009 & (c) 2010 and 2013. (d)-(f) same as (a)-(c) for MSLP (hPa) and (g)-(i) same as (a)-(c) for MSW (m/s) with KF CP, LIN MP and YSU PBL schemes

when compared with the observational data. The simulated intensity is stronger for the cyclones MALA and LAILA with the combination of KF CP scheme compared to NG CP scheme in both the PBL schemes for 72 h, 96 h and 120 h simulations. The median value of error in intensity increased from 72 h to 120 h simulations with the combination of KF and YSU for MALA and LAILA cyclones. For the cyclone NARGIS [Figs. 1 (f-i)], KF combinations simulated strongest intensity compared to NG combinations at 96 h, 120 h and 144 h of simulation. It can also be observed that the median value of error is minimum with KF combination. For the cyclone BIJILI, the KF+YSU combination predicted stronger intensity [Figs. 2(d-g)] and showed the minimum median value of error. For the cyclone SIDR, the KF combinations predicted stronger intensity and the median value of error in intensity increases from 72 h to 120 h. Even for cyclone WARD, the KF+YSU combination predicted stronger intensity compared to BMJ combinations. The KF combinations predicted stronger intensity compared to other combinations. The intensity error is minimized with the combination of KF+YSU for the cyclones MALA, LAILA, BIJLI and WARD for 72 h simulation.

3.3. *Performance of physical parameterization schemes in short range simulation*

The above results indicated that the track error is minimum with KF combinations for 72 h simulation. To elucidate this, we estimated the mean track and intensity errors for 33 cyclones with KF, BMJ, GD and NG of CP scheme, LIN of MP scheme and YSU of PBL scheme during 1999 to 2013. The mean track error for the 33 cyclones at 72 h simulation is shown in Fig. 3(a). From these observations, it is concluded that the KF scheme

TABLE 2

Simulation errors in track, intensity and landfall for different cyclones during 1999-2013

Cyclone Name	Track error (km)		MSLP (hPa)		MSW (m/s)		Landfall error	
	Cross	Along	MAE	RMSE	MAE	RMSE	Time (h)	Position (km)
CS- 000327	400	177	25	31	20	23	-	-
CS-001015	326	279	2	3	1	2	-	-
CS-001025	197	195	4	5	5	7	1	340
CS-011014	342	41	11	18	10	15	24	222
CS-021123	229	123	6	8	6	8	-	-
CS-021221	727	65	18	15	13	12	-	-
CS-HIBARU	68	35	3	3	2	2	-	-
CS-PYARR	367	57	13	16	8	12	0	220
CS-BAAZ	146	62	9	11	10	11	-	-
CS-FANOOS	118	57	5	6	6	7	0	462
CS-OGNI	34	76	5	5	4	6	17	14
CS-AKASH	66	122	4	5	5	5	-	-
CS-RASHMI	108	131	2	2	3	3	-11	58
CS-KHAIMUK	143	82	4	5	4	4	25	104
CS-NISHA	33	30	7	8	9	10	-6	23
CS-BIJLI	104	237	7	7	6	6	-	-
CS-WARD	183	154	4	5	7	8	3	163
CS-NILAM	76	101	14	17	17	18	-11	12
CS-VIYARU	44	56	16	17	13	15	-2	139
CS-Average	**195**	**109**	**8**	**10**	**8**	**9**	**4**	**160**
SCS-021110	175	121	4	4	2	3	9	165
SCS-031211	74	209	4	5	4	5	15	407
SCS-AILA	43	73	3	3	5	7	-2	60
SCS-LAILA	96	54	7	8	10	10	-6	214
SCS-JAL	85	52	11	12	12	12	2	130
SCS-HELEN	31	37	6	7	7	9	-3	29
SCS-Average	**84**	**91**	**6**	**7**	**7**	**8**	**3**	**168**
VSCS-001126	655	364	11	18	9	11	1	510
VSCS-001223	140	52	14	17	12	14	0	89
VSCS-030510	234	224	15	18	10	11	-	-
VSCS-040516	285	188	8	12	5	7	1	183
VSCS-MALA	46	164	9	10	10	11	-1	21
VSCS-SIDR	63	115	24	25	17	20	8	84
VSCS-NARGIS	88	67	18	21	9	11	-8	155
VSCS-GIRI	343	65	20	25	13	18	-8	452
VSCS-THANE	22	58	10	12	6	7	-8	175
VSCS-PHAILIN	20	24	7	9	9	9	1	81
VSCS-LEHAR	118	17	10	11	10	11	4	80
VSCS-MADI	37	81	6	6	6	7	1	182
VSCS-Average	**171**	**118**	**13**	**15**	**10**	**11**	**-1**	**183**

produced minimum error compared to other CP schemes except for the cyclones GIRI and RASHMI. However, the difference in track error is small among different schemes for the cyclones GIRI and RASHMI. Figs. 3(b-c) shows the mean intensity error for these cyclones for 72 h simulation. If the MSLP (MWS) is positive (negative) then the intensity simulated by the scheme is stronger and *vice versa*. For all the cyclones, the KF + YSU combination simulates stronger intensity compared to other combinations. The mean error in the intensity is minimum with a KF scheme for most of the cyclones. Similarly, we simulated all the cyclones with KF CP scheme and MYJ and YSU of PBL scheme. The difference in mean track error is small among YSU and MYJ schemes except for KHAIMUK, SIDR and BIJLI cyclones.

Further, simulations are carried out with the best set of physical parameterization schemes (KF of CP, LIN of MP and YSU of PBL scheme) for 33 cyclones for the 72 h simulation. This combination succeeded because the KF scheme computes updraft velocity, closure assumption and trigger function. It takes strong interaction between convection and the larger-scale environment near the mid-troposphere where the return flow associated with lower-level. Similarly, the LIN scheme is a relatively sophisticated microphysics scheme and includes six classes of hydrometeors : (*i*) water vapor; (*ii*) cloud water; (*iii*) raid; (*iv*) cloud ice; (*v*) snow; and (*vi*) graupel. The scheme does not have interactions among horizontal grid points and is very suitable for massively parallel computation. Finally, YSU attempts explicitly to account for entrainment into the PBL from the free atmosphere. It plays a major role in capturing the processes of turbulent mixing and phase change of hydrometeors during the lifetime of extreme weather event. Therefore, the logical combination of KF+LIN+YSU schemes utilizes the convective processes and hydrometeors along the turbulent mixing at the planetary boundary to provide precise track simulations along with the intensity of tropical cyclones. Fig. 4(a) shows the time series of track error along with their mean and standard deviation for the cyclones during 1999 - 2004. The simulations showed that the track error was the minimum for the cyclone 001223 and maximum for the cyclone 040516. During this period, the mean and standard deviation of the track error increased with time. The time series of cyclone track errors during 2005-2009 are shown in Fig. 4(b) and found that the track error is minimum for cyclone HIBARU and maximum for BIJLI. The time series of track error for the cyclones during 2010 - 2013 in Fig. 4(c) represents that the track error is minimum for cyclone PHAILIN and higher for cyclone GIRI. It is noticed that the track error decreased from 1999 to 2013 cyclones. This could be attributed to the improvement in the initial conditions and parameterization schemes of the WRF-ARW model. However, the intensity simulation did not decrease as such track error of the cyclone during 1999-2013. The predicted directional track errors and the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) of the MSLP and MSW and errors in the landfall time and position of 37 cyclones have presented in the Table 2. The details of 37 cyclones in Table 2 clearly indicated that the model predicted the minimum track error along the track compared to cross the track. It also observed that the value of error in the prediction of MSLP and MSW gradually decreased from 1999 to 2013.

4. Summary and conclusions

The present study investigated the simulation of TCs over BoB which were formed during 1999-2013 using the WRF - ARW model. First, the track and intensity (from genesis to weakening) of all cyclones were investigated to identify the best logical combination of CP, MP and PBL schemes. The Model simulation was better with the combination of NG+MYJ, NG+YSU, BMJ+YSU, KF+MYJ, KF+YSU and KF+YSU of CP and PBL schemes for the storms MALA, NARGIS, BIJLI, LAILA, SIDR and WARD. The best combinations of CP, PBL and MP schemes is also investigated for six cyclones at different ICs and found that the track and intensity are more sensitive to CP and PBL schemes compared to MP schemes. The combination of KF of CP, LIN of MP and YSU of PBL schemes predicted minimum track and intensity error for 38 storms at 72 h simulation. The mean and standard deviation of track error of all the cyclones showed a decreasing trend, however such a decreasing trend is not observed in intensity. The decreasing trend in the track error indicates that the performance of the model improved with the incorporation of improved physical parameterization schemes in the WRF-ARW model. These results are more useful for researchers in the field of disaster management, weather information and cyclone warning centers of India. It also provides the feedback for the model developer to develop a regional based physical parameterization schemes for the prediction of tropical cyclones.

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References

Bhaskar Rao, D. V. and Hari, D., 2007, "Sensitivity of tropical cyclone intensification to boundary layer and convective processes", *Nat. Hazards*, **41**, 429-445.

Chandrasekar, R. and Balaji, C., 2012, "Sensitivity of tropical cyclone Jal simulations to physics parameterizations", *J. Earth Syst. Sci*., **121**, 4, 923-946.

Deshpande, M. S., Pattnaik, S. and Salvekar, P. S., 2012, "Impact of cloud parameterization on the numerical simulation of a super cyclone", *Ann. Geophys*., **30**, 775-795.

Fovell, R. G. and Su, H., 2007, "Impact of cloud microphysics on hurricane track forecasts", *Geophys. Res. Lett*., **34**, L24810.

Gupta, A., 2006, "Current status of tropical cyclone track prediction techniques and forecast errors", *MAUSAM*, **57**, 1, 151-158.

Hirose, M. and Nakamura, K., 2002, "Spatial and seasonal variation of rain profiles over Asia observed by space borne precipitation radar", *J. Clim*., **15**, 3443-3458.

Krishna, O. K., Mohanty, U. C., Routray, A., Kulkarni Makarand, A. and Mohapatra, M., 2012, "Customization of WRF-ARW model with physical parameterization schemes for the simulation of tropical cyclones over North Indian Ocean", *Natural Hazards*, **63**, 3, 1337-1359.

Loh, W., Juneng, L. and Tandang, F., 2010, "Sensitivity of Typhoon Vamei (2001) simulation to planetary boundary layer parameterization using PSU/NCAR MM5", *Pure Appl. Geophys*., **168**, 10, 1799-1811.

Mandal, M., Singh, K. S., Balaji, M. and Mahapatra, M., 2016, "Performance of WRF-ARW model in real-time prediction of Bay of Bengal cyclone 'Phailin'", *Pure Appl. Geophys*., **172**, 1-19.

Mohanty, U. C. and Mandal Mand Raman, S., 2004, "Simulation of Orissa Super Cyclone (1999) using PSU/NCAR Mesoscale Model", *Nat. Hazards*, **31**, 373-390.

Mukhopadhyay, P., Taraphdar, S. and Goswami, B. N., 2011, "Influence of moist processes on track and intensity forecast of cyclones over the north Indian Ocean", *J. Geophys. Res*., **116**, D05116.

Pattanayak, Sujata, Mohanty, U. C. and Osuri Krishna, K., 2012, "Impact of parameterization of physical processes on simulation of track and intensity of tropical cyclone Nargis (2008) with WRF-NMM model", *The Scientific World Journal*, 671437. http://doi.org/10.1100/2012/671437.

Prater, B. and Evans, J. L., 2002, "Sensitivity of modeled tropical cyclone track and structure of Hurricane Irene (1999) to the convection parameterization scheme", *Meteorol. Atmos. Phys*., **80**, 103-115.

Raju, P. V. S., Jayaraman, P. and Mohanty, U. C., 2011, "Sensitivity of physical parameterizations on prediction of tropical cyclone Nargis over the Bay of Bengal using WRF model", *Meteorol. Atmos. Phys*., **113**, 3-4, 125-137.

Rao, G. V. and Bhaskar Rao, D. V., 2003, "A review of some observed mesoscale characteristics of tropical cyclones and some preliminary numerical simulations of their kinematic features", *Proc. Ind. Nat. Sci. Acad.*, **69A**, 523-541.

Reddy, M. V., Surendra Prasad, S. B., Murali Krishna, U. V. and Krishna Reddy, K., 2014, "Effect of Cumulus and Microphysical Parameterizations on the JAL Cyclone prediction", *Indian Journal of Radio & Space Physics*, **43**, 103-123.

Sathi Devi, K., Hari Prasad, D. and Bhaskar Rao, D. V., 2006, "The evaluation of Kain-Fritsch scheme in tropical cyclone simulation", *MAUSAM*, **57**, 3, 395-410.

Singh, K. S. and Bhaskaran, P. K., 2017, "Impact of PBL and convection parameterization schemes for prediction of severe land-falling Bay of Bengal cyclones using WRF-ARW model", *Jour. Atmos. Solar Terres. Phys*., **165**, 10-24.

Singh, K. S. and Bhaskaran, P. K., 2018, "Impact of lateral boundary and initial conditions in prediction of Bay of Bengal cyclones using WRF model and its 3D-Var data assimilation system", *Jour. Atmos. Solar Terres. Phys*., **175**, 64-75.

Singh, K. S. and Mandal, M., 2014, "Sensitivity of mesoscale simulation of Aila cyclone to the parameterization of physical processes using WRF model", In : Monitoring and Prediction of Tropical Cyclones in the Indian Ocean and Climate Change, Springer Netherlands, 300-308.

Singh, K. S. and Mandal, M., 2015, "Impact of Initial and Boundary Conditions on Mesoscale Simulation of Bay of Bengal Cyclones Using WRF-ARW Model", In : High-Impact Weather Events over the SAARC Region, Springer International Publishing, 179-189.

Singh, K. S. and Tyagi, B., 2018, "Impact of data assimilation and air-sea flux parameterization schemes on prediction of cyclone Phailin over Bay of Bengal using WRF-ARW model", *Meteorol. Appl*. doi : 10.1002/met.1734.

Singh, K., Panda, J., Osuri, K. K. and Vissa, N. K., 2016, "Progress in tropical cyclone predictability and present status in the North Indian Ocean Region", In : Lupo AR (ed) Recent developments in tropical cyclone dynamics, prediction and detection. In Tech Publishers, Croatia.

Skamarock, W. C., 2008, "A Description of the Advanced Research WRF Version 3", NCAR Tech. Note, June 2008/W.C. Skamarock. Available at: http://www.mmm.ucar.edu/wrf/users/docs (accessed at : 11.01.2013).

Srinivas, C. V., Venkatesan, R., Bhaskar Rao, D. V. and Hari Prasad, D., 2007, "Numerical simulation of Andhra severe cyclone (2003) : Model sensitivity to the boundary layer and convective parameterization", *Pure Appl. Geophys*., **164**, 1465-1487.

Xuanli, L. I. and Zhaoxia, P. U., 2009, "Sensitivity of Numerical Simulations of the Early Rapid Intensification of Hurricane Emily to Cumulus Parameterization Schemes in Different Model Horizontal Resolutions", *Journal of the Meteorological Society of Japan*, **87**, 3, 403-421.

Yang, M. J. and Ching, L., 2005, "A modeling study of Typhoon Toraji (2001) : Physical parameterization sensitivity and topographic effect", *Terr. Atmos. Oceanic Sci*., **16**, 177-213.