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SENSITIVITY OF CUMULUS PHYSICS IN ARW MODEL ON TRACK OF TROPICAL CYCLONES 'AMPHAN' AND 'BULBUL' OVER THE BAY OF BENGAL

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ABSTRACT

The Advanced Research Weather Research and Forecasting (ARW) model performance can be improved by analyzing the sensitivity of the physical parameterization schemes. In order to revalidate the performance of the ARW model in relation to the selection of Cumulus Physics (CP) schemes, the sensitivity of CP schemes for Tropical Cyclones (TCs) over the Bay of Bengal (BoB) region has been examined. National Centre for Environment Prediction (NCEP)'s Final Reanalysis (FNL) data ($1^0\times1^0$) have been used as lateral and initial conditions in the ARW model. The model has been configured in a single domain and runs for four different initial conditions in simulating TC 'Amphan' and for three different initial conditions in simulating TC 'Bulbul'. In this study, average track errors have been found between 40-50 km for Kain-Fritsch Cumulus Potential (KFCP) and Multi-Scale Kain-Fritsch (MSKF) schemes for TC Amphan and below 60 km for the Kain Fritsch (KF) scheme for TC Bulbul. Lower landfall position error has been found below 60 km for the KF scheme for TC Amphan, and 40 km for KFCP and MSKF schemes for TC Bulbul.

Keywords: *ARW, MSKF, KF, Track, Cumulus*

1. INTRODUCTION

Tropical Cyclone (TC) is one of the most destructive natural cataclysms in the atmospheric system which frequently occurs in the region of the North Indian Ocean (NIO). In India and Bangladesh TCs are the deadliest natural calamities that occur frequently in pre-monsoon (March-May) and post-monsoon (October-November) seasons (Vissaa *et al.*, 2013; Alam *et al*., 2003). TC can be defined as an organized anticlockwise circulation that occurs on a synoptic scale due to the low-pressure system over tropical and sub-tropical waters. A mature TC is made of a cyclonic storm in the lower troposphere and an anti-cyclonic storm in the upper troposphere with a circular shape and a low-pressure area in the center of the system.

In the coastal regions of any country Hurricanes over the Atlantic, typhoons over Western Pacific, and TCs over the NIO are some of the most destructive and dangerous weather phenomena, which occur on a synoptic scale. The Bay of Bengal (BoB) is marginally conducive to TC formation with an average of three to four storms annually forming in this region (Alam *et al*., 2003). According to the Regional Specialized Meteorological Centre (RSMC), New Delhi, the annual occurrence of TCs is 4-5 with a ratio of 4:1 over BoB and the Arabian Sea (Chaudhuri *et al.,* 2013).

The improvement of TC prediction and forecasting is the combined result of better observation; particularly the satellite and radar, and improvement in dynamics and mechanisms that govern the motion of TCs. So, accurate prediction is needed to reduce the destruction that is caused by TCs. For this purpose customization of different physics schemes in the ARW model is necessary because different physics play different roles in the genesis, intensification, and tracks of TCs (Skamarock *et al.*, 2019). The ARW model has computer programs that allow producing TC tracks by extrapolating the initial boundary condition. Modification of TCs prediction in Numerical Weather Prediction (NWP) models has been needed because of the variation in geographical location, initialization, physics options, and grid size. This model has some physical schemes such as Microphysics (MP), Cumulus Physics (CP), Planetary Boundary Layer (PBL) parameterization, radiation physics, etc. which are essential for operational and research purposes. Accurate representation of these schemes is necessary for better prediction in different weather events, weather conditions, and seasons (Deshpande *et al.,* 2010). Generally, the representation of physical schemes is important because they deal with micro- particle, cloud convection, heat flux, mass flux, radiation, etc. which provided the necessary energy which is needed for the intensification and tracking of TCs (Sandeep *et al.,* 2018). For these reasons in the last few decades, the development of physical schemes in the NWP models has been increased to reduce the prediction error for operational and research purposes (Raju *et al.*, 2011). Among these physics options in NWP models, CP represents

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deep convection, mass flux, adjustment, and sub-grid scale effect of convective clouds and PBL physics handles local and non-local turbulent mixing, heat flux, and mass flux into the atmosphere (Skamarock *et al.*, 2019).

By analyzing a combination of MP, CP, and PBL parameterization schemes in the ARW model on TCs Chandrasekar & Balaji (2012) concluded that all CP, MP, and PBL schemes have a strong sensitivity on track and intensity of TCs. Among all physics schemes, the track and intensity of TCs are sensitive to the choice of MP and PBL schemes concluded by Li and Pu (2008), but Deshpande *et al*. (2010) reported that CPs are more sensitive than MPs and PBL parameterization schemes. Pattanayak *et al.* (2012) reported that the effect of physical parameterization of the ARW model in simulating TC Laila Simplified Arakawa–Schubert (SAS), Yonsei University (YSU), and Eta schemes simulated track better compared to other combinations. Kanase and Salvekar (2015) found track well predicted by Betts-Miller-Janjic (BMJ), YSU, and WRF Single moment Class 6 (WSM6) schemes. Kloetzke *et al.* (2016) concluded that the combinations of YSU, Kain Fritsch (KF), and WRF Single Moment Class 3 (WSM3) predicted track with smaller errors. Debnath (2018) proposed that the combination of BMJ, WSM3 and Medium Range Forecast (MRF) physics options is better for TCs simulation. By testing the sensitivity of MP and CP schemes in the WRF model on TCs track and intensity Baki *et al.* (2021) suggested that the performance of the KF scheme was better in combination with all MPs that were considered.

Several Authors (Raju *et al.*, 2011; Osuri *et al.*, 2012) found that YSU in combination with the KF scheme gave a better performance in the analysis of the impact of PBL and CP schemes in the ARW model. Using high-resolution models to simulate TC Orissa, Rao and Prasad (2007) found that the combination of Mellor-Yamda-Janjic (MYJ) and KF scheme predicted TCs intensity and track better than other PBL-CP combinations, on the other hand, Mandal *et al.*, 2004 suggested that MRF and Grell's combination predicted TC track better than other combination.

In the present study, ARW model version 4.2.1 has been used to simulate track of selected TCs which were formed over the BoB to analyze the sensitivity of CP schemes. By analyzing the previous studies on MP and PBL schemes on TC's track over the BoB, WRF Double Moment Class 6 (WDM6) scheme used as MP scheme (Das and Alam, 2019), YSU scheme used as PBL scheme (Srinivas *et al.*, 2010) and eight CP schemes have been used to analyze tracks of a pre-monsoon and post-monsoon TC over the BoB.

The primary goal of this work is to investigate the suggested CP schemes, which are thought to be superior in the ARW model because both types of TCs frequently occur in BoB and make landfall in the coastal region of Bangladesh or close by Bangladesh (Singh *et al.*, 2000) the primary focus of this study is to check and revalidate the performance of CP schemes in the ARW model on the prediction of a pre-monsoon and a post-monsoon TC over BoB.

2. DATA USED AND METHODOLOGY

In this study, National Centre for Environment Prediction (NCEP)'s Final Reanalysis (FNL) data ($1° \times 1°$) have been used as lateral and initial conditions in the ARW model. 0000, 0600, 1200, and 1800 UTC are the initial fields of FNL data and these data have been interpolated and integrated for 120, 96, 72, and 48 hours for TCs 'Amphan (2020)' and 96, 72, and 48 hours for 'Bulbul (2019)'.

The model has been configured in a single domain with 9 km horizontal grid spacing with 271×317 grids in the west-east and north-south direction and 30 vertical levels. The model has been run for four different initial conditions (0000 UTC of 16, 17, 18, and 19 May 2020) to 0000 UTC of 21 May 2020 in simulating TC 'Amphan' and simulating TC Bulbul in three different initial conditions (0000 UTC of 6, 7 and 8 November 2019) to 0000 UTC of 10 November 2019 has been used in the model. For "Amphan" 4 initial conditions and 8 schemes that why in a total of 32 experiments and for "Bulbul" 3 initial conditions and 8 schemes in a total of 24 experiments have been done for TC 'Amphan' and 'Bulbul' respectively. The observed data including latitude, longitude, landfall position, and landfall time have been collected from Regional Specialized Meteorological Center (RSMC), India Meteorological Department (IMD), New Delhi. The track errors (T_{err}) have been measured by using both observed and simulated latitude and longitude which can be defined as,

$$T_{err} = \sqrt{(lat_{sim} - lat_{obs})^2 + (lon_{sim} - lon_{obs})^2} \quad (1)$$

At first track error is computed in degree then it has been converted to kilometer unit.

The details of the model domain and dynamics have been presented and the list of selected CP schemes is presented in Table 1.

Table 1. Details of WRF model dynamics

WRF core	ARW
Equation	Non-hydrostatic
Vertical co-ordinate	Terrain-following hydrostatic-pressure
Time integration scheme	3^{rd}order Runge-Kutta scheme
Horizontal grid type	Arakawa-C grid
Map projection	Mercator
Domain center	Lat 17.5^0N & Lon 87.5^0E
MP scheme	WRF Double Moment class 6 (WDM6),
CP schemes	Kain Fritsch (KF), Betts-Miller-Janjic (BMJ), Grell-Freitas Ensemble (GFE), Grell 3D Ensemble (G3DE), Tiedtke, Kain Fritsch Cumulus Potential (KFCP), Multi-Scale Kain-Fritsch (MSKF), and New Simplified Arakawa–Schubert (NSAS)
PBL schemes	Yonsei University (YSU)

2.1 Description of the Study Area

Bay of Bengal (BoB) is triangular in shape, bordered by India and Sri Lanka to the west, Bangladesh to the north and Myanmar and the Andaman & Nicobar Islands (India) to the east. BoB is the largest bay of the world covers an area of 2.2 million sq km. It is in the NIO between latitudes 5°N to 22°N and longitudes 80°E to 95°E. The region is influenced by monsoons and the out flow from several major rivers. The maximum depth of the Bay of Bengal is 5,258 m and average depth is 2600 m (Roy, 1995). The mean annual temperature of the surface water of BoB around 28°C. The maximum temperature is 30°C observed in May and the minimum temperature is 25°C observed in January-February (Thadathil *et al.,* 2002). The annual variation of temperature is not very large; it is about 2°C in the south and 5°C in the north (Rao, 2009).

2.2 Synoptic Description of Selected Cyclones

The Super Cyclonic Storm (SuCS) 'Amphan' originated over the South Andaman Sea (SAS) adjacent to southeast BoB during the period of 16-21 May 2020. On 13 May, a low pressure (LP) was formed in SAS adjacent to southeast BoB. After gaining favorable environmental conditions, it concentrated depression and Deep Depression (DD) in the early morning and afternoon of 16 May respectively. Moving north-northwestward the system intensified into Cyclonic Storm (CS) to Severe Cyclonic Storm (SCS) in the early morning of 17 May. After rapid intensification, the system turned into a Very Severe Cyclonic Storm (VSCS) in the evening of 17 May and SuCS around noon of 18 May. After that, dissipation started and the system crossed the coastal region of Bangladesh and India (West Bengal) as VSCS across Sundarban at the time of 1000-1200 UTC of 20 May 2020 (Ahmed *et al.,* 2021)

The VSCS 'Bulbul' originated in the North Andaman Sea (NAS) during the period of 05-11 November 2019. At first, a well-organized LP area system was formed in NAS during the period of 4 November. After gaining favorable cyclonic conditions, this LP concentrated into depression and intensified into DD over the Southeast BoB in the early morning of 5 and 6 November respectively. Moving north-northwestward the DD concentrated into CS and SCS in the late night of 6 November and the evening of 7 November over west-central adjoin east-central of BoB. After rapid intensification, the system turned into VSCS in the early morning of 8 November. After that, the system started to dissipate and crossed over the West Bengal- Bangladesh coastal area as SCS across Sundarban Dhanchi during 1500-1800 UTC of 9 November 2019 (RSMC report on Bulbul, 2019).

3. RESULTS

3.1 Track

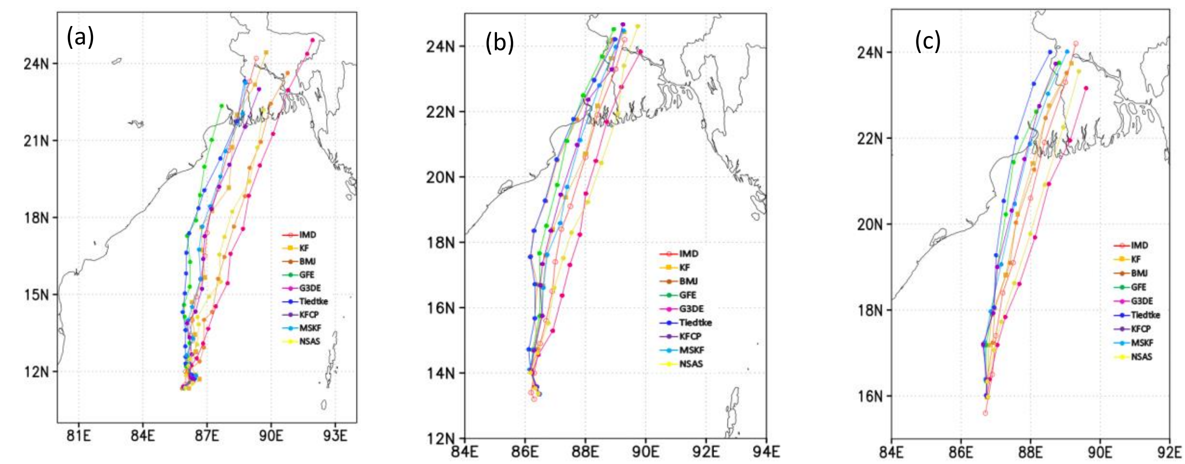
The simulated all tracks of TC 'Amphan' and 'Bulbul' for all CPs for all initial conditions and IMD estimated track have been moved in the north-northeastward direction and are presented in Figures 1(a-f).

For the initial condition of 0000 UTC of 16 May 2020 (not shown in the figure), it is observed that the model simulated track for all CPs and IMD estimated track moved northeastward direction. It is seen found that simulated tracks of NSAS, BMJ, and G3DE schemes deviated more rightward. The simulated landfall is found far away from the observed landfall (21.65°N, 88.3°E) (Ahmed *et al.,* 2021) for these three schemes. On the other hand, MSKF, Tiedtke, and GFE schemes simulated tracks that deviated leftward from the IMD estimated track in which landfall positions have been found near the observed landfall. It is observed from the figure that the Tiedtke scheme shows an irregular pattern of track and ends earlier compared to other CPs. The KF and KFCP schemes simulated tracks have been found very similar to IMD estimated track

The simulated tracks of ‘Amphan’ [Figure 1(a)] for G3DE, BMJ, and NSAS schemes have deviated more rightward and for GFE and Tiedtke schemes have deviated leftward from the IMD estimated track for the initial condition of 0000 UTC of 17 May 2020. The KFCP scheme simulated track seemed similar to the observed track but after 72 hours of simulation it deviated rightward and the MSKF scheme simulated track pattern is found similar to the IMD track.

For the initial conditions on 0000 UTC of 18 and 19 May (i.e., 72 and 48-hr), the track deviations [Figure 1(b-c)] is lower compared to the initial conditions of 0000 UTC on 16 (not shown in the figure) and 17 May [Figure 1(a)] (i.e., 120 and 96-hr) simulations. It is shown from the figure that all tracks are parallel with IMD estimated track and TC ‘Amphan’ moved in the northward direction and slightly tilt in the eastward direction. It is seen that the tracks for G3DE and NSAS schemes have deviated rightward and for MSKF, KFCP, GFE, BMJ, and Tiedtke schemes deviated leftward from the IMD estimated track. Overall less deviated tracks has been found for 0000 UTC of 18 and 19 May for MSKF and KFCP schemes.

From Figure 1(d) the simulated tracks of ‘Bulbul’ give an irregular pattern compared with the IMD observed track for all studied CPs except KF and KFCP schemes for the initial conditions of 0000 UTC on 6 November. The simulated tracks deviated leftward from the IMD estimated track for BMJ, NSAS, and Tiedtke schemes and GFE and MSKF schemes simulated tracks have deviated leftward from the observed track. KF and KFCP schemes simulated tracks have been found very close to the IMD observed track compared to other CPs. For a 96-hour (0000 UTC on 6 November to 0000 UTC on 10 November) simulation, BMJ and G3DE have been unable to predict the landfall time or position where observed landfall occurred 1500-1800 UTC on 9 November 2019 (RSMC report on Bulbul, 2019). On the other hand, for the initial condition of 0000 UTC on 7 November 2019 [Figure 1(e)], the BMJ and NSAS schemes simulated track deviated more in rightward direction compared to the observed track. On the other hand, other CPs simulated tracks that deviated leftward but were close to the observed track except for Tiedtke and KFCP experiments simulated tracks. For the 72-hour simulation (0000 UTC of 7 November to 0000 UTC of 10 November) G3DE scheme has been unable to predict landfall time and position. For the initial condition of 0000 UTC of 8 November [Figure 1(f)], it is clear that all tracks have deviated leftward from the observed track and have been found parallel with each other for all CPs schemes except G3DE and BMJ schemes. The movements of all tracks have been found initially in the northerly direction and then finally transformed into the northeastward direction as parallel to IMD estimated track. For this initial condition, larger deviations have been found for Tiedtke, BMJ, and KFCP schemes. Overall, for TC Bulbul for all initial conditions KF scheme simulated track has been found very close to the IMD estimated track.



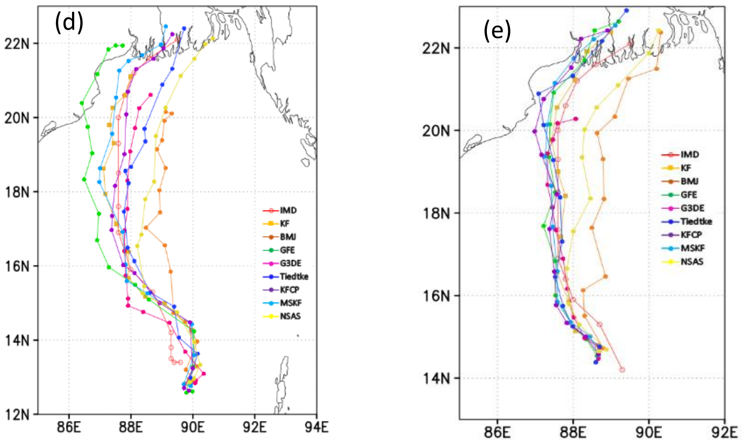
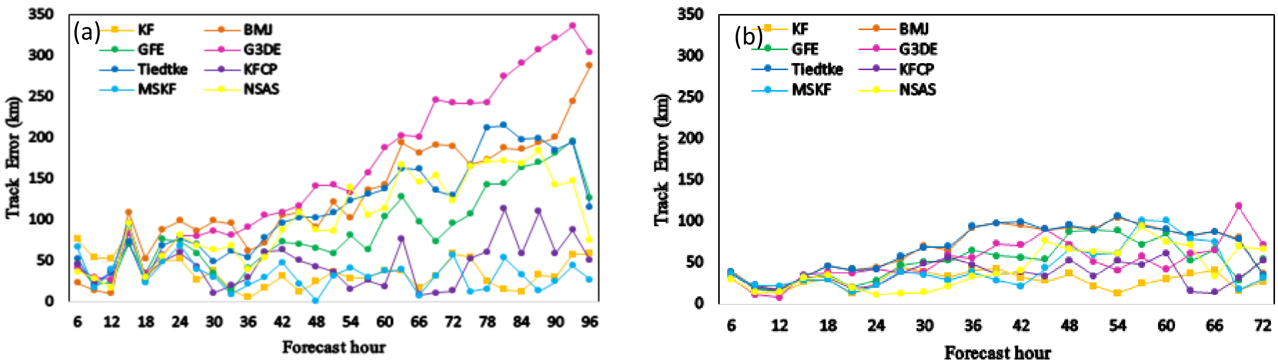


Figure 1: The time evolution of model-simulated tracks for the initial conditions of 0000 UTC of (a)-(c) 17-19 May 2020 and (d)-(f) 6-8 November 2019 for studied CPs with IMD estimated track of 'Amphan' and 'Bulbul' respectively

3.2 Tracks Error

The variations of track errors with forecast hour for different CPs for the initial condition on 0000 UTC of 16 (not presented in figure), 17, 18 and 19 May 2020 is presented in figure 2 (a-c) . It has been found for the initial condition of 0000 UTC of 16 May 2020 that the track errors were below 150 km till 48-hour of simulations for all CPs. After that, the track errors for KF, NSAS, G3DE, Tiedtke, and BMJ schemes increased rapidly till 108-hour of simulations and after that track errors for these schemes started to decrease. Comparatively, lower track errors have been found for KFCP, MSKF, and GFE schemes for the entire simulation hour. The variation of track errors with forecast hour for the initial condition of 0000 UTC of 17 May 2020 (Figure 2-a) all CPs simulated track errors are comparatively less and after 36-hour of simulations track errors increased rapidly. The track errors for G3DE, BMJ, Tiedtke, NSAS and GFE schemes have been found higher and greater than 150 km after almost 60-hour simulations. For this initial condition, comparatively lower track errors have been found for KFCP, MSKF, and KF schemes for the entire simulation period.

The variation of track errors for all CPs for the initial condition of 0000 UTC on 18 May 2020 is presented in figure 2(b). It is obvious from the figure that the track errors for all CPs found below 60 km till 36-hour of simulation and after that, it increased rapidly. The track errors were higher for BMJ, Tiedtke, NSAS, MSKF, and GFE schemes after 36-hour of simulations and the error crossed approximately 100 km for these schemes. The track error for the G3DE scheme shows an irregular behavior. Comparatively lower track errors have been found for KF and KFCP schemes for this initial condition. The variation of track errors with forecast time for the initial condition of 0000 UTC on 19 May 2020 has shown in Figure 2-c. It is clear from the figure that comparatively tracks errors have been found lower for MSKF, BMJ, and KF schemes and higher for NSAS, G3DE, and GFE schemes



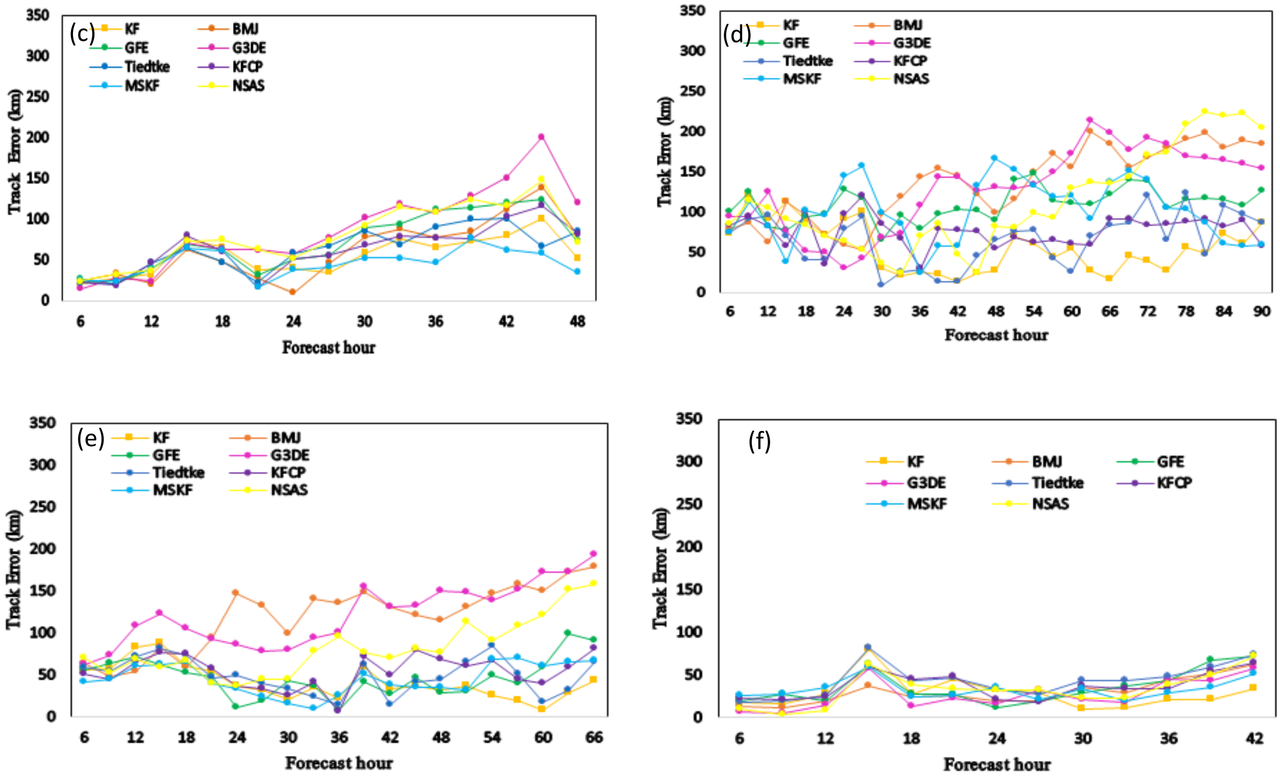


Figure 2. The time evolution of model-simulated track errors for the initial conditions of 0000 UTC of (a)-(c) 17-19 May 2020 and (d)-(f) 6-8 November 2019 for studied MPs with IMD estimated track of 'Amphan' and 'Bulbul' respectively

The time variation of track errors for the initial conditions of 0000 UTC of 6 November 2019 has been presented in figure 2(d). It is clear from the figure that, track errors with forecast hours for all studied CPs have been found in a zigzag pattern. KF, KFCP, and Tiedtke schemes simulated track error has been found lower (below 100 km) compared to other CPs within the entire forecast four. For this initial condition higher track errors have been found for BMJ, G3DE, GFE, and NSAS schemes. For the initial conditions of 0000 UTC of 7 November 2019, the track errors with forecast hour for all CPs schemes have been presented in figure (2-e) and it is obvious from the figure that for the entire forecast hour KF, MSKF, KFCP, Tiedtke, and GFE schemes track errors are under 60 km. On the other hand, higher track errors have been found for BMJ, G3DE, and NSAS schemes. Overall minimum track error has been found for the KF scheme. The track errors for all studied CPs for the initial condition of 0000 UTC of 8 November 2019 with forecast hour have been presented in figure (2-f). It has been shown from the figure that all CPs simulated track errors are under 40 km. All CPs errors pattern is very similar to forecast hours but lower errors have been found for KF and MSKF schemes.

3.3 Average Tracks Error

The average track error (km) of TC 'Amphan' and 'Bulbul' for all initial conditions and studied CPs are presented in Figure 3(a-b). From figure 3(a), for TC 'Amphan', For the initial conditions 0000 UTC of 16 May, all CPs simulated average track errors have been found higher (above 60 km) except MSKF and KFCP schemes. For the initial conditions at 0000 UTC on 17 May, KF, MSKF, and KFCP schemes simulated average track errors which have been found comparatively lower than that of other CPs. Overall, simulated track errors with all CPs were found comparatively lower for the 0000 UTC of 18 May initial condition with compared to the other initial conditions i.e., 0000 UTC of 16 and 17 May 19 May. Overall, lower average track errors have been found for all initial conditions for KFCP, MSKF, and KF schemes.

In the case of TC 'Bulbul' [Figure 3(b)], for the initial conditions of 0000 UTC of 6 November, the average track errors have been found higher (above 65 km) for all CP schemes except KF (56 km) and Tiedtke (65 km) schemes. The average track errors are found at 43, 46, 48, 50, 55, 81, 117, and 119 km for KF, MSKF, GFE, Tiedtke, KFCP, NSAS, BMJ, and G3DE schemes respectively for the initial conditions of 0000 UTC of 7 November. The comparatively lower track errors have been found for 0000 UTC of 8 November's initial condition for all CPs compared to 0000 UTC of 6 and 7 November's initial conditions. Overall, the KF scheme has simulated lower average track errors compared to other CPs.

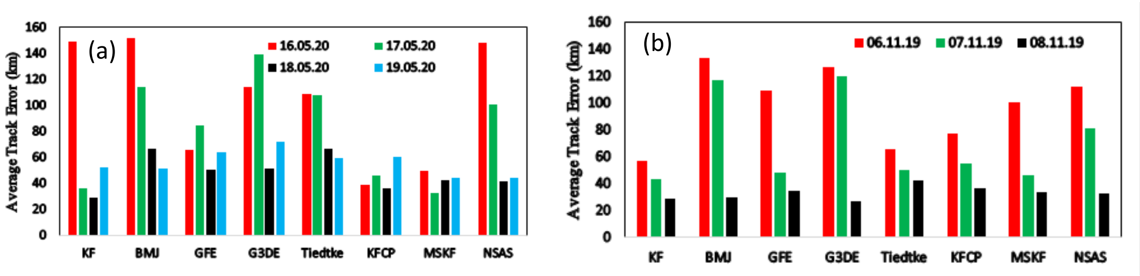


Figure 3. Average track errors for the initial conditions of (a) 0000 UTC of 16-19 May 2020 of TC 'Amphan' and (b) 0000 UTC of 6-8 November 2019 of TC 'Bulbul'

3.4 Landfall Position Error

Landfall position errors for TC 'Amphan' and "Bulbul' have been presented in Figure 4(a-b) and Tables 2 and 3 respectively for all initial conditions. It has been observed from Table 2 for "Amphan" that NSAS, BMJ, and G3DE schemes simulated landfall positions are far away from the observed landfall positions for initial conditions the 0000 UTC of 16 and 17 May. Landfall position errors are found at 222, 228, and 237 km for BMJ, G3DE, and NSAS schemes which are very big for the initial condition of 0000 UTC of 16 May, and using the initial condition of 0000 UTC of 17 May, the errors were 159, 246, and 157 km for BMJ, G3DE, and NSAS schemes respectively. Landfall positions simulated by other CPs were found approximately 10-100 km away from the observed landfall. Using the initial condition of 0000 UTC of 18 May it has been found that MSKF scheme simulated landfall position is very close to IMD estimated landfall position and position error has been found approximately 7.8 km. On the other hand lower landfall position error has been found 18 km for BMJ scheme using the initial condition of 19 May. Overall, the KF, KFCP and MSKF schemes simulated landfall position error has been found minimum among the studied CPs.

In the case of TC 'Bulbul', from Figure 4(b) and Table 3, it is clear that the GFE, Tiedtke, and NSAS schemes have simulated higher landfall position errors of 260, 170, and 219 km respectively from the IMD estimated landfall position (21.55^0N/88.5^0E) for the initial condition of 0000 UTC of 6 November. In this initial condition, KFCP, MSKF, and KF schemes simulated landfall position errors are 11, 20, and 75 km respectively. On the other hand, G3DE and BMJ schemes are unable to predict the landfall position because of time range we considered. But for the initial condition of 7 November, the landfall position errors have been found 4, 12, 22, 33, 34, 36, and 189 km for GFE, Tiedtke, BMJ, MSKF, KFCP, KF, and NSAS schemes respectively. For the initial conditions of 0000 UTC of 8 November, the landfall position errors lie in between 21-40 km all CPs except BMJ and G3DE schemes. Overall, for all initial conditions, it is clear from the figure that KF, KFCP, and MSKF schemes simulated landfall position is very close to the observed landfall position.

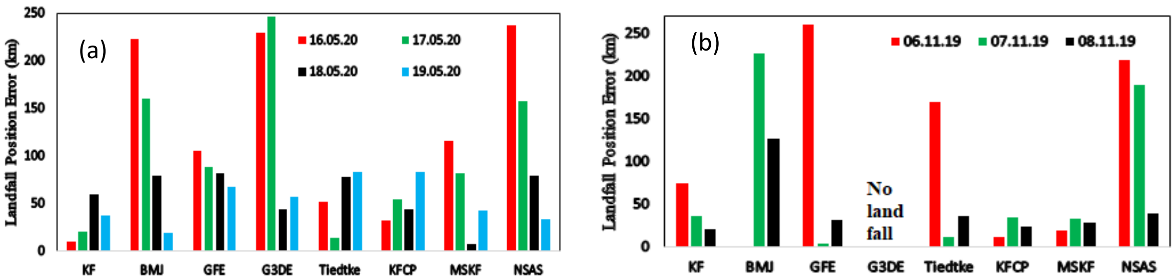


Figure 4. Landfall position errors for the initial conditions of (a) 0000 UTC of 16-19 May 2020 of TC 'Amphan' and (b) 0000 UTC of 6-8 November 2019 of TC 'Bulbul'

3.5 Landfall Time Error

The TC 'Amphan' made landfall at 1000-1200 UTC on 20 May 2020 according to RSMC, India (Ahmed *et al.*, 2021). In this study, for the initial condition 0000 UTC of 16 May, GFE and KFCP schemes simulated landfall time matched with the observed landfall time. On the other hand, KF, BMJ, and NSAS schemes simulated landfall advanced by approximately 4-hour, and the Tiedtke scheme simulated landfall delayed by 9-hour. For the initial condition of 0000 UTC of 17 May, GFE and NSAS schemes simulated landfall delayed by 3-hour and Tiedtke schemes landfall time delayed by 6-hour but other CPs simulated landfall time nearly matched with observed landfall time. For the initial condition of 0000 UTC of 18 and 19 May, the landfall time simulated by all CPs has been near the observed landfall time. Table 2 shows the landfall time, landfall position, and landfall position errors for all CP schemes for all the studied initial conditions under the study.

Table 2. Model simulated landfall time, landfall position, and landfall position error of TC 'Amphan' for different CPs for studied initial conditions. IMD estimated landfall time 1000-12000 UTC on 20 May 2020 and landfall position 21.65^{0}N/88.3^{0}E (Ahmed *et al.,* 2021).

CP schemes	Landfall time in UTC on 20 May(UTC)				Position (latitude^{0}N/longitude^{0}E)				Landfall position error (km)			
	16	17	18	19	16	17	18	19	16	17	18	19
KF	0600	0900-1200	0900	1200-1500	21.66/88.39	21.47/88.20	22.17/88.4	88.05/21.41	10	21	58	37
BMJ	0600	0900	1200	1200-1500	21.91/90.29	21.80/89.73	21.45/87.61	21.5/88.22	222	159	79	18
GFE	1200	1500	0600-0900	1200-1500	21.57/87.35	21.63/87.51	21.4/87.61	21.6/87.7	105	87	81	66
G3DE	0600-0900	0900	1200	1500	21.7/90.36	22.05/90.48	21.68/88.70	21.56/88.80	228	246	44	56
Tiedtke	2100	1800	1200	0900-1200	21.77/87.85	21.74/88.39	21.76/87.60	21.60/87.55	51	14	78	85
KFCP	1200	1200	0900	0900-1200	21.64/88.01	21.53/88.77	21.80/87.94	21.40/87.6	32	53	43	82
MSKF	0900	0900	0600-0900	1200	21.47/87.27	20.93/88.17	21.70/88.25	21.86/87.98	116	82	7	42
NSAS	0600	1500	0900-1200	1500	21.98/90.41	21.47/89.71	21.50/89.0	21.58/88.59	237	157	79	33

The TC 'Bulbul' made landfall at 1500-1800 UTC on 9 November 2019 according to RSMC, India (RSMC report on Bulbul, 2019). In this study, for the initial condition of 0000 UTC on 6 November, KF and NSAS schemes simulated landfall time which was found to match with the observed landfall time. On the other hand, the Tiedtke scheme simulated landfall delayed by approximately 3-hours, and KFCP and MSKF scheme simulated landfall advanced by 6-hours, and the GFE scheme simulated landfall time advanced by 15-hours. At this initial condition, the BMJ scheme was unable to predict the landfall time, and the G3DE scheme was unable to predict the landfall time of all initial conditions. For the initial conditions of 0000 UTC on 7 November, GFE and MSKF schemes simulated landfall advanced by 3-hours and BMJ delayed by 3-hours and other CPs simulated landfall time matched with the observed landfall time but for the initial condition of 0000 UTC of 8 November, all studied CPs except BMJ (which delayed by 3-hour) simulated landfall time has been matched with observed landfall time. Table 3 shows the landfall time, landfall position, and landfall position errors for all CP schemes and for all initial conditions of 'Bulbul'.

Table 3. Model simulated landfall time, landfall position, and landfall position error of TC 'Bulbul' for different CPs schemes for studied initial conditions. IMD estimated landfall time 1500-1800 UTC on 9 November 2019 and landfall position 21.55^{0}N/88.5^{0}E (RSMC report on Bulbul, 2019).

CP schemes	Landfall time (in UTC) on 9 November(UTC)			Position (longitude ^{0}E/latitude ^{0}N)			Landfall position error (km)		
Date	6	7	8	6	7	8	6	7	8
KF	1800	1500	1500	21.09/87.9	21.86/88.38	21.59/88.31	75	36	21
BMJ	-	2100	1200	-	22.07/90.29	21.13/87.79	-	22	126
GFE	0000	1200	1500	20.10/86.54	21.69/88.29	21.57/88.22	260	4	32
G3DE	-	-	-	-	-	-	-	-	-
Tiedtke	2100	1500	1500	21.93/89.81	21.67/88.41	21.61/87.97	170	12	36
KFCP	0900	1500	1500	21.57/88.36	21.90/88.11	21.50/88.14	11	34	24
MSKF	0900	1200	1500	21.66/88.12	21.74/88.01	21.45/88.14	20	33	28
NSAS	1500	1800	1800	21.80/90.27	21.87/89.99	21.66/88.66	219	189	40

4. DISCUSSIONS

By analyzing the sensitivity of CP schemes on the track of TCs, KF, KFCP, and MSKF schemes simulated tracks have been found very close and parallel to the IMD estimated track for both TCs studied. The lower average track errors have been found for KF, KFCP, and MSKF schemes compared to other CPs for TC 'Amphan' but for TC 'Bulbul', the lower average track error has been found for KF and Tiedtke schemes. In case of landfall position error, for TC 'Amphan', KF and KFCP schemes simulated landfall position comparatively lower than that of other CPs but for TC 'Bulbul' KF, KFCP, and MSKF schemes simulated landfall position in good agreement with the observed landfall position.

Several Authors (Deshpande *et al.*, 2010; Kloetzke *et al.*, 2014; Baki *et al.,* 2021;Fahad and Ahmed, 2015; Saifullah *et al.,* 2020; Saunders *et al.,* 2019) also found that the KF scheme simulated track better than other CPs simulated track. Comparing BMJ and GD schemes on the track of TC Megi Sun *et al*. (2014) suggested that the GD scheme reproduced track better than the BMJ scheme but Nasrollahi *et al*. (2012) found BMJ scheme simulated track better agreement with the observed track than the GD scheme. Chandrashekhar & Balaji (2012) reported that KF and BMJ schemes simulated track errors lower compared to Grell and GD schemes in simulating TC 'Jal'. By analyzing the TC track. On the other hand, Deshpande *et al.* (2010) reported that cumulus physics has sensitivity on track of TCs and found updated KF scheme results comparatively well. But Saikumar & Ramashri (2017) found Grell 3D ensemble (G3D) with Thomson scheme simulated track better match with estimated track. By analyzing the sensitivity of the cumulus scheme, Biswas *et al.* (2014) and Pattanayak *et al*. (2012) reported that Simplified Arkawa Schubert (SAS) simulated hurricane structure and track more realistic. By studying the sensitivity of MPs and CPs on Track and intensity of TC Bulbul, Baki *et al*. (2021) found that the KF scheme with all MPs simulated track better compared to other CPs.

5. CONCLUSIONS

This study's goal is to examine how the CP schemes in the ARW model affect the track of TCs because of the choices of CP schemes have a significant impact on the model's performance. For these reasons, 32 simulations have been done for TC "Amphan" and 24 simulations for TC "Bulbul" and it has been found that the performance of the ARW model is sensitive to the CP scheme selection. In every simulation, the tracks of both TCs have been found to be closely spaced and parallel to the track of the IMD estimation. CP schemes have a strong impact on the track of both TCs. Simulated tracks for all CPs for all initial conditions of both TCs were found north-northwestward and northeastward movement parallel with IMD estimated track. KF, KFCP, and MSKF schemes simulated tracks have been found very close and parallel to the IMD observed track. On the other hand, KF, KFCP, and MSKF schemes simulated average track error was lower compared to other CPs for TC 'Amphan' but for TC 'Bulbul', the lower average track error has been found for KF and Tiedtke schemes. . In this study, average track errors have been found between 40-50 km for KFCP and MSKF schemes for TC Amphan and below 60 km for the KF scheme for TC Bulbul. Lower landfall position error has been found below 60 km for the KF scheme for TC Amphan, and 40 km for KFCP and MSKF schemes for TC Bulbul. KF and KFCP schemes simulated landfall position error was comparatively lower than that of other CPs for TC 'Amphan', but for TC 'Bulbul' KF, KFCP, and MSKF schemes simulated landfall position in good agreement with the observed landfall position. KF and KFCP schemes simulated landfall time was comparatively better match with the observed landfall time for TC 'Amphan' and KF and NSAS schemes simulated landfall time matched with the IMD estimated landfall time for all initial conditions of TC 'Bulbul'. KF, KFCP and MSKF scheme predicted track better matched with the observed track and intensity compared to other studied CPs.

CONFLICTS OF INTERESTS

The Authors declared that there are no conflicts of interests.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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