Sensitivity of Microphysical Schemes on the Simulation of Post-Monsoon Tropical Cyclones over the North Indian Ocean

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Abstract: Tropical Cyclones (TCs) are the most disastrous natural weather phenomenon, that have a significant impact on the socio-economic development of the country. In the past two decades, Numerical Weather Prediction (NWP) models (e.g., Advanced Research WRF (ARW)) have been used for the prediction of TCs. Extensive studies were carried out on the prediction of TCs using the ARW model. However, these studies are limited to a single cyclone with varying physics schemes, or single physics schemes to more than one cyclone. Hence, there is a need to compare different physics schemes on multiple TCs to understand their effectiveness. In the present study, a total of 56 sensitivity experiments are conducted to investigate the impact of seven microphysical parameterization schemes on eight post-monsoon TCs formed over the North Indian Ocean (NIO) using the ARW model. The performance of the Ferrier, Lin, Morrison, Thompson, WSM3, WSM5, and WSM6 are evaluated using error metrics, namely Mean Absolute Error (MAE), Mean Square Error (MSE), Skill Score (SS), and average track error. The results are compared with Indian Meteorological Department (IMD) observations. From the sensitivity experiments, it is observed that the WSM3 scheme simulated the cyclones Nilofar, Kyant, Daye, and Phethai well, whereas the cyclones Hudhud, Titli, and Ockhi are best simulated by WSM6. The present study suggests that the WSM3 scheme can be used as the first best scheme for the prediction of post-monsoon tropical cyclones over the NIO.

Keywords: ARW model; microphysical schemes; North Indian Ocean; tropical cyclones; average track error; skill score; WSM3

1. Introduction

Among the world’s oceans, the North Indian Ocean (NIO) is a highly active region for the formation of tropical cyclones (TCs). The NIO accounts for 7% of the TCs that are formed over the globe [1]. TCs are one of the most dangerous natural weather calamities, which have a significant impact on the socio-economic aspects of the countries along the rim of the NIO [2]. TCs will cause substantial loss to humans, physical property, ecology and the environment at different levels when they make landfall [3]. The damage caused by TCs along the rim of the NIO may be attributed to its shallow bathymetry, low-lying flood prone areas, dense population along the coastlines, and poor socio-economic conditions [4].

The TCs over the NIO are highly seasonal and occur during the pre- and post-monsoon seasons with very few in the rest of the year. The seasonal occurrence of the TCs over the NIO may be
attributed to the presence of nearby equatorial troughs over the open ocean in the pre- and post-monsoon seasons [5,6]. The post-monsoon season is a highly active period for the formation of TCs over the NIO. The TCs that are formed in the post-monsoon season are approximately twice the TCs that are formed in the pre-monsoon season [3]. As per the annual and primary reports of the Regional Specialized Meteorological Centre, Indian Meteorological Department (RSMC-IMD) for the TCs over the NIO, a total of 20 cyclones were formed in the last five years (i.e., from 2014 to 2018). Of these, 60% of the TCs were formed in the post-monsoon season and the rest in the pre-monsoon [7–11]. By using the data from atlas maps published by Indian Meteorological Department (IMD) and their records for a period of 122 years (1877–1998), Singh et al. (2000) [12] evaluated the trends in post-monsoon TCs over the NIO and found an increasing trend of 20% in both the intensity and frequency of TCs. Mohanty et al. (2012) [13] found a large increase in the number of severe cyclonic storms (SCS) in the Bay of Bengal by evaluating the trends in cyclone data for a period of 120 years (1891–2010). The increasing number of tropical cyclones in the post-monsoon season may be attributed to the rise in sea surface temperature, weak vertical wind shear, El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) [13–16]. ENSO is an ocean-atmospheric coupled phenomenon which affects the intensity of the TCs [17]. The track of the TC is influenced by large-scale wind dynamics which include vertical wind shear, low-level rotational wind, low-level relative vorticity, and mid-troposphere [18,19].

With the advancements in computational power, significant improvements are seen in the field of TC prediction over the NIO using the Numerical Weather Prediction (NWP) models. Due to inconsistencies (initial and boundary conditions, grid resolution, representation of physics schemes, and geographical location) in the NWP models, there is need for further improvement in the prediction of TCs. Accurate representation of cloud processes in NWP models is crucial for the track and intensity prediction of TCs. Representation of cloud processes plays an important role in the production and distribution of heat, mass, and momentum in the atmosphere in both the horizontal and vertical directions with the help of precipitation, winds, and turbulence. The representation of physics schemes in the NWP model are important when the cloud processes and their effects are unresolved by the model [20,21]. In the last two decades, based on various assumptions, researchers have developed a number of parameterization schemes for track and intensity prediction and they are being used for both operational and research purposes [22]. Among all the physics schemes, Cloud Microphysics (CMP), Cumulus Parameterization Scheme (CPS), Planetary Boundary Layer (PBL), radiation (longwave and shortwave), and land-surface schemes are being used for weather predictions [23]. The cloud process in the model can be implicitly treated by CPS and explicitly treated by CMP schemes. CPS reduces the convective instability in a model through the redistribution of temperature and moisture in a grid column [24]. CMP schemes represent cloud and precipitation processes (condensation, nucleation, coalescence, phase changes, etc.) according to the atmospheric conditions in terms of temperature, wind, and moisture. Both CPS and CMP schemes control the spatio-temporal variations in precipitation and yield different profiles of moistening and heating in the atmosphere. Without double counting the thermo-dynamical impacts, both types of schemes represent the convective activity [20,21].

Numerous studies have been conducted to assess the impact of physics schemes on the prediction of track and intensity of the TCs using the Advanced Research Weather Research and Forecasting (ARW) model. Among all the schemes in the ARW model, convective processes play an important role in the development of TCs and boundary layer dynamics in their intensification [4,20,25,26], whereas microphysical schemes have significant impacts on the track prediction of TCs [26]. Pattanayak et al. (2012) [4] found that the track and intensity of the TC Nargis is well simulated by the Ferrier CMP scheme along with Yonsei University (YSU) PBL, Simplified Arakawa Schubert (SAS) CPS schemes. With the same CPS and PBL schemes, the Kessler CMP scheme provided better results for the TC Vardah [21]. Kanase and Salvekar (2015) [27] showed that the WSM6 scheme, in combination with Bettes-Miller-Janjic (BMJ) CPS and YSU PBL schemes, simulated better results for the TC Laila. Based on the sensitivity experiments conducted by Srinivas et al. (2013) and Lakshmi and Annapurnaiah (2016) [28,29], the Lin scheme improved the results for the TCs Sidr, Nisha, Tane,
Jal, Nargis, and Hudhud along with the combination of Kain–Fritsch (KF) CPS and YSU PBL schemes. With the same combination of CMP and PBL schemes, Choudhury and Das (2017) [30] suggested the Goddard scheme, and the Ferrier scheme was suggested by Raju et al. (2011) [26] and Reddy et al. (2014) [31] for the prediction of TCs. Osuri et al. (2012) [32] and Mahala et al. (2015) [33] reported that the TCs over the NIO, were better simulated by the WRF Single-Moment-3 (WSM3) scheme with the same CPS and PBL schemes.

Based on previous studies, it was found that Kain–Fritsch (KF) and Yonsei University schemes can be used as convective and boundary layer schemes [26,28,30,32], and various microphysical schemes such as Ferrier [26,31] WSM3 [32], Lin [28] and Goddard [30] can be used in the prediction of the track and intensity of the TCs over NIO.

From these studies, it may be difficult to identify a suitable microphysical scheme for the prediction of the TCs over the NIO region. In this study, numerical experiments were conducted to revalidate the suggested microphysical schemes for the simulation of TCs. This study mainly concentrated on the prediction of post-monsoon TCs, because 71% of the TCs that are formed in the post-monsoon season make landfall over the Indian coast, whereas, in the pre-monsoon season, the majority of the TCs over the Bay of Bengal (BoB) make landfall near Myanmar, and the TCs that are formed over the Arabian Sea (AS) make landfall near the Gulf countries [3,12].

**Tropical Cyclone Case Studies**

In the recent years, RSMC-IMD has adopted various techniques in the analysis and forecasting of the TCs over the NIO. RSMC-IMD uses a blending technique based on conceptual models, dynamical and statistical models, meteorological datasets, technology and expertise for TC analysis, prediction and decision-making process. For the purpose of TCs analysis and prediction, RSMC-IMD uses data from conventional observational networks, automatic weather stations, buoy and ship observations, cyclone detection radars and satellite imagery. RSMC-IMD provides a bulletin on tropical weather look, tropical cyclone advisories, storm surge guidance, maritime forecast bulletins, tropical cyclone advisories for aviation, national bulletins, cone of uncertainty forecasts, and wind forecasts for different quadrants. RSMC-IMD issues a national bulletin to the public on the formation of cyclones from the stage of depression (D) onwards. During the stages of depression or deep depression, RSMC issues the bulletins based on 00, 03, 06, 12, and 18 UTC observations. When the system intensifies into a cyclonic storm over the NIO, these bulletins are issued at 3-hour intervals based on previous observations, which gives the information on present status of the system, expected damage and action suggested. These bulletins are completely made for national users and disseminated through the various modes of communication (i.e., All India Radio, National TV, Telephone, SMS, print electronic media) and are made available at the RSMC-IMD website [11].

The eight TCs formed over NIO from 2014 to 2018 were considered in the present study in order to assess the impact of CMP on their track and intensity predictions. Among these TCs, two had formed over AS and the remaining were in BoB. The best tracks provided by the study cyclones are presented in Figure 1. The details about these cyclones are given in Table 1 and a brief summary is given below.

1. **Hudhud**
   
   On the morning of 6 October 2014, cyclone Hudhud formed as a low-pressure area (LPA) over BoB. It gradually intensified into a Very Severe Cyclonic Storm (VSCS) in the afternoon of 10 October 2014. It made landfall near Visakhapatnam with a northwestward movement in the morning of 12 October 2014 as VSCS and moved in the same direction. It then gradually weakened into a Well-Marked Low-Pressure Area (WMLA) on the evening of 14th October 2014 over eastern Uttar Pradesh [7];

2. **Nilofar**
   
   A VSCS Nilofar formed as an LPA over the southeast AS on the morning of 21 October 2014. The cyclone initially moved northward on the day of formation and then recurved northeastwards. It exhibited rapid intensification as well as rapid weakening and weakened into a WMLA near the North Gujarat coast on the morning of 31 October 2014 [7];

3. **Kyant**
Cyclone Kyant formed as a depression (D) over east central BoB on 21 October 2016. The track followed by this system is rare in nature as it experienced two re-curvatures during its life period. The rate of intensification was very slow and steady, taking about 4 days to become a cyclonic storm (CS) from the stage of D, and the rate of weakening was rapid as it reduced to a WMLA from the CS stage within 30 hours on the morning of 28 October 2016 [9];

4. Ockhi

Cyclone Ockhi formed as an LPA over Andaman Sea on 22 November 2017. There was a rapid intensification during its genesis stage, as it intensified into a CS within 6 hours from the stage of deep depression (DD). While moving west–northwestwards, Ockhi further intensified into a Severe Cyclonic Storm (SCS) over Lakshadweep area in the early morning of 1 December 2017 and VSCS over the southeast AS in the afternoon of the same day. It then moved northwestwards and reached its peak intensity in the afternoon of 2 December 2017. It moved north–northwestwards and then northeastwards, and crossed the south coast of Gujarat between Surat and Dahanu as a WMLA in the early morning of 06 December 2017 [10];

5. Daye

Daye is the first cyclonic storm formed over the NIO in the month of September after 2005. It formed as a D over the east central of BoB in the afternoon of 19 September 2018. Moving nearly west–northwestwards, it intensified into a DD on the morning of 20 September 2018 and further into a CS in the same day. It made landfall close to Gopalpur as a CS from 1900–2000 h UTC of 20 September 2018. It continued to move west–northwestwards, and weakened into an LPA over south Haryana on the morning of 24 September 2018 [11];

6. Titli

Titli cyclone formed as an LPA over the southeast BoB on the morning of 7 October 2018. Moving nearly west–northwestwards, it intensified into a DD on the morning of 8 October 2018, and further into a CS around noon on 9 October 2018. It then moved northwestwards, and in the early morning of 10 October 2018, it intensified into an SCS. It then moved north–northwestwards and further intensified into a VSCS around noon of 10 October 2018 and crossed the northern Andhra Pradesh and south Odisha coasts near Palasa from 2300 to 0000 h UTC as a VSCS. Moving further west–northwestwards, it weakened into an SCS around the noon of 11 October 2018 and a CS in the same evening. Under the influence of southwesterly winds, the system recurved northeastwards from 11 p.m., and gradually weakened into an LPA over Gangetic West Bengal and adjoining Bangladesh in the morning of 13 October 2018 [11];

7. Gaja

VSCS Gaja originated from an LPA which formed over the Gulf of Thailand and adjoining Malay Peninsula on the morning of 8 November 2018. Under the favorable conditions, it concentrated into a D over southeast BoB in the morning of 10 November. Moving west–northwestwards, it intensified into a DD in the same evening and further intensified into a CS in the early morning of 11 November 2018. It then moved nearly westwards till early morning of 12 November 2018. Thereafter, it recurved south–southwestwards and followed an anticlockwise looping track till the morning of 13 November 2018. It then moved west–southwestwards and intensified into an SCS southwest BoB on the morning of 15 November 2018 and into a VSCS in the same night. Moving further west–southwestwards, it crossed Tamil Nadu and Puducherry coast between Nagappattinam and Vedaranniyam from 1900 to 2100 h UTC of 16 Nov 2018. Thereafter, it moved nearly westwards, and weakened rapidly into an SCS, CS, and DD over interior Tamil Nadu on 16 November 2018. It then moved west–southwestwards and weakened into a D in the same evening over central Kerala. Moving nearly westwards, it emerged into southeast AS in the same night. Moving nearly westwards, it intensified into a DD over southeast AS in the early morning of 17 November 2018. Thereafter, it moved nearly west–northwestwards and crossed Lakshadweep Islands on the afternoon of 17 November 2018, as a DD. It continued to move west–northwestwards and weakened into a D over the same region around noon of 19 November 2018, WMLA in the same night, and an LPA on 21 November 2018 [11];

8. Phethai
A SCS Phethai formed as an LPA over the Equatorial Indian Ocean and adjoined the central parts of south BoB on the evening of 9 December 2018. It was laid as a WMLA over the same area on the morning of 11 December 2018. It continued to be WMLA till the morning of 13 December 2018, and, under favourable conditions, it concentrated into a D over southeast BOB. Moving north–northwestwards, it intensified into a DD over the same area on the same day and midnight. Continuing to move in the same direction, it intensified into a CS in the evening of the 15th and into an SCS in the afternoon of the 16th. It maintained its intensity of SCS till the early morning of the 17th and weakened into a CS in the same morning. Continuing to move north–northwestwards and then northwards, it crossed the Andhra Pradesh (south of and close to Yanam and 40 km south of Kakinada) coast during the 17th afternoon as a CS. After landfall, the cyclone moved north–northeastwards and weakened rapidly into a DD near the Kakinada coast in the same evening. Continuing to move in the same direction, it again crossed Andhra Pradesh coast near Tuni and weakened into a D over the coastal Andhra Pradesh during the same day and midnight. It further weakened into a WMLA over the northwest and adjoining west–central BoB and coastal Odisha in the early morning of the 18th, and into an LPA northwest BoB and adjoining Odisha in the same morning [11].

![Figure 1. Best tracks of tropical cyclones (TCs) considered in the present study.](image_url)

| S.No | Period                | Cyclone Name | Landfall   | Category                      |
|------|-----------------------|--------------|------------|-------------------------------|
| 1    | 7–17 October 2014     | Hudhud       | Visakhapatnam | Very Severe Cyclonic Storm    |
| 2    | 25–31 October 2014    | Nilofar      | No Landfall | Very Severe Cyclonic Storm    |
| 3    | 21–28 October 2016    | Kyant        | No Landfall | Cyclonic Storm                |
| 4    | 29 November–05 December 2017 | Ockhi | South Gujarat Coast | Very Severe Cyclonic Storm |
| 5    | 19–22 September 2018  | Daye         | Gopalpur   | Cyclonic Storm                |
| 6    | 8–13 October 2018     | Titli        | Palasa     | Very Severe Cyclonic Storm    |
2. ARW Model and Sensitivity Experiments

Advanced Research Weather Research and Forecasting (ARW version 4.0) model is an open-source atmospheric modelling system designed for broad use in research and operational studies at the National Centre for Atmospheric Research (NCAR) in collaboration with various universities [34]. The model supports atmospheric simulations across scales from large-eddy to globe, with a wide range of applications. The model integrates the compressible non-hydrostatic Eulerian equations using a terrain following vertical coordinates. The model uses the 3rd-order Runge–Kutta time integration scheme for low-frequency modes, whereas smaller time steps are used to integrate the high-frequency acoustic waves to maintain numerical stability. The horizontal propagating acoustic models and gravity waves are integrated using a forward–backward time integration scheme, and vertically propagating acoustic models and buoyancy oscillations are integrated using a vertical implicit scheme. This model and its earlier versions have the versatility to choose the region of interest, grid spacing in horizontal and vertical directions, interactive nested domains with various physics parameterization schemes for convection, boundary layer, microphysics, radiation, soil, and surface processes (48,49).

In this study, ARW v4.0 was used to conduct sensitivity experiments to predict the track and intensity of TCs. The initial and boundary conditions for the prediction of TCs were considered from the 0.5° × 0.5° resolutions of NCEP-GFS model forecasts with 6-hour intervals. The model was designed with two two-way nested domains with 27 and 9 km grid spacing. The terrain data of 10m resolution from the United States Geological Survey (USGS) were used for both domains. The model utilized a total of seven microphysical schemes, namely Lin, Thompson, Ferrier, Morrison, WSM3, WSM5 and WSM6, for both the domains. Yonsei University (YSU) PBL scheme, Rapid Radiative Transfer Model (RRTM) for long-wave radiation and Dudhia scheme for short-wave radiation were used for both the inner and outer domains, whereas the Kain–Fritsch (KF) convective scheme was used for the outer domain.

The various microphysics schemes deal with the mixing ratios of the prognostic variables with different approaches under different assumptions. The mixing ratios of the prognostic variables in all the microphysical schemes considered in the study are presented in Table 2. The Lin scheme includes all the prognostic variables. It is the most sophisticated scheme of the ARW model and suitable for research studies [35]. The new Eta Ferrier scheme has the ability to predict the changes in water vapor and estimates the precipitation ice density along with the mixing ratios [36]. The Thompson scheme used in the present study is a double-moment scheme which includes the prediction of ice concentration [37]. The scheme assumes that the snow size distribution depends on both the water and ice content and temperature [38]. Morrison scheme is also a double-moment scheme which predicts the mixing ratios and concentrations of all the prognostic variables. The scheme uses Kohler’s theory to calculate the homogeneity and heterogeneity in the nucleation process and quasi-stationary saturation adjustment algorithm for droplet concentration [39]. WSM3 is a simple ice scheme, which predicts only the liquid hydrometers (i.e., Qv, Qc, and Qr). The expressions considered by WSM3 to predict liquid hydrometers are assumed to be above the freezing point. Further, the scheme considers Q as Q and Q as Q when the temperature is less than or equal to the freezing point. The WSM5 scheme predicts the mixing ratios of all the prognostic variables except graupel [40]. The WSM6 scheme is similar to that of WSM3, but includes more complex processes for predicting the mixing ratios of all the prognostic variables [41]. Compared to the double-moment schemes, single-moment schemes have the capability of simulating TCs with a smaller eye, stronger tangential wind, high positive temperature and closer latent heating area to the cyclone center, and smaller radius of maximum wind [42].
Table 2. The mixing ratios of the prognostic variables in the Microphysical Schemes.

| Microphysical Schemes | Mixed Phase Variable Processes |
|-----------------------|-------------------------------|
| Ferrier               | Water Vapor (Q_v), Cloud Water (Q_c), Rain (Q_r), Ice (Q_i) |
| Lin                   | Water Vapor, Cloud Water, Rain, Ice, Snow (Q_s), and Graupel (Q_g) |
| Morrison              | Water Vapor, Cloud Water, Rain, Ice, Snow, and Graupel |
| Thompson              | Water Vapor, Cloud Water, Rain, Ice, Snow, and Graupel |
| WSM3                  | Water Vapor, Cloud Water/Ice and rain/snow |
| WSM5                  | Water Vapor, Cloud Water, Rain, Ice, and Snow |
| WSM6                  | Water Vapor, Cloud Water, Rain, Ice, Snow, and Graupel |

For the sensitivity experiments, a total of eight TCs were selected to study the sensitivity of microphysical schemes to the prediction of track and intensity of TCs over the NIO region that occurred from 2014 to 2018. The model initiation time and simulation period for the TCs are presented in Table 3. The simulated results of the TCs are validated against the best track given by IMD.

Table 3. Model initiation dates and simulation times considered for the study.

| Tropical Cyclone | Initial Date: Time (DD-MM-Year: hh) | End Date: Time (DD-MM-Year: hh) | Simulation Period (h) | Maximum Sustained Wind (MSW) (Kt) | Mean Sea Level Pressure (MSLP)(hPa) | Intensity Stages of TCs for Model Initialization |
|------------------|-------------------------------------|---------------------------------|-----------------------|-----------------------------------|-----------------------------------|--------------------------------------------------|
| Hudhud           | 09-10-2014: 00 Z                    | 13-10-2014: 00 Z                | 96                    | 45                                | 990                               | Severe Cyclonic Storm (SCS)                       |
| Nilofer          | 27-10-2014: 00 Z                    | 31-10-2014: 00 Z                | 96                    | 55                                | 990                               | Severe Cyclonic Storm (SCS)                       |
| Kyant            | 23-10-2016: 00 Z                    | 27-10-2016: 00 Z                | 96                    | 20                                | 996                               | Depression (D)                                   |
| Ockhi            | 01-12-2017: 00 Z                    | 05-12-2017: 00 Z                | 96                    | 50                                | 992                               | Severe Cyclonic Storm (SCS)                       |
| Daye             | 20-09-2018: 00 Z                    | 22-09-2018: 00 Z                | 48                    | 25                                | 996                               | Depression (D)                                   |
| Titli            | 09-10-2018: 00 Z                    | 13-10-2018: 00 Z                | 96                    | 30                                | 1000                              | Deep Depression (DD)                             |
| Gaja             | 12-11-2018: 00 Z                    | 16-11-2018: 00 Z                | 96                    | 40                                | 998                               | Cyclonic Storm (CS)                               |
| Phethai          | 14-12-2018: 00 Z                    | 18-12-2018: 00 Z                | 96                    | 30                                | 1002                              | Deep Depression (DD)                             |

3. Evaluation Method

Statistical analysis is the most common method used to find the uncertainty in the model forecasts with respect to the observations. The Direct Positional Error (DPE) was calculated by using the Haversine formula, which gives the geographical distance between the two points on a sphere. The detailed description about the Haversine formula. Mean Sea Level Pressure (MSLP) and Maximum Sustained Wind (MSW) were measured at each time step and evaluated against the IMD observations. The Mean Absolute Error (MAE), and Mean Square Error (MSE) were calculated with respect to IMD observations. MAE is an average prediction error and used to measure the forecast accuracy. MSE is a measure to determine the quality of a forecast with a positive value. If the value of MAE and MSE are close to zero, the quality of the forecast is better. The skill score (SS) of DPE, MSLP and MSW were calculated with respect to the reference forecast. SS is the relative accuracy score of a forecast over a reference forecast. The reference forecast was chosen based on the numerical experiments conducted by Srinivas et al. (2013) [29]. By conducting 65 numerical experiments, Srinivas et al. (2013) suggested that the Lin scheme provided better results for the prediction of the track and intensity of 21 TCs over the BoB. Hence, the sensitivity experiments with the Lin scheme considered as a reference forecast and the skill score for all the other microphysical schemes were
calculated. Positive (negative) values of SS indicate that the model is more (less) skilled than the configuration using the Lin scheme.

The SS of MSLP and MSW was calculated by using Equation (3).

\[
\text{Mean Absolute Error (MAE)} = \frac{1}{n} \sum_{i=1}^{n} |P_s - P_o|
\]  

\[
\text{Mean Square Error (MSE)} = \frac{1}{n} \sum_{i=1}^{n} (P_s - P_o)^2
\]

\[
\text{Skill Score (SS)} = 1 - \frac{\text{MSE}_{\text{Simulation}}}{\text{MSE}_{\text{Reference}}}
\]

In the above equations, \(P_s\) = Simulated Value of the Parameter, \(P_o\) = Observed Value of the Parameter, and \(n\) = Number of Observations. The SS for DPE is calculated using Equation (4).

\[
\text{Skill Score (SS}_{\text{DPE}}) = 1 - \frac{\text{DPE}_{\text{Simulation}}}{\text{DPE}_{\text{Reference}}}
\]

4. Results

The sensitivity of seven CMP schemes was analyzed to find the optimum combination physics schemes for the prediction of post-monsoon TC over the NIO using the ARW model. Except for the Daye cyclone, the simulation period for the selected TCs is 96 h. For the Daye cyclone, the simulation period is 48 h, as the lifespan of the cyclone itself is 48 h. The model errors for MSW, MSLP, and track position are calculated with respect to the observed value.

4.1. Track and Intensity Errors

The predicted tracks of the selected cyclones for all the combinations of CMP schemes and the best track provided by IMD are depicted in Figures 2–5 along with their respective direct positional errors (DPE). From the results, it is observed that the intensity stages (Depression, Deep Depression, Cyclonic Storm, Severe Cyclonic Storm, and Very Severe Cyclonic Storm) of TCs during the model initialization have a significant impact on its track prediction. The cyclones initiated at deep depression or higher stages showed an increasing trend in average track error from the model initiation to the end of the simulation, whereas the cyclones initiated at the depression stage showed a decreasing trend in their average track error until 48 h of model simulation, and then gradually increased to the end of the simulation. Except for the cyclones Daye and Kyant, the predicted track was near to the observed track during the initial stages of the model simulation, with an average error of 64 km for all the schemes. The results are in good agreement with previous studies [27, 32]. Subsequently, as the time of simulation increased, the predicted track also started moving away from the best track. At the end of the simulation period, the average track error was found to be 247 km. For cyclone Kyant, an average track error of 88 km was found during the initial stages and gradually reduced to 67 km up to 48 h of the model simulation, and then gradually increased to 347 km at the end. Similarly, for cyclone Daye, the average track error was gradually reduced from 162 to 78 km from the model initiation to the end of the simulation.

The model performance was evaluated by calculating the MAE, MSE, and average track errors at every 24h interval (i.e., 4, 48, 72h, and 96h). The 24-hourly average track error for the TCs is presented in Figure 6. The WSM3 scheme simulated the cyclones Nilofar, Kyant, Ockhi, Daye, and Phethai with an average track error ranging from 83 to 190 km, 45 to 195 km, 42 to 75 km, 102 to 47 km, and 113 to 115 km at 24h to end of the simulation time, respectively. Hudhud cyclone is well simulated by all the CMP schemes, with a maximum average track error of 63 km at a 24 h simulation time. From then, the average track error gradually increased to 555 km at the end of the simulation with a least error of 219 km by the WSM6 scheme. Cyclone Gaja is well simulated by Ferrier, with least average track errors of 110, 264, 231, and 139 km at 24, 48, 72, and 96h of the model simulation time. In the case of Titli, the average track was considered for the overall simulation period because the Morrison scheme gave the lowest average track error of 64 and 39 km during the initial stages of model simulation, whereas the WSM6 scheme produced the least error of 111 and 37 km at the end.
of the simulation. Hence, the WSM6 scheme was considered to provide superior results for Titli cyclone. The single-moment or double-moment schemes did not shown any significant variations in the TCs track prediction. The deviations in the predicted tracks may be attributed to the variations in the intensification process during the model simulation. The schemes which showed rapid intensification process during the model simulation showed minimum deviation from the observed track, whereas the schemes which showed a slower intensification process during the model simulation showed maximum deviation from the observed track [43].
Figure 2. Observed and predicted tracks of tropical cyclones initiated at depression stage along with DPE (a) tracks of Daye Cyclone, (b) DEP of Daye Cyclone, (c) track of Kyant Cyclone, (d) DEP of Kyant Cyclone.

Figure 3. Observed and predicted tracks of tropical cyclones initiated at deep depression stage along with DPE (a) track of Phethai Cyclone, (b) DPE of Phethai Cyclone, (c) track of Titli Cyclone, (d) DPE of Titli Cyclone.
Figure 4. Observed and predicted tracks of tropical cyclones initiated at cyclonic stage (Gaja) and severe cyclonic stage (Hudhud) along with DPE (a) track of Gaja Cyclone, (b) DPE of Gaja Cyclone, (c) track of Hudhud Cyclone, (d) DPE of Hudhud Cyclone.

Figure 5. Observed and predicted tracks of tropical cyclones initiated at severe cyclonic stage along with DPE (a) track of Nilofar Cyclone, (b) DPE of Nilofar Cyclone, (c) track of Ockhi Cyclone, (d) DPE of Ockhi Cyclone.
Figure 6. Average track error at every 24-hour interval of the tropical cyclones considered.
Figure 7. Mean Absolute Error (MAE), Mean Square Error (MSE) of Mean Sea Level Pressure (MSLP) and Maximum Sustained Wind (MSW) of the tropical cyclone Hudhud.

The Mean Absolute Error (MAE) and Mean Square Error (MSE) of MSW for all CMPs were calculated and the results of the TC Hudhud are presented in Figure 7. In the case of Nilofar, Kyant, Daye, and Phethai cyclones, WSM3 indicates the lowest MAE and MSE. The lowest MAE for the TCs ranged from 4.73 to 17.08 m/s, 6.84 to 4.63 m/s, 8.60 to 1.45 m/s, and 7.16 to 3.66 m/s for MSW from 24h to the end of the simulation. The lowest MSE for the TCs ranged from 10.14 to 11.31 m²/s², 2.89 to 4.97 m²/s², 6.56 to 0.88 m²/s², and 2.29 to 6.29 m²/s². The lowest MAE and MSE for the Gaja cyclone were obtained from the Ferrier scheme and are ranged from 4.19 to 9.94 m/s and 5.77 to 13.46 m²/s², respectively. However, for the Hudhud, Titli and Ockhi cyclones, the WSM6 and Lin scheme provided the lowest MAE, ranging from 2.44 to 9.49 m/s, 5.08 to 3.91 m/s and 4.85 to 3.85 m/s, and the MSE ranged from 1.60 to 1.48 m²/s², 5.39 to 8.63 m²/s²and 6.44 to 12.45 m²/s². The schemes which predicted the MSW well also predicted MSLP for the respective TCs.

The intensity of the TC cyclone is influenced by the auto conversion process between the hydrometers and the amount of latent heat released during the conversion process [44,45]. To assess the impact of various microphysical schemes on the intensity of TCs, the vertical profile of the area averaged mixing ratios was calculated at every 3-hour interval over the entire numerical domain. An average value of the prognostic variables over all the time steps was taken for the analysis. The averaged values of the prognostic variables for the cyclone Hudhud are presented in Figure 8 and other cyclones are presented in Supplementary Figures S1–S7. From the results, it can be observed that the WSM3 scheme only predicted the liquid hydrometers for all the cyclones. This indicates that the WSM3 scheme assumed that the temperature of the clouds was above the freezing point. Compared to the other microphysical schemes, the WSM3 scheme produced significant amounts of cloud water and rain in the lower troposphere for the cyclones Nilofar, Kyant, Daye, and Phethai. For the cyclones Kyant, Daye, and Phethai, all the microphysical schemes showed a significant decrease in the frozen hydrometers in the middle troposphere results in slowing down the vertical acceleration of the intense updrafts in the eye wall of the storm, which might be reason for inhibiting the storm intensification [46]. For the cyclone Nilofar, the frozen hydrometers predicted by all the microphysical schemes in the middle troposphere are negligible in quantity and the liquid hydrometers predicted by Lin, WSM5 and WSM6 in the lower troposphere are also negligible in quantity. Compared to the Ferrier, Morrison, and Thompson schemes, which produced cloud water and rain in the lower troposphere, the WSM3 scheme produced a higher amount. The presence of cloud water and rain in the lower troposphere helps in its intensification. Therefore, the WSM3 scheme produced a higher intensity for the cyclones Nilofar, Daye, Kyant, and Phethai.
The WSM6 scheme produced a significantly large amount of cloud water and rain in the lower troposphere compared to WSM3 for the cyclones Hudhud, Ockhi, and Titli. Due to the presence of cloud water and rain in the lower troposphere helping in the release of latent heat and cyclone intensification, the WSM6 scheme has given a higher intensity for the cyclones Hudhud, Ockhi and Titli, whereas the other microphysical schemes showed a significant decrease in the frozen hydrometers in the middle troposphere, which prevents the intensification of cyclones. In the case of Gaja cyclone, the Ferrier, Lin, Thompson, and WSM6 schemes produced cloud water in the lower
troposphere, and all the schemes produced negligible quantities of all the other prognostic variables. Compared to other schemes, due to the presence of a large amount of cloud water in the lower troposphere, the Ferrier scheme predicted the Gaja cyclone with greater intensity. The uncertainties in the predictions by various microphysical schemes can be attributed to the presence of a graupel hydrometer [47–49].

4.2. Skill Score

Skill Score (SS) was calculated to obtain information about the improvement in the model forecast over the reference forecast. It is easy to identify the improvement in the model performance as the SS provides a single value. In the present study, sensitivity experiments with the Lin scheme were considered as a reference forecast and the skill score for all the other microphysical schemes was calculated. The skill scores for the DPE, MSW and MSLP at the end of the simulation are provided in Tables 4–6.

| Cyclone/CMP | DPE | MSW | MSLP |
|-------------|-----|-----|------|
| Hudhud      | -0.52 | 0.33 | 0.45 |
| Nilofar     | 0.13 | 0.22 | 0.41 |
| Kyant       | -0.44 | 0.15 | 0.24 |
| Ockhi       | -0.54 | -0.24 | -0.85 |
| Daye        | -0.09 | 0.01 | -0.02 |
| Titli       | 0.49 | 0.13 | 0.11 |
| Gaja        | 0.35 | 0.62 | 0.47 |
| Phethai     | -0.11 | 0.27 | 0.23 |

The WSM3 scheme showed an improvement of 18%, 17%, 19%, and 41% in direct positional error (DPE) for the cyclones Nilofar, Kyant, Daye, and Phethai, respectively, whereas the WSM6 scheme showed an improvement of 17%, 35% and 58% in DPE for the cyclones Hudhud, Ockhi, and Titli. For the Gaja cyclone, the Ferrier scheme showed an improvement of 35% over the reference forecast. Similar results were obtained for MSW and MSLP.
5. Conclusions

In the present study, a total of 56 sensitivity experiments were conducted to assess the impact of seven microphysical schemes on the track and intensity of eight tropical cyclones over the NIO region that occurred from 2014 to 2018. To assess the model performance, DPE, MAE and MSE errors were calculated based on the observations provided by IMD and skill score was calculated over the reference forecast. The WSM3 microphysical scheme showed the lowest DPE, MAE and MSE for the tropical cyclones Nilofar, Kyant, Daye and Phethai, and WSM6 scheme showed the lowest values for the tropical cyclones Hudhud, Ockhi and Titli. Due to the presence of liquid hydrometers (i.e., cloud water and rain) in the lower atmosphere, the WSM3 has predicted more intensity for Nilofar, Kyant, Daye and Phethai cyclones, and WSM6 for Hudhud, Ockhi and Phethai. Compared to the model performance with the Lin scheme, the WSM3 scheme provided a significant improvement in the prediction of track and intensity for the tropical cyclones Nilofar, Kyant, Daye and Phethai and WSM6 for the tropical cyclones Hudhud, Ockhi and Titli. From the results, the WSM3 scheme can be suggested as a first best scheme for the prediction of the track and intensity of tropical cyclones over the NIO region. WSM3 appears to have better skills than other, more complex parameterizations, maybe due to the presence of fewer prognostic variables. The presence of more prognostic variables in other schemes may add uncertainty to the model simulations.

A study by Choudhary and Das (2017) on the impact of grid resolution on the track and intensity indicated that the domains with less than 5 km resolution have produced accurate results. When the size of the domain increases, the model results will be more dependent on the parameterization schemes. However, for operational purposes, the disaster management agencies need real-time forecasts within a short time with reasonable accuracy. Therefore, the methodology and the information about the microphysical applied in the study can be used in real-time forecasting of TCs over the NIO region.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4433/11/12/1297/s1, Figure S1. Time evolution of area averaged mixing ratios (g/kg) for the cyclone Daye (Qv-Water Vapor, Qc-Cloud Water, Qr-Rain Water, Qi-Ice, Qs-Snow, Qg-Graupel). Figure S2. Time evolution of area averaged mixing ratios (g/kg) for the cyclone Gaja (Qv-Water Vapor, Qc-Cloud Water, Qr-Rain Water, Qi-Ice, Qs-Snow, Qg-Graupel). Figure S3. Time evolution of area averaged mixing ratios (g/kg) for the cyclone Kyant (Qv-Water Vapor, Qc-Cloud Water, Qr-Rain Water, Qi-Ice, Qs-Snow, Qg-Graupel). Figure S4. Time evolution of area averaged mixing ratios (g/kg) for the cyclone Nilofar (Qv-Water Vapor, Qc-Cloud Water, Qr-Rain Water, Qi-Ice, Qs-Snow, Qg-Graupel). Figure S5. Time evolution of area averaged mixing ratios (g/kg) for the cyclone Ockhi (Qv-Water Vapor, Qc-Cloud Water, Qr-Rain Water, Qi-Ice, Qs-Snow, Qg-Graupel). Figure S6. Time evolution of area averaged mixing ratios (g/kg) for the cyclone Phethai (Qv-Water Vapor, Qc-Cloud Water, Qr-Rain Water, Qi-Ice, Qs-Snow, Qg-Graupel). Figure S7. Time evolution of area averaged mixing ratios (g/kg) for the cyclone Titli (Qv-Water Vapor, Qc-Cloud Water, Qr-Rain Water, Qi-Ice, Qs-Snow, Qg-Graupel).

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