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Demonstration of the Temporal Evolution of Tropical Cyclone "Phailin" Using Gray-Zone Simulations and Decadal Variability of Cyclones over the Bay of Bengal in a Warming Climate

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Abstract: The intensity and frequency variability of cyclones in the North Indian Ocean (NIO) have been amplified over the last few decades. The number of very severe cyclonic storms (VSCSs) over the North Indian Ocean has increased over recent decades. "Phailin", an extreme severe cyclonic storm (ESCS), occurred during 8-13 October 2013 over the Bay of Bengal and made landfall near the Gopalpur coast of Odisha at 12 UTC on 12 October. It caused severe damage here, as well as in the coastal Odisha, Andhra Pradesh, and adjoining regions due to strong wind gusts (~115 knot/h), heavy precipitation, and devastating storm surges. The fidelity of the WRF model in simulating the track and intensity of tropical cyclones depends on different cloud microphysical parameterization schemes. Thus, four sensitivity simulations were conducted for Phailin using double-moment and single-moment microphysical (MP) parameterization schemes. The experiments were conducted to quantify and characterize the performance of such MP schemes for Phailin. The simulations were performed by the advanced weather research and forecasting (WRF-ARW) model. The model has two interactive domains covering the entire Bay of Bengal and adjoining coastal Odisha on 25 km and 8.333 km resolutions. Milbrandt-Yau (MY) double-moment and WRF single-moment microphysical schemes, with 6, 5, and 3 classes of hydrometeors, i.e., WSM6, WSM5, and WSM3, were used for the simulation. Experiments for Phailin were conducted for 126 h, starting from 00 UTC 8 October to 06 UTC 13 October 2013. It was found that the track, intensity, and structure of Phailin are highly sensitive to the different microphysical parameterization schemes. Further, the precipitation and cloud distribution were studied during the ESCS stage of Phailin. The microphysics schemes (MY, WSM3, WSM5, WSM6), along with Grell-Devenyi ensemble convection scheme predicted landfall of Phailin over the Odisha coast with significant track errors. Supply of moisture remains a more crucial component than SST and wind shear for rapid intensification of the Phailin 12 h before landfall over the Bay of Bengal. Finally, the comparison of cyclone formation between two decades 2001–2010 and 2011–2020 over the Bay of Bengal inferred that the increased numbers of VSCS are attributed to the supply of abundant moisture at low levels in the recent decade 2011-2020.

Keywords: very severe cyclonic storm; Phailin; microphysics; hydrometeors; WRF model; Bay of Bengal

1. Introduction

During the post-monsoon season, tropical cyclones are the primary source for clouds and precipitation over the tropics [1–5]. It has been reported that clouds are the essential



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). meteorological element in the formation and structure of tropical cyclones (TCs). The wellorganized clusters of convective clouds around the central area of surface low-pressure over the sea surface help to develop the TC [6–9]. The energy required for a TC to intensify is acquired from the direct transfer of sensible and latent heat fluxes from the warm ocean surface via the convection process. The cloud bands in the inner regions of TC are mostly cumulonimbus in nature and happen to be located within the spinning vortex and intricately connected with the dynamics of the cyclone itself. Houze (2010) reported that as high-resolution core physics models become more widely used, forecasting the probabilities of extreme weather and heavy precipitation at specific times and locations will become a feasible goal for land-falling cyclones. Understanding the microphysical processes associated with TCs, particularly in the tropics, is challenging and remains unclear [10]. The microphysical parameterization (MP) is an important source of uncertainty in numerical weather predictions of mesoscale convective systems [11]. Due to the complexity of microphysical processes, various MP schemes have been developed over the past decades based on Eulerian approaches to represent cloud and precipitation in mesoscale models. For simulation of TCs over the Bay of Bengal (BoB), cloud microphysics schemes, such as Kessler, WSM3/5/6, Ferrier, Godard, Thompson, Milbrandt–Yau, Morrison, WDM, and Lin, have been widely used in the WRF model. However, single-moment bulk microphysical schemes calculate the mixing ratio categories (cloud, water, rain, cloud ice, snow, and graupel). In contrast, the double-moment bulk microphysical scheme predicts the corresponding mixing ratio number with concentration and mass mixing ratios [12]. Further, there are differences in the number of anticipated moments, while such MP schemes follow gamma distribution for precipitating hydrometers. Hong et al., (2004) concluded that the WSM3 simple ice scheme without mixed phase can capture the warm rain processes better than mixed-phase schemes such as WSM5 and WSM6 over tropical regions [13]. They further concluded that the simple ice scheme without mixed-phase microphysics is good enough to resolve the mesoscale features in 25 km grid resolution. The horizontal grid spacing between around 5 and 12 km is referred to as the convective gray-zone resolution (hereafter referred to as gray-zone resolution for short), which avoids convection scheme uncertainties as the results rely on the cloud microphysics and PBL schemes [14].

Clouds associated with TCs are typically organized into large rings and bands. TCs have clouds and precipitation structures that are similar to the mesoscale convective systems over mid-latitude [7]. Therefore, similarly to improving numerical weather prediction (NWP) models for quantitative precipitation forecasts, the problem of improving TC forecasts from NWP is closely related to how to better simulate microphysics of winds, rainfall, and moisture. It has been recognized that experiments with various complex microphysical processes could significantly influence the TC's intensity, structure, and evolution at finer horizontal and vertical resolutions [9,13]. The TCs are among the most devastating extreme weather phenomena in the tropics. Models' skills in predicting the TC track and intensity over the Bay of Bengal (BoB) have been discussed in detail by previous studies [6,15,16]. There are numerous MP schemes available in weather research and forecasting (WRF) models [17]. Most of these schemes, such as LIN explicit, WSM6, Thompson, WDM6, Thompson and Morrison, WSM 3-class simple ice, and Ferrier have been widely used for TC forecasts over the North Indian Ocean and the results are discussed in [18–22]. The parameterized production rate of hydrometeors is the crucial aspect for the sensitivity of the quantitative precipitation forecast (QPF) to different MP schemes [9,23,24]. It is important to provide an accurate QPF during the severe cyclogenesis stage and at the land-fall stage of Phailin or any other cyclone. The simulation of different stages of a TC is very much associated with the convection and cloud process. Thus, using various MP schemes, the models can accurately capture the natural variability and dynamics of cloud processes [11]. During the cyclone evolution, the intensity and track forecast largely depend on the diabatic heating rates [25,26], which arise mainly by latent heat release by the condensation processes within the system. However, the diabatic heating rates induce mixing over the convective and stratiform rainfall regions. The vertical profiles of

diabatic heating rates and microphysical properties of clouds further define the diurnal and temporal extent of the cyclone [25].

In post-monsoon season, especially in October, the number of severe to super severe cyclone formations remains the highest and quite strongly affects the Indian subcontinent, Bangladesh, Myanmar, Sri Lanka, Oman, Somalia, and Yemen. In the latest decade (2011–2020) the number of severe cyclones over the Indian Ocean has increased, while the number of depressions has decreased. A few of the intensified and severely damaging cyclones (of a total nearly in the billions) were Gonu, Nargis, Giri, Thane, Phailin, Nilofar, Vardah, Ockhi, Mekunu, Fani, Kyarr, and the latest super cyclone Amphan in 2020 (IMD Archives). Over the last few decades, two ESCSs (Odisha, 1999; Phailin, 2013) have made landfall over the Odisha coast. The VSCS occurred during the post-monsoon season and caused socio-economic damages and casualties [27,28].

The simulation studies of the Phailin cyclone were done by [19,29–31], but none of the studies paid attention to the cloud microphysical aspects of the Phailin cyclone. However, the microphysical processes and characteristics of different hydrometeor concentrations may be considered as a decisive factor for TC intensity prediction [18]. In the present study, the sensitivity experiments of various MP parameterization schemes with 25 km and 8.333 km model resolutions were used to highlight the track and intensity prediction of Phailin. The objective of this study was to investigate the sensitivity of single and double-moment MP schemes in the WRF model to simulate the track, intensity, circulation dynamics in the eyewall, precipitation, and vertical cross-section of extreme severe cyclonic storm Phailin (ESCS). Thus, the present study discusses the track, intensity, and dynamical mechanisms that are responsible for the eyewall formation, rainfall, and characteristics of hydrometeors. In this article, synoptic conditions of Phailin are discussed in Section 2, details of numerical experiments and data used are discussed in Section 3, results and discussions are presented in Section 4. Recent changes in TCs formation over the BoB are presented in Section 5, and, finally, the essential findings based on the results are discussed in Section 6.

2. The Synoptic Conditions during Phailin Cyclone

The Phailin cyclone with a lifespan of 6 days (8–13 October 2013) initially originated as a depression near Andaman and Nicobar Island (in BoB, India). The pressure (hPa) and wind speed (knots) corresponding to different stages of Phailin are represented in Table 1. A low-pressure system that occurred on 8 October 2013 over the BoB was named Phailin. The Phailin initially started as depression and reached up to a very super cyclonic storm (VSCS) on 06 UTC of 10 October 2013. Initially, the low-pressure system lingered over the same location 12° N–96° E as a depression (D) for a day. The system got intensified into a deep depression (DD) in the next 24 h and then moved in the northwest direction.

Table 1. Synoptic conditions of Phailin during 8–13 October 2013 obtained from IMD report.

Stage	Time	Pressure (hPa)	Wind Speed (kts)	Duration (Hours)/ Shape of the System	Latitude/Longitude
Depression (D)	03 UTC 8 Oct 2013	1004	25	24 Dense clouds	12.0° N; 96.0° E
Deep Depression (DD)	03 UTC 9 Oct 2013	1001	30	09 Dense clouds	13.0° N; 93.5° E
Cyclonic Storms (CS)	12 UTC 9 Oct 2013	999	35	12 Dense clouds	13.5° N;92.5° E
Severe cyclonic storm (SCS)	03 UTC 10 Oct 2013	990	55	03 Very dense clouds	14.5° N; 91.0° E
Very severe cyclonic storm (VSCS)	06 UTC 10 Oct 2013	984	65	21 Almost closed eye and fair	15.9° N; 90. 5° E

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Stage Time		Pressure (hPa)	Wind Speed (kts)	Duration (Hours)/ Shape of the System	Latitude/Longitude
Extreme severe cyclonic storm (ESCS)	03 UTC 11 Oct 2013	940	115	20 Almost closed eye and good	16.0° N; 88.5° E
Extreme severe cyclonic storm (ESCS)	03 UTC 12 Oct 2013	940	115	24 Almost closed eye and more prominent	17.8° N; 86.0° E
Severe cyclonic storm (SCS)	03 UTC 13 Oct 2013	990	55	Almost closed Eye	17.8° N; 85.9° E

Table 1. Cont.

This DD further intensified within the next 12 h as a cyclonic storm (CS) at 12 UTC, 9 October 2013 (IMD, 2013). Phailin became a VSCS at 06 UTC on 10 October 2013, located at 14.5° N, 91.0° E, and stirred northwestwards with a maximum sustained wind speed of 55 knots and 990 hPa. Due to the vertical wind shear of 5-10 knots, the cyclonic storm became a VSCS with a wind magnitude of 70 knots, and pressure dropped 26 hPa off 990 hPa on 10 October 2013. The VSCS persisted over the middle of the BOB for 24 h, with a central sea level pressure (CSLP) of 940 hPa and wind speed of 115 knots, and continued to move in the northwest direction until it gradually became an ESCS. Figure 1 illustrates the double eyewall of ESCS Phailin at 00 UTC, 12 October 2013. To evaluate the tropical cyclone's structural characteristics, the satellite images derived from the water vapor and rain rate of Phailin are shown in Figure 1a,b. The rain rates were derived using a combination of passive microwave channels (F-17) representing the core rain bands and eyewall decoration of Phailin during the ESCS stage. The eyewall represented the consolidated system and underwent a second eyewall formation, as shown in Figure 1b with a categorization of 5 in terms of intensity. The system subsequently made landfall later that day (13 October) near the Gopalpur coast of Odisha around 22:30 IST (17 UTC), near peak intensity, which caused severe damages as discussed [18]. The Phailin with VSCS intensity passed through the Gopalpur coast of Odisha and adjoining Andhra Pradesh at 15 UTC on 12 October 2013 at latitude 19.2° N and 84.9° E (IMD, 2013). After 24 h of landfall, the intensity of the ESCS declined and turned into an SCS, holding a CSLP of 990 hPa and wind speed of 55 kt. Satellite images of Phailin on 24 h temporal intervals were used to determine whether the TC intensified, weakened, or retained intensity, as followed by the Dvorak method (1975). Therefore, the NOAA satellite pictures were considered at two different stages of Phailin at 24 h intervals, as represented in Figure 1a,b. The rain rate patterns identified for the eyewall development for Phailin were valid on 11 October 2013 at 23:30 UTC (Figure 1c), which rapidly intensified into a further severe cyclone. Figure 1d shows an intensive rain rate with a well-organized spiral eyewall that was maintained by cold clouds at the upper troposphere surrounded by warm temperatures in the eye region.



Figure 1. (a) Track of Phailin during 8–13 October 2013; according to SSHWS, the system became equivalent to a Category 5 (NASA) on 00 UTC 12 October 2013; Satellite images METEO 7 of ESCS Phailin, (b) water vapor 00 UTC 12 October 2013, (c) rain rate valid on 11 October 2013 at 23:30 UTC, (d) rain rate after landfall valid on 13 October 2013 at 11:30 UTC shown double eyewall features [for details https://rammb-data.cira.colostate.edu/tc_realtime/, (accessed on 21 August 2021)].

3. Numerical Experiments and Data Used

3.1. WRF Model Setup

The model used in this study was the advanced research WRF (ARW), version 3.7.1 [17]. The analyses and 6 h forecast fields of the final analysis (FNL) of the NCEP at $1.0^{\circ} \times 1.0^{\circ}$ grid space were taken as the initial and boundary conditions for the ARW model. The lateral boundary conditions were updated in a 6 h intervals, and the SST was kept constant throughout the model integration. The United States Geological Survey (USGS) data with 10 min and 5 min resolution were used to provide permanent land surface fields, such as terrain/topography. A double domain of 25 km and 8.333 km (gray-zone simulations) were chosen, which extended from 75–110° E and 4–32° N with 42 vertical levels [14]. The vertical levels were closely placed in the lower levels (12 levels below 850 hPa and 22 levels between 850–500 hPa) and were relatively coarser in higher levels. The domains are presented in Figure 2. The model was integrated at a 3 h interval using the Yonsei University [32] (YSU) planetary boundary layer (PBL) scheme, with Grell and Devenyi ensemble [33] (GDE) for the convective parameterization scheme. For TC simulation, the GDE scheme has the least errors in terms of the intensity of tropical cyclones, as discussed in [34,35]. Thus, GDE convective scheme was used in this study. The thermal diffusion (slab) scheme [36] was used for the land surface representation in the WRF model.



Figure 2. WRF model domains used for experiments of Phailin and horizontal resolutions of D01 (25 km) and D02 (8.333 km, gray-zone grid), respectively.

The rapid radiative transfer model (RRTM) longwave radiation scheme and the shortwave radiation scheme of [37] were used to simulate the radiative forcing. To explore the sensitivity of cloud microphysical parameterization schemes, four MP schemes were chosen to perform the experiments up to 126 h, and the model's outputs were generated after 3 h intervals. The details of domain and physics options used in the model experiments are represented in Table 2. The MP schemes and their characteristics are discussed in Table 3.

3.2. Classification of Single- and Double-Moment Microphysics

The primary microphysical species are water vapor, cloud droplets, rain droplets, cloud ice crystals, snow, rimed ice, graupel, and hail. Microphysics budgets depend on atmospheric dynamical and thermodynamical conditions, which determine the partitioning of hydrometeors [38]. Most of the schemes may have two or three ice categories; however, the degree of sophistication used to represent the microphysics processes varies considerably [39]. There has been rapid progress in the understanding of cloud microphysical processes in recent decades, and many microphysical schemes have been developed for applications in NWP and climate models. Thus, cloud processes can be studied with more confidence, especially from the point of view of linking cloud-scale processes to large-scale atmospheric circulations [40]. Numerous studies have discussed a couple of atmospheric models that applied an Eulerian approach for the cloud and thermodynamic variables, not only for the temperature and water vapor but also for the prognostic variables, such as ice particles, which occur as sparsely distributed liquid drops and ice particles [41,42]. The detailed descriptions and formulation of hydrometeors are illustrated in Table 3.

Model Features	Non-Hydrostatic				
Version	3.7.1				
Horizontal resolution	25 km, 8.333 km				
Vertical levels	42				
Topography	USGS				
Dynamics					
Time integration	3rd order Runga-Kutta				
Time steps	30 s				
Horizontal grid distribution	Arakawa C-grid				
Spatial differencing scheme	6th order centered differencing				
Physics					
Radiation scheme	Dudhia for short wave radiation/RRTM longwave radiation				
Surface layer	Monin–Obukhov similarity theory				
Land surface parameterization	5-layer thermal diffusion				
PBL parameterization scheme	Yonsei University scheme (Hong et al. 2006)				
Cumulus parameterization scheme	Grell-Devenyi Ensemble (GDE)				
Cloud microphysics	 Milbrandt–Yau double-moment 7-class (MY) WSM6-class WSM5-class WSM3-class 				

Table 2. WRF model and domain configurations.

Initial and boundary conditionsReal data from NCEP FNL (1×1 degree)WSM3: The WRF model is a community model suitable for research and forecasting [43,44]. In this scheme, the
water mixing ratios are prognostic and single-moment in nature. In the WRF model, the modifications of the
microphysics of clouds and precipitation are implemented as NCEP simple ice (three classes: vapor, cloud/ice,
and rain/snow), referred to as WSM3 scheme, and details are discussed [45]. WSM5: The mixed-phase (five
classes: vapor, cloud, ice, rain, and snow) schemes are referred to as WSM5 schemes. Hong et al. (2004) suggested
that there is a significant role of the microphysical properties on mesoscale forecast [46]. They further added that
the simple ice scheme without mixed-phase microphysics is enough to resolve mesoscale features on a 25 km
grid resolution. The modifications in the ice microphysical processes result in a realistic distribution of clouds
through auto-conversion of cloud water to rain, similar to Kessler's formula [47]. WSM6: The WSM6 scheme has
been developed by adding additional processes related to graupel to the WSM5 scheme [48]. Milbrandt and Yau
(MY): A bulk parameterization microphysics scheme in atmospheric models is important to develop details on
rainfall and other features of a system. MY [49,50] is a computationally efficient scheme, thus, it is widely used to
understand the strength and limitations of various rain-bearing processes.

Table 3. WRF v3.7.1. Cloud microphysical schemes used for the Phailin experiment.

mp_Physics	Microphysical Scheme Name	Abbreviation	Hydrometeors
9	Milbrandt–Yau double-moment 7-class [Milbrandt and Yau 2005; Milbrandt and Yau 2005]	МҮ	vapor, cloud, rain, ice, snow, graupel, and hail
6	WRF single-moment 6-class [Hong et al., 2006]	WSM6	vapor, cloud, rain, ice, snow, and graupel
4	WRF single-moment 5-class [Hong et al., 2004]	WSM5	vapor, cloud, rain, ice, and snow
3	WRF single-moment 3-class [Hong et al., 2004]	WSM3	vapor, cloud/ice, and rain/snow.

4.1. Intensity and Structure of Phailin

Evaluation of track and intensity is given priority for the precise forecasting of lowpressure systems. The simulated track positions of Phailin from different MP experiments and IMD observations are represented in Figure 3. It was noticed that the MP experiments simulated slight deviation in tracks during the genesis stage of the Phailin.



Figure 3. Model-simulated track positions of Phailin during 00 UTC, 8 October to 06 UTC, 13 October 2013 using 00 UTC, 8 October 2013 as initial conditions. The positions were identified through the minimum sea level pressure from different WRF experiments along with IMD observations.

The simulated track positions from DD to VSCS have deviated to the east and north of the IMD observation. However, following later landfall of VSCS, positions of simulated tracks were located west of the IMD observed track. From the model experiments, the initial location of the simulated tracks may have shifted relative to observations [39,51]. The track errors from different MP scheme experiments were drawn using the formula from [52] and are shown in Figure 4. The simulated track errors from the MP experiments from domain 1 (D01: 25 km) and domain 2 (D02: 8.333 km) resolutions indicate the sensitivity of tracks in terms of resolutions. The track errors during the simulations were found to vary, as shown in Figure 4a,b. The average number track errors over 12 h was lower in D02 as compared to D01, especially for the MY scheme, which was expected from MP experiments and may be due to the changes in explicit moisture processes. Overall, among the four MP experiments, the WSM3 scheme showed less track errors than MY, WSM6, and WSM5 schemes during the simulations in both domains. During the simulation period, WSM6 and WSM5 showed more track errors compared to MY and WSM3 schemes because the moisture process was being resolved accurately in the latter schemes.

WRF-simulated MSLP and 10 m wind field of Phailin based on 00 UTC, 08 October 2013 initial conditions along with IMD observations are represented in Figure 5a,b. To understand the different stages of Phailin, some of the important parameters were analyzed such as center sea level pressure (CSLP) and maximum sustained wind (MSW) evolution during 8–13 October 2013. For Phailin, the observed estimates indicate that the lowest pressure drops and MSW were about 940 hPa and 115 knots, respectively, at 00 UTC, 13 October 2013. Though the simulation experiments using MY, WSM6, WSM5, and WSM3 schemes underestimated the peak pressure drops, the evolutions expressively agreed with IMD values.



Figure 4. Simulated track errors from the 12 h average derived from different WRF experiments at (a) D01 and (b) D02 resolutions. The bar and scheme are in the sequence of MY, WSM6, WSM5, and WSM3 respectively.



Figure 5. Intensity simulation of (**a**) MSLP (hPa) and (**b**) 10 m maximum sustained wind (MSW; knots) derived from IMD and WRF model experiments during different stages of Phailin at 8.333 km resolution.

As per the IMD report, during a 72 h period, the low-pressure system intensified and reached the stage of VSCS with a wind speed of 60–100 knots (IMD, 2013) at 00 UTC, 11 October, whereas simulations with MP schemes could not predict similar intensity. The MY scheme could simulate maximum sustained wind of 55 knots with the lowest CSLP of 970 hPa, as depicted in Figure 5a. For wind field, MY and WSM3 MP schemes captured maximum wind of 55 knots, whereas WSM6 and WSM5 MP schemes were unable to simulate the same feature. Furthermore, WSM3, WSM5, and WSM6 MP schemes carry biases in simulating the wind speed, as simulated by the MY scheme. The RMSE of CSLP (hPa) and MSW (knots) double-moment MY schemes showed relatively fewer errors than WSM6 and WSM5 in D02 experiments, as illustrated in Table 4.

Stage of Phailin	Simulation Length	RMSE of CSLP (hPa)				RMSE of Wind at 10-m (Knots)			
		MY	WSM6	WSM5	WSM3	MY	WSM6	WSM5	WSM3
D	03z08	1.2	1.5	1.4	1.1	0.48	0.48	0.48	0.48
DD	03z09	1.2	3.2	3.2	1.2	3.32	5.28	3.32	3.32
CS	03z10	2.2	5.5	3.5	4.1	4.04	4.04	6.1	15.8
ESCS	03z11	26.1	33.1	31.2	28.1	36.2	55.8	53.84	46.0
ESCS	03z12	28	36	35	26	30.32	32.28	34.24	40.12
SCS	03z13	5	5	1	1	11.88	11.88	11.88	5.76

Table 4. The 24-h average RMSE of CSLP (hPa) and MSW (knots) for the Phailin cyclone derived from D02 experiments.

The simulated total cloud fractions at 00 UTC on 12 October 2013 when Phailin reached ESCS stage are shown in Figure 6. The dense number of closed isobars (Figure 6a,c,e,g) following high clouds are represented in Figure 6b,d,f,h. The INSAT 3A satellite pictures (IMD, 2013) show heavy dense clouds aligned around the cyclone in Figure 6i. Similarly, the simulated circularly organized cloud bands with the extension of clouds in the northeast and southeast sectors indicate a broken comma structure. The cloud imager clearly shows a significant eyewall formation in MP experiments. The comparisons of simulated wind, pressure distribution, and cloud fractions from different experiments (MY, WSM6, WSM5, and WSM3) with NOAA and the INSAT 3A cloud imagery are represented in Figures 1a and 6i. The results indicate a more intensive cyclone in MY, WSM6, and WSM5 schemes than WSM3 (Figure 6h). The central eyewall formation was well-simulated in all MP schemes and finely represents the observed cloud bands. However, the WSM3 scheme could simulate the spatial distribution, as well as the position of the eyewall region, more comprehensively than other MP schemes.

All the simulations underestimated the pressure drop and maximum sustained wind at different stages, such as DD, SC, and SCS, of the storm. It attained maximum intensity at 06 UTC, 10 October 2013, lasted for more than 48 h, and persisted over the Bay of Bengal. The MP experiments underestimated the pressure intensity by nearly 18 hPa, thus resulting in weaker wind speed (knots) than the IMD observations. These simulations seem to have produced gradual deepening and mature phases of Phailin close to the timings of the observed storm. The significant underestimation in the pressure drop between the model and the observed, starting from the pre-deepening to weakening phases of the storm, was probably due to the cold start initialization of the WRF model.



Figure 6. MSLP (hPa) and total cloud distributions (%) during the ESCS stage of Phailin derived from WRF simulation experiments using (**a**) MY, (**c**) WSM6, (**e**) WSM5, (**g**) WSM3 schemes, and (**i**) METOSAT 7 observation valid at 00 UTC, 12 October 2013 [initial condition of 00 UTC, on 8 October 2013] at 8.333 km resolutions; similarly, 10 m wind speed (shaded; knots) and direction obtained from (**b**) MY, (**d**) WSM6, (**f**) WSM5, (**h**) WSM3 schemes, and (**j**) CIRA observation respectively.

4.2. Circulations and Dynamical Mechanism for Eyewall Development

The movement of the cyclone is governed by the circulation and the intensification of eyewalls. Formation of the eye within any TC is one of the significant features owed to eyewall convection. The eyewall is created by organized convection that is lost for a longer period, with narrow rain bands, called spiral bands, oriented in the same direction as the horizontal wind speed appearing to spiral around the center of the TC [4]. In the case of Phailin, a significant eyewall was formed after 12 h of VSCS stage at 00 UTC, on 12 October 2013 [51–53]. Another important characteristic of the eyewall region is the warm temperatures (due to subsidence) that extend up to the tropospheric level, then to the surrounding environment, as discussed in [54]. Thus, the latent heat flux and temperature at the 300 hPa level are considered here. The contrast in temperature distributions between the warmest part of the eyewall and the coldest surrounding modulates the convection activity of VSCS Phailin (Figure 7i-l). The remarkable features, such as the core of the ESCS warmest of temperature $(-14 \,^{\circ}\text{C})$ were simulated in all the schemes of the MY, WSM6, WSM5 and WSM3 experiments. Moreover, the WSM3 scheme showed the location of Phailin far away from the coastal Odisha, whereas MY, WSM6, and WSM5 simulated the location close to the coast. The curved band patterns of temperature, as depicted in Figure 6i–l, are associated with the lowest core of pressure and larger vorticity fields. The wind speed and direction at 10 m height, along with the averaged vertical velocity at 1000–700 hPa level derived from MP experiments, are shown in Figure 7e-h.



Figure 7. Average (1000–700 hPa level) vorticity field ($\times 10^5 \text{ s}^{-1}$) derived from WRF (D02) experiments using (**a**) MY, (**b**) WSM6, (**c**) WSM5, and (**d**) WSM3 schemes, valid at 00 UTC, 12 October 2013; similarly, vertical velocity ($\times 10$; ms⁻¹) and 10 m wind fields (knots) obtained with (**e**) MY, (**f**) WSM6, (**g**) WSM5 and (**h**) WSM3 schemes are shown; along with latent heat flux (W m⁻², shaded) and temperature (°C; contours) at 300 hPa level derived from (**i**) MY, (**j**) WSM6, (**k**) WSM5, and (**l**) WSM3 experiments, respectively.

The surface winds are calm at the axis of rotation, while strong winds extend well into the eyewall of a TC, as reported by [55]. Interestingly, similar characteristics were captured by WRF simulations in the D02 region. The magnitude of 70 knots with a circular ring-like structure was captured by the WSM3 scheme (Figure 6h), whereas other microphysical parameterization schemes (MY, WSM6, and WSM5) were unable to represent the same (Figure 7e–g). However, except for WSM3, other MP processes have shown the fast movement of the vortex from the BoB towards the Odisha coast and that maximum wind intensity occurred in the east sector of ESCS Phailin. The MY scheme showed the location of the eyewall over the Chilka lagoon, which deviated a bit as compared to the satellite picture shown in Figure 1b. It is to be noted that the calm wind of 10 knots was well-captured by all of these MP schemes, but well-organized features were noticed in the WSM3 scheme.

The circulation budget was computed following the method employed by [56]. The rate of change of relative vorticity can be written in a form that relates to the circulation tendency within a boxed region, accounting for both eddy and mean contributions:

$$\frac{\partial c}{\partial t} = -\bar{\eta}\,\hat{\partial}A - \oint \dot{\eta}\,v \cdot n\,\,dl + \oint \omega \,\left(k \,\times \frac{\partial v}{\partial p}\right) \cdot n\,dl + \oint (k \times F) \cdot n\,dl \qquad (1)$$

where *C* is the circulation, η is the absolute vorticity, $\hat{\partial}$ is the mean divergence over the area A of the box, \oint is the line integral around the perimeter of the box, *v* is the horizontal wind vector, *n* is the direction normal to the perimeter of the box, ω is the vertical velocity in the pressure coordinates, *p* is pressure, and *F* is the frictional force. To identify the key

mechanisms responsible for the circular pattern of the eyewall, the average (1000–700 hPa) relative vorticity of Phailin was computed during the ESCS stage, valid at 00 UTC on 12 October 2013, and the same is shown in the upper panel of Figure 7a–d. The vorticity at 300 hPa (not shown) also confirmed the positive temperature anomalies over the upper level (300 hPa). Therefore, it supports and maintains circulation from surfaces to the upper level. The results included in Figure 7a–d reveal significant differences in the structure of Phailin. It seems both WSM3 and MY schemes were capable of simulating the well-organized circular structure of the relative vorticity field better than the WSM6 and WSM5 schemes. However, the latent heat fluxes, as shown in Figure 7i–l, were consequently favored with the relative vorticity budgets, and those that persisted over the BoB. MY and WSM3 schemes exhibited stronger relative vorticity than WSM5 and WSM6 schemes.

4.3. Middle and Vertical Atmospheric Features

Apart from the surface facilitating elements, vertical sustainability of temperature, water vapor, and wind, etc. are crucial. As Phailin gradually intensified, the location and intensity estimations became more accurate, with well-developed characteristic features of TCs, such as the eyewall, central dense overcast (CDO), lowest cloud top temperature (CTT), and curved band features [57]. Mohapatra et al. (2013) suggested that satellite and radar techniques are more appropriate for exact location and intensity forecasting of TCs over the Indian Ocean using [58]. Typically, the four types of spiral rainbands are principal, secondary, distant, and inner rain bands [59]. The principal rain band distributions were prominent in the case of ESCS Phailin. Therefore, horizontal cross-sections of equivalent potential temperature, relative humidity, and water vapor at 700 hPa (z = 3.02 km) at 00 UTC on 12 October 2013 are considered in this section. Figure 8 appears to fit the description of principal rain bands, as shown in Figure 1b. Figure 8a-h show equivalent potential temperature and relative humidity associated with the VSCS stage of Phailin. At 700 hPa (z = 3.02 km), a close-up view of principal rainbands in the WSM3 scheme (Figure 7d) produced more realistic features than other (MY, WSM6, and WSM 5) MP schemes. The performance of the WSM3 scheme for equivalent potential temperature (Figure 8d) and relative humidity (Figure 8h) showed significantly closer variations against observations, which may have been possible because of the slight increase in cloud ice and decrease of snow at warm temperatures during the microphysical process [57]. At 00 UTC, 12 October 2013, the spatial structure of relative humidity and water vapor mixing ratio coincided with the equivalent potential temperature. The MY, WSM6, and WSM5 schemes (Figure 8e-g) demonstrated convectively active elements of relative humidity (>70%) located close to the Odisha coast. In contrast, the center of Phailin in WSM3 reproduced over the oceanic region. Moreover, the MY scheme showed (Figure 8e) maximum intensity in terms of equivalent potential temperature, relative humidity, and water mixing ratio at 700 hPa level. Figure 9a–c is similar to Figure 8, but represents vertical profiles over Visakhapatnam meteorological station (17.68° N, 83.22° E) at 00 UTC, 12 October 2013, which can provide details on how MP schemes differ from each other from the surface to upper tropospheric level at a particular station. For all experiments, WSM3 was slightly different and better than the other MP schemes. The equivalent potential temperature value increased from the middle to upper tropospheric level (Figure 9a), whereas the water vapor mixing ratio decreased at all levels (Figure 9c). Three MP schemes, MY, WSM6, and WSM5, simulated the relative humidity above 90% of moisture contents from the surface up to 400 hPa level (Figure 9b), whereas WSM3 simulated lower than 90% of moisture content, which was closer to the observations. For this reason, it seems that WSM3 captured middle atmospheric features in a better way than other MP schemes.



Figure 8. Model-simulated equivalent potential temperature (°C) at 700 hPa level derived from WRF (D02) experiments using (a) MY, (b) WSM6, (c) WSM5, and (d) WSM3 schemes valid at 00 UTC, 12 October, 2013. Figures (e–l) are the same as (a–d), but represent relative humidity (%) and water vapor mixing ratio ($\times 10^3$; gm·kg⁻¹) respectively.



Figure 9. Vertical profiles of (**a**) equivalent potential temperature (°C), (**b**) relative humidity (%), and (**c**) water vapor mixing ratio (gmkg⁻¹) derived at Visakhapatnam meteorological station valid at 00 UTC, 12 October 2013.

The east–west vertical cross-section of temperature anomaly (°C), horizontal wind speed (ms⁻¹), and direction of Phailin at the ESCS stage valid at 00 UTC, 12 October 2013 are represented in Figure 10. The positive temperature anomaly indicates the shift of warming in the middle to upper tropospheric levels (600–150 hPa) during the ESCS stage of Phailin. The MY scheme simulated that maximum warming of 5 °C persisted above 500 to 200 hPa level (Figure 10a). However, an extra amount of warming was simulated in WSM6 (Figure 10c), WSM5 (Figure 9e), and WSM3 (Figure 10g) schemes over 400–300 hPa compared to the MY scheme.



Figure 10. Vertical level and longitudinal cross-sections of (**a**) temperature anomaly ($^{\circ}$ C) and (**b**) wind field (shaded; ms⁻¹) derived from MY experiment; similarly (**c**,**d**), (**e**,**f**) and (**g**,**h**) were derived from WSM6, WSM5, and WSM3 experiments valid at 00 UTC, 12 October 2013 [as per Saffir–Simpson hurricane wind scale, the wind speed (contour) shown fits category 3, as simulated by WRF experiments].

This is consistent with earlier studies of Orissa super cyclone 1999 [59] and Andhra severe cyclone (2003), as discussed in Srinivas et al. (2007). One significant change was the temperature anomaly from the MP experiments, where the WSM3 single-moment schemed showed slower progress towards the Odisha coast than the double-moment schemes. The distribution of wind fields indicates that the presence of cyclonic winds remained in western ($30-40 \text{ ms}^{-1}$) and eastern (maximum 45 ms^{-1}) sides, as noticed in the WSM3 experiment. In the vertical space, the calm wind also extended from the surface up to the upper tropospheric level, as captured by the WSM3 scheme. Moreover, WSM6 and WSM5 simulated maximum winds of 40 ms^{-1} up to 300 hPa level. In contrast, MY captured the maximum wind speed of 40 ms^{-1} limited up to 500 hPa level (Figure 10 b,d,f,h), which means that double moment MP cannot simulate the wind speed in the middle atmosphere during the ESCS stage of Phailin.

4.4. Rainfall Variability Due to Cyclone

A low-pressure system like a cyclone provides widespread and heavy rainfall over an extended region. One-day accumulated precipitation distribution associated with Phailin at the ESCS stage is illustrated in Figure 11. The heavy rain that occurred during the ESCS stage of Phailin according to TRMM and the rain predicted from the WRF model at 00 UTC, 12 October 2013 were almost similar in spatial pattern. Maximum precipitation bands occurred over the BoB, in the southwest zone of the center of Phailin during 00 UTC 12 October 2013.

Under the influence of ESCS, heavy to intense rainfall occurred over coastal Odisha, Andhra Pradesh, and adjoining areas. Critical analysis of rainfall from WRF simulation experiments and comparison against TRMM inferred that MP schemes such as MY, WSM6, WSM5, and WSM3 could capture the spatial pattern of rainfall correctly, but the WSM3 scheme simulation closely agreed with TRMM rainfall in terms of location and magnitude (Figure 11e). Besides, the rainfall from the IMD rain gauge stations of Odisha and Andhra Pradesh as valid at 03 UTC, on 12 October 2013 was comparable with the WRF experiments.

The magnitudes of rainfall derived from WRF model and IMD observations are included in Table 5. During landfall, it caused maximum damage to coasts and inland areas because the strong wind gust from the offshore region entered into the core of Phailin. The area average rainfall (mm·d⁻¹) over the domain of 82–92° E and 13–23° N during the simulation period (8-13 October 2013) is represented in Supplementary Figure S1. The 24, 48, 72, 96, and 120 h rainfall agreed well with the WSM3 scheme. However, 72, 96, and 120 h rainfall was substantially higher in MY, WSM6, and WSM5 schemes as compared with TRMM observation. Such differences are attributed to the inclusion of the different types of mixing ratios in microphysical parameterization schemes. Moreover, the rainfall distribution during the ESCS phase depends on the characteristics of hydrometeors that persisted in the Phailin storm. The magnitude of moisture convergence is also affected by the choice of cloud microphysical parameterization [60]. The spatial distribution of hydrometeors is analyzed and shown in Figures 12 and 13. The difference in the skills of microphysics schemes to simulate cloud and rainwater in the upper tropospheric levels will affect the total rainfall patterns. Moreover, WSM5 and WSM6 have shown that precipitating cloud and rainwater is more prominent within lower to intermediate levels, which may be the poor skill of these schemes.



Figure 11. Comparison of 24 h accumulate precipitation (mm·d⁻¹) of Phailin at the ESCS stage derived from TRMM 3B42 satellite (**a**) and WRF model experiments using (**b**) MY, (**c**) WSM6, (**d**) WSM5, (**e**) WSM3 schemes, valid at 00 UTC, 12 October 2013 at D02 resolution; figures (**f**–**j**) are the same as (**a**–**e**), but valid at 00 UTC, 13 October 2013 respectively.

State	Station	Latitude	Longitude	IMD (cm)	МҮ	WSM6	WSM5	WSM3
Orissa	Tikarpara	20.60	84.79	17	10.32	7.41	9.24	8.70
	Rajghat	21.07	86.50	92	14.94	12.34	16.42	8.05
	Nischintakoili	20.48	86.18	11	16.62	13.59	15.27	13.72
	Mundali	20.44	85.75	25	16.72	15.29	18.12	9.16
	Banki	20.38	85.53	38	13.19	12.25	15.67	6.51
	Hindol	20.61	85.20	23	13.72	12.23	14.04	9.93
	Mohana	19.44	84.26	19	11.96	18.62	19.48	11.56
	Ramba	19.51	85.09	14	1.54	11.22	11.14	8.23
	Purusottampur	19.52	84.89	18	1.82	8.15	9.82	4.01
	Chandikhol	20.71	86.10	15	14.08	19.32	23.78	15.17
	Danagadi	20.97	86.08	19	17.05	23.45	21.78	9.68
	Daringibadi	19.90	84.13	17	9.49	35.84	32.74	1.66
	Pattamundai	20.59	86.57	15	14.50	14.02	13.74	8.91
	Joda	22.02	85.41	19	14.03	12.01	11.81	4.56
	Banpur	19.77	85.16	20	5.71	18.63	14.55	8.79
	Bangiriposi	21.91	85.90	21	5.72	6.53	6.49	2.14
	Balimundali	21.74	86.63	31	22.40	23.74	18.83	16.19
	Nayagarh	20.12	85.10	18	9.27	11.27	13.99	10.86
	Ranpur	19.90	85.40	30	13.12	20.23	19.70	6.65
	Puri	19.81	85.83	12	5.64	16.64	12.32	8.05
Coastal AP	Palasa	18.76	84.42	10	0.49	5.78	3.92	3.80
	Sompeta	18.95	84.58	11	1.34	10.79	5.63	1.42
	Itchapuram	18.88	84.45	20	1.26	11.01	4.76	1.87
Jharkhand	Tenughat	23.73	85.79	7	3.58	2.58	4.38	1.20
	Dhanbad	23.80	86.43	7	3.15	2.52	3.65	0.50
	Chaibasa	22.55	85.80	20	13.2	5.28	8.17	2.62

Table 5. Accumulated rainfall (cm) derived from IMD and WRF models (8.333 km) at D02 resolution at different stations over Odisha, coastal Andhra Pradesh, and Jharkhand, valid at 03 UTC, 12 October 2013.

The accurate simulation of different precipitation hydrometeors (shown in Table 3) leads to better rainfall prediction. Thus, WSM3 can capture the warm rainfall processes better than WSM5 and WSM6. The WSM3 scheme does not include mixed-phase microphysical processes, such as freezing, which occurs instantaneously where the temperature is colder than 0 °C, and melting, which occurs, similarly, one level below the freezing level. Moreover, the Phailin at the ESCS stage has a warm rain (>0 °C) process, thus representing the sub-grid-scale precipitations in a better way in WSM3 than MY, WSM6, and WSM5 schemes.



Figure 12. Time-pressure cross-section of the WRF simulations of Qcloud ($\times 10^{6} \text{ kg} \cdot \text{kg}^{-1}$) derived from (**a**) MY (**b**) WSM6, (**c**) WSM5, (**d**) WSM3 schemes, and (**i**) ERA5 reanalysis with the averaged area over 82–92° E and 14–20° N from 00 UTC, from 10 to 13 October 2013, measured in 3-hourly intervals at D02 resolutions. Similarly, Qrain ($\times 10^{6} \text{ kg} \cdot \text{kg}^{-1}$) mean mass contents are derived from (**e**) MY, (**f**) WSM6, (**g**) WSM5, and (**h**) WSM3 schemes, and (**j**) observation respectively.



Figure 13. Horizontal distributions of average (1000–100 hPa) level precipitation hydrometeors (Qcloud and Qrain) derived from WRF (**a**) MY, (**b**) WSM6, (**c**) WSM5, and (**d**) WSM3 D02 experiments and (**e**) ERA5 reanalysis during the ESCS stage of Phailin valid at 00 UTC, 12 October 2013. Distributions in (**f**–**j**) are the same as (**a**–**e**), but valid at 00 UTC, 13 October 2013.

4.5. Characteristics of Precipitation Hydrometeors

Cossu and Hocke documented how the various microphysical processes in MP schemes are responsible for the differences in the rainfall-related variables [60]. Those represent various components of the precipitation (i.e., water cycle) [61] in the WRF model. The available MP schemes, ranging from simple, efficient, and sophisticated, are more com-

putationally expensive. Moreover, both the newly developed schemes in the WRF model and well-used schemes, such as WSM3 and WSM6, are currently used in operational models [62]. Therefore, each scheme can simulate a certain number of variables, as discussed in Table 2. Consequently, the structures of spatial distributions of hydrometeors are significant in the case of ESCSs. Hence, this is further discussed in this section. Among the different water mixing ratios, Qcloud and Qrain are referred to as precipitation hydrometeors [39,63]. The precipitation hydrometeors, Qcloud and Qrain, are shown in Figure 12. The model grid points in the 8.333 km simulation region (D02) are recognized as the leading rainfall occurrence regions during ESCS phase of Phailin, as discussed in the previous section (Figure 10). The area averages of hydrometeors such as cloud water mixing ratio (Qcloud) and rainwater mixing ratio (Qrain) from00 UTC, from 9 to 13 October 2013 in a combination of four MP schemes are discussed. A time-height series of averaged hydrometeors, such as Qcloud and Qrain, are shown in Figure 12. The average was computed within area D02 where Phailin intensified (i.e., attained minimum MSLP). The amounts of the mean cloud water contents in the four experiments were significantly different from each other. The ESCS Phailin simulated with MY scheme produced maximum Qcloud water (>5 gm \cdot kg⁻¹) as compared to the other three experiments (WSM6, WSM5, and WSM3), and the peak values extended from 900 hPa to 300 hPa level during VSCS stages from 00 UTC, from 11-12 October 2013.

The experiments with WSM6 and WSM5 schemes generated similar Qcloud characteristics (900 hPa to 500 hPa), as shown in Figure 12c,e; however, WSM3 showed very different results than these schemes. The experiment with the WSM3 scheme showed two distinct features: (1) The maximum mixing ratios (5 $\text{gm}\cdot\text{kg}^{-1}$) were in between 300 hPa to 200 hPa levels and (2) another maximum was ($2 \text{ gm} \cdot \text{kg}^{-1}$) at 800 hPa to 600 hPa level (Figure 12g). The evolution of the Qrain rate is examined in Figure 11e–h. The area-averaged mixing ratios were computed within the inner core region of ESCS Phailin. The convection processes produced the main features of the rainwater contents. The different hydrometeor distributions, such as rainwater contents, induced the different structures during the intensity phase of Phailin (11–12 October 2013). MP schemes MY, WSM6, and WSM5 showed relatively similar rainwater content patterns with slightly different intensities (Figure 12e-g). The maximum Qrain of 5 gm kg^{-1} from the surface to 500 hPa level was simulated in MY, WSM6, and WSM5, whereas WSM3 captured the maximum peak shown in Figure 11h above 600 hPa to 150 hPa level. Overall, the vertical patterns of cloud and rainwater mixing ratios pointed out the other moisture representations in each MP scheme. The horizontal distributions of precipitation hydrometeors are measured by the combination of both Qcloud (non-precipitating hydrometers) and Qrain (Figure 13). The vertical level averages (1000–400 hPa) of the horizontal distribution of precipitation hydrometers derived from four MP schemes (MY, WSM6, WSM5, and WSM3), valid at 00 UTC on 12 October 2013, are shown in Figure 13a,c,e,g.

The horizontal distributions of precipitation hydrometeors showed a diminishing rate of precipitation hydrometeors with MY, WSM6, and WSM5 schemes. Again MY, WSM6, and WSM5 schemes generated a lesser amount of precipitation hydrometeors, both horizontally and vertically. However, hydrometeor precipitations were slow-moving towards the coast of Odisha, as captured in the WSM3 scheme, which was close to satellite images of Figure 1c,d.

5. Impact of Global Warning on Cyclones

Warming in the tropical Indian Ocean has increased faster, at 0.15 °C/decade during 1951–2015, compared to the global ocean at 0.11 °C/decade [64]. Researchers added that this warming has been non-uniform and ~90% of warming is attributed to anthropogenic activities. Changes in the SST and moisture availability (specifically humidity) for two decades have contributed positively to TC formation [65], as shown in Figure 14a,b. The warming over the western and central Indian Ocean is one of a few prominent features of local warming. The availability of moisture in the atmosphere in the recent decade is an



essential aspect of the rapid intensification and strengthening of tropical cyclones before landfall (Figure 14b).

Figure 14. Variations of cyclone related variables over the BoB: (a) difference in SST ($^{\circ}$ C) and (b) specific humidity (shaded; gm·kg⁻¹), along with wind field (ms⁻¹) at 850 hPa level during two recent decades 2011–2020 and 2001–2010, derived from NOAA reanalysis.

SST over the North Indian Ocean (NIO) has been intensifying in recent decades due to global warming [66,67]. Based on the rising of ocean temperatures, consistent theory by Elsner (2020) has suggested that tropical cyclones during 1981–2006 and 2007–2019 showed the strongest tropical activity, which is getting stronger with time [68]. Over the Bay of Bengal basin, numerous studies have been conducted with an upward intensity trend of ESCSs. Under the global warming scenarios, there may be several plausible reasons for the rapid intensification of storms just before landfall. However, SST and moisture supply are two driving factors over the Indian Ocean during the post-monsoon season. Table 6 shows the formation of the total number of low-pressure systems over the Bay of Bengal and the Arabian Sea during October–November in the last 20 years (2000–2020). There were significant variations in the number of cyclones formed in the first decade 1991–2000. The depressions have decreased while severe cyclones have increased. Furthermore, due to warming, the intensity of the land-falling cyclones from severe to very severe cyclonic storms (SCS/VSCS) have escalated 24 h before landfall.

Year	DD	* SCS	ESCS	Duration of $ESCS \ge 24 h$
2001–2010	20	14	2	2
2011–2020	19	11	6	6

Table 6. Decadal variability in the number of tropical storms over the Bay of Bengal during the months of October–November, 2001–2020.

* SCS = SC + SCS; DD = Deep Depression; SCS = Severe Cyclonic Storms.

The number of ESCSs has increased threefold during 2011–2020 as compared to 2001–2010 over the Bay of Bengal (Table 7). Such changes are attributed to the enhancement in the necessary and sufficient conditions for cyclone formations in the region, which includes the supply of abundant moisture and warmer SST in recent years (Figure 14). The comparison of SST, moisture, and winds in the last two decades shows the favorable conditions that facilitated the formation of VSCS.

Stage		VSCS/ESCS du	ıring 2001–2010					
	Phailin (MSLP/Wind)	Lahar (MSLP/Wind)	Hudhud (MSLP/Wind)	Titli (MSLP/Wind)	Gaja (MSLP/Wind)	Bulbul (MSLP/Wind)	Sidr (MSLP/Wind)	Giri (MSLP/Wind)
D	1004 (25)	1004 (25)	1004 (25)	1002 (25)	1002 (25)	1004 (45)	1004 (25)	1002 (25)
DD	1001 (30)	1002 (30)	1000 (30)	1000 (30)	1000 (30)	1001 (30)	1002 (30)	1002 (30)
SC	999 (35)	996 (45)	990 (45)	998 (35)	999 (35)	998 (35)	998 (40)	998 (50)
SCS	990 (55)	988 (55)	988 (60)	990 (55)	990 (55)	992 (50)	992 (55)	980 (60)
VSCS	984 (65)	982 (70)	970 (75)	972 (70)	988 (60)	983 (65)	986 (65)	976 (70)
ESCS	940 (115)	980 (75)	950 (100)	972 (80)	976 (70)	976 (75)	968 (90)	964 (90)
ESCS	940 (115)	988 (55)	950 (100)	972 (80)	-	982 (70)	944 (115)	950 (105)
SCS	990 (55)	998 (40)	987 (40)	996 (45)	999 (55)	998 (45)	1000 (45)	992 (45)
DD	996 (30)	1000 (30)	998 (30)	1001 (30)	1003 (30)	1002 (30)	1002 (25)	998 (25)

Table 7. Different stages of tropical cyclones' mean sea level pressure (hPa) and maximum sustainable wind (knot) from October–November, during the 2011 to 2020 and 2001 to 2010 decades over the Bay of Bengal.

Table 7 represents the details of VSCS cyclone formations in the last two decades. There has been a notable shift in the total number of severe to extremely severe cyclones over the Bay of Bengal during the last 20 years. Regional or remote influence may provide a further explanation for such a shift. There may be a decadal or large-scale shift in the basic components of atmospheric and ocean conditions that facilitate the tropical cyclone formation. An increase in cyclonic activity over the BoB, due to SST-induced moisture supply, has been found. Studies by [69,70] have suggested that aerosol concentrations in the middle atmosphere play an important role in latent heat release that probably reduces the basin-wide vertical wind shear and creates a favorable environment for intense tropical cyclones over the NIO. Other methods are explained in [71] to understand the role of anthropogenic influence on cyclones. The impact of local, regional, and global warming on cyclone intensification and formation will have an impact on property damage, affecting buildings and flood extents.

6. Conclusions

This study intended to address the role of the microphysical processes influencing the simulations from the initial phase to the ESCS stage of Phailin over the BoB. The fundamental difference between two MP schemes, double- and single-moment, is illustrated at 8.333 km of the resolution, a gray-zone simulation. To this end, we analyzed several parameters, such as MSLP, 10m wind, track, cloud, precipitation, and hydrometeors, to study the differences in the simulated track, intensity, and structural evolution of Phailin. The key findings are highlighted below.

- The gray-zone simulations of track, intensity, and precipitation processes during ESCS stage were sensitive to the parameterization of different microphysical processes.
- One of the most sensitive results found that the eyewall clouds and characteristics during the deep depression (DD) to severe cyclonic storm (SCS) stage were better represented by the MY scheme than other MP schemes. However, WSM3 showed relatively better results regarding landfall over the Odisha coast and lower track errors than other MP schemes (Figure 4).
- Above 700 hPa, the water vapor in the cloud condenses into water, droplets releasing the latent heat, which originally evaporates the water. Latent heat provides the energy to drive the tropical cyclone circulation. However, lower heat release was utilized by Phailin to lower its surface pressure and increase the wind speeds (Figure 6).
- The eyewall development and its dynamical mechanism were analyzed with doubleand single-moment MP schemes, which are sensitive and indicate the linkage between water vapor on one side and precipitation on the other. All the MP schemes simulated rainfall in terms of location and magnitude and closely agreed with TRMM rainfall (Figure 10e).

- Based on the above results, we can conclude that a double-moment cloud microphysical scheme (MY) is preferred for cyclonic systems. However, the MY scheme is unable to simulate the wind speed in the middle atmosphere.
- The clouds associated with Phailin that contribute to the vertical and horizontal redistribution of water vapor contents are well-simulated in all the schemes (WSM3, MY, WSM6, and WSM5).
- It is also important to assess the sensitivity of the simulated results of the doublemoment MP schemes in WRF to provide helpful information towards improving cloud microphysics parameterization in the future. All the schemes show different results. Thus, a unified scheme is suggested for a consensus among various schemes by applying equal/unequal weight.
- There is a shift in cyclone formation over the Indian Ocean due to regional warming and availability of moisture supply in the Bay of Bengal, which has been especially evident over the western region in the recent decade (2011–2020) compared to the previous decade (2001–2010).
- The uncertainty that arises due to model physics could be identified with individual simulations, but multi-physics ensemble techniques using a number of physical parameterization schemes (PBL, cumulus convection, and cloud microphysics) are better at simulating track and intensity of TCs over NIO.

We are not certain if such a shift in the formation of cyclones over the Indian Ocean basin is temporary or permanent. In forthcoming articles, we will use the simulation of 500 m resolution datasets of multiple ESCSs to further focus on microphysical schemes to simulate more TCs (processes in the formation of convective cells) over the BoB and the Arabian Sea. Variability in the cyclone formation and rapid intensity of TCs just before landfall during the post-monsoon season (October–December) can be studied.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10 .3390/oceans2030037/s1, Figure S1: The time-series of simulated rainfall (mmd⁻¹) averaged over the domain (82–92° E and 13–23° N) derived from observation and MY, WSM6, WSM5 and WSM3 experiments during 24-, 48-, 72-, 96- and 120 h).

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