UNIVERSITY OF NAIROBI

SIMULATION OF TROPICAL CYCLONE ACTIVITIES OVER THE SOUTHWESTERN INDIAN OCEAN

BY

WILFRED PAULO KESSY

I56/40434/2021

A dissertation submitted for examination in partial fulfilment of the requirements for the award of the degree of master of science in meteorology of the University of Nairobi

2023

DECLARATION

I declare that this Dissertation is my original work and has not been submitted elsewhere for examination, award of a degree, or publication. Where other people's work or my work has been used this has properly been acknowledged and referenced following the University of Nairobi's requirements.

Signature ………………………….. Date 06th August 2023 ……………………...

Kessy, Wilfred Paulo

I56/40434/2021

Department of Earth and Climate Science

Faculty of Science and Technology

University of Nairobi

This thesis is submitted for examination with our approval as research supervisors

	Signature	Date
Prof. Franklin J. Opijah	…………….	14/8/2023 …………
Prof. Joseph N. Mutemi		……… 14/8/2023

Prof. Franklin J. Opijah
Department of Earth and Climate Science
University of Nairobi
P.O Box 30197-00100
Nairobi Kenya

Prof. Joseph N. Mutemi
Department of Earth and Climate Science
University of Nairobi
P.O Box 30197-00100
Nairobi Kenya

DEDICATION

My parents and relatives have been there for me throughout my education journey. To my classmate who has pushed me through tough times and provided moral support to ensure that I complete my dissertation on time.

ACKNOWLEDGEMENT

Thanks to almighty God for his countless blessings throughout this work and my journey toward the completion of my Master's Degree. Secondly, my utmost thanks go to the KFW Bank of Germany, the Inter-University Council for East Africa (IUCEA), and Adroit Consult for the financial support that helped me complete my studies at the University of Nairobi. Special thanks to my Supervisor Dr. F.J Opijah and Dr. J.N Mutemi from the Department of Meteorology at the University of Nairobi for their supervision, mentorship, and un-waivered support throughout my project work.

Finally, this work and my entire Master's Degree journey would not have been smooth if it was not for Ms. Doreen, the scholarship officer from IUCEA, her support and timely communication between me and the scholarship committee. To my colleague, I am grateful for the ideas, support, and recommendations.

ABSTRACT

The current study assessed the ability of the WRF-ARW model to forecast tropical cyclones over the Southwest Indian Ocean. The characteristics of tropical cyclones Jobo (2021), Kenneth (2019), and Idai (2019) were simulated using WRF-ARW numerical model, and 6 hourly near real-time Global Forecast System (GFS) data were used as initial and boundary conditions. Kain-Fritsch and newly modified Tiedtke schemes were used to investigate the impacts of cumulus parameterizations on the forecasted tropical cyclone's characteristics. The microphysics sensitivity experiments used the complex and simple WRF-ARW single-moment microphysics schemes (WRF Single Moment class 6 and WRF Single Moment 3). WRF model forecasted well the movement of the tropical cyclones to the landfall location, the tracks were closer to the observations with a lead time of up to 4 days. The average Direct Positional Error (DPE) was found to be 58 ± 6, 86 ±17.2, 146±43.7 and 240 ±145 km at 24, 48, 72, and 96 hours lead forecasts time, respectively. The values of Along Track Error (ATE) and Cross Track Error (CTE) showed that the model had a southward and a slow bias near the land. WRF forecasted central pressure (maximum wind speed) was higher (lower) than the observations. 24 hourly accumulated precipitations from the model were compared against observations on the landfall day. The result showed that the cumulus convection and microphysics of the model affect the simulated tracks, intensity, and precipitation of tropical cyclones. Kain Fritsch schemes provided the central pressure and wind evolution tendencies closer to the observations than the Modified Tiedtke scheme. The combination of the WSM6 and KF schemes gave the best estimates of the intensities of the cyclones closer to the observations compared to the MT scheme. The Tiedtke scheme produced good forecasts of the tracks of Tropical Cyclone Idai. The cyclones modelled using KF schemes were slower than in the observation causing the forecast to lag the observed location. The study showed that the WRF model had a large slowdown bias closer to the land, and the intensity during intensification and decay peaks were poorly simulated this requires further investigations. Overall, the study concludes that the WRF-ARW model simulated well the trajectory of tropical cyclones over the Southwest Indian Ocean for up to 4 days. The characteristics of tropical cyclones forecasted with the WRF-ARW model were dependent on the microphysics and cumulus convection parameterizations. Studies on other characteristics of tropical cyclones should be carried out to find the best parameterizations to be used in operational forecasting.

ABBREVIATIONS AND ACRONYMS

ATE	Along Track Errors
CTE	Cross-Track Errors
DPE	Direct Positional Errors
EA	East Africa
GFS	Global Forecasts System
GPM	Global Precipitation Mission
IBTrACS	International Best Track Archive for Climate Stewardship
IMERG	Integrated Multi-satellitE Retrievals for GPM
ITCZ	Intertropical Convergence Zone
JTWC	Joint Typhoon Warning Centre
KF	Kain Fritsch cumulus convection scheme parameterizations
MSLP	Minimum Sea level pressure
MT	Modified Tiedtke Cumulus parameterization scheme
RSMC	A Regional Specialized Meteorological Centre
SW	Southwest Indian Ocean
TC	Tropical cyclones
WMO	World Meteorological Organizations
WRF	Weather Research and Forecasting
WRF-ARW	Advanced Research Weather Research and Forecasting model
WSM3	WRF Single Moment 3- Class
WSM6	WRF Single Moment 6- class

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Tropical cyclones are among the most disastrous weather phenomena that threaten property and life, especially those around coastal areas (Devi et al., 2019; Mawren et al., 2020a; Vidya et al., 2021). The associated gusty winds and heavy rainfall that may lead to widespread flooding and storm surge manifest the hazardous effects of cyclones in a particular area. On average, tropical cyclones contribute to property loss, approximately US$ 28 billion annually, and 15,500 deaths globally (GAR, 2015). The effects of tropical cyclones can also be evidenced over the coasts of East Africa directly and indirectly on precipitation by induced dry or wet spells (Finney et al. 2020). For example, the location of tropical cyclones over the Southwestern Indian Ocean (SWIO) has been shown to coincide with the dry spells over Ethiopia (Shanko and Camberlin, 1998). The tropical cyclone Idai formed over SWIO and intensified as it moved over the Mozambique channel to land over Beira City in Mozambique, resulting in a dry spell over Northern Tanzania and Turkana (Kebacho, 2022).

Globally around 80 to 90 tropical cyclones form annually on average, with about 49 cyclones reaching hurricane intensity (Mavume et al., 2010; Ramsay and Ramsay, 2017). On average, 14 tropical cyclones develop in each season over the Southwestern Indian Ocean, of which at least 4 of these reach hurricane intensity (Gray, 1975; WMO, 2017). The tropical cyclone season over the Southwestern Indian Ocean extends from November to April, with most activities occurring in January and February (Leroux et al., 2018; Mavume et al., 2009; Msemo et al., 2021). The landfall of tropical cyclones over the coast of East Africa and Mozambique occurs between January and March and, in rare cases, during the late period of April (Mawren et al., 2020b)

The probability of annual landfall of tropical cyclones over Tanzania is 3% for those with storm intensity and 0% for cyclones with hurricane intensity (Blumel, 1984). Tanzania experienced three tropical cyclone cases before 2019 in three different areas: the Lindi cyclone of 1952, the Zanzibar cyclone of 1872, and cyclone Alberta of 1989 (Msemo et., al 2021). Projected increased precipitation intensity near the centre of the landfall of tropical cyclones over East Africa needs the investigations of evolutions of these events (Stocker et al., 2013). The preferred landfall position of a Tropical cyclone over the Southwestern Indian Ocean is projected to shift northward toward northern Mozambique and southern Tanzania (Malherbe et al., 2013). The Intensification of Mascarene's High pressure is suggested as the possible mechanism for the northward shifts in the landfall location. An accurate forecast of tropical cyclone tracks, intensity variations along the cyclone's path, and associated precipitation for the community along the cyclone's path is essential to reduce the loss of lives and properties.

The most common challenge across all the basins in operational forecasting is an accurate prediction of the tracks, intensity (maximum sustained wind and central pressure), and associated hazards (winds, storm surge, and extreme rainfall) of the tropical cyclones (Bousquet et al. 2021; Hoarau et al. 2018; Pianezze et al. 2018; WMO, 2017). Another challenge is the model setup's inapplicability in different basins. Model performance in capturing the characteristics of the cyclones in one basin does not necessitate the same result over other basins because of the difference in the climatological and geographical characteristics between basins (Roy and Kovordányi, 2011). This makes it necessary to customize the model to include the basic features of the specific basin of concern to produce reliable forecasts.

Several factors affect the accuracy of model forecasts over a Basin, including accurate initial and Boundary conditions, Horizontal and vertical resolutions, and physical processes parameterizations in the model. Microphysics and Cumulus parameterization represents the effects of cloud processes in the model. The performance of models can be significantly improved by incorporating improved surface parameters, coupled modelling systems, and improved data assimilation (Mohanty et al., 2019, Trivedi et al., 2002). Cumulus parameterization accounts for the contribution of the unresolved sub-grid scale convection processes on large-scale environmental conditions. (Deshpande et al., 2012). The cloud microphysical processes at a grid-resolved scale in the model are treated by the microphysics parameterizations predictions (Pattanayak et al., 2012). Questions like how well WRF parametrizations of physical processes affect the tropical cyclone's attributes like the TC tracks, intensity, and even the validity of the TC forecasts over SWIO and the areas of direct impact like landfall are poorly understood and answered in the Basin.

1.2 Statement of the Problem

Ocean-air interactions control the weather over the neighbouring land areas as the ocean redistributes its stored energy. TCs are caused by air interactions linked to heat and moisture fluxes, thereby influencing the Moisture flows and precipitation of the coastal areas. The influence of tropical cyclone Kenneth and Idai on East Africa (EA) precipitation was investigated in (Kai et al., 2021; Kebacho, 2022) studies. Southwest Indian Ocean tropical cyclones have been linked with the amount of snow cover over Mountain Kilimanjaro (in Tanzania) via direct moisture transport and indirectly triggered westerly that transport moisture from the inland (Collier et al., 2019). TCs also have been associated with the destruction of properties and life over the SW Basin; improving TCs tracks and intensity forecasts is essential for reducing the vulnerability. Little attention has been focused on Tropical cyclones activities over the SWIO and their impacts on communities in Eastern Africa. Progress has been made in forecasting the tracks of tropical cyclones over the years, including significantly reducing the forecast error in different basins. Despite the progress made in forecasting tropical cyclone tracks, the accurate forecast of cyclone's intensity changes, landfall location, and time is a challenge in operational forecasts.

Several factors (initial and boundary conditions, model physics (physical process parameterizations), and resolution) have been shown to affect the accuracy of tropical cyclones forecasting (Singh and Mandal, 2015).

Sub-grid physical processes such as cloud convections, boundary layer exchanges, shallow convection, and radiation are hard to represent in models. Models use different parameterization schemes to represent the sub-grid processes which in turn introduces forecast errors. The magnitude of errors introduced depends on the weather system of interest and the schemes' complexity. The capability of tropical cyclone forecasting using the WRF model has been well explored by considering different model physics parameterizations over the northern hemispheric Basins (Bopape et al., 2021; Chan and Chan, 2016; Park et al., 2020).

Through several experiments, National Centre for Atmospheric Research (NCAR) found the best sets of physics parameterization for accurate forecasts of tropical cyclones over these Basins with the WRF-ARW model and Model for Prediction Across Scales (MPAS). This bests setup is known as the Tropical physics suite comprising New Tiedtke Cumulus convection, WSM6 microphysics, RRTMG (Rapid Radiative Transfer Model for Global) short and long wave schemes, YSU boundary layer. Cloud microphysics and cumulus convection have been changed in several studies and observed to significantly affects tropical cyclone's tracks and intensity over the North Indian Ocean (Mohanty et al., 2019). The number and nature of hydrometeors in the microphysics schemes control the latent heat releases in the simulated clouds, thereby affecting the cyclone's structures and intensity.

The model physics influence on tropical cyclones tracks and intensity forecasts has not been explored over the Southwest Indian Ocean. The best combinations of WRF model physics for tropical cyclone forecasts over the Southwestern Indian Ocean have not been explored and documented as guides to the operational use of the model. The current study tends to address the gap in tropical cyclone studies (over SW Basins) by analyzing the Tracks and intensities of tropical cyclones Jobo, Idai, and Kenneth were forecasted with WRF-ARW model version 4.2. The sensitivity of tropical cyclones tracks and intensity forecast were assessed by comparing the forecasted data to observations.

1.3 Research questions

The current study is pursued centred on the subsequent key questions:

i. What is the skill of the WRF model to forecast the SWIO tropical cyclones and areas of direct impact over the region?
ii. What is the difference in the forecasted tropical cyclone tracks, intensity, and associated precipitation for modified Tiedtke and Kain Fritsch cumulus convection schemes?
iii. What is the difference in the forecasted tropical cyclone tracks, intensity, and associated precipitation for WRF single moment 3 class (WSM3) and WRF single moment 6 class (WSM6) microphysics?

1.4 Objectives of the Study

The study aims to determine the tracks, strength, and precipitation pattern of tropical cyclones over the Southwestern Indian Ocean Basin using the Weather Research and Forecasting-Advanced Research WRF numerical model.

To help me achieve the above overall objective, the specific objectives below were pursued: -

i. To simulate the past tropical cyclones (TCs) over the Southwest Indian Ocean using the WRF-ARW model to learn the model's usefulness in forecasting the TCs.
ii. To investigate the sensitivity of the forecasted tracks, intensity, and precipitation pattern of tropical cyclones on the choice of the parameterization scheme of cumulus convection.
iii. To investigate the sensitivity of the forecasted tracks, intensity, and precipitation pattern of tropical cyclones on the choice of the parameterization scheme of microphysics.

1.5 Justification of the Study

Tropical cyclones are very damaging weather phenomena. Understanding these phenomena is particularly important in early preparations against the impacts of these phenomena. The communities living along the coast of the Southwestern Indian Ocean are highly vulnerable to direct cyclone landfall and indirect tropical cyclones influence. Poorly constructed infrastructure and poor planning of the highly growing cities along the East African coasts cannot withstand the extreme precipitation, strong wind, or storm surges from the landfall of the cyclones.

The impact from systems of even a storm-scale strength can result in flooding that may cause massive loss of life and property. In the context of climate change, more frequent events are projected over Eastern Africa, so understanding the characteristics of these events is essential. Modelling provides a tool to get a full diagnostic description of dynamic, physical, and thermodynamic interactions of these events with our environment and their influence on our weather systems.

Little attention to these events has resulted in significant losses to the economies and lives over the coast of East Africa whenever they are hit directly by these events or their remnants. A vivid example is during the 2015/16 season when the remnants of tropical cyclone Fantala caused the death of 13 people, and 13,933 people were left homeless in different regions of Tanzania.

Tropical cyclone Idai had the massive destruction of properties and lives in northern Mozambique and southern Tanzania in 2019. Indirectly the tropical cyclones originating from the Southwestern Indian Ocean led to extreme dryness and delays in the onset of precipitation, thus lack of rainfall for crops leading to food scarcity and a decline in agricultural production.

Understanding the characteristics of tropical cyclones, their distributions, and their associated influence on the weather systems over East Africa is essential for the well-being of the community around this part of the world. Modelling cyclonic tropical storm systems and their associated changes in the environment and circulation systems is also essential in understanding how they modulate the weather systems over the East Africa region at different spatial and time scales. The modelling results can provide information on sustainable coastal urban area strategic planning and storm drainage network maintenance.

Numerical models allow us to study weather systems that are difficult to study in the real world. By using numerical models, we can objectively analyse the key characteristics of the weather systems and be able to explain the physics behind the evolutions of these events. To fully utilize the model in the study of weather systems, we need to assess whether the model can accurately reproduce the system's features of interest.

1.6 Significance of the Study

Weather forecasts are significant in early warning and disaster management processes. WRF-ARW model has been used extensively to study and forecast tropical cyclones in the basin outside the southwest Indian Ocean. The current study applied WRF-ARW in forecasting tropical cyclones over the Southwest Indian Ocean. It further investigated the sensitivity of the forecasted cyclone’s characteristics to the physical parameterizations. The study’s findings will suggest the best configuration of the microphysics and cumulus convection schemes and provide an operational guide in using the model to forecast the SWIO TCs and their direct impacts over the region, for example, over Tanzania and Mozambique.

CHAPTER 2

LITERATURE REVIEW

2.1 Tropical Cyclones Seasons and Genesis

The World Meteorological Organization (WMO) describes the tropical oceans where tropical cyclones form as tropical cyclones formation Basins. Around the world, there are seven tropical cyclones Basins (thereafter, Basins) including the North Western Pacific Ocean, South Western Pacific Ocean, North Atlantic Ocean, the South Eastern Pacific Ocean, the North Indian Ocean, the Southwestern Indian Ocean, and the Southeastern Indian Ocean(Means, 2021). The area where a tropical cyclone originates is termed the genesis area/region. Monitoring of the tropical cyclones over these Basins has been designated to special regional bodies known as the Regional Specialized Meteorological Centres (RSMC). Over the Southwestern Indian Ocean, the RSMC La Reunion is the designated body that monitors tropical cyclones over the Basin.

The World Meteorological Organization (WMO) uses different terms to classify tropical cyclones based on their stages of development given by the strength of the sustained wind. A cyclonic system with maximum surface winds not exceeding 34 knots is known as a tropical depression. If the systems strengthen and the speed of wind reaches 34 knots or higher it is called a tropical storm. A name is given to a cyclonic system after reaching a maximum wind speed of 34 Knots (Guard et al., 1992). In the Southwestern Indian Ocean (thereafter Southwest Indian Ocean) Basin, a closed circulation having low pressure at its center and with the speed of wind about 64 knots and not exceeding 90 knots is termed a tropical cyclone. Tropical Cyclone is termed an intense cyclone if the sustained wind is between 90 - 120 knots above this then a system is categorized as a very intense tropical cyclone (Guard et al., 1992).

Globally 80-90 tropical cyclones with a maximum wind speed of 34 knots are observed each year, of these 56% reach tropical cyclone/hurricane/typhoon strength (wind speed >64 knots). About 15 tropical systems (depressions and storms) are observed, 5 of these reaching tropical cyclones strength during the Southwest Indian Ocean tropical cyclone season(Frank, 2016). Southwestern Indian Ocean season begins in November and ends in April, activities are more pronounced during the austral summer (January and February) (Burns et al., 2016; Mawren and Reason, 2017). Based on the final and initial coordinates of the cyclones, the Southwestern

Indian Ocean Basin has three global cyclone hatch areas: the eastern zone (75^0E - 90^0E), Central (50^0 E- 75^0E), and the western region (30^0E - 50^0 E) including the Mozambique channel (Ash and Matyas, 2012). The eastern area forms a home for most of the observed cyclones followed by the eastern Basin (Ash and Matyas 2012; Kuleshov et al. 2009).

2.2 Observed and Projected Trend of Tropical Cyclones Activities over Southwest Indian Ocean

Projections studies of global tropical cyclones activities established a projected decrease in the frequency of tropical cyclones over most of the Basin and an increase in the proportion of intense tropical cyclones and associated precipitation (Huang et al., 2022; T. Knutson et al., 2020; T. R. Knutson et al., 2010; Sugi et al., 2017) Studies have investigated the tropical cyclones trend in over Southwestern Indian Ocean (Malherbe, 2013a; Mavume et al., 2010; Seneviratne et al., 2021b; Vidya et al., 2021). Malherbe (2013) used a conformal-cubic atmospheric model to study the future and past cyclones activities over the Southwestern Indian Ocean under the A2 scenario from 1961 to 2100. Results of this study reveal a decreased cyclone landfall over Southern Africa (Southern Mozambique channel and South Africa) and a northward shift of the landfall of the cyclone over the Southwestern Indian Ocean (Southern Tanzania and Northern Mozambique). These changes are projected to occur in parallel with an increased January – March rainfall over Southern Tanzania and Northern Mozambique. Vidya et al., (2020) investigated the intensity of impacts of the warming over the Southwest Indian Ocean on tropical cyclones Potential Destruction Intensity during 1980-2016. The study reveals that during the 1999-2016 period, the destruction potential increased significantly compared to the 1980-1998 period. The increased destruction has been attributed to the increased cyclones intensities and duration (slowing down of the cyclone's speed) during the 21st century. Investigation of the climatology of tropical cyclones observations from 1980-2007 over the Southwestern Indian Ocean, the number of intense tropical cyclones was higher (56 cyclones) in the 1994-2007 period compared to the number of cyclones (36) in the 1980-1993 period (Mavume et al., 2010). Seneviratne et al., (2021) projected an increase in the wind speed, associated maximum precipitation, and an increase in the number of intense and very intense tropical cyclones over South Eastern Africa and other parts of the world.

2.3 Tropical Cyclones and Steering Mechanisms

The easterly trade winds and beta effects produced by circulations in the outer rainbands over the Southwestern Indian Ocean steer the tropical cyclones south-westward before they recurve south/south-eastward into open seas and mid-latitudes as they approach the East African coasts (Ash and Matyas 2012; Leroux et al. 2018; Mawren and Reason 2017). The beta effect refers to the north-westward (south-westward) drifts of tropical cyclones due to the effect of the changes in the relative planetary vorticity in the northern (southern) hemisphere (Chan, 2005; Holland, 1983; Leroux et al., 2013; Magnusson et al., 2019). The beta effect is the product of the interaction between changes in planetary vorticity and tropical cyclone circulations (Wang et al., 1998). The air tends to move equatorward on the eastern side of the cyclone and poleward on the western, this results in the decrease (increase) planetary vorticity to the west (east) of the cyclones (J. C. L. Chan, 2005; Wang et al., 1998). In the Southern Hemisphere, a secondary pair of rotating vortices (named beta gyres) develops moving in opposite directions, anticyclonic to the southeast and cyclonic to the southwest(Holland, 1983; Wang et al., 1998). The beta gyres create longitudinal variations in the planetary vorticity and hence cause the tropical cyclone to move Southwestward in the southern hemisphere(Wang et al., 1998).

Variability in various modes of natural seasonal, intra-seasonal, and inter-annual large-scale modulate the tracks of tropical cyclones in different basins. In the Northwest Pacific Ocean, the zonal (parabolic/recurving) track is more pronounced during weak (strong) monsoons, strong (weak) easterlies, positive (negative) intra-seasonal Indo western Pacific convection oscillation (Wang et al., 2018; Chen et al., 2009; Zhang et al., 2013). A rare departure from normal tracks is observed for the cyclones developing east of 75°E, they move longer distances westwards (Ash and Matyas, 2012). Some of these westward-moving cyclones recurve northwest near the northern coast of Madagascar making landfall over the coast of Tanzania or threatening the islands on the path.

2.4 Impacts of Tropical Cyclones over Southwest Indian Ocean

Extreme weather events accounted for 50% of the disaster between 1970-2019, resulting in 45% of deaths and 74% of economic losses globally. Tropical cyclones are among the deadliest and costliest extreme weather event in people's lives (54% death of all reported death 1970-2019) and properties (39% of the economic losses 1970-2019), but crucial element of the earth's climate system (Dominguez and Magaña, 2018; Sriver, 2013). Over Africa, Tropical cyclones account for 8% of all disasters resulting in economic losses of 25% (with the increase in the 2010-2019 decade). Tropical cyclones have proven to be very harmful to the society and economy of the coastal areas, contributing to half of the loss brought about by natural disasters worldwide (Kunze, 2021). The direct effects of tropical cyclones are due to high-speed damaging wind, storm surges, and heavy rainfall. Cyclone Tropical cyclones have been attributed to the death of many people, and it is also forecasted that the death threat will increase in the warming world (Kai et al., 2021; Kunze, 2021).

Tropical cyclones are essential in energy and moisture redistribution within the earth's climate system. This makes tropical cyclones an essential modulator of climate variability on various timescales. Tropical cyclones transport moisture directly from one place to another. Tropical cyclones have also been known to indirectly affect the weather activities over an area depending on the trajectory and their positions from the coast (Dominguez and Magaña, 2018). Over northern America, the trajectory of tropical cyclones has been linked to a wet and dry spell during the rainfall season. Tropical cyclones over the Southwest Indian Ocean have been linked to drought and heavy rainfall during short rain seasons over Ethiopia on a seasonal and daily basis. A season with above-normal (low) cyclonic activity in the Southwest basin corresponds to weaker convective and dry conditions (heavy precipitation) over Ethiopia(Shanko and Camberlin, 1998)). In the study of analysis of the impacts of tropical cyclone Fantala on Tanzania, Kai et al. (2021) found that Tanzania has been affected by tropical cyclones. The 2019 dry spell and famine over Turkana and North Tanzania were linked to cyclone Idai in the Mozambique channel (Kai et al., 2021; Kebacho, 2022).

2.5 Tropical Cyclone Modelling using WRF Model

It is a challenge to apply a single model with the same customization in all cyclone formation basins due to the differences in their climatological and geographical characteristics (Roy and Kovordányi, 2012). WRF model is one of the numerical weather prediction models used by the most important operational centres worldwide to generate weather forecasts. Indian Meteorological Department uses WRF with three domain configurations (27km-9km-3km) in operational forecasts of the Northern Indian Ocean. Indian Meteorological Department uses

WRF with three domain configurations (27km-9km-3km) in operational forecasts of tropical cyclones.

WRF model is used in the operational forecasting of tropical cyclones by the Indian Meteorological Department; numerous studies have investigated the efficacy of the model forecast/simulation of tropical cyclones in North Indian and Western North Pacific basins (Akhter and Alam, 2013; Chandrasekar and Balaji, 2016; Lui et al., 2021; Mallik et al., 2015; Moon et al., 2021; Park et al., 2020; Singh et al., 2016). Using 3DVAR in the WRF model improved the forecast of tropical cyclones tracks during the 2013 season over the Bay of Bengal with mean track errors of 70, 114, 182, and 184 km at forecast lead times 24, 48, 72, and 96 hours, respectively (Chandrasekar and Balaji, 2016). In the study, mean absolute errors for Minimum Sea level pressure (Maximum surface wind) were found to be 8, 10, 13, and 13 hPa (6, 10, 9, 8 ms^{-1}) at 24, 48, 72, and 96 hours, respectively.

High-resolution WRF model has shown exemplary skills in simulating the tracks, intensity, and landfall (with reasonable time and space errors) of tropical cyclones over the Northern Indian Ocean but has deficient performance in simulating the intensity of cyclones (Sea level pressure and maximum surface winds) (M. A. E. Akhter et al., 2016; Lui et al., 2021; Mallik et al., 2015; Mohanty et al., 2019). Bousquet et al. (2020) evaluated the ability of the France model customized for operational forecasting over the Southwest Indian Ocean basin AROME-IO. The study found that the AROME-IO model has a reliable performance over the basin; average track forecasts errors at 24, 72, and 120 hr lead times are 70, 130, and 200 km, respectively. Moon et al. (2021) found that using the 12 km grid WRF model, tropical cyclone track simulation errors are sensitive to accurately representing the environmental wind field (steering mechanism vector). Over the western North Pacific, WRF skills in predicting tropical cyclone tracks were good for the first two days (48 hours), and it started to underperform after that (Lui et al., 2021).

2.6 Role of Cumulus and Microphysics Parameterizations in Tropical Cyclones Track and Intensity Forecasts

The prediction of the path of a tropical cyclone is influenced by multiple factors such as weather conditions, wind, pressure, sea surface temperature, air temperature, and the Coriolis force (Korvodanyi, 2011). The same model has been found to produce different forecasts of the tracks and intensity when different model physics are used in the forecast over different basins (Mandal et al., 2004; Reed and Jablonowski, 2011). Different studies investigated tropical cyclone's sensitivity to physical parameterization schemes over the North Indian Ocean and Western North Pacific (Chan and Chan, 2016; Chinta et al., 2018; Deshpande et al., 2012; Fovell et al., 2009; Lakshmi and Annapurnaiah, 2016; Li et al., 2019; Mahala et al., 2015; Mohan et al., 2019; Nekkali et al., 2022; Park et al., 2020; Shenoy et al., 2021; Baki et al., 2021; Srivastava and Blond, 2022). Chan and Chan, (2016) investigated the effect of microphysics on the tropical cyclone forecasts over the Western North Pacific basin during the 2013 season, results concluded that microphysics has significant effects on the intensity and not the cyclone's track forecasts.

Deshpande et al., (2012) attributed the difference in tracks forecasted using different cumulus schemes to the difference in the forecasted potential vorticity changes in the tropopause among the schemes. Changes in potential vorticity affect the wind field and hence result in different tracks among the schemes. The intensity and size of the cyclone control the effect of large-scale flow on the cyclone motion, stronger and larger cyclones tend to dominate the large-scale effect (Deshpande et al., 2012). Further, the Kain Fritsch (KF) scheme was found to forecasts intensity comparable to the observations hence the resulting cyclone's track was close to the observations. Baki et al., (2021) showed that the KF scheme showed better results than the Arakawa Schubert scheme and other cumulus parameterization schemes used in the study.

Previous cumulus sensitivity studies have employed the KF and TK schemes to investigate the simulated tropical cyclone tracks' sensitivity and intensity on the cumulus schemes over the North and Southwestern Pacific Basin (Delfino et al., 2022; Parker et al., 2017). The studies pointed out that the wide range of use of the modified Tiedtke (Tiedtke) and KF schemes is due to the characteristics of these two cumulus schemes, making them ideal CU choices for tropical cyclones. TK schemes have active shallow convection treatment that is based on the assumption that moisture flux at the surface and through the cloud are equal. While KF scheme is both a deep and shallow convection scheme such that shallow convection is activated when the deep convection criteria are fulfilled in a grid (Parker et al., 2017).

Delfino et al., (2022) found that the TC's tracks and intensity forecast are sensitive to the choice of CU parameterization, with TK schemes producing tracks closer to observation than the KF scheme. Large track bias in the track forecast by the KF scheme is a result of the northward bias in the mean steering flow and the higher temperature gradient forecast in the 700 mb levels. Further, they suggested that the KF scheme produced a better estimate of the cyclone's intensity compared to the TK schemes which is attributed to the active shallow convection in the TK scheme which suppresses deep convections. Further, the simulated vertical wind shear was found to be higher when using the TK scheme in comparison to the KF scheme, hence KF schemes produced more intense cyclones. The KF scheme estimated the precipitation closer to the observations compared to the TK schemes (Delfino et al., 2022; Parker et al., 2017).

Tropical cyclone motion depends on large-scale wind flows and the Beta effect. The beta effect is found to be dependent on the TC size and intensity (Deshpande et al., 2012; Fovell et al., 2009; Park et al., 2020). Park et al., (2020) found that accurate forecasts of the TC intensity are linked to the forecast of its size and structure. Both intensity and tracks of tropical cyclones were found to be dependent on the microphysics schemes, and the effect was the function of latitudinal location. Fovell et al., (2009) showed that the circulations in the outer wall of the cyclones contribute to the advection of planetary vorticity that controls the formulation of the beta gyres. The beta gyres control the movement of tropical cyclones in the environment with weak wind fields (Fovell et al., 2009). The speed of falling of the hydrometeors on the microphysics was linked to the temperature gradient thereby controlling the strength of the wind in the outer rainbands and the difference in the tracks (Fovell et al., 2009). WSM6 schemes released more latent heat, resulting in stronger TCs than the WSM3 schemes over Western North Pacific and consequently better tracks (Park et al., 2020a).

Improvement of physical parameterization of surface processes, convection, and cloud microphysics significantly improves model forecasts (Bousquet et al., 2020). The forecast's choice of physical process parameterization schemes depends on the Basin (Chutia et al., 2019). Results of the study by Mohan et al. (2019) suggested that the choices of Microphysics scheme are important in the forecast of tropical cyclone tracks and intensity over the North Indian Ocean; Goddard Microphysics scheme was shown to be the best scheme for operational forecasts. Modulation of coupling between thermodynamics and dynamics, moisture distribution, latent heating, and convection in tropical cyclones by different microphysics (MP) schemes affect cyclones intensity significantly (slightly affects cyclones tracks) over the North Indian Ocean (Mohan et al., 2019). The movement (size) of the tropical cyclone was shown to be less (more) sensitive to the MP scheme by Nekkali et al. (2022). The number of Hydrometeors in the MP scheme has less effect on tropical cyclones' tracks, intensity, and size over the Western North Pacific Basin (Chan and Chan, 2016).

2.7 Conceptual Framework

Figure 1 shows briefly the linkage between data (GFS data, IBTrACS, and IMERG) and the representations of the cloud and precipitations processes in the WRF model to summarize outputs from the study objectives. WRF model was used to forecast tropical cyclones over Southwest Indian Ocean Basin. Weather Research and Forecasting (WRF) model has been used to model tropical cyclones over the different basins and the results showed good skills by the model in reproducing the tracks and intensity of the cyclones. Accurate representation of the physical process using a parameterizations scheme has been linked to the accuracy in the forecast of cyclones track and intensity. The objective of this study is to determine the ability of the WRF model in forecasting tropical cyclone tracks and intensity over the Southwestern Indian Ocean. Kain Fritsch and Tiedtke cumulus parameterization schemes have shown good skills and have been used widely in forecasts of extreme weather events over the tropics (Park et al., 2020a). The study used the two cumulus schemes, the Kain Fritsch and Modified Tiedtke schemes to parameterize convections over the Southwestern Indian Ocean and simulated the tropical cyclones Jobo, Kenneth, and Idai. The resulting cyclone tracks and intensities were then compared against the observations objectively using the verifications measures that are used by forecasting centers to investigate how sensitive the model forecasts are sensitive to cumulus schemes. The WRF Single Moment 6-class (WSM6) scheme was used for parameterization during cumulus sensitivity experiments.

Further, the study carried out additional experiments using WRF Single Moment 3-class (WSM6) using all the two cumulus schemes. The results of WSM6 and WSM3 simulations were compared against the observations to determine how the forecasts are sensitive to the microphysics schemes and which of the two microphysics schemes produces the best forecasts.

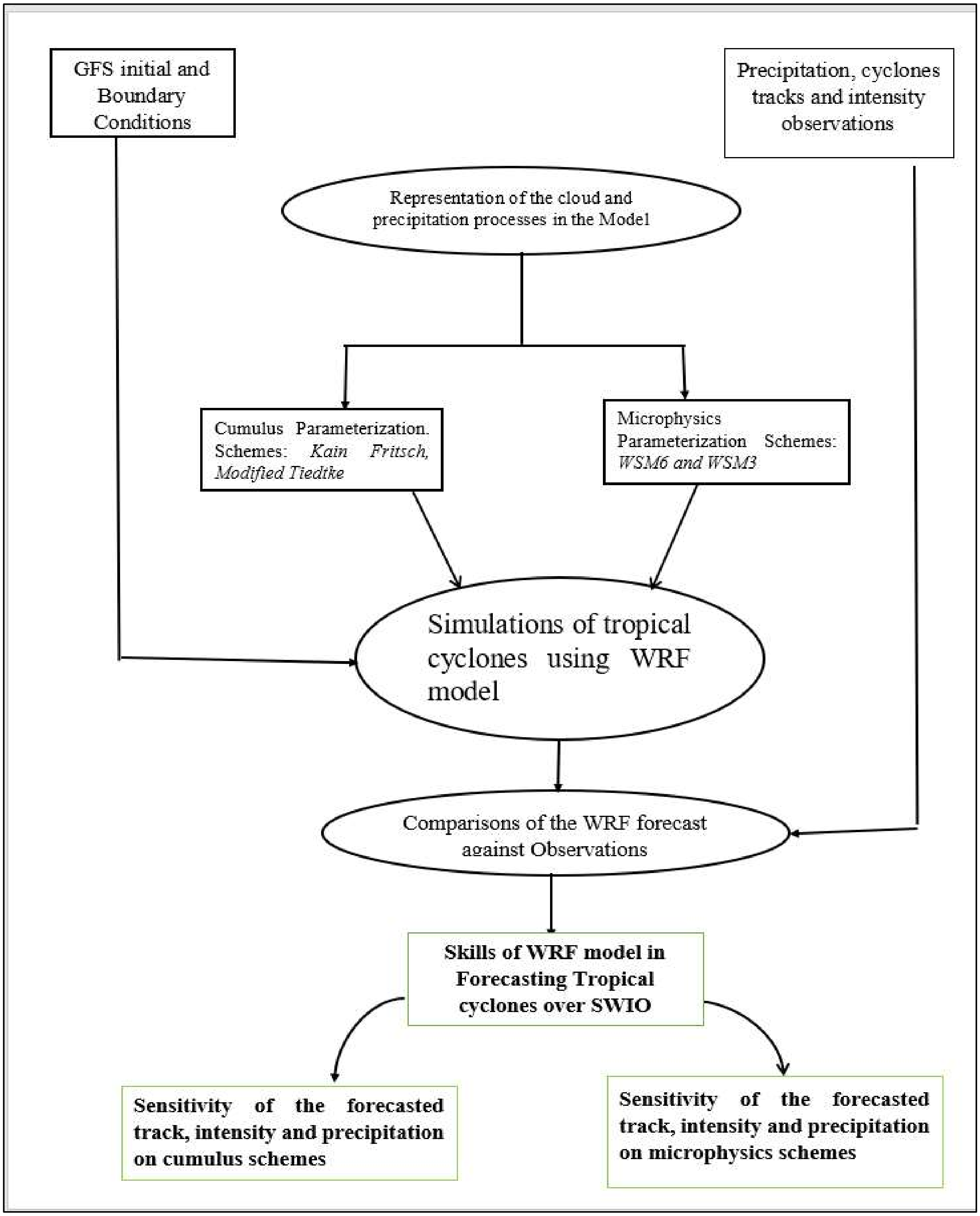

Figure 1: The conceptual framework of the study. The past global forecast system (GFS) data were integrated into the WRF-ARW model. Model Cumulus and Microphysics schemes were changed to investigate how the tropical cyclone tracks, intensity, and associated precipitation were sensitive to the respective parametrizations.

CHAPTER 3

METHODOLOGY

This chapter discusses the area of the study, the datasets used, and the method applied to study and simulate the characteristics (numbers, track, strength, and precipitation) of cyclones in the Southwestern Indian Ocean.

3.1 Area of Study

Figure 2 shows the Southwest Indian Ocean Basin, found between the equator and 40 °S bounded by the Eastern coasts of Africa (30 °E) and 90 °E (Barthe et al. 2021; Commission 2018). The Southwestern Indian Ocean has a shallow thermocline attributed to Ekman drifts that transport waters southwestward from the northern edge of the trades. Precipitation tends to migrate northward and southward following the apparent migration of the sun and warm Sea Surface Temperature (Schott et al., 2009). Regional Specialized Meteorological Centre (RSMC) La Réunion is a World Meteorological (WMO) centre responsible for observing and monitoring tropical cyclones over the Basin. Tropical cyclones season over the basin occurs during the Austral summer (September – April) and is more pronounced in January and February when the Intertropical Convergence Zone (ITCZ) is over the area (Malherbe, 2013b; Mavume et al., 2009).

Genesis area over the Southwest Indian Ocean is oriented in (or along) the East North East -West South West direction following the structure of ITCZ and Sea Surface Temperature (SST) trends. The unique feature of the basin is the region of upwelling (55°E - 65°E and 5°S-12°S) called the Seychelles-Chagos Thermocline Ridge, which marks an area of significant air-sea interactions and intercepts the region of maximum cyclone genesis (Hermes and Reason, 2008; Kang et al., 2021). The depth of the Seychelles-Chagos Thermocline ridges in austral summer is linked to several tropical cyclones over the basin, with more cyclonic activities during a deeper thermocline ridge (Hermes and Reason, 2008). Large-scale synoptic features over the Southwest Indian Ocean (El Niño Southern Oscillation, Subtropical Indian Ocean Dipole, Mascarene high, Madden Julien Oscillation, Southern Annular Mode, and convectively coupled Equatorial waves) control favorable tropical cyclones genesis area concentrated between 5 °S and 20 °S and the

Mozambique Chanel (Ash and Matyas, 2012; Bessafi and Wheeler, 2006; Malherbe et al., 2014; Pillay and Fitchett, 2021).

Tropical cyclones in the basin tend to follow a parabolic path and escape to the extratropics or a zonal track threatening the lives of the coastal areas of East Africa (Tanzania and Mozambique). La Nina years are associated with a more zonal westerly steering flow around 850 – 200 hPa over the basin (Ash and Matyas, 2012; Ho et al., 2006). Systems that range from the depression scale stage to tropical cyclones have made direct landfall over Tanzania and Mozambique. Major 21st-century remarkable systems that made landfall over Mozambique include Cyclone Kenneth and Idai (Sallema and Mtui, 2008).

Figure 2: Southwestern Indian Ocean Basin (Chang-Seng and Jury, 2010)

Tanzania is a coastal state lying between 29°E and 49°E and 1°S and 12°S, including the Zanzibar archipelago. Tanzania's coastline stretches to about 1,424 Km, characterized by a narrow, sharply falling shelf. The northern coastal region (Tanga and Dar es Salaam areas) experiences a biannual modal rainfall regime peaking between October-December and March–May, Southern coastal region falls under a uni-annual modal regime with a maximum in October-April. Tanzania's coastal regions are of low relief and also low altitude above mean sea level (Kabanda, 2018).

Mozambique has the longest lowland coastline in Africa elongated over 2,470 km with 60% of the total population (USAID, 2017). An uneven and unpredictable uni-modal rainfall regime is experienced with a single maximum in October – April. On average at least one tropical cyclone strikes the coast of Mozambique resulting in $70 Million in damage to properties (GFDRR, 2019; Matyas, 2016).

3.2 Data

This study used tropical cyclone records from the International Best Track Archive for Climate Stewardship (IBTrACS), National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) data, and rainfall data from Integrated Multi-satellitE Retrievals for Global Precipitation Measurement Mission (IMERG) to study tropical cyclones activities over the Southwestern Indian Ocean.

IBTrACS data are obtained after a reanalysis of the location and intensity of storms collected from all available data such as; ship, surface, and satellite observations (Kruk et al., 2010). Information about Global cyclone tracks is collected by the National Centers for Environment Prediction to simplify global understanding of cyclones' distribution, frequency, and intensity. Data are provided from all 12 different agencies (Knapp, 2019). IBTrACS data spans from 1965 to the present and has a spatial resolution of 0.1° (10 km) taken at 6 hourly intervals; the data are numerically interpolated into 3 hours intervals (Knapp, 2019). Real-time GFS data provided by the National Centres for Environmental Prediction will serve as the initial conditions in the simulation processes. Simulated cyclones from the WRF-ARW model were verified against the observed tropical cyclones data (IBTrACS).

Passive microwave sensors on low Earth orbiting platforms are the sources of the most accurate precipitation data sets. Multi-satellitE Retrievals for GPM (IMERG) is an algorithm that merges, inter-calibrate and interpolates all passive microwave precipitation with in situ precipitation observations and all other precipitation estimates to produce high-resolution precipitation estimates across the globe (Huffman et al., 2020). IMERG has been shown to have a good representation of precipitation over East Africa (Ageet et al., 2022). IMERG data have 0.1° x 0.1° spatial resolution n and temporal resolution 30 minutes (Huffman et al., 2020). The current study accumulated the IMERG data over 24 hours on the 24th of April 2021 for cyclone Jobo and the 25th of April 2019 for cyclone Kenneth. IMERG dataset was compared against the WRF model forecasted precipitation.

3.3 Descriptions of Case Studies

The study considers tropical cyclones that presented challenges operational in the forecasts during the 2018/19 and 2020/21 seasons. Tropical Cyclone Idai (2019), Kenneth (2019), and Cyclone Jobo (2021) were selected as case studies for this study. Cyclones Jobo and Kenneth have been chosen as a case study because their path and landfall location aligned with the projected landfall behavior of the cyclones over the Southwestern Indian Ocean. Cyclone Idai has been selected as a representative of the cyclones originating over the Mozambique Channel and resulting in delayed rainfall and dry condition in some parts of East Africa. A brief description of the observed characteristics of the cyclones used as a case study is presented in the following subsections.

3.3.1 Tropical Storm Jobo April 2021

Tropical cyclone Jobo was named and tracked as severe tropical storm Jobo at 15UTC, 20th April 2021, when its center was located at 195.4 km from the northern edge of Madagascar (Meteo France, 2021). The storm wind speed was approximated to about 40 knots with gusts of up to 55 knots and was associated with heavy rainfall and intense winds. The best track observations showed Jobo as a zone of disturbed weather from 18th April 2021 at 06 UTC and categorized into a tropical disturbance on the 19th at 00 UTC. Later 20th, at 12 UTC the tropical disturbance intensified and reached a moderate tropical storm category with a maximum wind speed of 35 kt.

Mid-troposphere ridge located over the centre of the Mozambique channel and low-level flow over the northern part of the channel steered tropical storm Jobo west-northwesterly toward Tanzania Coasts. The intensity reached by tropical storm Jobo was category 1 strength with the lowest pressure of 985 hPa and maximum winds sustained at 65 knots at 12 UTC on 21st April 2021. The smaller size of cyclone Jobo presented high uncertainty in the prediction of the storm intensity and hence the impacts on the nearby islands and landfalling region. Uncertainty in the track forecast was also high due to the weaker steering flow as the system was moving. The system made landfall over Tanzania between April, 29th and 30th with heavy rainfall and intense winds affecting the eight regions of Tanzania and it was reported to have resulted in 22 deaths (Tanzania Red Cross Society, 2021).

3.3.2 Tropical Cyclone Idai March 2019

Tropical cyclone Idai was first tracked on the 04th March 2019 when it had tropical depression strength with maximum sustained winds of 30 knots near the Mozambique coast. The system made landfall over Mozambique on the same date resulting in heavy precipitations over the country. The system recurved back over the ocean on the 09th March 2019 moving to the east toward Madagascar. The system intensified into a moderate tropical storm and was named Idai at 23Z the same day. The recorded maximum wind speed and minimum sea level pressure were 37 kts and 996 hPa, respectively. The intensities peaks observed were 953 hPa (95 kts) and 940 hPa (105 kts) at 12UTC, 11th March and 00UTC,14th March 2019, respectively. The system made landfall at Beira in Mozambique on the 15th of March having intense cyclone strength corresponding to a minimum sea level pressure of 960 hPa and maximum sustained 90 knots.

3.3.3 Tropical Cyclone Kenneth April 2019

The 2018/19 cyclone season is recorded as the most intense cyclone season over the Southwestern Indian Ocean. During this season A history-breaking cyclone named Kenneth was observed to make a landfall over Mozambique near the border with Tanzania. Tropical Cyclone Kenneth developed as a disturbance on the 21st of April 2019 at 18 UTC off the coast of northern Madagascar. Kenneth moved westward and strengthened into A tropical storm and was named at 12 UTC on 23rd April. The system continued moving west-southwestward making landfall at Cabo Delgado in Mozambique on the 12UTC of 25th April 2019.

3.4 Methods

The studies simulated tropical cyclones over the Southwest Indian Ocean using the WRF-ARW model with different cumulus convection and microphysics schemes. The forecasted cyclone's track and intensities were compared with the observations. The model physics and resolutions for the study are explained in the following sections. The method used to evaluate the forecasted tracks and intensities is described in the following sections.

3.4.1 Model and Numerical experiment designs

WRF-ARW model version 4.2 with an automatic vortex following algorithm was used. The automatic vortex nest (d02) tracks the cyclone's centre location and intensity (minimum sea level pressure and maximum wind speed). The tropical suite physical parameterization setup was used for the simulations. The original suite uses WSM6 microphysics, Modified Tiedtke convection scheme, Yonsei University (YSU) planetary boundary layer parameterization scheme, and Rapid Radiative Transfer Model for Global Climate Models (RRTMG) for long and shortwave parameterizations. Description of the model setup and physics used in this study are described in **Table 1**, and the domain configurations are found in **Figure 3**. Tropical cyclone Jobo (2021), Idai (2019), and Kenneth (2019) were selected in experiments to investigate the effect of Cumulus and Microphysics schemes on their tracks and intensity. The model was initialized twice daily at 00 and 12 UTC for all cyclone cases, similar to the initialization period at the RSMC La Reunion. The model initialization dates for all cyclones are presented in **Table 2**.

Mass flux-based parameterization, Modified Tiedtke (thereafter, Tiedtke) and Kain Fritsch (KF) cumulus parameterization schemes were used to investigate the effect of cumulus convection on cyclone tracks and intensity over the Southwest Indian Ocean. In this experiment, the WSM6 microphysics scheme as used in the original tropical suite is kept constant. Previous studies have employed the KF and Tiedtke schemes to investigate the simulated tropical cyclone tracks and intensity sensitivity to the cumulus schemes over the North and Southwestern Pacific Basin (Delfino et al., 2022; Park et al., 2023; Parker et al., 2017). These studies pointed out that the wide range use of the Tiedtke and KF schemes is due to the characteristics of these two cumulus schemes, making them ideal cumulus parameterization choices for simulation of extreme events over the tropical ocean such as tropical cyclones.

The difference between the two schemes lies in the mechanism that triggers convection. Larger scale vertical velocity triggers convections in the KF scheme, while the convection Tiedtke activates convection close to the surface when the parcel is 0.5 K warmer than the environment (Kain, 2004; Zhang et al., 2011). TK schemes have active shallow convection treatment that is based on the assumption that moisture flux at the surface and through the cloud are equal. While KF scheme is both a deep and shallow convection scheme where shallow convection is activated when the deep convection criteria are fulfilled in a grid and is based on the turbulent kinetic energy.

The sensitivity of forecasted cyclone tracks and intensity to the microphysics parameterizations were investigated using WRF Single Moment 3-class (WSM3) and WRF Single Moment 6-class (WSM6). Studies on the sensitivity of tropical cyclone forecasts on microphysics have concluded that a number of hydrometeors included in a scheme affects the forecasts of track and intensity(Park et al., 2020b). WSM6 differs from WSM3 in that, the WSM6 scheme considers 6 hydrometeors as the prognostic variables (rainwater, snow, cloud ice, cloud water, water vapor, and graupel) while the WSM3 scheme uses only three prognostic moisture variables (water vapor, rainwater/snow, and cloud water/ice). WSM3 is formulated such that above (below) 0 ℃, cloud water and rainwater (ice and snow) coexist (Hong et al., 2004; Park et al., 2020). Only the liquid phase variables are considered in the WSM3 scheme, and solid-type water variables like graupel are not considered in this scheme. The WSM6 scheme includes a supercooled water phase(Hong et al., 2004).

Table 1: Model setup and physical parameterization schemes used in simulations of tropical cyclones over the Southwestern Indian Ocean.

Model setup	
Horizontal resolution Vertical levels Atmospheric top	27 km (Larger Domain), 9 km (Smaller Domain/moving nest) 45 eta levels 50 hPa
Model physics	
Microphysics parameterizations	WRF Single Moment 6-class (WSM6) and WRF Single Moment 3-class (WSM3)
Cumulus convection	New Tiedtke convection scheme: (Zhang et al., 2011) and Kain Fritsch (Kain, 2004).
Longwave Radiation	Rapid Radiative Transfer Model for Global Climate Models (RRTMG) (Iacono et al. 2008)
Shortwave Radiation	Rapid Radiative Transfer Model for Global Climate Models (RRTMG) (Iacono et al. 2008)
Boundary layer	Yonsei University (YSU) PBL scheme (Hong et al. 2006)

Table 2: The model initialization time and lead forecast hours for the sensitivity experiments

Cyclones	**Initialization time**	**Lead forecast hours**
Jobo (2021)	00UTC, 21st April, 12UTC, 21st April, 00UTC, 22nd April, and 12UTC, 22nd April	84, 72, 60, 48
Kenneth (2019)	00UTC, 23rd April, 12UTC, 23rd April, 00UTC, 24th April, 12UTC, 24th April, 00UTC, 25th April	96, 84, 72, 60, 48
Idai (2019)	00UTC, 11th March, 12UTC, 11th March, 00UTC, 12th March, 12UTC, 12th March, 00UTC, 13th March	108, 96, 84, 72,60

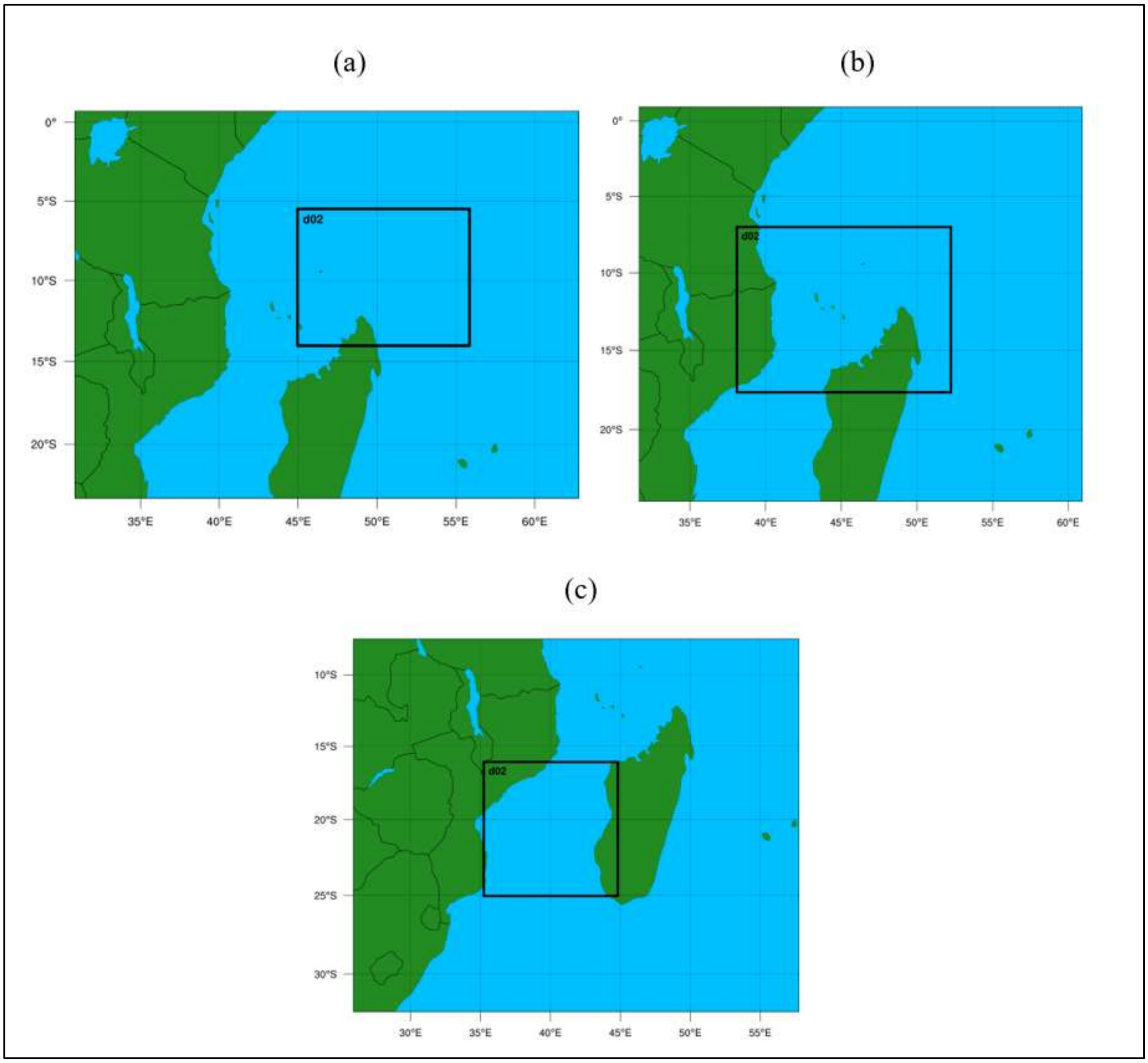

Figure 3: Model setup used in the simulation of (a) cyclone Jobo, (b) cyclone Kenneth, and (c) cyclone Idai. The inner domain demarcated by a black box marked d02 shows the nested domain that detects and tracks the cyclone vortex automatically.

3.4.2 WRF Model Forecast Verifications

The forecasted cyclones' track and intensity were objectively verified against the observations by using measures of errors similar to those used by the regional specialized centres for cyclone observations. The description of the measures used in the study for both the intensity and location forecasts is presented in this section.

Tracks Forecasts verifications

Model simulated cyclones were compared against the Observations (best track data) to verify the model's ability to represent tropical cyclone tracks and intensity over the Southwestern Indian Ocean basin. Operational centres quantify the errors in the cyclone tracks forecast using three measures, namely, direct positional error (DPE), along track error (ATE), and cross-track error (CTE). **Figure 4** shows the consideration of the track forecast error as used by operational centers. OB1(x_i, y_i) is the initial observed location of the cyclone at the time of the model initialization, OB2(x_0, y_0) is the observed cyclone location at lead time t from initialization and the FC(x_f, y_f) is the forecasted location of the cyclone at time t. (x_n, y_n) represent the longitude and latitude on the earth's surface corresponding to the position of the cyclone in a model or observations. RSMC La reunion measures the DPE as the straight-line distance between the observed tropical cyclone location (OB2) in the best track data and model forecasted tropical cyclone's location (FC) at a given time.

DPE is a measure of the distance from the forecasted position (FC) to the Observation (OB2) and is given by equation (i).

$$\mathrm{DPE} = \sqrt{(y_f - y_0)^2 + (x_f - x_0)^2} \quad \text{.......................... (i)}$$

DPE indicates how well the cyclone was simulated but this error cannot inform us of how the error was caused by the relative speed of simulated tropical cyclones or by deviation of the simulated track from the actual track (Kotal et al., 2014).

To assess the role that the speed of a simulated tropical cyclone plays on track forecast error ATE and CTE are used. ATE measures the track forecast error caused by the speed of predicted tropical cyclones being different from the observations (positive values show that the cyclone in the model moves faster than in the observations). CTE measures the northward or southward deflection of the forecasted tracks from the observed position.

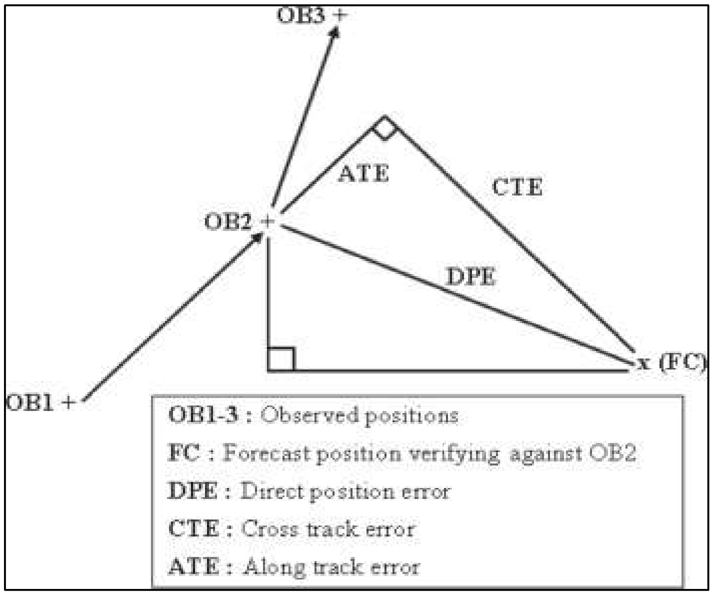

Figure 4: Measures of cyclones track forecast errors adopted from Regional Specialized Meteorological Centres (Kotal et al., 2014)**.**

Intensity Forecast Verifications

RSMC-La reunion uses the central mean sea level pressure or maximum sustained 10m-average winds to quantify tropical cyclone intensity. To obtain the error in cyclone intensity simulation the difference between the simulated and best track mean sea level pressure or 10m average wind speed. The absolute error (Δp) in the intensity forecast is given by equation (ii)

$$\Delta p = P_f - P_o \quad \text{.......................................} \quad \text{(ii)}$$

P_f and P_o are the forecasted and observed minimum sea level pressure/the maximum wind speed at the same time, respectively. The lower (higher) the minimum sea level pressure (Maximum wind speed) the more intense the cyclone. The model overestimates the intensity of the cyclone if the forecast is more intense than the observed cyclone. For the absolute errors in the minimum sea level pressure, the negative (positive) sign indicates an over (under) estimation of the intensity. Negative (Positive) absolute errors for the wind speed imply under (over) estimation of the intensity.

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter presents the results and discussion of the study with a focus on the tracks and strength of the tropical cyclones over the Southwest Indian Ocean. The discussion also includes the sensitivity experiments and verification of the TC forecasts.

4.1 Forecasted Cyclones Characteristics

The study used WRF-ARW to carry out simulations of tropical cyclones Jobo (2021), Idai (2019), and Kenneth (2019). The simulated tracks, sea level pressure, maximum speed of the wind, and rainfall distribution were compared against the observations to investigate the ability of the model over the Southwest Indian Ocean. **Figure 5** shows the simulated tracks for cyclone Jobo, Kenneth, and Idai. Results show that the WRF model simulated well the direction of movement of all tropical cyclones toward the landfall location over Mozambique and Tanzania. All the simulated cyclones tracks were closer to the observed location of tropical cyclones for the 24, 48, 72, and 96 hours lead forecasts time and the average DPE (Direct Positional Error) at the respective lead forecasts time was 58 ± 6, 86 ±17.2, 146±43.7 and 240 ±145 km. Similarly, Park et al., (2020) found that the error DPE increases as the lead forecast time increases.

The simulated tracks of cyclone Jobo follow the general west-northwest direction toward the Tanzania coast like the observed track of cyclone Jobo for all the cumulus schemes used. The general westward (slightly west-southwestward) motion of tropical cyclone Kenneth was well captured in the WRF simulation for all schemes. WRF forecasted the landfall of cyclone Idai closer to the landfall location.

Figure 8 shows the time variations of the simulated intensity of tropical cyclones Jobo, Kenneth, and Idai. WRF model simulated the relative intensification and weakening cycles of cyclone Jobo, Kenneth, and Idai comparable to the observations but underestimated the magnitude of the intensity changes. Tropical cyclone Jobo reached the strength of the tropical cyclone with a recorded wind speed of 65 knots and Mslp of 985 hPa at 12UTC, on the 21st of March 2021. During this time WRF model simulated cyclone Jobo as a moderate tropical storm with a speed reaching 43 kt. The results corroborate the results found by other studies over the North Indian

Ocean and Western North Pacific which concluded that the WRF model underestimates the magnitude of MSLP and wind speed (Cruz and Narisma, 2016; Delfino et al., 2022; Park et al., 2020, 2023; Parker et al., 2017; Pattanayak et al., 2012; Zhang et al., 2011).

4.2 Assessment of the Tropical Cyclones Characteristic Simulated using WRF-ARW model.

The results of sensitivity experiments on the tracks of tropical cyclones and their intensity based on the different physics parameterizations are presented in this section. The aim was to investigate the applicability of the WRF-ARW model for cyclones forecasts over the Southwest Indian Ocean. The experiments were conducted exhausting different cumulus and microphysics schemes to investigate how each scheme improves the forecasts of the tropical cyclones over the Basin.

4.3 Sensitivity of Cyclones Tracks and Intensity on Cumulus Schemes

4.3.1 Tracks Forecasts

To investigate the influence of Cumulus convection on the tropical cyclones forecasted using WRF- ARW model microphysics scheme WSM6 was used throughout the experiments. The comparisons of the tracks for tropical cyclone Jobo and Kenneth RSMC observations and WRF simulation using two cumulus parameterization choices (Modified Tiedtke and Kain- Fritsch) is presented in **Figure 5**.

For all cyclones, the simulated initial location of the vortex was independent of the cumulus scheme choice. Accurate forecasts of the initial cyclone position in a forecast cycle are key to improving the prediction of cyclone tracks (Holland 1984). The forecasted and observed initial locations of the cyclones were not more than 50 km further apart for all cases.

The effect of cumulus parameterization on the tropical cyclones track forecasts was evaluated by using the average separation between the observation and forecast position. KF schemes produced a better forecast of the tracks close to the observations for cyclone Jobo with a small Direct Positional Error (DPE) (69.4 km) compared to the simulation using MT schemes with an average DPE of 98.7 km. MT (KF) cumulus convection schemes produced an average DPE of 82.4 and 143.6 km (88.3 and 180.4 km) cyclone Kenneth and Idai, respectively.

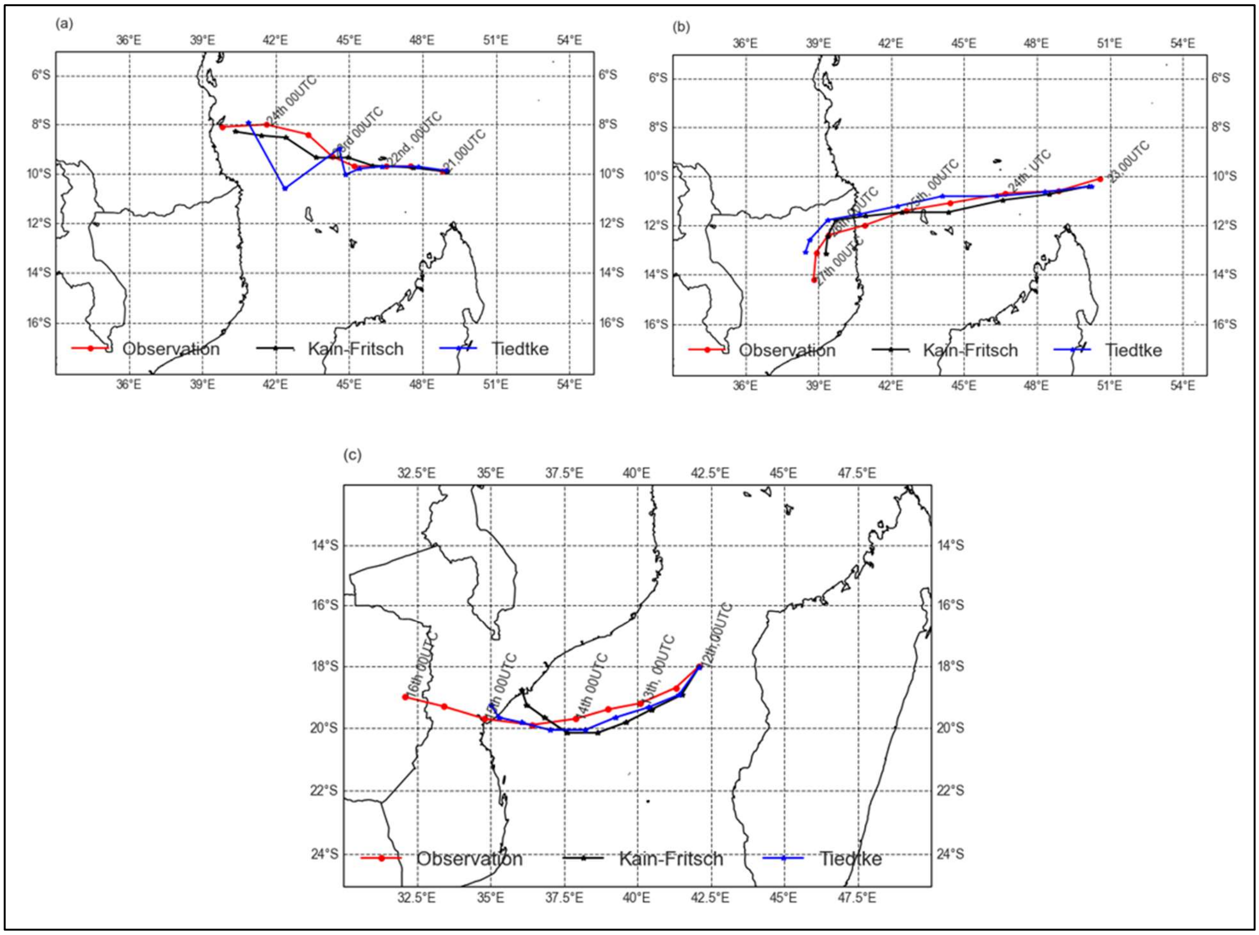

Figure 5: Forecasted tracks of tropical cyclone (a) Jobo (b)Kenneth and (c)Idai from the WRF model. Model initializations were from 00UTC on 21st April 2021 (Cyclone Jobo), on 23rd April 2019 (cyclone Kenneth), and Cyclone Idai was initialized from 00UTC, on 12th March 2019. Forecasted trajectories from the WRF model using Kain Fritsch and Tiedtke cumulus convection scheme are shown by black lines and blue curves, respectively. The best track observations from RSMC La Reunion are shown by red lines.

The comparisons of Average DPE between MT and KF scheme for Tropical cyclone Jobo, Kenneth, and Idai are presented in **Figure 6,** which reveals that cumulus convection parameterization influences the tropical cyclones track forecasts. This correlates to the results of several studies that concluded that tropical cyclones track over the Bay of Bengal and the Western North Pacific Basin are sensitive to cumulus schemes (Delfino et al., 2022; Pattanayak et al., 2012). For cyclone, Jobo the DPE for the two schemes was comparable over the first 12 hours. The average DPE for KF (MT) cumulus convection for 24, 48, and 72 hours lead forecasts hours were 53.4, 75.6, and 103.2 (68.8, 120.2, and 213.1) km, respectively.

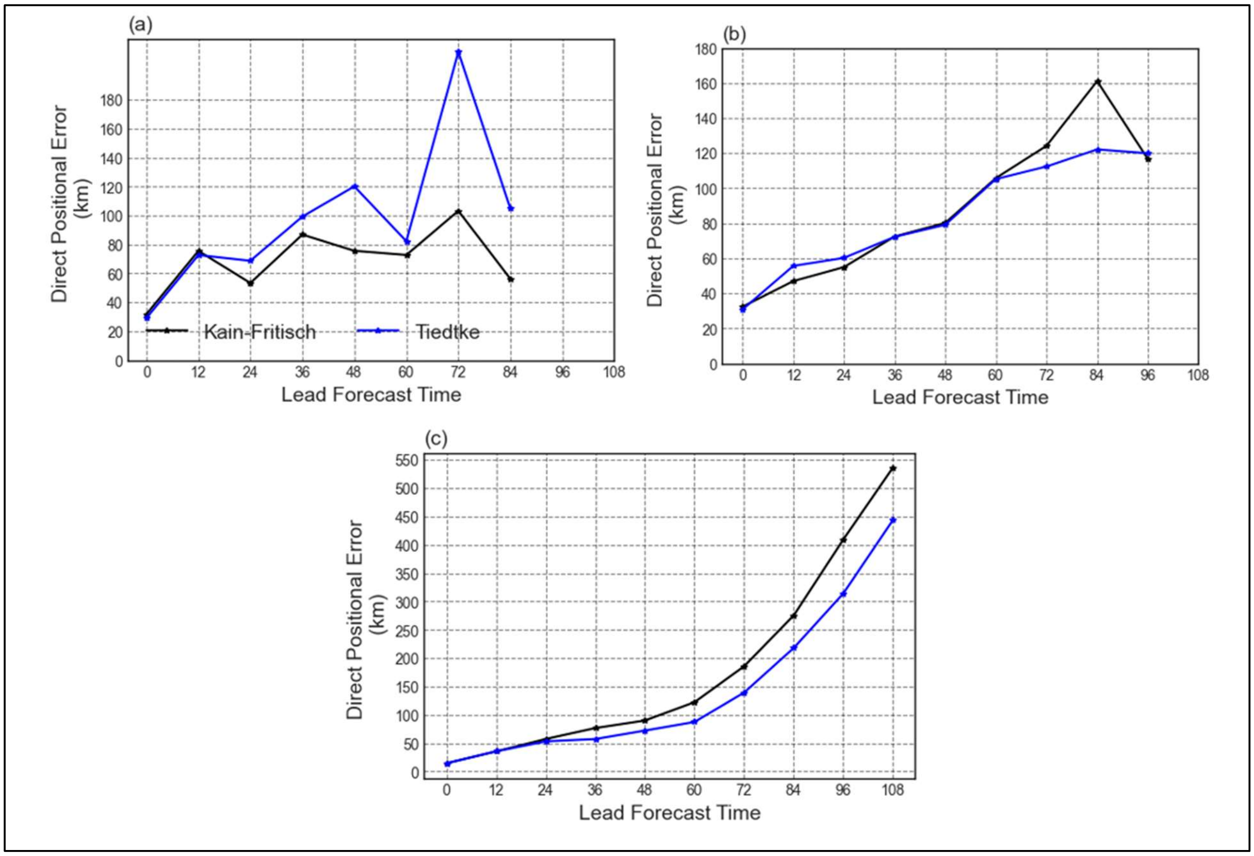

Figure 6: Average bias in the forecasted track of tropical cyclones in terms of the direct position error (DPE) for the tropical cyclone Jobo, Kenneth, and Idai are shown in a, b, and c, respectively. Blue lines show the DPE for modified Tiedtke and the black line for Kain Fritsch cumulus parameterization.

DPE shows the distance between forecasted cyclone tracks and the observations but does not explain in detail the reasons for the deviation between forecasts and observations. Along-track error (ATE) and cross-track error (CTE) were calculated to assess bias in the predicted cyclone's speed and poleward deflection by the steering motion, respectively. **Figure 7** shows the ATE and CTE for cyclone Jobo, Kenneth, and Idai. The negative ATE values when the cyclones are closer to the land shows reveal that the WRF model has a slow speed bias closer to the land. KF's scheme ATE (CTE) ranged from -50 to 70 (-80 to 40) km for cyclone Jobo, -100 to 85 (-50 to 68) km for cyclone Kenneth, and -140 to 260 (-50 to 150) km for cyclone Idai. The ATE was found to range from -145 to 10 km (cyclone Jobo), -110 to 88 km (cyclone Kenneth), and -140 to 162 km (cyclone Idai) for MT cumulus convection schemes. MT's CTE ranged from -260 to 58 km, -48 to 70 km, and -90 to 150 km for cyclone Jobo, Kenneth, and Idai, respectively.

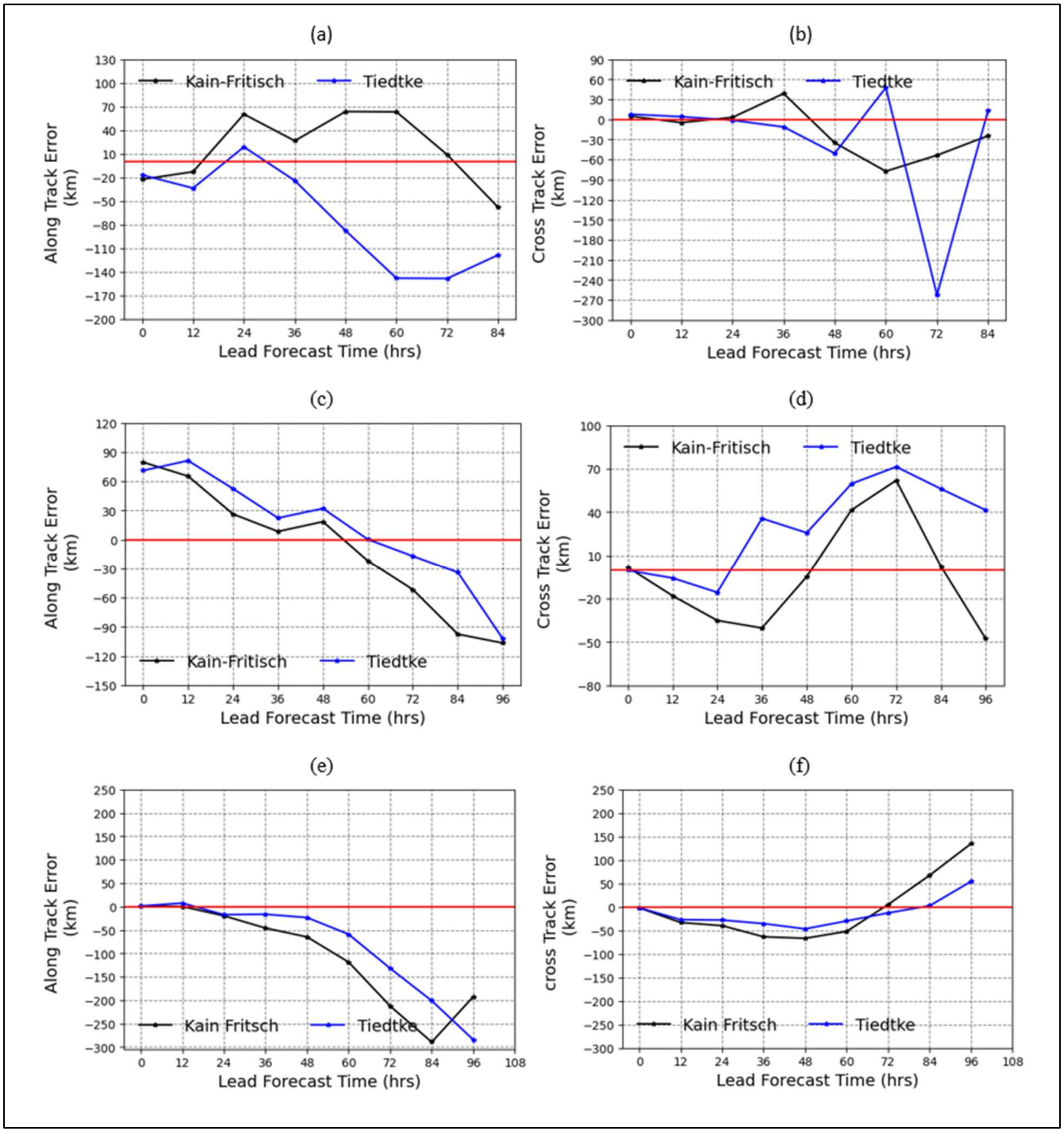

Figure 7: Along track error (left panel) and cross track error (right panel) for tropical cyclone (a and b) Jobo, (c and d) Kenneth, and (e and f) Idai. Blue curves show the simulations using Tiedtke cumulus convection and black lines for Kain-Fritsch.

The positive value of ATE for KF's scheme indicated that the simulated speed of movement of cyclone Jobo was higher for simulations with KF cumulus convections than that of the Tiedtke scheme at all forecast times. This corroborates the results by Pattanayak et al., (2012) who found that tropical cyclones forecasted using the KF scheme move faster in comparison to the simulations using MT schemes.

The largest southward bias for cyclone Jobo was recorded 72 hours from initialization as indicated. Large negative values of ATE from 72 hours for both cumulus schemes reveal that the forecasted speed of movement of cyclone Jobo decreased significantly as the system was approaching the coast. For cyclone Kenneth ATE decreased after 48 hours from initialization for both schemes, with the KF scheme showing sharp retardation of the cyclone Kenneth compared to the MT scheme.

4.3.2 Intensity Forecasts

To investigate how the cumulus schemes affect the forecast of the intensity of tropical cyclones, the minimum sea level pressure and the maximum winds from the model and observations were compared. **Figure 8** shows the variations of TC's maximum wind speed and lowest sea level pressure with time. MT and KF schemes forecasted well the wind and pressure variations with time as in the observations but underestimated the intensity of the cyclones. KF scheme captured well the intensification trend of cyclone Jobo over the first 12 hours but overestimated the lowest sea level pressure value. To illustrate this overestimation of the lowest pressure, the simulated was 1000.7 hPa while the observed was 985 hPa therefore an estimation of 15.7 hPa. KF schemes forecasted the second intensification of the cyclones 60 hours from initialization time (12UTC, 23rd April 2021) with a slightly higher (lower) maximum wind speed (sea level pressure) than in the observations. MT scheme did not forecast the first and second intensification cycles for tropical cyclone Jobo.

Cyclone Kenneth underwent a rapid intensification starting 12 hours (12UTC, 23rd April 2019) from initialization to the lowest pressure (934 hPa) 48 hours later (00UTC, 25th April 2019). KF scheme simulated the pressure deepening during this period but the size of change of the pressure and wind speed was smaller to justify the rapid intensification. MT scheme did not capture the cyclone's intensification during this period. The highest (lowest) value of wind speed (sea level pressure) recorded were 65 knots (985 hPa), 934 hPa (120 knots), and 940 hPa (105 m/s) for cyclone Jobo, Kenneth, and Idai, respectively. The lowest sea level pressure and highest sustained winds from the model using KF (MT) were 968 (990) hPa and 85(62) knots respectively for cyclone Kenneth.

Objective verifications of the intensity forecast were conducted using the absolute errors of the maximum wind speed and minimum sea level pressure. The average absolute error in the WRF forecasted lowest minimum pressure using KF (MT) cumulus convections were 10.2 hPa (11.85 hPa), 23.6 hPa (31.82 hPa) and 11.97 hPa (31.17 hPa), for cyclone Jobo, Kenneth and Idai, respectively. The time variations of the absolute errors for cyclone Jobo, Kenneth, and Idai are depicted in **Figure 9**. The MT scheme forecast of intensities produced large absolute errors in comparison to the KF.

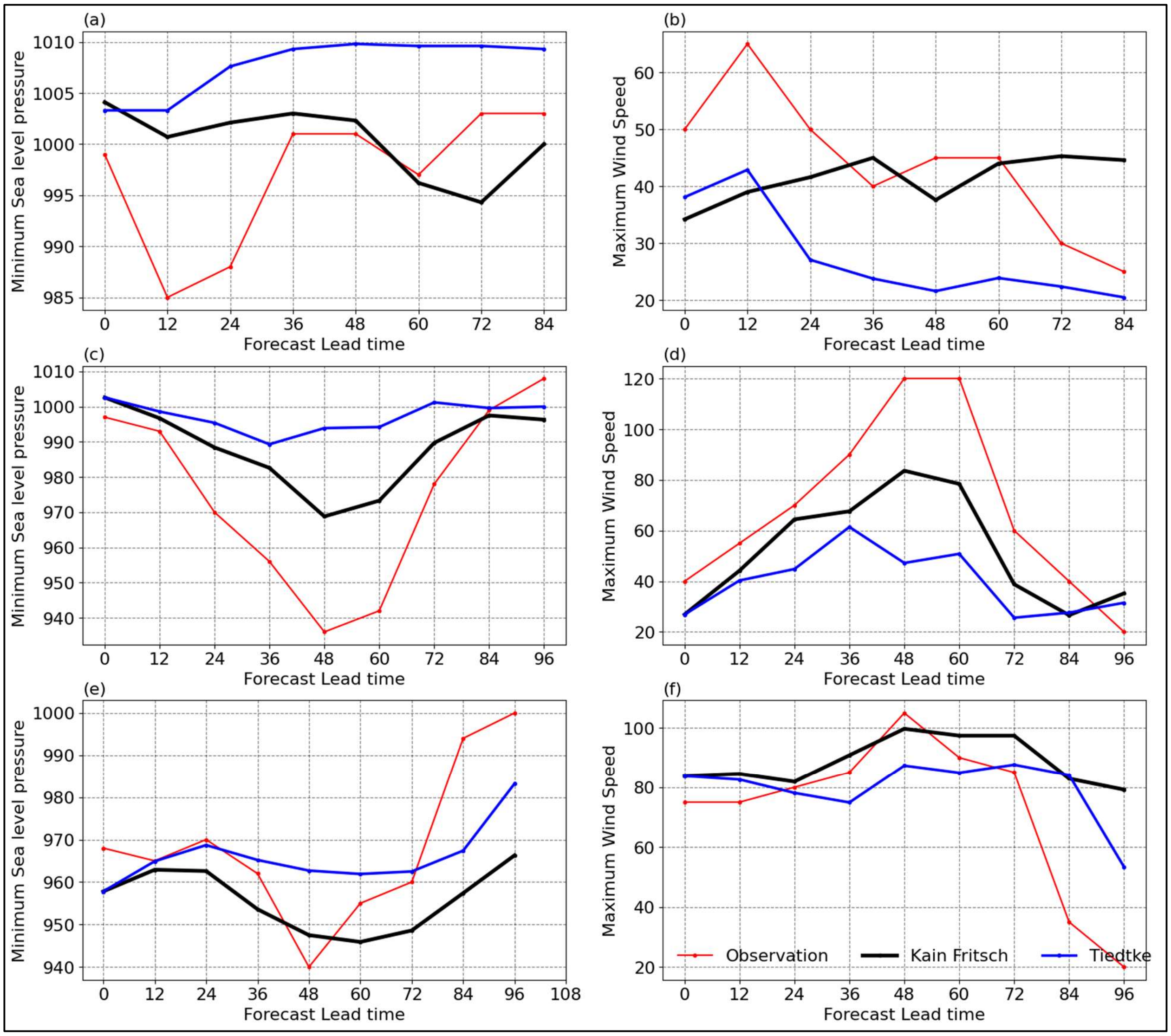

Figure 8: Minimum Sea level pressure (left panels) and maximum wind speed (right panels) variations with time for the tropical cyclone Jobo (a and b), Kenneth (c and d), and Idai (e and f). Forecasted trajectories from the WRF model using Kain Fritsch (black lines) and Tiedtke (blue lines) cumulus convection scheme were compared to the observations (red lines) from RSMC La Reunion.

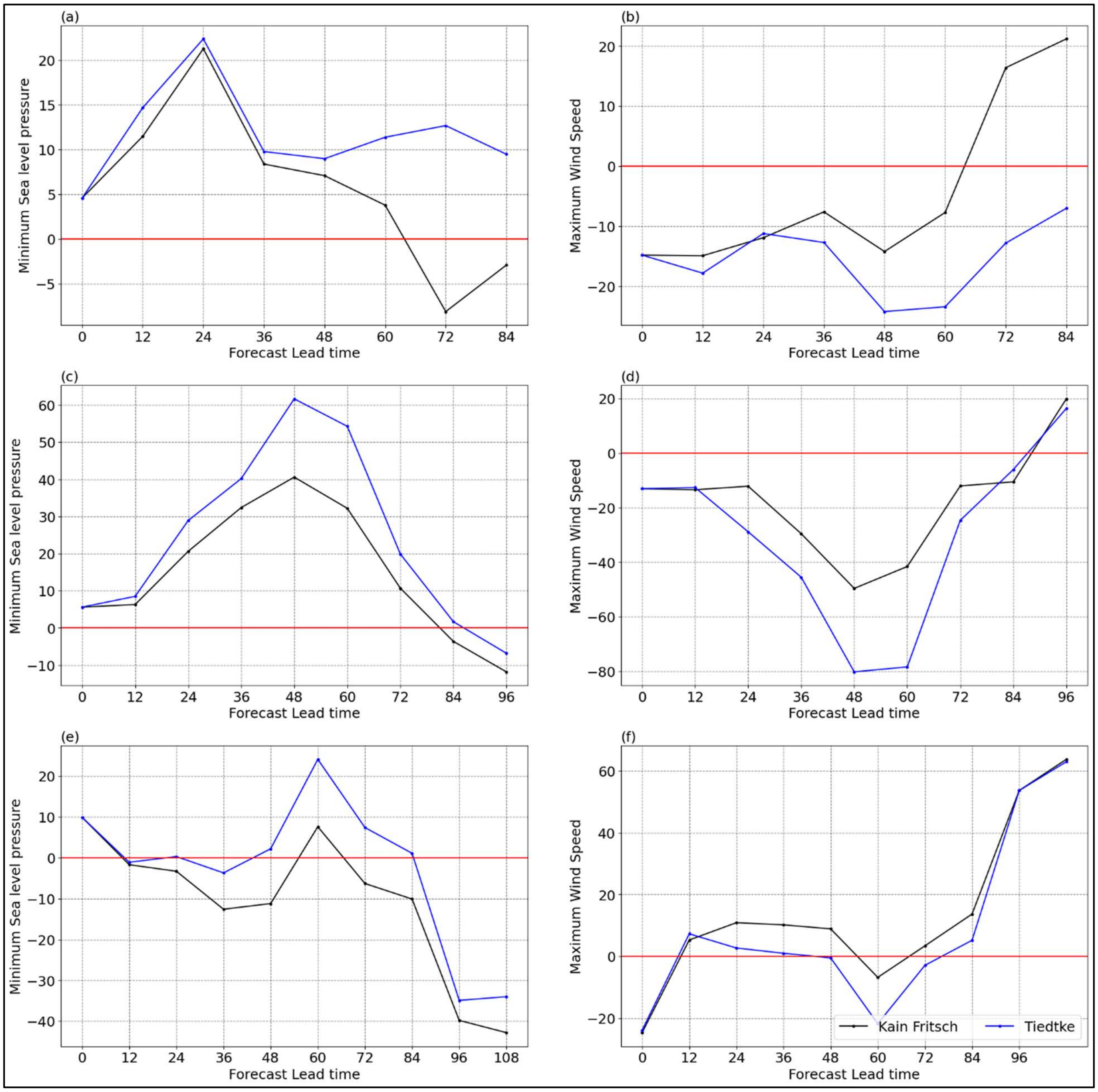

Figure 9: Time variations of absolute errors in minimum sea level pressure (left panels) and maximum wind speed (right panels) for the tropical cyclone Jobo (upper panel), Kenneth (middle), and Idai (bottom). Error obtained for the Kain Fritsch (black lines) and Tiedtke scheme (blue lines) are compared.

Results revealed that the model intensities were closer to the observations for the KF scheme in comparison to the MT scheme. These findings are in agreement with the results of (Delfino et al., 2022; Pattanayak et al., 2012) that the KF scheme simulated better the intensity of the tropical cyclone over the Bay of Bengal and Northwestern Pacific Ocean. This implies that the cumulus convection schemes have effects on forecasts of tropical cyclone intensity.

4.3.3 Precipitation forecast

The comparisons of the spatial distributions of the observed precipitation derived from GPM-IMERG and WRF forecasted cyclones using two cumulus schemes on the day that Cyclone Jobo (24th April 2021) and Kenneth (25th April 2019) made landfall over Tanzania and Mozambique, respectively is shown in Figure 10. The precipitation accumulated over 24 hours period on the day of landfall for all the cyclones. For cyclone, Jobo, the region of highest precipitation was observed along the coast of Tanzania and Mozambique (between 9°-13°S) with the highest precipitation accumulated over 24 hours ranging from 300 mm of rain found over the Ocean. The figure reveals that the MT scheme simulated similar spatial distribution along the coasts as in the observations but underestimate the amount of rainfall and the region is wider than in the observations. MT Scheme did not forecast the observed precipitation over Mozambique. Moderate rain amount not exceeding 80 mm was forecasted by the MT scheme along the Tanzania coast. A region of maximum precipitation forecasted in the KF scheme was confined near the Tanzania coast but smaller than the region observed in GPM-IMERG. The orientation of the maximum precipitation was different from the observed pattern. The KF scheme simulated rain not exceeding 80 mm along the Mozambique coasts.

For cyclone, Kenneth (**Figure 10** b), the region of maximum precipitation (purple-colored area) is in the center of the cyclone with clear rain bands. The region of maximum rainfall extends over land and ocean bounded between (10°-13°S, 38°- 44°E) most of this area is over the ocean. MT schemes (**Figure 10** d) underestimate rainfall amount compared to the KF schemes (**Figure 10** f). The purple region is narrower in the MT scheme while the area is comparable to the observations in the KF scheme. The results correspond to comparable results by Otieno et al., (2020) who founds that the KF scheme simulates better the precipitation over East Africa. The results are also in correspondence with the results by Delfino et al., (2022) which concluded that KF scheme simulated precipitation associated with cyclone Haiyan over the Philippines.

The results revealed that the location of the forecasted maximum precipitation was behind the location of the highest precipitation in the observations. This suggests that the location of the center of the cyclone in the model controls the spatial distribution of the maximum precipitation. Further, magnitude and spatial extent depend on the cumulus scheme.

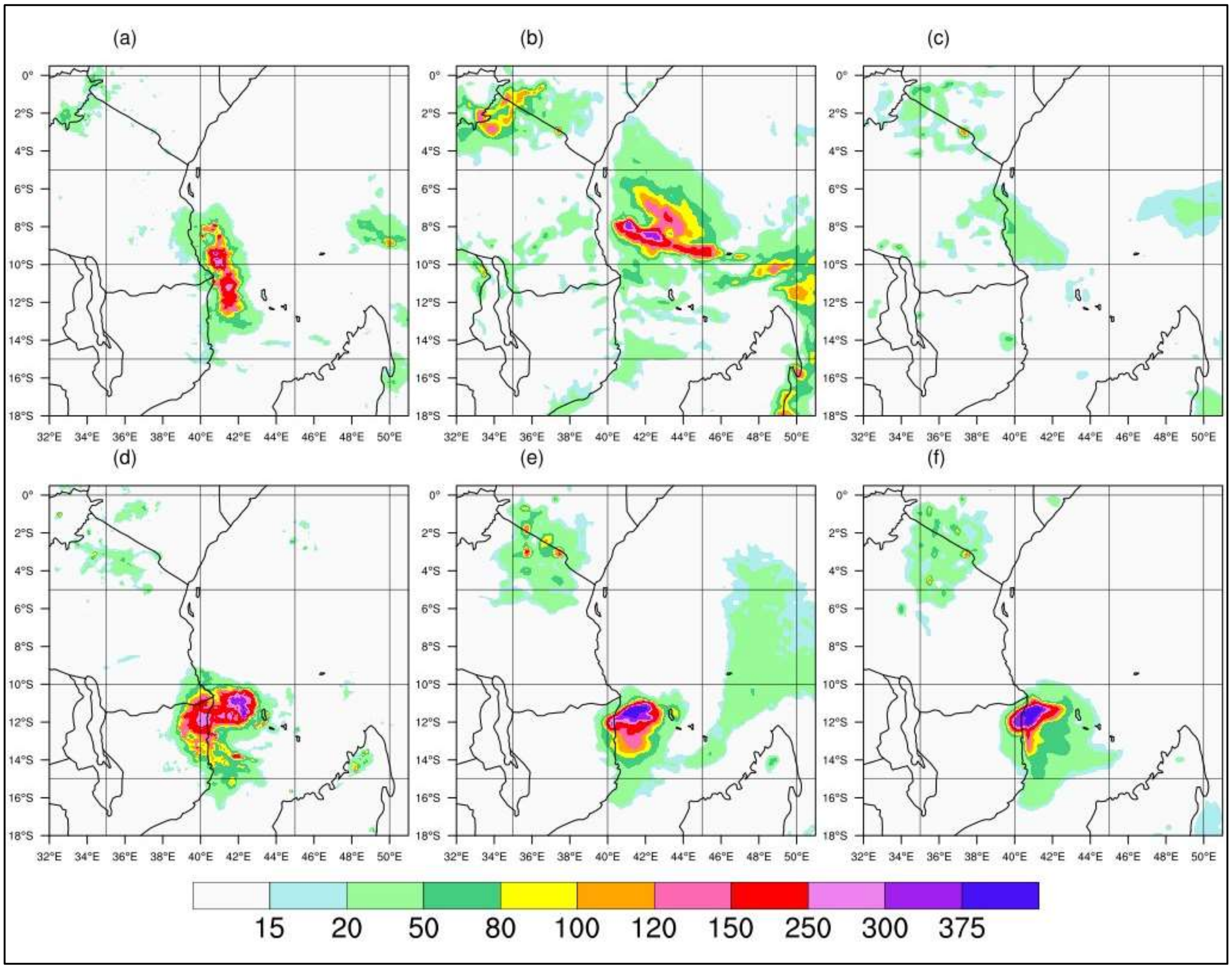

Figure 10: WRF forecasted precipitation and the observed precipitation (a and d) derived from IMERG for cyclone Jobo 2021(b and c) and Kenneth 2019(e and f). Modified Tiedtke was used in (c) and (f). In (c) and (e) Kain Fritsch was used. Precipitation was accumulated over 24 hours on the day of the landfall of cyclones Jobo (24th April 2021) and Kenneth (25th April 2019).

4.4 Sensitivity of Tropical Cyclones Track and Intensity to Microphysics Schemes

Simulation of Cyclone Jobo, Idai, and Kenneth with a similar setup of the cumulus, radiation, and land parameterization as in the preceding section was carried out with a change in the microphysics setup. A WRF Single Moment 3- class (WSM-3) parameterization scheme is used as an alternative to WRF Single Moment 6- class (WSM-6). The sensitivity of cyclone tracks, intensity, and precipitation are presented below.

4.4.1 Tracks Forecasts

Figure 11 shows the comparison of the observations and WRF forecasted tracks for cyclone Jobo and Kenneth using the WSM-3 and WSM-6 microphysics. The figure reveals that cyclone tracks are sensitive to microphysics schemes as they are sensitive to cumulus conventions. WMS-3 micro physics improved the simulated tracks of cyclone Jobo and Kenneth significantly for all cumulus schemes used. The forecasted cyclones were found to be closer to the observed location for WSM3 schemes. For cyclones, WSM3 reduced the average DPE to 75.6 and 67.8 km MT and KF schemes, respectively. When the WSM3 scheme was used the DPE for cyclones Kenneth and Idai for the forecasts using KF (MT) cumulus schemes were found to be 88.4 (81.3) and 145.64 (101.62) km. Mahala et al., (2015) simulated well the track of cyclone Phailin over the North Indian Ocean using WSM3 and KF cumulus convection.

The comparisons of the direct positional errors between WSM3 and WSM6 microphysics schemes are presented in **Figure 12**. The bias in initial intensity and vortex location is the same for all simulations because the same initial and boundary conditions were used. For Tiedtke cumulus convection, the average DPE for WSM6 (WSM3) microphysics for the 24, 48, and 72 lead forecasts hours was 68(47.9), 120.2(78.6) and 213.1(95.2) km, respectively. The KF scheme average DPE for WSM6 (WSM3) microphysics for the 24, 48, and 72 lead forecast hours was 53.4 (65.4), 75.6 (79.5), and 103.2 (120.6) km, respectively.

The CTE between the two-microphysics scheme for cyclone Jobo, Kenneth, and Idai were compared and presented in **Figure 13**. The figure reveals that the WSM3 scheme had a southward bias and WSM6 showed both southward and northward deflection at different lead times. The result of comparisons of the ATE for the WSM6 and WSM3 schemes in **Figure 14** reveals that the speed of the simulated cyclones was slightly improved for the WSM3.

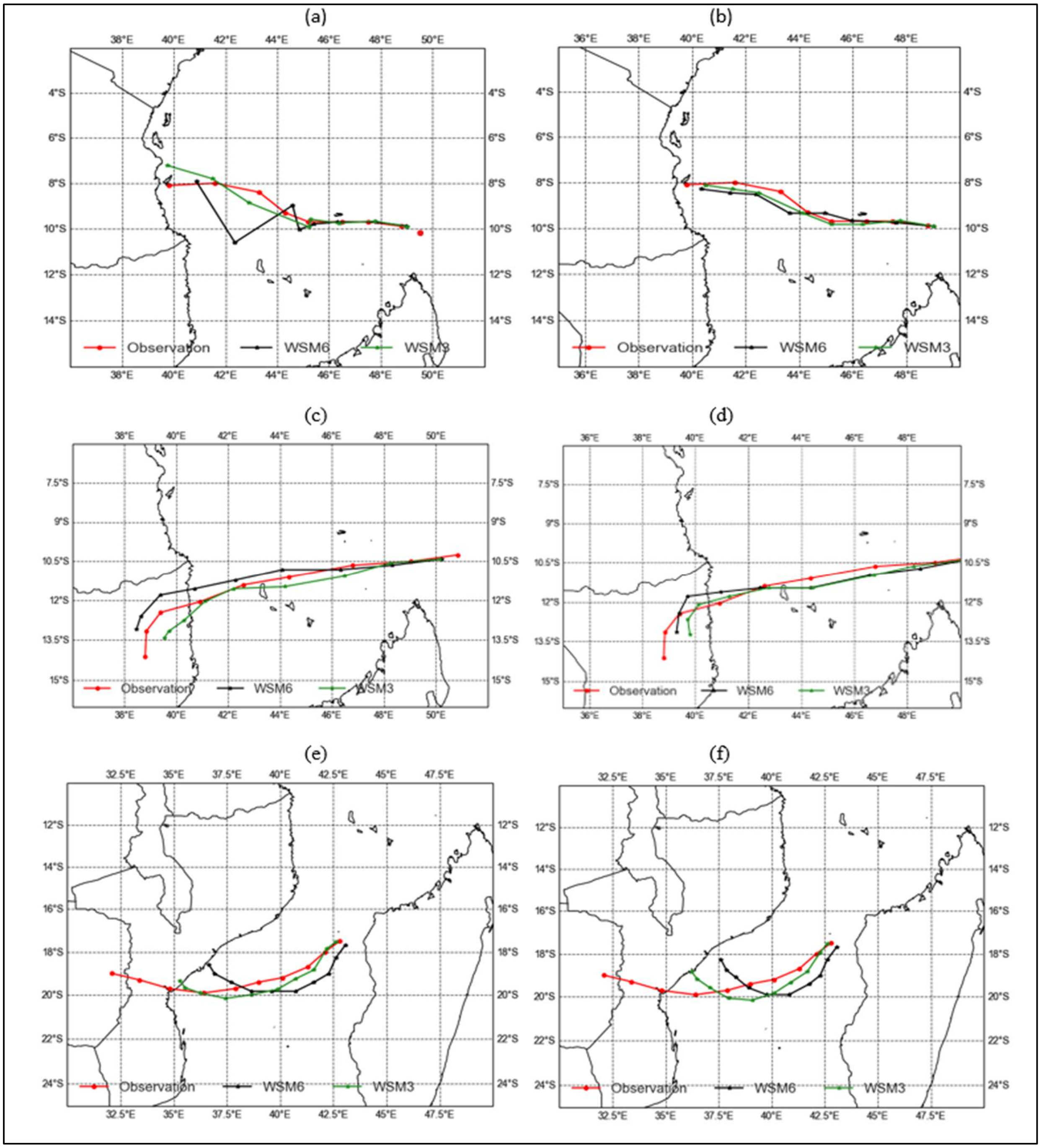

Figure 11: Observed and forecasted trajectory of tropical cyclones for cyclone Jobo (upper panel), Kenneth (middle), and Idai (bottom). In the left (right) panel Tiedtke (Kain-Fritsch) scheme was used for Cumulus parameterization. Green (black) lines are the WRF forecasted trajectory where WSM3 (WSM6) was used for microphysics parameterizations.

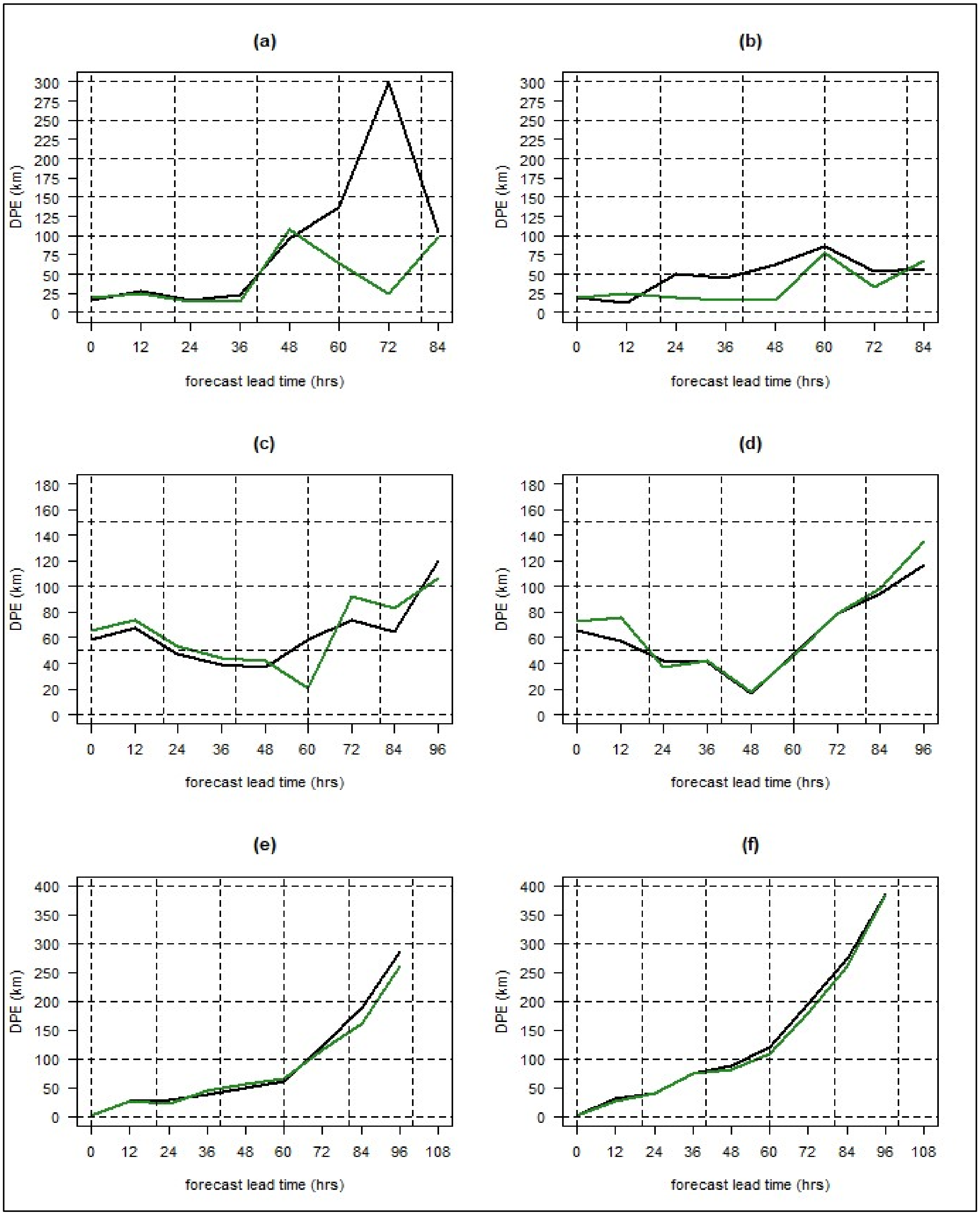

Figure 12: Cyclones track errors for cyclones Jobo (upper panel), Kenneth (middle), and Idai (bottom). left panels are the simulations using the Tiedtke scheme and the right panels are for Kain Fritsch convection schemes. green lines show the simulations with WSM3 microphysics and black for WSM6.

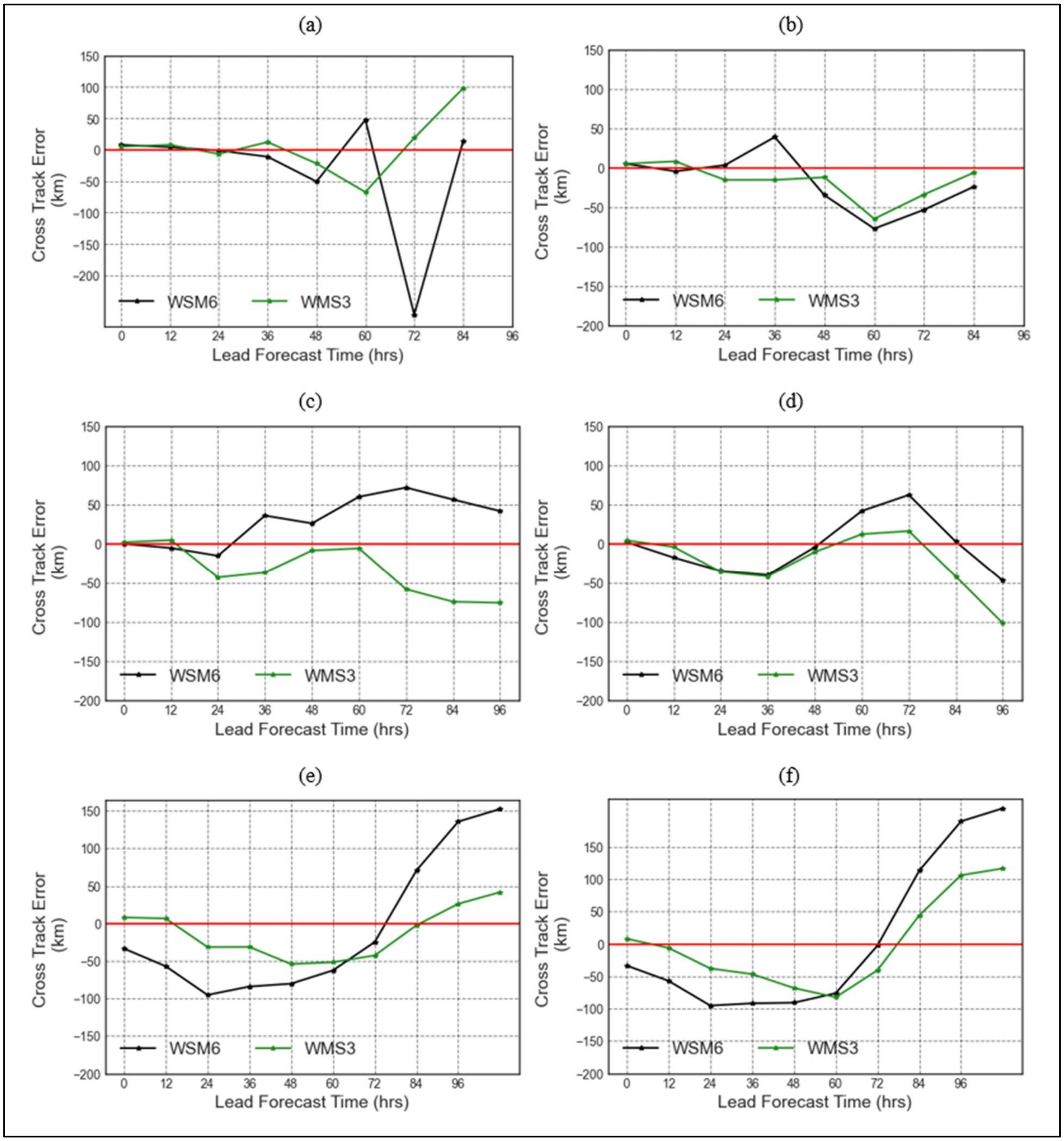

Figure 13: Cross-track errors for tropical cyclone (upper panel), Kenneth (middle), and Idai (bottom) Idai. Black lines show the simulations using WSM6 microphysics parameterizations and green lines for the WSM3 scheme. The left panels show simulations using Kain Fritsch cumulus convection and the right panels for Tiedtke schemes.

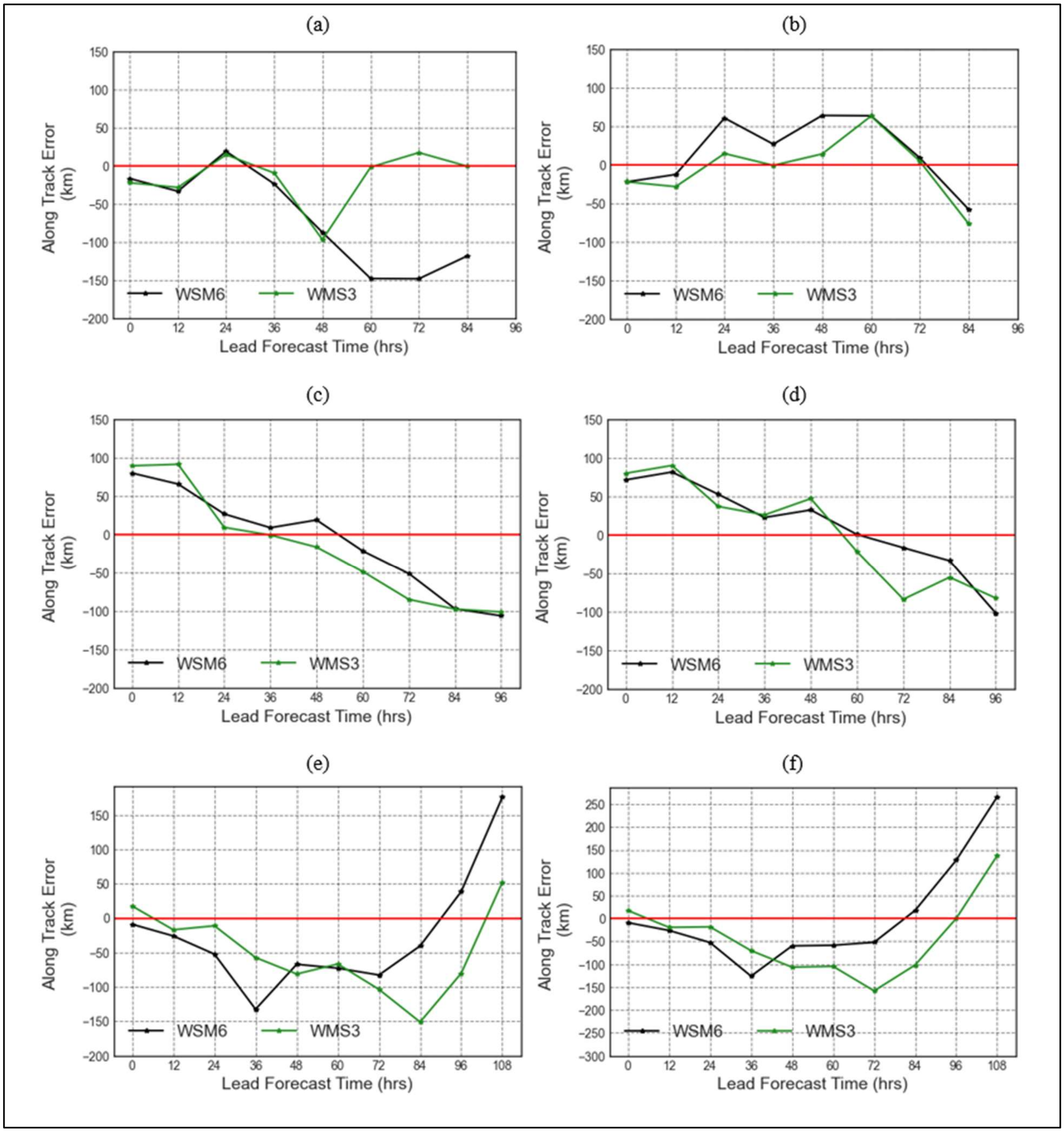

Figure 14: Along track errors for tropical cyclone (upper panel), Kenneth (middle), and Idai (bottom) Idai. Black lines for the WSM6 microphysics parameterizations and green lines for the WSM3 scheme. The left panels show simulations using Kain Fritsch cumulus convection and the right panels for Tiedtke schemes.

Therefore, results have revealed that the WSM3 scheme simulated the tracks of cyclones over SWIO very close to observations compared to WSM6 schemes. This implies that cyclones track forecasts are dependent on the microphysics schemes and WSM3 schemes result in small track error forecasts compared to the WSM6.

4.4.2 Intensity Forecasts

Figure 15 shows the comparisons of the variations of the pressure and wind speed with time for WSM6 and WSM3 microphysics schemes for the cyclone Jobo, Kenneth, and Idai. The results reveal that the WSM6 and WSM3 underestimate the intensity of the forecasted tropical cyclones. Time variations of the intensity forecasted using WSM6 microphysics are closer to observations compared to the WSM3 intensity forecasts.

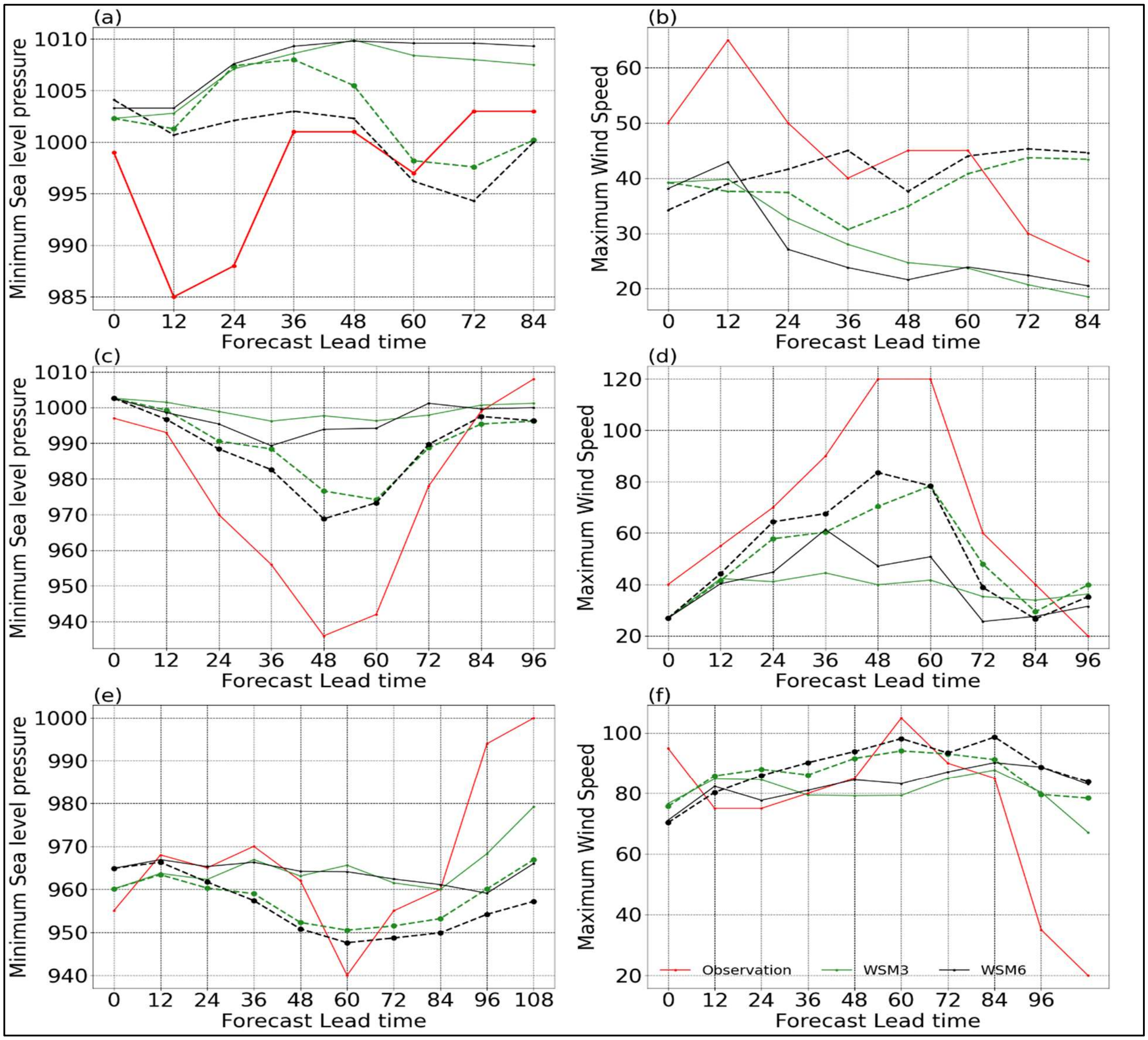

Figure 15: Minimum Sea level pressure (left panels) and maximum wind speed (right panels) variations with time for the tropical cyclone Jobo (upper panel), Kenneth (middle), and Idai (bottom). Green (Black) curves for the forecasts using WSM3(WSM6) microphysics parameterizations. The dotted lines are for the simulations where the Kain Fritsch scheme was used for cumulus convection parameterizations.

The magnitude of the simulated MSLP and MWS was closer to the observations for the combinations of all the microphysics schemes (WSM6 and WSM3) with the KF cumulus convection scheme. MT schemes underestimate the simulated intensity for all microphysics schemes used. **Figure 16** shows the absolute errors in the forecasts of the intensities for all cyclones.

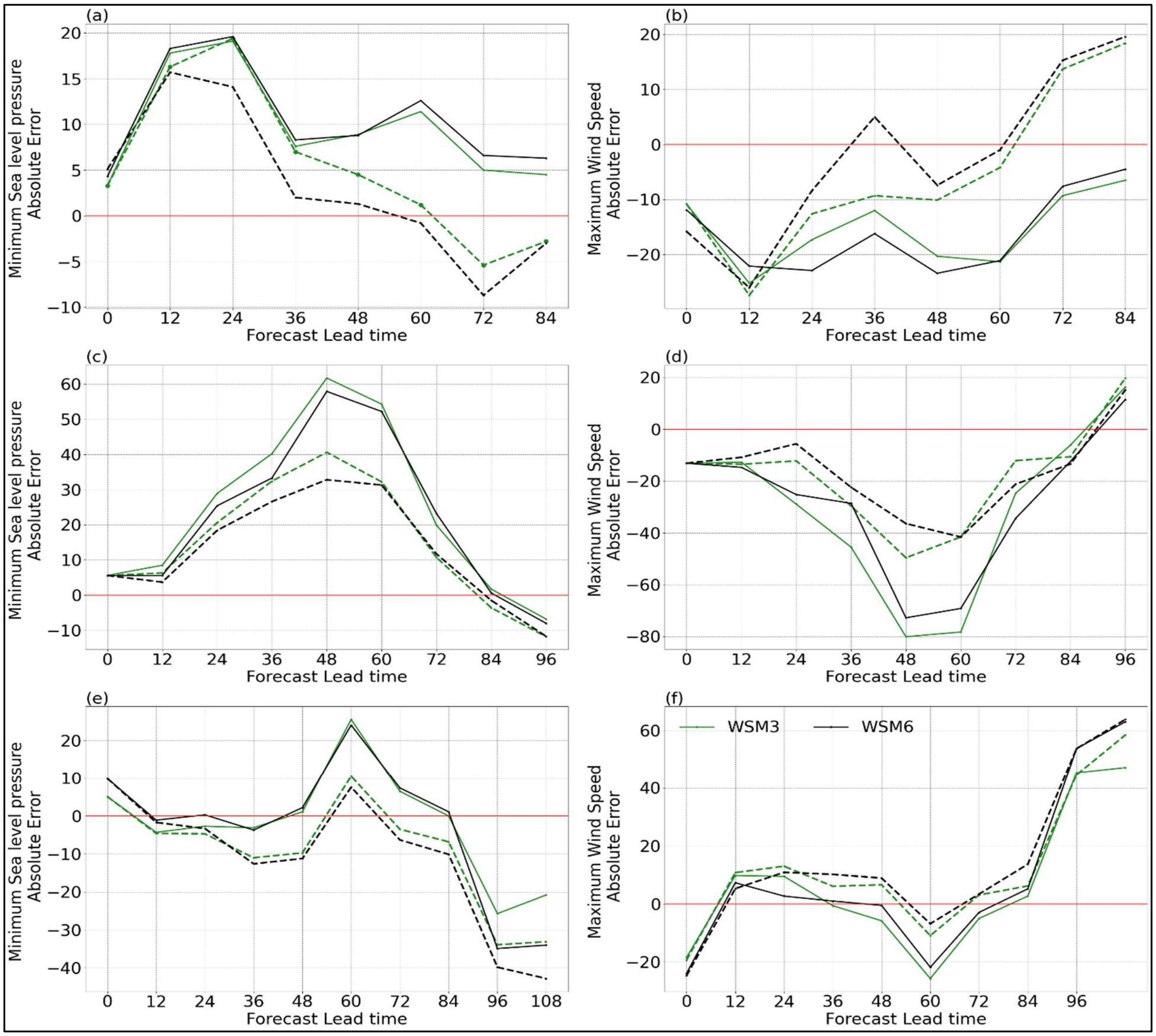

Figure 16: Bias in the intensities forecasts for tropical cyclone Jobo (a and b), Kenneth (c and d), and Idai (e and f). The left panels show the sea level pressure bias and the right panel for the wind speed bias. The black (Green) line represents the forecasts using WSM6(WSM3) microphysics parameterizations. The dotted lines are for the simulations using Kain Fritsch and the full lines are for the modified cumulus scheme.

For all cyclones, the largest errors were found during a period of sharp intensification and deterioration of the cyclones, showing that WSM6 and WSM3 poorly simulate the intensifications and deterioration of the tropical cyclones Jobo, Kenneth, and Idai. Tropical cyclone Jobo intensified from 00UTC, 21st April 2021 (initialization time) to the highest intensity on the 12UTC, 21st April 2021. Cyclone Kenneth intensified from 12UTC, 23rd April

2019 (12 hours from initializations) up to 12UTC, 25th April 2019. WSM6 with KF cumulus convection captured the intensification trend for cyclones Jobo, Kenneth, and Idai.

4.4.3 Precipitation Forecasts

Figure 17 shows the precipitation forecasted using the WRF model with the WSM3 MP scheme for cyclone Jobo and Kenneth. **Figure 10** shows the precipitation simulated using WRF with WSM6 MP and the observed precipitation. The forecasted precipitation changed significantly when the WSM3 scheme was used for all Tiedtke cumulus convection. The WSM6 could not simulate tropical cyclones Jobo precipitation along the Mozambique coasts, the WSM3 schemes simulated rainfall less than 50 mm over the area. The magnitude of precipitation for WSM3 improved to about 80 mm but still underestimate the precipitation when compared to observations. For cyclone Kenneth, the KF scheme forecasted the maximum precipitation area close to the observed area. For cyclone Jobo the WRF scheme still underestimated the forecasted precipitation.

The results reveal that the forecasted area of maximum precipitation is seen to be behind the observed location, which can be explained by the error in the forecasted location of tropical cyclones. This result implies that the location of the maximum precipitation is dependent on the forecasted location of the cyclone.

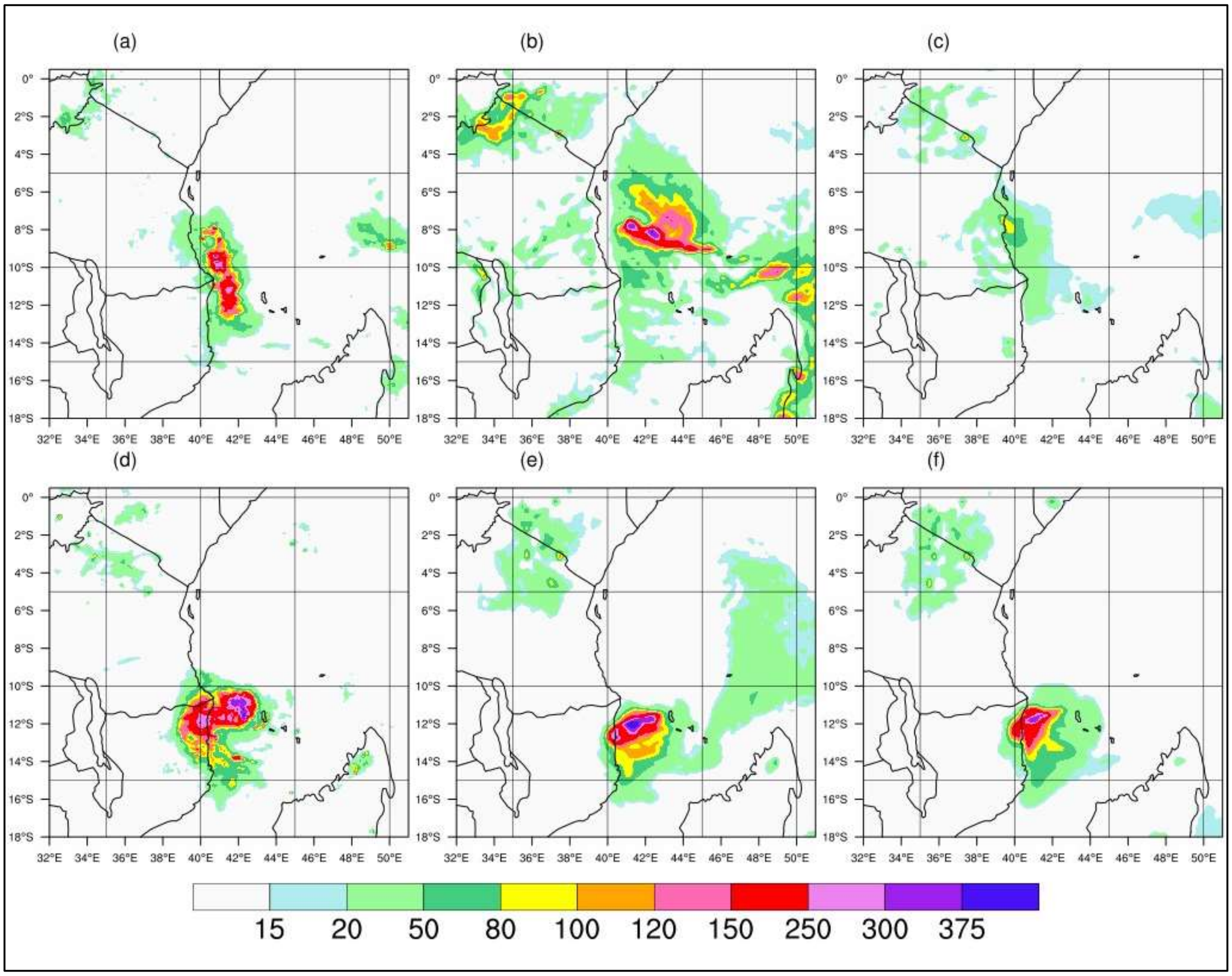

Figure 17: WRF forecasted precipitation when the WSM3 scheme was used for Microphysics parameterization on landfall day of cyclone Jobo (b, c) Kenneth (e, f). Tiedtke and Kain-Fritsch schemes are shown in the left and right panels, respectively.

CHAPTER 5

SUMMARY, CONCLUSION, AND RECOMMENDATIONS

The chapter presents the summary of the key findings of the study and the conclusion drawn. The chapter also includes the recommendation on the use of the results and the prospective studies to better understand tropical cyclones over the basin.

5.1 Summary and Conclusions

The study addresses the applicability of the WRF-ARW model for forecasting the tracks, strength, and precipitation of tropical cyclones in the Southwest Indian Ocean (SWIO). The WRF-ARW model was used to forecast tropical cyclones over the SWIO. The model was initialized by using the past real-time Global Forecasts System (GFS) data. Tropical cyclones Jobo (2021), Kenneth (2019), and Idai (2019) were selected based on their trajectory and considering that the landfall locations coincide with the projected properties of cyclones in the changing climate. The forecasted trajectory, lowest sea level pressure, maximum sustained winds, and associated precipitation were compared against the observations.

Further, the study investigated the sensitivities of the simulated characteristics of the tropical cyclones on cumulus convection and microphysics parameterization schemes. The Kain Fritsch (KF) and modified Tiedtke schemes were used alternatively to investigate how the forecasted track, strength, and precipitations change with respective cumulus parameterizations. The WRF Single-Moment 3-class (WSM-3) and WRF Single-Moment 6-class (WSM-6) microphysics schemes were used to assess the sensitivity of the tracks and intensity of tropical cyclones to the parameterization of the microphysics in the model. The study used direct positional errors (DPE), along-track errors (ATE), and cross-track errors (CTE) to quantify the errors in the forecasted tracks of tropical cyclones. Errors in the simulation of the tropical cyclone intensity were quantified using the difference between the forecasts and observations of the lowest sea level pressure and maximum sustained winds.

The forecasted initial location was found not more than 50 km away from the observed location at the time of initializations for all cases. The average DPE was found to be 58 ± 6, 86 ± 17.2, 146 ± 43.7, and 240 ± 145 km at 24, 48, 72, and 96 hours lead forecasts time. The general motion of the cyclones from Genesis points up to the landfall locations was well captured by the WRF model. The positive values of ATE over the first 48 hours show the forecasted position of the cyclone is always ahead of the observations. As the cyclones move closer to the land (48 hours from initializations) the speed of forecasted cyclones slows down as shown by the negative values of ATE. The WRF model was found to have positive CTE values, which shows that the WRF model had a southward bias.

The results revealed that the WRF model underestimated the maximum wind speed and minimum sea level pressure over the Southwest Indian Ocean with an average absolute error of 7 hPa and –5.9 m/s, respectively. Observations from Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG) were compared with the forecasted precipitation for cyclone Jobo and Kenneth. Simulated precipitation was found to follow spatial distributions closer to the observed distributions in the IMERG with a difference in the positions of the forecasted cyclones.

Results of the sensitivity experiments suggest that cumulus parameterizations affect the forecasts of tropical cyclones tracks, lowest sea level pressure, maximum wind speed, and precipitation. The average DPE for KF (MT) cumulus convections with forecast lead times of 24, 48, and 72 hours were 53.4 km, 75.6 km, and 103.2 km (68.8 km, 120.2 km, and 213.1km), respectively. KF (MT) schemes produced forecasts of the tracks of tropical cyclones with an average DPE of 69.4 (98.7), 88.3 (82.4), and 180.4 (143.6) km for cyclone Jobo, Kenneth, and Idai, respectively. Cyclone Kenneth underwent a rapid intensification 12 hours (12UTC, 23rd April 2019) from initialization to the lowest pressure (maximum wind speed) of 934 hPa (120 knots) 48 hours later (00UTC, 25th April 2019). The lowest simulated sea level pressure and highest sustained winds for KF (MT) were 968 (990) hPa and 85(62) knots respectively for cyclone Kenneth. The average absolute error in the WRF forecasted lowest minimum pressure using KF (MT) cumulus convections were 10.2 hPa (11.85 hPa), 23.6 hPa (31.82 hPa) and 11.97 hPa (31.17 hPa), for cyclone Jobo, Kenneth and Idai, respectively. The KF scheme simulated the spatial distribution of precipitation from the tropical cyclones closer to the observed patterns with timing errors of the location of the maximum precipitation due to the errors in the forecast of tropical cyclones' location. The simulated precipitation is slightly behind the observed location.

The experiments on the sensitivity of the tropical cyclone forecast on microphysics revealed that the tracks and intensity of tropical cyclones are dependent on the choice of the microphysics scheme. For cyclone Jobo, WSM3 reduced the average DPE to 75.6 and 67.8 km MT and KF schemes, respectively. When the WSM3 scheme was used the DPE for cyclones Kenneth and Idai for the forecasts using KF (MT) cumulus schemes were found to be 88.4 (81.3) and 145.64 (101.62) km. For Tiedtke cumulus convection, the average DPE for WSM6 (WSM3) microphysics for the 24, 48, and 72 lead forecasts hours was 68(47.9), 120.2(78.6) and 213.1(95.2) km, respectively. The KF scheme average DPE for WSM6 (WSM3) microphysics for the 24, 48, and 72 lead forecast hours was 53.4 (65.4), 75.6 (79.5), and 103.2 (120.6) km, respectively. WSM6 scheme simulates the intensity of the cyclones comparable to the observations of the WSM3.

Overall, the WRF-ARW model simulated well the trajectory of tropical cyclones over the Southwest Indian Ocean for up to 4 days. The results revealed that the location of forecasted maximum precipitation was behind the location of the maximum rainfall in the observations. This suggests that the location of the center of the cyclone in the model controls the spatial distribution of the maximum precipitation. Further, magnitude and spatial extent depend on the cumulus scheme. The characteristics of tropical cyclones forecasted with the WRF-ARW model were dependent on the microphysics and cumulus convection parameterizations. More case studies on the characteristics of tropical cyclones should be carried out to find the best parameterizations to be used in operational forecasting.

5.2 Recommendations

With the changing climate, an increase in the proportion of more intense cyclones and a northward shift of the landfall locations is projected over the Southwest Indian Ocean. Therefore, different stakeholders have a part to play in reducing the impacts of these events around the coastal areas and hinterland.

5.2.1 To research community

The current study investigated only three cyclones. Other researchers could extend the study to cover more cyclones with similar characteristics to draw a general conclusion and improve the model's applicability in operational forecasting over the basin. Future studies could carry out the simulations of the cyclone track to cover more seasons (at least 10) to quantify the average errors in the track forecast (especially, along track errors (ATE) and cross-track errors (CTE)). The CTEs are particularly important in explaining the possible extent of the cyclone's trajectory. Sensitivity analysis could be extended to cover other physical parameterizations. Hence establishing the best model physics for cyclone forecasting using the WRF model over the Southwest Indian Ocean. Further study of the tropical cyclones steering mechanisms of tropical cyclones over the basin is needed to investigate the bias in speed and deflections of the cyclones as they approach the coasts.

5.2.2 To government and meteorological organizations over the basin

Initial conditions are the key to improving tropical cyclones and other extreme weather events forecasting. The leading meteorological organization in the basin could help improve the initial conditions by increasing data collection networks over the locations. The governments of countries around the basin could help strengthen the infrastructures to reduce the impacts of flooding from the associated precipitation. Dissemination of the news about the forecasted path of cyclone Jobo by different media resulted in chaos in the community. Proper channels should be put in place to ensure correct and verified early warnings reaches the community at risk.

5.2.3 To the local community around Southwestern Indian Ocean Basin

The use of social media has side effects during preparations for natural disasters. People should be careful and ensure that they listen to the guidance and warning issued by the governing body and take prompt actions s per guidance. The community should ensure that the drainage systems are intact and avoid building residences in flood-prone areas.

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APPENDICES

A. The forecasted cyclones track all initialization times for cumulus convection sensitivity tests.

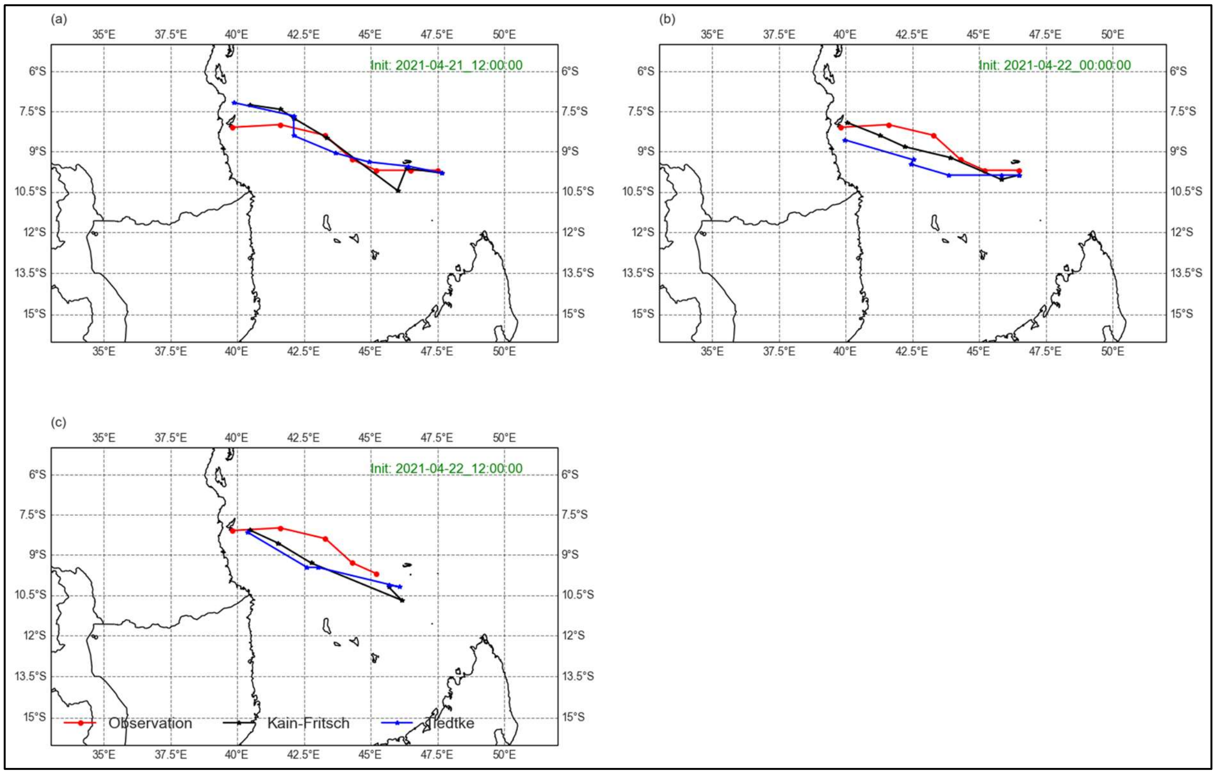

Figure 18: Observed and WRF forecasted trajectory of cyclone Jobo WSM6 as Microphysics scheme, Tiedtke, and KF cumulus scheme. The simulations have been initialized at 00UTC on 21st April (upper left), 12UTC on 21st April (upper right), 00UTC on 22nd April (lower left), and 00UTC on 22nd April 2021.

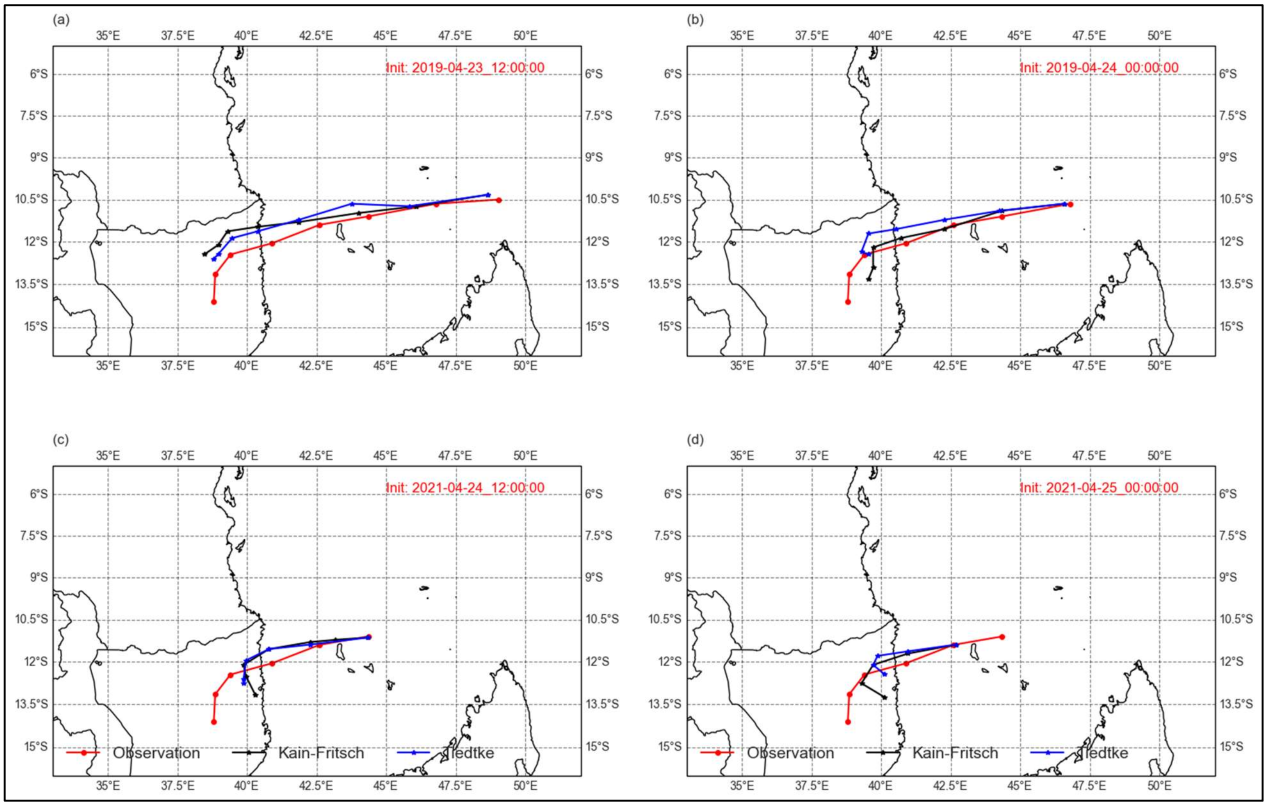

Figure 19: Observed and WRF forecasted trajectory of cyclone Kenneth. WSM6 as Microphysics scheme, Tiedtke (blue curves) and KF (black curves) cumulus scheme. The simulations have been initialized at 12UTC on 23rd April (upper left), 00UTC on 24th April (upper right), 12UTC on 24th April (lower left), and 00UTC on 25th April 2019.

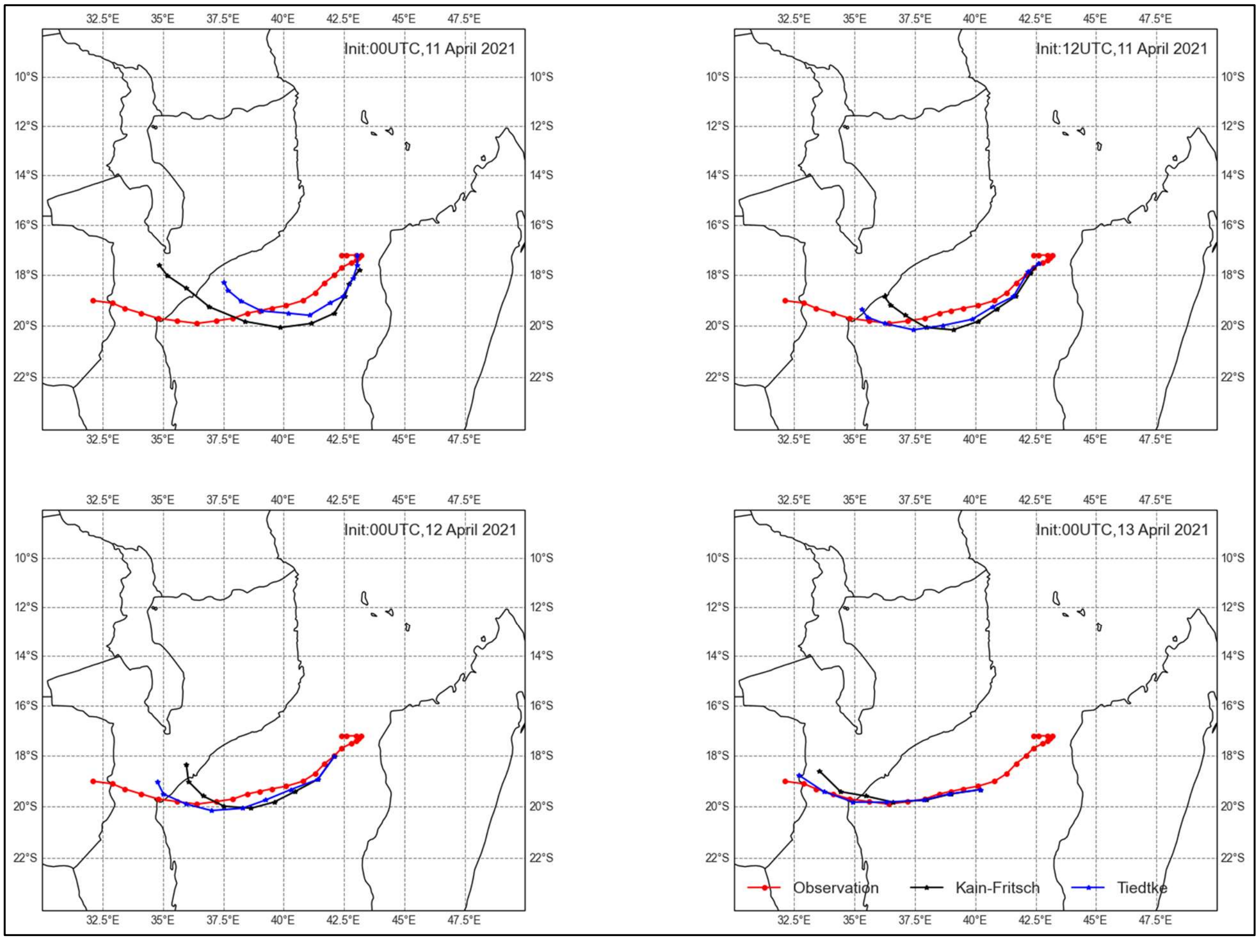

Figure 20: Observed and WRF forecasted trajectory of cyclone Idai. WSM6 as Microphysics scheme, Tiedtke (blue curves) and KF (black curves) cumulus scheme. The simulations have been initialized at 00UTC on 11th March (upper left), 12UTC on 11th March (upper right), 00UTC on 12th April (lower left), and 00UTC on 13th March 2019.