

Simulating the Characteristics of Tropical Cyclones over the South-West Indian Ocean: Sensitivity to Model Horizontal Resolution



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DECLARATION I

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Signed by candidate

Paige Tayla Donkin

DECLARATION II

Parts of this dissertation have been submitted and are under review for publication in the following papers:

- Donkin, P.T., Abiodun, B.J., James, R., Washington, R., Dyer, E. and Webb, T. (2022) The Impact of Model Horizontal Resolution on Simulating South-West Indian Ocean Tropical Cyclones. Under Review – *Climate Dynamics*
- Donkin, P.T. and Abiodun, B.J. (2022) Performance of MPAS-A in simulating Tropical Cyclones Idai and Kenneth over the South-West Indian Ocean. Under Review – *Atmospheric Research*.

ABSTRACT

Tropical cyclones (TCs) are the deadliest and most economically devastating of all natural hazards. Those that occur in the South-West Indian Ocean (SWIO) often strike vulnerable nations and can have serious socio-economic impacts, yet there is a dearth of information on how well these systems are simulated by contemporary climate models. This study investigates the performance of four global climate models and one variable-resolution climate model in simulating the characteristics of SWIO TC activity through both a climatological and individual event analysis, and investigates the influence of horizontal resolution on the simulated TC characteristics. The climatological analysis makes use of a multi-model, multi-resolution set of simulations from four modelling groups included in the CMIP6 HighResMIP project, covering the period 1980-2009. The individual event analysis focuses on the simulation of two highly destructive TC events which occurred in the SWIO in early 2019 – namely TC Idai and TC Kenneth. The simulation of individual events makes use of the atmospheric Model for Prediction Across Scales (MPAS-A), a non-hydrostatic variable-resolution model which is employed at multiple resolutions ranging from 60km–3km. In both analyses, systems were identified using a novel resolution-dependent tracking algorithm that includes wind speed, vorticity, and warm core thresholds. All model simulations were validated against the Reunion Specialised Meteorological Centre (RSMC) best track observations and the European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation reanalysis dataset (ERA5).

The results of the CMIP6 analysis indicate that all models produce realistic representations of TCs over the SWIO, but underestimate TC intensity, and feature a westward shift bias in the spatial distributions of TC activity. Increasing model horizontal resolution enhances the quality of the simulated TC frequency and intensity, with higher-resolution models showing more realistic storm counts and an increased ability to represent the full range of observed TC intensities. However, increasing horizontal resolution does not improve the spatial distribution of cyclogenesis locations

or TC tracks, nor the ability of the models to capture the long-term trends in TC activity. Similarly, the results of the MPAS-A analysis indicate that MPAS-A produces realistic TC tracks, but shows considerable southward track and landfall biases, and severely underestimates the intensities of the systems. A local increase in horizontal resolution over the SWIO improves all aspects of the TC simulation, including the TC track, intensity, wind-pressure relationship, and vertical structure. However, the level of improvement differs based on the physics parameterization suite employed in the model, the characteristic of interest, and the event in question. The present study illustrates the extent to which an increase in model horizontal resolution can improve simulated TC characteristics and offers insights on how to improve future projections of TC activity over the SWIO region.

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DEDICATION

To my Grand-mère, Maryse North-Coombes.

For the dreams she had for me.

LIST OF ACRONYMS

ACE	Accumulated Cyclone Energy
CAM	Community Atmosphere Model
CAM-EULAG	Community Atmospheric Model with EULAG dynamics
CAPE	Convective available potential energy
CFSR	Climate Forecast System Reanalysis
CMIP	Coupled Model Intercomparison Project
CMIP6	6 th Coupled Model Intercomparison Project
DMI	Dipole Mode Index
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño Southern Oscillation
EPV	Ertel's potential vorticity
ERA5	ECMWF fifth-generation reanalysis dataset
ERA-Interim	ECMWF interim reanalysis dataset
ERC	Eyewall replacement cycle
GCM	Global climate model
GPI	Genesis potential index
GWDO	Orography-induced gravity wave drag
HighResMIP	High Resolution Model Intercomparison Project
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
JTWC	Joint Typhoon Warning Centre
KDE	Kernel density estimation

MC	Mozambique Channel
MJO	Madden-Julian Oscillation
MPAS	Model for Prediction Across Scales
MRF	Medium Range Forecast
MSLP	Mean sea level pressure
MSW	Maximum sustained wind
PBL	Planetary Boundary Layer
PDF	Probability density function
PRIMAVERA	Process-based climate simulation: advances in high-resolution modelling and European climate risk assessments
PV	Potential vorticity
RCM	Regional climate model
RCP	Representative Concentration Pathway
RMSE	Root mean square error
RRTMG	Rapid Radiative Transfer Model for GCMs
RSMC	Reunion Specialised Meteorological Centre
SLP	Sea level pressure
SST	Sea surface temperature
SWIO	South-West Indian Ocean
TC	Tropical cyclone
VGCM	Variable-resolution global climate model
WRF	Weather Research and Forecasting Model
WSM6	WRF Single-moment 6-class microphysics scheme
YSU	Yonsei University

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CHAPTER 1 : Introduction

1.1 Background

The South-West Indian Ocean (SWIO) region is home to a number of culturally and economically diverse nations. Along the east coast of southern Africa, the region includes the countries of South Africa, Zimbabwe, Mozambique, Tanzania, and Kenya (Fig. 1.1). These countries are rich in natural resources, boasting abundant mineral reserves and agricultural wealth (Coface, 2021a, 2021b, 2021c, 2021d, 2021e). These natural resources contribute significantly to each nation's gross domestic product, with agricultural and mining products comprising their top exports (Observatory of Economic Complexity (OEC), 2019a, 2019d, 2019e, 2019f, 2019g). The SWIO also encompasses several island nations, including Madagascar, Zanzibar, Comoros, Seychelles, and the Mascarene Islands (Reunion and Mauritius). With their tropical climates, warm ocean waters and sandy beaches, these island nations attract millions of tourists each year (Obura *et al.*, 2017). Like many countries along the east coast of southern Africa, the islands of Madagascar and Mauritius rely heavily on natural resources for economic growth. Madagascar is the world's leading exporter of vanilla, while Mauritius has a thriving sugar industry (OEC, 2019b, 2019c).

Despite their great economic potential, many SWIO nations are among the poorest in the world (Obura *et al.*, 2017). The economic contribution of their mineral and agricultural industries is thus central to alleviating poverty and improving quality of life for the region's 220 million inhabitants. However, extreme weather events from tropical cyclones (TCs) continue to threaten the natural resources and agricultural practices that underpin the socio-economic activities in this region.

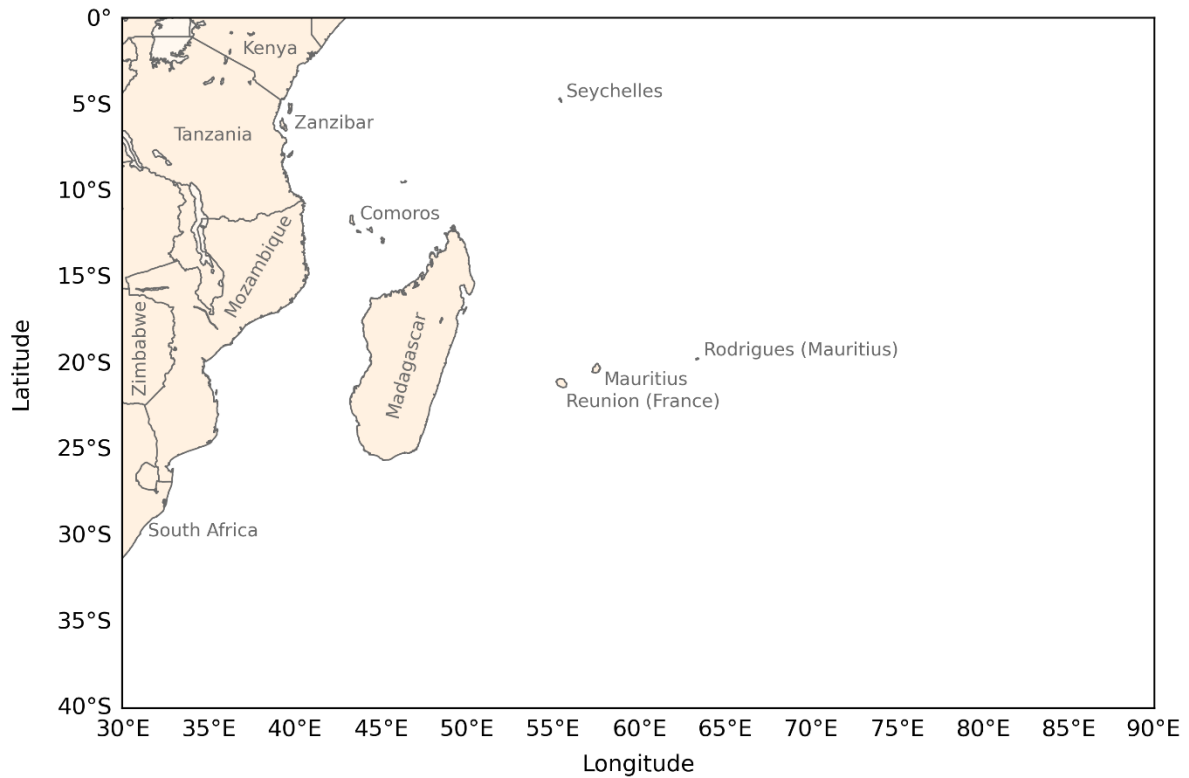


Figure 1.1 Map of the SWIO and surrounding countries.

1.2 What is a tropical cyclone?

1.2.1 Definition

A TC is a non-frontal synoptic-scale convective system that develops over tropical or subtropical waters. These systems are characterised by the presence of a warm core, low-pressure centre, closed cyclonic surface circulation, and organised deep convection (Holland, 1993). TCs can be classified based on their maximum sustained wind (MSW), which is a measure of system intensity (World Meteorological Organization (WMO), 2021). However, there are notable differences in TC classification depending on the basin in which the system occurs. One such difference is the definition of MSW. In the South Indian and South-West Pacific Oceans, the MSW is defined as the 10-minute average wind speed, whereas in the North Atlantic and North-East Pacific Oceans, the 1-minute average wind speed is used (WMO, 2021).

Furthermore, while the classification of tropical depressions ($MSW < 63\text{km/h}$) and tropical storms ($63\text{km/h} < MSW < 117\text{km/h}$) is largely consistent across basins, systems with a MSW exceeding 118km/h are classified in a basin-dependent manner (WMO, 2021). The general terms used to describe such systems ($MSW > 118\text{km/h}$) are: Tropical Cyclone (over the South Indian and South-West Pacific Oceans), Typhoon (over the North-West Pacific Ocean), and Hurricane (over the North Atlantic and North-East Pacific Oceans) (WMO, 2021). However, the most prominent storm classification scale is the Saffir-Simpson Hurricane Wind Scale (Table 1.1), which is used primarily to classify hurricanes in the North Atlantic and North-East Pacific but often used globally to allow for relative comparisons of TC intensities in different ocean basins (e.g., Murakami *et al.*, 2012, 2015; Zarzycki and Jablonowski, 2014).

Table 1.1 Saffir-Simpson Hurricane Wind Scale (MSW – 1-minute average wind speed).

Category	Maximum sustained wind speed	
	knot	km/h
Tropical Depression	0–34	0–62
Tropical Storm	35–63	63–117
Category 1	64–82	118–153
Category 2	83–95	154–177
Category 3	96–113	178–208
Category 4	114–135	209–251
Category 5	≥ 136	≥ 252

The TCs that occur in the SWIO are monitored by Météo-France Regional Specialized Meteorological Centre (RSMC) located on Réunion Island. RSMC uses an alternative scale to classify TCs in the basin (Table 1.2). A comparison between the Saffir-Simpson and Météo-France scales is given in Figure 1.2.

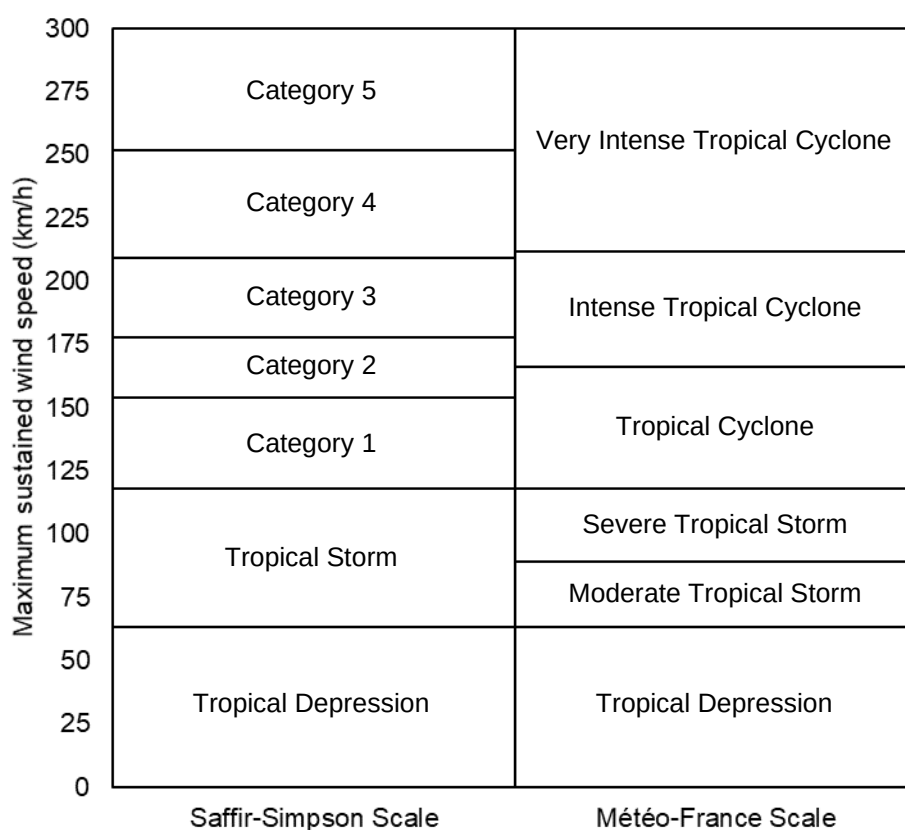


Figure 1.2 Comparison of Saffir-Simpson and Météo France classification scales.

Table 1.2 Météo-France Tropical Cyclone Scale (MSW – 10-minute average wind speed).

Category	Maximum sustained wind speed	
	knot	km/h
Tropical Depression	28–33	51–62
Moderate Tropical Storm	34–47	63–88
Severe Tropical Storm	48–63	89–117
Tropical Cyclone	64–89	118–165
Intense Tropical Cyclone	90–115	166–212
Very Intense Tropical Cyclone	> 115	> 212

1.2.2 Structure

TCs are characterised by a calm eye in the centre of the system, an eyewall with strong winds and rainfall, and rainbands of clouds and thunderstorms that spiral outwards (Fig. 1.3) (National Weather Service (NWS), 2021). Subsidence motion in the eye results in a cloud-free region of calm winds, which typically spans 32–64km in diameter (NWS, 2021). The eye also features a pressure deficit of up to 10% of the ambient pressure, requiring the vertical extension of the system's warm core throughout the troposphere (Haurwitz, 1935; Kepert, 2010). The formation of an eye generally occurs when the system reaches TC intensity (MSW > 118km/h). At this stage, the strong cyclonic rotation of the system balances the inflow to the centre, resulting in ascending air and the formation of an eyewall (NWS, 2021).

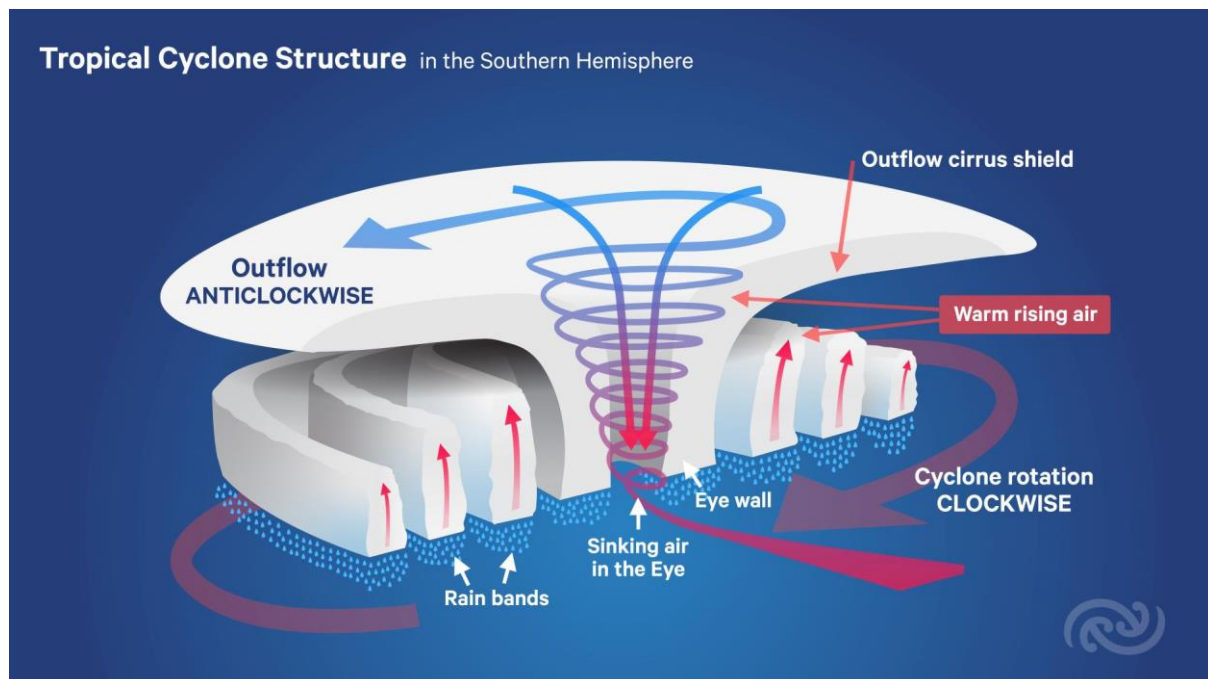


Figure 1.3 General structure of a Southern Hemisphere TC showing the eye, eyewall, and rainbands (Source: Science Media Centre; <https://www.sciencemediacentre.co.nz/2020/02/15/tropical-cyclones-expert-qa/> (Accessed: 9 November 2021)).

The eyewall, which surrounds the eye of the TC, consists of a ring of deep convective thunderstorms (Kepert, 2010; NWS, 2021). Due to the presence of deep convection and thunderstorm updrafts in the eyewall, this region of the TC is generally associated

with the most intense winds and rainfall (Kepert, 2010). The formation of the TC's warm core is also associated with the eyewall because, as moist air parcels rise and cool in the thunderstorm updrafts, condensation results in the release of latent heat (Pennsylvania State University (PSU), 2021). Furthermore, once the rising air reaches the top of the troposphere, its divergence away from the storm centre reduces the weight of air columns near the eye, lowering the sea level pressure (SLP) (PSU, 2021). While the majority of rising air diverges away from the centre of the system, the cyclonic rotation of the TC creates a vacuum in the eye, causing some of the air to sink in the TC centre to replace the loss of air mass (NWS, 2021; PSU, 2021). The sinking air warms, contributing to the TC's warm core and further intensifying the system (due to the effect of warming on air density within the eye, which reduces the SLP) (PSU, 2021). Any change in the eye and eyewall's size or structure can affect the TC's wind speed and, subsequently, the system's intensity (NWS, 2021).

Rainbands of clouds and thunderstorms spiral outward from the eyewall and often produce strong gusts and heavy rain (NWS, 2021). In intense systems, the outer rainbands can form a concentric or secondary eyewall, which moves inward and eventually interferes with the moisture and momentum of the inner eyewall, causing a temporary weakening of the system as the TC undergoes an eyewall replacement cycle (ERC). Once this process has been completed, the system's intensification resumes (NWS, 2021). The intensification increases the TC's category on the Saffir Simpson Scale (Table 1.1), as well as its destructive power.

1.3 Socio-economic impacts of tropical cyclones

TCs can have a devastating impact on the socio-economic activities of coastal communities, as landfalling systems are usually accompanied by extreme rainfall, storm surges, and strong winds. This often results in widespread flooding, damage to infrastructure, and loss of life (Badarinath *et al.*, 2012). For instance, in the United States alone, the cumulative damages from TCs between 1980–2021 have totalled over 1 trillion dollars (2022 USD) (National Centers for Environmental Information (NCEI), 2022). With the continued growth of coastal populations and rapid increases

in coastal development over the past decades, these systems will likely continue to cause the largest economic losses among the natural hazards.

In the SWIO, TCs pose a major socio-economic threat as many nations rely heavily on natural resources and over 60% of the local populations in both Mozambique and Madagascar reside in coastal areas (Mavume, 2008). With the SWIO experiencing high levels of TC activity each year, these countries are subject to widespread destruction annually, especially during the Indian Ocean cyclone season (November–April).

The costliest, deadliest, and most active cyclone season in the recorded history of the SWIO occurred in 2018/19. On 15 March 2019, TC Idai made landfall over Beira, Mozambique, causing catastrophic damage in Mozambique, Zimbabwe, and Malawi (Fig. 1.4). Described as the deadliest TC ever recorded in the SWIO, TC Idai claimed over 1,300 lives (Hope, 2019). Merely one month later, on 25 April 2019, TC Kenneth made landfall over Pemba, Mozambique, becoming the strongest landfalling system in the country's history (Hope, 2019). The extreme rainfall and extensive flooding that resulted from these events displaced over 2.2 million people and destroyed thousands of hectares of agricultural land (United Nations Children's Fund (UNICEF), 2019; Wachiaya, 2020). Stagnant water from widespread flooding provided favourable conditions for malaria, and an insufficient water supply led to a cholera outbreak – with over 6,700 cases reported in Mozambique alone (Mongo *et al.*, 2020). The quick succession of these events stretched relief efforts to breaking point, worsening food security and the socio-economic problems already confronting Mozambique and the surrounding nations. In total, nearly 3 million people were affected, and the cost of cumulative damages reached almost 3 billion USD (2019 USD) (World Bank, 2019; Arntzen, 2021). One year later, 100,000 people were still reported to be living in resettlement sites (World Vision, 2019). The aftermath of these events highlights the great potential that TCs have for causing unprecedented damage in many of southern Africa's developing countries, most of which have agriculture-dominated economies, poor hazard-warning systems and undeveloped risk-mitigation strategies (Leroux *et al.*, 2018).



Figure 1.4 Widespread flooding and destruction in Buzi, Mozambique, on 20 March 2019 following the landfall of TC Idai (Source: Weather Underground; <https://www.wunderground.com/cat6/Africas-Hurricane-Katrina-Tropical-Cyclone-Idai-Causes-Extreme-Catastrophe> (Accessed: 11 November 2021)).

1.4 Importance of tropical cyclones

Despite the negative socio-economic impacts, TCs are an important part of mean climate cycles (Roberts *et al.*, 2020a). On a larger scale, TCs act to regulate the temperature of the Earth system by cooling surface waters as they propagate across ocean basins (Loewe *et al.*, 2021). In addition to surface cooling, TCs cause vertical displacements of the oceanic thermocline, thereby transporting nutrients from deep layers to the ocean surface. This increase in surface nutrients subsequently promotes the growth of phytoplankton, the world's largest producers of oxygen (Loewe *et al.*, 2021).

TCs also account for 2% of total global annual rainfall (Loewe *et al.*, 2021) and play an important role in water availability by bringing rainfall to areas of drought,

recharging aquifers, and increasing stream flow (Paya, 2020). In the SWIO, TCs contribute significantly to regional rainfall totals over the north-eastern parts of South Africa. In the semi-arid Limpopo River Basin, over 50% of multi-day heavy rainfall events are attributed to these systems (Malherbe *et al.*, 2012). Incidentally, studies project a decrease in SWIO TC activity in the future, which will be accompanied by a decrease in rainfall over the Limpopo River Basin (Malherbe *et al.*, 2013). This lack of adequate precipitation could have serious implications for water availability and the risk of drought in the region.

Given their huge potential for causing damage and their fundamental importance in the climate system, it is clear that there is a pressing need for accurate forecasting of TCs on both seasonal and sub-seasonal scales. Improving our forecasting competencies will allow nations to adequately prepare for the passage of these events and adopt plans to minimise their negative impacts. Conversely, improved forecasting will also allow affected populations to exploit their important rainfall contributions. However, accurate forecasting of TC occurrences requires reliable tools for simulating these events.

1.5 Tools for simulating tropical cyclones

Climate models (or atmospheric models) are the most viable tools for simulating atmospheric features such as TCs. Climate models provide a mathematical representation of the Earth system by dividing the planet into a 3-dimensional grid (Fig. 1.5) and employing differential equations based on the laws of physics, fluid motion, and chemistry. Different types of climate models are commonly used to simulate TCs, namely: global climate models (GCMs), regional climate models (RCMs), and variable-resolution climate models (VGCMs). The following section outlines each method of modelling, as well as each model's application in TC simulation.

1.5.1 Global climate models

GCMs, which use a uniform-resolution grid globally and simulate all areas of the planet (Fig. 1.5), have been used to simulate TC activity in numerous studies (e.g., Zhao *et*

al., 2009; Manganello *et al.*, 2012; Kim *et al.*, 2018; Moon *et al.*, 2020; Roberts *et al.*, 2020a, 2020b). Early studies on TC simulation in GCMs were limited to the simulation of TC-like structures in low-resolution grids (Maoyi *et al.*, 2018). While these TCs were comparable to observed TCs in terms of their spatial and temporal distribution, the low-resolution GCMs were unable to intensify the simulated systems to TC strength, and the spatial scales of the simulated storms were often larger than observed (Manabe *et al.* 1970; Bengtsson *et al.*, 1982; Vitart *et al.*, 1997). An increase in computing power over the past decades has improved the representation of these systems in GCMs, with long-period, high-resolution simulations becoming increasingly possible. However, they remain economically costly and computationally demanding. For this reason, GCMs are still commonly run at relatively coarse resolutions (100–200km), thereby limiting the simulation of small-scale TC features, which are central to numerous physical processes (Maoyi *et al.*, 2018). It is essential to investigate how the characteristics of simulated TCs vary across contemporary GCMs and how the simulated characteristics vary with model resolution. The present study offers such insights.



Figure 1.5 Example of a global climate model (GCM) grid. (Source: Lawrence Livermore National Laboratory; <https://str.llnl.gov/december-2017/bader> (Accessed: 10 January 2022)).

1.5.2 Regional climate models

RCMs have also been used to simulate TCs (e.g., Mohanty *et al.*, 2010; Islam *et al.*, 2015; Hegde *et al.*, 2016). By simulating only the region of interest, these models are less computationally demanding than GCMs and thus allow for the use of higher-resolution grids (Fig. 1.6). However, the TC simulation in RCMs can be compromised by the accuracy of the boundary conditions used in the model (Maoyi *et al.*, 2018). Boundary condition errors are especially problematic in the simulation of TCs as they often weaken the representation of large-scale features such as the El Niño Southern Oscillation (ENSO), the Madden-Julian Oscillation (MJO), and the Indian Ocean Dipole (IOD), which are known to modulate TC activity (Strachan *et al.*, 2013). Since TCs in one region are often influenced by remote features (such as sea surface temperature (SST)) in another region (Vitart *et al.*, 1999), RCMs may therefore require relatively large domains to capture large-scale feedbacks and circulations (Laprise *et al.*, 2012); a requirement that is seemingly contradictory to their intended purpose.

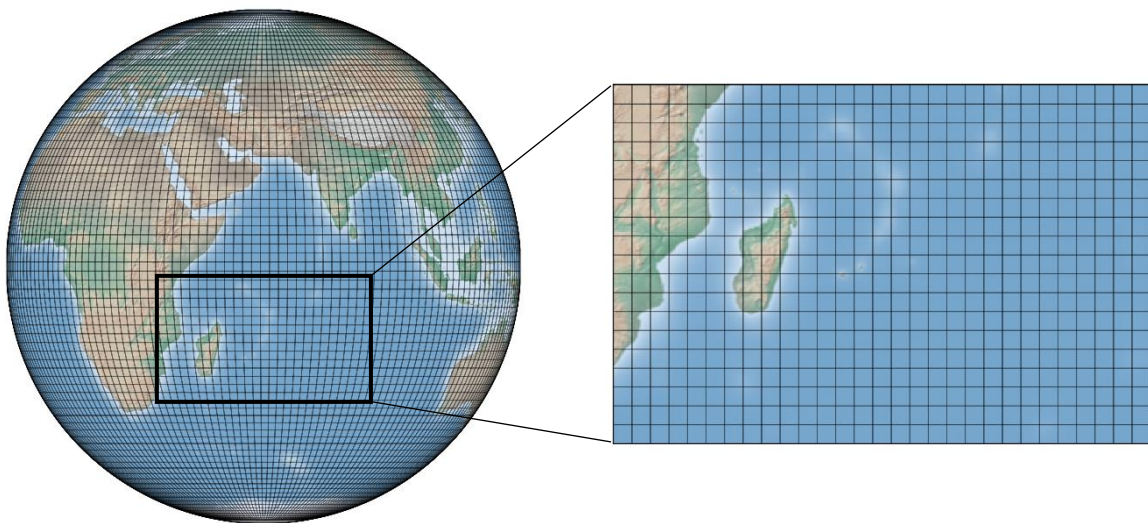


Figure 1.6 Example of a regional climate model (RCM) grid.

1.5.3 Variable-resolution global climate models

VGCMs overcome the challenge of RCMs by eliminating the need for boundary conditions and allowing for high-resolution simulation over a region of interest, while

still simulating the rest of the globe (Fig. 1.7). Therefore, unlike RCMs, these models support the communication of remote feedbacks. VGCMs have shown considerable skill in simulating TC activity. For instance, in terms of spatial patterns, frequency, and intensity (Zarzycki and Jablonowski, 2014; Maoyi *et al.*, 2018), VGCMs often produce superior simulations to those of a coarse-grid uniform-resolution GCM. Further, the use of a variable-resolution grid has been shown to significantly decrease the computational demand required for a simulation compared to a global uniform grid at the same resolution (Zarzycki and Jablonowski, 2014). However, despite their advantages, VGCMs are a relatively new tool that require further development and fine-tuning. For this reason, VGCMs are not yet widely used in climate application studies and most modern studies that have utilised these models have focused on their evaluation (e.g., Davis *et al.*, 2016; Michaelis *et al.*, 2019; Kramer *et al.*, 2020; Gilliam *et al.*, 2021; Hsu *et al.*, 2021; Lui *et al.*, 2021; Zheng *et al.*, 2021). This study makes use of a VGCM called the Model for Prediction Across Scales (MPAS).

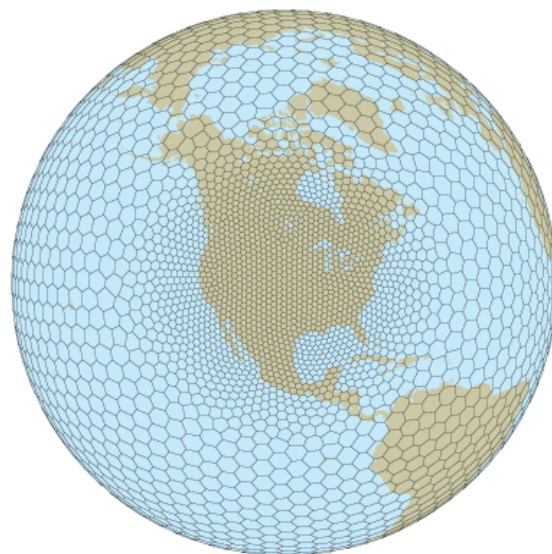


Figure 1.7 Example of a variable-resolution climate model (VGCM) grid (Source: Haupt *et al.*, 2020).

MPAS employs a spherical centroidal Voronoi mesh and supports the use of both uniform- and variable-resolution grids (Zhao *et al.*, 2019). MPAS has been used to study various atmospheric processes and features including TCs (Davis *et al.*, 2016; Michaelis *et al.*, 2019; Lui *et al.*, 2021); monsoons (Lau *et al.*, 2020; Hsu *et al.*, 2021);

air quality (Gilliam *et al.*, 2021); CO₂ transport (Zheng *et al.*, 2021); and even large-scale features such as the MJO (Pilon *et al.*, 2016).

In the simulation of TCs, MPAS has proven to be a valuable tool for studying features on spatial scales that would be unachievable in most GCMs, indicating that this model may be a suitable choice for seasonal TC forecasting over the SWIO. However, MPAS has not yet been used in any studies to simulate SWIO TC activity. Therefore, before adopting this model for application over the region, there is a need to test its capability in simulating the characteristics of TCs over the SWIO, as high model skill in one region does not necessarily translate to equal performance in another region. The present study seeks to address this.

To further guide the application of MPAS for seasonal forecasting over the SWIO, it is necessary to test the sensitivity of MPAS to the model configuration. Model horizontal resolution (hereafter referred to as resolution) is one of the most influential factors in the simulation of TCs, and while there is a general consensus that higher-resolution models produce more realistic TC simulations (Bengtsson *et al.*, 1995, 2007; Murakami *et al.*, 2015; Roberts *et al.*, 2020a, 2020b), the operational use of these models requires an understanding of the optimal resolution that is needed to accurately capture TC characteristics. However, even at equal resolutions, models show considerable variations in their ability to simulate TC characteristics (Shaevitz *et al.*, 2014; Roberts *et al.*, 2020a), and thus the optimal resolution for TC simulation will differ between models. Hence, before MPAS can be applied over the SWIO, there is a need to understand the model's sensitivity to resolution and obtain the optimal resolution for SWIO TC simulations. This forms part of the investigation in the present study.

At any given resolution, there are some atmospheric processes that cannot be resolved and thus require parameterization for their influence to be felt in the climate simulation. However, climate models are highly sensitive to parameterization schemes (Hill and Lackmann, 2009; Reed and Jablonowski, 2011a; Kepert, 2012). While some parameterizations are suitable at any resolution, some are only appropriate for either low- or high-resolution simulations. For this reason, it is important to understand the

sensitivity of MPAS to the physics parameterizations used in the model in order to ensure compatibility between the model's resolution and parameterization. This is a focus of this dissertation.

At a fundamental level, the reliability of any model depends on the accuracy of its initial conditions. This is because unless the present conditions are explicitly known, it is impossible to obtain an accurate prediction of the future state (Lorenz, 1963). Consequently, even small errors in the initial conditions can result in large errors in the subsequent forecast. Since there are several datasets that are commonly used to initialize climate models, there is a need to test the sensitivity of MPAS to initial conditions and determine which dataset offers the best simulation of TCs over the SWIO. This dissertation will improve knowledge in this area.

1.6 Aim and objectives

This dissertation aims to examine how well contemporary GCMs and MPAS simulate the characteristics of TCs over the SWIO and to explore the sensitivity of the simulated TCs to model configurations, such as resolution.

The objectives of the study are to:

- Evaluate the performance of CMIP6 models in capturing the characteristics of TCs over the SWIO;
- Examine the influence of changes in model resolution on the characteristics and environments of the TCs;
- Evaluate the performance of MPAS in simulating the characteristics of TC Idai and TC Kenneth; and
- Investigate the sensitivity of the simulated TCs to model initial conditions, physics parameterizations, and model resolution.

1.7 Dissertation outline

This dissertation is organised into six chapters. The present chapter introduces TCs and their associated phenomena; explains the impact and importance of TCs over the

SWIO; outlines the various tools that are used for TC simulation; and motivates for why there is a need to increase our understanding of the performance of these tools in simulating the characteristics of TCs over the SWIO region.

Chapter 2 consists of a literature review that gives a comprehensive overview of the capability of climate models to simulate TCs and the challenges associated with the modelling of these systems. The chapter goes on to discuss the environmental conditions conducive to TC development; the differing approaches to tracking TCs in climate model output; and the results of studies that have explored observations and simulations of TC characteristics over the SWIO.

Chapter 3 describes the methodology of the dissertation. This includes the study domain; the datasets used in the study; MPAS model set-up; a description of the TC tracking algorithm and its implementation; the TC metrics used in the model evaluation; and a description of the two TC events simulated with MPAS.

The results of the dissertation are presented and discussed in the following two chapters. Chapter 4 focuses on the performance of CMIP6 models in simulating the characteristics of TCs over the SWIO, including the influence of the resolution on the characteristics and environments of the simulated TCs. By contrast, Chapter 5 focuses on the performance of MPAS in simulating the characteristics of two individual SWIO TC events, including the sensitivity of the simulated TCs to the initial conditions, physics parameterizations, and resolution of MPAS.

Chapter 6 provides is the conclusion, which includes a summary of the findings of this dissertation, their application, and suggestions for future work.

CHAPTER 2 : Literature Review

This chapter provides a comprehensive review of literature relating to TCs, with a focus on the numerical modelling of TCs and TC activity over the SWIO. The review starts with the capability of climate models to simulate TCs (Section 2.1), followed by the challenges in TC simulation (Section 2.2). This chapter goes on to give an overview of the studies that have been conducted on the environmental conditions for TC development (Section 2.3); the rapid intensification of TCs (Section 2.4); and the tracking of TCs in climate model output. Finally, it discusses past studies on the observations and simulations of SWIO TC activity (Section 2.6).

2.1 The capability of climate models in simulating tropical cyclones

2.1.1 Global climate models

The capability of GCMs to simulate TCs has been extensively documented (see review by Camargo and Wing, 2016). Manabe *et al.* (1970) were the first to record the presence of TC-like vortices in climate models. Their study, which focused on the characteristics of tropical circulation in GCMs, noted the occurrence of cyclonic vortices in regions of TC formation. While these vortices were accompanied by TC-like phenomena (such as low surface pressures, heavy precipitation, surface convergence, and upper-atmosphere divergence), the low-resolution model could not intensify these systems to TC strength. A later study on these vortices by Bengtsson *et al.* (1982) found that they were comparable to observed TCs in terms of their spatial and temporal distribution. Towards the end of the 1980s, the successful forecasting of individual events shed some light on the model characteristics required to accurately simulate TCs.

Krishnamurti *et al.* (1989) showed the importance of certain GCM features (including the adequate resolution of surface layer fluxes and parameterizations of boundary layer, cumulus convection, and radiative processes) in simulating TCs. Most

importantly, the authors found an improvement in storm formation and track with increased resolution. A follow-up study by Krishnamurti and Oosterhof (1989), which employed a high-resolution model and advanced data-assimilation scheme in tracking TCs, successfully forecasted a typhoon from tropical depression to landfall stage – paving the way for future work on TCs.

One focus of TC modelling studies in the 1990s was on the ability of climate models to reproduce the modulation of TC activity by large-scale climate oscillations, such as ENSO. Wu and Lau (1992), forcing the Geophysical Fluid Dynamics Laboratory (GFDL) model with observed SSTs for 15 years, were able to shed some light on how this modulation occurs by analysing changes in environmental fields during the different ENSO phases. This led to the development of dynamical TC seasonal forecasts by Vitart *et al.* (1997). Vitart *et al.*'s study, which focused on TC frequency, noted that model prediction skill was much higher in certain regions (specifically over the North Pacific and North Atlantic Oceans) than in others. It also noted an increase in predictability during years of strong ENSO signals (Vitart *et al.*, 1997). In a later study, Vitart *et al.* (1999) confirmed the predictability of other TC characteristics including intensity and genesis locations. This study also found that SSTs in remote regions can impact simulated tropical storm statistics in other regions through the large-scale atmospheric circulation, thereby demonstrating the ability of GCMs to simulate the large-scale environment.

The Coupled Model Intercomparison Project (CMIP) is a standard experimental framework for studying GCM output that facilitates model evaluation and subsequently informs model development (Climate Data Guide, 2022). The capability of the most recent project (CMIP6), which comprises the state-of-the-art GCMs, to simulate global TC activity has been investigated by some studies (e.g., Moon *et al.*, 2019; Roberts *et al.*, 2020a, 2020b; Han *et al.*, 2021). For example, Roberts *et al.* (2020b) found that high-resolution model simulations from the CMIP6 High Resolution Model Intercomparison Project (HighResMIP) show considerable skill in simulating TC frequency, intensity, and spatial distribution. Similarly, Han *et al.* (2021) employed 33 CMIP6 models to simulate the large-scale TC environmental fields in all ocean basins. Like Roberts *et al.* (2020b), the authors noted that the models with the highest

resolutions generally offered the best performance. However, Han *et al.* (2021) explained that the model skill varies based on the region and metric evaluated.

Despite the numerous studies done on the capability of CMIP6 models to simulate TCs over various regions of the world, none of them have focused on the SWIO region. This makes the SWIO the least studied TC region, especially when it comes to documenting the capability of contemporary models to simulate TC activity in the basin. This dissertation, therefore, attempts to address this gap by evaluating the performance of four CMIP6 models in simulating TC activity in the SWIO. This work aims to provide insights into those models' biases over the region and establish evidence for the most suitable CMIP6 models in simulating TC characteristics over the SWIO.

2.1.2 Regional climate models

The use of RCMs has been adopted by many modelling groups as a more computationally-economical approach to high-resolution TC simulations (Camargo and Wing, 2016). For instance, Huang and Chan (2014) used a region climate model (RegCM3) to investigate the predictability of TC landfall in East Asia. While the authors found that the regional model driven by the National Centers for Environmental Prediction (NCEP) Climate Forecast System Version 2 (CFS2) data exhibited a better forecast skill than CFS2 alone, there are several downfalls associated with RCM TC simulation.

One of the clear drawbacks of using RCMs to simulate TCs has already been mentioned in relation to the study by Vitart *et al.* (1999). Vitart *et al.* (1999) found that tropical systems are often influenced by remote features communicated by the large-scale environment. It is therefore crucial that the domain chosen for an RCM simulation not only encompasses the region of interest, but also all the other regions that influence this area and the general climate characteristics of the model. When Landman *et al.* (2005) investigated the impact of domain choice on the simulation of tropical cyclone-like vortices in the SWIO, the authors found that the eastern boundary of the domain exerted a strong influence on the life cycles of simulated vortices.

Furthermore, the authors noted that storm tracks were also affected by the presence of Madagascar, through its influence on the low-level atmospheric flow. While these findings do have application for improving RCM TC simulation in the SWIO, they do not overcome the issues associated with the need for boundary conditions. Strachan *et al.* (2013) found that the use of boundary conditions weakened the representation of large-scale processes, such as ENSO and the MJO, which exert a remote, rather than local, influence on the region.

Despite these shortfalls, RCMs have also shown considerable skill in simulating TCs (e.g., Mandal *et al.*, 2003; Hegde *et al.*, 2016; Patricola and Wehner, 2018). One study by Done *et al.* (2015), for example, focused on the resolution sensitivity of the Nested Regional Climate Model (NRCM). This study found that the use of a higher resolution was favourable in that it allowed for the accurate simulation of the small-scale TC structure. However, they noted that this level of detail was not necessary for climate predictions and thus may not be the optimal use of resources, suggesting that RCMs are more suited to the simulation of individual events. The present study will not consider the performance of RCMs in SWIO TC simulation.

2.1.3 Variable-resolution global climate models

As part of the effort to strike a balance between accuracy and computational demand (while still allowing for two-way interactions between regional and global processes by eliminating the need for lateral boundary forcings), several studies have evaluated the capability of VGCMs in simulating TCs (e.g., Daloz *et al.*, 2012; Zarzycki and Jablonowski, 2014, 2015; Maoyi *et al.*, 2018). For instance, Maoyi *et al.* (2018) employed a stretched-grid GCM (Community Atmospheric Model (CAM) with EULAG dynamics (CAM-EULAG)) to simulate the characteristics of TCs over the SWIO. This study found that the VGCM could produce realistic simulations of both the regional climate and the spatial distributions of TC activity. In the North Atlantic, Zarzycki and Jablonowski (2014) performed a multidecadal simulation of TC activity using a VGCM (CAM Spectral Element). They found that the use of a variable-resolution grid significantly decreased the computational demand required for the simulation. Furthermore, the study noted that compared to a coarse-grid uniform-resolution GCM,

the increased resolution over the study domain improved simulated TC frequency and intensity.

Davis *et al.* (2016) examined the skill of MPAS for medium-range TC forecasts over the North Pacific Ocean, by comparing the model performance in a 15km uniform-grid simulation and a 60–15km variable-grid simulation. They found that these simulations produced similar TC forecasts, indicating that VGCMs offer a cost-effective approach to medium-range TC forecasting. Lui *et al.* (2021) compared the performance of the Weather Research and Forecasting Model (WRF) with MPAS in simulating several historical TC events in the North Pacific between 1979–2018. While the study noted that both models produce realistic storm tracks and underestimate TC intensity, the performance of MPAS was superior to that of WRF. Another study on Northern Hemisphere TC activity by Michaelis *et al.* (2019) also employed MPAS with a 60–15km variable resolution configuration. The authors found that MPAS reasonably represented the large-scale atmospheric features and annual precipitation patterns. Furthermore, the authors noted that MPAS adequately captured the characteristics of Northern Hemisphere TCs. The study therefore identified MPAS as a valuable tool for studying the effects of climate change at spatial scales that would be unachievable in most GCMs. Despite these promising results from MPAS TC simulations, no studies have evaluated the performance of MPAS for TC simulation in the SWIO region. The present study will demonstrate the capability of MPAS in simulating TC events over the SWIO and analyse the sensitivity of the simulated TCs to the model configuration.

2.2 Challenges in tropical cyclone simulation

TC simulations have been shown to be highly sensitive to model parameters, including resolution (e.g., Gentry and Lackmann, 2010; Roberts *et al.*, 2020a), physics parameterizations (e.g., Reed and Jablonowski, 2011b; Islam *et al.*, 2015), and initial conditions (e.g., Mohanty *et al.*, 2010; Yamaguchi *et al.*, 2012). The following section provides an overview of the current knowledge of the impact of each parameter on TC simulation.

2.2.1 Horizontal resolution

Previous studies agree that model resolution is one of the most influential factors in the simulation of TCs. Early studies by Manabe *et al.* (1970), Bengtsson *et al.* (1982), and Krishnamurti *et al.* (1989) were limited to the simulation of TC-like structures in low-resolution grids. However, despite this limitation, these studies demonstrated the importance of model resolution in TC simulation. Another early study by Bengtsson *et al.* (1995) demonstrated an improvement in simulated TC intensity and structure when employing the TL106-L19 model at a resolution of 150km (as compared to 300km). Bengtsson *et al.* (1995) noted that the low-resolution simulations (300km) produced weaker and larger storms with less realistic vertical and horizontal structures. Increases in computing power over the past decades have improved the representation of TCs in GCMs through the use of high-resolution meshes. However, Roberts *et al.* (2020a) explained that many models, such as those included in the CMIP ensembles, are still run at relatively coarse resolutions (~100km). For this reason, the impact of model resolution on TC simulation remains a focus in the modern literature.

Recent studies investigating the impact of resolution on TC simulation using contemporary models have noted improvements in several TC characteristics when employing high-resolution grids. Mandal *et al.* (2003) employed a regional weather prediction model at varying resolutions (165km and 55km) to simulate two TC events that formed over the Bay of Bengal in 1995 and 1997. This study noted an improvement in the simulated TC structure, intensity, and track for both events at the finer resolution (55km). At a comparable resolution of 50km, Zhao *et al.* (2009) noted a high correlation between observations and the simulated TC interannual variability in the North Atlantic ($r=0.83$) using the Atmospheric Model version 2.1 (AM2.1). However, this correlation was reduced in the Pacific Ocean, and no significant correlation was noted in the Indian Ocean – thereby supporting the early work of Vitart *et al.* (1997), who found that model prediction skill is much higher in the North Atlantic and Pacific regions. This lack of improvement in the simulation of TC activity in the Indian Ocean, despite computational advances toward high-resolution simulations in

the 12 years between Vitart *et al.* and Zhao *et al.*'s studies, highlights the need for further work on the SWIO region.

A later study by Manganello *et al.* (2012) investigated multi-year simulations of Northern Hemisphere TC activity with the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS). Employing this model at four resolutions (10km, 16km, 39km, 125km), their study noted several significant improvements in TC simulation with increasing resolution. Firstly, the study found a systematic improvement in the spatial distributions of TC tracks and cyclogenesis locations with increased resolution. Further, the authors indicated that the 10km simulation provided the most accurate representation of the observed TC intensity distribution and the structure of the most intense storms. Additionally, Manganello *et al.* (2012) showed that at 10km, simulated TC frequency in the North Atlantic is comparable to observations, while the lower-resolution simulations all underestimate this metric. However, in line with Zhao *et al.* (2009) and Vitart *et al.* (1997), the authors noted that model skill was higher in the North Atlantic compared to other regions. Upon further investigation, the study found that errors in simulated TC frequency in the North Pacific were associated with errors in the large-scale environmental conditions in the model over this region, a discrepancy that was consistent at all resolutions. Supporting the notion that increasing resolution improves the simulated TC frequency, Camargo (2013) investigated TC activity in CMIP5 models and found that while all models underestimated the observed annual TC frequency, the models with the highest resolutions produced the greatest TC counts. Nevertheless, Camargo (2013) emphasised that despite this relationship, model resolution is not the only factor that determines simulated TC frequency.

A ground-breaking study by Murakami *et al.* (2012) documented the first instance of category 4 and 5 TCs in a multidecadal simulation. Using high-resolution meshes (20km and 60km) in the Meteorological Research Institute atmospheric general circulation model (MRI-AGCM version 3.2), the study found that at a resolution of 20km, the model was able to capture extremely intense (category 4 and 5) TCs, improving on the results of 60km simulation, as well as the previous version of the model (version 3.1).

Later studies by Wehner *et al.* (2014) and Murakami *et al.* (2015) provided further evidence for the simulation of intense TCs in high-resolution grids. Using CAM version 5.1 (CAM5.1) at 0.25° , Wehner *et al.* (2014) noted the occurrence of category 5 TCs in all ocean basins. This study also provided insight into the impact of model resolution on simulated rainfall; comparing CAM5.1 simulations at 0.25° , 1° and 2° , the authors noted increased amounts of extreme precipitation in the high-resolution simulations. Simulating global TC activity, Murakami *et al.* (2015) found that when increasing the resolution of the atmospheric component of the Geophysical Fluid Dynamics Laboratory (GFDL) coupled model from 50km to 25km, the model was able to simulate and predict category 4 and 5 TCs, as well as their interannual variations. Their study represents the first instance of category 4 and 5 TCs in a multi-century simulation. Further, the study noted an improvement in simulated TC structure, intensity, spatial distribution, seasonal variability, and interannual variability at 25km. These findings are supported by Roberts *et al.* (2015), who performed global simulations (1986–2010) at resolutions of 25km, 60km and 130km and noted an improvement in simulated TC frequency and interannual variability with increasing resolution. A more recent study by Moon *et al.* (2020) investigated the results of eight GCM simulations with varying resolutions (0.25° to 1°) and found that increasing resolution improves the representation of TC inner-core wind structures. However, the study did note that despite this improvement, the simulated TC radius of maximum winds is still larger than in observed systems.

While these modern studies have provided valuable insights into the effects of model resolution on TC simulation, the use of different models and TC tracking algorithms can make it difficult to discern the general applicability of their results. In an attempt to fill this gap, Roberts *et al.* (2020a) made use of six models from the European Union Horizon 2020 project PRIMAVERA (Process-based climate simulation: Advances in high-resolution modelling and European climate risk assessments) using a common forcing protocol from the CMIP6 HighResMIP to investigate the impact of model resolution on TC simulation. All the models utilised in the study were run with a common protocol, at both a standard- and enhanced-resolution, and the study employed two different TC tracking algorithms to provide a more robust assessment

of the impact of resolution (Roberts *et al.*, 2020a). The study noted several consistent responses to an increase in resolution, including an increase in TC frequency and seasonal accumulated cyclone energy (ACE) in the North Atlantic; improved representation of TC intensities; and improved spatial patterns of TC tracks and cyclogenesis locations. Further, the study demonstrated that these improvements in TC simulation with increased resolution were robust with both trackers utilised in the study, namely TRACK (Hodges *et al.*, 2017) and TempestExtremes (Ullrich and Zarzycki, 2017), inspiring confidence in the results. While Roberts *et al.* (2020a) offer important insights into the impact of model resolution on TC simulation, their focus, like most studies in the literature, remains on the Atlantic and Pacific regions. At present, no studies have investigated the impact of model resolution on the characteristics of simulated TCs in the SWIO region. The present study will fill this gap.

2.2.2 Parameterization

Many physical processes within the Earth system occur on sub-grid scales and thus require parameterization for their representation in numerical climate models. Anthes (1982) outlines that parameterization of cumulus convection, surface fluxes of momentum, moisture, heat, and vertical mixing within the planetary boundary layer (PBL) play an important role in simulating the development of TCs. Of these, Osuri *et al.* (2012) noted that PBL and convection parameterizations represent the most important processes in simulating TC genesis and intensification.

Braun and Tao (2000) used the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) to conduct parameterization sensitivity experiments in the simulation of Hurricane Bob (1991). This study compared the results of two simulations with differing PBL parameterization schemes (Medium Range Forecast (MRF) PBL scheme and Blackadar PBL scheme) and noted significant model sensitivity – with the simulated intensity of the system differing by up to 16 hPa and 15 m.s⁻¹ in terms of minimum mean sea level pressure (MSLP) and maximum wind speed respectively. However, it should be noted that these schemes do not operate in isolation, and the chosen combination of schemes

plays a significant role. For example, using the same model and PBL schemes as Braun and Tao (2000), Mandal and Mohanty (2004) found that, when paired with the Betts-Miller convection scheme, there was no variation in TC central pressure with differing PBL schemes. However, the study did note that the system's location was better predicted for the MRF PBL scheme simulation. Further, Mandal and Mohanty (2004) reported that for all other convection schemes included in the model, the model displayed significant sensitivity to PBL parameterization – with the MRF PBL scheme producing better estimates of both MSLP and TC central locations. Considering the parameterization of convection, Reed and Jablonowski (2011) used two versions of CAM, namely versions 3.1 (CAM3.1) and 4 (CAM4), to study the development of a tropical system in an idealised environment. The authors explained that the main difference between the two versions of the model is centred around the physical parameterization of deep convection, with CAM4 including a convective available potential energy (CAPE) calculation and convective momentum transport. This study found that CAM4 produces larger and stronger TCs at all resolutions, and the simulated TCs exhibit an earlier onset of intensification. Reed and Jablonowski (2011) concluded that the new CAPE calculation in CAM4 is largely responsible for the aforementioned TC development and intensity variations.

Given the importance of convective parameterizations in the simulation of TCs, the present study will assess the sensitivity of MPAS TC simulations to physics parameterization suites.

2.2.3 Initial conditions

Several studies have found initial condition data to be a key determinant in the forecast skill of numerical models. Lorenz (1963) explained that accurate future prediction of the atmospheric state is impossible unless the present conditions are explicitly known. Further, Sanders (1987) investigated the skill of National Meteorological Centre Operational Dynamical Models in predicting explosive cyclogenesis and found that model forecast skill largely depends on the accuracy of the initial condition data.

Studies by Anthes *et al.* (1983) and Kuo and Reed (1988) found improved TC forecasts when supplementing operational analyses ordinarily used to initialize models with detailed manual analyses that included additional data not available in real-time. Anthes *et al.* (1983) explained that the inclusion of this additional data resulted in superior representations of the shallow cyclonic circulation, small low-level static stability, and enhanced lower-tropospheric water vapour content. Kuo and Reed (1988) found that without including this additional data, the intensification of the simulated event was delayed and the final intensity of the system was underestimated. Conversely, Orlanski and Katzfey (1987) argued that while the use of different initial condition data does lead to differences in TC simulation, these are minor compared to those arising from differing physical parameterizations.

Nevertheless, Mullen and Baumhefner (1989) noted that in some instances, uncertainty in initial conditions can be as significant as the choice of physical parameterizations in simulating explosive cyclogenesis. In order to gain a comprehensive understanding of model performance, it remains important to understand the model's sensitivity to different parameters. The present study assesses the sensitivity of MPAS TC simulations to initial condition data by comparing the simulated TC characteristics of simulations initialized with the ECMWF fifth-generation reanalysis dataset (ERA5) to those initialized with the Climate Forecast System Reanalysis (CFSR).

2.3 Environmental conditions for tropical cyclone development

Past studies have identified environmental conditions that favour the formation and development of TCs. Seasonal studies of cyclogenesis by Gray (1968, 1975) showed that most TCs form in regions where the following six conditions are met: (i) sufficiently high SSTs ($> 26.5^{\circ}\text{C}$); (ii) a deep oceanic thermocline ($\sim 60\text{m}$); (iii) atmospheric surface-layer conditional instability; (iv) elevated levels of mid-tropospheric relative humidity; (v) elevated levels of low-level vorticity; (vi) weak vertical wind shear; and (vii) sufficient distance from the equator (because the Coriolis Parameter tends to zero near the equator, thereby inhibiting the development of organised systems).

The former three conditions are considered thermodynamic, while the latter three are considered dynamic. Gray (1975) noted that while the required thermodynamic and Coriolis conditions are often present in the tropics over long periods, low-level vorticity and wind shear can show significant changes on smaller spatial and temporal scales. For this reason, Gray (1975) suggested that low-level vorticity and vertical wind shear are the major short-term determinants of cyclogenesis. Additionally, Gray (1975) defined a seasonal genesis parameter as the product of the seasonal thermal and dynamic potential. This seasonal genesis parameter was found to closely resemble observed cyclogenesis frequency, emphasising the importance of the environmental conditions outlined above with regard to TC formation. However, Tory and Frank (2010) suggest that numerous TC forecasting schemes developed using the genesis parameters outlined by Gray (1968, 1975) are unable to provide a precise range of conditions necessary for TC genesis. They add that impermanent environmental features affecting cyclogenesis, such as subtropical waves, cannot be explicitly included in such schemes. For this reason, it is important to consider that even in an environment where the required conditions are met, there is no assurance of TC formation.

Several studies have shown the specific environmental conditions influencing TC development in different ocean basins. For example, Inoue *et al.* (2002) noted that local ocean-atmosphere interaction in the Caribbean strongly influences tropical cyclogenesis in the region. The authors explained that cyclogenesis in the North Atlantic generally peaks in September, while the Caribbean shows two distinct peaks in June and October, with a significant minimum in July. Their study found that this minimum in cyclogenesis is related to the strengthening of the easterly trade winds over the region, which results in enhanced oceanic upwelling and produces unfavourable conditions for TC development. These unfavourable conditions include: cooler SSTs; higher MSLP; an increase in outgoing longwave radiation; increases in upper-tropospheric vertical wind shear; and a decrease in precipitable water content. Conversely, the authors also explained that the trade winds weaken during October and reduce upwelling in the Caribbean, leading to favourable conditions for TC development.

Elsewhere, Yanase *et al.* (2012) used a genesis potential index (GPI) to investigate the environmental factors responsible for cyclogenesis in the Bay of Bengal. The study noted that weak vertical wind shear during pre- and post-monsoon seasons is associated with a high GPI, promoting cyclogenesis. Conversely, the authors found that strong vertical wind shear during the monsoon season is associated with a low GPI, suppressing cyclogenesis. However, there is a dearth of information on conditions conducive to TC development in the SWIO. Through a climatological analysis of CMIP6 model data, the present study will offer insights into the environmental conditions influencing cyclogenesis in this region. It will also investigate the impact of model resolution on these environmental fields.

2.4 Rapid intensification of tropical cyclones

While rapidly intensifying TCs (defined as an increase in TC maximum wind speed of 15.4 m.s^{-1} over a 24-hour period) are associated with the highest forecast errors (Bhatia *et al.*, 2019a), there is no agreement in the literature on the factors that control their development. For example, Fudeyasu *et al.* (2018) noted that rapidly intensifying systems tend to develop into intense TCs due to favourable environmental conditions (e.g., weak vertical wind shear and high CAPE). However, Hendricks *et al.* (2010) found that there is often little difference in the environmental conditions between slowly- and rapidly-intensifying TCs. Hendricks *et al.* (2010) have thus argued that the system's internal processes are more likely to control the rapid intensification of a TC. To this end, Judt and Chen (2016) found that the rapid intensification of a TC is associated with distinct physical processes that occur at different stages of the TC's life cycle. The authors identified two dominant modes of rapid intensification. The first mode of intensification occurs during the early stages of the TC life cycle. In this mode, TCs generally experience a rapid contraction of the radius of maximum winds accompanying the development of an eyewall. In the other mode, TCs intensify later in their life cycle, often forming an upper-level warm core during the process of rapid intensification.

Despite competing theories about the factors that control TC rapid intensification, most studies agree that rapidly intensifying systems are expected to become more

prominent in the future (Bhatia *et al.*, 2018, 2019b; Vecchi *et al.*, 2019; Emanuel, 2021). A recent study by Emanuel (2021), for example, which investigated the response of global TC activity to increases in atmospheric CO₂, noted that the probability of TC rapid intensification is expected to increase due to atmospheric warming. Similarly, Bhatia *et al.* (2019) found a significant increase in the intensification rates of TCs in the Atlantic basin over the period 1982–2009, driven partly by anthropogenic forcing. Since Lee *et al.* (2016) explained that TC's that undergo rapid intensification reach intense TC status 79% of the time (Saffir Simpson Scale category 3 – category 5), an increase in the frequency of these systems could have devastating consequences for coastal communities around the globe. This is yet one more reason why better forecasting of rapidly intensifying systems is required. Investigations of historical instances of rapid TC intensification offer insights into the model parameters necessary to simulate this process and can therefore aid in improving the modelling and forecasting of these systems. This dissertation aims to contribute to this effort by investigating the ability of a VGCM, MPAS, to simulate the rapid intensification of TC Kenneth.

2.5 Tropical cyclone tracking

The detection and tracking of TCs in climate models is a widely contested topic in the literature as TC tracking techniques and threshold criteria are often subjective and differ significantly between studies. Shaevitz *et al.* (2014) explained that TC tracking schemes generally identify a point of minimum MSLP, a minimum (maximum) in vorticity in the Southern (Northern) Hemisphere, and the existence of a warm core. They added that despite variations in threshold values and warm core definitions, all tracking schemes have similar characteristics that originate from the works of Bengtsson *et al.* (1982) and Vitart (1999).

Bengtsson *et al.*'s 1982 study was one of the first to employ TC detection criteria to identify TCs in model output. Using the ECMWF operational global forecasting model at a coarse resolution of 200km, this study used a simple tracking algorithm that included only two detection criteria. First, the tracking algorithm identified a point of maximum wind speed at 850 hPa, over a threshold value of 25 m.s⁻¹. Following this,

the point of maximum vorticity (Northern Hemisphere systems) was detected in a $7.5^\circ \times 7.5^\circ$ box centred at the point of maximum wind speed, with a threshold value of $7 \times 10^{-5} \text{ s}^{-1}$. While this simple detection technique successfully eliminated the number of false alarms associated with regions of high-wind speeds due to extratropical cyclones, several cases of strong horizontal wind shear resulting from the onset of the Summer Monsoon in the Arabian Sea had to be manually filtered out. Later studies by Broccoli and Manabe (1990) and Lau (1991) also employed simplistic tracking algorithms, including only surface pressure, wind speed and vorticity criteria. Vitart *et al.* (1997) explained that these early TC tracking algorithms were limited by the coarse resolution of climate models at the time, which made it difficult to distinguish between extratropical and tropical disturbances. To overcome this constraint, Haarsma *et al.* (1993) and Bengtsson *et al.* (1995) opted to include a warm core criterion, which was able to effectively eliminate all extratropical disturbances. These later studies also included minimum duration thresholds. However, while Haarsma *et al.* (1993) required that a candidate system meet all criteria for a minimum of 3 days to be considered a TC, Bengtsson *et al.* (1995) only required the criteria to be met for 1.5 days.

While wind speed, relative vorticity, warm core and duration criteria are included in most TC tracking algorithms today, threshold values of these parameters remain a source of debate. Camargo and Zebiak (2002) explained that the use of threshold criteria taken from observational climatological values is problematic because it does not account for model biases. For example, Bengtsson *et al.* (1995) found that simulated TC intensity, and thus simulated wind speed, was largely dependent on model resolution, with low-resolution simulations producing weaker systems that would not be captured when employing threshold values from observed systems. For this reason, the use of model-dependent criteria, which account for differences in model configuration, such as resolution, seems only appropriate. To this end, Camargo and Zebiak (2002) demonstrated that the use of model-dependent threshold criteria does improve the representation of TCs in many GCMs. However, since studies on TC simulation have all employed different models with varying resolutions, there are no universally accepted threshold values for detecting TCs in model output.

Receiving the most attention in the literature is the wind speed parameter, with notable differences in threshold values across multiple studies, even at equal resolutions. For example, Nguyen and Walsh (2001) and Sugi *et al.* (2002) opted for wind speed threshold values of $>5 \text{ m.s}^{-1}$ at 10-m and $>15 \text{ m.s}^{-1}$ at 850 hPa, respectively, despite both studies utilising models with resolutions of 125km. To address this disparity, Walsh *et al.* (2007) derived resolution-dependent wind speed threshold criteria that could be applied to any climate model simulation. According to the authors, it is widely accepted that low-resolution models are unable to generate TCs with wind speeds as high as observations. For this reason, they argue that to understand the relative ability of a model to generate tropical systems, the wind speed thresholds in TC tracking algorithms should be adjusted to account for the resolution of the model in question. Further, Walsh *et al.* (2007) recommend that model wind speeds be corrected to 10-m, given that wind speeds of observed systems are measured at this height.

The present study has used a modified version of the tracking algorithm described by Maoyi *et al.* (2018) to detect and track TCs in CMIP6 and MPAS model output. This algorithm employs the resolution-dependent wind speed thresholds outlined in Walsh *et al.* (2007). Modifications were made jointly due to data availability and to improve the results of the tracking algorithm over the SWIO basin. The full tracking algorithm and all modifications are described in Chapter 3 of this study.

2.6 Observations and simulations of tropical cyclones over the South-West Indian Ocean

2.6.1 Observations of tropical cyclone characteristics

Past studies investigating observed characteristics of TCs over the SWIO have established that an average of 9 TCs are recorded in the basin each year, with only 5% making landfall over the subcontinent (Reason and Keibel, 2004; Reason, 2007; Muthige *et al.*, 2018). Mavume (2008) has explained that most TCs in the region are formed east of 50°E , between the latitudes of 8°S – 15°S . Reason (2007) found that these systems generally track westwards across the basin before re-curving south-eastwards over Madagascar. Le Borgne (1987) also noted that a small percentage of

SWIO TCs form in the Mozambique Channel (MC) and are characterised by their small size, rapid development, and short life span. Reason (2007) explained that systems originating in the MC typically follow a southward track out of the channel before propagating eastwards over the subtropical SWIO.

Previous studies investigating the interannual variability of SWIO TC activity have noted both local and remote influences that can be attributed to several natural cycles, including ENSO, the IOD, and the MJO (e.g., Ho *et al.*, 2006; Mavume, 2008; Ash and Matyas, 2012; Burns *et al.*, 2016; Maoyi *et al.*, 2018). For example, ENSO is known to be responsible for significant SST variability in tropical regions (Annamalai *et al.*, 2005). Given the importance of SST in TC formation, ENSO may be responsible for variability in SWIO TC activity through its influence on SSTs and the large-scale atmospheric circulation. Mavume *et al.* (2010) investigated SWIO TC activity between 1980–2007 and noted that intense TCs were more frequent in the basin during La Niña years. Further, Vitart *et al.* (2003) reported a strong link between ENSO and TC zonal steering flow in the SWIO, resulting from the remote impact of Pacific equatorial SSTs on the large-scale circulation in the southern Indian Ocean. This study concluded that the negative zonal steering flow in the SWIO associated with a La Niña event increases the risk of TC landfall over Mozambique.

The IOD is another source of SST variability in the SWIO that may influence TC activity (Ash and Matyas, 2012). Burns *et al.* (2016) explained that IOD events may affect the Barrier Layer Thickness in the SWIO through propagating Rossby waves. This study found that an early peak in the IOD resulted in increased SSTs in the SWIO during October, leading to earlier TC occurrence and an earlier peak in TC season (Burns *et al.*, 2016). The authors further explained that no direct correlation exists between the Dipole Mode Index (DMI), which represents the intensity of the IOD and the number of TC days for any given year. Instead, Burns *et al.* (2016) noted a 4–5 month lag relationship between these two features, likely due to the time taken for the downwelling Rossby waves to propagate westward across the tropical Indian Ocean basin.

Another source of SWIO TC variability is the MJO, an eastward propagating disturbance, characterised by large regions of enhanced and suppressed rainfall that is mainly observed over the Indian and Pacific Oceans (Met Office, 2021). The Met Office (2021) outlines that each MJO cycle lasts approximately 30–60 days and consists of 8 phases. Ho *et al.* (2006) noted that TC frequency in the SWIO increases during phases 2–4, where the convective phase of the oscillation moves eastwards over Africa and the Indian Ocean (Liebmann *et al.*, 1994; Met Office, 2021). Liebmann *et al.* (1994) explained that this increase in TC frequency during the MJO wet/convective phase is most likely due to the large-scale low-level cyclonic relative vorticity and convergence anomalies that develop westward and poleward of the anomalous MJO convection. However, the authors also noted that the relative number of storms that form per tropical depression is independent of the MJO phase. They explained that the observed increase in TC frequency during the wet phase of the MJO is thus simply due to an increase in the number of tropical depressions that develop over the SWIO at this time.

While several studies have investigated trends and drivers of SWIO interannual TC variability, very few have assessed the ability of current GCMs to capture this variability. The present study will analyse the performance of four CMIP6 models in simulating SWIO TC frequency and temporal variability.

2.6.2 Modelling studies on South-West Indian Ocean tropical cyclone activity

While there has been extensive work done on evaluating climate model performance in simulating TC activity over the Atlantic, Pacific, and North Indian Ocean regions, very few studies have focused on model evaluation over the SWIO region. One exception is a study by Maoyi *et al.* (2018), who employed a stretched-grid GCM (CAM-EULAG) to investigate the characteristics of simulated SWIO TCs between 1999-2010. The study noted that while the model was able to produce realistic simulations of SWIO climate and TC spatial patterns (tracks and cyclogenesis locations), atmospheric features over the MC presented some disparities compared to observations. Specifically, the authors explained that the model simulates a substantial cyclonic feature over the MC, which results in an overestimation of TC

frequency in this region. Additionally, the model underestimates TC frequency in the eastern portion of the SWIO basin, which, when coupled with increased TC frequency in the MC, presents as a westward shift in TC activity. Further, Maoyi *et al.* (2018) noted that while CAM-EULAG performs well in reproducing the monthly variation in TC activity, the interannual variability is poorly represented.

Most studies that simulate TC activity in the SWIO have focused on future projections in a warming environment (Malherbe *et al.*, 2013; Muthige *et al.*, 2018; Thompson *et al.*, 2021). For example, Malherbe *et al.* (2013) projected a decrease in TC frequency in the SWIO between 1961–2100 and similarly, Muthige *et al.* (2018) noted a decrease in landfalling systems over Southern Africa under different extents of global warming (1.5°C, 2°C, 3°C). Both studies mention that while these reductions in TC activity in the SWIO will be beneficial in terms of the reduced potential damage and losses associated with TC events, they are also likely to result in a decrease in rainfall over semi-arid regions, which will be detrimental to agricultural practices.

Despite these projected decreases in TC frequency, Thompson *et al.* (2021) recently investigated the characteristics of a typical SWIO TC under the Intergovernmental Panel for Climate Change's (IPCC) Representative Concentration Pathways (RCP) 8.5 emissions scenario. This study noted that a typical TC in the SWIO region will experience, on average, a 6.5% increase in maximum intensity, a 33.8% increase in median rainfall rate, and a 9.2% decrease in spatial extent. The findings of Thompson *et al.* (2021) are supported by a 2013 study by Emanuel, which notes a probable increase in TC maximum intensity in the South Indian Ocean between 2006–2100 (relative to the period 1950–2005). However, Emanuel's study also notes an increase in TC frequency in the South Indian Ocean over the same period, contradicting the findings of Malherbe *et al.* (2013) and Muthige *et al.* (2018).

A more recent study by Emanuel (2021) noted a projected increase in the frequency of intense systems as a response to increasing levels of atmospheric CO₂. Additionally, both Fitchett and Grab (2014) and Green *et al.* (2021) explained that a projected poleward migration of TC activity is expected to increase the risk of TC landfall over the east coast of southern Africa. Together with the acute lack of literature

on TC simulation in the SWIO, these factors expose a need for further work to be done in the region. The limited number of studies on SWIO TC simulation means that there is very little information on models that perform well in the region or the model parameters required to adequately simulate TCs. The present study aims to provide a comprehensive overview of TC simulation in the SWIO region.

CHAPTER 3 : Methodology

This chapter presents the methodology used in this dissertation. It describes the study domain (Section 3.1); the two individual TC events analysed in this study (Section 3.2); and the characteristics and sources of the data analysed (Section 3.3). It also describes all the methods employed in the study (Section 3.4), including a description of MPAS, the model configuration, the TC tracking algorithm, and the model performance metrics.

3.1 Study domain

The main study domain for this dissertation is the South-West Indian Ocean (SWIO) region (0°S - 40°S , 30°E - 90°E) (Fig. 3.1). The SWIO region encompasses a number of countries along the east coast of southern Africa, including South Africa, Zimbabwe, Mozambique, Tanzania, and Kenya. The island of Madagascar, located between 12°S - 25°S and 44°E - 50°E , features a mountain range extending from its northern to southern coasts. With an elevation of over 2000m in some areas, this topographic feature can have implications for the atmospheric circulation over the region. Barimalala *et al.* (2018) explained that the Mozambique Channel Trough, a region of cyclonic circulation most prominent in austral summer, can be generated due to the dynamical adjustment of the easterlies flowing over the Mozambican mountain range. In addition to Madagascar, the SWIO is home to a number of small island nations, including Mauritius, Reunion, and the Seychelles. The region also features an oceanic plateau, called the Mascarene Plateau, located to the north-east of Madagascar. The Mascarene Plateau exerts a strong influence on oceanic currents in the SWIO region, dividing the South Equatorial Current into northern and southern branches as it passes through the Mascarene Ridge (Mavume, 2008).

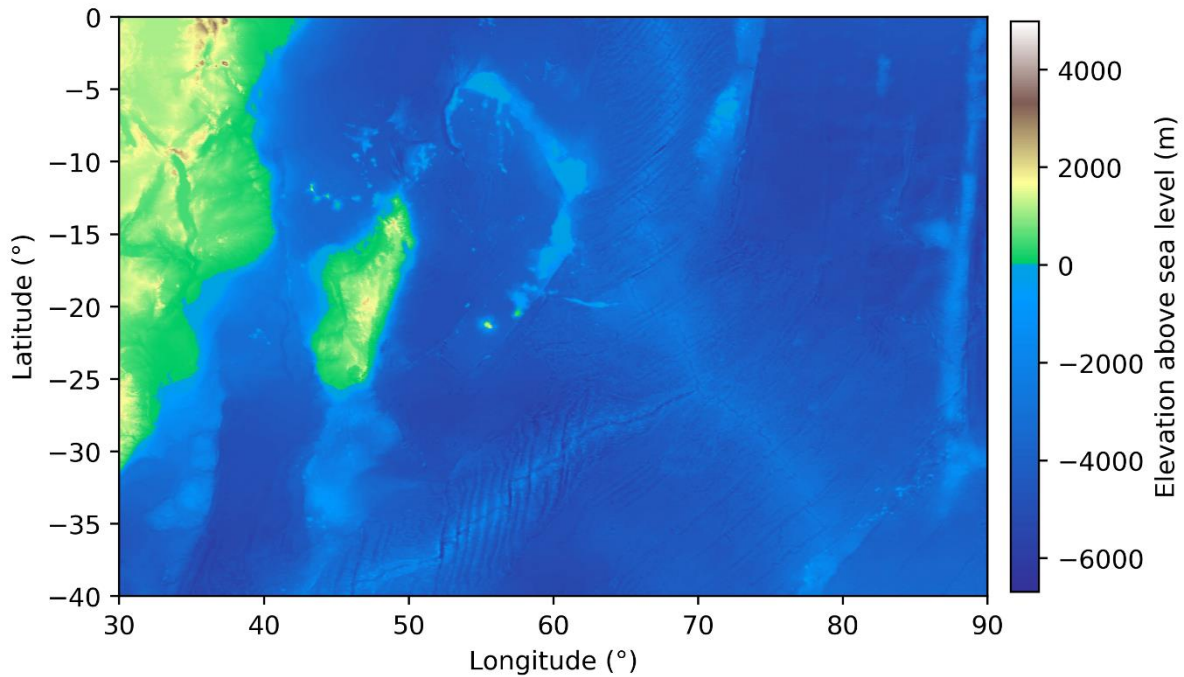


Figure 3.1 Topographic map of the SWIO region (0°S-40°S, 30°E-90°E).

3.2 Description of individual tropical cyclone events

This dissertation investigated all TCs that formed over the study region in the period 1980–2009 to study the climatology of TCs - but selected two specific TC events to use as case studies. The characteristics of the two events are described below.

3.2.1 Tropical Cyclone Idai

On 4 March 2019, a tropical depression formed along the east coast of Mozambique. The system made landfall on the evening of 4 March and moved inland before recurving toward the MC and emerging as a moderate tropical storm on 9 March. The system continued to intensify, and on the evening of 10 March (18h00), the system was upgraded to TC status and named TC Idai. TC Idai reached an initial peak intensity of 955 hPa (MSW of 48.87 m.s⁻¹) on 11 March (12h00). Following this initial intensity peak, the eye of the TC began to deteriorate due to dry air entanglement. Additionally, the RSMC reported that at this time TC Idai had begun an ERC, which

would act to limit the TCs intensity and result in a temporary weakening of the system. Upon completion of the ERC (13 March, 18h00), TC Idai continued to intensify, reaching a final peak intensity of 940 hPa (MSW of 54.02 m.s^{-1}) on 14 March (00h00). Following its final intensity peak, TC Idai began to dissipate. TC Idai made landfall over Beira (Mozambique) in the early hours of 15 March (Météo France, 2019).

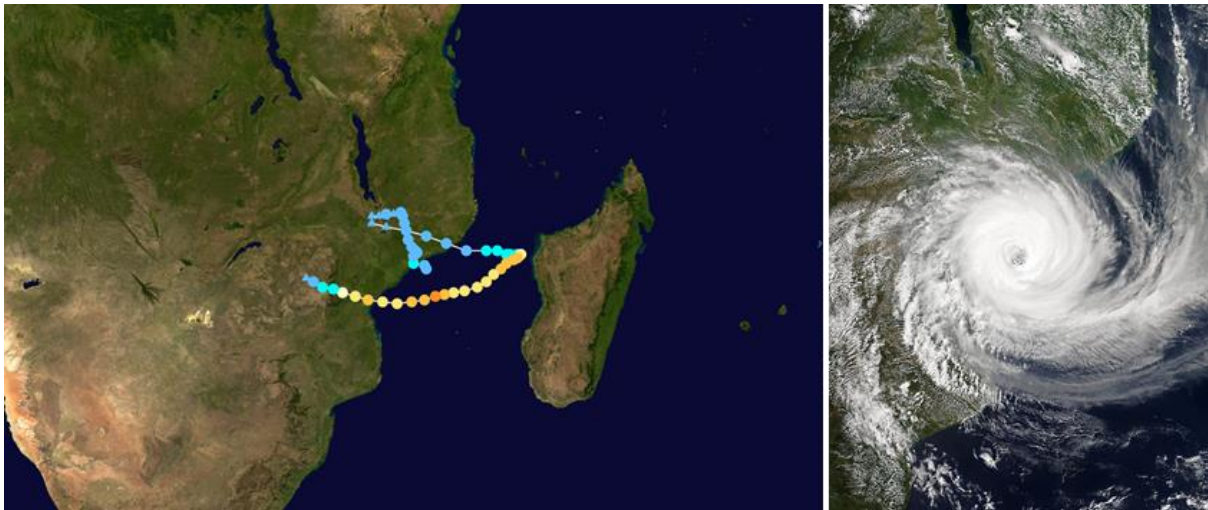


Figure 3.2 TC Idai track and satellite picture on 14 March 2019, shortly after reaching peak intensity (Source: NASA; <https://worldview.earthdata.nasa.gov/> (Accessed: 20 December 2021)).

3.2.2 Tropical Cyclone Kenneth

TC Kenneth originated from a tropical disturbance situated on the north-east of Madagascar on 21 April 2019. The system tracked westwards across the MC and was upgraded to a moderate tropical storm 23 April (12h00). The storm continued to intensify and was upgraded to TC status on 24 April (09h00). Rapid intensification of the system followed and by 25 April (06h00), TC Kenneth reached a peak intensity of 934 hPa, with MSWs of 59.16 m.s^{-1} – corresponding to a category 4 TC. At this time, RSMC noted that TC Kenneth had also begun an ERC, which would increase the radius of destructive winds and subsequently widen the area of maximum danger, both in terms of strong winds and storm surges. TC Kenneth made landfall just north of

Pemba (Mozambique) on 25 April (13h00). Following its landfall, TC Kenneth began to rapidly deteriorate (Météo France, 2019).

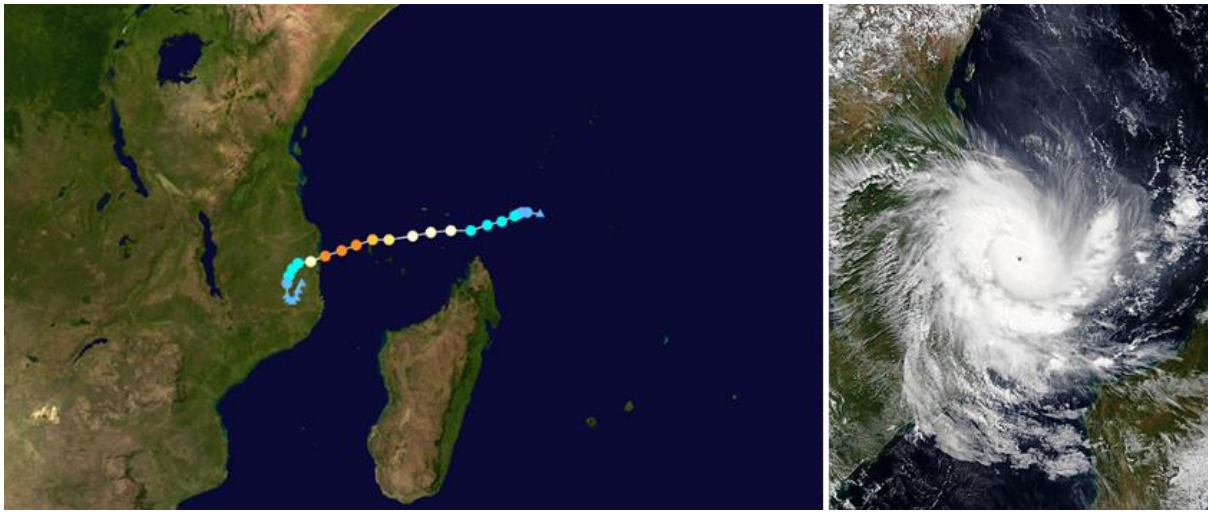


Figure 3.3 TC Kenneth track and satellite picture on 25 April 2019, at peak intensity (Source: NASA; <https://worldview.earthdata.nasa.gov/> (Accessed: 20 December 2021))

3.3 Data

This dissertation analysed three groups of datasets, namely: observation, reanalysis, and model simulations. Detailed descriptions of datasets in each group and the sources are provided below.

3.3.1 Observation datasets

The two observation datasets used in the study include the Reunion Specialised Meteorological Centre (RSMC) and the Joint Typhoon Warning Centre (JTWC) best track data; both were obtained from the International Best Track Archive for Climate Stewardship (IBTrACS – Knapp *et al.*, 2010, 2018). Over the SWIO, TCs are monitored by the RSMC, which is located between Madagascar and Mauritius. Since there are minor discrepancies between the observational datasets, the RSMC data has been used as the primary dataset, with the JTWC data included for reference. Both the RSMC and JTWC use the Dvorak technique to estimate TC intensity (Dvorak, 1984). This method makes use of visible and infrared satellite imagery to analyse

cloud patterns, which are often indicative of cyclogenesis. The RSMC and JTWC provide 6-hourly information on TC location (latitude and longitude), minimum MSLP and MSW. The RSMC best track dataset was used to evaluate the climatology of the simulated TCs (1980–2009). Both datasets (RSMC and JTWC) were utilised to evaluate the characteristics of the simulated TCs Idai (11–16 March 2019) and Kenneth (23–27 April 2019).

3.3.2 Reanalysis datasets

Two reanalysis datasets were used in the study. The first is the European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation reanalysis dataset (ERA5 - Hersbach *et al.*, 2018a, 2018b). This reanalysis product provides hourly data with a resolution of 31km and 137 vertical levels (National Center for Atmospheric Research (NCAR), 2021a). It is an updated version of the popular ECMWF interim reanalysis dataset (ERA-Interim), offering improved representation of TCs (Hoffmann *et al.*, 2019). In the present study, ERA5 reanalysis was used to evaluate the performance of CMIP6 models in simulating SWIO TCs over the period 1980-2009. In addition, this reanalysis was used to provide initial condition data and to evaluate the simulation of TCs Idai and Kenneth with MPAS.

The second reanalysis dataset is the Climate Forecast System Reanalysis (CFSR - Saha *et al.*, 2011). CFSR is a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system which provides 6-hourly data with a resolution of 38km and 64 vertical levels (NCAR, 2021b). The CFSR dataset was used to investigate the sensitivity of the MPAS simulations to initial conditions.

3.3.3 Climate simulation datasets

Two types of climate simulation datasets were analysed in this dissertation. The first simulation dataset was the CMIP6 High Resolution Model Intercomparison Project (HighResMIP). The HighResMIP consists of both low- and high-resolution runs, allowing for the systematic investigation of the impact of model resolution through a multi-model ensemble approach. The models included in the CMIP6 HighResMIP form part of the European Union Horizon 2020 project PRIMAVERA (Process-based

climate simulation: Advances in high-resolution modelling and European climate risk assessments), and use a common CMIP6 HighResMIP protocol, with common integration periods, forcing and boundary conditions (Haarsma *et al.*, 2016). Further, to highlight the differences due to resolution alone, this protocol recommends minimal changes in model parameterization between the low- and high-resolution simulations (Roberts *et al.*, 2020a). This study makes use of Tier 1 atmosphere-only experiments with a 6-hourly temporal resolution. The models included in this analysis, along with their respective resolutions, are outlined in Table 3.1. The CMIP6 HighResMIP dataset was used to analyse the capability of the selected CMIP6 models to simulate the climatology of TCs over the SWIO (1980-2009), and to study the sensitivity of the simulations to the resolution of the models. The results of the CMIP6 simulations are presented in Chapter 4 of this dissertation.

Table 3.1 Characteristics of CMIP6 HighResMIP models used in the climatological analysis.

Short name	Full name	Mesh spacing at 0°N in km (degrees)	Grid name	Vertical Levels	Description
CNRM-LR	CNRM-CM6.1	156 (1.41°)	T1127	91	Voldoire <i>et al.</i> (2019)
CNRM-HR	CNRM-CM6.1-HR	55 (0.5°)	T1359	91	
EC-LR	EC-Earth3P	78 (0.7°)	T1255	91	Haarsma <i>et al.</i> (2020)
EC-HR	EC-Earth3P-HR	39 (0.35°)	T1511	91	
HadGEM-LR	HadGEM3-GC3.1-LM	208 (1.84°)	N96	85	Roberts <i>et al.</i> (2019)
HadGEM-HR	HadGEM3-GC3.1-HM	39 (0.35°)	N512	85	
MPI-LR	MPI-ESM1.2-HR	104 (0.93°)	T127	95	Gutjahr <i>et al.</i> (2019)
MPI-HR	MPI-ESM1.2-XR	52 (0.47°)	T255	95	

As part of the dissertation, the second simulation dataset was generated with MPAS. This dataset, which consists of simulated TCs Idai and Kenneth, was used to evaluate the capability of MPAS in simulating the TCs, and to investigate their sensitivity to the initial condition dataset, resolution, and physics parameterizations employed in the

model. A detailed description of MPAS is given in Section 3.4.1 and the model configuration for the study is presented in Section 3.4.2. The results of the MPAS simulations are presented in Chapter 5.

3.4 Methods

3.4.1 MPAS description

The climate model adopted for the study is the atmospheric component of the Model for Prediction Across Scales (MPAS), developed by NCAR. MPAS is a VGCM that allows for a multiscale modelling approach by employing a spherical centroidal Voronoi mesh (Zhao *et al.*, 2019). MPAS supports the use of both uniform- and variable-resolution grids, allowing for the comparison of a variable-resolution approach with the more traditional methods used in most GCMs (uniform grid). When running MPAS on a variable-resolution grid, the Voronoi mesh allows for smooth transitions between low- and high-resolution areas to overcome issues commonly associated with local refinement, where the transitions are often abrupt.

The MPAS-Atmosphere dynamical core solves the fully compressible nonhydrostatic equations of motion and is described in Skamarock *et al.* (2012). MPAS uses different schemes to parameterize various physical processes in the atmosphere. However, to facilitate and ensure the choice of compatible schemes, MPAS has two default physics parameterization suites, namely; mesoscale reference and convection-permitting. The corresponding parameterization schemes for each physics suite are outlined in Table 3.2 below. A comprehensive description of the MPAS Voronoi mesh, dynamic core, and physics parameterization schemes can be obtained in Skamarock *et al.* (2012).

Table 3.2 *Parameterization schemes included in each of the default MPAS physics suites.*

Parameterization	Mesoscale Reference	Convection-permitting
Microphysics	WSM-6	Thompson
Convection	New Tiedtke	Grell-Freitas
PBL	YSU	Mynn
GWDO	YSU GWDO	YSU GWDO
Longwave radiation	RRTMG	RRTMG
Shortwave radiation	RRTMG	RRTMG
Cloud	Fraction	Fraction
Surface layer	Monin Obukhov	Mynn
Land surface model	Noah	Noah

3.4.2 MPAS configuration

For each TC event, MPAS was applied to perform six simulations (Table 3.3). In the first simulation (CONTROL), which serves as the reference for the other simulations, MPAS used a 60km horizontal uniform-grid resolution, 41 vertical levels, and the mesoscale reference physics parameterization suite. The duration of the CONTROL simulation was 5 days (11–16 March 2019) for the TC Idai simulation and 4 days (23–27 April 2019) for the TC Kenneth simulation. The simulation was initialized with the ERA5 reanalysis data (at 00h00 UTC) and forced with observed SST data from the ERA5 reanalysis dataset.

The model set-up for the second simulation (CFSRCTR), used to examine the sensitivity of the simulated TC to initial boundary condition data, was the same as that of the CONTROL, except that the CFSR dataset was used to initialize the simulation. The next three simulations (MR15, MR10, and MR03), used to examine the sensitivity of the simulated TC to model resolution, had the same model set-up as the CONTROL

but used the variable-resolution grid mesh with higher resolution (i.e., 15km, 10km, and 3km, respectively) over the SWIO and 60km resolution outside the domain (Fig. 3.4).

The last two simulations (CP10 and CP03), used to investigate the sensitivity of the simulated TC to the physics parameterization suites, were similar to MR10 and MR03, except that they used the convection-permitting suite. It should be noted that the convection-permitting suite is applied over the entire simulation domain – in both the low- and high-resolution areas. This is an appropriate application as the Grell-Freitas convection scheme transitions from a conventional parameterization of deep convection at hydrostatic scales (60km resolution) to a parameterization of precipitating shallow convection at non-hydrostatic scales (<10km resolution).

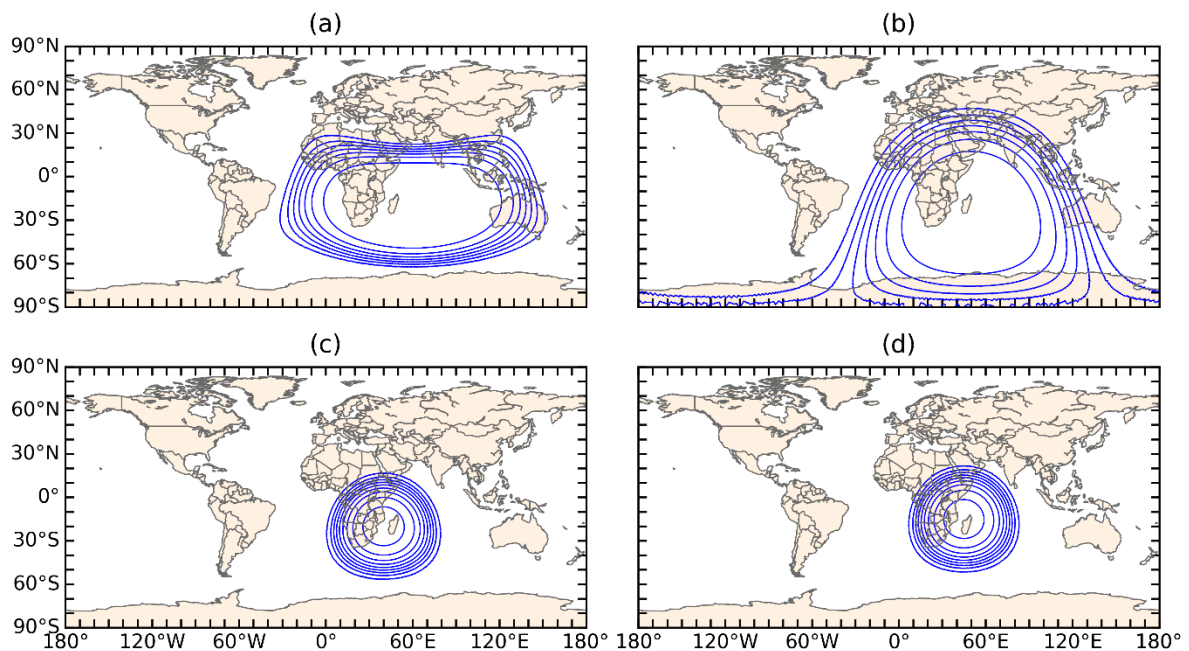


Figure 3.4 Simulation domain for MPAS experiments. Blue contours show the region of transition from low resolution to high resolution for the (a) 60–15km, (b) 60–10km, (c) 60–3km (TC Idai) and (d) 60–3km (TC Kenneth) meshes. Contour lines are shown in 5km intervals and the value of the innermost contour is 15km in (a), 10km in (b), and 5km in both (c) and (d).

The capability of each simulation to reproduce the observed characteristics was then examined. The TC characteristics that were considered, include the storm tracks,

intensity, propagation speed, landfall, wind-pressure relationship, and vertical structure. The observed and simulated storms were then classified into intensity classes based on their MSW using the Saffir-Simpson Scale (Table 1.1).

Table 3.3 Details of MPAS experiments

Experiment	Horizontal resolution	Initial conditions	Physics suite	Integration Timestep
CONTROL	60km uniform	ERA5	Mesoscale	360s
CFSRCTR	60km uniform	CFSR	Mesoscale	360s
MR15	60-15km variable	ERA5	Mesoscale	90s
MR10	60-10km variable	ERA5	Mesoscale	60s
MR03	60-3km variable	ERA5	Mesoscale	18s
CP10	60-10km variable	ERA5	Convection	60s
CP03	60-3km variable	ERA5	Convection	18s

3.4.3 Tropical cyclone tracking algorithm

To detect and track the TCs, a modified version of the TC tracking algorithm described in Maoyi *et al.* (2018) was used, which is similar to the methods described in Vitart *et al.* (1997), Kleppek *et al.* (2008), and Zarzycki and Jablonowski (2014). The algorithm was, however, modified for three reasons. First, the warm core criterion used in Maoyi *et al.* (2018) could not be utilised in its current form as the climate simulation data were not available on the required pressure levels. Subsequently, the use of an absolute threshold value was deemed inappropriate, given the relationship between temperature and atmospheric height. It was, therefore, decided to include a warm-core criterion that considered the warm core temperature relative to the surrounding environment, as described by Zhao *et al.* (2009).

Second, to exclude mid-latitude cyclones from the analysis, a vertical dynamics threshold was implemented, as described in Camargo and Zebiak (2002). For both the warm core and vertical dynamics criteria, 250 hPa level data (instead of 300 hPa) was utilised due to the lack of simulation data at 300 hPa. However, for each case, the effect of the modification was tested using ERA5 reanalysis, which has data at both 300 hPa and 250 hPa, and the difference was found to be negligible. As in Maoyi *et al.* (2018), the tracking algorithm included the resolution-dependent wind speed threshold criteria outlined in Walsh *et al.* (2007), providing a simple means of comparison between models, reanalyses and observations. All modifications and testing of the tracking algorithm are described in Appendix A. TCs were detected in 6-hourly model and reanalysis datasets as follows:

- Point of minimum MSLP over the study domain (30°E-90°E, 10°S-40°S) was identified – this was defined as the centre of a potential low-pressure system.
- The minimum 850 hPa relative vorticity within 4° of the minimum MSLP was detected - this had to be less than $-3.5 \times 10^{-5} \text{ s}^{-1}$.
- The maximum 10-m wind speed within 5° of the minimum MSLP was detected – this had to be greater than a resolution-dependent threshold value, as outlined in Walsh *et al.* (2007).
- In order to identify a warm core, the average 500-250 hPa integrated temperature over a 10° x 10° block centred at the minimum MSLP was calculated. The maximum of this temperature field within 2° of the minimum MSLP was then identified – this was defined as the centre of the warm core. The warm core temperature had to be at least 1°C greater than the surrounding environment.
- The average wind speed over a 6° x 6° block centred at the minimum MSLP must be greater at 850 hPa than at 250 hPa.

If a system met the above criteria:

- The following 6-hour period was analysed – if the tracking algorithm was able to detect a qualifying system within 4.5° of the previous minimum MSLP, it was

considered to be the same system. However, if no qualifying system was detected, the track was considered to have stopped.

- The storm had to have a minimum lifetime of 48 hours to be considered a TC.

Further measures:

- In order to minimise the number of broken tracks associated with an intermittent weakening of the system, one time step failure was allowed.
- To minimise any bias introduced by a resolution-dependent wind speed threshold, any system that did not reach at least tropical storm strength (maximum 10-m wind speed $> 17 \text{ m.s}^{-1}$) during its lifetime was excluded from the dataset.

For the climatological analysis, this tracking algorithm was applied to each simulation to generate an event set of TCs for each model. For the analysis of individual events, this tracking algorithm was applied to capture the simulated track of each system. Events were then classified into intensity classes based on their MSW using the Saffir-Simpson Scale (Table 1.1).

In addition to the tracks obtained using this algorithm, the climatological analysis makes use of tracks obtained by Roberts *et al.* (2020a) using the TempestExtremes tracking algorithm in order to determine if the response of the models to an increase in resolution is robust with multiple trackers. It should be noted that Roberts *et al.* (2020a) made use of two tracking algorithms, TRACK and TempestExtremes. The choice to use only TempestExtremes as a means of both validation and comparison was due to several factors. Firstly, as with the tracking algorithm used in this study, TempestExtremes makes use of MSLP as the feature-tracking variable. Further, Roberts *et al.* (2020a) noted that as compared to TRACK, results from TempestExtremes show a more systematic increase in TC frequency with increasing resolution. They also noted that the hemispheric asymmetry in TC activity obtained with TempestExtremes is more consistent with observations.

3.4.4 Tropical cyclone characteristics metrics

Following previous studies (e.g., Maoyi *et al.*, 2018; Murthy and Boos, 2019; Roberts *et al.*, 2020a), this dissertation used several metrics to quantify the characteristics of TCs over the SWIO. The metrics are described below.

3.4.4.1 Kernel density estimation

A kernel density estimation (KDE), a non-parametric estimate of probability density, was used in this analysis to provide density plots of TC tracks and cyclogenesis locations. The kernel estimate allows for smoothing of the track and cyclogenesis density and is preferred over traditional methods where the data is often discontinuous and dependent on bin positions (Hodges, 1996).

3.4.4.2 Wind-pressure relationship

The wind-pressure relationship is an empirical approximation of the relationship between two measures of tropical cyclone intensity, minimum MSLP and 10-m maximum wind speed (Chavas *et al.*, 2017). This relationship was considered for observations, reanalysis, and all model simulations. This relationship was presented as a scatter plot of minimum MSLP versus 10-m maximum wind speed, and all series were curve fit with a second-order quadratic equation.

3.4.4.3 Accumulated cyclone energy

In order to analyse the interannual variability of SWIO TC activity, the accumulated cyclone energy (ACE) was calculated for observations, reanalysis, and all simulation datasets. The ACE is a measure of TC activity that combines system duration and intensity, and is defined as:

$$ACE = 10^{-4} \sum V_{max}$$

Where V_{max} is the MSW (in knots) for a TC at a given interval, summed over the lifetime of the TC. ACE is usually considered as an annual statistic, comprising the

cumulative ACE of all events occurring within a basin for a given year (Bell *et al.*, 2000).

3.4.4.4 Velocity potential composite analysis

Velocity potential is a scalar field that is proportional to divergence and can be used to identify regions of enhanced convection (Laing and Evans, 2015). A composite analysis of velocity potential over the SWIO was performed to offer some insight into the large-scale environmental conditions present in each model on TC days. The velocity potential is the divergent component of flow and was analysed over the region 10°E-130°E, 30°N-50°S. A box is included to indicate the study area (Fig. 4.7).

The velocity potential was calculated at both lower- (850 hPa) and upper-levels (250 hPa) using the Python package Windspharm, which allows for computations on global wind fields in spherical geometry using only the zonal and meridional wind components.

3.4.4.5 Propagation speed

The propagation speed of each simulated TC was calculated through a simple vector displacement model developed in Fortran. This model employs the Haversine formula to calculate the great-circle distance between two points on a sphere:

$$a = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos\phi_1 * \cos\phi_2 * \sin^2\left(\frac{\Delta\lambda}{2}\right)$$

$$c = 2 * \text{atan2}(\sqrt{a}, \sqrt{1-a})$$

$$d = R * c$$

Where ϕ is latitude, λ is longitude, and R is the mean radius of the Earth (6371km).

3.4.5 Model evaluation metrics

This dissertation used several metrics to quantify the performance of the models (CMIP6 and MPAS) in simulating TCs over the study domain. The metrics are presented in this section.

3.4.5.1 Spatial correlation

Spatial correlation provides a measure of the correlation between variables across a spatial area (GIS Geography, 2022). In order to calculate the spatial correlation of the simulated KDE of TC tracks and cyclogenesis location with the observed KDE, the linear regression was calculated in the XY plane using the following equation:

$$r = \frac{Cov(PQ)}{\sqrt{Var(P) * Var(Q)}}$$

Where r is the spatial correlation, P is the observed array, and Q is the simulated array.

3.4.5.2 Root mean square error

The intensity analyses were presented as a time series to show the evolution of the simulated maximum wind speed and minimum MSLP over the lifetime of the TC. The root mean square error (RMSE), a common error metric for numerical predictions, was calculated for the reanalysis and model time series to show the deviation from observations. The RMSE is defined as:

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(\hat{y}_i - y_i)^2}{n}}$$

Where $\hat{y}_i$ is the predicted value, y_i is the observed value, and n is the number of observations (Neill and Hashemi, 2018).

CHAPTER 4 : Performance of CMIP6 models in simulating South-West Indian Ocean tropical cyclones

This chapter presents and discusses the performance of four CMIP6 models in simulating climatological SWIO TC activity between 1980-2009. First, this chapter outlines the performance of each model in simulating TC frequency, intensity, spatial and temporal distribution, and investigates the impact of model resolution on these characteristics (Section 4.1). The chapter goes on to explore the atmospheric conditions over the SWIO which may influence TC activity, and analyses how these conditions are influenced by an increase in resolution (Section 4.2). The chapter concludes with a summary of the results and outlines the limitations of the analysis (Section 4.3).

4.1 Characteristics of South-West Indian Ocean tropical cyclones

4.1.1 Cyclogenesis locations and tracks

The spatial patterns of cyclogenesis locations and TC tracks over the SWIO between 1980–2009 are shown in Figures 4.1 and 4.2 respectively. The RSMC observations indicate that cyclogenesis generally occurs between 5°S–25°S, with a concentration of activity along the eastern boundary of the basin (5°S–15°S, 55°E–90°E) and a weaker tongue extending over the MC. It also shows the largest concentration of TC tracks between 10°S–30°S and 50°E–90°E, with no TC activity near the equator. These patterns are consistent with studies by Vitart *et al.* (2003) and Mavume *et al.* (2010). While very few systems originate south of 30°S, observed TCs between the latitudes 30°S–35°S are influenced by the mid-latitude atmospheric circulation and thus tend to recurve eastward due to the prevailing westerlies (Maoyi *et al.*, 2018). ERA5 captures the spatial patterns well in terms of both cyclogenesis locations ($r = 0.72$, $p\text{-value} = <0.001$) and tracks ($r = 0.86$, $p\text{-value} = <0.001$) but shows a westward and southward shift of the concentrated region with respect to RSMC in both cases.

Maoyi *et al.* (2018) reported that, with respect to observations, ERA-Interim also features westward shift in TC activities over the SWIO and underestimates TC activity in the eastern portion of the basin.

All models produce realistic simulations of the spatial patterns of cyclogenesis locations (Fig. 4.1) and TC tracks (Fig. 4.2), though with substantial biases. For example, in agreement with observations, all models simulate genesis locations between 5°S-25°S and feature very little cyclogenesis south of 30°S or north of 5°S, which aligns with the observations. The lack of cyclogenesis north of 5°S can be attributed to the weak Coriolis parameter (tends to zero near the equator) which inhibits the development of strong organised vortices (Maoyi *et al.*, 2018). However, most models show a southward and westward shift of the concentrated cyclogenesis region as compared to observations. Observations show that 67% of events over the period 1980-2009 formed in the eastern portion of the basin (65°E-90°E), with only 13% forming in the MC. All models and the ERA5 reanalysis underestimate the percentage of events in the eastern portion of the basin (13%-48%) and overestimate the percentage of events in the MC (14%-44%). These results are in line with the findings of Maoyi *et al.* (2018), who noted a GCM with stretched grid capabilities (CAM-EULAG) underestimated the percentage of events forming in the eastern portion of the basin, and overestimated the percentage of events forming in the MC. Among the models, CNRM-LR and HadGEM-HR perform best in simulating the spatial patterns of both cyclogenesis locations and storm tracks, with concentrated regions of activity that are closest to the observed. As a result, these models exhibit the highest correlation with observations in both Figure 4.1 ($r=0.80$, $p\text{-value} = <0.001$ and $r=0.90$, $p\text{-value} = <0.001$, respectively) and Figure 4.2 ($r=0.86$, $p\text{-value} = <0.001$ and $r=0.93$, $p\text{-value} = <0.001$, respectively). Notably, HadGEM-HR is the only model in which a southward shift in track activity is not present, contributing to its high spatial correlation with observations. While all models show a slight westward shift in the concentration of TC tracks, this is most pronounced in MPI-LR, MPI-HR and HadGEM-LR. These models show high levels of TC activity in the MC, explaining their low correlation with observations. Conversely, CNRM-LR and EC-LR concentrate TC activity towards the central and eastern parts of the basin, contributing to their high spatial correlation

($r=0.86$, $p\text{-value} = <0.001$ and $r=0.85$, $p\text{-value} = <0.001$, respectively). The MPI model performs poorly in simulating the spatial patterns of both cyclogenesis locations and tracks, with very few events captured in both the LR and HR runs. In this model, the concentration of TC activity shifts towards the west of the basin, significantly overestimating the relative frequency of cyclogenesis in the MC and resulting in the lowest correlation with observations in both Figure 4.1 ($r=0.41$, $p\text{-value} = <0.001$ and $r=0.49$, $p\text{-value} = <0.001$, respectively) and Figure 4.2 ($r=0.59$, $p\text{-value} = <0.001$ and $r=0.67$, $p\text{-value} = <0.001$, respectively). The performance of the MPI model is in line with the findings of Roberts *et al.* (2020a), who noted that this model captured very few TCs in any ocean basin.

The response of the simulated spatial patterns of cyclogenesis locations (Fig. 4.1) and storm tracks (Fig. 4.2) to changes in model resolution differs among the models. One consistent response to an increase in resolution is evident in that the LR models tend to show TC track activity concentrated over a smaller latitude range than their HR counterparts, as tracks do not extend as far south as seen in observations and reanalysis. This suggests that the simulated TCs in LR models have shorter lifetimes, possibly due to an inability of the tracking algorithm to capture weakening systems in coarse-resolution grids. In both Figures 4.1 and 4.2 an increase in resolution improves the simulated KDE (i.e., increases the spatial correlation with respect to observations) in MPI and HadGEM, but deteriorates it in CNRM and EC. This suggests that resolution is not a controlling factor on the spatial distribution of cyclogenesis locations and TC tracks. This finding is supported by the results of Roberts *et al.* (2020a). Cyclogenesis locations and storm tracks obtained by Roberts *et al.* (2020a) using the TempestExtremes tracking algorithm (Fig. 4.3) show that for all models, both trackers show similar shifts in the concentrated regions of activity with an increase in resolution. Furthermore, results from both trackers indicate that an increase in resolution improves the spatial correlation with respect to observations in HadGEM and MPI, but deteriorates it in CNRM and EC. Thus, the response of the models to an increase in resolution is robust with two trackers, supporting the finding that resolution is not a controlling factor on the spatial distribution of TC activity in the SWIO.

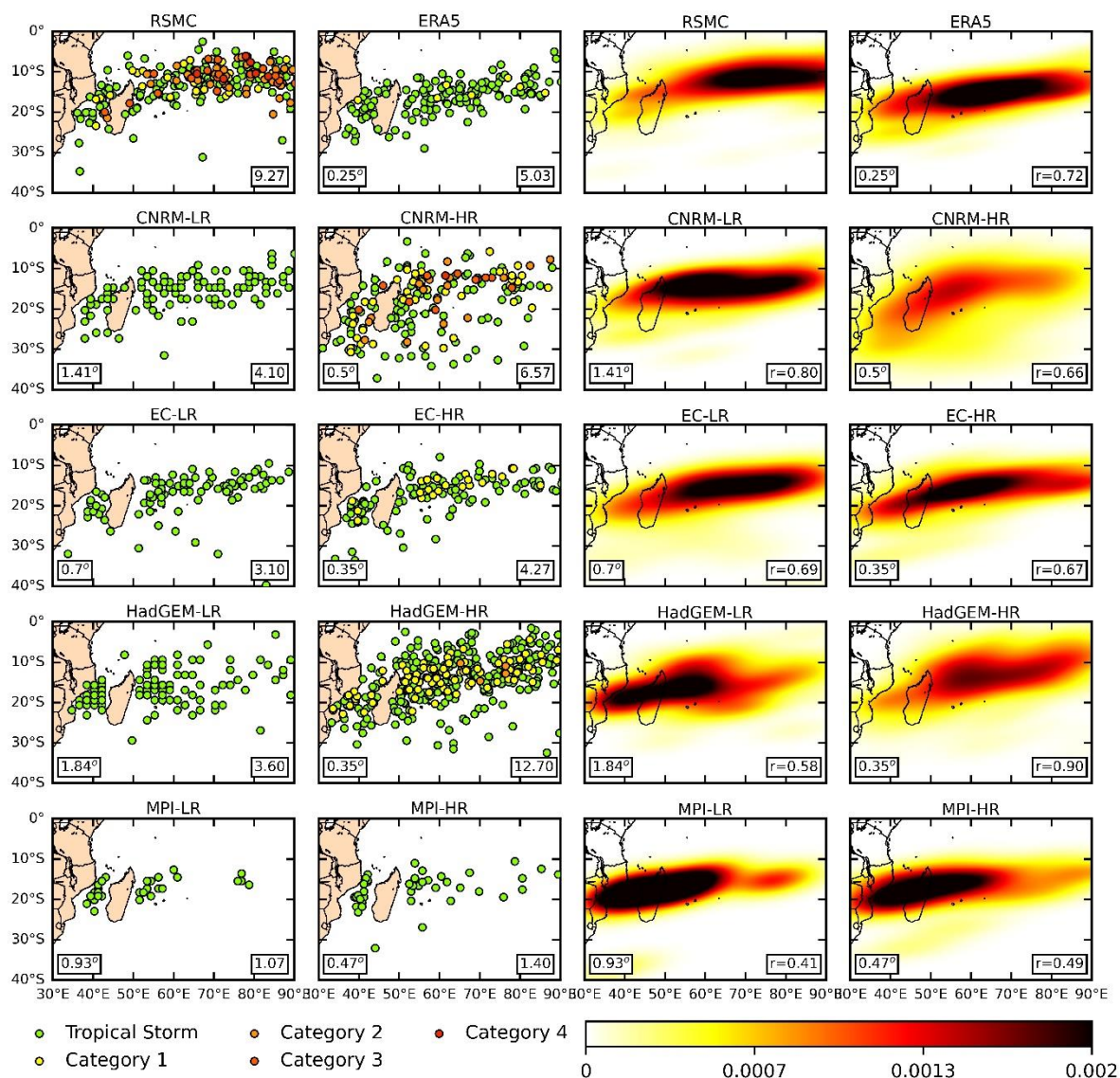


Figure 4.1 Cyclogenesis locations of tropical systems in the SWIO from 1980-2009. The panels on the left show the spatial distribution of genesis locations, with the colour of the dot corresponding to the maximum lifetime intensity of the system. The average annual TC frequency is presented in the bottom right of each panel. The panels on the right show a kernel density estimation (KDE) of these genesis locations, with the spatial correlation with respect to observations (RSMC) given in the bottom right. In both cases, the model resolution is indicated in the bottom left of each panel.

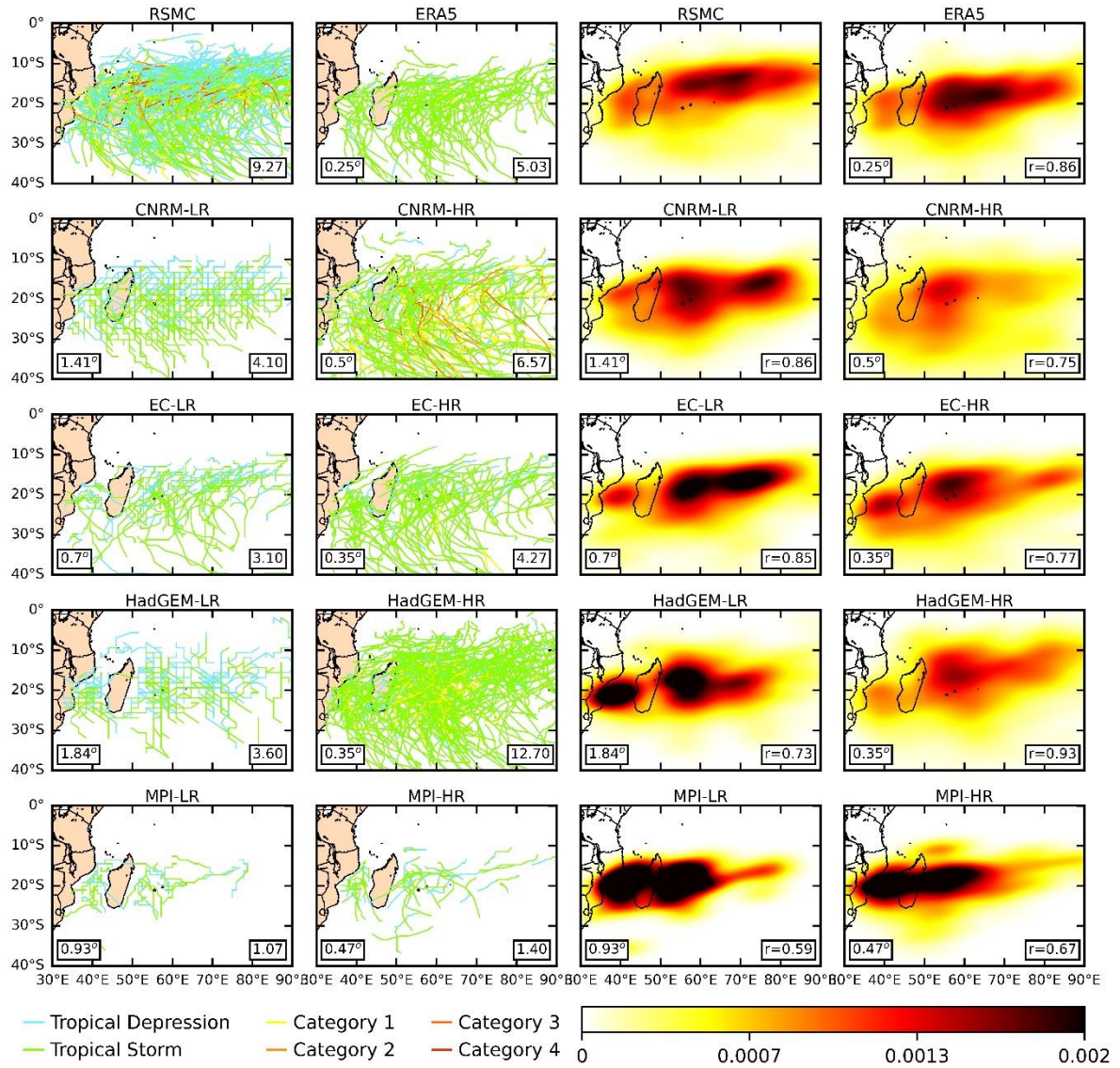


Figure 4.2 Tracks of tropical systems in the SWIO from 1980-2009. The panels on the left show the spatial distribution of the tracks, with the colour of the line corresponding to the intensity of the system. The average annual TC frequency is presented in the bottom right of each panel. The panels on the right show a kernel density estimation (KDE) of these tracks, with the spatial correlation with respect to observations (RSMC) given in the bottom right. In both cases, the model resolution is indicated in the bottom left of each panel.

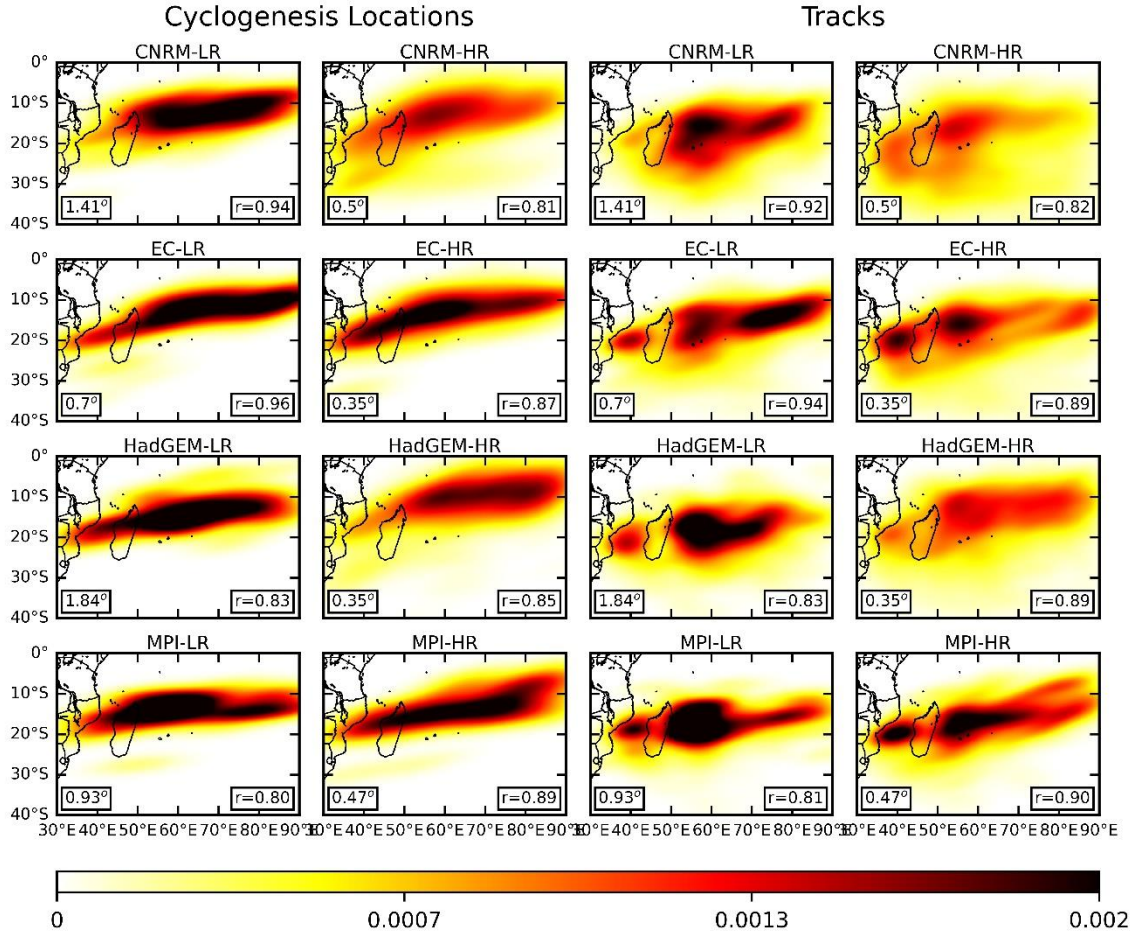


Figure 4.3 Kernel density estimation (KDE) of TC (a) cyclogenesis locations and (b) tracks over the period 1980-2009, using the TempestExtremes tracking algorithm. Tracks were obtained from the results of Roberts et al. (2020a).

4.1.2 Frequency

RSMC observations indicate that, over the period 1980-2009, the SWIO experienced an average of 9.27 TCs each year. While ERA5 adequately reproduces the observed spatial patterns, the reanalysis underestimates TC frequency by 4.24 events per year (Figs. 4.1 and 4.2). All models underestimate TC frequency compared to observations, except for HadGEM-HR, which overestimates TC frequency over the study period (by 3.43 events per year). However, the extent of this bias differs considerably between models. CNRM-HR produces the most realistic approximation of TC frequency, only underestimating the observed frequency by 2.7 events per year. Conversely, MPI-LR captures only 1.07 events per year, thus underestimating the observed frequency by

8.20 events per year. It should be noted that at the same resolution, the simulated TCs in EC-HR account for only 34% of those in HadGEM-HR. This suggests that resolution is certainly not the only factor responsible for modulating simulated TC frequency in this region, and model-to-model differences play a significant role. The biases in the model simulations can indeed be attributed to several factors, including limitations on model resolution, dynamic cores, and physics parameterization schemes.

An increase in resolution increases and improves the simulated TC frequency in all models. This increase ranges from 0.34 events per year in the MPI model, to 9.1 events per year in the HadGEM model. The large increase in TC frequency with an increase in resolution in HadGEM may be attributed to the fact that this model has the largest resolution disparity of all models between the LR and HR runs. However, research also suggests that the influence of stochastic physics schemes could be at play (Roberts *et al.*, 2020a). Stochastic physics schemes are designed to represent the variability in unresolved sub-scale grid processes, and have been found to be beneficial in the modelling of long-term climate (Strommen *et al.*, 2019). While the influence of such schemes decreases as resolution is increased, Vidale *et al.* (2021) suggested that stochastic physics schemes can lead to an increase in TC mean frequency by up to 30% at some resolutions.

4.1.3 Intensity

Figure 4.4a shows the normalised probability density function (PDF) of the 10-m wind speed, taken at peak TC intensity. When considering the observed distribution, it is evident that tropical systems over this period covered a wide intensity range, with no significant peak in the relative frequency in any one intensity category. ERA5 is unable to provide a realistic approximation of the intensity distribution seen in observations, showing a significant peak at 26 m.s⁻¹. This indicates that the majority of systems captured in the reanalysis dataset are of tropical storm strength. Unlike observations, where the relative frequency remains constant in the higher wind speed tails (only reaching a relative frequency of zero following 66 m.s⁻¹), the intensity distribution in ERA5 decreases steadily following its peak. At wind speeds greater than 40 m.s⁻¹, the

relative frequency is reduced to zero. ERA5 is therefore unable to capture the increased probabilities in the higher wind speed tails as seen in observations.

While most of the models are unable to capture the intensity distribution seen in observations, certain models perform better than others. CNRM-HR is the only model that is able to reproduce an intensity distribution comparable to observations, capturing the increased probabilities in the higher wind speed tails. HadGEM-HR and EC-HR also perform relatively well, capturing the increased frequencies in the higher wind speed tails. Once again, even at equal resolutions (0.35° simulations), noteworthy variations exist in the intensity distributions of EC-HR and HadGEM-HR. Both show considerable variations in both the location of the peak intensity, as well as the frequencies in the higher wind speed tails. The peak of the HadGEM-HR simulation ($\sim 28 \text{ m.s}^{-1}$) is found at a higher wind speed than the EC-HR simulation ($\sim 22 \text{ m.s}^{-1}$). Furthermore, HadGEM-HR has a greater frequency of occurrence in the higher wind speed tail compared to EC-HR. Recent studies investigating the simulation of TCs in high resolution models (grid spacing smaller than 0.5°) have noted significant model-to-model differences in TC intensity (Shaevitz *et al.*, 2014; Roberts *et al.*, 2015). As with TC frequency, this finding suggests that resolution is not the only factor that exerts a strong influence on the characteristics of simulated TCs. Of note is that HadGEM-HR shows a peak at the highest wind speeds of all models, suggesting that this model consistently overestimates TC intensities with respect to wind speed. All LR models, as well as MPI-HR, indicate a peak at 18 m.s^{-1} and are unable to capture the increased frequencies in the higher wind speed tails, resulting in more symmetrical distributions. However, although both MPI model simulations show a peak in the intensity distribution at 18 m.s^{-1} , MPI-HR has a greater relative frequency in the higher wind speed tail as compared to MPI-LR.

To provide more information on TC frequency within each intensity category, Figure 4.4b shows the average annual storm count for observations, reanalysis, and models. Observations show that tropical systems in the SWIO over the period 1980-2009 ranged from tropical storm to category 4 TC strength. Tropical storms were most frequent in the dataset, with an average of 5 systems occurring in the SWIO each year.

ERA5 does well to reproduce the tropical storm count, but underestimates the number of category 1 systems, and is unable to simulate events in any of the higher intensity categories.

As in Figure 4.4a, CNRM-HR performs best in reproducing the storm count distribution seen in observations. While this model does underestimate storm frequency within each intensity category, it is the only model which is able to capture the full intensity range seen in observations. HadGEM-HR also captures a relatively wide intensity range, with systems reaching category 2 intensity. However, this model overestimates the number of tropical storm and category 1 systems, with storm counts almost double that of observations in both categories. Furthermore, in each model, the number of systems present within the tropical storm category is very similar between the LR and HR runs. This is true for all models except HadGEM, where the tropical storm count in HadGEM-HR is more than double that of HadGEM-LR. EC-HR is the only other model that is able to simulate systems exceeding tropical storm strength. However, system frequency is underestimated with respect to observations in both intensity categories. All other models underestimate the number of systems within each intensity category, with none of the LR models able to simulate events greater than tropical storm strength. In contrast, while most of the HR models were not able to capture the full intensity range shown in observations, they exhibited greater skill than the LR models in this regard, with 75% of the HR models simulating events of at least category 1 strength. MPI-HR is the only HR model that is unable to simulate any events greater than tropical storm strength, likely due to the low number of events captured in this model.

All models show a consistent response to an increase in resolution, as seen in Figure 4.4. The intensity distribution in Figure 4.4a demonstrates that as resolution increases, there is a systematic shift of the peak of the intensity distribution toward higher wind speeds, and the relative frequencies in the higher wind speed tails increase. Together with the average annual storm counts in Figure 4.4b, these results suggest that an increase in resolution improves the ability of the model to represent the full spectrum of TC intensities, supporting the widely accepted idea that higher-resolution simulations produce a greater frequency of intense storms (Bengtsson *et al.*, 1995,

2007; Murakami *et al.*, 2015; Roberts *et al.*, 2020a, 2020b). However, the clear differences in the intensity distributions and storm counts between models of the same resolution emphasize that model-to-model differences also play a significant role in the intensities of simulated TCs.

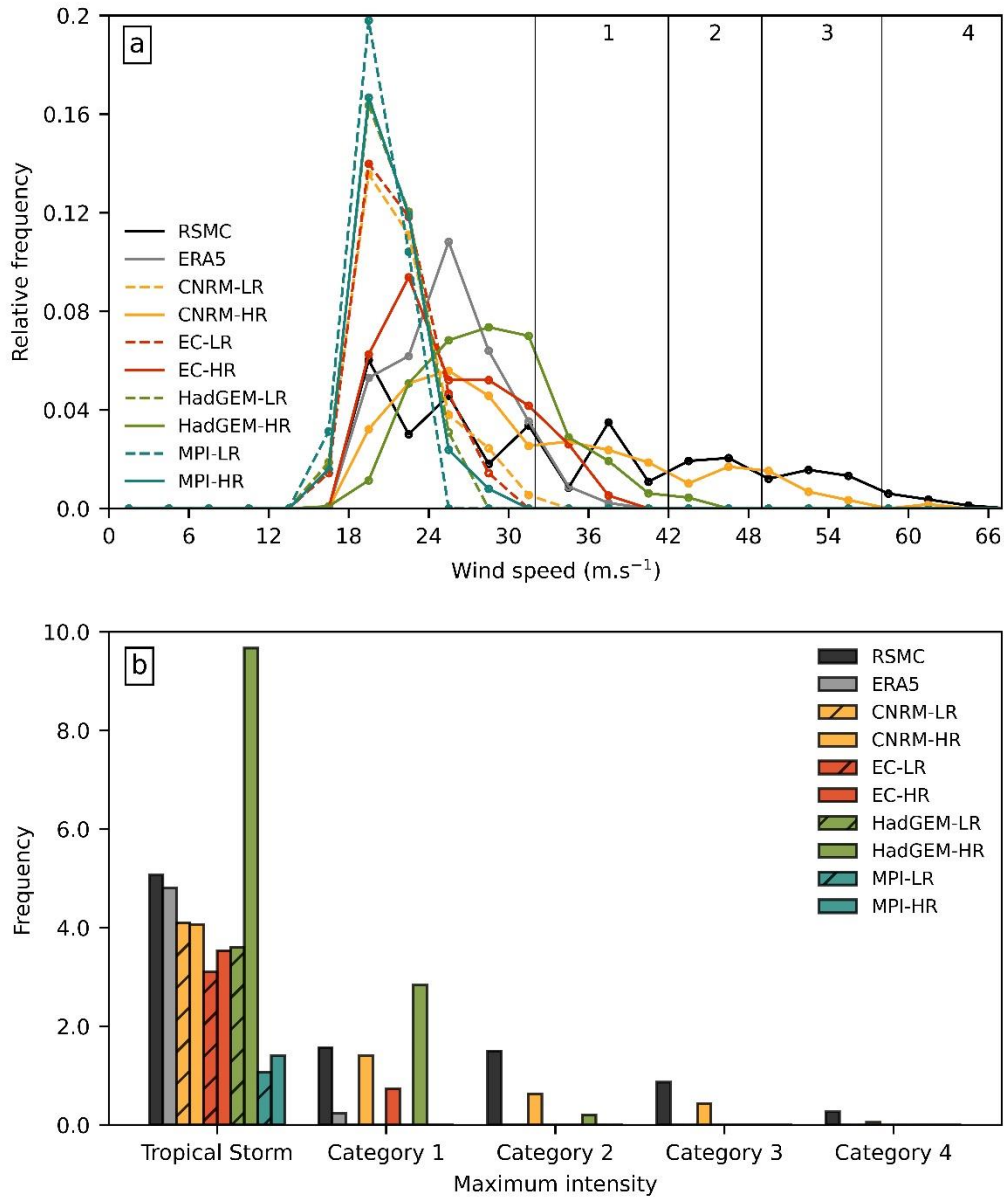


Figure 4.4 Intensity distribution of SWIO TCs from 1980-2009 showing (a) normalized probability density function (PDF) of 10-m maximum wind speed, taken at the lifetime peak TC intensity and (b) the average annual storm count.

4.1.4 Wind-pressure relationship

There is good overall agreement between observations, models, and reanalysis on the wind-pressure relationship (Fig. 4.5), with the highest wind speeds corresponding to the lowest minimum MSLP. ERA5 reproduces this relationship well but is unable to capture the low MSLP and high wind speed values seen in observations.

All models also struggle to achieve storm intensities as in observations. CNRM-HR is an exception to this, while this model is unable to simulate the low MSLP values seen in observations, it is capable of simulating storms with wind speeds reaching category 4 intensity. Davis (2018) reported that only models with a resolution finer than 0.25° should be able to simulate a realistic number of category 4 and 5 systems. The performance of CNRM-HR therefore exceeds the expected capability of a model at this resolution (Roberts *et al.*, 2020a). Upon investigation, Chauvin *et al.* (2020) suggested that the new Cuxart–Bougeault–Redelsperger turbulence scheme employed in CNRM may be responsible for enhancing simulated TC strength via convection (Roberts *et al.*, 2020a). It is also of note that 75% of the HR simulations were able to simulate storms of greater intensity than ERA5 – this is unexpected for two reasons. Firstly, ERA5 reanalysis has a resolution of 0.25° , which indicates that it is of higher resolution than all of the HR models. Secondly, ERA5 reanalysis is forced by observed data, and as such, one would expect to obtain a more realistic representation of atmospheric phenomena.

In summary, Figure 4.5 indicates that there is a systematic shift of model intensities to higher values when resolution is increased. This is clearly illustrated by comparing the LR and HR runs for each model. In each case, the HR model is able to capture lower MSLP and higher wind speed values than its lower resolution counterpart.

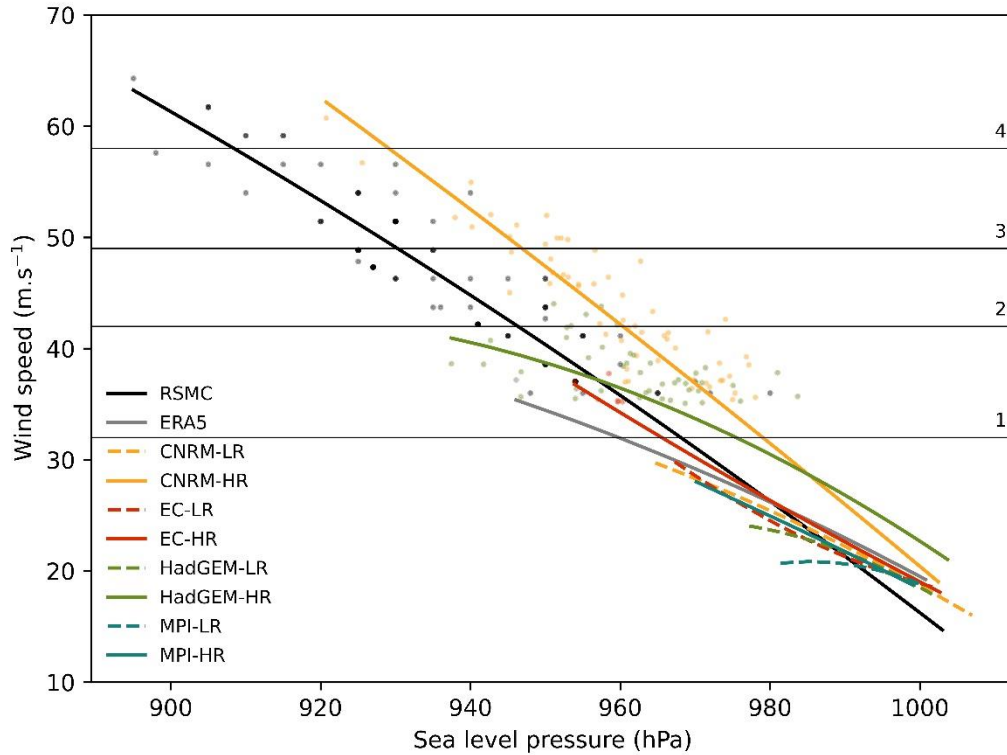


Figure 4.5 Wind-pressure relationship (10-m maximum wind speed versus minimum mean sea level pressure (MSLP)) of SWIO TCs at peak intensity.

4.1.5 Temporal variation

The temporal variation in SWIO TC activity is illustrated in Figure 4.6. Observations indicate that TC activity in the SWIO generally occurs between November and April, with peak activity in January and February (Fig. 4.6a). ERA5 captures this seasonal variability well, but consistently underestimates TC frequency compared to observations. Similarly, the monthly variation is well represented among the models ($r=0.84$ to $r=0.96$), with all models showing peak activity in either January or February. The EC model is an exception to this, with peak activity in January and March, and this is consistent among both the LR and HR runs. While HadGEM-HR is able to produce a reasonable estimation of the monthly variation of TC activity, it is the only model which consistently overestimates the number of genesis events for each calendar month. Furthermore, HadGEM-HR shows elevated levels of activity outside

of TC season, when genesis frequency in all other models, observations and reanalysis is reduced to zero. CNRM-HR also overestimates TC frequency, though only during April and May, while the frequency during the other months is underestimated. Of note is the large disparity in the distributions of HadGEM-LR and HadGEM-HR, while the CNRM, EC and MPI models show very little difference between the LR and HR simulations. This is likely influenced by the relatively larger resolution difference between the LR and HR simulations for the HadGEM model. Although most models consistently underestimate TC frequency for each month, the HR models tend to produce a more realistic approximation of the monthly TC count. Further, the correlation between the models and observation improves with an increase in resolution in EC and MPI and show no change in CNRM and HadGEM. This suggests that while resolution may not be a critical factor in simulating the monthly TC variability, increased resolution can be beneficial in certain models.

In order to assess the interannual variability of TC activity in the SWIO basin, Figure 4.6b shows yearly anomalies of the ACE in the SWIO basin for observations, models, and reanalysis. Observations show a mean annual ACE of $57.11 \times 10^4 \text{ kn}^2$, with a clear upward trend between 1980-2009 (line of best fit gradient = 2.07). While ERA5 captures the interannual ACE variability well ($r=0.85$; $p\text{-value} < 0.001$), likely due to the use of the observed atmospheric state in the reanalysis data (Maoyi *et al.*, 2018), it underestimates the average magnitude of the ACE by $38.91 \times 10^4 \text{ kn}^2$. Furthermore, even though ERA5 captures a slight upward trend in the magnitude of ACE (gradient = 0.37), this is underestimated with respect to observations.

There are clear variations in the performance of the models in simulating the annual ACE. HadGEM-HR performs best, with an annual average ACE of $61.35 \times 10^4 \text{ kn}^2$. Although this model overestimates the ACE compared to observations (by $4.24 \times 10^4 \text{ kn}^2$) (likely due to the overestimation of wind speed seen in Figure 4.4), this value resembles the observed value more closely than any of the other models. In addition, HadGEM-HR captures the strongest positive trend in ACE activity among all models and reanalysis (gradient = 0.59). This may be due to HadGEM being the only model to make use of stochastic physics schemes. As mentioned in 4.1.2, the inclusion of these schemes has shown to be beneficial in modelling long-term climate (Strommen

et al., 2019). CNRM-HR also performs well, despite underestimating the average annual ACE by $18.15 \times 10^4 \text{ kn}^2$, this model has the highest correlation with observations ($r=0.35$, $p\text{-value}=0.06$). However, CNRM-HR is unable to capture the upward trend in ACE activity present in observations (gradient = -0.06). All other models significantly underestimate the average annual ACE and are unable to capture the observed upward trend in ACE.

In all models, an increase in resolution leads to a more realistic approximation of the average ACE. This response is expected given the relationship between resolution and wind speed outlined in Figure 4.5. However, in CNRM, EC and MPI, an increase in resolution appears to be detrimental to the ability of the model to capture the observed upward (positive) trend in ACE activity. CNRM-LR, EC-LR and MPI-LR all indicate weak positive trends in ACE activity. As resolution is increased in the models, the gradient of the line of best fit decreases and the trend flattens. These results suggest that while an increase in resolution does lead to a more realistic approximation of the annual ACE, it does not improve the ability of the model to capture the long-term trends in TC activity.

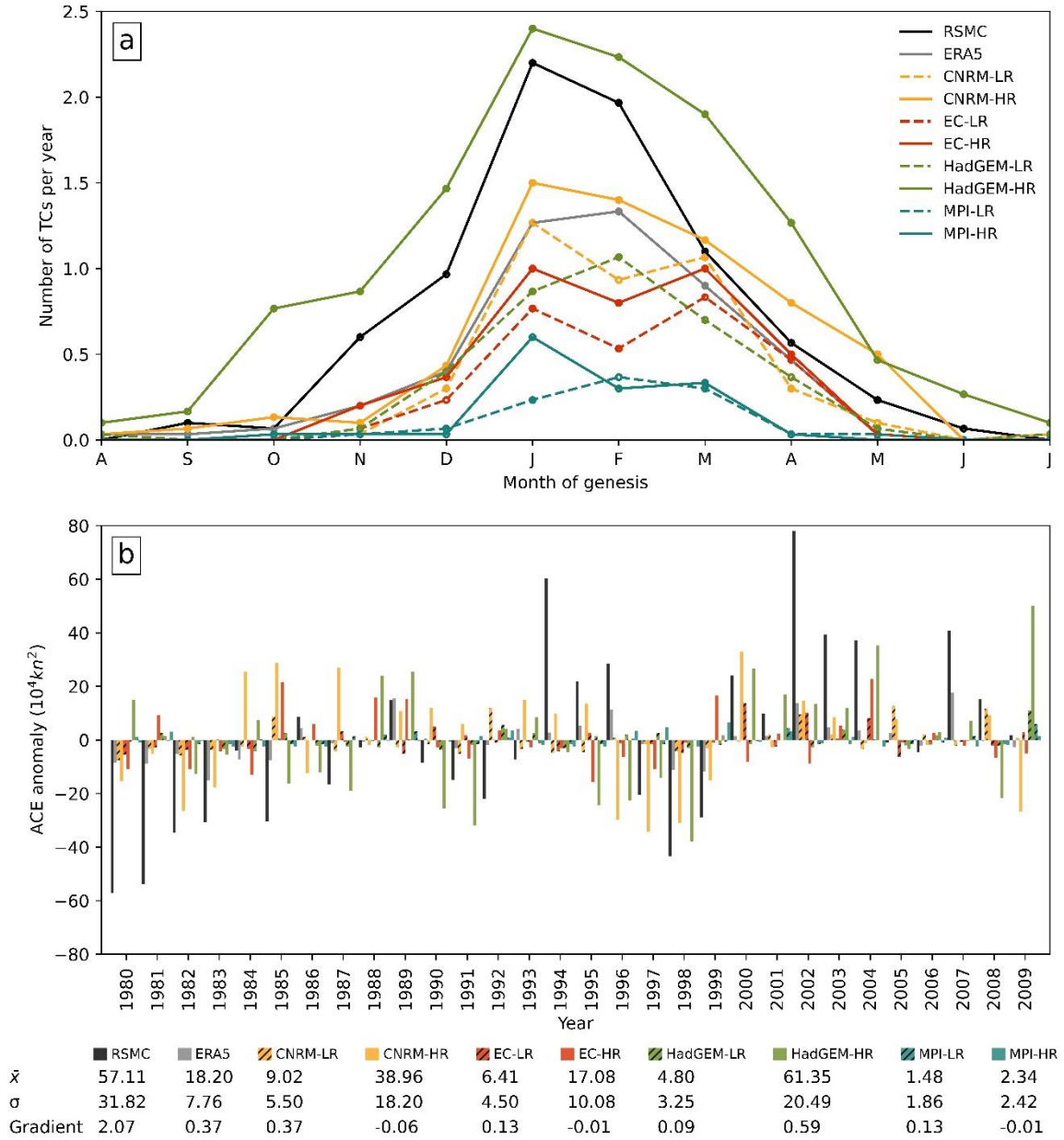


Figure 4.6 Temporal variation of SWIO TC activity from 1980-2009 showing (a) the monthly variation of SWIO genesis frequency and (b) the interannual variability of the accumulated cyclone energy (ACE).

4.2 Atmospheric conditions influencing the characteristics of tropical cyclones over the South-West Indian Ocean

4.2.1 Velocity potential

In order to gain some insight into the large-scale environmental factors influencing the characteristics of simulated systems, Figure 4.7 provides a composite analysis of velocity potential at both upper (250 hPa) and lower (850 hPa) levels. The ERA5 reanalysis dataset shows weak divergence (negative velocity potential) present over the SWIO, with an area of weak convergence (positive velocity potential) to the north-west of Madagascar in the MC, as well as in the south-east quadrant of the basin. Upper tropospheric convergence results in subsidence and thus reduces deep convection. This may explain the absence of genesis locations and storm tracks in these areas in Figures 4.1 and 4.2. Although upper-level divergence is present over the majority of the SWIO basin, the magnitude does not exceed $4 \times 10^6 \text{ m}^2.\text{s}^{-1}$. The strength of the divergence may explain the small intensity range of simulated storms in the ERA5 reanalysis dataset. When considering the velocity potential at lower levels, the increase in lower-level convergence, and therefore convection, as one moves eastwards may explain the concentration of genesis locations in the central and eastern regions of the basin in Figure 4.1.

In many of the models, the change in velocity potential over the basin as resolution is increased may explain the associated changes in the characteristics of simulated storms, in terms of TC intensity, frequency, and spatial distribution. Since CNRM-LR shows strong upper-level divergence over the entire SWIO basin, the lack of a localized region of deep convection makes it difficult to deduce how the upper-level velocity potential composite may influence the spatial patterns of TC activity. However, the lower-level velocity potential composite may offer some insight. Both CNRM-LR and CNRM-HR show strong lower-level convergence that increases in strength as one moves further east. Although both models show the same pattern, the strength of the convergence is reduced as resolution is increased. The region of strong lower-level convergence in CNRM-LR (70°E-90°E) may explain the concentration of TC activity towards the east of the basin in Figures 4.1 and 4.2. As resolution increases, the

strength of the lower-level convergence decreases and TC activity shifts towards the centre of the basin. While the lower-level velocity potential can provide insight on the spatial patterns of TC activity in this model, it cannot explain the changes in frequency and intensity that are observed with an increase in resolution.

EC-LR has strong upper-level convergence present over western SWIO (30°E-70°E). Upper-level convergence results in subsidence and, consequently, inhibits convection, thereby reducing TC activity. As a result, EC-LR has events concentrated towards the east of the basin, contributing to its high correlation with respect to observations in Figures 4.1 and 4.2. As resolution increases, the upper-level convergence is reduced, with weak upper-level divergence present over the basin, thus shifting the concentrated region of TC activity towards the centre of the basin in EC-HR (Figs. 4.1 and 4.2). Furthermore, this reduction in upper-level convergence (and increase in upper-level divergence) as resolution increases may explain, at least in part, the increase in TC frequency and intensity in EC-HR. These results suggest that in the EC-Earth model, changes in TC spatial patterns, frequency and intensity that result from an increase in resolution, may be explained by the influence of resolution on the upper-level velocity potential on TC days.

In contrast to EC-LR, HadGEM-LR features strong upper-level divergence over the majority of the SWIO. As resolution increases, this upper-level divergence is reduced, with HadGEM-HR showing strong upper-level convergence in the MC, and weak upper-level divergence over the east of the basin (75°E-90°E). The increase in upper-level convergence and subsidence over the MC as resolution is increased may explain the shift of TC activity towards the east of the basin in HadGEM-HR (Figs. 4.1 and 4.2). However, as with CNRM, while the upper-level velocity potential in HadGEM can provide insight on the spatial patterns of TC activity, it cannot explain the changes in frequency and intensity that are observed with an increase in resolution.

Given the negligible difference in spatial patterns of TC activity between MPI-LR and MPI-HR in Figures 4.1 and 4.2, it is difficult to determine the influence of the velocity potential on this feature. However, both the upper- and lower-level velocity potential patterns may explain changes in frequency and intensity that are observed with an

increase in resolution. MPI-LR shows weak upper-level convergence over the western portion of the basin (30°E-70°E) and strong upper-level divergence over the east of the basin (70°E-90°E). As resolution increases, divergence is present over the entire SWIO. Similarly, at lower levels, MPI-LR features weak divergence over the western portion of the basin (30°E-70°E) and moderate convergence over the east of the basin (70°E-90°E). As resolution increases, convergence is present over the entire SWIO and the strength of the convergence increases, thereby promoting convection. This increase in basin-wide upper-level divergence and lower-level convergence with an increase in resolution may explain why simulated storms in MPI-HR have a greater frequency and intensity than in MPI-LR. This suggests that in the MPI model, changes in TC frequency and intensity resulting from an increase in resolution may be explained by the influence of resolution on the upper-level velocity potential on TC days.

The differences in the velocity potential composite between each model is also noteworthy. For example, the CNRM model features strong upper tropospheric divergence over the entire Indian Ocean basin, consistent in both the LR and HR runs. Since strong upper tropospheric divergence results in deep convection, the velocity potential composite in Figure 4.7 may explain the increased intensity of simulated storms in CNRM as compared to the other models. Both CNRM-LR and CNRM-HR simulated a greater frequency of events at higher wind speeds than all other LR and HR models respectively, indicated by the relative frequency in the higher wind speed tails in Figure 4.4. Chauvin *et al.* (2020) suggested that a new turbulence scheme used in CNRM is likely responsible for increasing TC strength via convection.

Bengtsson (2007) found that velocity potential patterns are strongly coupled with SST. Subsequently, ENSO can exert a strong influence on the large-scale velocity potential. For example, Gore *et al.* (2020) demonstrated that in the SWIO, El Niño events tend to result in anomalous upper-level convergence over the region, while La Niña events are associated with anomalous upper-level divergence. Furthermore, Gore *et al.* (2020) explained that the upper-level divergence over the SWIO during La Niña is further strengthened by the associated warm SST anomalies in the region. Additionally, Reason (2001) demonstrated that during an SST dipole event, when

SSTs are anomalously warm in the SWIO, the January-March velocity potential patterns display anomalous lower-level convergence over the SWIO, and divergence over Australia and Indonesia. These patterns suggest a local enhancement of the Walker circulation over the SWIO region. This link between SST and large-scale velocity potential patterns may offer some insight into changes in the velocity potential field of each model with increasing resolution. For example, HadGEM-HR has the highest instance of TC occurrence outside of TC season (Fig. 4.6) and also features reduced lower-level convergence and upper-level divergence on TC days compared to HadGEM-LR (Fig. 4.7). Since TC season in the SWIO occurs during austral summer when SSTs are high and act to the strengthen upper-level divergence over the region, the increased instance of events outside of TC season in HadGEM-HR would likely result in a dampening of this pattern in the model.

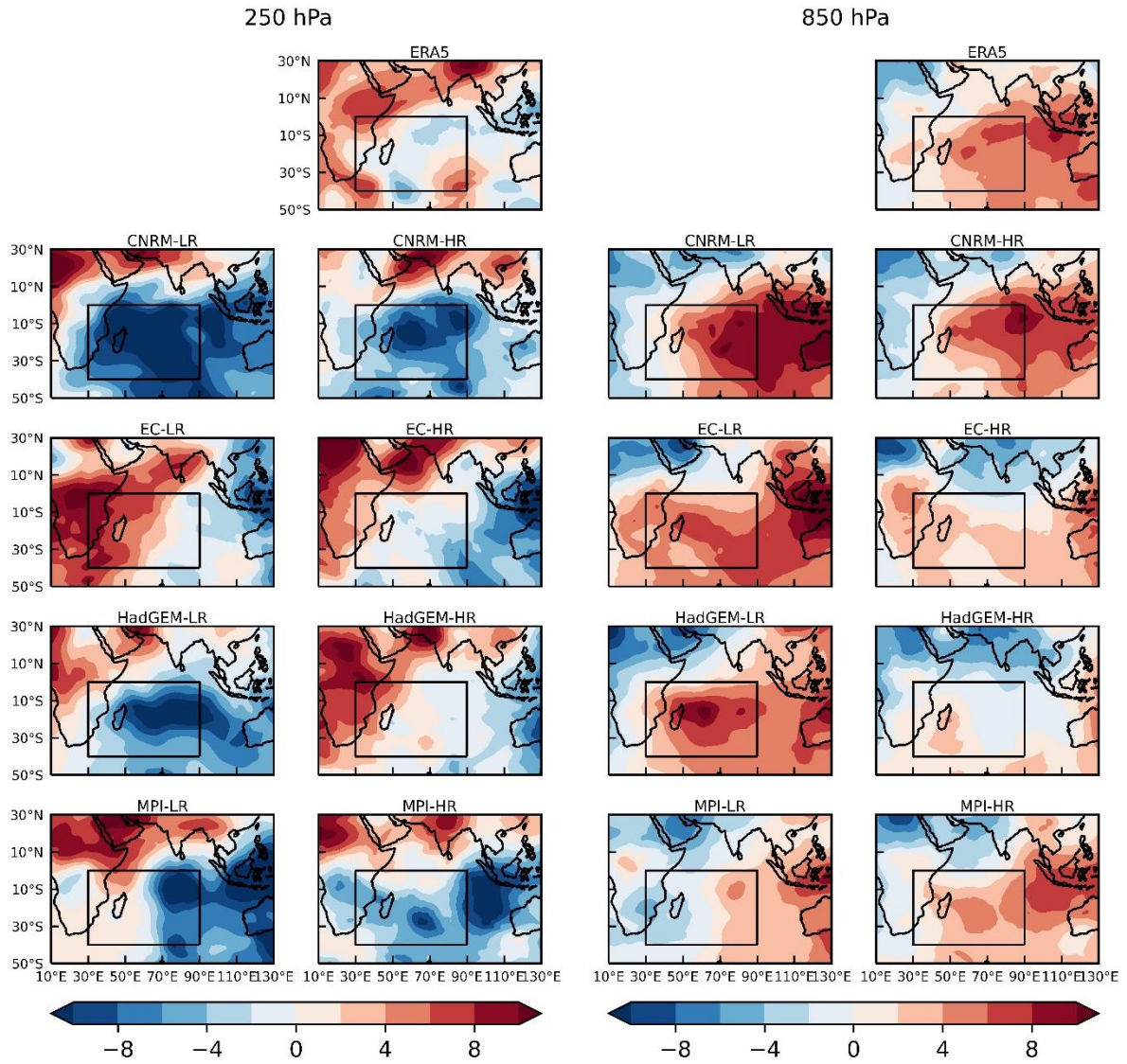


Figure 4.7 Velocity potential composite for all storm days over the period 1980-2009 at 250 hPa and 850 hPa. Positive values indicate convergence and negative values indicate divergence.

4.2.2 Wind shear

To offer further insight into the potential environmental influences on simulated TC characteristics, the mean 850-250 hPa wind shear for November to April 1980-2009 is shown in Figure 4.8. Each model appears to have a distinct pattern of shear, which shows little variation with a change in resolution. In all models, an area of strong wind shear ($> 20 \text{ m.s}^{-1}$) is present south of 18°S , extending to approximately 35°S . However, the longitudinal range of this area of increased wind shear ($> 20 \text{ m.s}^{-1}$) shows clear differences between models. The wind shear patterns present in both the EC-Earth and MPI models are very similar to that of ERA5 reanalysis, with a band of strong wind shear ($> 20 \text{ m.s}^{-1}$) present across the entire SWIO basin (30°E - 90°E). Conversely, in the CNRM and HadGEM models, this region of strong wind shear does not span the entire basin, but rather extends from $\sim 50^\circ\text{E}$ - 90°E , with the western portion of the basin featuring weaker shear compared to the other models and ERA5 reanalysis. Further, northward of 10°S , the HadGEM model shows the weakest shear of all models and reanalysis ($> 5 \text{ m.s}^{-1}$). When investigating TC activity in this region, observations show that only 6.4% of all TC activity in the SWIO over the period 1980-2009 occurred north of 10°S . HadGEM-HR produces the highest incidence of TC activity in this region (13.1%) out of all models and reanalysis. Similarly, while HadGEM-LR underestimates the TC activity with respect to observations, this model does have the highest TC frequency of all LR models in the region north of 10°S (3.4%). Considering overall TC frequency, CNRM-LR has the greatest frequency of events among the LR models, followed by HadGEM-LR. Conversely, HadGEM-HR has the greatest frequency of events across HR models, followed by CNRM-HR. The wind shear patterns shown in Figure 4.8 suggest that the high frequency of events in HadGEM and CNRM may be attributed to the weaker climatological wind shear present over the eastern and northern parts of the SWIO basin in these models.

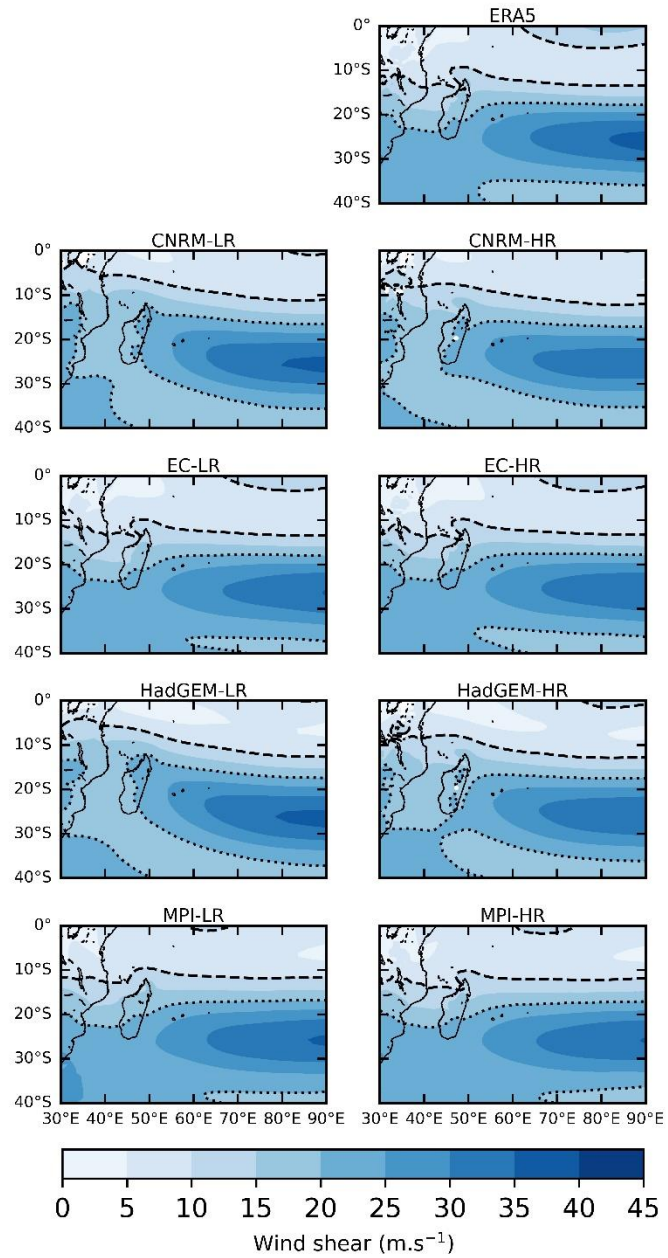


Figure 4.8 Wind shear between 850 hPa and 250 hPa for the mean over November-April. The dashed and dotted lines show regions of 10 m.s^{-1} and 20 m.s^{-1} respectively.

4.3 Summary and limitations

Despite numerous studies on the impact of model resolution on TC simulation, none have focused on SWIO TC activity. This study investigated the impact of model resolution on the characteristics of SWIO TCs over the period 1980-2009 by analysing the results of four CMIP6 HighResMIP models with both standard- and enhanced-resolution runs. The model simulations were compared to RSMC observations and ERA5 reanalysis data to assess the skill of the models in capturing the characteristics of SWIO TC activity. For each model, the characteristics of the simulated TCs were compared between the low- and high-resolution runs to determine the effect of increasing resolution on each metric. Large-scale atmospheric features were also investigated to offer insight into the mechanisms that may be responsible for changes in TC characteristics resulting from an increase in resolution. An objective tracking algorithm was used to detect and track TCs. The results of the study can be summarized as follows:

- All models produce realistic simulations of TC tracks and cyclogenesis locations, but feature a westward shift in TC activity towards the MC and away from the eastern portion of the SWIO basin. Increasing model resolution improves the simulated spatial patterns in half of the models. This result is robust with two trackers.
- With the exception of HadGEM-HR, all models underestimate TC frequency. The MPI model performs notably poorly, capturing very few events over the study period. Increasing model resolution increases and improves the simulated TC frequency in all models. However, considerable variations between different models of the same resolution indicate that model-to-model differences play a significant role in this regard.
- CNRM-HR is the only model that is able to reproduce an intensity distribution comparable to observations, while all other models struggle to reproduce the high observed intensities. In all models, an increase in resolution improves the ability of the model to reproduce the range of TC intensities seen in observations. The above point regarding variations between models of the same resolution is also applicable to simulated TC intensity.

- The monthly TC variability is well represented among the models, with half of the models showing improved representation with an increase in resolution. However, in all models, increased resolution leads to a more realistic approximation of the monthly TC count.
- The models show considerable variation in simulating the average annual ACE. In all models, an increase in resolution increases and improves the simulated average annual ACE. However, increased resolution does not improve the ability of the model to capture the long-term trends in TC activity.
- In some models, the influence of increasing resolution on TC characteristics can be explained by changes in the velocity potential field over the SWIO region.
- Wind shear patterns are model-specific and show little variation with changes in resolution. Weaker climatological wind shear present over parts of the SWIO in HadGEM and CNRM may contribute to the high frequency of events in these models.

This chapter has provided valuable insights into the impact of model resolution on SWIO TC simulation. However, the nature of the models and the temporal scale of the analysis introduces some limitations. Firstly, this analysis covers a 30-year period (1980-2009), which makes it difficult to determine the ability of the models to capture observed TC intensities. While storm intensity is still investigated on the climatological scale, through the analysis of the simulated ACE, this metric provides annual basin-wide statistics that are influenced by the simulated TC frequency, as well as system duration. In order to fully understand the ability of a model to simulate high-intensity storms with severe impacts, these cases need to be investigated on an individual level. Secondly, for all models analysed in this chapter, only two resolution runs are available. Conducting an analysis at multiple resolutions may offer more insight into the impact of model resolution on simulated TC characteristics. Finally, all models included in this analysis are uniform-resolution GCMs, which are extremely computationally demanding when run at high-resolutions. For this reason, the highest resolution of all models is only 0.35° (~39km). The use of a VGCM will allow for TC simulation at higher resolutions that would be computationally inefficient in a uniform-

resolution GCM. The following chapter attempts to fill these gaps through the simulation and analysis of two highly destructive TC events which occurred in the SWIO in early 2019. The use of MPAS, a VGCM, allows for the simulation of these events at multiple resolutions on both hydrostatic (60km, 15km) and non-hydrostatic scales (10km, 3km). Further, the simulation of individual events will allow for more control over the model configuration, providing the opportunity to investigate the sensitivity of MPAS to initial conditions and physics parameterizations, in addition to resolution. Given the shortage of work on TCs in the SWIO region, conducting this investigation on differing spatial and temporal scales will offer a holistic overview of how TCs are modelled in the SWIO region, and the impact of resolution thereon. This is the focus of the next chapter.

CHAPTER 5 : Performance of MPAS-A in simulating Tropical Cyclones Idai and Kenneth over the South-West Indian Ocean

This chapter presents and discusses the performance of MPAS simulating two highly destructive TCs which occurred in the SWIO in early 2019. The chapter begins by evaluating the performance of MPAS in simulating the TC tracks and intensities at a resolution of 60km (Section 5.1). It goes on to demonstrate and discuss the sensitivity of MPAS to initial conditions (Section 5.2), as well as resolution and physics parameterization suites (Section 5.3). This chapter also investigates the performance and sensitivity of MPAS in simulating the rapid intensification of TC Kenneth (Section 5.4). Finally, this chapter provides a summary of the results (Section 5.4).

5.1 Evaluation of the simulated tropical cyclones

The CONTROL simulations of TCs Idai (Fig. 5.1a) and Kenneth (Fig. 5.1b) reasonably represent the observed tracks of these events but show southward track and landfall biases. In both cases, there is good agreement between observations (RSMC and JTWC) and ERA5, with the reanalysis showing little deviation from the observed tracks. The southward track bias present in the CONTROL simulations results in landfall displacement errors of approximately 115km and 130km for TCs Idai and Kenneth, respectively. Furthermore, both simulations show reduced propagation speeds compared to observations and reanalysis. This disparity results in landfall-time errors, with the simulated TCs making landfall approximately 12 hours later than their respective observed landfall times. Additionally, the CONTROL simulations of both TCs Idai and Kenneth significantly underestimate the TC intensity in terms of both wind speed and MSLP (Figs. 5.2 and 5.3). The lack of skill in these TC hindcasts is likely related to inadequacies in model resolution, physical parameterizations, or initial conditions (Cacciamani *et al.*, 2000; Mohanty *et al.*, 2010). These results support the findings of Lui *et al.* (2021), who noted that while MPAS TC simulations could

reasonably reproduce the observed TC tracks, simulated TCs exhibited reduced propagation speeds and a severe underestimation of TC intensity. Bopape *et al.* (2021) also reported a southward track bias in a WRF simulation of TC Idai with the Tiedtke convection scheme, which is the convection scheme used in the mesoscale reference simulations in the present study.

The southward shift biases in simulations of TCs in MPAS and contemporary atmospheric models have implications for TC forecasting or early warning systems. The purpose of TC forecasting and TC early warning systems is to provide information on predicted TC tracks, intensities and landfalling times, so that affected nations may respond swiftly and thus reduce their vulnerability to TC-related hazards. In the case of both TC Idai and TC Kenneth, the use of MPAS to forecast these events would result in a severe underestimation of the intensity of each system. Further, incorrect information on the location and time of landfall would likely arise from the southward track biases and reduced propagation speeds of the simulated TCs. As a result, affected nations would underestimate the potential for damage from these events and forgo the necessary measures to mitigate impacts and reduce loss of life. As an attempt to improve the simulation of TCs with MPAS, this chapter presents and discusses the sensitivity of the simulated TCs to MPAS initial conditions, physics parameterization suites, and resolution in the remaining sections of the chapter.

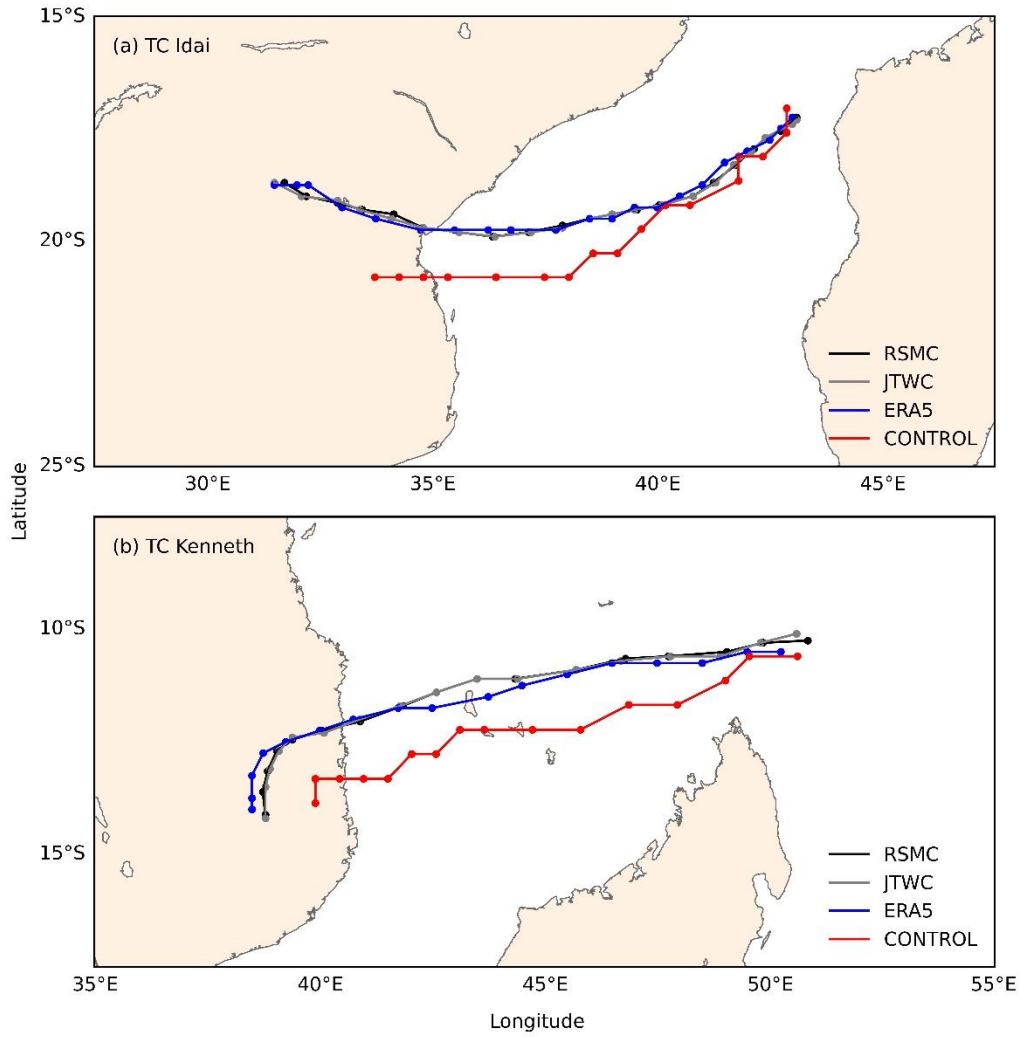


Figure 5.1 Track of (a) TC Idai (00h00 11 March 2019 - 06h00 16 March 2019) and (b) TC Kenneth (00h00 23 April 2019 - 00h00 27 April 2019) for observations, ERA5 reanalysis, and MPAS CONTROL simulation.

5.2 Sensitivity to initial conditions

The sensitivity of the simulated TCs to the choice of initial condition datasets (i.e., ERA5 versus CFSR) is shown in Figures 5.2 and 5.3. For both TC events, it is clear that using ERA5 data to initialize the model gives better results. For both TC Idai (Fig. 5.2) and TC Kenneth (Fig. 5.3), the 60km simulation initialized with ERA5 data (CONTROL) follows the observed track more closely than the simulation initialized with CFSR data (CFSRCTR). Additionally, the tracks of both TCs are better

represented in the ERA5 dataset than the CFSR dataset, which shows a somewhat erratic movement of each TC. This is further supported by the wind-pressure relationship of each TC (Figs. 5.2b and 5.3b), as well as the time-series of maximum 10-m wind speed (Figs. 5.2c and 5.3c) and minimum MSLP (Figs. 5.2d and 5.3d). For both TC Idai and TC Kenneth, the 60km MPAS simulation initialized with ERA5 data (CONTROL) simulates higher wind speed and lower MSLP values than the simulation initialized with CFSR (CFSRCTR), resulting in a lower RMSE value in all cases. The use of ERA5 initial conditions thus produces a wind-pressure relationship and intensity hindcast closer to the observed for both TC Idai and TC Kenneth. The better performance of ERA5 than CFSR in this study can be attributed to several reasons. Firstly, ERA5 has a higher resolution than CFSR, with resolutions of 30km and 38km, respectively. The higher resolution of the ERA5 data will thus provide more detail in the initial conditions used by the model. Additionally, the time series of wind speed (Figs. 5.2c and 5.3c) and MSLP (Figs. 5.2d and 5.3d) for both TCs Idai and Kenneth indicate that CFSR considerably overestimates the initial MSLP and underestimates the initial wind speed for each event. Further, the MSLP and 850 hPa wind fields for the initial times in the reanalysis datasets (Fig. 5.4) show that for both events, the ERA5 dataset features a tighter eye, deeper central pressure, and stronger cyclonic winds than the CFSR dataset, which is less organised and features a large area of low pressure without a clear minimum. This explains the deeper initial MSLP and higher initial wind speeds in the CONTROL simulations compared to the CFSRCTR simulations. Since the model forecast skill is largely dependent on the accuracy of the initial condition data (Sanders, 1987), this may explain the superior performance of ERA5 as compared to CFSR. Lui *et al.* (2021) also reported that MPAS gives better simulations of TCs (in terms of both intensity and track) when initialized with ERA5 than with ERA-Interim. They found that when initialized with ERA5, the simulated storms showed tighter / more well-defined eyes, stronger cyclonic winds, and better resolved horizontal wind structures. Lui *et al.* (2021) also noted that the MPAS simulations initialized with ERA5 featured deeper initial central pressures than those initialized with ERA-Interim. They suggested that the relatively poorer performance of MPAS when initialized with ERA-Interim is likely due to the inferior representation of storms in the ERA-Interim initial fields. For the remaining part of the present study,

only the results of MPAS simulations initialized with ERA5 are presented and discussed.

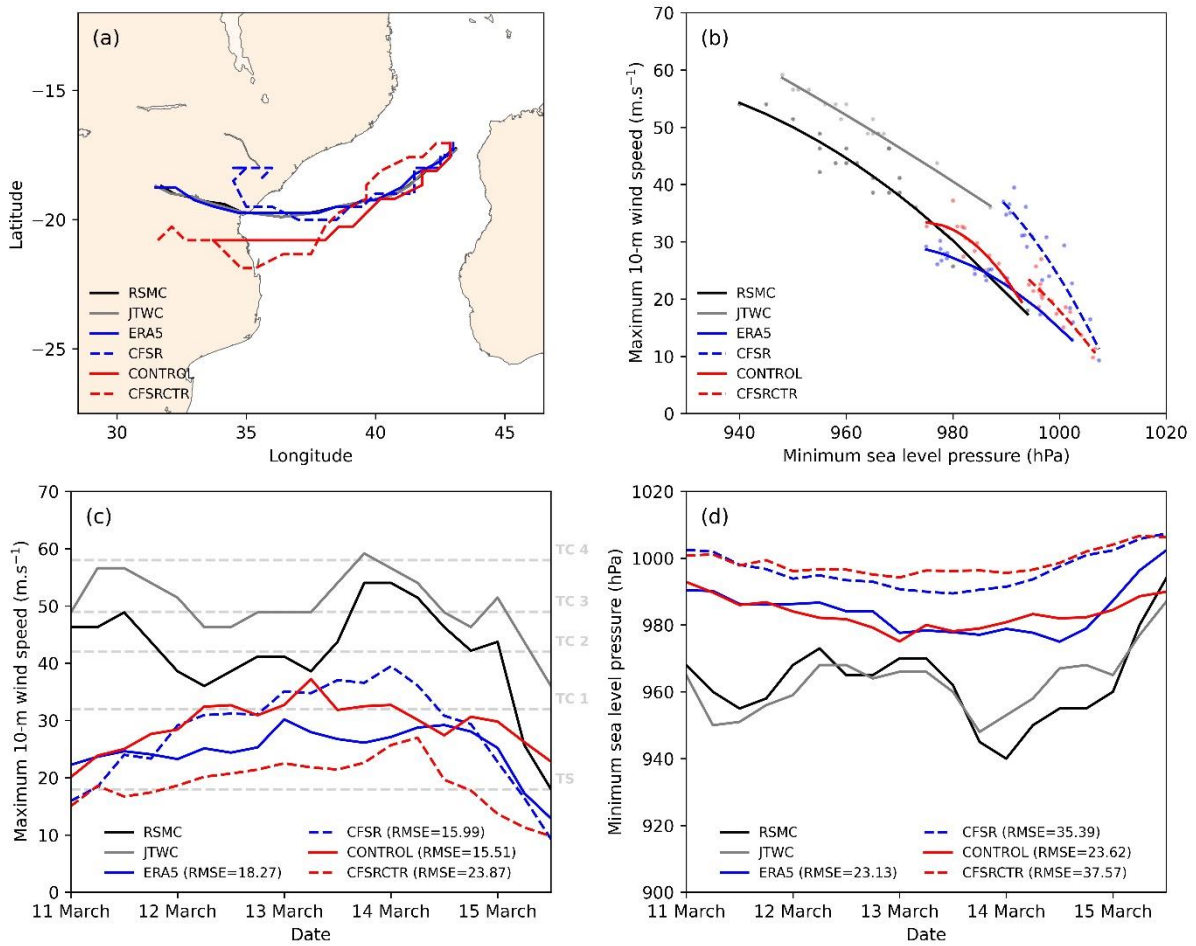


Figure 5.2 Sensitivity of the simulated TC Idai to initial conditions: (a) track, (b) wind-pressure relationship, (c) wind speed time series and (d) mean sea level pressure (MSLP) time series for observations, ERA5 reanalysis, MPAS CONTROL and CFSRCTR simulations.

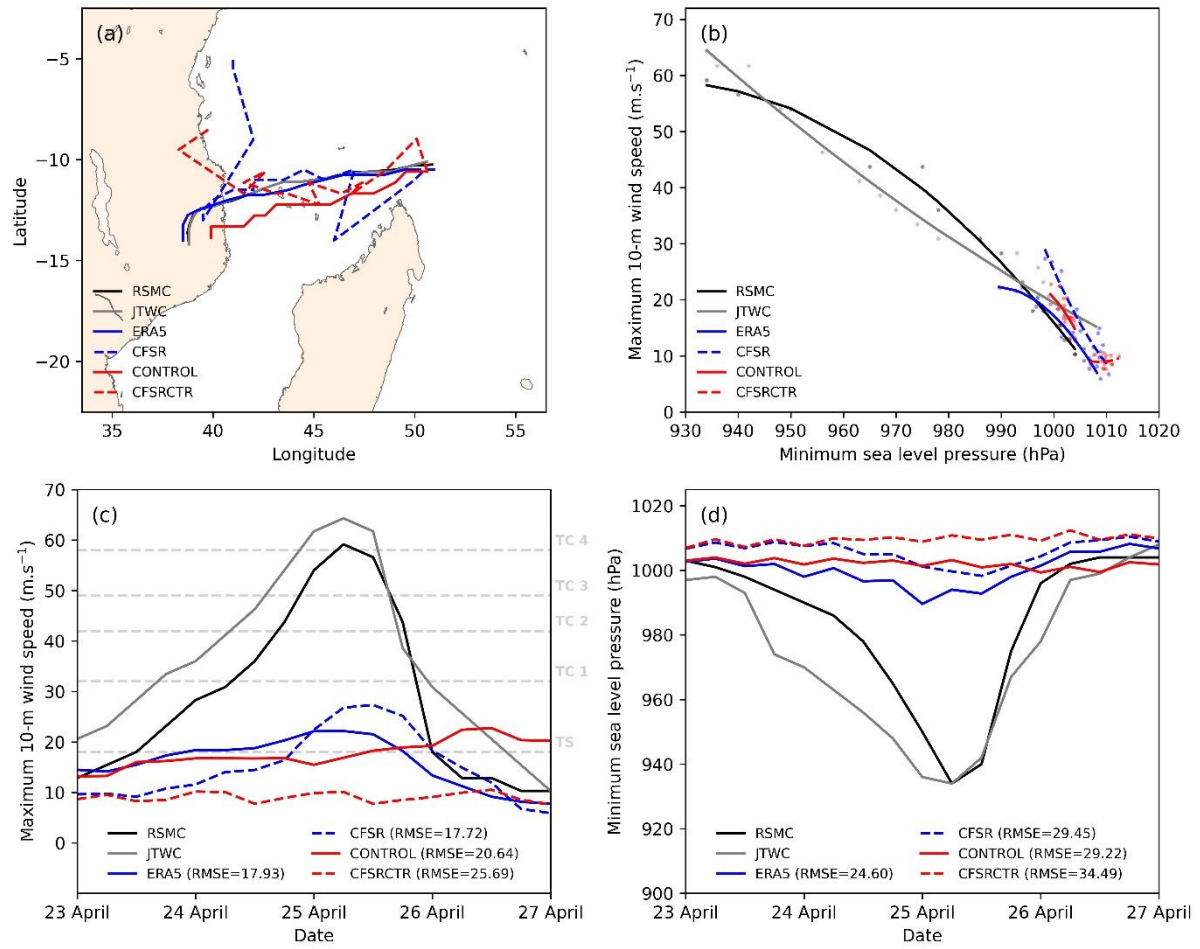


Figure 5.3 Same as Figure 5.2 but for TC Kenneth.

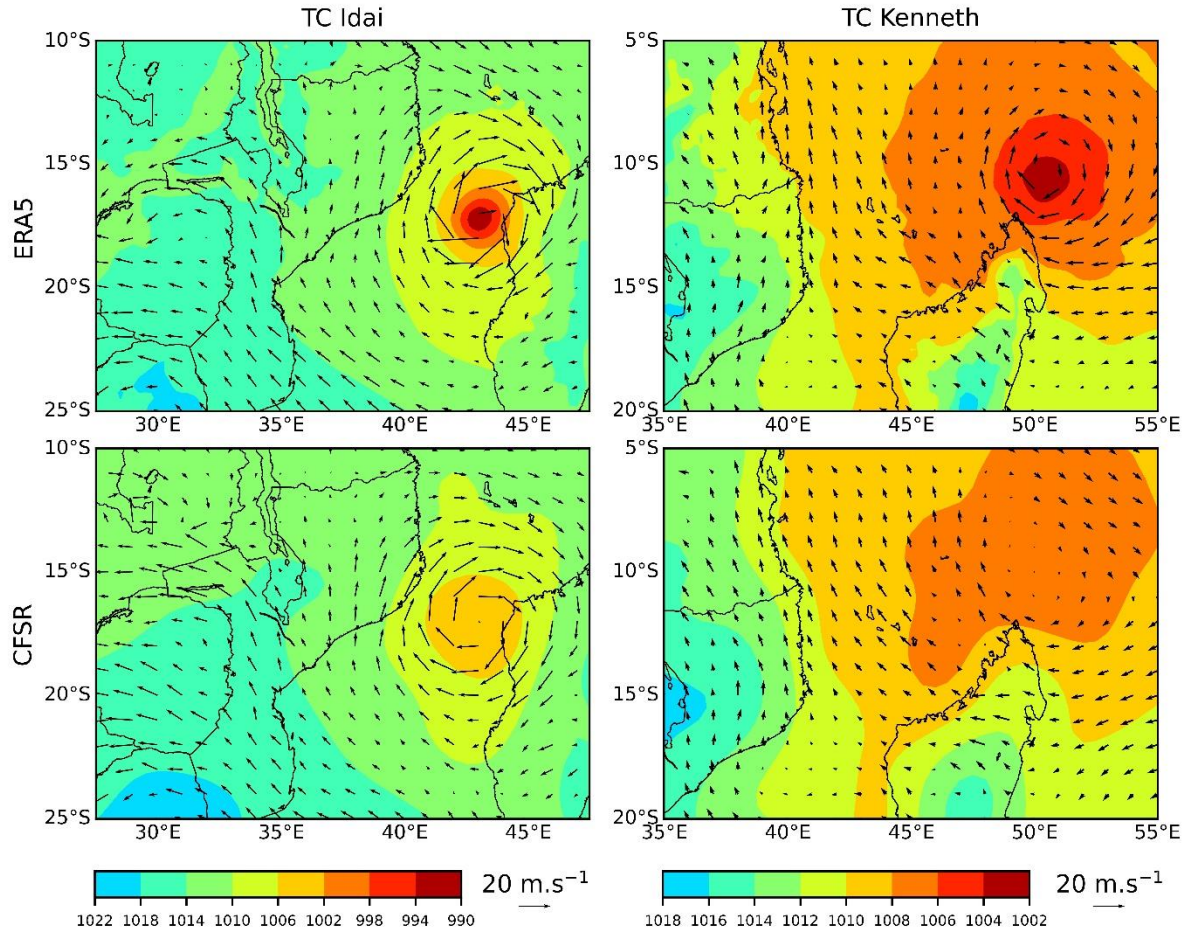


Figure 5.4 The mean sea level pressure (MSLP) (shaded, in hPa) and the 850 hPa wind fields (arrows) of ERA5 and CFSR datasets used in initializing MPAS simulations for TC Idai (00h00 11 March 2019) and TC Kenneth (00h00 23 April 2019). The length of the arrows indicate the wind speed ($m.s^{-1}$).

5.3 Sensitivity to resolution and physics parameterizations

The sensitivity experiments show that increasing the resolution of MPAS generally improves the simulated TC (Figs. 5.5, 5.6 and 5.7). However, the improvement differs among the TC events, depends on the choice of physics parameterization suite, and varies with TC characteristics. For both TC events, an increase in resolution shifts the track of the simulated TC northward, bringing it closer to the observed track and reducing the southward landfall bias and landfall-time error of the simulated system (Fig. 5.5). It also improves the propagation speed of the simulated TC Idai, but only for the mesoscale reference suite simulations. For TC Idai, the track of the simulated system is better represented in the convection-permitting suite simulations (CP03 and CP10), which follow the observed track more closely than their mesoscale counterparts and thus give a better landfall location of the TC. Conversely, the use of the convection-permitting suite is detrimental to the track of TC Kenneth because CP03 shifts the simulated track too far northwards (resulting in a northward landfall bias), and CP10 is unable to reproduce the landfall of the TC (despite the movement of the TC toward the coast). This northward shift in the track seen in CP03 may be due to the Grell-Freitas convection scheme used in the convection-permitting simulations. Bopape *et al.* (2021) found that the Grell-Freitas convection scheme shifted the track of TC Idai northwards when simulating this event in WRF. However, with reference to observations in both TC events, the mesoscale reference suite simulations (MR10 and MR03) feature a slower TC and a delay in the TC's landfall, whereas the convection-permitting suite simulations (CP10 and CP03) feature a faster TC and earlier landfall (except in TC Kenneth where CP10 does not make a landfall).

The increase in MPAS resolution also improves the intensity of the simulated TCs (Fig. 5.6). For both TC events, the increase in resolution generally deepens the MSLP of the TCs, increases the associated wind speed, and reduces the RMSE of these variables. For both the mesoscale reference and convection-permitting suites, a systematic increase in model resolution generally results in a linear increase in the lifetime maximum wind speed of the simulated TC Idai. The same is true for TC Kenneth, but only for the mesoscale reference suite simulations. However, across resolutions, the relative performance of the physics parameterization suites in

replicating the observed TC intensity varies and depends on the simulated TC event. For instance, at a resolution of 10km, the mesoscale reference suite (MR10) outperforms the convection-permitting suite (CP10) in simulating the intensity of both TC events. Conversely, at 3km, the convection-permitting suite (CP03) performs better than the mesoscale reference suite (MR03) in the TC Idai simulation, while the mesoscale reference suite performs better in the TC Kenneth simulation. However, in all cases, the convection-permitting suite simulations show a delay in the intensification of the simulated TC. The convection-permitting suite simulations use the Grell-Freitas convection scheme, a scale-aware scheme designed to become less active as model resolution increases (Kramer *et al.*, 2020). Kramer *et al.* (2020) noted that the scheme is mostly inactive at a resolution of 3km. This may explain the late intensification of the simulated TCs in the convection-permitting suite simulations. Unlike the mesoscale reference suite simulations, where the convective parameterizations act to reduce CAPE and adjust the modelled convection within an explicit time interval, the convection-permitting suite simulations allow for the gradual vertical transport of moisture and heat, thereby delaying the intensification of the simulated TC.

The simulated wind-pressure relationship also improves with the increase in model resolution (Fig. 5.7). As resolution increases, the wind-pressure relationship curve stretches toward a higher intensity range (i.e., lower MSLP and higher wind speed values). For TC Idai, regardless of physics parameterization suite and resolution, all simulations produce a reasonable estimation of the wind-pressure relationship, with all the simulated wind-pressure relationship curves falling within the two observed curves. The same is true for TC Kenneth, except for the 3km simulations. At 3km, in both the mesoscale reference and convective permitting suite simulations, the gradient of the simulated wind-pressure relationship curve for TC Kenneth is steeper than the observed; this suggests that for a given MSLP value, the increase in resolution results in an overestimation of wind speed. In addition, the wind-pressure relationship curve for the 3km convection-permitting simulation lies at a low intensity range (Fig. 5.7).

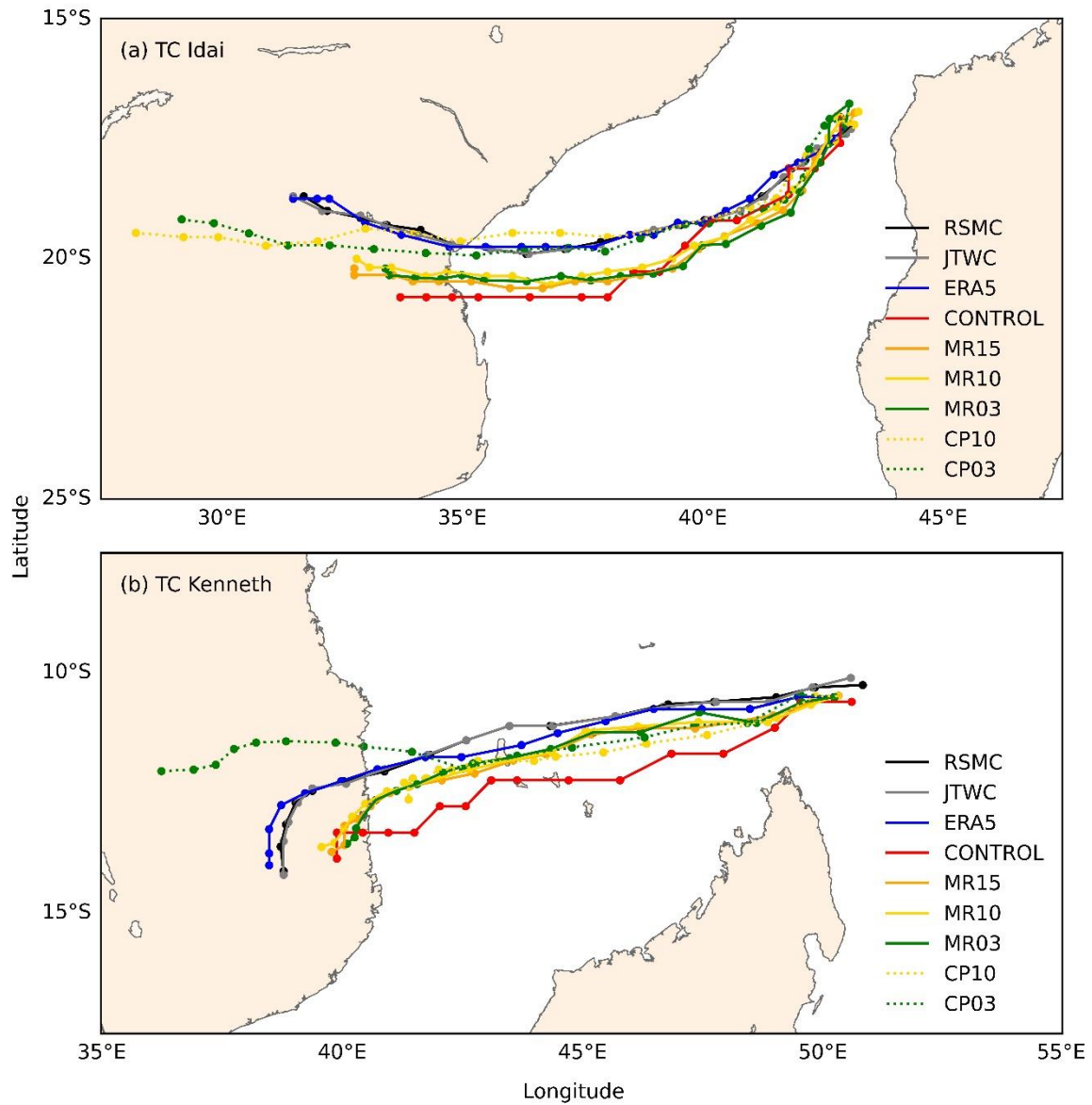


Figure 5.5 Sensitivity of the simulated TC tracks to resolution and physics parameterizations: (a) TC Idai (00h00 11 March 2019 - 06h00 16 March 2019) and (b) TC Kenneth (00h00 23 April 2019 - 00h00 27 April 2019) for observations, ERA5 reanalysis, CONTROL, MR15, MR10, MR03, CP10, and CP03.

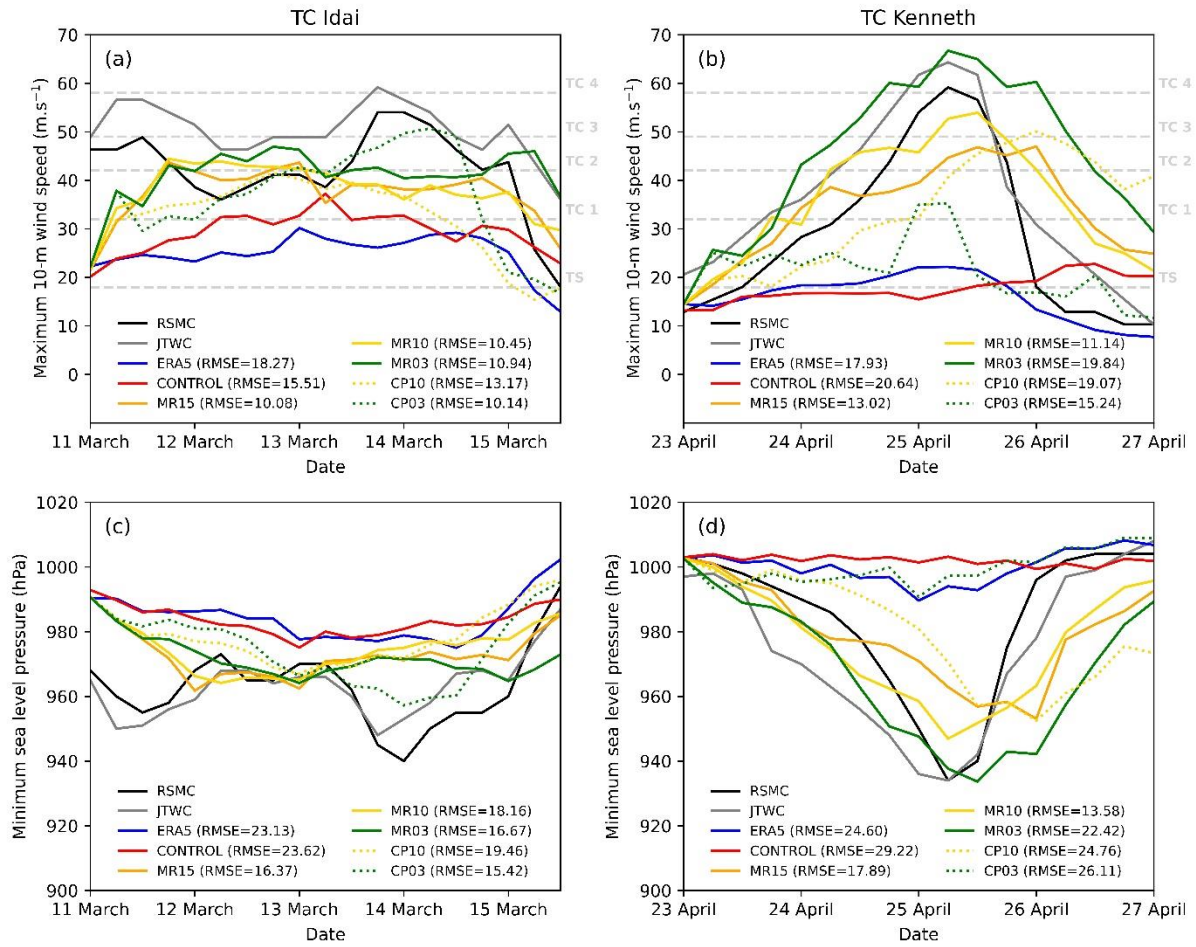


Figure 5.6 Sensitivity to resolution and physics parameterizations: TC Idai (a) wind speed time series and (c) mean sea level pressure (MSLP) time series and TC Kenneth (b) wind speed time series and (d) MSLP time series - for observations, ERA5 reanalysis, CONTROL, MR15, MR10, MR03, CP10, and CP03.

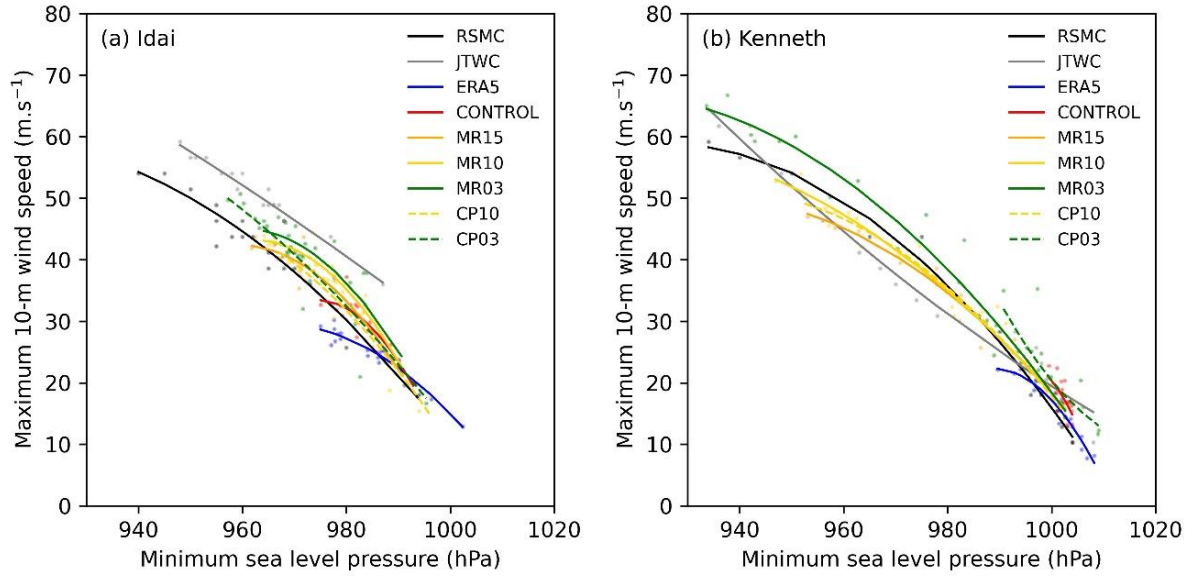


Figure 5.7 Sensitivity of the simulated wind-pressure relationship to resolution and physics parameterizations: (a) TC Idai and (b) TC Kenneth for observations, ERA5 reanalysis, CONTROL, MR15, MR10, MR03, CP10 and CP03.

5.4 Simulating the dynamics of tropical cyclone rapid intensification

The previous section (Section 5.3) demonstrates how changes in model resolution and physics parameterization suites influence the ability of MPAS to simulate the TC characteristics. The following section outlines how these changes influence the dynamics of TC intensification. This is achieved by comparing the vertical structure of the TC in a simulation that captures the rapid intensification of TC Kenneth (MR03) with that of simulations that do not capture the rapid intensification (CONTROL and CP03). While a comparison of the CONTROL and MR03 simulations will show the influence of model resolution on the rapid intensification of the system, a comparison of MR03 and CP03 will offer insights into the influence of the physics parameterization suites.

5.4.1 Sensitivity to resolution

With the mesoscale reference suite, an increase in resolution from 60km (in CONTROL) to 3km (in MR03) alters the vertical structure of the simulated TC (Figs.

5.8, 5.9 and 5.10). Although the vertical structure of the temperature (i.e., TC warm core) in the CONTROL and MR03 simulations are identical at the initial stage (23 April 2019, 00h00), the vertical structures evolve differently afterwards (Fig. 5.8). At 18h00 on the same day, both simulations feature a stronger warm core than at the initial stage, indicating vertical latent heating in the system (Murthy and Boos, 2019). Murthy and Boos (2019) showed that the vertical latent heating is due to shallow convective heating (below 800 hPa), deep convective heating (through the troposphere but peaked at 600 hPa), and heating from cloud microphysics (occurring above the melting level: 600 hPa). However, the vertical heating rate is stronger, deeper (i.e., extending throughout the troposphere), and concentrates over a smaller area in MR03 than in the CONTROL because the higher resolution helps MR03 to better resolve the horizontal structure of the system. For example, while MR03 features an area of low-level cooling around the TC centre, such cooling is absent from the CONTROL. Twenty-four hours later (24 April 2019, 18h00), the warm core continues to strengthen in MR03 but weakens in the CONTROL, indicating that the simulated TC intensifies in MR03 and not in the CONTROL.

The vertical extent of the warm core in MR03 indicates increased vertical transport of heat and moisture to upper levels in this simulation. This vertical motion creates an area of low surface pressure, giving rise to a horizontal pressure gradient which drives lower-level convergence toward the centre of the simulated TC, intensifying the system. Additionally, an increase in resolution also strengthens the tangential winds of the simulated TC (Fig. 5.9), thereby increasing the cyclonic rotation of the system. Moving towards the centre of the system, the radial winds in MR03 decrease by $\sim 4 \text{ m.s}^{-1}$ within a 1° radius, compared to an increase of $\sim 2 \text{ m.s}^{-1}$ over the same region in the CONTROL simulation. This decrease in radial winds toward the centre of the system indicates surface convergence and uplift in MR03, further contributing to the system's intensification. The simulated Ertel's potential vorticity (EPV) vertical structure in the CONTROL (Fig. 5.10) is consistent with that of a tropical depression as discussed by Murthy and Boos (2019), while the simulated EPV vertical structure in MR03 agrees with that of a TC as discussed in Montgomery and Smith (2017). Murthy and Boos (2019) showed that tropical depressions generally feature a mid-

tropospheric potential vorticity (PV) maximum. In contrast, Montgomery and Smith (2017) showed that TCs tend to feature deep convective heating that dominantly generates PV in the lower troposphere throughout the life cycle of the TC.

5.4.2 Sensitivity to physics parameterizations

At a resolution of 3km, the use of the convection-permitting suite decreases the magnitude and vertical extent of the simulated TC warm core, thereby reducing the vertical transport of heat and moisture (Fig. 5.8). Figure 5.8 shows that during the TC intensification period (23-24 April 2019), both MR03 and CP03 show similar vertical latent heating rates in the warm core, but the heating is broader (i.e., less localised) and shallower (i.e., limited below ~ 500 hPa) in CP03 than in MR03, suggesting that the deep convective heating is weaker in CP03. This suggests that, at 3km, the Grell-Freitas convection scheme, which is designed to become less active as model resolution increases (Kramer *et al.*, 2020), may be too weak (or even inactive) in transporting moisture and heating to the upper atmosphere in the CP03 simulation. Furthermore, in comparison with MR03, the broader and shallower heating in CP03 produces weaker TC tangential wind speeds (i.e., less spinning), weaker radial wind speeds (i.e., less low-level moisture convergence), and weaker vertical motion (i.e., less vertical transport of warm moist air), subsequently retarding the TC intensification (Fig. 5.9). Figure 5.10 shows that, in agreement with Montgomery and Smith (2017), CP03 features deep convection that dominantly generates PV in the lower troposphere throughout the TC life cycle, but the deep convection does not extend to the upper-troposphere to induce the spinning of the TC throughout the troposphere as in MR03. Studies (e.g., Molinari *et al.*, 1998; Montgomery and Smith, 2017) have shown that the rapid intensification of a TC requires positive vorticity (i.e., spinning of the TC) throughout the troposphere.

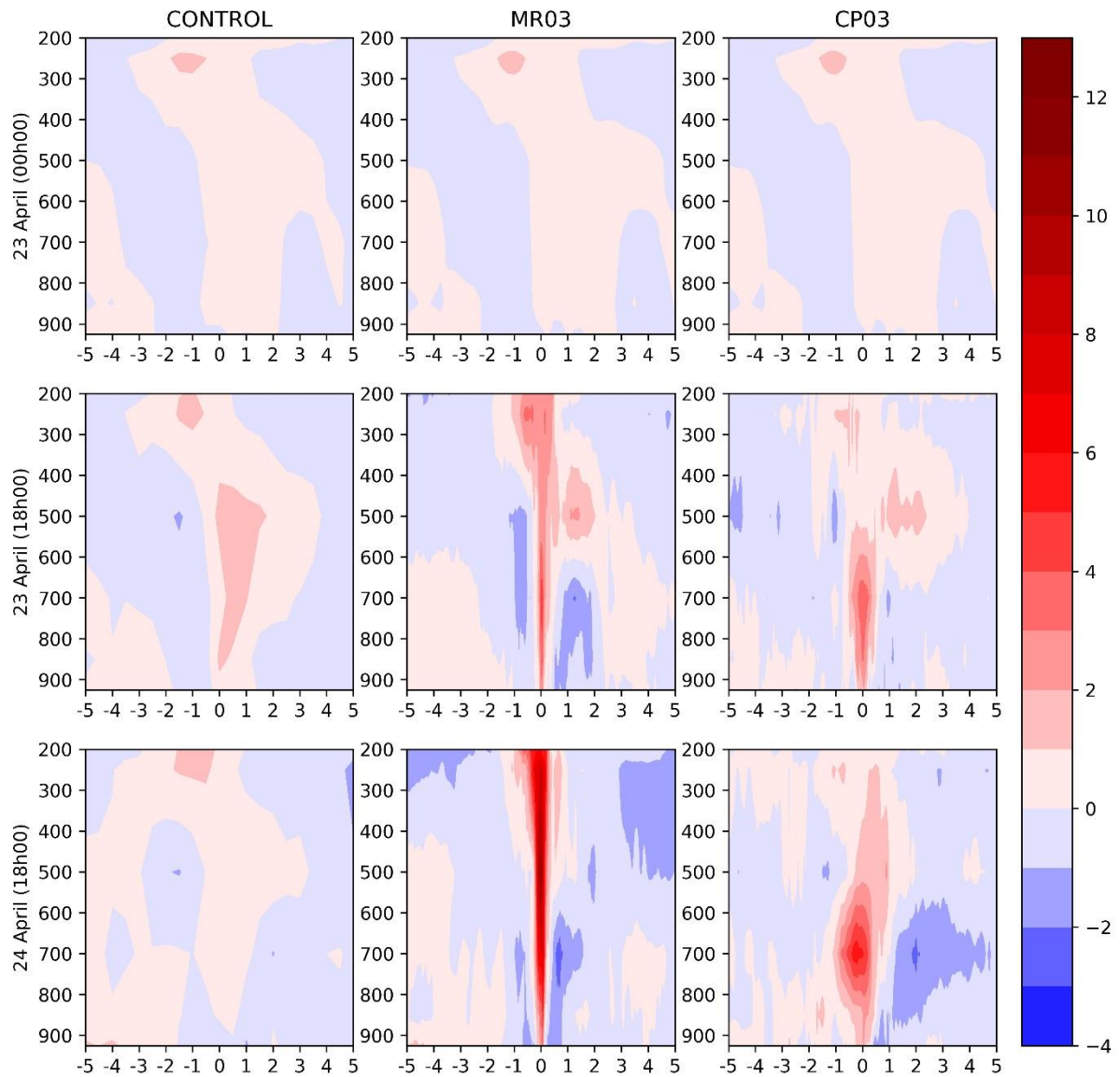


Figure 5.8 The warm core of simulated TC Kenneth in CONTROL, MR03 and CP03 simulations during the period of rapid intensification (24 -25 April 2019). The x-axis shows the distance from the TC centre in degrees, the y-axis indicates the corresponding pressure level, and shading denotes the temperature of the warm core relative to the surrounding environment ($^{\circ}\text{C}$).

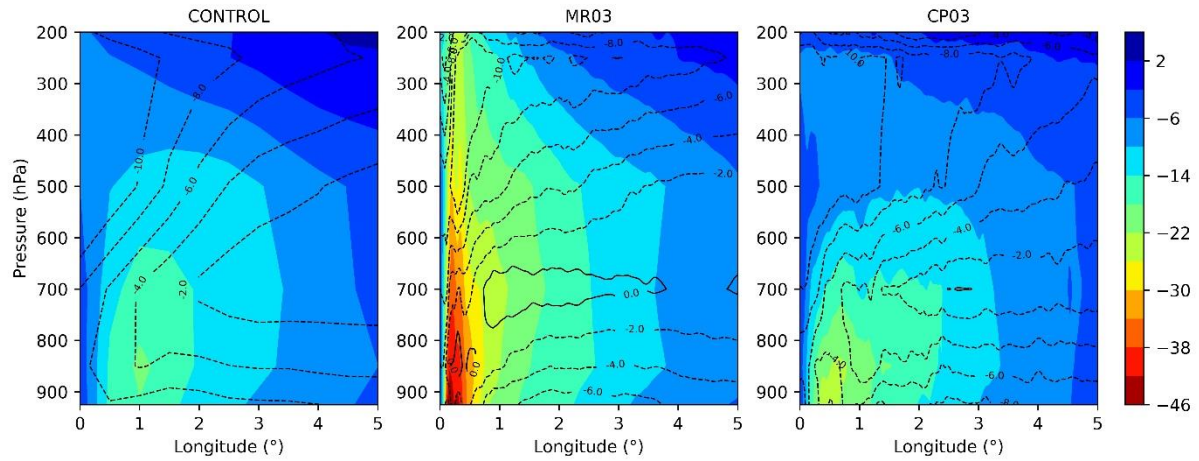


Figure 5.10 Vertical wind profiles of the simulated TC Kenneth in CONTROL, MR03 and CP03 simulations, presented as a composite mean over the period of rapid intensification (24-25 April 2019). The x-axis shows the radial distance from the TC centre in degrees, and the shading denotes the magnitude of the tangential wind speed (m.s^{-1}). Contour lines indicate the magnitude of the radial wind speed (m.s^{-1}), with an interval of 2 m.s^{-1} .

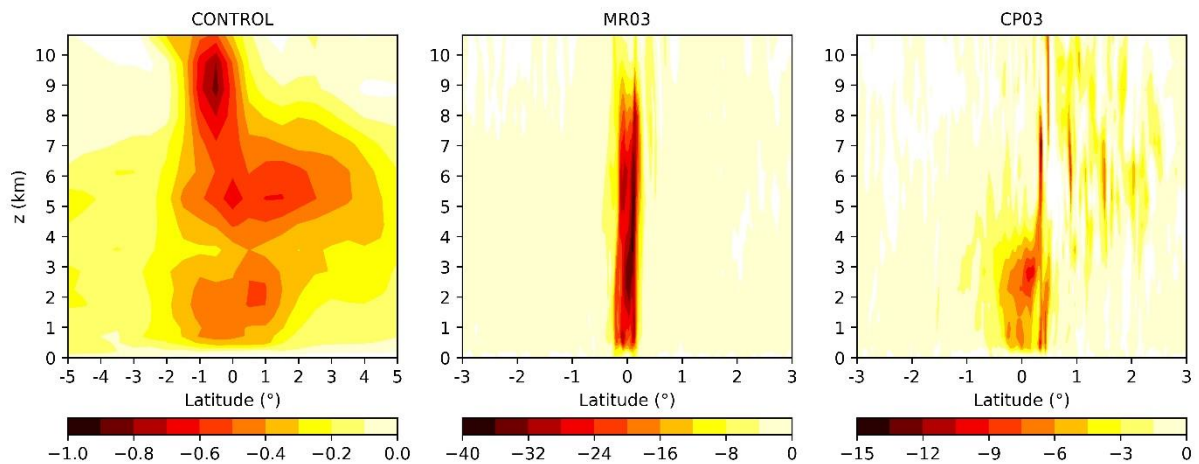


Figure 5.9 Latitude-height cross section of TC Kenneth for CONTROL, MR03 and CP03 simulations, showing a composite mean of Ertel's potential vorticity (EPV) over the period of rapid intensification (24 -25 April 2019). The x-axis shows the radial distance from the TC centre in degrees, and the shading denotes the magnitude of the EPV (PV units).

5.5 Summary

This chapter has evaluated the capability of MPAS in simulating the characteristics of two intense landfalling TCs that occurred in the SWIO in early 2019 – namely TC Idai and TC Kenneth. The model was first applied to simulate the TCs (CONTROL simulations) and then to investigate the sensitivity of the simulated TCs to the model's initial atmospheric conditions (i.e., ERA5 and CFSR), physics parameterization suites (i.e., mesoscale reference and convection-permitting suites), and resolution (i.e., 60km, 15km, 10km and 3km). The characteristics of the simulated TCs that were considered include the track, propagation speed, landfall (time and location), intensity (maximum wind speed and minimum MSLP), wind-pressure relationship, and vertical structure. The study also showed how an increase in resolution can influence the rapid intensification of TC Kenneth. The results of the study can be summarised as follows:

- The CONTROL simulations (60km uniform mesh) produce realistic tracks of both TCs but show southward track and landfall biases and severely underestimate the intensities of the events. The model fails to capture the rapid intensification of TC Kenneth.
- Using the ERA5 dataset (instead of the CFSR dataset) to initialize MPAS produces a better simulation of TCs Idai and Kenneth.
- The simulated TCs are very sensitive to the choice of physics parameterization suite. The mesoscale reference physics parameterization suite performs better than the convection-permitting suite in some cases, while the convection-permitting suite performs better in others.
- Increasing the model resolution generally improves the characteristics of the simulated TCs. However, the improvement depends on the physics parameterization suite and the TC event. While the increase in model resolution from 10km to 3km improves the simulation of TC Idai (with either of the physics parameterization suites) and TC Kenneth with the mesoscale reference suite, it deteriorates the simulation of TC Kenneth with the convection-permitting suite.

- With the convection-permitting suite, increasing the model resolution from 10km to 3km weakens the rapid intensification of TC Kenneth because the 3km simulation fails to transport heat and moisture to the upper troposphere.

CHAPTER 6 : Conclusion

6.1 Summary

It is well known that the TCs that form over the SWIO and make landfall along the eastern coast of southern Africa devastate the socio-economic activities of poor coastal communities, however, the capability of contemporary models to simulate TCs in the region remains unknown. As part of efforts to improve this understanding, this study has investigated the performance of four GCMs and one VGCM in simulating TCs over the SWIO. This study has also explored the sensitivity of the TC simulations to model parameters such as resolution. For the GCM analysis, this study utilised four CMIP6 HighResMIP models with both standard- and enhanced-resolution runs to investigate simulated climatological SWIO TC activity over the period 1980-2009. The model simulations were compared to RSMC observations and ERA5 reanalysis data to assess the skill of the models in capturing the characteristics of SWIO TC activity. For each model, the characteristics of the simulated TCs were compared between the low- and high-resolution runs to determine the impact of increasing resolution on each metric. Large-scale atmospheric features were also investigated to offer insight into the mechanisms that may be responsible for changes in TC characteristics resulting from an increase in resolution. For the VGCM analysis, this study evaluated the capability of MPAS in simulating the characteristics of two intense landfalling TCs that occurred in the SWIO in early 2019 – namely TC Idai and TC Kenneth. MPAS was first applied to simulate the TCs at a uniform resolution of 60km, and then to investigate the sensitivity of the simulated TCs to the model's initial atmospheric conditions, physics parameterization suites, and resolution. The analysis also demonstrated how an increase in resolution can influence the rapid intensification of TC Kenneth.

First, the performance of four CMIP6 models in capturing the characteristics of TCs over the SWIO for the period 1980-2009 was evaluated. The analysis found that all models and the ERA5 reanalysis produce realistic simulations of TC tracks and cyclogenesis locations, but feature a westward shift in TC activity toward the MC.

These results are consistent with the findings of Maoyi *et al.* (2018), who noted a westward bias in SWIO TC activity in CAM-EULAG and ERA-Interim reanalysis. Further work is planned to investigate this bias. With the exception of HadGEM-HR, all models and ERA5 reanalysis underestimate TC frequency. CNRM-HR produces the most realistic approximation of TC frequency over the study period, while the MPI model performs notably poorly and captures very few events in both the low- and high-resolution simulations. The poor performance of the MPI model is in line with the findings of Roberts *et al.* (2020a), who evaluated this model on a global scale and found that it captured very few events in any ocean basin. Also in line with the results of Roberts *et al.* (2020a) is the superior performance of CNRM in simulating TC intensity. In the present study, CNRM was the only model that was able to simulate systems exceeding category 2 intensity and, subsequently, the only model to capture the full intensity range seen in observations. For both simulated frequency and intensity, there are considerable differences in model performance even at equal resolutions, suggesting that resolution is not the only factor that exerts an influence on the characteristics of simulated TCs and model-to-model differences play a significant role in this regard. This finding is supported by previous studies (e.g., Shaevitz *et al.*, 2014; Roberts *et al.*, 2015) that found significant model to model differences in simulated TC intensity among high-resolution simulations. While the monthly variation in TC activity is well represented among all models, none of the models are able to reproduce the interannual TC variability. To this end, HadGEM-HR offers the best performance, capturing the strongest upward trend in ACE over the study period. The poor performance of all models in simulating the interannual variability of SWIO TCs concurs with the findings of previous studies, which noted that model skill in simulating interannual TC variability is much higher in the well-documented Atlantic and Pacific regions than in the Indian Ocean (Vitart *et al.*, 1997; Zhao *et al.*, 2009; Manganello *et al.*, 2012), highlighting the need for further studies on TC simulation in the region. Overall, CNRM-HR and HadGEM-HR offered the best representation of SWIO TC activity between 1980-2009.

Next, the influence of resolution on the simulated TC characteristics and large-scale environments of the four CMIP6 models was investigated. The analysis showed that

increasing resolution improves the simulated TC frequency and ACE in all models, and improves the ability of each model to represent the full spectrum of TC intensities. These improvements in the simulated TC characteristics with increasing resolution are consistent with previous studies that employed high-resolution models in other regions (e.g., Zhao *et al.*, 2009; Manganello *et al.*, 2012; Murakami *et al.*, 2012, 2015; Camargo, 2013; Michael F. Wehner *et al.*, 2014; Roberts *et al.*, 2015, 2020a, 2020b). However, the present study found that increasing resolution did not improve the spatial patterns of TC tracks and cyclogenesis locations, nor the ability of the model to capture the long-term trends in TC activity. Changes in the velocity potential fields of each model with increasing resolution may explain changes in the spatial distribution of TC activity observed with an increase in resolution in CNRM, EC and HadGEM, and changes in frequency and intensity in EC and MPI. However, velocity potential fields are strongly coupled with SST and thus may be influenced by the monthly variability of TC occurrence in each model. Wind shear patterns are shown to be model-specific and show little change with an increase in resolution, supporting the findings of Roberts *et al.* (2020a) who evaluated these patterns on a global scale. HadGEM and CNRM feature weaker wind shear over the eastern and northern parts of the SWIO compared to EC and MPI, which may contribute to the high frequency of events in these models over the eastern and northern parts of the SWIO basin.

On an individual event scale, this study evaluated the performance of MPAS in simulating the characteristics TC Idai and TC Kenneth. At a uniform resolution of 60km, MPAS produces realistic tracks of both TCs, but features southward track and landfall biases. Furthermore, MPAS severely underestimates the intensities of both events and fails to capture the rapid intensification of TC Kenneth.

The present study then investigated the sensitivity of the MPAS TC simulations to model resolution, physics parameterizations and initial conditions. First, the impact of initial conditions was considered. The analysis found that using the ERA5 dataset (instead of the CFSR dataset) to initialize MPAS produces a better simulation of TCs Idai and Kenneth – in terms of the track, intensity, and wind-pressure relationship. This was attributed to the fact that the initial fields in the ERA5 dataset featured a more well-defined eye, a deeper minimum in MSLP, and stronger cyclonic circulation than

the CFSR dataset. This finding is in line with the results of Lui *et al.* (2021), who noted the same occurrence when comparing MPAS simulations initialized with ERA5 to those initialized with ERA-Interim. Next, the sensitivity of MPAS to physics parameterization suites and resolution was assessed. The analysis found that increasing the model resolution generally improves the characteristics of the simulated TC, but the improvement depends on the physics parameterization suite employed in the model, as well as the event being simulated. For example, for both events, the simulated intensity of the system shows a systematic increase with increasing resolution when considering only the mesoscale reference simulations. However, when employing the convection-permitting parameterization suite at 10km and 3km, the results differ based on the event. For TC Idai, the use of the convection-permitting suite at 3km further increases and improves the simulated intensity of the system. Whereas at 10km, the simulated intensity decreases compared to the mesoscale reference simulation. For TC Kenneth, the convection-permitting suite decreases the simulated intensity compared to the mesoscale reference suite at both resolutions. Furthermore, this study investigated the impact of model resolution and physics parameterizations on the rapid intensification of TC Kenneth. The results show that when employing the mesoscale reference suite, increasing resolution systematically improves the ability of MPAS to simulate the TCs rapid intensification. However, when employing the convection-permitting suite, increasing resolution from 10km to 3km weakens the rapid intensification of TC Kenneth because the 3km simulation fails to transport heat and moisture to the upper troposphere. This is likely due to the use of the Grell-Freitas convection scheme in the convection-permitting simulations, which becomes less active as resolution increases.

6.2 Application

The results of this dissertation have several applications in improving the modelling and forecasting of TCs over the SWIO region. This study has identified the simulated TC characteristics that are both well represented and poorly represented in four CMIP6 HighResMIP models, which will guide model developers in identifying features that require the most attention. This study has also illustrated a model bias present

over the region, in that all CMIP6 models and ERA5 reanalysis feature a westward shift in TC activity towards the MC. Since this westward shift bias is consistent with a previous study on SWIO TC activity by Maoyi *et al.* (2018), despite the use of a different model and reanalysis dataset, this work reinforces the need to correct this bias over the region and guides model developers toward achieving this goal. By identifying the CMIP6 models that offer the best representation of SWIO TC simulation, this work will not only allow developers of climate models and TC early warning systems to delve further into the configurations and features of these models to identify the model parameters that underpin their superior performance, but will also guide future studies on TC simulation over the region. The present study has also shown that MPAS simulations initialized with ERA5 reanalysis data offer improved TC hindcasts compared to those initialized with CFSR, which has application in informing future work on SWIO TC simulation. By providing a comprehensive overview of the sensitivity of MPAS TC simulations to resolution and parameterization suites, this study provides the first evaluation of MPAS in simulating TCs over the SWIO region and can thus be used to inform modellers and policy makers of its suitability for adoption in seasonal forecasting and early warning systems over the region. Furthermore, this study has demonstrated the model parameters necessary to simulate rapid TC intensification with MPAS, such knowledge will aid in the application of MPAS for TC early warning systems over the SWIO.

6.3 Recommendations

For climate impact applications over the SWIO, the robustness of the findings in this study can be improved in several ways. For instance, due to available computational resources, the study only analysed four GCMs. Future studies may extend the analysis to other CMIP6 models to identify all reliable GCMs for simulating SWIO TC characteristics in the present-day climate. Such analysis would foster model development over the SWIO region and aid in focusing future projections of TC characteristics on reliable models, eliminating the models that perform poorly over the region. While one could argue that a model performing well in the present-day climate does not guarantee the reliability of its future projections, if a model cannot capture

the present-day climate, there is no basis for relying on its future projections to aid in planning and risk mitigation.

In addition, the superior performance of the high-resolution models in simulating some TC characteristics over the SWIO, as found in the present study, may not be solely due to the increase in the model resolution. In some models, increasing model resolution requires a change in some physics parameterizations (e.g., convection and boundary layer schemes). Future work could separate the contributions of model resolution and physics parameterizations and obtain the optimal resolution for simulation of TCs over the SWIO basin. Such activities could foster model development because they would guide in identifying and fixing biases in physics parameterizations, rather than blindly increasing the model resolution to obtain better simulations of the TCs.

Furthermore, increasing the sample size of individual TC events by performing additional simulations of TCs that vary in intensity and geographical location will allow for a more robust assessment of the ability of MPAS to simulate SWIO TC activity. While this work has used the two default physics suites included in MPAS, namely mesoscale reference and convection-permitting suites, future work on the impact of individual parameterization schemes on the characteristics of simulated TCs will offer further insights into the sensitivity of MPAS. Given the sensitivity of MPAS to even small perturbations in the initial conditions, the use of ensemble experiments is recommended for future work. The ensemble experiments, which would help in exploring and quantifying the uncertainty in the model simulations, would provide more robust results than that of a single experiment.

Nevertheless, the present study has highlighted the strengths and weaknesses of four CMIP6 models in representing TC activity over the SWIO and has demonstrated the suitability and sensitivity of MPAS in simulating intense systems over the region. This study has investigated the performance of several models on differing spatial and temporal scales, thereby offering a holistic overview of how TCs are modelled in the SWIO region. Furthermore, this work has also illustrated the extent to which an

increase in model resolution can improve simulated TC characteristics and offered insights on how to improve future projections of TC activity over the SWIO.

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APPENDIX A

TRACKING ALGORITHM DEVELOPMENT

I. Initial Testing

The tracking algorithm employed in this study used a method similar to that described in Maoyi *et al.* (2018). For the MSLP, relative vorticity and wind speed thresholds, similar criteria were employed:

- Mean sea level pressure (MSLP)
 - Point of minimum MSLP over the study domain (30°E-90°E, 10°S-40°S) was identified – this is defined as the centre of a potential low-pressure system.
- Relative vorticity
 - The minimum 850 hPa relative vorticity within 4° of the MSLP was detected - this must be less than $-3.5 \times 10^{-5} \text{ s}^{-1}$ (Maoyi *et al.*, 2018).
- Wind speed
 - The maximum 10-m wind speed within 5° of the MSLP was detected – this must be greater than a resolution-dependent threshold value outlined in Walsh *et al.* (2007).

However, the warm core criterion could not be included in its current form due to data availability. Maoyi *et al.* (2018) defined the warm core as “The closest local maximum of 850–300 hPa average temperature.” For all model data, only the 250 hPa pressure level was available. For this reason, the warm core criterion was modified to suit the data availability.

II. Warm Core Criterion

The full warm core criterion included by Maoyi *et al.* (2018) is defined as follows:

- “The closest local maximum of 850–300 hPa average temperature is defined as the centre of the warm core. The average temperature must be greater than 0 °C. The warm core is defined within 2° from the centre of the low pressure.”

The inclusion of an absolute threshold value (0°C) at a differing pressure level was not deemed appropriate, given the relationship between temperature and atmospheric height (temperature decreases as height increases). For this reason, a warm-core criterion that considered the warm core temperature *relative* to the surrounding environment was used.

Zhao *et al.* (2009) included such a criterion, defined as:

- “The local maximum temperature averaged between 300 and 500 hPa is defined as the center of the warm core. The distance of the warm-core center from the storm center must not exceed 2°. The warm-core temperature must be at least 1°C warmer than the surrounding local mean.”

This allowed for testing of the tracking algorithm using ERA5 data at both 300 hPa and 250 hPa. This testing was completed for both cyclogenesis locations and TC tracks for the period 1990-2009.

i. Cyclogenesis Locations

The cyclogenesis locations for the testing of the warm core criterion are shown in Figure A.1. Considering the average annual TC frequency, indicated in the bottom right of the first column, it is evident that the use of the 250 hPa level is superior to that of 300 hPa. Observations show that the SWIO experienced an average of 8.40 TCs per year between 1990-2009. The use of 250 hPa as the upper level of the warm core produced the same number of TCs as observations, while the 300 hPa experiment underestimated the average annual TC frequency with an average of 7.85 TCs per year. The spatial correlation of the cyclogenesis locations with respect to observations, indicated on the bottom right of the second column, showed little difference based on

the pressure level used in the warm core criterion, with a correlation of $r=0.80$ (p-value = <0.001) for the 250 hPa level and $r=0.82$ (p-value = <0.001) for the 300 hPa level.

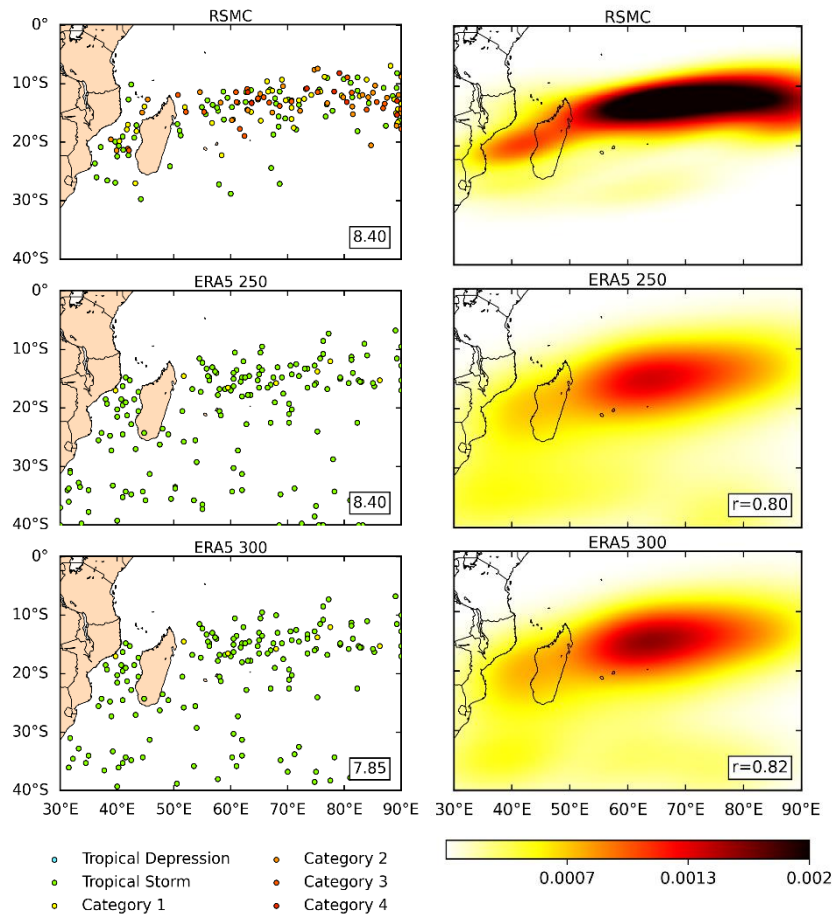


Figure A.1 Algorithm testing of the warm core criterion showing genesis locations of tropical systems in the SWIO from 1990-2009. The panels on the left show the spatial distribution of genesis locations, with the colour of the dot corresponding to the maximum lifetime intensity of the system. The average annual TC frequency is presented in the bottom right of each panel. The panels on the right show a kernel density estimation (KDE) of these genesis locations, with the spatial correlation with respect to observations (RSMC) given in the bottom right.

ii. Tracks

The results of the track analysis (Figure A.2) were largely in line with the cyclogenesis locations. Both simulations (250 hPa and 300 hPa) produced track plots that were comparable to observations, with little to no activity present north of 10°S . The spatial correlation of the simulated track plots with respect to observations was high, with the 300 hPa level again slightly outperforming 250 hPa ($r=0.86$, p-value = <0.001 and $r=0.85$, p-value = <0.001 , respectively). However, this difference was deemed

negligible given the large sampling base, and 250 hPa was thus employed as the upper level of the warm core criterion.

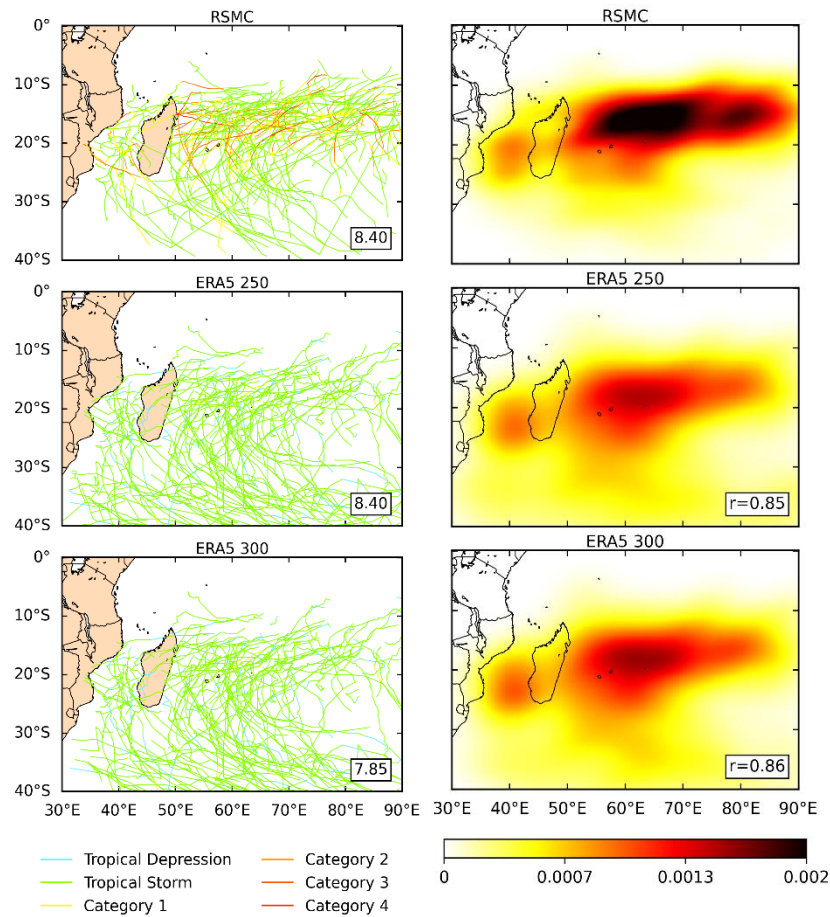


Figure A.2 Algorithm testing of the warm core criterion showing tracks of tropical systems in the SWIO from 1990-2009. The panels on the left show the spatial distribution of the tracks, with the colour of the line corresponding to the intensity of the system. The average annual TC frequency is presented in the bottom right of each panel. The panels on the right show a kernel density estimation (KDE) of these tracks, with the spatial correlation with respect to observations (RSMC) given in the bottom right.

III. Vertical Dynamics

Despite the inclusion of the warm core criterion, the algorithm was not effectively excluding genesis below 30°S, which is often indicative of mid-latitude systems. During the early stages of this work, preliminary results were presented at a model evaluation workshop. It was suggested that the use of a vertical dynamics threshold may improve the results on this front.

A modified version of the vertical dynamics criterion included in Camargo and Zebiak (2002) was used, which once again made use of the 300 hPa level:

- “The mean speed averaged over a 7 X 7 grid box is larger at 850 hPa than at 300 hPa.”

Once again, the tracking algorithm was tested using ERA5 data at upper levels of 300 hPa and 250 hPa. This testing was completed for both cyclogenesis locations and TC tracks for the period 1990-2009.

a. Cyclogenesis Locations

When considering the cyclogenesis locations (Figure A.3), it is evident that the inclusion of the vertical dynamics criterion is beneficial to the performance of the tracking algorithm. The inclusion of this criterion effectively excluded the majority of cyclogenesis locations south of 30°S, improving the spatial correlation with respect to observations – from $r=0.80$ (p-value = <0.001) in the ERA5 Control (which excluded the vertical dynamics threshold), to $r=0.89$ (p-value = <0.001) in the 250 hPa experiment and $r=0.90$ (p-value = <0.001) in the 300 hPa experiment. Despite the slightly improved performance at 300 hPa (as compared to 250 hPa) in terms of both TC frequency and spatial correlation, the inclusion of this criterion at 250 hPa offered a marked improvement to the tracking algorithm performance.

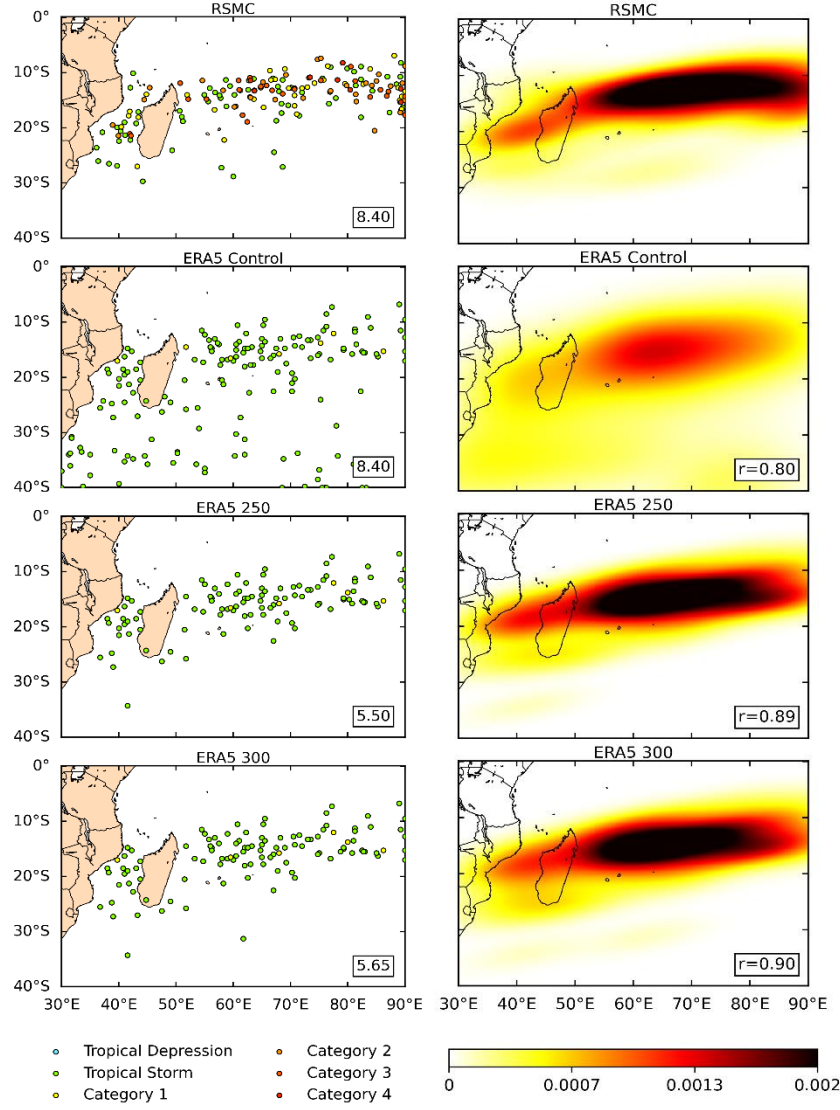


Figure A.3 Algorithm testing of the vertical dynamics criterion showing genesis locations of tropical systems in the SWIO from 1990-2009. The panels on the left show the spatial distribution of genesis locations, with the colour of the dot corresponding to the maximum lifetime intensity of the system. The average annual TC frequency is presented in the bottom right of each panel. The panels on the right show a kernel density estimation (KDE) of these genesis locations, with the spatial correlation with respect to observations (RSMC) given in the bottom right.

b. Tracks

The spatial patterns of the TC tracks (Figure A.4) showed the same improvement with the inclusion of the vertical dynamics criterion. The track plots in the ERA5 250 hPa and 300 hPa experiments more closely resembled observations than the ERA5 Control experiment, which showed too much activity south of 30°S. This was confirmed when considering the spatial correlation of the TC tracks, which increased

from $r=0.85$ ($p\text{-value} = <0.001$) in the Control, to $r=0.93$ ($p\text{-value} = <0.001$) and $r=0.92$ ($p\text{-value} = <0.001$) for the 250 hPa and 300 hPa experiments respectively. Contrasting Figure A3, the 250 hPa experiment produced the highest correlation with observations, confirming the choice to include this level in the tracking algorithm.

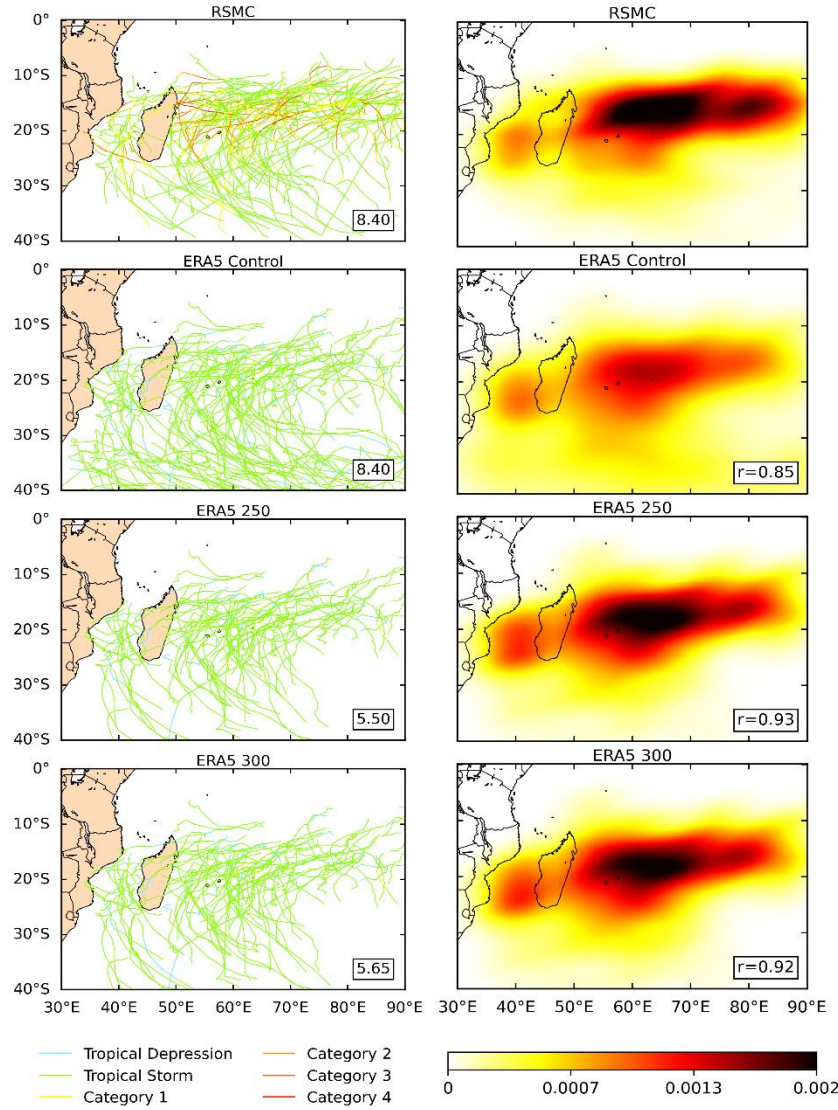


Figure A.4 Algorithm testing of the vertical dynamics criterion showing tracks of tropical systems in the South-West Indian Ocean from 1990-2009. The panels on the left show the spatial distribution of the tracks, with the colour of the line corresponding to the intensity of the system. The average annual TC frequency is presented in the bottom right of each panel. The panels on the right show a kernel density estimation (KDE) of these tracks, with the spatial correlation with respect to observations (RSMC) given in the bottom right.

IV. Further Measures

The following measures regarding the tracking of a candidate storm and the lifetime threshold criterion from Maoyi *et al.* (2018) were included in the algorithm:

- “Search for the nearest storm within 500km following the 6-hour period. If a storm is detected, it is considered to be the same storm. However, if there is no storm, then the track of the storm is considered to have stopped.”
- “The storm must persist for at least 2 days to be considered a TC (Zarzycki and Jablonowski, 2014).”

Two additional criteria were also included to improve the tracking algorithm performance :

- In order to minimise the number of broken tracks associated with an intermittent weakening of the system, one time step failure was allowed (Murakami *et al.*, 2012).
- To minimise any bias introduced by a resolution-dependent wind speed threshold, any system that did not reach at least tropical storm strength (maximum 10-m wind speed $> 17 \text{ m.s}^{-1}$) during its lifetime was excluded from the dataset. This criterion was also applied to the observation dataset.

The final form of the tracking algorithm is presented in Chapter 3 Section 3.4.3.