Simulation of tropical cyclone-like vortices over the southwestern Indian Ocean

by

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DECLARATION

I declare that the dissertation that I hereby submit for the MSc degree in Meteorology at the University of Pretoria is my own work and has not previously been submitted by me for degree purposes at any other university or institution.

SIGNATURE:……………………………………DATE:………………………………....
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Summary

Tropical cyclones claim a huge number of lives and cause substantial damage to property and crops in many regions each year. Southern Africa is no exception. This makes the process of forecasting tropical cyclones of great importance to the region's economy and to public safety. Skillful seasonal forecasts of tropical cyclone activity could be used to warn the communities affected by tropical cyclones of the likely occurrence of such systems ahead of the cyclone season. This could result in reduced damage and fatalities associated with such systems. Both statistical and dynamical techniques have been employed in an attempt to predict tropical cyclone activity on a seasonal time scale over a number of ocean basins. The skills of such techniques vary from one technique to another and from one basin to another. This study investigates the predictability of tropical cyclone activity on a seasonal time scale over the southwestern Indian Ocean (SWIO) by nesting a regional climate model (RCM), the RegCM3 within a coarse-resolution atmospheric general circulation model (AGCM), the ECHAM4.5. The national meteorological centres of most southern African countries do not have the required dedicated computational resources to run the high-resolution GCMs that are suitable to predict these systems operationally.

However, these systems can be very devastating on the southern African region and need to be predicted on various time scales, including the seasonal time scale. Therefore, it is instructive that research be done to better our understanding of these systems and their predictability using physical models. This study examines the simulations of the genesis locations and the number of tropical cyclones produced in RCM integrations nested within an AGCM forced by observed sea-surface temperatures (SSTs). The season of interest is the mid-summer period of December to February. Four members of the AGCM generated at the International Research Institute for Climate and Society (IRI) are used to force the RCM. Four-month integrations over a 10-year period (1991/92-2000/01) are performed. An objective procedure for detecting model-generated tropical cyclones is applied to this ensemble. Some characteristics of the simulated cyclones are compared with the observations. In addition, some statistical techniques are employed to evaluate the capability of the RCM to reproduce some aspects of the observed tropical cyclones during the aforementioned period. The results show that there is a good agreement between two of the simulated and observed environmental variables that influence tropical cyclone formation, viz. vertical wind shear and relative vorticity. In particular, the simulated and observed vertical wind shear show a similar pattern in most parts of the model domain. With regards to the relative vorticity, the highest agreement is found in the Mozambique Channel and in the region east of Madagascar. In addition, there is an appreciable agreement between the simulated and observed tropical cyclone characteristics such as tropical cyclone genesis locations and frequency. The model also simulated the interannual variability in the tropical cyclone frequency skillfully.

Simulasie van tropiese sikloon-agtige vortekse oor die suid-westelike Indiese Oseaan

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Samevatting

Tropiese siklone is verantwoordelik vir ‘n goot aantal sterftes en veroorsaak beduidende skade aan eindom asook oeste oor etlike areas elke jaar. Suidelike Afrika is nie ‘n uitsondering nie. Hierdie verliese maak die voorspelling van tropiese siklone van groot belang vir die gebied se ekonomie asook vir publieke veiligheid. Vaardige seisoenale voorspelling van tropiese sikloon aktiwiteit kan gebruik word om gemeenskappe wat onderhewig is aan die invloed van tropiese siklone te waarsku oor die kans vir sulke sisteme om voor te kom voordat die tropiese sikloon seisoen ‘n aanvang neem. Vroegtydige waarskuwings kan tot gevolg hê dat daar minder verwant skade en laer sterftes is. Beide statistiese en dinamiese tegnieke is al in die verlede gebruik om tropiese sikloon aktiwiteit oor verskeie oseaankomme op ‘n seisoenale tydskaal te probeer voorspel. Die vaardigheid van hierdie tegnieke hang af van die tipe tegniek wat gebruik word asook watter oseaankom beskou word. Hierdie studie ondersoek die voorspelbaarheid van tropies sikloon aktiwiteit op ‘n seisoenale tydskaal oor die suid-westelike Indiese Oseaan deur gebruik te maak van ‘n streeksmodel, die RegCM3, genes in ‘n growwe-resolusie algemene sirkulasie model van die atmosfeer, die ECHAM4.5. Die nasionale weerdienste van die meerderheid Suider-

Afrikaanse lande beskik nie oor die nodige rekenaars om geskikte hoë-resolusie algemene sirkulasie modelle te loop om sodanige sisteme mee operasioneel te voorspel nie. Desnieteenstaande kan hierdie tropiese sisteme verwoestend wees en daarom behoort hulle voorspel te word op verskeie tydskale, insluitende seisoenale tydskale. Dit sal dus insiggewend wees om navorsing te doen om sodoende ons begrip oor hierdie sisteme en hul voorspelbaarheid te verbeter deur gebruik te maak van fisiese modelle. Hierdie studie gaan ondersoek instel oor die simulasie van tropiese siklone oor hul ontwikkelingsgebiede en die aantal tropiese siklone wat 'n streeksmodel, genes in 'n algemen sirkulasie model van die atmosfeer wat geforseer word deur waargeneemde see-oppervlak temperature, kan produseer. Die seisoen van belang is die mid-somer periode van Desember tot Februarie. Vier ensemble lede afkomstig vanaf die algemene sirkulasie model wat geloop is by die *International Research Institute for Climate and Society* word gebruik om die streeksmodel mee te forseer. Model integrasies word oor 'n 4-maand periode gedoen en vir 'n 10-jaar tydperk (1991/92-2000/01). 'n Objektiewe vorteks opsporingsprosedure word dan toegepas op die 4-lid ensemble om model-geskepte tropiese siklone te identifiseer. Sommige van die karakteristieke van die gesimuleerde siklone word dan vergelyk met die waargeneemde tropiese stelsels. Hiermee saam word statisiese tegnieke ingespan vir die genoemde tydperk om die vermoë van die streeksmodel te ondersoek om sekere aspekte van waargeneemde storms te herproduseer. Die resultate wys dat daar 'n goeie ooreenkoms is tussen twee van die gesimuleerde en waargeneemde omgewingsveranderlikes wat tropiese sikloon ontwikkeling beinvloed, nl, vertikale windskuiwing en relatiewe vortisiteit. In besonder het die gesimuleerde en waargeneemde vertikale windskuiwing ooreenstemmende patrone gelewer oor die grootste

gedeelte van die streeks model-area. Wat relatiewe vortisiteit betref, is die beste ooreenkoms oor die Mosambiek kanaal en in die gebied oos van Madagaskar gevind. Verder is daar 'n sterk ooreenkoms tussen die gesimuleerde en waargeneemde tropiese sikloon karakteristieke soos by die tropiese siklone se ontwikkelingsgebiede asook hul frekwensie. Die model he took daarin geslaag om die inter-jaarlikse veranderlikheid van tropiese sikloon frekwensie suksesvol te simuleer.

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CONTENTS

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LIST OF SYMBOLS

n Sample size

r_s Spearman rank correlation coefficient

D Difference between the ranks of corresponding values of the two sets of data

T42 Spectral triangular 42

T62 Spectral triangular 62

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LIST OF ABBREVIATIONS

AGCM	Atmospheric General Circulation Model
ATL	Atlantic Ocean
AUS	Australian Ocean basin
BATS	Biosphere-Atmosphere Transfer Scheme
BATS1E	Biosphere-Atmosphere Transfer Scheme version 1e
C-CAM	Conformal-cubic atmospheric model
CCM3	Community Climate Model version 3
CDO	Central Dense Overcast
CO_2	Carbon dioxide
CPC	Climate Prediction Center
DARLAM	Division of Atmospheric Research Limited Area Model
DJF	December-January-February
ECHAM	German Atmospheric General Circulation Model
ECMWF	European Centre for Medium Range Weather Forecasts
ENP	Eastern North Pacific Ocean basin
ENSO	El-Niño Southern Oscillation
GCM	General Circulation Model
hPa	Hectopascal
IRI	International Research Institute for Climate and Society
ITCZ	Intertropical Convergence Zone
JTWC	Joint Typhoon Warning Centre
MIT	Massachusetts Institute of Technology
MJO	Madden-Julian Oscillation
MM5	Mesoscale Model version 5

MPI	Max Planck Institute for Meteorology
MRF	Medium Range Forecast model
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NI	North Indian Ocean basin
NWP	Numerical Weather Prediction
OISST	Optimum Interpolation Sea-Surface Temperature
RCM	Regional Climate Model
RegCM3	Regional climate model version 3
SAWS	South African Weather Service
SI	South Indian Ocean basin
SP	South Pacific Ocean basin
SST	Sea-Surface Temperature
SUBEX	Sub-grid Explicit Moisture Scheme
SWIO	southwestern Indian Ocean
TCLV	Tropical Cyclone-like Vortex
U.S	United States
UCL	University College of London
USGS	United States Geological Survey
UTC	Universal Time, Coordinated
WMO	World Meteorological Organization
WNP	Western North Pacific Ocean basin
ZAR	South African Rand

Chapter 1

INTRODUCTION

1.1 BACKGROUND TO THE RESEARCH

Tropical cyclones claim a huge number of lives and cause substantial damage to property and crops in many regions each year. This makes the process of forecasting tropical cyclones at various time scales of great importance to the region's economy and to public safety. Tropical cyclones are amongst the most life threatening and destructive natural phenomena on earth (Montgomery and Farrell, 1993). Coastal area communities for instance need to be alerted for safety purposes of the approaching or likelihood of tropical cyclones hitting their areas. Tropical cyclones making landfall especially over densely populated areas often lead to catastrophic situations and substantial fatalities.

Many techniques have been employed in an attempt to predict tropical cyclone activity on a seasonal time scale over a number of ocean basins. Some of these are statistically-based (Nicholls, 1992; Gray *et al.*, 1993; Hess *et al.*, 1995) and others make use of the large-scale variables predicted by general circulation models (GCMs) (Vitart *et al.*, 1997; Vitart and Stockdale, 2001; Camargo and Zebiak, 2002). GCMs are computationally expensive to run since they often require super or multi-processor computers. Although statistical models are computationally inexpensive to run, they require a long period of reliable historical data. Developing countries do not always have the necessary resources to make use of GCMs. This makes it almost impossible for such tools to be utilized by countries that are under-resourced. Furthermore, some of these techniques require considerable specialized expertise (see Randall, 1996), which is currently unavailable in developing/transitioning countries.

The need, amongst others, for forecasting regional effects of global climate change has led to the development of regional models, which can be utilized at a regional level (Giorgi, 1990). The principal cause of drought in East Africa is a change in the regional atmospheric circulation that may not be sufficiently captured by large-scale models and associated rain producing weather systems (Shanko and Camberlin, 1998). Through the use of regional modelling, theoretical knowledge and human experience, weather and climate prediction at a regional scale have improved over the years. When initial conditions and time-dependent lateral boundary conditions are introduced at the lateral boundaries of the regional climate model (RCM), it produces a prediction (Giorgi, 1990).

For a tropical cyclone forecasting procedure to be useful, it should be able to capture a tropical cyclone well in advance before it causes damage. An ideal procedure would be able to predict significant characteristics of tropical cyclones such as wind speed and trajectories as well as the remaining lifecycle of the storm. The procedure would even be of great benefit if it could also estimate the potential damage of a cyclone. Such procedures do not exist at present due to a range of factors such as our limited knowledge of tropical cyclone dynamics and uncertainties in the models themselves such as inaccurate parameterization of unresolved physical processes (Walsh, 1997). Additionally, the observation coverage on the open oceans is often inadequate to allow forecasting of such characteristics.

The problem of predicting the time and location of cyclone formation has proven to be very difficult (Montgomery and Farrell, 1993) and the prediction of tropical cyclone intensity is currently a very challenging task (Peng *et al.*, 1999). A more realistic procedure at the moment on a seasonal time scale is to predict the frequency of tropical cyclones. One way of doing this is to nest a RCM within a coarse resolution GCM. There are two ways to do this, namely one-way nesting technique and two-way nesting procedure (Giorgi and Bates, 1989).

To date two methods of utilizing dynamical models to predict tropical cyclone activity on a seasonal time scale have been employed. One such method involves computing a seasonal cyclogenesis index from the large-scale variables that have an effect on tropical cyclone activity (Gray, 1979) and then deducing the number of tropical cyclones from such index (Ryan *et al.*, 1992). The other involves detecting and tracking tropical cyclones in the dynamical models' output (Vitart *et al.*, 1997; Camargo and Sobel, 2005). This method makes use of an algorithm to detect model tropical cyclones in the dynamical model simulations. This is done when chosen dynamical and thermodynamical variables exceed thresholds determined from the observed tropical storm climatologies (Camargo and Zebiak, 2002).

There has also been a growing debate on whether or not global climate change has an impact on the frequency and/or intensity of tropical cyclones. Recently, several researchers investigated this (see e.g. Emanuel, 2006). The results of such research have to this end been contradictory. No attempt is made in this study to address this question or the dichotomy of these research findings.

1.2 MOTIVATION FOR THE RESEARCH

The impact of tropical cyclones on developing/transitioning countries such as those in Southern African Development Community is enormous. Tropical cyclones are associated with storm surges, strong surface winds, sea swells and heavy precipitation which can cause a catastrophic situation. In general, the Southern Hemisphere does not experience as many tropical cyclones as does the Northern Hemisphere. In particular, there are very few tropical cyclones that make landfall over the east coast of the southern African region. However, those that do often cause flooding and great loss of life and property. Numerous people lose their lives while others more are left homeless (Daily News, 2000; Pretoria News, 2000; Beeld, 2000; The Star, 2000). For example, tropical cyclone Eline severely affected a large number of southern African countries in the year 2000 (Dyson and van Heerden, 2001; Jury and Lucio, 2004; Reason and Keibel, 2004). It was reported that cyclone Eline left at least 100 people dead and at least 1-million severely affected by the flooding in Mozambique, Zimbabwe and South Africa's Limpopo Province [Pretoria News, 2000]. The damage caused by cyclone Eline and another tropical weather system that occurred in the same month on the infrastructure of water resources under the South African

Department of Water Affairs and Forestry's authority was estimated at ZAR50 million (Dyson and van Heerden, 2001). In addition, the damage to road infrastructure and bridges in South Africa's Limpopo Province was estimated at ZAR1.3 billion (Dyson and van Heerden, 2001).

The most severe impact on the coastal communities comes from high winds, heavy rain and storm surges associated with such weather systems (Chan *et al.*, 2004). Moreover, there is usually an outbreak of mosquito-borne diseases such as malaria due to torrential rains associated with a tropical cyclone. This exacerbates societal problem. Malaria is one of the major public health concerns on this continent (DaSilva *et al.*, 2004; Thomson *et al.*, 2005). There is a general belief that society has become more vulnerable to the impacts of tropical cyclones (Pielke and Landsea, 1998). In developed countries, it is believed that loss of lives from tropical cyclones has significantly decreased over the recent years. This may be attributed to improvement in the tropical cyclone forecasting and warning systems on short time scales. However, an increased damage to property has been observed and has been attributed to the inflation, growth in population and increased wealth of people in the coastal areas (Raghavan and Rajesh, 2003).

Skillfully forecasting tropical cyclone activity on a seasonal time scale can aid the governments in the areas subject to risk of tropical cyclone impacts to prepare disaster mitigation measures before the cyclone season (Liu and Chan, 2002). Lack of reliable historical meteorological data in the Southern Hemisphere has for years hampered meteorological research on tropical cyclones. This has also affected research on the tropical cyclone activity over the southwestern Indian Ocean (SWIO). Other regions have over the years enjoyed extensive research as a result of the availability of reliable data.

The impact of tropical cyclones developing and/or migrating into the SWIO on the southern African region, especially Mozambique and its neighbouring countries gives a substantial importance to the problem of forecasting seasonal tropical cyclone frequency. GCMs have been found to have considerable skill for dynamical seasonal forecasts of tropical cyclone activity (Manabe *et al.*, 1970; Vitart *et al.*, 1997; Camargo and Sobel, 2005). However, most of the African countries at present have a limited computational capacity, and consequently are unable to run GCMs at the required high resolution, but they can access coarse resolution GCM data from major centres. Furthermore, due to lack of economic resources and technology, most African countries are severely affected by the adverse impacts of tropical cyclones. As research into this type of systems is a necessity for the survival of the people in this region, the use of limited-area model or RCM serves as an alternative and currently economically viable method for such countries.

RCMs are nested within the GCMs that are run at major meteorological centres (Walsh and McGregor, 1997). These models have shown some promise. RCMs have been found to produce cyclones that are weaker than those observed, but more realistic than the GCM generated ones (Walsh and Watterson, 1997). This is mainly attributed to their high resolution since high resolution of the RCM enhances the characteristics of tropical cyclones (Camargo *et al.*, 2005).

1.3 OBJECTIVES OF THE RESEARCH

The main objective of this research is to investigate the predictability of the tropical cyclone activity on a seasonal time scale over the SWIO using numerical models. This can be accomplished through the following specific objectives:

To establish a procedure to detect tropical cyclones in a regional climate model.

This is attained by modifying an objective procedure for detecting model-generated tropical cyclones that was previously applied to an atmospheric general circulation model output (Vitart *et al*.,1997), so that it can be applied to the regional climate model output over the SWIO.

To investigate the interannual variability in the frequency of the tropical cyclones generated by regional climate model over the SWIO.

This is accomplished by applying the modified detection procedure to the RegCM3 output and obtaining the interannual variability in the frequency of the model tropical cyclones. These are compared with the observed interannual variability of tropical cyclones using data from the Joint Typhoon Warning Center (JTWC).

To investigate the genesis locations of tropical cyclones generated by the regional climate model over the SWIO.

The tropical cyclones that impact the southern African region develop in different locations over the SWIO. Some of these tropical cyclones develop outside the boundaries of the SWIO basin, and then migrate into it. Therefore, it is important to examine whether the genesis locations of model tropical cyclones occur in the same regions as those in the real world. Plots showing the genesis locations of model tropical cyclones are produced. Such plots are then compared with the genesis locations of the observed tropical cyclones that developed over the area of study over the period 1991/92-2000/01.

1.4 STRUCTURE OF THIS DISSERTATION

Chapter 2 gives a brief review of some of the aspects of tropical cyclones. It focuses mainly on the environmental conditions needed for the development of tropical cyclones, tropical cyclone motion and demise, and the tropical cyclone physical structure.

In Chapter 3, different methods of forecasting tropical cyclone activity on a seasonal time scale are reviewed. The major focus is placed upon the use of dynamical methods, since this study is interested in the use of such methods.

Chapter 4 discusses the characteristics of the tropical cyclones that have been observed over the southwestern Indian Ocean from 1981/82 to the recent past. It also highlights the influence of the ENSO phenomenon on these weather systems.

Chapter 5 presents the analysis of the regional climate model results, outlines all the experiments conducted in this study and provides a thorough model validation statistics.

Chapter 6 summarizes the major findings of this study.

Chapter 2

TROPICAL CYCLONE CHARACTERISTICS AND IMPACTS

2.1 INTRODUCTION

Tropical cyclones are defined as cyclonic systems that form over warm ocean waters in tropical regions (Montgomery and Farrell, 1993). As noted in Chapter 1, tropical cyclones rank amongst the most destructive natural phenomena. It is widely believed that tropical cyclones have to this end caused more destruction than any other storm type (Pielke and Landsea, 1998). The extent of the impacts of tropical cyclones on developed and developing countries differ. The latter are severely affected as a result of being under-resourced. Tropical cyclones affect both the society and the environment. The societal impacts of tropical cyclones include loss of human lives and property. The environmental impacts include loss of fertile soil, among others. This chapter reviews some of the most important aspects of tropical cyclones such as their formation and motion.

2.2 TROPICAL CYCLONE FORMATION

Our understanding of the tropical cyclone formation is still limited. However, recent years have seen a significant improvement in this regard through better observing systems such as aircraft and satellite reconnaissance.

These observations together with field experiments and other research efforts have resulted in our appreciable understanding of these systems. Numerous observational studies have shown that tropical cyclones always originate from some pre-existing large-scale perturbations (e.g. Riehl, 1948; Kuo, 1965; Briegel and Frank, 1997). There are numerous of such pre-existing disturbances. These include Intertropical Convergence Zone (ITCZ) disturbances, cloud clusters in the deep trade winds, easterly waves and the cloudiness associated with stagnant midlatitude cold fronts (McBride, 1981).

Several studies identified environmental factors that are believed to be relevant to formation and intensification of tropical cyclones (Palmen, 1948; Gray, 1968, 1979). A set of conditions that are believed to be relevant to tropical cyclone genesis were established and have since formed the basis for many procedures for the detection and tracking of tropical cyclones in dynamical model output (Palmen, 1956; Gray, 1979). They have also been used extensively in statistical seasonal tropical cyclone forecasting techniques. These include:

- A pre-existing tropical disturbance with thunderstorms
- A distance of at least 500 km from the equator
- Sea-surface temperature of at least 26°C to a minimum depth of at least 50 m below the surface
- Substantial moisture in the lower and middle parts of the atmosphere
- Low vertical wind shear
- An unstable atmosphere

Three classes of equatorial waves play significant roles in the formation of many tropical cyclones that form each year within the major tropical cyclone ocean basins (Briegel and Frank, 1997). These wave types include the Madden-Julian Oscillation (MJO), equatorial Rossby waves, and high-frequency westward-moving mixed Rossby-gravity waves and tropical-depression-type disturbances. The most common location for cyclogenesis is within or close to the ITCZ, particularly in the portions of the ITCZ that exhibit a monsoon trough configuration with westerly flow equatorward of the trough axis (Frank and Roundy, 2006).

Tropical cyclones in the SWIO form most frequently along the ITCZ near 13°S, 63°E (Vermeulen and Jury, 1992). Typhoons in the northwest Pacific Ocean have a tendency to form in the ITCZ when a midlatitude trough is north-northwest of the eastern end of the monsoon trough (Briegel and Frank, 1997). Over the Atlantic Ocean, tropical cyclones typically form from tropical waves in the basin between the African coast and the Caribbean Islands from mid-August to mid-October (DeMaria *et al.*, 2001). Pre-existent forcing of cyclogenesis over the SWIO occur through easterly waves and by surges of the north-west monsoon (Jury *et al.,* 1991). It has been established that African easterlies initiate most Atlantic tropical cyclones (e.g. Landsea *et al.*, 1998). The development of one of the hurricanes in the 2002 Atlantic hurricane season was associated with a decaying frontal zone that had persisted in the area for several days (Pasch *et al.*, 2003).

Tropical cyclones derive their energy from the latent heat of condensation released by convective clouds around the center (Kleinschmidt, 1951; Ooyama, 1969; McBride, 1981). The evaporation from a large area under the tropical cyclone circulation is extremely important for supporting the convective activity in the central region of the cyclone (Chan and Liang, 2003).

Tropical cyclones spin clockwise in the Southern Hemisphere and counterclockwise in the Northern Hemisphere as a result of the earth's rotation (Mahendran, 1998). The impact of Coriolis force on the structure and motion of a tropical cyclone and the importance of its inclusion in the horizontal momentum equation due to vertical motion in the modelling of tropical cyclones were recognized (Liang and Chan, 2005).

Storms undergo major changes in structure during their lifetime (Frank and Ritchie, 1999). A tropical cyclone is the generic term that includes tropical depression, tropical storms, cyclones, hurricanes or typhoons (WMO, 1996). Tropical cyclones are classified according to their maximum sustained 1-minute or 10-minute average surface wind speed and/or central pressure (Elsner *et al.*, 1996; Mahendran, 1998). Air begins to spiral in from the outer region towards the storm center (Emanuel, 2003). Over the SWIO, a tropical depression is a tropical cyclone with wind estimated to be 33 knots or less. A moderate tropical storm is a tropical cyclone in which the maximum of the average wind speed is estimated to be in the range 34 to 47 knots. A severe tropical storm is a tropical cyclone in which the maximum of the average wind speed is estimated to be in the range 48 to 63 knots. A tropical storm in which the maximum of the average wind speed is estimated to be in the range 64 to 90 knots is simply referred to as a tropical cyclone over the SWIO. An intense tropical cyclone is a cyclone in which the maximum of the average wind speed is estimated to exceed 90 knots (WMO, 1996).

Storms reaching tropical cyclone strength are given names to assist in reaching insurance claims, to assist warning people of the coming storm and to further indicate that these are important storms that should not be ignored (WMO, 1993). These names are taken from lists, which vary from region to region and drafted a few years ahead of time. The lists are decided upon depending on the regions either by the committees of the World Meteorological Organization (WMO) or by national weather offices involved in the forecasting of the storms. Each year, the names of particularly destructive cyclones are retired and new names are chosen to take their place. The use of those easily remembered names greatly reduces the confusion when two or more tropical cyclones occur at the same time.

There are seven main ocean basins that support the existence of tropical cyclones. These include the north Indian Ocean (NI), the western North Pacific Ocean (WNP), eastern North Pacific (ENP), Atlantic (ATL), south Indian (SI), Australian (AUS) and south Pacific (SP) as shown in Figure 2.1 (e.g. Vitart *et al.*, 1997; Camargo and Zebiak, 2002). Our focus area is part of the SI (the marked area in Figure 2.1).

In order to provide timely and accurate information and warnings regarding tropical cyclones, these ocean basins have been divided into overlapping geographical areas of responsibility (WMO, 2006). The South Indian Ocean, for instance has been divided into the southwestern Indian Ocean (SWIO), which is the region west of the 90°E line of longitude and the rest of it has been incorporated into the Australian basin (WMO, 2006). Each of these basins has its distinctive annual cyclone season.

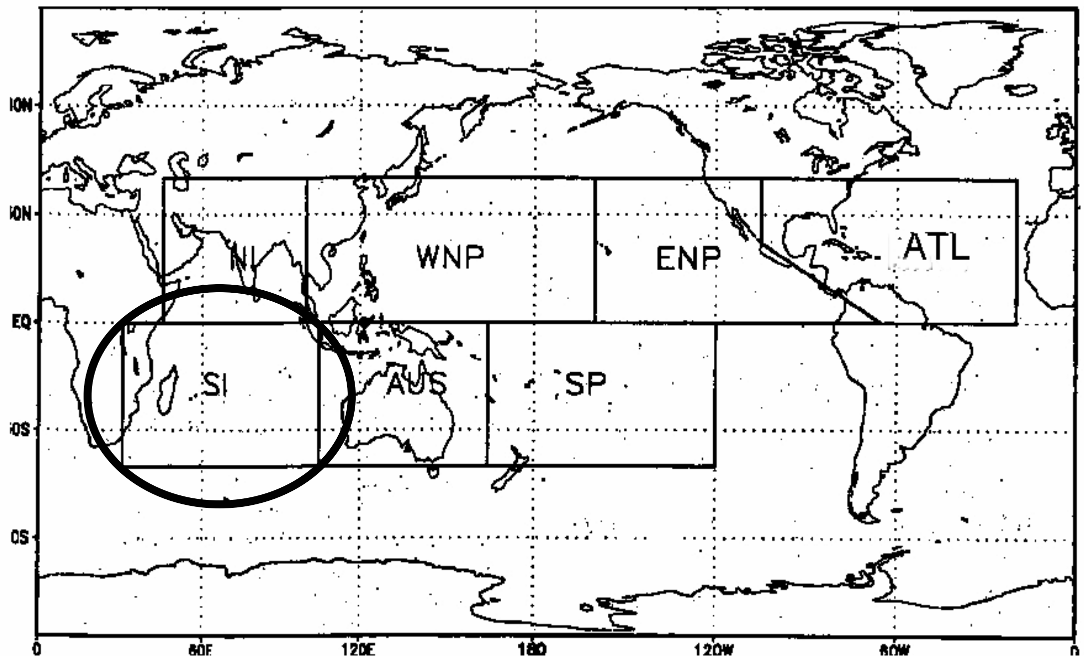


Figure 2.1: Specification of the ocean basin domains: north Indian (NI), western North Pacific (WNP), eastern North Pacific Ocean (ENP), Atlantic Ocean (ATL), south Indian Ocean (SI), Australian basin (AUS) and south Pacific (SP) (Vitart *et al*., 1997; Camargo and Zebiak, 2002).

2.3 TROPICAL CYCLONE MOTION

Tropical cyclone motion is one of the most challenging aspects of tropical cyclones. Several researchers have made efforts to study tropical cyclone movement (Holland, 1983; 1984; Chan and Gray, 1982; Hodanish and Gray, 1993; and many others). This has led to what is referred to as the steering flow theory (Chan and Gray, 1982). All these studies agree that the environmental flow plays a significant role in the movement of tropical cyclones. However, the steering flow theory does not fully explain the process involved in cyclone movement (Chan and Gray, 1982). In order to do so, the interactions between the vortex and the environmental circulations must also be taken into account (Chan and Gray, 1982; Holland, 1984). The short-term motion of a tropical cyclone is determined by two mechanisms, namely, advection by the environmental wind field and propagation by interaction with the earth's vorticity field and such mechanisms may be modified over a period of days by slowly evolving nonlinear interactions at an abrupt change of environment (Holland, 1993). Surface friction has also been found to have some effect on the cyclone motion. However, such effects are minute and tropical cyclone size also plays a role on its motion (Holland, 1984). It was found that the future position of the tropical cyclone coincided with the predicted position of maximum vorticity (Chan, 1984).

Tropical cyclones in the SWIO usually move in a southwesterly direction (Neumann and Randrianarison, 1976). The subtropical westerlies, the highlands of Madagascar and a semi-permanent subtropical trough contribute to the poleward recurvature of the tropical cyclones in the SWIO (Jury and Pathack, 1991). Tropical cyclones developing in the SWIO usually travel west then southwest and finally recurve to southeast, generally before reaching the east African coast (Shanko and Camberlin, 1998). Landfall is defined as the instant of time when the center of a tropical cyclone encounters the coastline (Tuleya and Kurihara, 1978). Tropical cyclone recurvature is defined as the turning of a tropical cyclone from an initial path west and poleward to a subsequent heading east and poleward (JTWC, 1988). Significant track deflection can occur when a tropical cyclone interacts with topography (Wong and Chan, 2006). Increased friction over land plays the dominant role in the tropical cyclone drift and the reduced moisture availability over land has influence on the tropical cyclone intensity (Wong and Chan, 2006). In the WNP the approach of a westerly trough and eastward retreat of the subtropical ridge are favourable conditions for recurvature (Liu and Chan, 1999).

2.4 TROPICAL CYCLONE DISSIPATION

There are several ways in which a tropical cyclone can lose its tropical characteristics and subsequently dissipate. One such way is when it moves over land, thus depriving it of the conditions favourable for intensification. Most tropical cyclones lose strength after landfall and become disorganized areas of low pressure. A tropical cyclone may dissipate if it remains in the same area for too long, drawing heat off of the ocean surface until it becomes too cool to support the storm. Cool surface waters have the weakening effects upon typhoons (Brand, 1971). Once a tropical cyclone experiences wind shear or moves over colder water, it could dissipate. Tropical cyclones rarely dissipate over tropical waters (Frank and Ritchie, 1999). Previous research has revealed that even moderate changes in the magnitude or vertical shear of the mean winds can alter the storm in ways that could potentially affect the structure and intensity of the cyclone as well as its path (e.g. Jones, 1995; DeMaria, 1996; Bender, 1997; Wong and Chan, 2004). The decay rates of a tropical cyclone upon landfall are dependent upon the impact of the surface roughness change and evaporation depletion on the strength of the warm-core and the associated solenoidal circulation in the radial vertical plane (Tuleya and Kurihara, 1978). Tropical cyclone decay is also affected by downslope, topographically-induced subsidence (Bender *et al.*, 1985).

2.5 PHYSICAL STRUCTURE OF TROPICAL CYCLONE

All mature tropical cyclones comprise of various components. All tropical cyclones regardless of the strength rotate around an area of low atmospheric pressure near the earth's surface. The warm core is a very important component of a tropical cyclone. At any given altitude except near the surface where the water temperature dictates air temperature, the environment inside the cyclone is warmer than the outer surroundings. Thunderstorms of the eyewall produce a shield of cirrus clouds commonly known as the Central Dense Overcast (CDO). Because of the warm core at the center of the storm, the upper levels of a tropical cyclone feature winds headed away from the center of the storm with an anticyclonic rotation. The air diverges in the upper levels and gradually descends on larger scales as it cools (Frank and Ritchie, 1999). Winds at the surface are strongly cyclonic, weaken with height, and eventually reverse themselves.

A mature tropical cyclone has three main parts, namely the eye, the eyewall and the spiral rainbands (Oda *et al.*, 2006). The eye of a tropical cyclone is an approximately inverted, truncated cone (Willoughby, 1998). The air aloft in the eye is clear, warm and dry separated by an inversion from moist, usually cloudy air near the surface (Jordan, 1952). The eye is normally circular in shape. The strongest winds of the tropical cyclone occur in the eyewall (Mahendran, 1998). The eye is characterized by a sinking air at the center of the circulation. Because of this, weather in the eye is normally calm and free of clouds. In weaker tropical cyclones, the CDO covers the circulation center, resulting in no visible eye. The eyewall is a band around the eye of greatest wind speed and precipitation is heaviest. The eyewall ring of cumulonimbus convection surrounds the eye and contains the sharpest radial pressure gradient nearly coincident with strongest winds (Willoughby, 1998). The heaviest wind damage is caused by the winds at the eyewall. Spiral rainbands are bands of showers and thunderstorms that spiral cyclonically towards the center of the storm. High winds gusts and heavy downpours often occur in individual rainbands, with relatively calm weather between the bands. Tornadoes often form in the rainbands of landfalling tropical cyclones.

2.6 SOCIETAL IMPACTS OF TROPICAL CYCLONES

The impacts of landfalling tropical cyclones on society can be devastating. The extent of such impacts varies from one area to another. Societal impacts vary between developed and developing countries (Shultz *et al.*, 2005). When tropical cyclones impact developing countries, the impacts are often experienced for longer than in developed countries due to lack of resources. In addition, developing countries take longer to recover from the impacts of such systems.

There are a variety of public health consequences associated with tropical cyclones (Shultz *et al.*, 2005). For instance, the occurrence of tropical cyclones is often followed by the outbreak of typhoid and vector-borne diseases such as dengue fever (Mosley *et al.*, 2004). The outbreak of mosquito-borne illnesses also occurs as a result of large areas of standing water caused by flooding (Shultz *et al.*, 2005). Bridges, roads and buildings are destroyed by flooding and high winds of tropical cyclones (Lai *et al.*, 2003; Mosley *et al.*, 2004). These result in disruption of, for instance, the supply of piped water and emergency response (Lai *et al.*, 2003; Mosley *et al.*, 2004). Landslides often occur (Lai *et al.*, 2003).

Widespread communication and power outages occur (Pasch and Avila, 1999; Lai *et al.*, 2003). Roads are blocked due to flooding from the storm surge and from torrential rains (Pasch and Avila, 1999; Lawrence *et al.*, 2005). Flood waters sweep away livestock and crops. Boats are sunk. Structures collapse. Extensive saltwater damage is also observed (Lawrence *et al.*, 1998). Numerous trees drown knocking out power to many people. People drown in strong waves and residual rip currents (Franklin *et al.*, 2006). Tropical cyclones often spawn tornadoes that down trees, damage roofs and kill people (Franklin *et al.*, 2006). Buildings collapse due to scouring of the sand from underneath the foundations by wave action (Franklin *et al.*, 2006). At times, people are killed by falling debris. Tropical cyclones usually cause damage to roof claddings (Mahendran, 1998).

2.7 ENVIRONMENTAL IMPACTS OF TROPICAL CYCLONES

Tropical cyclones often uproot trees and strip, twist and snap vegetation (Pasch *et al.*, 2004). Vegetation along the coastal areas is usually covered with sand, and some suffer the effects of salt-water inundation (Lawrence *et al.*, 1998). Many areas experience erosion. Tropical cyclones have a tremendous impact on the ecological health of birds. Salt and sandy sprays burn much of the vegetation. Tropical cyclones strip viable vegetation and food crops and much of the land surface lose valuable layers of topsoil that is necessary for supporting plant growth (Pasch *et al.*, 2004). In some places, the ground is scoured down to bare rock by the rain and storm surge.

2.8 SUMMARY

In this chapter, some of the most important aspects of tropical cyclones have been reviewed. It specifically looked at the tropical cyclone formation, motion, dissipation as well as the physical structure. Finally, the chapter has been concluded with a brief summary of the societal and environmental impacts of tropical cyclones. The next chapter will look into the various techniques that can be used to predict tropical cyclones on a seasonal time scale.

Chapter 3

SEASONAL TROPICAL CYCLONE ACTIVITY FORECASTING TECHNIQUES

3.1 INTRODUCTION

In this chapter, different methods of predicting seasonal climate and their applications to tropical cyclone forecasting are reviewed. The destruction inflicted by the landfalling tropical cyclones is often catastrophic. For example, Hurricane Mitch caused at least 11000 deaths through flash flooding and landslides in Central America in October 1998 (Cerveny and Newman, 2000). Flooding from tropical cyclone Eline in February 2000 resulted in the loss of hundreds of lives and a considerable damage to the infrastructure over the northeastern interior of South Africa (Dyson and van Heerden, 2001). The prediction of such systems may prevent or mitigate the detrimental consequences thereof. As discussed in Chapter 1, there have been attempts to do this. The techniques used include both statistically-based and dynamically-based methods. Statistical methods are currently being used as seasonal tropical cyclone activity forecasting tools by several meteorological centres and universities. These include Colorado State University (Landsea *et al.*, 1994), University College of London (UCL, 2002) and the Climate Prediction Center of the National Oceanic and Atmospheric Administration (CPC, 2002). Most recently, several meteorological centres have started issuing experimental dynamical seasonal forecasts of tropical cyclones. These include the European Centre for Medium-Range Weather Forecasts (ECMWF; Vitart and Stockdale, 2001) and the International Research Institute for Climate and Society (IRI; Camargo *et al.*, 2005). This chapter reviews these techniques, stressing what has been done to this end on the subject matter.

3.2 STATISTICAL CLIMATE MODELLING

Statistical methods have been used extensively for decades to predict seasonal climate throughout the world (see e.g. Goddard *et al.,* 2001) and in Southern Africa (Landman and Mason, 2001 and references therein). Statistical models are cheaper to develop and run than numerical models (Anderson *et al.*, 1999). These methods have also been adopted by many national and international meteorological centers and universities to predict tropical cyclone activity in different regions (e.g. Gray *et al.*, 1992; 1993; 1994; Nicholls, 1992; Chan *et al.,* 2001). These regions include the Atlantic Ocean basin (Gray *et al.*, 1994), the Australian ocean basin and the western North Pacific (Nicholls, 1992; Chan *et al.*, 1998). In a statistical climate model, past data is examined mathematically to look for relationships that can be used to make forecasts (Watterson, 1996). This method is based on the assumption that the future climate will behave as in the past (Tippett *et al.,* 2005). This makes statistical models vulnerable to changes in climate. Another shortcoming is that empirical methods need a huge quality record of historical data (Tippett *et al.,* 2005). The historical record of reliable data is currently very limited and the shortness and quality of the climate record affect the accuracy of the climate forecasts (Tippett *et al.,* 2005).

Some statistical models use the results of dynamical models and then apply various statistics to them (Glahn and Lowry, 1972; Landman and Goddard, 2002). These methods have been used with varying degrees of success. For example, a recalibration technique, model output statistics was used to recalibrate large-scale circulation features produced by the ECHAM3.6 GCM to observed regional rainfall in southern Africa (Landman and Goddard, 2002). This study found that the recalibrated forecasts outscore area-averaged GCM simulated rainfall anomalies as well as forecasts produced using a simple linear forecast model. One of the biggest advantages of this sort of method is that statistical models are generally cheap to run since they do not need supercomputers (Vislocky and Fritsch, 1995).

The foundation of the idea of early empirical methods of seasonal climate forecasting was the observed connected climate anomalies in different areas (Goddard *et al.*, 2001). Statistical methods in current seasonal forecasting include, for example, regression analysis, discriminant analysis, cluster analysis, analogue method, time-series analysis and period analysis (Zhaobo, 1994). The most widely used empirical prediction method is linear regression (Vislocky and Fritsch, 1995; Goddard *et al.*, 2001). These models assume that a given change in the value of a predictor results in a fixed change in the expected value of the predictand (Goddard *et al.*, 2001). In the recent past, numerous sophisticated statistical models have also been developed. This includes neural networks (McCann, 1992).

3.3 STATISTICAL MODELLING OF TROPICAL CYCLONES

There has been a significant progress in the statistical forecasts of seasonal tropical cyclone activity since the late 1980s (e.g. Gray *et al.*, 1992, 1993, 1994; Nicholls, 1992; Hess *et al.*, 1995). A statistical prediction scheme for the annual number of landfall tropical cyclones using the projection-pursuit regression technique based on the ENSO-related indices was developed (Liu and Chan, 2003), and for the seasonal prediction of landfalling hurricanes along the Atlantic coast of the United States (Lehmiller *et al.*, 1997). Operational statistical forecasts of seasonal tropical cyclone activity over the WNP and the South China Sea based on a 30-year of data were also developed (Chan *et al.*, 1998). Another example is nonlinear Poisson regression applied with some success to predict Atlantic hurricane activity (Elsner and Schmertmann, 1993). These statistical forecasts can be issued up to a year in advance (Gray *et al.*, 1992). Numerous centres currently issue routine seasonal forecasts of tropical storm frequency using statistical methods, particularly in the Atlantic sector, Australian sector as well as the North Pacific (Nicholls, 1992; Gray *et al.*, 1993; Chan *et al.*, 1998). These techniques have not yet been explored much over the SWIO. However, the prediction of tropical cyclone days using a statistical method has been studied (Jury *et al.*, 1999).

3.4 DYNAMICAL CLIMATE MODELLING

A dynamical model is a set of computer codes representing the governing equations of the atmosphere numerically to predict the future atmospheric states. These equations include conservation of momentum, mass, energy, water vapour as well as the ideal gas law (Holton, 2004). The foundation of the idea of numerical weather prediction (NWP) may be traced back to Bjerkness (1904). He first suggested that it was possible to predict the atmosphere using a set of governing equations of wind, temperature, pressure and humidity. Richardson (1922) followed and produced a 6-hour forecast of the surface pressure at two points over Europe with such equations, which turned out to be a complete failure due to a number of reasons. Charney *et al.* (1950) later managed to produce the first successful 24-hour numerical forecast of 500 hPa geopotential height using the adiabatic quasi-geostrophic equivalent-barotropic model. Carl-Gustaf Rossby subsequently managed to produce a 3-day operational forecast in 1954 (Phillips, 1998).

In the mid-1950s, NWP became operational in the U.S (Randall, 2000). Later, many other countries followed such as Japan in the late 1950s (Randall, 2000). Phillips (1956) conducted a numerical experiment that achieved a remarkable success in predicting some variables such as mean zonal wind and mean meridional circulations of the atmosphere. The barotropic and baroclinic models were replaced in the 1960s by primitive equation models. Since then, there have been considerable improvements in NWP. There are currently a huge number of numerical models all over the globe with improved temporal and spatial resolutions. These improvements are often attributed amongst others to the increase in availability of computational capacity. Such models have been applied to a variety of atmospheric and oceanic prediction problems (Haltiner and Williams, 1975).

3.5 DYNAMICAL MODELLING OF TROPICAL CYCLONES

Recently, there has been increased interest in using dynamical models to simulate or forecast tropical cyclone activity. The ultimate goal of a tropical cyclone forecasting procedure is to prevent or mitigate disaster associated with these systems. One of the greatest advantages of using a numerical model is that many parameters related to storm intensity can be analyzed in detail without the problem of insufficient data and poor data resolution (Peng *et al.*, 1999). There are two primary methods by which dynamical climate models may be used to predict tropical cyclone activity on a seasonal time scale. One such method involves computing the seasonal cyclogenesis index from the variables that are known to affect tropical cyclone activity, and then deducing the number of tropical cyclones from this index (Ryan *et al.*, 1992). The other approach consists of detecting and tracking of the tropical cyclone-like structures in a dynamical model itself (Bengtsson *et al.*, 1995; Vitart *et al.*, 1997). To do the latter, two types of dynamical climate models have been used to this end, namely, GCMs and nesting RCMs. This section reviews how these models have been used in the prediction of seasonal climate as well as how they have been applied to the problem of tropical cyclone forecasting on a seasonal time scale.

3.6 GENERAL CIRCULATION MODELS

GCMs, which have their origin in numerical weather prediction, are being used extensively in seasonal forecasting globally (Palmer and Anderson, 1994; Goddard *et al.*, 2001). GCMs have been in existence since the mid-1950s (Phillips, 1959; Randall, 1996). Some of the earliest GCMs include the Mintz-Arakawa model that was developed at the University of California, Los Angeles (Randall, 2000). This GCM was a global two-level model based on the primitive equations with terrain-following sigma coordinates (Johnson and Arakawa, 1996). Such GCMs demonstrate skill at global or even continental scale (Dickson, 1985; Hong and Leetma, 1999; Landman and Goddard, 2002). GCMs have also been used for climate change studies at a continental scale (e.g. McAvaney *et al.*, 2001).

Because the horizontal domain of GCMs is the whole earth, they usually cannot be run at high resolution (Giorgi, 1990; Hong and Leetma, 1999). Due to its usual coarse resolution, GCM cannot simulate local climate conditions (Walsh and McGregor, 1995). Moreover, GCMs do not account for surface features, such as topography and landuse that determine much of the significant climate features at regional scales (Giorgi, 1990; Hong and Leetma, 1999). One of the reasons GCMs produce unrealistic small-scale features is the poor representation of the topography in the models (McGregor *et al.*, 1993). Climate models are the key for simulating possible climates (Johnson and Arakawa, 1996). However, GCMs are computationally expensive in terms of development, integration as well as validation (Anderson *et al.*, 1999). The increased speed of computers is having a dramatic positive effect on global atmospheric modelling (Randall, 1996). In recent years, fully coupled ocean-atmosphere GCMs have been developed and are increasingly becoming popular (Anderson *et al.*, 1999).

Lately, variable resolution GCMs using a global stretched grid with enhanced uniform resolution over the region(s) of interest have been used (Fox-Rabinovitz *et al.*, 2006). Another such model is the Commonwealth Scientific and Industrial Research Organisation conformal cubic atmospheric model (C-CAM) (McGregor, 2004; McGregor and Dix, 2008). Such GCMs have been found to produce accurate and cost-effective regional climate simulations with enhanced regional resolution (Fox-Rabinovitz *et al.*, 2006). This approach has been used along with or as an alternative to the nested-grid approach considered here. One of the major advantages of variable resolution stretched-grid GCMs is that they do not require any lateral boundary conditions, and as a consequence they provide self-consistent interactions between global and regional scales of motion and their associated phenomena as in uniform grid GCMs (Fox-Rabinovitz *et al.*, 2006).

3.7 GENERAL CIRCULATION MODELS AND TROPICAL CYCLONES

Tropical cyclones generated by GCMs with various horizontal resolutions have been found to have considerable similarities to observed tropical cyclones (Manabe *et al.*, 1970; Krishnamurti, 1988). The latter study evaluated how the track and the structure of a tropical storm are affected by increasing resolution. The impact of atmospheric CO_2 increase on tropical storm frequency was investigated using spectral models coupled with an ocean model (Broccoli and Manabe, 1990). An atmospheric GCM (AGCM) forced by climatological SSTs was used to study tropical cyclone activity over all ocean basins (Bengtsson *et al.*, 1995). A method of tracking tropical cyclones in low resolution GCMs was used by Vitart *et al.* (1997) and Camargo and Sobel (2005). Tropical storms are generally detected when dynamic and thermodynamic variables meet specified criteria (Camargo and Zebiak, 2002). The barotropic and baroclinic models were applied to simulate tropical cyclone recurvature under idealized environmental conditions (Evans *et al.*, 1991; Holland and Wang, 1995). The use of an ensemble of coupled GCM integrations to predict tropical storm activity was explored (Vitart and Stockdale, 2001). The interannual variability of tropical storms in GCMs was investigated by Wu and Lau (1992).

Tropical storms produced by an AGCM using an ensemble of integrations and their relation to the large-scale circulation and sea-surface temperature variability were investigated by Vitart and Anderson (2001). Considerably fewer tropical storms were simulated with El Niño SSTs imposed over the tropical Pacific and Indian Oceans than with La Niña conditions. The AGCM-produced tropical cyclones were detected and tracked by using an objective tracking algorithm (Camargo and Zebiak, 2002). It was found that the objectively defined detection criteria improve simulations of tropical storm climatology and interannual variability in the low-resolution AGCM. Currently, several centers including the ECMWF and the IRI produce experimental dynamical seasonal tropical storm activity forecasts for a variety of ocean basins. ECMWF tropical cyclone forecasts are based on a coupled ocean-atmosphere GCM (Vitart and Stockdale, 2001). IRI seasonal tropical cyclone forecasts are based on an AGCM (Camargo *et al.*, 2005).

3.8 REGIONAL CLIMATE MODELLING

RCMs are mathematical representations of the atmosphere limited to specific regions of interest rather than at a global scale. The idea that the limited area models could be used for regional climate studies was originally proposed by Dickinson *et al.* (1989) and Giorgi (1990). Regional models use the same laws of physics described in terms of mathematical equations, as do global models. The goal of regional modelling is to make a detailed forecast for a given limited area of interest by focusing resolution over it and the immediate vicinity (Staniforth, 1997).

The use of RCMs offers certain advantages over the use of GCMs (Giorgi *et al.*, 2003), namely, RCMs are more economical to run than GCMs of similar grid resolution (Giorgi, 1990) because RCM simulations are restricted to the area of interest. Since they cover smaller areas, they can have higher spatial resolution, for the same number of gridpoints as a global model. This allows better resolution of mountains and coastal areas, for instance where a distance of 50 km can mean a dramatic change in climate. It also means that smaller-scale weather systems are better resolved (Walsh and McGregor, 1997; Fu *et al.*, 2005). The drawback of RCMs is that since they do not span the entire globe, they must rely on the information provided at the lateral boundaries in order to simulate climates for the interior of their model domains. RCMs are either nested within the observational data or within a GCM to provide climate simulations of certain regions (Giorgi, 1990). One of the greatest advantages of RCMs over the statistical methods is that they can capture nonlinearities relating mesoscale process to large-scale flow (Hong and Leetma, 1999).

There are two methods by which a RCM may be nested within a GCM. One such method is referred to as a non-interactive approach, and the other is an interactive approach (Anthes, 1983; Arakawa, 1984). In the non-interactive approach, a coarse resolution model forecast/simulation is used to specify time-dependent lateral boundary conditions for the RCM (Giorgi *et al.*, 1992; Staniforth, 1997). In this approach, there is actually no atmospheric circulation feedback from the RCM to the GCM (Giorgi, 1990). This makes a RCM vulnerable to the errors propagating from the GCM to its lateral boundaries (Staniforth, 1997). However, this method has been employed in many studies as compared to the other approach (Walsh and McGregor, 1995; Walsh and Watterson, 1997; Walsh and Katzfey, 1999; Landman *et al.*, 2005; Giorgi *et al.*, 2003). In the interactive approach, the resolution is varied in some manner away from the fine resolution of the area of interest to the coarser resolution of the outer region, and the flows inside and outside the area of interest mutually interact within a single dynamic framework (Staniforth, 1997). In recent years, several RCMs have been developed to provide adequate resolution within a limited domain. Most of the RCMs available to this end are gridpoint models, but a few regional spectral models have also been developed (e.g. Juang and Kanamitsu, 1994).

3.9 REGIONAL CLIMATE MODELLING AND TROPICAL CYCLONES

A limited-area model DARLAM was used to study tropical cyclone-like vortices over the Australian region (Walsh and Watterson, 1997) and it was found that the vortices generated by the RCM are much more realistic than those generated by the GCM. A RCM was used to study the interannual, decadal and transient greenhouse simulations of tropical cyclone-like vortices in South Pacific (Nguyen and Walsh, 2001). The effect of RCM domain choice on the simulations of tropical cyclone-like vortices in the SWIO was investigated (Landman *et al.*, 2005) and it was demonstrated that the position of the boundaries play a pivotal role in the simulations of tropical cyclones propagating into the domain of interest. For example, the simulated tropical cyclones migrating into the SWIO from the east were found to be affected by the location of the eastern and northern boundaries of the RCM.

The impact of climate change on the poleward movement of tropical cyclone-like vortices in a RCM was examined (Walsh and Katzfey, 1999). A limited-area numerical model was used to study the outflow layer of tropical cyclones (Shi *et al.*, 1990) and the effect of planetary vorticity gradient and the presence of a uniform mean flow on the intensification of tropical cyclones were studied using a limited-area primitive equation model (Peng *et al.*, 1999).

3.10 SUMMARY

The techniques used in climate modelling, both statistical and dynamical have been introduced. The relevance of such techniques in forecasting the tropical cyclone activity on a seasonal time scale has also been highlighted, and the history of numerical weather prediction has been reviewed. In the next chapter the characteristics of observed historical tropical cyclones are discussed based on the Joint Typhoon Warning Center (JTWC) best-track data set.

Chapter 4

CHARACTERISTICS OF TROPICAL CYCLONES OVER THE SOUTHWESTERN INDIAN OCEAN

4.1 INTRODUCTION

Despite considerable advances in recent years in both tropical cyclone activity forecasting on a seasonal time scale as well as in our understanding of the behaviour of such systems, the SWIO has not enjoyed as much attention as the rest of the ocean basins where tropical cyclones occur. This little coverage could be attributed to the lack of historical meteorological data in the Southern Hemisphere.

Both statistical and dynamical techniques have emerged in the literature as candidate solutions to the problem of tropical cyclone prediction. The merits of both these techniques have been discussed at length in the literature. This study builds mainly on the work of Jury *et al.* (1999), Vitart *et al.* (2003), Reason and Keibel (2004), Landman *et al.* (2005), Reason (2007) and Klinman and Reason (2008).

To improve our understanding of the tropical cyclone activity in the SWIO, this chapter discusses some of the most important characteristics of the tropical cyclones over this basin. In addition, the impact of ENSO phenomenon on the tropical cyclone activity over this basin is also reviewed. It has been established in other regions such as in the WNP that ENSO has a considerable impact on tropical cyclone activity (Chan, 1985). The locations of tropical cyclone formation during years between ENSO warm and cold phase years were compared over the WNP (Chen *et al.*, 1998). The sea-surface temperature conditions over the equatorial central and eastern Pacific were used as predictors of the seasonal tropical cyclone activity over the WNP (Chan *et al.*, 1998). The SWIO is chosen because it is tropical cyclones that either develop or migrate into this basin that impact the southern African region, particularly Mozambique.

4.2 THE JTWC BEST-TRACK DATA

Tropical cyclones over the SWIO during the period 1981/82-2001/02 form the basic dataset for this chapter. The data has been obtained from the Joint Typhoon Warning Center (JTWC). The study has been restricted to the data collected after the introduction of satellites in 1979 (Kalnay *et al.*, 1996; Tennant, 2004). In addition, this chapter focuses only on the named mature tropical cyclones. These are cyclones that have reached the tropical cyclone intensity on the Beaufort scale i.e. maximum sustained winds greater than 63 knots. Thus, tropical depressions and tropical storms are not considered in this chapter and in the analysis.

The JTWC maintains an archive of tropical cyclone track data, commonly referred to as “best-tracks”. Each best-track file contains tropical cyclone center locations and intensities. These are the maximum 1-minute mean sustained 10-meter wind speed at six-hour intervals. The geographical domain of the archive is the WNP, NI and Southern Hemisphere.

Three disparate data sources are used to construct the JTWC archive (1) the National Climate Data Center database, (2) a fleet Numerical Meteorology and Oceanography Center database and (3) the Automated Tropical Cyclone Forecasting System database (Sampson and Schrader, 2000). The JTWC archive includes data from 1945, cross-validations are limited to years from 1950 for the WNP, years from 1971 for the NI and years from 1985 for the Southern Hemisphere's best tracks contain 6-hourly tropical cyclone positions. The best-tracks data are available on the JTWC Tropical Cyclone Best Track Data site. The best-track data employed in this study is for the period 1981/82-2001/02.

4.3 MONTHLY VARIATIONS

Figure 4.1 displays the number of observed tropical cyclones for each month of the year over the SWIO for the period 1981/82-2001/02. The tropical cyclone season really only starts in November and ends in May. At least one tropical cyclone was observed in the month of October over the period considered here. Tropical cyclones show a strong maximum in January, with most cyclones occurring between December and March, and no significant events before November or after May.

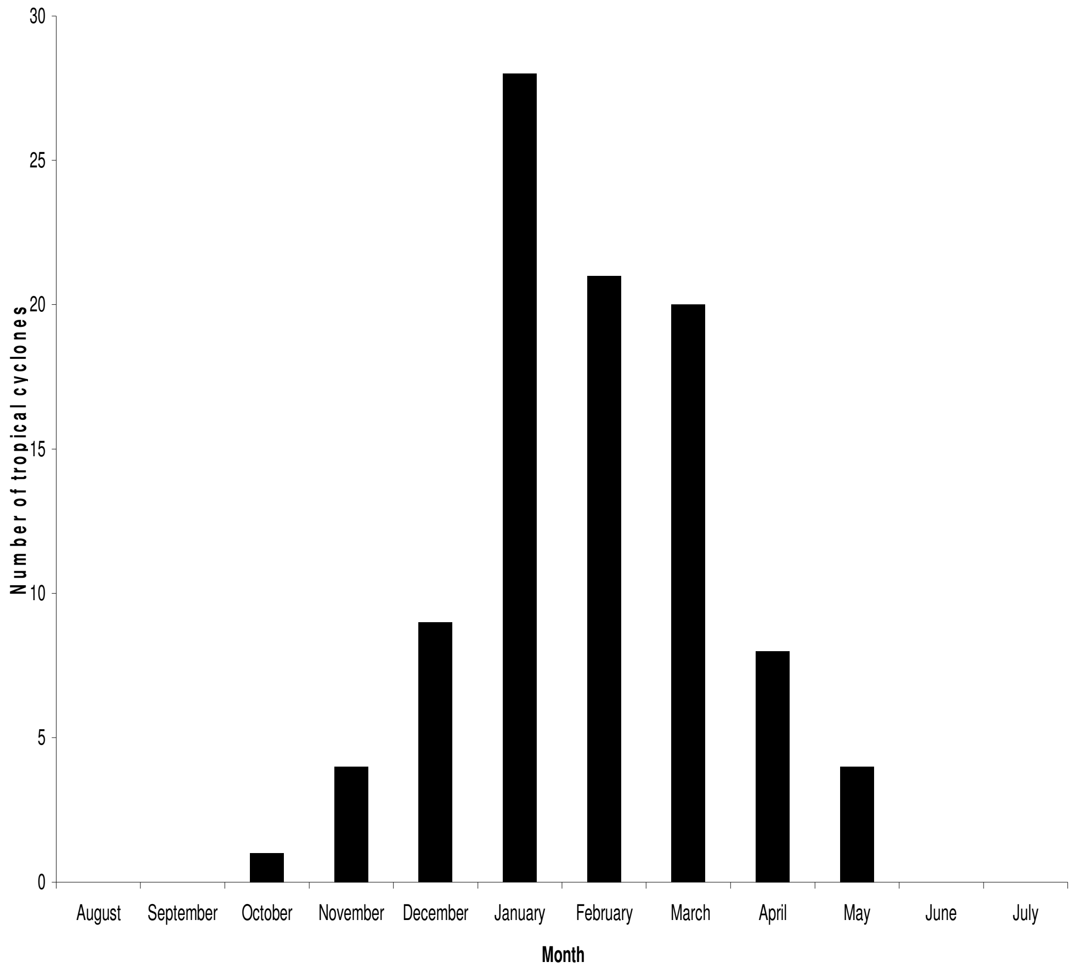


Figure 4.1: Annual cycle of number of tropical cyclones in the SWIO basin.

4.4 ANNUAL VARIABILITY

Figure 4.2 details the yearly variations of the tropical cyclones over the period 1981/82-2001/02. It is evident that the number of SWIO tropical cyclones shows a very pronounced seasonal variability in the level of activity. Over the period considered here, the number of observed tropical cyclones per season ranged from 1 to 9. The mean number of the tropical cyclones over the period of study is 5.0. Observations display the highest number of tropical cyclones in the 1993-1994, 1996-1997 and 2001-2002 seasons. The smallest numbers of tropical cyclones are displayed in the 1982-1983, 1984-1985 and 1986-1987 seasons. It is evident that observed tropical cyclones were more numerous in the 1980s than in the 1990s. It is beyond the scope of this study to investigate what brought this about.

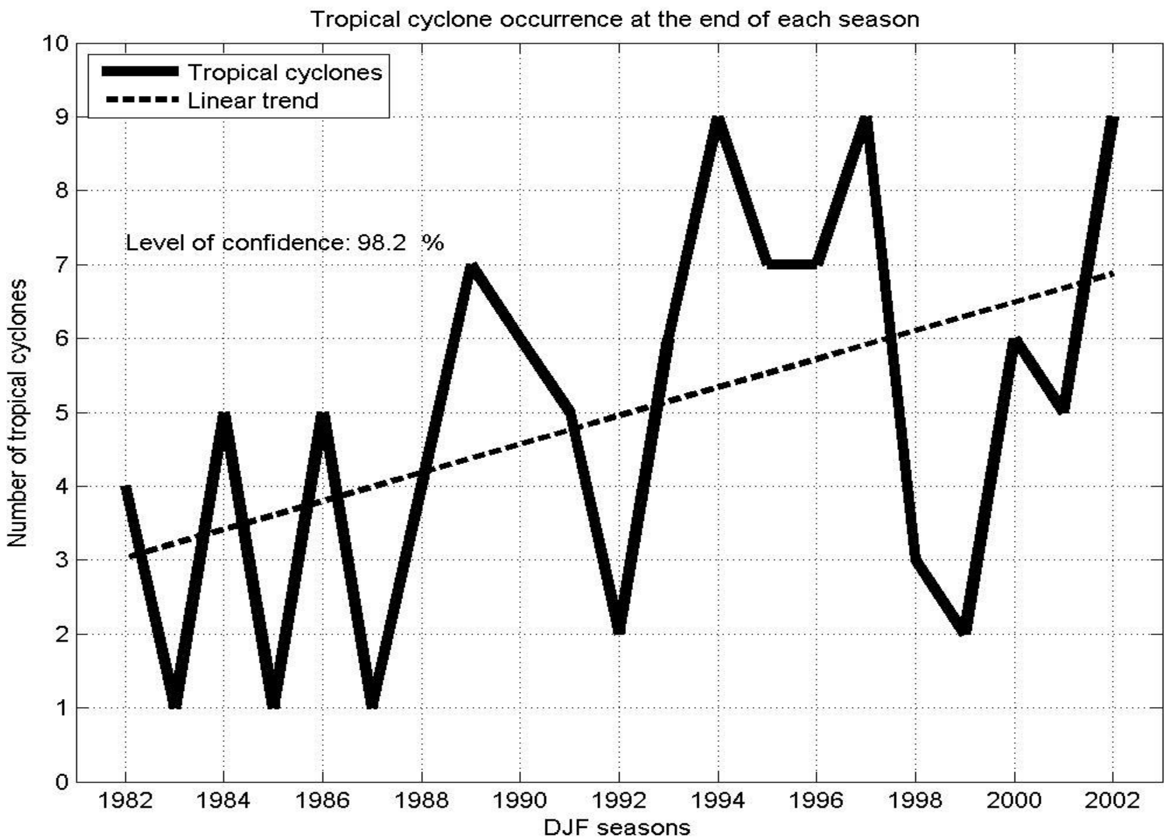


Figure 4.2: Interannual variability of the observed number of tropical cyclones.

To determine if the trend of the tropical cyclone occurrences is statistically significant, Monte Carlo tests are performed (Livezey and Chen, 1983; Wilks, 2006). The best linear fit is calculated for the re-randomized time series, and repeated for 1000 times. The slopes of each re-randomized linear fit are calculated, sorted and the 950th test statistic is obtained. The interest is only in performing a one-tailed test since the significance of the upward linear trend is required. If the original time series of occurrence has a slope less than that of the test statistic, the upward trend is not statistically significant at the 95% level of significance. In this case, the trend is statistically significant at the 98.2% confidence level. The true trend of tropical cyclones per year is 3.84.

4.5 DURATION OF TROPICAL CYCLONES OVER THE SWIO

In Figure 4.3 the distributions of number of tropical cyclone days for all the seasons from 1981-1982 to 2001-2002 are given. The number of tropical cyclone days in the SWIO displays a significant variability from one season to another. Some cyclone seasons start earlier than others. The number of tropical cyclone days is a function of the frequency of tropical cyclones and/or the length of the lifetimes of the tropical cyclones that occur in a particular season (Camargo and Sobel, 2005). For instance, the 1999-2000 cyclone season had two tropical cyclones whose life cycles were exceptionally long but there was not a particularly great number of cyclones that occurred in this season. The lifetimes of the latter two cyclones accounted for both the increased number of days of cyclonic activity and the average lifetime. Similarly, the length of the lifetime of the tropical cyclone Davina in 1998-1999 cyclone season contributed to the high number of the tropical cyclone days and average lifetime in this season.

The four cyclone seasons that had the highest number of tropical cyclone days over the period of the study are 1986-1987, 1998-1999, 1999-2000 and 2000-2001. The 1986-1987 cyclone season was the least active season among the four seasons in terms of the tropical cyclone frequency. The 1999-2000 cyclone season had a very high tropical cyclone activity, which resulted in the high number of tropical cyclone days.

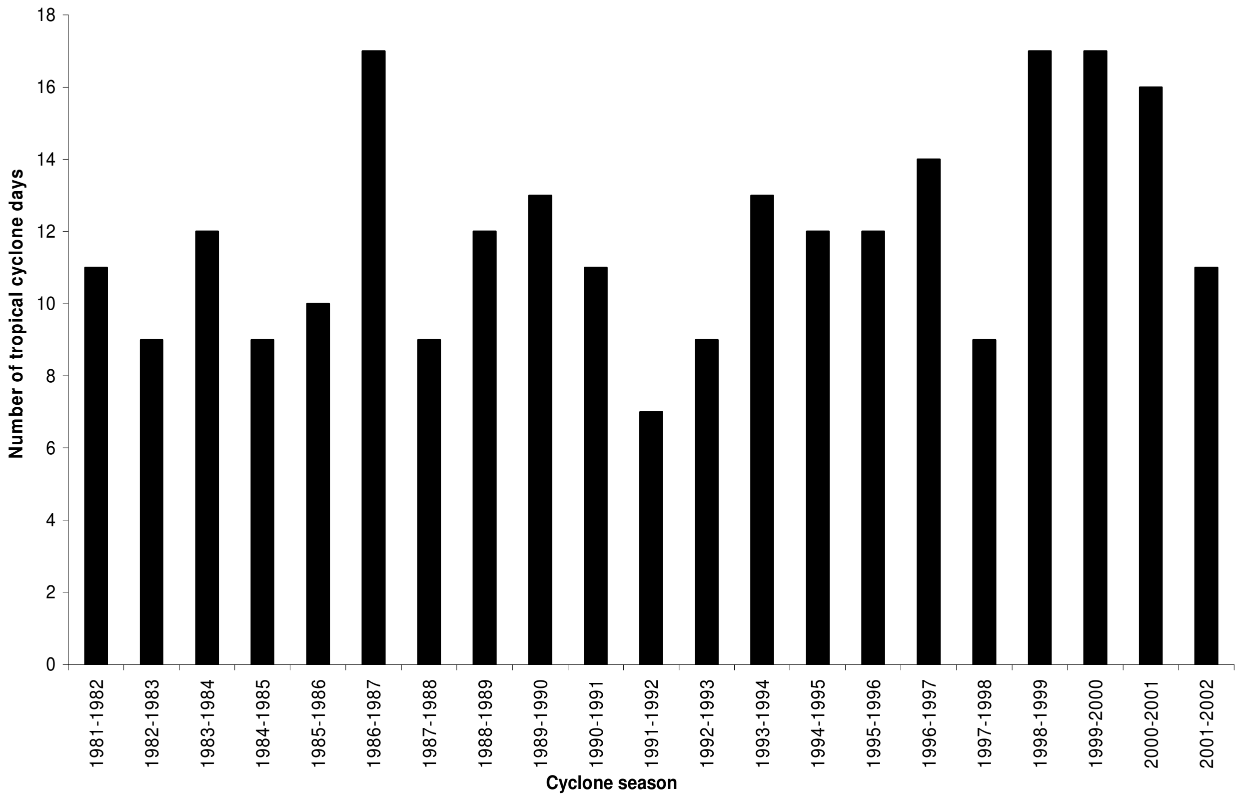


Figure 4.3: Average duration of the observed tropical cyclones per season.

4.6 ANNUAL VARIATION OF INTENSE TROPICAL CYCLONES

Figure 4.4 depicts the frequency of the occurrence of intense tropical cyclones over the SWIO for the period 1981/82-2001/02. The occurrence of intense tropical cyclones in the SWIO basin is very limited compared to other ocean basins. The highest number of such tropical cyclones occurred in the mid-1990s. The highest number of intense tropical cyclones observed per season over the SWIO basin over the period considered is three. Most of the tropical cyclones that develop over this basin do not reach the intense tropical cyclone stage. The intense tropical cyclones show a substantial increase in activity with time. Intense tropical cyclones occurred more frequently from the beginning of the 1990s than in the 1980s.

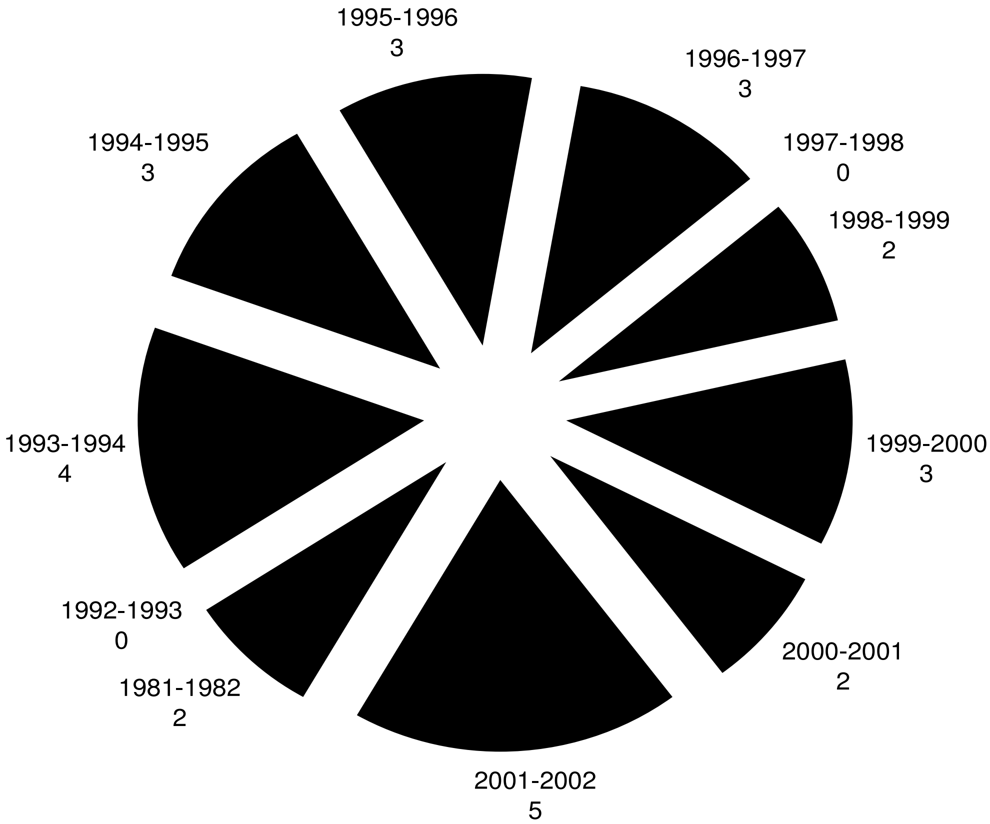


Figure 4.4: Intense tropical cyclone numbers over the SWIO basin for the period 1981/82-2001/02.

4.7. IMPACTS OF ENSO

In this section, the impacts of El Niño-Southern Oscillation (ENSO) phenomenon on tropical cyclone activity over the SWIO are reported. This gives some insights into the frequency and behaviour of tropical cyclones during either an El Niño event or a La Niña event. An El Niño event is the anomalous warming of the equatorial Pacific Ocean (Liu and Chan, 2003; Chan and Liu, 2004), which influences atmospheric circulation, and consequently rainfall, and temperature in specific areas around the world. A La Niña event is the anomalous cooling of the equatorial Pacific Ocean (Liu and Chan, 2003; Chan and Liu, 2004).

The ENSO years are obtained from a webpage of the Climate Prediction Center http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). The El Niño years are 1982-1983, 1986-1987, 1991-1992, 1993-1994, 1997-1998 and La Niña years are 1988-1989, 1995-1996, 1998-1999, 1999-2000, 2000-2001 and 2001-2002.

4.7.1 Frequency of tropical cyclones in El Niño and La Niña years

The impact of ENSO on the tropical cyclone frequency over the SWIO is not clearly evident (Figure 4.5). The two seasons that stand out are the 1993-1994 (El Niño season) and 2001-2002 (La Niña season) that had equal number of tropical cyclones. This is in agreement with the findings of Vitart *et al*. (2003), who found a very low correlation (correlation of 0.013 over the period 1950-2000) between the interannual frequency of tropical cyclones over the SI and ENSO. The latter study also established that El Niño conditions are conducive to a significant increase of vertical wind shear over the SI and to warmer SSTs over the SI. These two conditions have contradictory effects on the tropical cyclone activity. The increased vertical wind shear hampers the tropical cyclone activity, whereas increased SSTs promote it. However, what is worth noting is that 1982-1983, 1986-1987, 1991-1992 and 1997-1998 cyclone seasons are among the least active cyclone seasons and are all related to marked El Niño episodes. Strengthened subtropical upper-westerly winds often limit the potential for the development of the tropical cyclones in the SWIO during El Niño years (Jury *et al*., 1999).

It is also evident from the figure above that La Niña years tend to have more tropical cyclone activity than El Niño years. La Niña conditions are associated with reduced vertical wind shear over the SI, which creates more favourable conditions for tropical cyclone genesis (Vitart *et al.*, 2003). This implies that La Niña conditions in conjunction with warmer SSTs over the SWIO would lead to possible increased tropical cyclone activity over this basin.

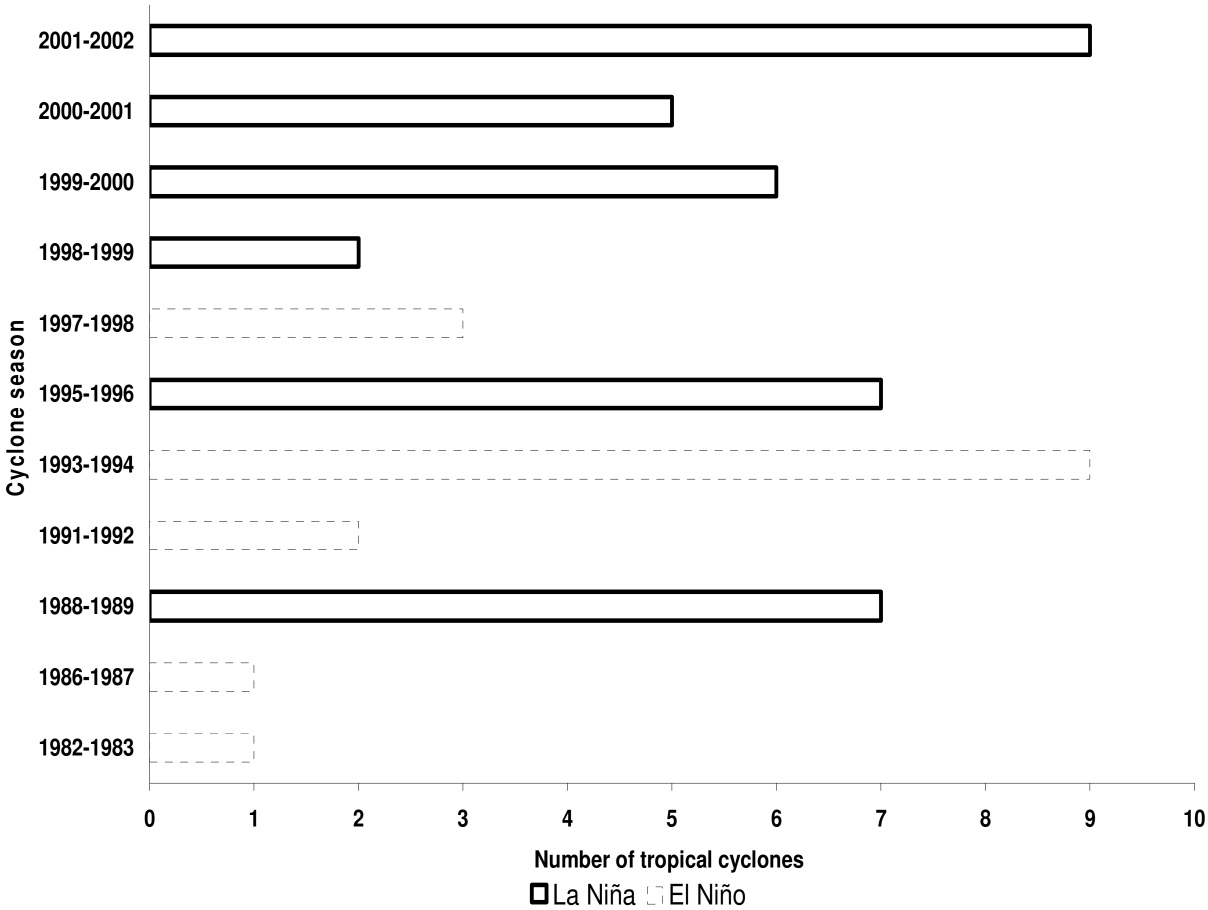


Figure 4.5: Tropical cyclone frequencies during El Niño and La Niña years over the SWIO.

4.8 SUMMARY

The characteristics of tropical cyclones over the SWIO have been discussed. The data that formed the basis of analysis has been described. Several aspects of tropical cyclone activity have been discussed. These include monthly variation of tropical cyclones, annual variability as well as the duration of tropical cyclones over the SWIO. The chapter has been concluded with the impacts of ENSO phenomenon on tropical cyclone frequency over the SWIO. In the next chapter the data, methods and models used to simulate tropical cyclones over the SWIO are described in detail.

Chapter 5

TROPICAL CYCLONE SIMULATIONS USING THE RegCM3

5.1 INTRODUCTION

A currently economically viable method for developing countries to do research and predict systems on a seasonal time scale is through the use of RCMs. The implementation of this method was found to produce tropical cyclones that appear to be more realistic than those generated by the GCMs (Walsh and Watterson, 1997). It has been shown that the RCM is useful for studying sub-GCM grid processes (Giorgi, 1990). In this chapter, a RCM is nested within the GCM. An objective algorithm for detecting tropical cyclones is applied to the RCM output, similar to what has been used in the past (e.g. Walsh and Watterson, 1997; Liu and Chan, 2003; Landman *et al.*, 2005)

The ability of the nested RCM to simulate regional climate depends on the capacity of the forcing GCM to reasonably simulate the climate of the area of interest (Giorgi, 1990). In the areas where the GCM was able to simulate a realistic large-scale circulation, it was also able to simulate a realistic interannual variability of the tropical storm frequency reasonably well (Vitart and Anderson, 2001). Therefore, it is important to assess the ability of the forcing GCMs to capture the potential variables (climate) in the region of interest, before using its output as the forcing fields for the RCM. Out of several GCMs that were used to study the climate of southern Africa, the ECHAM AGCM is the one that produced the best results (Landman and Goddard, 2003). It is this reason that ECHAM4.5 AGCM was chosen as the driving GCM for the RCM in this study.

In this chapter, an objective algorithm for detecting model-generated tropical cyclones is applied to the ECHAM4.5-RegCM3 output. To assess the ability of this system to simulate the environmental variables required for the formation and development of tropical cyclones, its output of such variables as vertical wind shear and relative vorticity is compared with NCEP reanalysis fields (Kalnay *et al.*, 1996). The description of the NCEP reanalysis data used and the GCM whose output was utilized to force the RCM is given. The detailed experiments conducted with the RCM are also covered in this chapter.

5.2 DEFINITION OF SWIO TROPICAL CYCLONES AND BASIN DOMAIN

In this section, the terminology used for the purpose of this study is defined. Some of the terms utilized here have been defined differently from those used by others in the past. The reasons for such unique terms are also stipulated.

5.2.1 The SWIO tropical cyclones

In this dissertation, tropical cyclones are defined as cyclonic systems with a maximum sustained surface wind velocity of greater or equal to 17m/s (Vitart *et al.*, 1997). The SWIO tropical cyclones are defined as the tropical cyclones with at least a portion of their track within the SWIO, though the genesis location does not necessarily need to be within the SWIO (Vitart *et al.*, 2003). The tropical season is defined as the period of the year during which most tropical disturbances occur. The genesis position corresponds to the position where tropical cyclone has been detected for the first time by the objective procedure.

This study is more interested in the simulations for the months on both sides of the peak month of January, and for this reason the entire month of November is discarded to allow for model spin-up (Anthes *et al.*, 1989). An experiment carried out at the South African Weather Service (SAWS) found that the output for two different integrations, one started on the 1st of January (a 12-month run) and the other started on the 1st of November (a 4-month run) yielded insignificant differences for DJF rainfall and temperature (pers.comm.Kgatuke, 2007). This means for RegCM3 output using one month as a spin-up period is assumed sufficient here. Hence, in this dissertation November has been used for this purpose. As noted in Chapter 3, December, January and February are the most active months of the tropical cyclone season in the SWIO in terms of tropical cyclone frequency.

Although March is also one of the most active months, it does not form part of the analysis as it was omitted in the initial RCM integrations, because the model was originally configured to study the rainfall variability during the mid-summer season

(DJF) over southern Africa. Hence, the simulation data ends in February. Notwithstanding, the shortened season presented here is still long enough to provide evidence whether or not the seasonal prediction of tropical cyclone occurrence over SWIO is feasible.

5.2.2 The SWIO basin

For the purposes of this study, the SWIO basin is defined as the region bounded by 0º-40ºS and 30º-70ºE so that tropical cyclones migrating towards the west of Madagascar and those developing in the Mozambique Channel are considered. It is such tropical cyclones that affect the southern African subcontinent, which is a region of interest for this study.

The locations of the lateral boundaries of the RCM have a considerable effect on the simulations (Landman *et al.*, 2005). Placing the lateral boundaries far enough from the region of interest limits the impact of the lateral boundaries (Giorgi *et al.*, 1992; Wu *et al.*, 2005). The Madagascar Island not only affects the moisture flux from the Indian Ocean, but also the migration of the tropical cyclones over the SWIO towards the southern African subcontinent (Landman *et al.*, 2005). Because of its influence, Madagascar needs to be included in the model domain (Seth and Giorgi, 1998).

In light of these, the positions of the eastern and northern boundaries were chosen in such a way that they will have the least effect on the simulated storms. The western and the southern boundaries do not have any influence on the storms propagating from east-to-west (Landman *et al.*, 2005). The model domain extends from about the

0° line of latitude to about 40°S, and from Greenwich line to 70°E as shown in Figure 5.1.

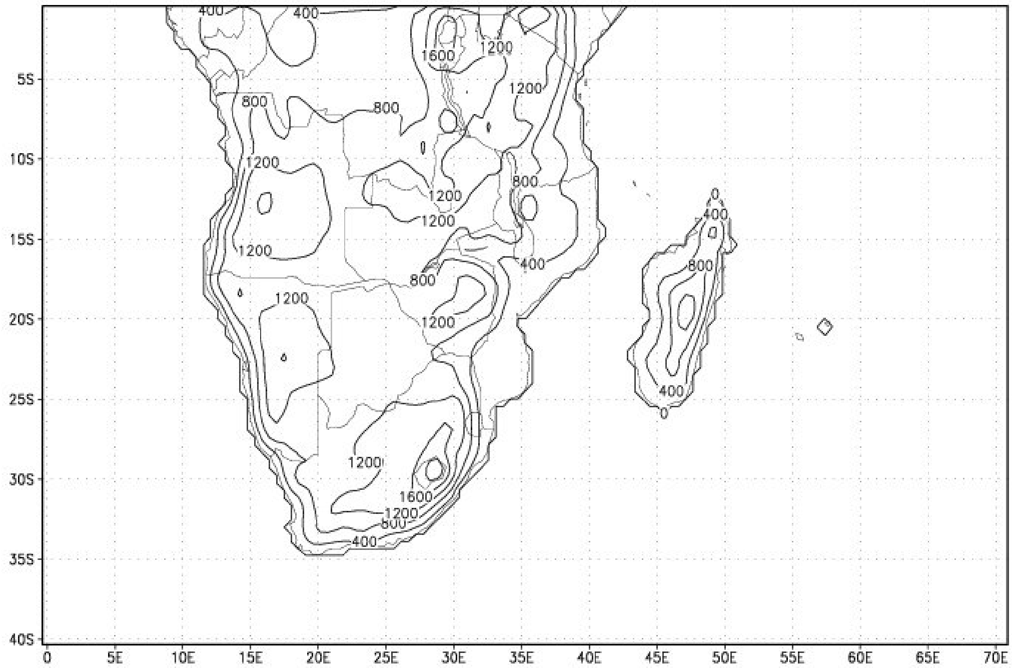


Figure 5.1: The RegCM3 model topography in meters and the model domain with 84X135 grid points.

5.3 EXPERIMENTAL DESIGN

In this section, the experiments conducted with the RCM are described. Details about the data and models used in the experiments are provided, the experimental procedure is outlined and the results of the experiments are discussed.

5.3.1 The NCEP reanalysis dataset

To examine the ability of the ECHAM4.5-RegCM3 system to simulate the environmental factors relevant to the formation and development of tropical cyclones, the nested output was compared with the NCEP reanalysis fields. So, here the reanalysis fields are treated as the "observed" fields. This section gives a brief description of the NCEP reanalysis data set. The NCEP reanalysis data are generated using the Medium Range Forecast (MRF) model (Kalnay *et al.*, 1996). This dataset consists of a reanalysis of the global observation network of the meteorological variables and a forecast system at a triangular spectral truncation of T62 to perform data assimilation. Data have a spatial resolution of 2.5° latitude X 2.5° longitude and a temporal resolution of 6-hours (0000, 0600, 1200 and 1800 UTC) on 17 pressure levels from 1000 hPa to 10 hPa. The data available is from 1948 to present. The introduction of satellite data in 1979 has produced a discontinuity in the data, particularly in the upper troposphere, south of 50°S (Kistler *et al.*, 2001) and in the stratosphere (Huesmann and Hitchman, 2003). Climatologies should be constructed using the 1979 to the present period (Kistler *et al.*, 2001). The scarcity of observation data over the Southern Ocean prior to 1979 has a potentially serious effect on any attempt to re-create atmospheric analysis for this period (Tennant, 2004). Considering all these, it was decided to use the data post-1979.

5.3.2 The ECHAM4.5 AGCM

The GCM outputs used as forcing fields for the RCM were obtained from the ECHAM4.5 AGCM. This model was developed at the Max Planck Institute for Meteorology (MPI) in Germany and was originally derived from a spectral weather forecast model of the ECMWF (Roeckner *et al.*, 1996). The ECHAM4.5 AGCM is a spectral model at T42 resolution, approximately 2.8° in horizontal resolution and 19 levels in the vertical. It uses the mass flux for deep, shallow and midlevel convections and cumulus convection schemes developed by Tiedtke (1989). The Monin-Obukhov similarity theory is used to calculate the turbulent surface fluxes (Louis, 1979). The mass flux scheme is used along with the modified closure scheme for penetrative convection and the formation of organized entrainment and detrainment (Nordeng, 1995). The radiative transfer is modelled by the modified version of the ECMWF scheme (Sun *et al.*, 2006).

A modified bucket model with improved parameterization of rainfall runoff is utilized as the land surface scheme (Dumenil and Todini, 1992). The computation of the vertical diffusion is done with a higher-order closure scheme depending on the turbulent kinetic energy (Sun *et al.*, 2006). Four-and six-band intervals are respectively used in the solar and terrestrial part of the spectrum (Sun *et al.*, 2006). The drag associated with orographic gravity waves is simulated following Miller *et al.* (1989). The vertical coordinate system used is from Simmons and Burridge (1981). This model is used at the IRI for routine seasonal forecasts (Mason *et al.*, 1999) and also at the SAWS. The 24-member simulation runs were produced at the IRI by forcing the ECHAM4.5 model with observed simultaneous monthly mean SSTs (Goddard *et al.*, 2001). Each ensemble member is integrated with different atmospheric conditions but with the same SSTs, thus providing 24 independent realizations of the model's internal variability. In this dissertation, only four ensemble members were used owing to the limited computational capacity made available for this study.

5.3.3 The RegCM3

The RCM used in this study is the Regional Climate Model version 3, better known as RegCM3. A detailed description of the earlier version of the model is documented in Giorgi *et al.* (1993a; 1993b). This RCM was developed at the International Center for Theoretical Physics in Italy. The version of the model used here was released in the year 2003. RegCM3 is a 3-dimensional primitive equation gridpoint RCM. The model has 18 sigma-coordinate levels in the vertical. The dynamical core of the model is similar to that of the hydrostatic version of MM5 (Grell *et al.*, 1994a). It uses the radiation scheme of the NCAR CCM3. Dickinson *et al.* (1993) described at length the BATS1E (Biosphere-Atmosphere Transfer Scheme) used to perform the surface physics.

The planetary boundary layer scheme used is based on a non-local diffusion concept that takes into account counter-gradient fluxes resulting from large-scale eddies in an unstable, well mixed atmosphere and was developed by Holtslag *et al.* (1990). Convective precipitation is computed using either the Grell scheme (Grell, 1993), the Modified-Kuo scheme (Anthes, 1977) or the MIT-Emanuel scheme (Emanuel, 1991; Emanuel and Zivkovic-Rothman, 1999). Grell scheme has two options of closure assumptions, namely the Arakawa and Schubert closure (Grell *et al.*, 1994a) and the Fritsch and Chappell closure (Fritsch and Chappell, 1980). The sub-grid Explicit Moisture Scheme (SUBEX) is used to handle non-convective clouds and precipitation resolved by the model. There are two options available to calculate the pressure gradient force. One such method uses the full fields. The other way is the hydrostatic deduction scheme that uses perturbation temperature. There are two options for ocean flux parameterization, namely the BATS and Zeng scheme. BATS uses standard Monin-Obukhov similarity relations to compute the fluxes with no special treatment of convective and very stable conditions. The Zeng scheme describes all stability conditions and includes a gustiness velocity to account for the additional flux induced by boundary layer scale variability. The dust emission calculation is based on parameterizations of soil aggregate saltation and sandblasting processes. Terrestrial variables (including elevation, land-use and sea-surface temperature) and threedimensional isobaric meteorological data are horizontally interpolated from a latitude-longitude mesh to a high-resolution domain on either a Rotated or Normal Mercator, Lambert Conformal or a Polar Stereographic projection. Vertical interpolation from pressure levels to the sigma surfaces near the ground closely follow the terrain, and the higher-level sigma surfaces tend to approximate isobaric surfaces.

5.3.4 Experimental procedure

Having described the data and the models used in the experiments, a description of the experiment is now provided. The nested system used in this study is referred to as ECHAM4.5-RegCM3 system. One of the most crucial goals of the climate models is to produce real-time forecasts. To do so, a RCM has to be forced with the real-time forecast from the GCM. In this experiment, the model is run at a horizontal resolution of 60 km and a time step of 150 s. Fine spatial resolution is required in order to simulate tropical cyclone-like vortices (Keen and Glenn, 1998). It has been found that a 40 km horizontal resolution did not significantly improve the simulation performance as compared to the 60 km resolution (Landman *et al.*, 2005). Given that integrating the model at a resolution higher than 60 km additionally has been found to be computationally demanding, and so, it was decided to use the 60 km horizontal resolution for this study. This resolution is still less than that of the coarse resolution ECHAM4.5 GCM. The Grell cumulus parameterization scheme with the Fritsch and Chappell closure assumption (Grell, 1993) is employed to make simulations. The model outputs the data at a six-hourly interval from 0000 UTC up to 1800 UTC. The model output consists of a variety of variables, but only a selected few are used for analysis in this study. One-month of simulation is used as a spin-up period in order to eliminate the direct effects of the initial conditions (Anthes *et al.*, 1989). The data from the spin-up period (November) is excluded from the analysis here.

5.3.4.1 The ECHAM4.5-RegCM3 system

Four out of the 24 ensemble members generated by the ECHAM4.5 GCM are used as the forcing fields for the RegCM3. Such ensemble members are generated in order to capture the uncertainties in both the GCM and RCM predictions (Misra and Yau, 2001; Palmer, 2002). The 4-month simulations are made over a 10-year period for the months of November, December, January and February. Initial and boundary conditions are derived by standard interpolation procedures from the ECHAM4.5 data grid to the RegCM3 grid. The USGS Global Land Cover Characterization and Global 30 Arc-Second elevation datasets are used to create the terrain files. The monthly optimum interpolation sea-surface temperatures (OISSTs) are used as surface boundary conditions (Reynolds and Smith, 1994). The four ensemble members generated by the ECHAM4.5-RegCM3 system will henceforth be referred to as simply ensemble members 1 to 4.

5.4 TROPICAL CYCLONE DETECTION ALGORITHM

The objective procedure for detecting model tropical cyclones used in this study has been adopted from Vitart *et al.* (1997). This procedure has been modified so that it can be applied to the RCM output. It is subsequently tested on the RegCM3 output for 1999-2000 season from the first ensemble member. This season is chosen based on the fact that it had a number of tropical cyclones such as tropical cyclone Eline that caused enormous devastation in a number of southern African countries including Mozambique, Limpopo Province of South Africa and Zimbabwe. The criteria defining this objective procedure are chosen and adjusted to give the most realistic output for these datasets. The criteria are not modified when applied to the remaining members and years of the ensemble.

5.4.1 The detection procedure

The tropical cyclone detection algorithm (Vitart *et al.*, 1997) first locates the position of the intense vortices with a warm core for each day as follows:

- A local maximum of vorticity larger than 2.0 X10^{-5} s^{-1} at 850 hPa is located.
- The closest local minimum sea-level pressure is defined as the center of the storm.
- The closest local maximum of average temperature between 500 and 200 hPa is located and is defined as the center of the warm core. The distance between the center of the warm core and the center of the cyclone must not exceed 2° latitude. From the center of the warm core the temperature must decrease by at least 0.5°C in all directions within a distance of 8° latitude.
- The closest local maximum thickness between 1000 and 200 hPa is located. The distance between this local maximum and the center of the cyclone must not exceed 2° latitude. From this local maximum the thickness must decrease by at least 50 m in all directions within a distance of 8° latitude.

5.5 RESULTS AND DISCUSSIONS

Now that all the simulations have been made, the next step is to analyse the data. In order to apply the tropical cyclone detection algorithm to the data, certain variables have to be extracted from this RCM data. The results of the detailed analysis carried out on the model output are discussed below.

5.5.1 Life cycle of the RegCM3 simulated TCLVs

Model tropical cyclones can have lifecycles and tracks that are similar to those that occur in the real world (Walsh and Watterson, 1997). In this section, examples are shown where the RegCM3 simulated TCLVs that exhibit such characteristics.

(a) First simulated TCLV

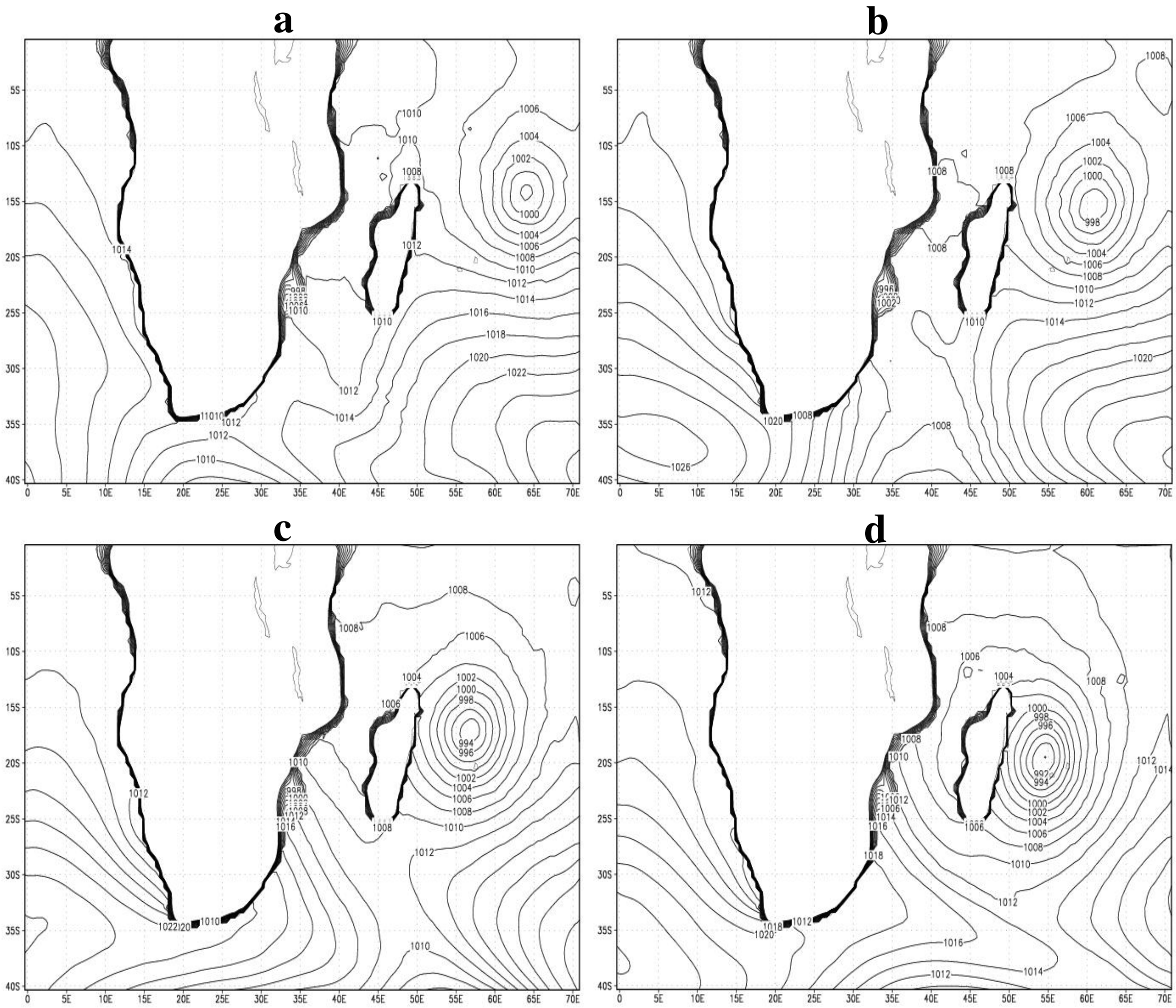


Figure 5.2: Simulated mean sea-level pressure of a tropical cyclone-like vortex in the SWIO, for (a) day 67 of simulation, (b) day 68, (c) day 69, (d) day 70, (e) day 71, (f) day 72, (g) day 73, (h) day 74 , (i) day 75 and (j) day 76.

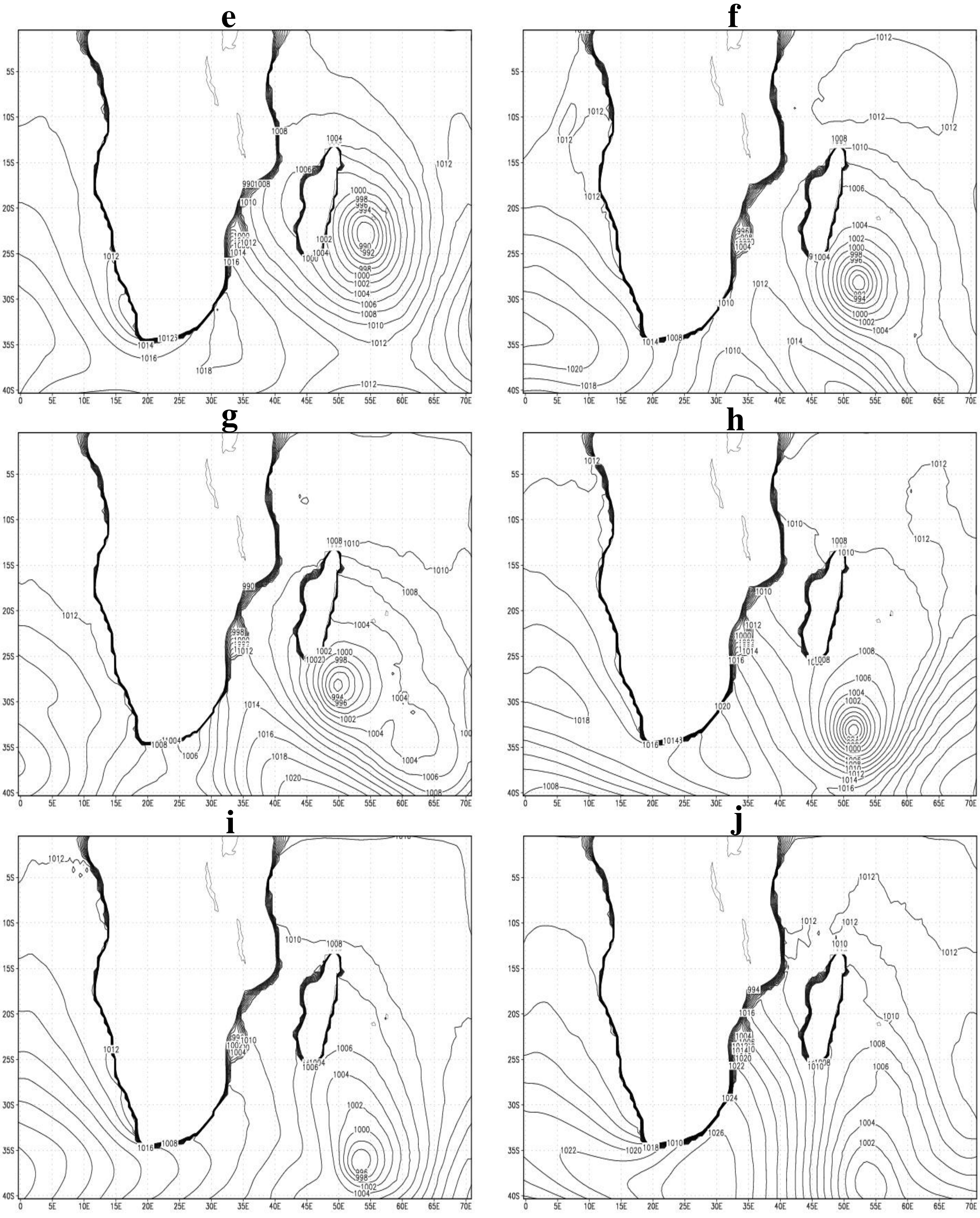


Figure 5.2 :(*Continued*)

Numerous studies have attempted to determine the relationship between the central pressure and the maximum sustained winds in tropical cyclones (e.g. Takahashi, 1939; Takahashi, 1952; Holliday, 1969). A number of such studies have been reviewed for the WNP (Atkinson and Holliday, 1977). The maximum sustained surface wind in tropical cyclones depends on the radius of maximum wind and the local maximum pressure gradient (Atkinson and Holliday, 1977). For a while the JTWC forecasts used as a rule of thumb that tropical depressions with central pressures near 1000 hPa normally have maximum winds around 30 knots and the systems usually develop tropical storm force winds as the pressures drop a few millibars below 1000 hPa (Atkinson and Holliday, 1977). It has been found that the 1000 hPa corresponds to winds of 30 knots and 997 hPa to winds of 34 knots (minimum tropical storm intensity) (Atkinson and Holliday, 1977). Here, as in Walsh and Watterson (1997), a TCLV in the SWIO is defined as one with a central mean sea level pressure less than 997 hPa. The figures are shown at 0600 UTC for successive days.

Figure 5.2 depicts a series of plots that details the life cycle of a TCLV as represented by one of the members of the ensemble. This approach was adopted from the study done by Walsh and Watterson (1997). The RegCM3 simulated a low-pressure system located northeast of Madagascar that seems to have migrated from east of the eastern boundary of the study area two days prior to the TCLV formation (Figure 5.2 (a) and (b)). On day 68, this system moved southwestwards towards the east coast of Madagascar. Figure 5.2 (c) shows the system after attaining the TCLV status located northeast of Madagascar (on day 69 of the four-month simulation). The TCLV moved southwestwards from its previous position, just approaching the east coast of Madagascar (on day 70). On the following day (day 71), the TCLV turned southwards.

On day 72, the TCLV continued with its southward motion. It continued tracking southwards until the 74th day of the four-month simulation. It then slightly turned southeastwards on day 75. The system lost its TCLV status on day 76. The TCLV analyzed here exhibited a typical behaviour of the tropical cyclones over the SWIO that develop east of Madagascar. It has been pointed out in the previous studies that most tropical cyclones in the SWIO tend to recurve southeastwards after approaching, or making landfall on, the east coast of Madagascar (e.g. Reason and Keibel, 2004).

(b) Second simulated TCLV

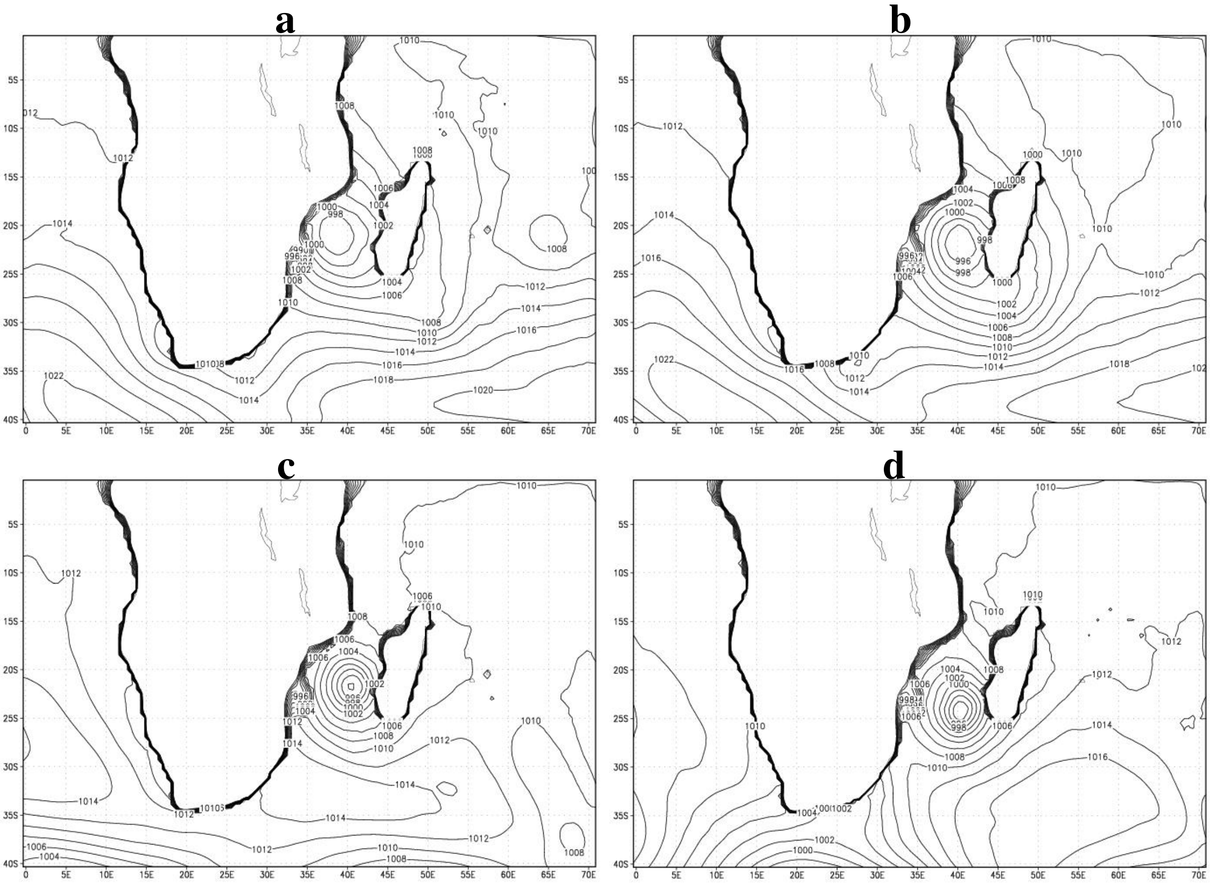


Figure 5.3: Simulated mean sea-level pressure of a tropical cyclone-like vortex in the SWIO, for (a) day 97 of simulation, (b) day 98, (c) day 99, (d) day 100, (e) day 101, (f) day 102, and (g) day 103.

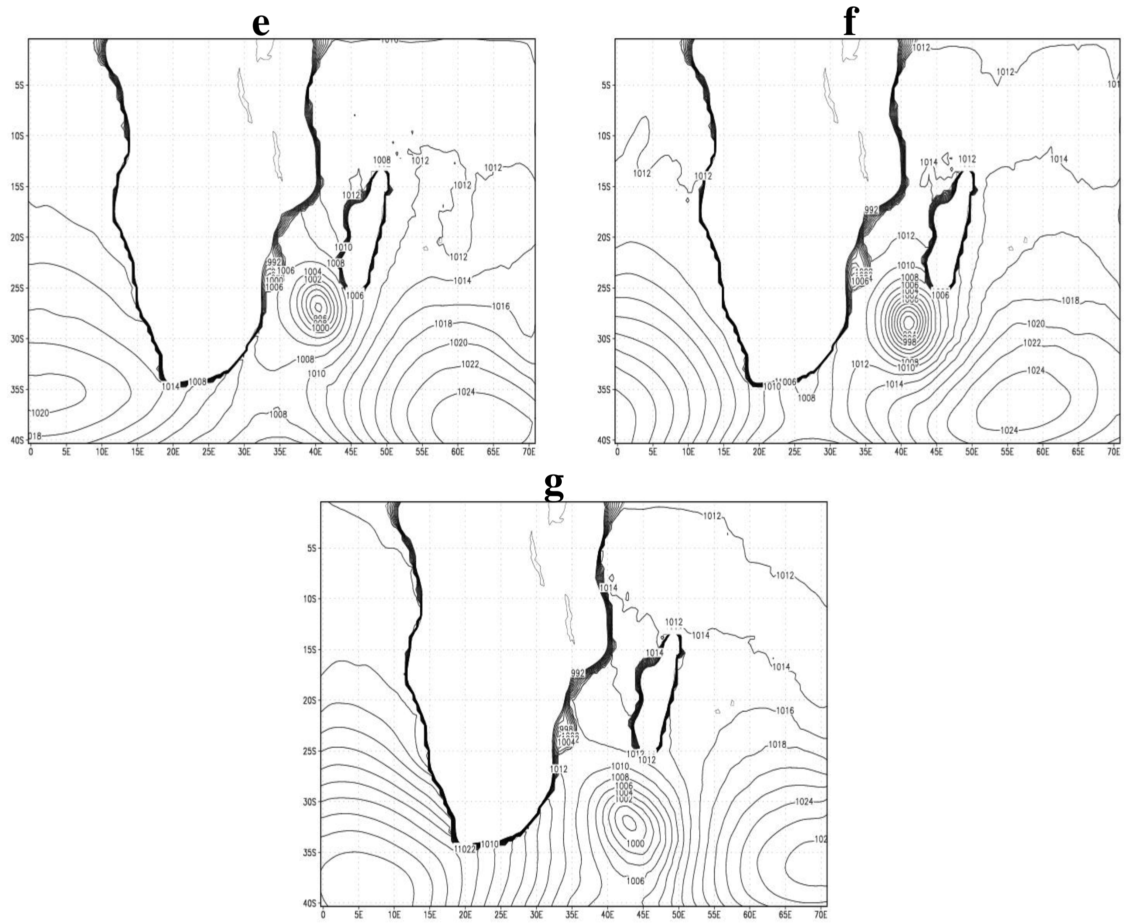


Figure 5.3 :(*Continued*)

Figure 5.3 depicts a series of plots that details the life cycle of a TCLV as represented by one of the members of the ensemble. On day 97 of the four-month simulation, RegCM3 simulated a low-pressure system with a closed circulation located in the Mozambique Channel west of Madagascar. On day 98, the system attained TCLV status and had just moved slightly south from its initial position. The TCLV continued moving southwards on day 99. It continued moving southwards until it lost its TCLV status on day 103 of the four-month simulation. The tropical cyclone-like vortex analyzed here also displayed characteristics consistent with the findings of the previous studies. Several observational studies have indicated that the small number of systems generated in the Mozambique Channel tend to move southwards out of the Channel and then eastwards out over the subtropical SWIO (e.g. Klinman and Reason, 2008). It has also been pointed out that over the last 50 years or so, only about 5% of the tropical cyclones generated in the SWIO have actually made landfall on Mozambique or elsewhere in the southern African mainland (e.g. Reason and Keibel, 2004). These figures demonstrate that the RegCM3 can simulate TCLV movement that is similar to that of the real world tropical cyclones. It is evident from the above figures that the GCM-RCM system is able to simulate TCLVs developing both in the Mozambique Channel as well as those developing or migrating from the east of Madagascar.

5.5.2 RegCM3 simulation of environmental variables required for tropical cyclone formation

In this section, two of the most critical environmental factors for cyclogenesis simulated by the RegCM3 will be compared to the NCEP reanalysis to investigate the model's ability to simulate the factors needed for tropical cyclone formation. Such factors are vertical wind shear and low-level cyclonic vorticity (Vitart *et al.*, 1999; Vitart and Stockdale, 2001; Walsh and Syktus, 2003). It is well known that high values of vertical wind shear impede the formation of tropical cyclones. Similarly, the low-level vorticity has a huge impact on the cyclogenesis. The formation of tropical cyclones requires strong relative vorticity. The NCEP reanalysis fields were first interpolated bilinearly to a 60 km grid for better comparison with the finer resolution model fields (Heymsfield *et al.*, 2000; Kuligowski and Barros, 2001).

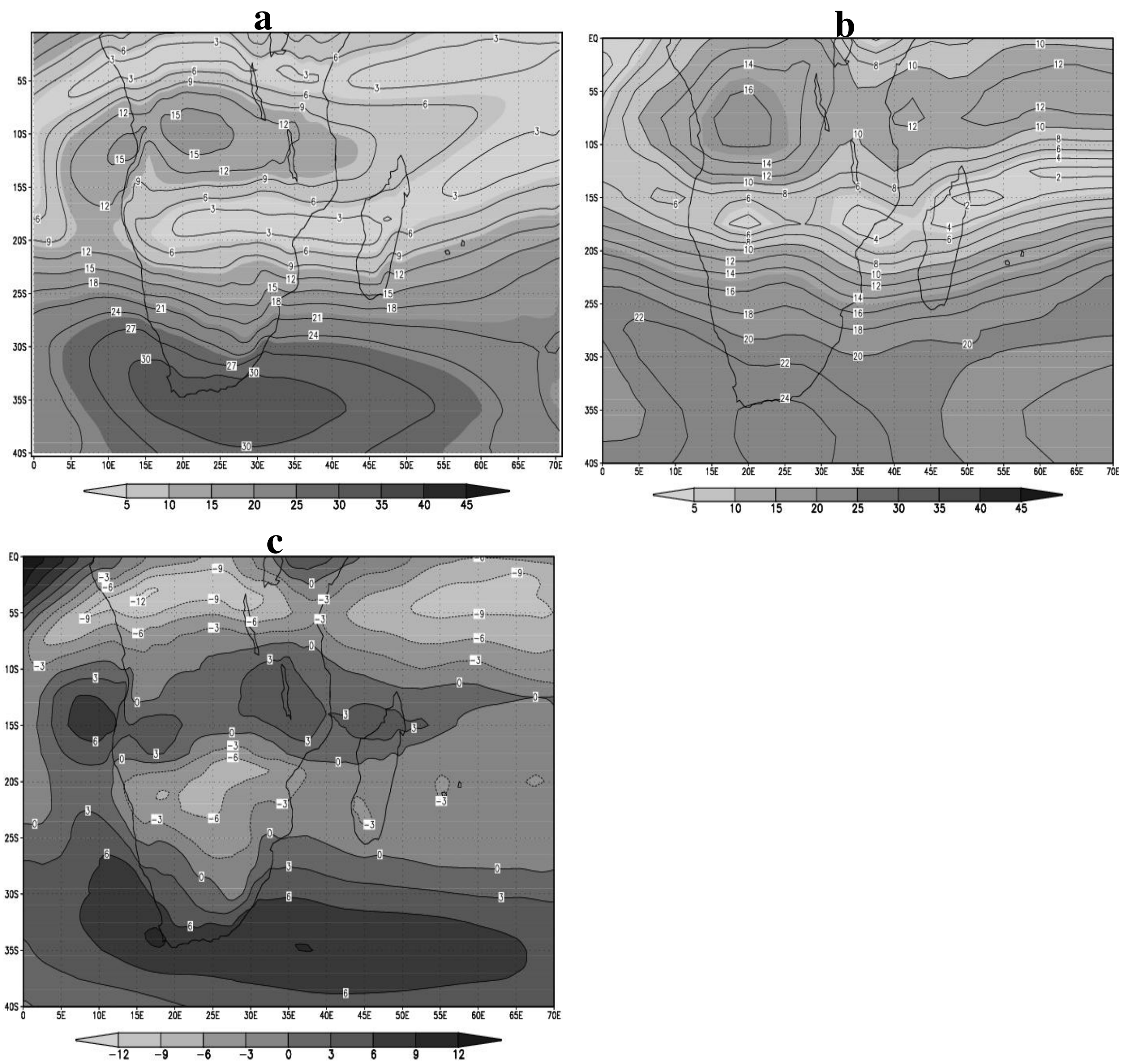


Figure 5.4: The vertical wind shear (ms^{-1}) between 200 and 850 hPa, (a) simulated by RegCM3, (b) in the NCEP reanalysis, and (c) the difference (a) minus (b). The vertical wind shear has been averaged over the period from December to February and from 1991/92 to 2000/01. The simulated vertical wind shear has also been averaged over all the four members of the ensemble.

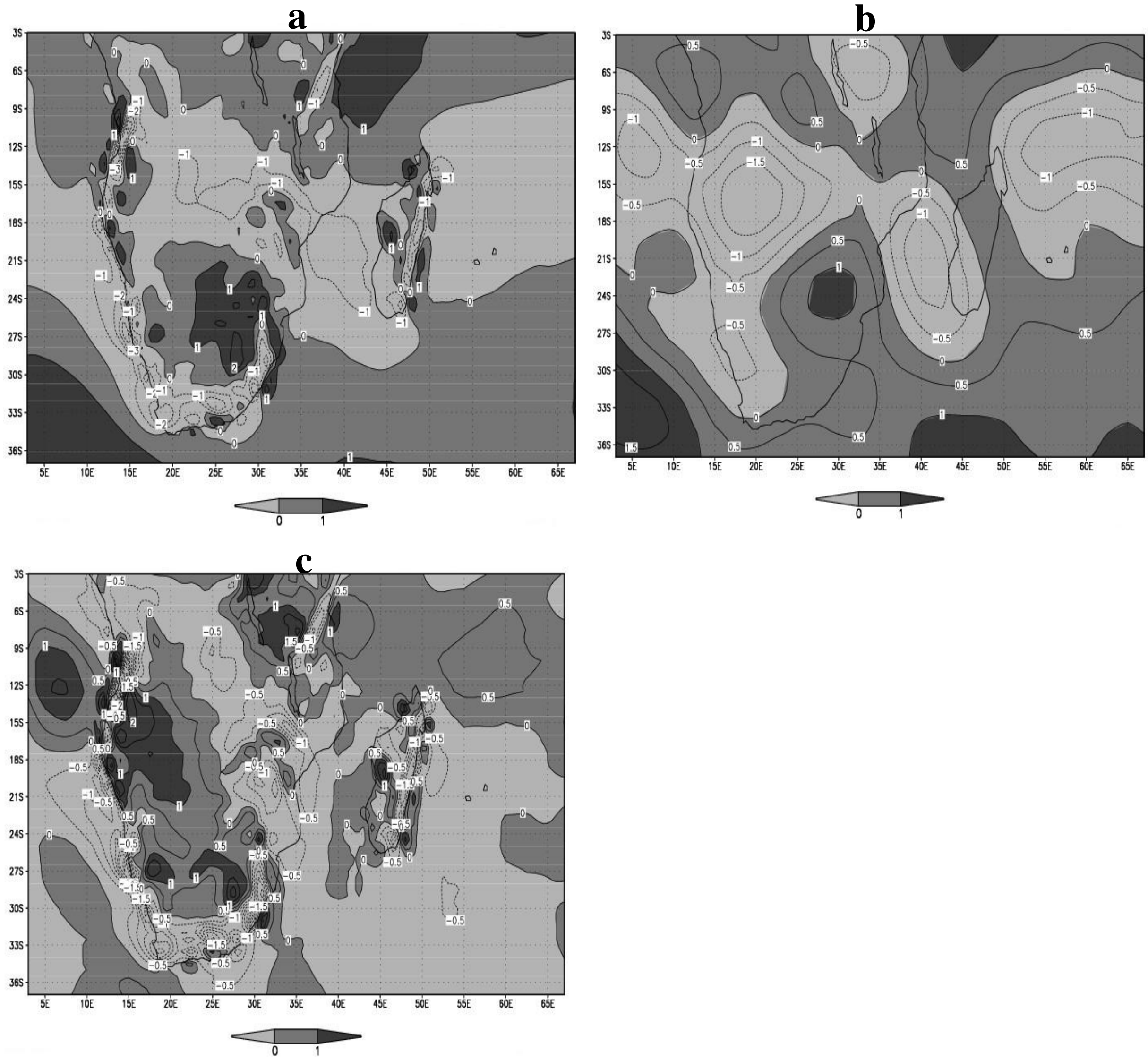


Figure 5.5: The 850 hPa relative vorticity ($\times10^{-5}s^{-1}$) (a) simulated by RegCM3, (b) in the NCEP reanalysis, and (c) the difference (a) minus (b). The relative vorticity has been averaged over the period from December to February and from 1991/92 to 2000/01. The simulated relative vorticity has also been averaged over all the four members of the ensemble.

Figure 5.4 shows the mean vertical wind shear of the ECHAM4.5-RegCM3 and the NCEP reanalysis as well as the difference between them. The vertical wind shear has been averaged over the period from December to February and from 1991/92 to 2000/01. The simulated vertical wind shear has also been averaged over all the four members of the ensemble. It is evident in the figure that the simulated vertical wind shear and the observations show a similar pattern in most parts of the model domain. However, there are some regions that show significant differences between the simulations and the observations as can be seen in Figure 5.4(c). The biggest difference is observed in regions further north of Madagascar. The RegCM3 simulated vertical wind shear values north of Madagascar are lower than those of the NCEP reanalysis. This means that the simulated conditions are more conducive to TCLV evolution than is the case in reality. Both the RegCM3 simulated and the observed vertical wind shear values in the latter region are higher than everywhere else over the SWIO. There is also reduced tropical cyclone activity in this area. This reduction is expected as high vertical wind shear hampers the development of tropical cyclones. In general, there is a good agreement between the simulated and the observed vertical wind shear values in the regions west and northeast of Madagascar, which are also the regions that experienced increased tropical cyclone activity.

Figure 5.5 shows the relative vorticity for DJF for ECHAM4.5-RegCM3 and NCEP reanalysis as well as the difference between them. The relative vorticity has been averaged over the DJF period and from 1991/92 to 2000/01. The simulated relative vorticity has also been averaged over all the four members of the ensemble. The RegCM3 simulated relative vorticity and the observed values largely have a similar pattern. This can clearly be seen in the Mozambique Channel and in the region east of Madagascar.

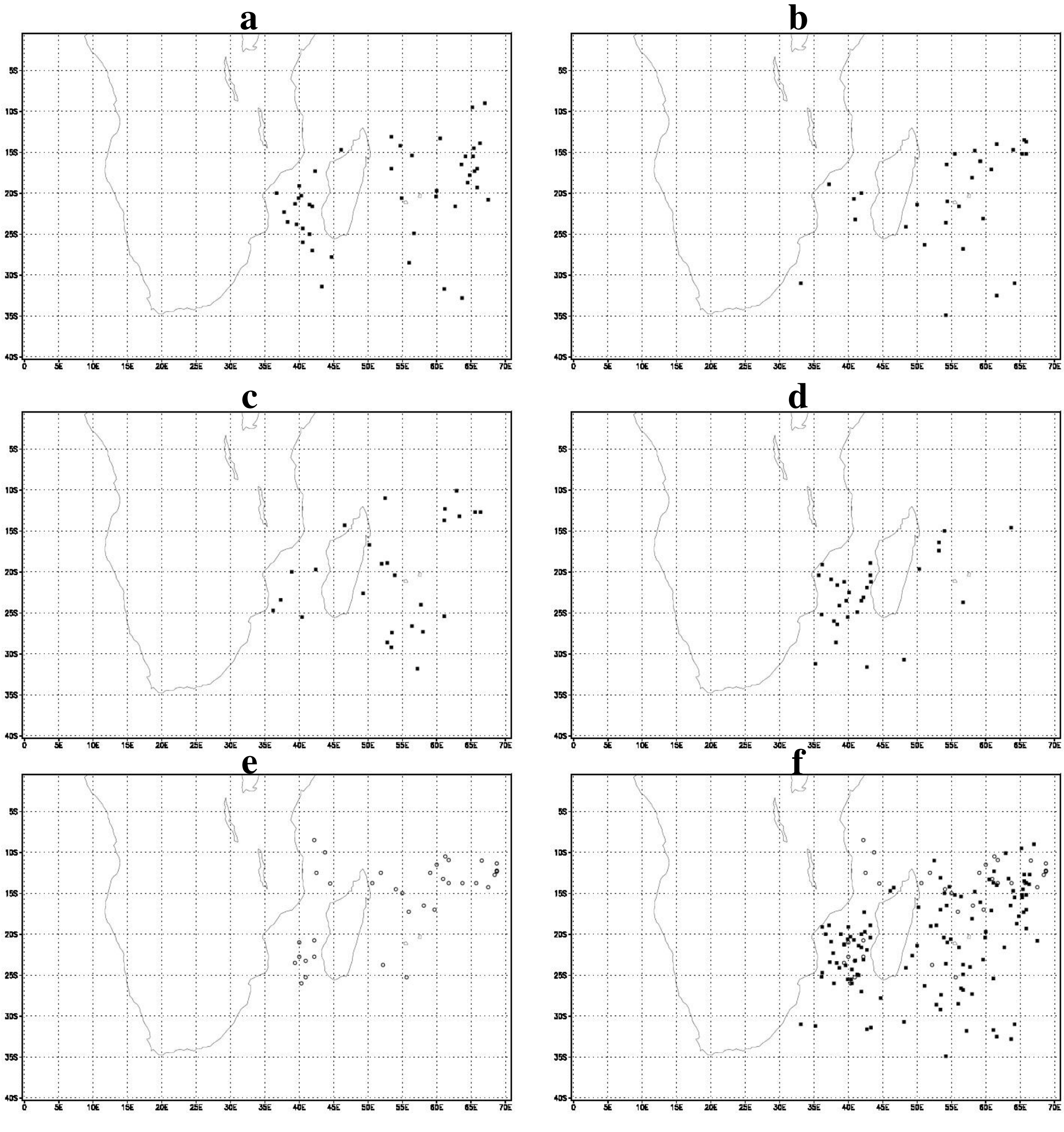
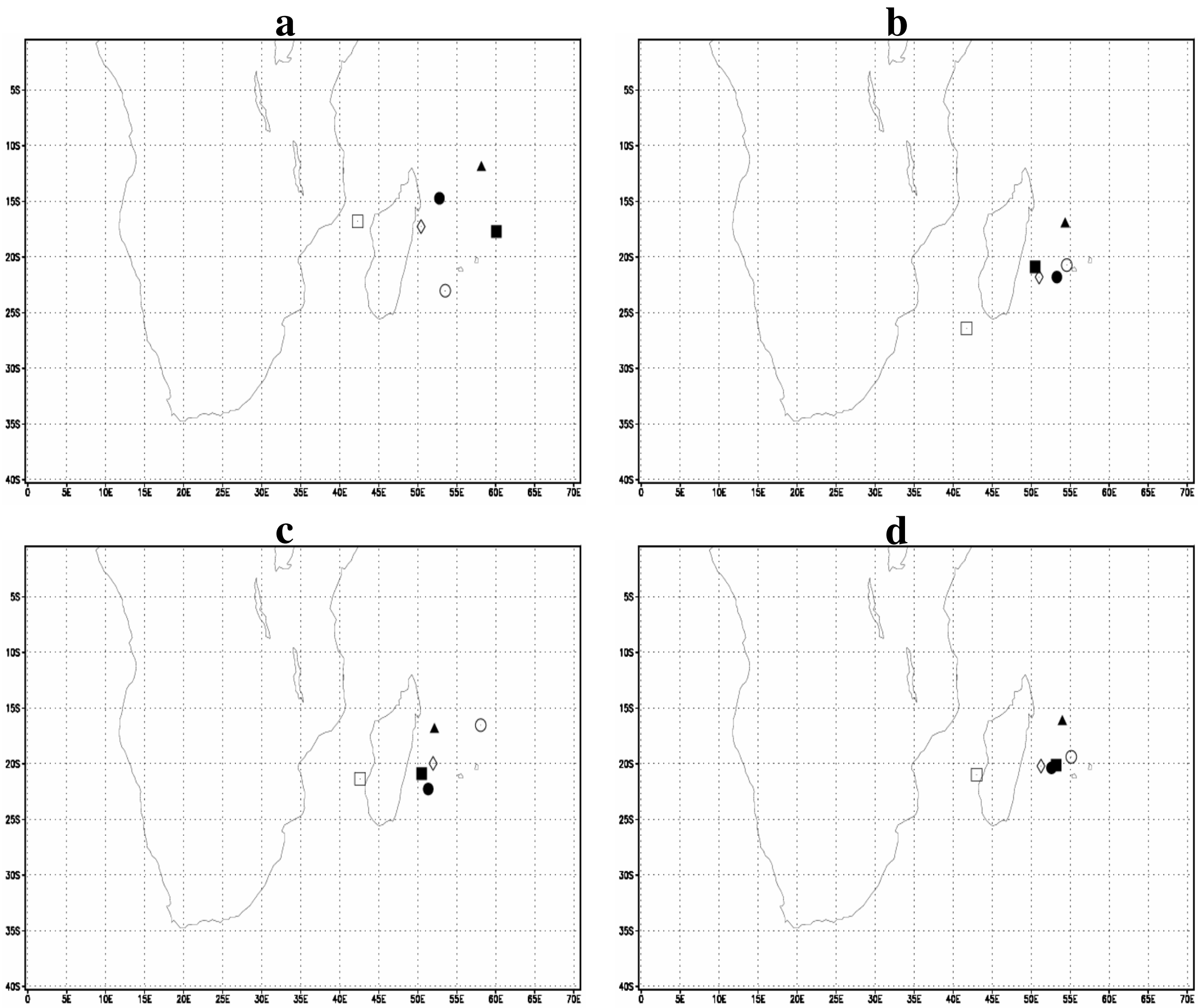


Figure 5.6: First positions of all the tropical cyclones generated by (a) Ensemble member 1, (b) Ensemble member 2, (c) Ensemble member 3, (d) Ensemble member 4, (e) in the observations, and (f) all ensemble members (dots) and the observations (circles) during the period 1991/92-2000/01. Each point represents the first appearance of at least one tropical cyclone.

Figures 5.6 (a), (b), (c) and (d) depict tropical cyclone genesis locations of all the tropical cyclones generated by all four ensemble members over the 10-year period of study. Figure 5.6 (e) presents the observed genesis locations of all the tropical cyclones that occurred over the domain of interest during the same period, while Figure 5.6 (f) displays a combination of model simulated (all ensemble members) and observed tropical cyclone genesis locations. There is an appreciable agreement between the simulated genesis locations and observed locations as can be seen in Figure 5.6(f). There is not much variation amongst all the ensemble members in terms of the tropical cyclone genesis locations either. The simulated geographical distribution of the first positions of the TCLVs occur in the same preferred regions as found in the observations, i.e. the majority of cyclone origins are found east of Madagascar while a smaller percentage of them are found in the Mozambique Channel (Vitart *et al.*, 2003; Reason, 2007). In fact, only one of the ensemble members had the channel as the preferred area of cyclogenesis.

As noted above, ECHAM4.5-RegCM3 system simulated lower vertical wind shear values between 0° and 10°S as compared to the reanalysis. This implies more conducive conditions to the formation of model tropical cyclones in that region. However, the effect of such conditions is only evident in the number of tropical cyclones generated by only one ensemble member. This ensemble member generated two tropical cyclones in this region as compared to only one in the observations, which is hardly a significant difference. The rest of the ensemble members did not generate any cyclone in the same region. It is worth noting that none of the ensemble members generated tropical cyclones within the 3° latitude from the equator which is again in good agreement with the observed (Vitart and Stockdale, 2001). It is also interesting to see that most of the model tropical cyclones genesis locations are over the main SWIO tropical cyclone development region of 10-25°S (Vitart *et al.*, 2003).



▲Observations ■ Ensemble member 1 ○Ensemble member 2●Ensemble member 3 □Ensemble member 4 ◊Ensemble mean

Figure 5.7: Mean genesis positions of all the tropical cyclones that occurred over the period 1991/92-2000/01 over the southwestern Indian Ocean for (a) December, (b) January, (c) February, and December-January-February (DJF). Each symbol represents each member of the ensemble, ensemble mean and observations.

Figure 5.7 depicts the mean genesis locations of all the tropical cyclones generated by all four ensemble members and in the observations for the period 1991/92-2000/01 over the domain of study (Vitart and Stockdale, 2001). The simulated tropical cyclones over the SWIO have genesis located in different directions relative to the observations. However, the model did manage to show correctly that the preferred development area is east of Madagascar, and at the same time has demonstrated that it can also produce vortices that originate in the channel, which has also been observed to have happened.

Figures 5.8 and 5.9 show the first positions of all tropical cyclones generated by all ensemble members and in observations expressed in terms of a frequency of cyclone genesis for each 4° latitude interval (Camargo *et al.*, 2005). The maximum number of tropical cyclones generated by different ensemble members occurs at different latitudes (Figure 5.8). The maximum number of tropical cyclones generated by two of the ensemble members occurs between 20° and 24°S. One ensemble member has two maximum values, one between 16° and 20°S and the other between 24° and 28°S. The maximum number of tropical cyclones generated by the remaining ensemble member occurs between 12° and 16°S. The maximum of the observations occurs between 12° and 16°S while the maximum of the ensemble mean occurs between 20° and 24°S. This means that the maximum of the model occurred south of the observed maximum. Tropical cyclones were neither observed nor simulated between 0° and 8°S. However, the model created tropical cyclones between 32° and 40°S, which are not observed in the real world. It is evident from Figure 5.9 that there is a southward bias in the tropical cyclone frequency simulated by the model. One ensemble member produced the maximum number of tropical cyclones at the same latitude band as observed.

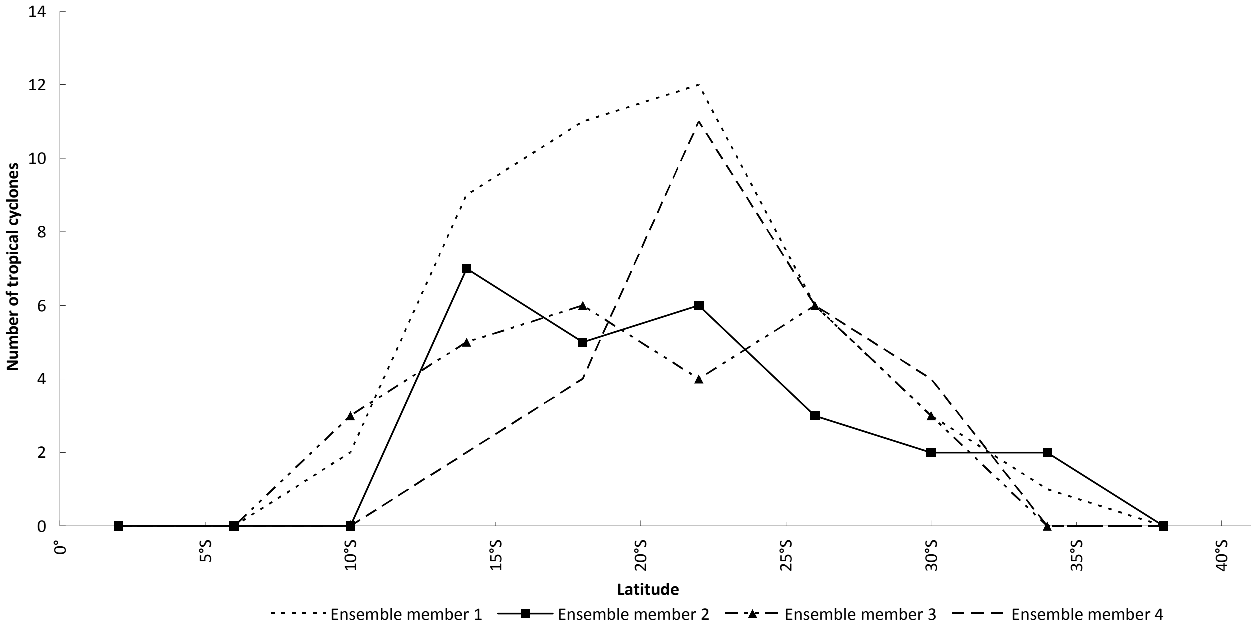


Figure 5.8: Number of tropical cyclones by genesis location per 4° of latitude (averaged over all longitudes) for all ensemble members for DJF over the period 1991/92-2000/01

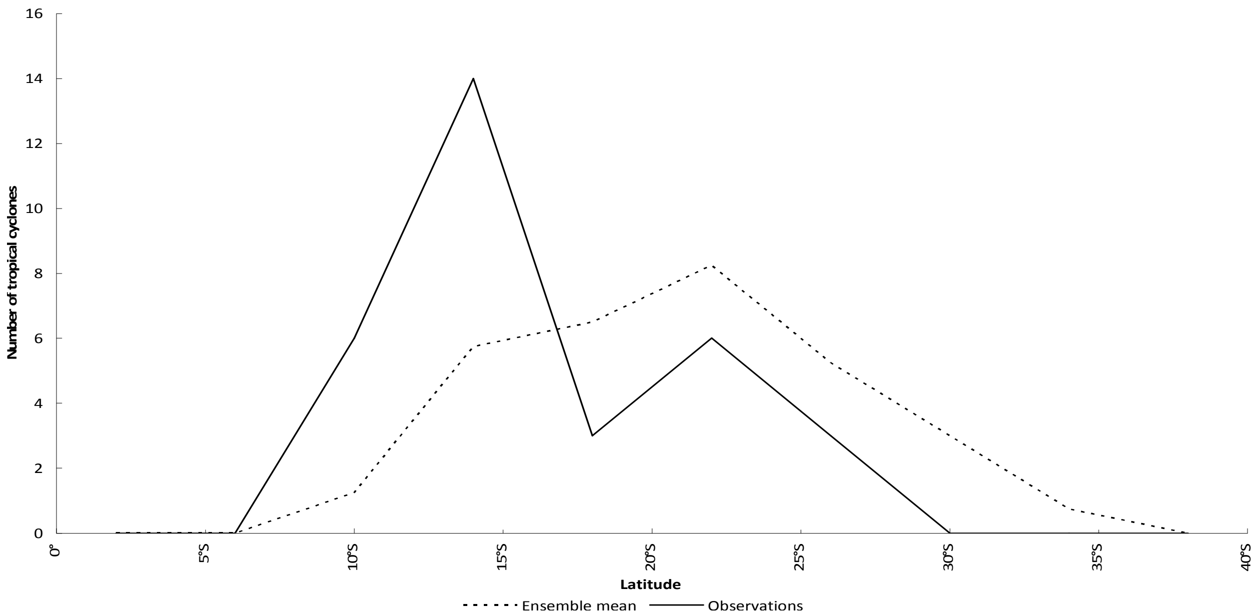


Figure 5.9: Ensemble mean number of tropical cyclones by genesis location per 4° of latitude (averaged over all longitudes) and observations for December-January-February over the period 1991/92-2000/01.

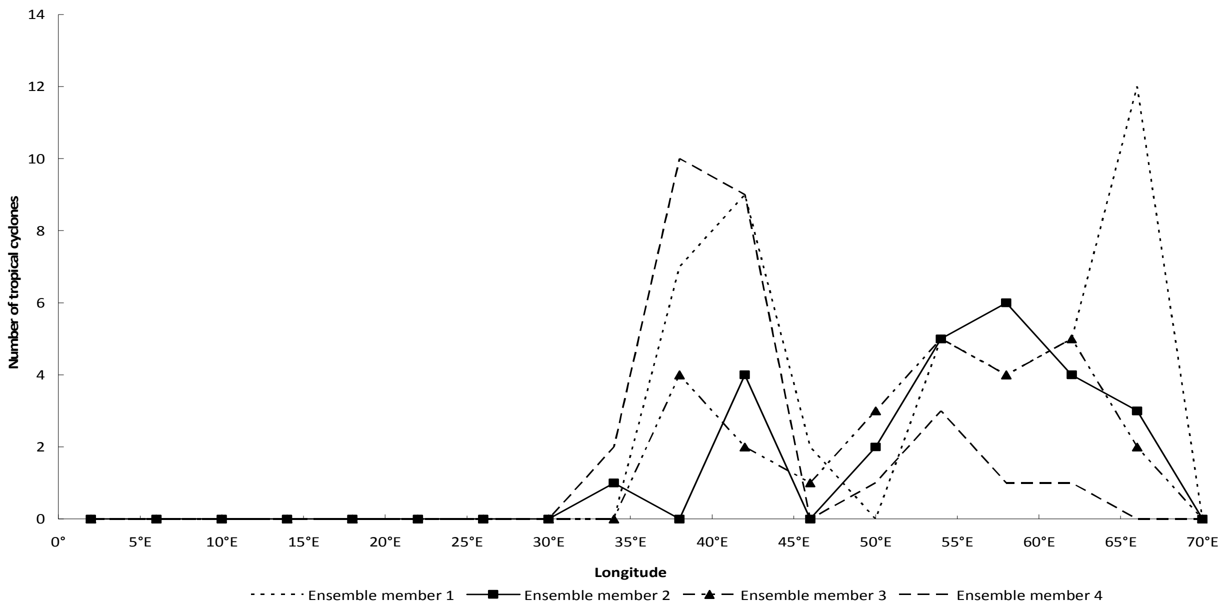


Figure 5.10: Number of tropical cyclones by genesis location per 4° longitude (averaged over all latitudes) for all ensemble members for December-January-February over the period 1991/92-2000/01.

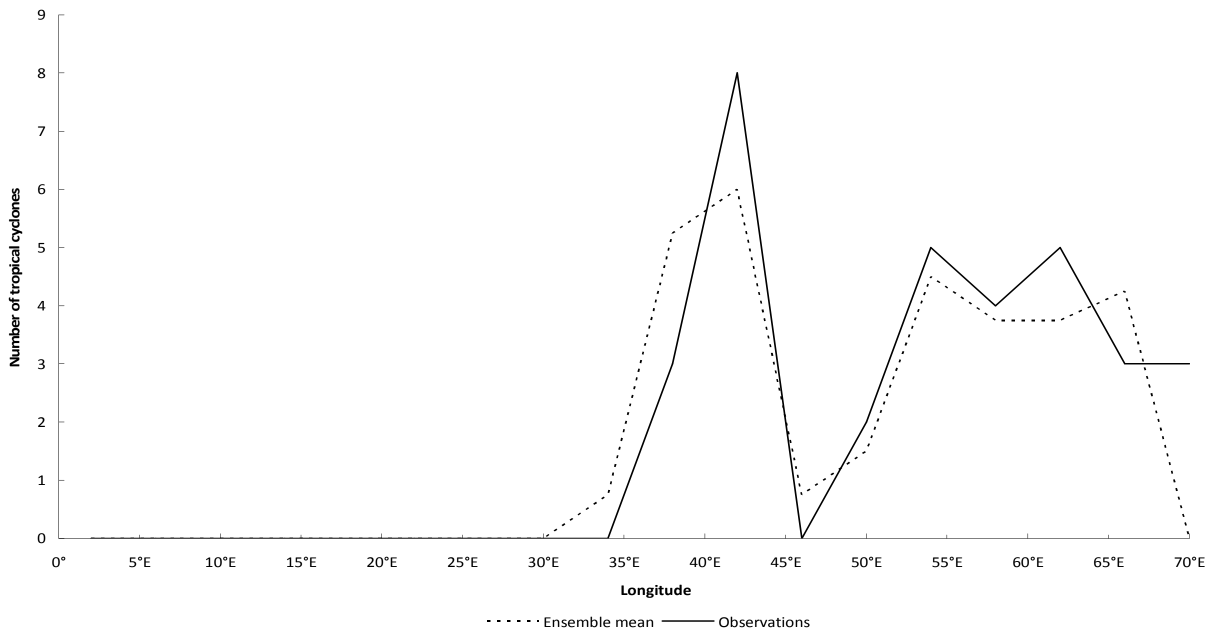


Figure 5.11: Ensemble mean number of tropical cyclones by genesis location per 4° longitude (averaged over all latitudes) and observations for December-January-February over the period 1991/92-2000/01.

As observed above, the maximum number of TCLVs of the ensemble members occurs at different longitude bands (Figure 5.10). The maximum of one ensemble member occurs between 64° and 68°E. As was observed with the latitude bands above, one ensemble member has two maximum values, one between 52° and 56°E, and the other between 60° and 64°E. The remaining two ensemble members have maximum number of TCLVs between 56° and 60°E, and between 36° and 40°E, respectively. The maximum values of the ensemble mean and the observations occur at the same longitude band (between 40° and 44°E) (Figure 5.11). This suggests that the model has skill in simulating the genesis locations of tropical cyclones over the area of study.

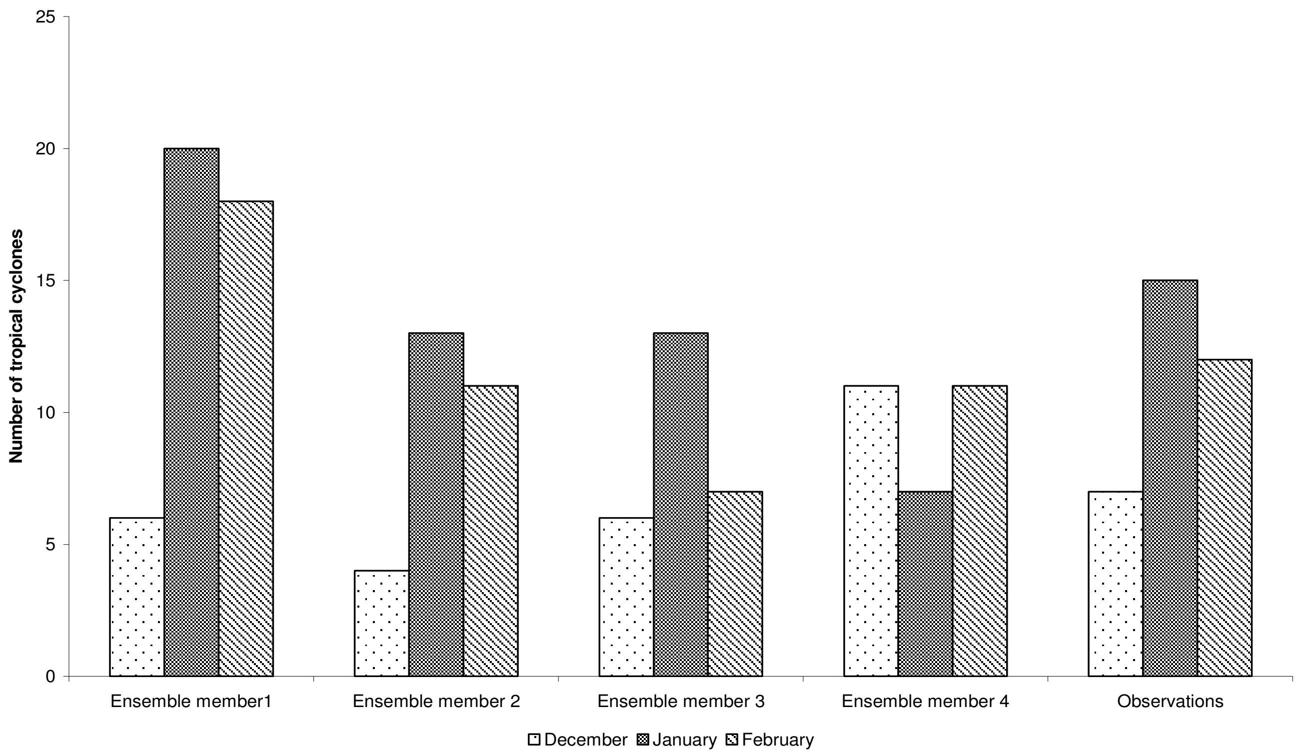


Figure 5.12: December-January-February tropical cyclone frequency over the SWIO in observations and four ensemble members generated by RegCM3 for the period 1991/92-2000/01.

Except for one ensemble member, all ensemble members underestimated the number of tropical cyclones in the month of December (Figure 5.12). Only one ensemble member overestimated the number of tropical cyclones in the January month. The same scenario occurred in February as well. All but one ensemble member, display a realistic peak season in the SWIO (December-January-February), with January being the most active month and December being the least active month in terms of the number of tropical cyclones.

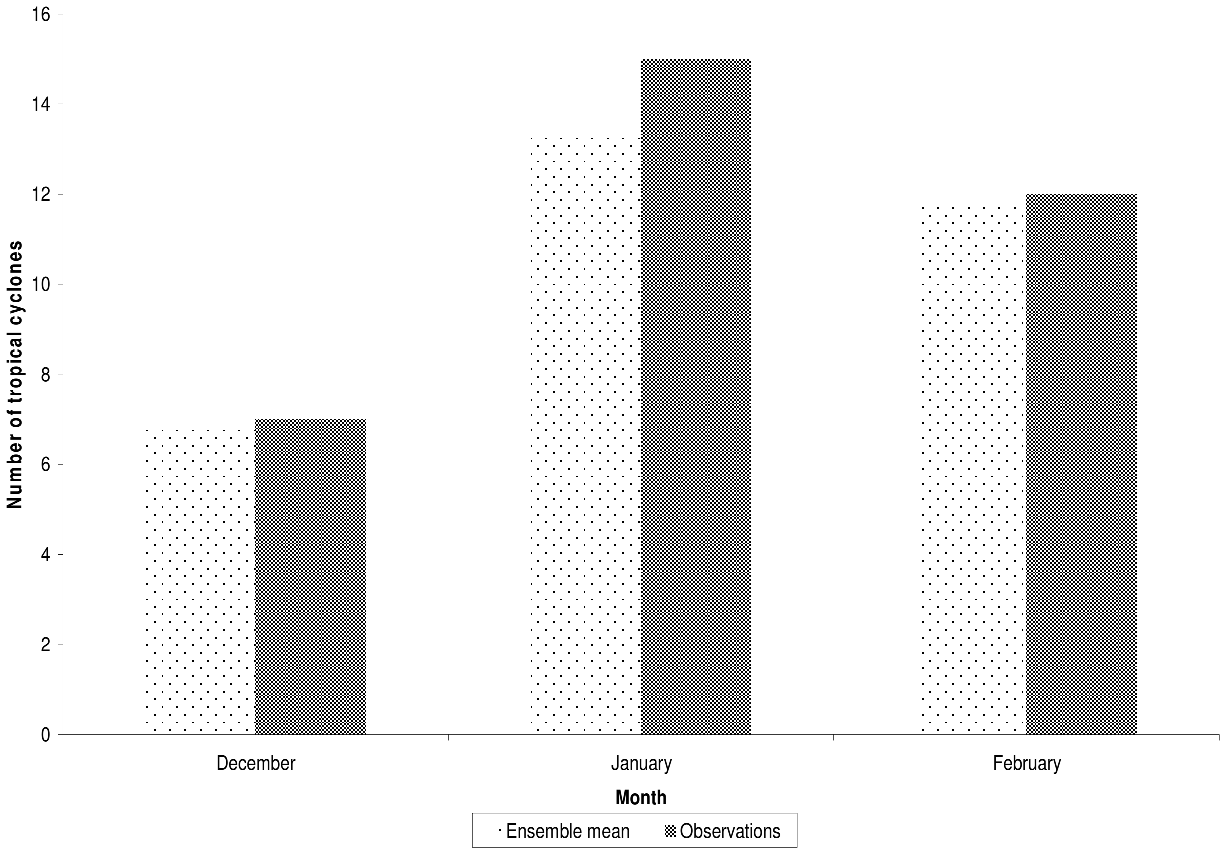


Figure 5.13: Ensemble mean number of tropical cyclones and observed number of tropical cyclones as a function of month.

Figure 5.13 shows the average number of model and total number of observed tropical cyclones for the three months of December, January and February over the 10-year period of the study. Although the model generally underestimated the number of tropical cyclones, it managed to reproduce that January is the peak month of tropical cyclone season in the SWIO and that December is the least active month in terms of cyclone activity. This is consistent with the observations, and therefore evidence that the model simulated the monthly numbers of tropical cyclones skillfully.

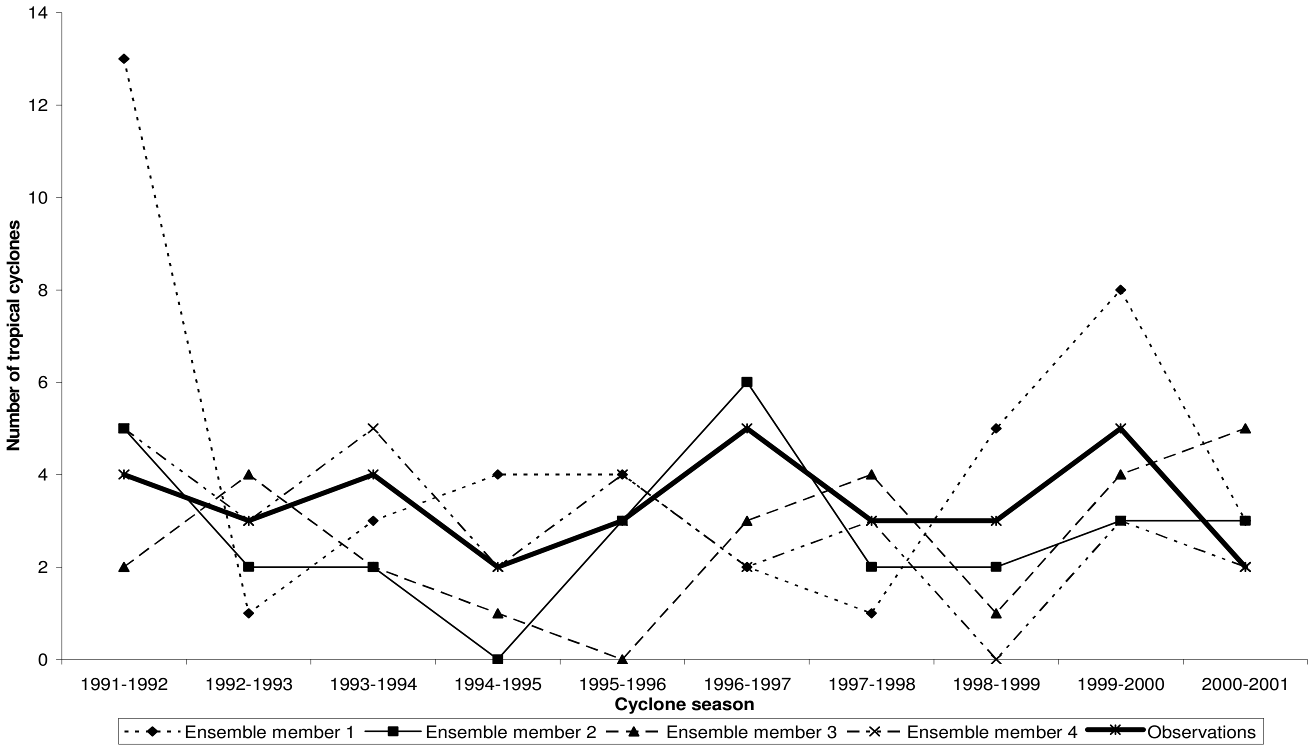


Figure 5.14: Interannual variability of tropical cyclone frequency in the southwestern Indian Ocean for the period 1991/92-2000/01.

The interannual variability of the number of tropical cyclones generated by all four ensemble members and the observations is shown as time series in Figure 5.14. Each ensemble member displays a distinct interannual variability in the number of TCLVs. In addition, such variability differs somewhat from the observed interannual variability in tropical cyclone frequency. However, there are certain cyclone seasons where some ensemble members managed to reproduce the observed number of tropical cyclones. For instance, for the 1992-1993 season, one ensemble member produced exactly the same number of tropical cyclones as observed. There are also some seasons in which some ensemble members generated unrealistic numbers of tropical cyclones. One such season is the 1991-1992 where one ensemble member produced 13 tropical cyclones while only 4 were observed. There are also some seasons in which the objective detection procedure did not detect any tropical cyclone-like vortex even though a considerable number of such systems were observed. This is the case with two of the ensemble members in the 1994-1995 and 1995-1996 cyclone seasons, respectively.

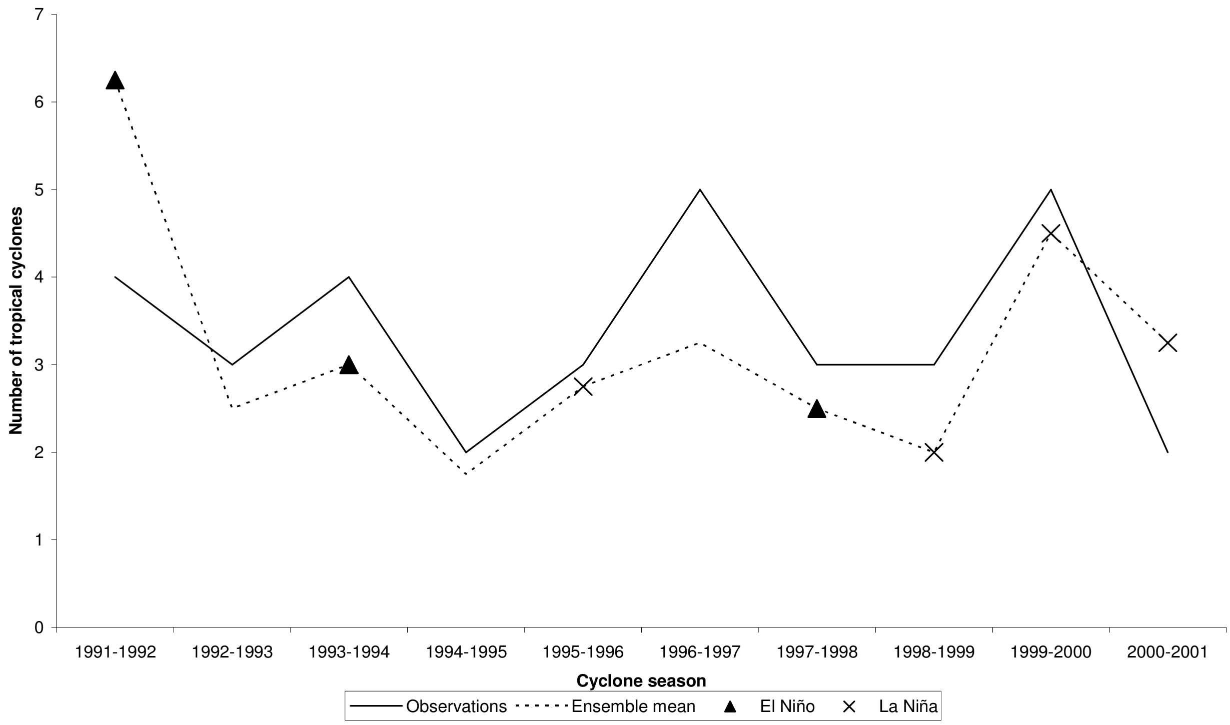


Figure 5.15: Interannual variability of tropical cyclone frequency in the southwestern Indian Ocean for the period 1991/92-2000/01. The dashed line represents the mean of the four ensemble members, and the black line the observations.

Figure 5.15 shows the interannual variability of the observed tropical cyclone frequency and TCLV frequency of the ensemble mean over the SWIO for the period 1991/92-2000/01. The number of tropical cyclones generated by the model over the period December-January-February (1991/92-2000/01) was counted for each ensemble member. It is important to note that the definition of tropical cyclones used here also includes tropical storms. It can be seen in the figure that there is generally a good agreement in the interannual variability between the model tropical cyclones and those observed in the real world. In most cyclone seasons, where the observations display a small number of tropical cyclones, the model also simulated a small number of tropical cyclones. This is true in almost all the seasons. The same goes for the seasons in which the observations display a large number of tropical cyclones. The major difference is in the actual numbers of the simulated and observed tropical cyclones. For most cyclone seasons, the ensemble mean numbers are less than the observations. This is true for all the cyclone seasons except for two seasons of 1991-1992 and 2000-2001. This underestimation of the number of tropical cyclones could be attributed to the fact that such a small ensemble was used.

The impact of ENSO on the interannual variability of tropical cyclones over the SWIO is not clear (see Figure 5.15). As mentioned in Chapter 4, the interannual frequency of tropical cyclones over the South Indian Ocean has been found to be poorly correlated with ENSO (Vitart *et al.*, 2003). The latter study found that ENSO has dual impact on South Indian Ocean tropical cyclone frequency. El Niño conditions are favourable for a considerable increase of vertical wind shear over the South Indian Ocean and to warmer SSTs over the SI. It is well known that increased vertical wind shear hampers the formation of tropical cyclones while increased SSTs promote the formation of such systems.

5.6 MODEL VALIDATION

A statistical assessment of the correspondence between model simulations and observations is carried out here. Although a 10-year period (1991/92-2000/01) may not be long enough to give a complete picture of the skill or performance of the model, it can still give a general idea of the capability of the RCM to reproduce the observed tropical cyclone properties. The statistical technique employed for this purpose is the Spearman rank correlation. Linear correlation is a measure of the strength of linear association between two variables. A correlation coefficient is a number between 1 and -1 which measures the degree to which two variables are linearly related. If there is no linear correlation, correlation coefficient is close to 0. A value near zero means that there is a random, nonlinear relationship between two variables. When there is a perfect linear relationship with positive slope between the two variables, a correlation coefficient equals 1. When there is a perfect linear relationship with negative slope between the two variables, a correlation coefficient equals -1.

The Spearman rank correlation was employed instead of the commonly used Pearson correlation, because the former accommodates non-normal data such as that used here. Spearman rank correlation can be used in a variety of situations. The Spearman correlation is a distribution-free test. A distribution-free test makes no assumption about the shape of the distribution from which the data are drawn. This Spearman rank correlation is defined mathematically below.

(1) Spearman rank correlation coefficient

$$r_s = 1 - \frac{6\sum D^2}{n^3 - n}$$

Where n is the number of values in each data set

D is the difference between the ranks of corresponding values of the two sets of data

r_s is the Spearman rank correlation coefficient

Table 1 shows the Spearman rank correlation coefficients obtained from the above mentioned process at the 90%, 95% and 99% level of confidence. To determine if the Spearman rank correlation is statistically significant, Monte Carlo tests were performed (Livezey and Chen, 1983; Wilks, 2006). This was done by re-randomizing the time series of tropical cyclone occurrences, and then calculating the Spearman correlation of the re-randomized time series. This step is repeated 1000 times. The resulting correlations are then simply sorted, resulting in a one-tailed test since there is only interest in the positive correlations between the two time series. The 950th sorted correlation value is the level of the 95% level of confidence. In this case the correlation between the observed and simulated (ensemble mean) interannual variability has been found to be 0.5636, significant at the 95% confidence level. This suggests that the RCM has some skill in simulating realistic tropical cyclone frequency over the SWIO.

Table 1: Spearman rank correlation between observed and ensemble average number of tropical cyclones during the period 1991/92-2000/01 from a Monte Carlo analysis significant at 90%, 95% and 99% confidence level.

Confidence level (%)	Correlation
90	0.44
95	0.55
99	0.73

5.7 SUMMARY

The RegCM3 RCM was nested within the ECHAM4.5 AGCM simulations over a 10-year period. A four-member ensemble of four-month integrations is produced with the ECHAM4.5-RegCM3 system. The ability of this system to realistically simulate the tropical cyclone activity depends on its ability to simulate the climate over the area of interest. In order to evaluate the skill of the latter system in simulating the environmental variables that are believed to influence the formation of tropical cyclones two of the most important variables simulated by the aforementioned system are compared with the NCEP reanalysis fields. The variables considered for this evaluation are the 850 hPa relative vorticity and the vertical wind shear between the 200 hPa and 850 hPa levels. The comparison shows a good agreement between the observations and simulations for both variables. It was also found that model tropical cyclones can exhibit characteristics similar to those observed in real world (Walsh and Watterson, 1997). This study found an appreciable agreement between the simulated and observed genesis locations of tropical cyclones. TCLVs captured by the ensemble members are also concentrated in the same regions as in the observations.

The mean genesis locations of tropical cyclones produced by all four ensemble members are located in different directions relative to the observed. However, the model did manage to show correctly that the preferred development area is east of Madagascar, and at the same time has demonstrated that it can also produce vortices that originate in the channel, which has also been observed to have happened. All but one ensemble member, display a realistic distribution of the number of tropical cyclones within the peak season in the SWIO (DJF), with January being the most active month and December being the least active month. It has also been found that there is generally a good agreement in the interannual variability between the model tropical cyclones and those observed in the real world.

Finally, the chapter has been concluded with the statistical assessment of the correspondence between model simulations and observations. A Spearman rank correlation coefficient of 0.5636 was obtained between interannual variability of tropical cyclone frequency simulated by the model (ensemble mean) and the observed, significant at the 95% confidence level.

Chapter 6

CONCLUSIONS

Despite considerable advances in seasonal tropical cyclone activity forecasting, more research still needs to be conducted to enhance our understanding of the predictability of such systems. Both statistical and dynamical techniques have emerged in the literature in an attempt to predict such systems on a variety of time scales, including the seasonal time scale. The merits and demerits of both these techniques have been discussed at length in the literature.

The main objective of this dissertation was to investigate the predictability of tropical cyclone activity over the SWIO on a seasonal time scale. To achieve this objective, secondary objectives were set. Firstly, because tropical cyclone-like features are detected in model simulations through the use of an objective procedure, it was decided to develop such a procedure capable of detecting tropical cyclones in the RCM simulations. Similar procedures have been utilized and shown to work well by numerous authors. Secondly, the interannual variability in the frequency of tropical cyclones generated by a RCM over the SWIO had to be investigated, and subsequently compared to the observed variability. Finally, the genesis locations of tropical cyclones generated by the RCM over the SWIO had to be investigated, in order to examine whether they occur in the same locations as in the real world. The objectives have been met, and the findings from this study are summarized below.

(1) Detection algorithm

An objective procedure for detecting model tropical cyclones was developed. This was accomplished by modifying the detection algorithm previously applied to the AGCM output by Vitart *et al.* (1997). Since the original algorithm was developed to be applied to the simulations of a global model, alterations had to be made so that it could be applied to simulations of a RCM. The modified algorithm was initially applied to the RCM output of one of the most tropical cyclone active season over the SWIO, namely the 1999-2000 cyclone season. It was modified until the detected number of TCLVs was found to compare reasonably well with the observed number of tropical cyclones for that season. The algorithm was subsequently applied to the rest of the RCM output over a 10-year period without any further modifications being made to the algorithm. The algorithm has been found to give realistic output.

(2) Tropical cyclone interannual variability

After applying the detection algorithm to all the RCM output, the number of detected tropical cyclone-like features was counted for each cyclone season and for each ensemble member from the 1991-1992 season to 2000-2001 season. A time series plot showing the year-to-year variability in the number of tropical cyclones generated by the model as well as the observed ones was produced. The results show an appreciable agreement between the simulations and observations.

(3) Tropical cyclone genesis location

It is crucial to investigate whether or not the genesis of TCLVs occurs in the same locations as in the real world. To accomplish this, the genesis locations of all the TCLVs were plotted and compared with the observed genesis locations. The mean genesis locations of model tropical cyclones are only somewhat removed from the observed location. Moreover, the model did manage to show correctly that the preferred development area is east of Madagascar, and at the same time has demonstrated that it can also produce vortices that originate in the Mozambique Channel, which has also been observed to have happened.

The 10-year period (1991/92-2000/01) used in this study is not long enough to give a complete picture of the skill or performance of the model, but it should be able to give a general idea of the capability of the RCM to reproduce the observed tropical cyclone properties. This study presented evidence that the GCM-RCM system was able to reproduce a number of important features of tropical cyclones. This finding has paved the way for developing operational dynamical systems that can predict tropical cyclone activity on a seasonal time scale over the southwestern Indian Ocean.

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