Tropical systems from the Southwest Indian Ocean into southern Africa: Impacts, variability and projected changes

By

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Tropical systems from the Southwest Indian Ocean into southern Africa: Impacts, variability and projected changes

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Abstract

The study considers the influence of tropical systems (cyclones, storms, depressions) from the Southwest Indian Ocean (SWIO) over the Limpopo River Basin and provides an outlook towards projected decadal scale variability and change throughout and towards the end of the 21st century. These systems have been linked to widespread heavy rainfall and subsequent flooding over the region. Due to the semi-arid nature of this area, variation and change in time of significant rain contributing synoptic systems are very relevant to the agricultural community.

Combining several historical datasets, it is shown that tropical systems from the SWIO contribute roughly 10% of the annual average rainfall as revealed by rainfall records of a number of stations located over the eastern parts of the Limpopo River Basin. The contribution to rainfall over the interior is further shown to be confined to the period January-March (JFM). These systems are however shown to be responsible for a significant proportion of widespread heavy rainfall events over parts of the Limpopo River Basin. Furthermore, a pronounced cycle in the influence of these systems over the region is identified and it is shown to vary with a cycle in the total seasonal rainfall known as the Dyer-Tyson cycle over southern Africa at a bi-decadal (18-20year) scale.
The association of this type of synoptic weather event (landfall of tropical system followed by movement into the Limpopo River Basin) with the Dyer-Tyson cycle is used to identify regional to Hemispheric circulation anomalies that explain the bi-decadal rainfall variation and also to increase understanding of variation in the influence of tropical systems from the SWIO over the region. At a hemispheric scale, the Southern Annular Mode (SAM) is shown to be significantly correlated with regional anomalies during JFM that are associated with tropical systems moving into the Limpopo River Basin and also above-normal seasonal rainfall. As the SAM is known to be sensitive to external forcing and there exist regional climatological associations over several parts of the Southern Hemisphere with it, it provides a potential avenue towards exploring external drivers of decadal scale variability.

An external driver of the bi-decadal (18-20-year) cycle in climate records has been postulated to be variation in lunar tidal forcing associated with the 18.6-year lunar nodal cycle. Therefore, the association of the SAM with tidal forcing is investigated and proposed to be a role player in the variation at the decadal time scale of tropical systems from the SWIO over the Limpopo River Basin and also of the Dyer-Tyson rainfall cycle. Based on an observed influence of tidal forcing on the SAM, an index is developed to estimate the seasonal JFM SAM based on tidal forcing during Austral summer. The predictability of the seasonal JFM SAM by the index is evaluated through multiple linear regression and a prediction is made for the period ending in 2050, noting the association between the SAM and tropical systems from the SWIO over the Limpopo River Basin.

Finally, towards understanding the projected changes by the end of the 21st century in the climatology of tropical systems over the SWIO and in particular influences over the Limpopo River Basin, simulations of an Atmospheric Global Circulation Model (AGCM) based on SST simulations by several Assessment Report 4 (AR4) Global Coupled Models (GCMs) are scrutinized. The findings are presented within the context of projected changes in regional circulation anomalies and atmospheric temperature and humidity profiles relevant to the tracks followed, development and intensification of tropical systems.
Declaration

I, Johan Malherbe, herewith declare that this thesis, which I submit for the degree PhD in Meteorology at the University of Pretoria, is my own work and has not previously been submitted for a degree at this or any other tertiary institution.

SIGNATURE: 
DATE: 2013-11-01

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I would like to thank God for giving me the time and space on Earth to observe the splendor and complexity of weather. I also thank my parents for being great role models and for supporting me in everything I’ve ever done. I also thank Prof. W.A. Landman and Dr F.A. Engelbrecht, my supervisor and co-supervisor, for direction and expert advice throughout this project. Furthermore I thank my friends for supporting me and understanding the demands of part-time studies. I would like to express my gratitude to the Agricultural Research Council for supporting further studies by researchers. Finally, the Water Research Commission is acknowledged for supporting a large part of the work of this thesis through project nr K5/1847.
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List of Abbreviations

AGCM  Atmospheric Global Circulation Model
AR4  Assessment Report 4
CCAM  Conformal Cubic Atmospheric Model
CGCM  Coupled Global Climate Model
CMIP  Coupled Model Intercomparison Project
CTCGP Convective Tropical Cyclone Genesis Parameter
ENSO El Niño Southern Oscillation
GCM  Global Coupled Model
IPCC  Intergovernmental Panel on Climate Change
MLD Maximum Lunar Declination
SAM  Southern Annular Mode
SOM  Self-Organizing Map
SST  Sea-Surface Temperature
SWIO Southwest Indian Ocean
TCLV Tropical Cyclone-Like Vortex
TCSGP Tropical Cyclone Seasonal Genesis Parameter
1. Introduction

Occasionally, tropical cyclones, storms or depressions (from here on referred to collectively as tropical systems) following an inland track contribute to widespread heavy rainfall over the Limpopo River Basin, southern Africa, and have in the past been associated with large flood events in the basin (Dunn 1985, Reason and Keibel 2004). Most of this region, located in the subtropical latitudes, is a semi-arid area with high temperatures during summer (Schulze 1965). The rural population in the region is primarily dependent on rain-fed agriculture and therefore vulnerable to the impacts of rainfall variability (Vogel and O’Brien 2003). The peak of the rainy season coincides with the maximum in the annual cycle of tropical systems such as tropical cyclones, depressions and weaker tropical systems (e.g. Karoly and Vincent 1998, Preston-Whyte and Tyson 1988, Crimp and Mason 1999), some of which invade the area from the Southwest Indian Ocean (SWIO).

The tracks followed by tropical systems from the SWIO have the potential to contribute strongly to climate variability over the Limpopo River Basin, as supported in rainfall records. Most often, once a tropical cyclone has entered into the Mozambique Channel, it moves towards the south and curves to the southeast back into the Indian Ocean (Mavume et al. 2009), having little influence on the interior of the Limpopo River Basin. When tropical cyclones remain over the Mozambique Channel or make landfall without significant inland penetration, conditions over southern Africa include a dominating high pressure region and dry conditions over the interior (Preston-Whyte and Tyson 2000, Klinman and Reason 2008). However, if a zonal track is followed into the Limpopo River Basin, widespread rain and flooding occur (e.g. Dunn 1985, Reason and Keibel 2004).

The impact in the region by and variability of tropical cyclones have indicated a need for research on tropical cyclones that affect southern Africa and a better understanding of the synoptic conditions during landfall which could aid in predictions of the risk of making landfall (Reason and Keibel 2004). A multi-year period with a relatively high number of occurrences of these systems over the Limpopo River Basin occurred from 1995 to 2000. Two similar periods have additionally been observed in the 1970’s and 1950’s. The existence of such multiyear periods of larger contributions by these systems further necessitates a need not only to understand the synoptic conditions during landfall, but also to investigate the possible influence of decadal-scale variability of large-scale circulation anomalies on the tracks of tropical systems influencing the region.
It has been suggested that large-scale conditions may aid in forecasting the likelihood of tropical cyclone landfall months in advance through the influence on both frequency and the tracks of such systems (Vitart et al. 2003). While the understanding of risk factors can aid in the forecast of tropical cyclone landfall at seasonal time scale (Vitart et al. 2003, Reason and Keibel 2004), investigating the variability of these systems at multi-year to decadal time scale has not been attempted yet. In other regions such as the Atlantic and Pacific oceans, large-scale circulation anomalies such as the Pacific-Decadal Oscillation and Atlantic Multidecadal Oscillation have been shown to cause decadal-scale variability in the tracks of tropical cyclones (Chu 2002, Liu and Chan 2008, Matsuura et al. 2003, Kubota and Chan 2009, Goldenberg et al. 2001). These findings suggest that decadal-scale variation, if it exists in the tracks of tropical systems in the SWIO and adjacent southern Africa, may then also be associated with variation in large-scale circulation anomalies at decadal time scale.

Predicting climate variability at decadal time scale is recognized as a potentially important contributor for water, agricultural, and land use planning (e.g., Mehta et al. 2013, Cane 2010). However prediction at this scale is very much an experimental activity, with factors such of verification topics of ongoing research (Goddard et al. 2013). While climate change is treated as a reality, extremes and variability is expected to have large impacts, underlining the importance of being able to resolve decadal variability (Goddard et al. 2012). Spatial scales of predictable climate signals increase for longer time scales, suggesting that the predictable spatial scales will be larger for decadal variability than for seasonal variability (Goddard et al. 2012). The need however exists for climate scientists to be able to predict regional scale climate variability such as variation of tropical cyclones over time scales of decades (Hurrell et al. 2010).

Results of the Coupled Model Intercomparison Project Version 5 (CMIP5) have emphasized the importance of external forcing for prediction at the interannual-to-decadal scale (Goddard et al. 2012). Research of external forcing mechanisms and climate system responses therefore should contribute towards the enhancement of Coupled Global Models that can become relevant at the decadal time scale. Variation in climate at decadal scale has statistically been linked to solar and lunar forcing (Currie 1984, Currie 1994, Cook et al. 1997). Research based on physical responses of the climate system to external forcing therefore also considers external forcing mechanisms such as solar variability and lunar cycles (e.g. Labitzke and van Loon 1995, White and Liu 2008, McKinnell and Crawford 2007, Yasuda 2009, Yndestad...
2006, Tanaka *et al.* 2012) as well as volcanism (Gu and Adler 2011, McGregor and Timmermann 2010).

Assessment Report Four (AR4) of the IPCC has emphasized the need to conduct studies to explore the potential impact of enhanced anthropogenic forcing on the attributes of tropical cyclones over the SWIO (Christensen *et al.* 2007). Over and above understanding the projected change towards the end of the century of the attributes of tropical cyclones in the region, appreciation of decadal scale variability can contribute towards prediction of periods of extremes within the projected change. Such a methodology may provide a link between forecasts at seasonal timescale and climate change projections. Predictable decadal scale variability can in sectors such as agriculture and hydrology enable the development of responses at practical time scales of decades towards longer-term responses. Understanding decadal scale variability in the region can further also help to explore the capacity of Earth System Models (Claussen *et al.* 2001, Flato 2011) to resolve climate variability, and provide a regional signal to which the models can be verified.

The approach followed in the current study is to explore the climate variability linked to a specific synoptic weather system type, in this case tropical systems over the SWIO tracking into the Limpopo River Basin. Since various types of weather systems contribute to the total seasonal rainfall over the subtropical regions, considering total rainfall only will include contributions from a range of weather system types, subsequently obscuring the relative contributions of the different types. Isolating variability of a certain synoptic weather type may further provide a physical association to large-scale circulation anomalies, supporting more easily the establishment of a link with decadal-scale variability and identification of potential external forcing mechanisms. Therefore, if an association can be made between tropical systems over the region and large-scale circulation anomalies at decadal scale, such findings may contribute to creating or enhancing decadal-scale forecasting capability at regional scale whilst also supplementing regional climate change projections.
Research problem

Tropical systems from the SWIO are responsible for extreme rainfall events and related floods that occur over the Limpopo River Basin (e.g. Dun 1985, Reason and Keibel 2004). The tracks followed by these systems during and after landfall have a large bearing on the associated impacts in the Limpopo River Basin. Studies that focus on these systems and their contribution collectively in South Africa or southern Africa are sparse in the literature. Existing studies focus on landfall of individual systems (e.g. Reason and Keibel 2004, Crimp and Mason 1999, Klinman and Reason 2008) or take into account only landfall (e.g. Mavume et al. 2009) without elaborating on inland impacts or are focused only on intense systems (e.g. Dun 1985) even though weaker systems such as depressions from the SWIO are also associated with flood events over the Limpopo (e.g. Crimp and Mason 1999, Dyson and van Heerden 2002). The most recent publically available work found, providing a summary of historical contributions of (only) tropical cyclones over the eastern parts of South Africa (Dun 1985), was published more than 20 years ago.

Observations of rainfall associated with tropical systems from the SWIO suggest a decadal-scale variation in contribution by these systems over the Limpopo River Basin. While decadal-scale forecasting is still an area of ongoing research (Goddard et al. 2013), the Limpopo River Basin may provide a study area where such forecasts could be verified at regional scale in terms of rainfall variation and synoptic weather systems contributing to such variation. The absence of any studies considering the collective climatological influence over the region by tropical systems from the SWIO however makes such undertakings challenging. Vulnerability in the Limpopo River Basin together with projections of lower water availability (Shewmake 2008) further also compels an understanding of projected impacts at longer time scales over the region. In relation to this, the SWIO region has been singled out as an area where more needs to be done towards understanding the projected influence of anthropogenic forcing on the climatology of tropical cyclones (Christensen et al. 2007).
Aims and Objectives

Given the research problem above, the aim of the project is to describe the collective contribution of tropical systems from the SWIO into the Limpopo River Basin, explore its potential association with climate variability at decadal scale whilst also giving an indication of projected changes in the occurrence of these systems over the region towards the end of the 21st century.

Hence the specific project objectives are:

- Determine from historical synoptic-scale weather data and rainfall records, spanning more than 50 years, the impact of tropical systems from the SWIO over parts of the Limpopo River Basin where sufficient rainfall data are available.

- Investigate and describe the variability of tropical systems from the SWIO over the Limpopo River Basin within the context of broader climate variability in the region.

- Identify possible external forcing mechanisms acting on the variability of tropical systems from the SWIO over the region.

- Analyze the simulations of multi-decadal climate change over southern Africa with the emphasis on changes projected in the climatology of tropical systems over the southwest Indian Ocean, and associated changes in rainfall over the Limpopo River Basin.

Thesis Outline

Section 2 provides, in the form of an already published peer reviewed journal paper, a historical perspective on the influence of tropical systems from the SWIO over parts of the Limpopo River Basin. Specifically, the contribution by tropical systems from the SWIO to the total rainfall and to widespread heavy rainfall events over the region is explored. Likewise, cyclicity in the rainfall contributed by tropical systems from the SWIO is explored. Section 3, also in the form of an already published peer reviewed journal paper, focusses firstly on the regional circulation anomalies associated with tropical systems moving into the Limpopo River Basin. Secondly, decadal-scale variation in the contribution by these systems is placed into context with variation in relevant regional and global circulation anomalies.
Section 4 explores a possible external forcing mechanism which may contribute to the decadal-scale variation indicated in Section 2 and Section 3 while providing also an outlook up to the middle of the 21st century of projected bi-decadal variability in the occurrence of tropical-cyclone related impacts over the Limpopo River Basin. This part of the thesis is also presented in journal paper format, and has been submitted for peer review. The outlook given in Section 4 can be verified over the next number of years and then extended towards the end of the century and beyond. Whilst Sections 2 – 4 provides insight into the occurrence of tropical systems from the SWIO over the Limpopo River Basin as well as observed and projected decadal-scale variability, Section 5 provides insight on the projected changes towards the end of the 21st century of the climatology of tropical systems over the SWIO and the influence over the Limpopo River Basin due to a change in circulation patterns associated with anthropogenic forcing. The Section consists of an already published peer-reviewed journal paper of a study conducted on the output of a 6-member ensemble of an Atmospheric Model based on the SST output of Global Circulation Models of Assessment Report 4 for the period 1961 – 2100. It provides information on the trend in the occurrence of tropical systems from the SWIO over the Limpopo River Basin over and above decadal-scale variability. Section 6 is a summary of the main findings of the thesis together with a list of key recommendations.

Given that all figures are specific to published papers, a list is not provided in the contents section. Furthermore, each paper (Section 2 – 5) is followed by the reference list specific to that paper. The reference list for Section 1 and 6 is provided at the end of Section 6.
2. Historical Overview

Preface

This section consists of 1 peer reviewed paper as follows:


Towards reaching the first objective of the study, the paper provides the historical overview of rainfall events over the interior of the Limpopo River Basin associated with tropical systems making landfall and moving sufficiently far inland to cause rain over the interior of the Limpopo River Basin. The dataset of tropical systems created in this paper is used also during the subsequent sections for analyses based on the historical cases of tropical systems responsible for rainfall over parts of the Limpopo River Basin. The rainfall totals contributed by the systems responsible for significant rainfall specifically over South Africa during the period are shown in Appendix 1. While the paper explores the collective contribution by tropical systems from the SWIO over the Limpopo River Basin, decadal-scale variability in the occurrence of such systems over the area is also investigated.

The paper was co-authored with FA Engelbrecht, WA Landman and CJ Engelbrecht. I conceptualized the paper, obtained all the historical datasets used and did all the analyses myself. I adapted an existing tracking algorithm by adding additional criteria for temperature, vorticity and wind while expanding the number of atmospheric levels considered towards focusing on the identification and tracking of tropical weather systems specifically.
Tropical systems from the Southwest Indian Ocean making landfall over the Limpopo River Basin, southern Africa: a historical perspective

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Abstract

The study provides perspective on the contribution of landfalling tropical systems (cyclones, depressions, storms, lows) from the Southwest Indian Ocean (SWIO) towards rainfall over the eastern interior of southern Africa, over the period 1948 to 2008. Although these systems contribute to less than 10% of the annual rainfall occurring over the region, their relative contribution to local and widespread heavy rainfall events is shown to be highly significant. About 50% of widespread heavy rainfall events over northeastern South Africa are caused by landfalling tropical systems. Fourier analysis performed on the time-series of rainfall occurring over northeastern South Africa in association with these systems reveals the existence of a quasi-18-year cycle. The cycle coincides with the well-known quasi-18-year Dyer-Tyson cycle in rainfall over the summer rainfall region of South Africa. These results suggest that atmospheric and surface conditions leading to wet phases of the Dyer-Tyson cycle also favour the landfall and subsequent westward movement of tropical systems from the SWIO over southern Africa – and their eventual contribution to rainfall over northeastern South Africa.
**Key words:** Tropical cyclone, landfall, rainfall cyclicity, southern Africa, Fourier analysis, closed low tracking.

**Introduction**

Between 1995 and 2003, a weather system type that has received relatively little attention in the context of southern African climate dynamics was responsible for large amounts of rainfall over the northeastern parts of South Africa, Zimbabwe and Mozambique - sometimes causing devastating floods and record rainfall totals over these regions. This weather system is the landfalling and westward-moving tropical system (cyclone, storm or depression) that develops over the Indian Ocean from where it moves into the eastern interior of the southern African subcontinent. The devastating floods during 1996 over parts of the Limpopo River Basin (Figure 1) were caused by a westward moving tropical depression (Crimp and Mason 1999). In February 2000, tropical cyclone Eline moved westward over the southern African mainland causing devastating floods over Mozambique and heavy rainfall deeper into the interior (Reason and Keibel 2004). Heavy rainfall caused by a tropical low located over Botswana during February 2000, but which had its origin over the Southwest Indian Ocean (SWIO), is described by Dyson and Van Heerden (2002). The 2007 floods over Mozambique (Padgett 2007, Klinman and Reason 2008) were likewise caused by a landfalling tropical cyclone and tropical depression. The westward movement of these systems tends to occur at latitudes where some of the large southern African river basins are found (e.g. Dyson and Van Heerden 2002) and the effects downstream in terms of flooding can be immense.
Figure 1. The eastern parts of southern Africa with the Limpopo River Basin clearly visible. Stations in the basin used for rainfall analysis are also indicated.

On average, eleven tropical disturbances reach tropical depression intensity over the SWIO per year (Jury and Pathack 1991). Landfall of these systems over the southern African subcontinent does not occur every year, however. In fact, systems approaching the subcontinent usually recurve in the Mozambique Channel and mostly do not contribute to rainfall over the African Plateau (e.g. Dunn 1985, Jury and Pathack 1991). Landfalling systems may either track further westward into the southern African interior, or may be deflected towards the south or north. This study investigates the contribution of landfalling tropical systems to rainfall totals and extreme rainfall events over the Limpopo River Basin in southern Africa (Figure 1).

The characteristics of the landfalling systems (e.g. frequency of occurrence and preferred tracks) are also examined. Of particular interest is the possible existence of natural cycles in the frequency of occurrence of landfalling tropical systems over southeastern southern Africa. The existence of such cycles, if sufficiently understood and captured within climate models, would make feasible the skillful prediction of the likelihood of occurrence of westward
moving systems at the seasonal to multi-decadal timescales (e.g. Landman and Goddard 2005, Engelbrecht et al. 2009)

The Limpopo River Basin is located in northeastern South Africa, southern Zimbabwe and southern Mozambique, and is a semi-arid area with an altitude of less than 800 m above sea level and with a mean total annual rainfall ranging between 300 and 600 mm. Within this climatic context, however, the region supports a large rural population dependent on rain-fed agriculture as well as large national parks. The region is therefore vulnerable with regard to the impact of rainfall variability (Vogel and O’Brien 2003). The eastern escarpment of southern Africa, stretching from the South African Drakensberg in the south northwards over the eastern parts of Zimbabwe and with an altitude that exceeds 1200 m above sea level (Figure 1), receives in excess of 1500 mm per annum over some areas. More than 85% of the rainfall over the eastern interior of the Limpopo River Basin occurs within the summer months (October to March). After dry winters, rainfall increases rapidly only from November and December, and maintains a steady rise during January and February after which it declines rapidly from March onwards (e.g. Schulze 1965). The peak of the rainy season coincides with the maximum frequency of occurrence in the annual cycle of tropical disturbances that control the summer rainfall season to a large degree (Preston-Whyte and Tyson 2000). During this time of the year, tropical weather systems invade southern Africa in the form of tropical cyclones, tropical lows and easterly waves (e.g. Karoly and Vincent 1998). Also, wet spells during summer are pulsed at frequencies that are consistent with the passage of tropical waves over the southeast African and SWIO region (Hayasi and Golder 1992) while anomalous easterly flow in the 5° – 20°S band in the region of Madagascar leads to increased rainfall over southeast Africa (Mulenga et al. 2003).

When landfalling tropical systems do occur over the eastern interior of southern Africa, the rainfall they produce within a time span of a few days can be a significant contribution to the annual total. Synoptic systems that generate rainfall over the region also include disturbances in the westerlies such as westerly waves and cut-off lows as well as ridging anticyclones (Schulze 1965, Harrison 1984, Taljaard 1985, Preston-Whyte and Tyson 2000). Quite often, rainfall over eastern South Africa results from tropical-temperate cloud bands, where a westerly wave combines with a tropical trough or low to the north to form a tropical-temperate trough (Harrison 1984, Preston-Whyte and Tyson 2000).
Large-scale circulation patterns have been shown to affect the formation and movement of tropical cyclones significantly at the seasonal and inter-annual time scales over different regions of the world (e.g. Elsberry 1987). A major factor affecting tropical cyclone frequency and tracks globally at the inter-annual time scale is the El Niño Southern Oscillation (ENSO) phenomenon (Chan 1985, Wang and Chan 2002, Ho et al. 2006). Over the Atlantic Basin, Goldenberg et al. (2001) found that major hurricane activity is oscillatory, modulated by a multidecadal mode of Sea-surface Temperature (SST) variability, namely the Atlantic Multidecadal Oscillation. Certain large-scale atmospheric patterns have also been shown to favour the occurrence of tropical cyclones over the SWIO. During summers with a relatively high number of tropical cyclones forming over the SWIO, upper easterlies and lower westerlies in the equatorial zone to the north of Madagascar form a Walker cell anomaly in conjunction with the east phase of the quasi-biennial oscillation (QBO), providing uplift over the ocean around 50 to 75°E (Jury 1993). During such summers easterly trade winds strengthen in the subtropics while mid latitude westerlies shift polewards (Jury 1993).

Local SSTs over the SWIO as well as SSTs in the Pacific Ocean (ENSO) have been shown, through a set of experiments using an atmospheric model, to have an impact on the landfall frequency of tropical cyclones over Mozambique (Vitart et al. 2003). La Niña conditions in the Pacific Ocean, positive SST anomalies over the Mozambique Channel, pronounced SWIO high-pressure anomalies and anomalously high soil moisture conditions and resulting higher vegetation activity over the interior of southern Africa have been reported to favour westward penetration of tropical cyclones into the southern African subcontinent (Reason and Keibel 2004).

Over South Africa, the existence of a quasi-18-year cycle in the summer rainfall was first noted by Dyer and Tyson (1977), and confirmed in the independent studies of Tyson et al. (1975) and Van Rooy (1980). That is, South African summer rainfall shows rainfall variability at a near decadal scale with a period of +/- 9 years with rainfall about 10% above normal followed by +/- 9 years with rainfall about 10% below normal (Taljaard 1996). The near-decadal scale variability also enhances or opposes the effects of El Niño and La Niña events depending on whether these occur within the drier or wetter parts of the cycle (Kruger 1999). Although uncertainty exists regarding the origin or forcing mechanism(s) driving the cycle at these time scales, the periods of above normal rainfall display La Niña-like SST anomalies, while the periods with below normal rainfall display El Niño-like SST anomalies.
(Reason and Rouault 2002). This is supported by a positive relationship between the Southern Oscillation Index and rainfall over southern Africa (Nicolson and Entekhabi 1986). The cycle manifests not only periods of above or below-average rainfall, but in sequential periods of about 9 years in length marked by either drought or flood events (e.g. Alexander 1995). In this regard, it may be noted that devastating flood events that frequent southern Africa, such as the 2000 floods over northeastern South Africa and Mozambique, tend to occur within the slowly varying background of longer-term SST and sea level pressure modes dominated by ENSO-like patterns on various decadal to multi-decadal scales (Reason and Rouault 2002).

During the wetter than average periods over the summer rainfall region of South Africa, anomalously high surface pressures have been shown to occur to the south and southwest of southern Africa, while the Indian Ocean high to the east of the subcontinent weakens (Tyson 1981). Low pressure anomalies then occur over southern Africa and the Indian Ocean. During such periods, anomalously strong onshore low-level wind anomalies and low-level convergence occur over eastern South Africa, indicating an increase in the advection of moist, maritime air over the region (Reason and Rouault 2002). Some of these circulation anomalies are also conducive to the landfall of tropical systems over the southern African subcontinent from the SWIO (Reason and Keibel 2004)

Against this background of an apparent relationship between the wet phase of the quasi-18-year rainfall cycle, an anomalously high frequency in the occurrence of La Nina-like conditions in the Pacific Ocean during such periods, and circulation anomalies over southern Africa and the SWIO favouring the occurrence of landfalling tropical cyclones, this paper also explores the possible cyclicity in the occurrence of landfalling tropical systems from the SWIO over southern Africa.

**Data and Methods**

In order to quantify the contribution of tropical systems to rainfall over the eastern interior of southern Africa, it is necessary to objectively identify these systems throughout the length of a data record from a number of different data sources. Within this study, the focus is on tropical systems that can be identified as having formed a geopotential minimum (a closed low) in the mid-levels of the troposphere, and that have developed over the SWIO before making landfall over southern Africa. Such systems include tropical low-pressure systems, tropical depressions, tropical storms and tropical cyclones.
The study area is the Limpopo River Basin and adjacent eastern escarpment in northeastern South Africa, southern Mozambique and southern Zimbabwe. Figure 2 gives an overview of the mechanism studied and the study area. In the context of the study, a westward-moving tropical system is identified as having the following properties:

1. A closed low (minimum in geopotential height) at 700 hPa and 500 hPa that exists for at least 24 hours, and is replaced by a high pressure system/absence of a low pressure system at 250 hPa.

2. The closed low as described above can be identified while the system occurs over the SWIO (but not necessarily when it is present over land).

3. The centre of the region of low pressure must make landfall (either in the mid-levels or in the lower atmosphere, but not necessarily in closed low form).

4. Responsible for rainfall over the eastern interior of southern Africa – over the escarpment of South Africa and/or the Limpopo River Basin, within South Africa or Zimbabwe.

Figure 2 A track followed by several tropical systems from the SWIO making landfall and moving westward over southern Africa.
Various datasets were analyzed in order to identify tropical systems that satisfy the above definition. Synoptic-scale circulation data of sufficient quality and spatial resolution is only available from 1948 onwards, which determined the starting point of the analysis. The systems were identified through the simultaneous analysis of the following datasets:

- 6-hourly National Centres for Environmental Prediction (NCEP) - National Centre for Atmospheric Research (NCAR) reanalysis data (Kalnay et al. 1996). NCEP reanalysis data describes various atmospheric parameters at a spatial resolution of 2.5°, at 6-hourly time intervals, for the period 1948 to present.

- Daily synoptic data and weather maps from the South African Weather Service (SAWS) as contained in the SA Weather Bulletins - available for the period 1950 to present. These data are maps of daily surface pressure and 850 hPa heights for Africa south of 15°S and the surrounding oceans.

- Daily rainfall data covering South Africa (from the Agricultural Research Council – Institute for Soil, Climate and Water (ARC-ISCW) Climate Information System which also contains data from the South African Weather Service) as well as data for a station from the Zimbabwean Meteorological Services. Data for the South African stations are available since the 1920’s and since 1950 for the Zimbabwean station.

- La Réunion cyclone tracks data – a database of tropical cyclones and tropical depressions that have occurred over the SWIO region since 1848. The intensity of the system at sea level as well as its location is described in this dataset.

The scarcity of observational data over the Southern Ocean prior to 1979 (when satellite data started to become available) has a potentially serious effect on any attempt to recreate atmospheric analysis for that period (Tennant 2004). For this reason, the synoptic data from the SAWS, interpolated rainfall fields over South Africa and the La Réunion cyclone track data described above were utilized, in addition to the NCEP Reanalysis data, to identify tropical systems from the SWIO for the entire period under consideration.

As a first step to identify tropical systems, the 6-hourly NCEP data were inspected visually for the period 1948-2008 and all events of land-falling and westward moving low-pressure systems from the SWIO were identified and flagged. The systems identified had to display a geopotential minimum within the 700 hPa height (a condition less strict than required by (1))
and (2) above). This served as a broad measure to obtain a large set of tropical systems that would span the set described by (1) to (4).

The visual inspection of NCEP Reanalysis data was followed by the objective identification of closed-low tracks over the SWIO. The closed-low finding-and-tracking algorithm employed is based on the following two-step procedure:

The identification of all local geopotential minima (closed-lows) on the desired pressure levels (500 hPa and 700 hPa) for all of the 6-hourly time-levels. A geopotential minimum is defined to exist at a given gridpoint by considering the point as the centre of a 9-gridpoint stencil, and by checking if the geopotential at the centre gridpoint is a local minimum. In exceptional cases, it was found that up to three adjacent grid points recorded the same geopotential minimum value at a given time-level. For such cases, the stencil was enlarged and the algebraic average of the longitudinal and latitudinal coordinates of the gridpoints sharing the geopotential minimum value were taken as the position of the closed-low at time-level t (e.g. Lambert 1988, Blender and Schubert 2000).

The tracking of closed-lows in time, is carried out in an iterative procedure where all the height minima identified at time-level t are subjected to the tracking criteria that entail the following:

- For each height minimum identified at time-level t, all height minima at time-level t+1 that are located within a radius of 700 km from a time-level t height minimum, are considered for the track associated with the time-level t height minimum.
- If more than one such a height minimum occurs at time-level t+1, the height minimum at time-level t+1 closest to the time-level t height minimum is considered to be the time-level t+1 realization of the time-level t minimum.
- A closed-low track is only constructed if a closed low minimum can be tracked for at least 24 hours (that is, the closed low can be tracked over at least 5 of the time-levels).

This algorithm was employed at 700 and 500 hPa to identify cases where closed lows were present at both these levels simultaneously – with the 500 hPa system, when projected onto the 700 hPa level, occurring within a radius of 355 km of the 700 hPa system. Additionally, it was required that cyclonic circulation was absent at 250 hPa. These requirements describe
condition (1) mentioned earlier, and in combination effectively distinguish closed-low systems of a tropical nature from cut-off lows of the westerly wind regime (e.g. Taljaard 1985). All the output tracks of the algorithm for the period 1948-2008 were analyzed to identify the land-falling systems. All the systems identified by the objective tracker formed part of the larger set of systems identified by visual inspection.

Apart from the NCEP Reanalysis data, the daily weather bulletins obtained from the SAWS were additionally used to independently identify possible cases of westward-moving tropical systems - by studying the more detailed daily sea level and 850 hPa height analyses of the bulletins and comments made by the forecasters. The systems identified from the bulletins to make landfall at the surface also turned out to be, with the exception of one system, a subset of those identified through visual inspection of the 700 hPa NCEP reanalysis data.

The La Réunion cyclone track data describes tropical systems of only tropical depression or tropical cyclone intensity over the southwestern Indian Ocean, and were also used to supplement the analysis of systems identified from the NCEP Reanalysis data and weather bulletin data. Except for two systems, one occurring in 1948 and another in 1960, all landfalling systems from the SWIO identified from the La Réunion data were elements of the set of systems obtained from visual inspection of the NCEP data.

Because the study focuses on tropical systems from the SWIO that had a direct impact in terms of precipitation over the Limpopo River Basin and adjacent escarpment, rainfall data also had to be utilized to select the relevant systems. Daily rainfall data from weather stations covering the entire South Africa were used to construct rainfall images that could be applied to identify the influence of tropical systems on rainfall. Daily rainfall values from between 1500 and 2000 stations throughout the period 1948 to 2008 were interpolated over South Africa with the inverse distance weight method and taking the effect of topography into account (by using the long-term average summer rainfall as a spatial trend). The time series of rainfall surfaces were used to identify rainfall patterns in terms of timing, distribution, amount and direction of propagation that indicated that a land-falling tropical system caused the rainfall over the area. By studying rainfall patterns associated with tropical systems causing rain over the area, a typical rainfall pattern associated with these systems over the northeastern parts of South Africa was identified. This entails a dry period over the area of interest resulting from subsidence to the west of an approaching system (e.g. Preston-Whyte
and Tyson 2000) followed by a westward propagation of rainfall starting over the eastern fringes of the area and intensifying also from the east with highest rainfall amounts occurring over the mountainous eastern escarpment.

If such a characteristic rainfall pattern could be identified from the station data, it was regarded as an additional indication that a tropical system from the SWIO may have made landfall over the area of interest.

The data from all four sources (NCEP Reanalysis, SAWS daily synoptic maps, La Réunion track data and rainfall data) were combined to identify the tropical systems that influenced the area of interest in terms of a contribution towards precipitation. Because the focus is on tropical systems causing rainfall over the interior of southern Africa, the first prerequisite for identifying a system was that at least some measurable rain had to occur at any of the rainfall recording stations over the eastern edges of the area of interest with a record length spanning the entire period. These stations are Musina, Pafuri and Makoholi (Figure 1). Additionally, at least three of the following criteria had to be satisfied:

- Visual inspection identification of landfalling system at 700 hPa.
- Landfalling system identified by objective tracker.
- Typical rainfall pattern associated with tropical systems from the SWIO according to daily rainfall maps.
- Landfall and westward movement of tropical system from the SWIO identified in SAWS daily synoptic charts.
- Landfalling system identified in La Réunion dataset.

All these criteria provide strong indication that rainfall over the area of interest was indeed caused by a tropical system from the SWIO. From the combination of the datasets according to the selection criteria described above, it was finally concluded that 44 tropical systems from the SWIO have caused rainfall over the eastern interior of southern Africa over the period 1948 to 2008. Table 1 shows the complete set of systems identified and also the selection criteria they've satisfied. Figure 3 shows a summary of the number of datasets used to identify the systems as also shown in Table 1.
Table 1  List of all tropical systems making landfall over southern Africa from the SWIO, responsible for rain over the area of interest and datasets containing evidence of the systems.

<table>
<thead>
<tr>
<th>Date of landfall of tropical system responsible for rain over the area of interest</th>
<th>NCEP - Geopotential heights at 700 hPa (Visual Inspection)</th>
<th>NCEP data (Objective tracking algorithm)</th>
<th>La Réunion Tropical Cyclone Database</th>
<th>SAWS daily synoptic maps</th>
<th>Time series of rainfall maps (Distinct rainfall pattern)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 March 1948</td>
<td>X</td>
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<tr>
<td>02 February 1950</td>
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<td>X</td>
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<td>17 January 2012</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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</table>
A third of the total number of systems identified was present in all the datasets considered. Of the 44 systems finally identified, 35 were present in the automatic objective tracker dataset, 31 were present in the cyclone track database from La Réunion and 38 were present in the SAWS daily synoptic weather maps. Only two systems were not present in the dataset from visual inspection of NCEP Reanalysis data. These were tropical storms that occurred in 1948 and 1960 - and they were present in the La Réunion track dataset.

In order to quantify the relative contribution of tropical systems to rainfall over the interior of the subcontinent, data from several stations within South Africa and Zimbabwe with a complete daily rainfall record stretching over the period 1948 to 2008 were analyzed. These stations were chosen to spatially represent the escarpment and Limpopo River Basin with the positions of the stations ranging from 19°S to 26°S and 28°E to 32°E (Figure 1).

Rainfall events associated with the tropical systems identified earlier were flagged for further analysis. This was achieved by extracting from the daily rainfall records of each of the 6
stations (Figure 1) the rainfall values associated with tropical systems from the SWIO and calculating the total rainfall associated with each event. Following this procedure, rainfall amounts associated with individual events were summed per year, yielding the total yearly rainfall amount caused by tropical systems from the SWIO for each station, for the period 1948 to 2008. Fourier analysis was applied to identify possible cycles in the occurrence of total yearly rainfall caused by tropical systems from the SWIO, for each of the six stations separately. To emphasize the existence of cycles at periods of several years, the Fourier analysis was performed on the five-year moving averages of the original time series of rainfall, calculated for each station for the period 1948 to 2008. To test for the statistical significance of the peaks in the resulting periodograms, “observed” time series for periods similar to the ones used to calculate the true cycle lengths were randomly created by resampling the real rainfall data through a Monte Carlo process (Livezey and Chen 1983, Wilks 2006). A sequence of 5000 time series was randomly created, the 5-year moving average was calculated for each case and Fourier analysis was subsequently performed on the 5000 random time series and the amplitudes of the relevant cycles determined. These amplitudes were then ranked and the 4500th and 4750th values determined per cycle. These were then considered respectively to be the values associated with the 90% and 95% levels of confidence. This entire procedure was repeated for the total annual rainfall at the 6 stations separately to identify any relevant cycles in the total yearly rainfall (as opposed to the total rainfall attributed to tropical systems from the SWIO) over the area of interest.
Results and Discussion

Frequency of occurrence of landfalling systems

From the closed-low tracks identified objectively from NCEP data by the automatic tracking system, the frequency of occurrence of tropical closed-lows making landfall from the SWIO is plotted in Figure 4. Note that the systems identified through objective tracking represent only a subset of the total number of tropical systems identified, as some systems that made landfall having lost the property of closed-low circulation at 700 or 500 hPa. The graph shows the number of 6-hourly time intervals during which the centers of tropical closed lows at 700 hPa were located at specific grid points. Figure 4 reveals that the preferred tracks of westward penetrating tropical systems from the SWIO into the southern African subcontinent are in the latitudinal band between and including 17.5 °S and 20 °S, which coincides spatially with the northern half of the Limpopo River Basin. The sharp west-east gradient near the coastline is the result of both the deflection to the north or south of some landfalling systems, as well as the loss of a closed circulation when some systems move westward over land.

![Figure 4](image-url)  
*Figure 4* Frequency of occurrence of tropical systems from the SWIO making landfall over southern Africa (units are the numbers of 6-hourly geopotential lows per grid point over the period 1948-2006) as tracked by an objective tracking algorithm applied to NCEP Reanalysis daily 700 hPa Geopotential Height data.
Figure 5 shows the time series of the annual number of tropical systems from the SWIO that were responsible for precipitation over the Limpopo River Basin in South Africa or Zimbabwe.

![Graph showing number of tropical systems from the SWIO per year](image)

**Figure 5**  Number of tropical systems from the SWIO per year, as identified through the combination of synoptic and rainfall datasets, that caused rainfall over the Limpopo Basin (bars) with a linear trend line (solid line) fitted and the 5-year moving average (dotted line).

From the graph it can be seen that there were two periods with a relatively high frequency of landfalling systems causing some rain over the area of interest - the 1960s/70s and the late 1990s, separated by a lull in the 1980s. There is also no strong trend visible in the time series, lending weight to the objectivity of the identification process (that is, the suspected lower quality of NCEP reanalysis data for the period prior to 1979 did not induce an artificial increase in the frequency of occurrence of identified systems as a function of time).
Characteristics of rainfall events induced by tropical systems

Of the 44 systems identified, 18 were responsible for daily rainfall amounts greater than 50 mm at one or more rainfall stations shown in Figure 1. This value (50 mm) in a 24-hour period is considered heavy rainfall by the South African Weather Service (e.g. Dyson 2009). For the systems that caused heavy rain over Entabeni on the escarpment, the average number of rain days per system is 5.6. At Musina, located to the north and therefore closer to the preferred track of closed lows centers, but in the Limpopo River Valley, the average number is 3.3 – resulting in an average value of 4.5 days between these two stations. Another feature of the temporal distribution of the rainfall associated with these systems is a dry period just prior to the commencement of rainfall associated with the systems as a result of the subsidence occurring towards the west of the approaching systems (Preston-Whyte and Tyson 2000). Therefore, for the analysis of rainfall events typically associated with these systems, a moving period of 5 days with daily increments was used. This ensures that the total rainfall associated with individual systems can be considered and separated from other systems responsible for rainfall. From the data of available stations over South Africa and Zimbabwe (Figure 1), the total contribution to rainfall during the years since 1948 by tropical systems from the SWIO is around 7% over the escarpment (Entabeni) and Limpopo River Basin of northeastern South Africa (Musina, Pafuri) and southern Zimbabwe (Makoholi), with lower contributions further to the south and west. Table 2 summarizes the contribution of these systems to the total annual rainfall and late-summer (here defined as January to March) rainfall for the six selected stations in the northeast of South Africa and southern Zimbabwe.

<table>
<thead>
<tr>
<th>Station</th>
<th>Nelspruit</th>
<th>Entabeni</th>
<th>Pafuri</th>
<th>Musina</th>
<th>Villanora</th>
<th>Makoholi (Zim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Rainfall (mm)</td>
<td>847</td>
<td>1795</td>
<td>440</td>
<td>360</td>
<td>421</td>
<td>647</td>
</tr>
<tr>
<td>In Jan-Mar (%)</td>
<td>42</td>
<td>54</td>
<td>52</td>
<td>50</td>
<td>49</td>
<td>51</td>
</tr>
<tr>
<td>Tropical system contribution - Jan-Mar (%)</td>
<td>10</td>
<td>14</td>
<td>14</td>
<td>15</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Tropical system contribution - All Year (%)</td>
<td>4</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

The westward and southward reduction in total rainfall contribution by tropical systems can be seen from Musina (8% average contribution to annual total rainfall) to Villanora (3%) in the west and Nelspruit (4%) in the south. Table 2 indicates that tropical systems from the

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SWIO contribute a relatively small portion of the total rainfall over the Limpopo River Basin and adjacent escarpment, with a somewhat higher proportional contribution during late summer (January to March). However, their contribution to extreme rainfall events over the area is quite significant, as will be illustrated below.

The importance of tropical systems from the SWIO over the area of interest in terms of high multi-day total rainfall can be seen in Figure 6. It shows that for both the escarpment (Entabeni) and the Limpopo River Valley (Musina), these systems were responsible for the highest five-day rainfall totals (rainfall summed over 5 days) on record since 1948, and that these systems play a relatively larger role as the magnitude of the rainfall event increases.

![Figure 6](image)

**Figure 6** Contribution of tropical systems from the SWIO to 5-day rainfall events exceeding various threshold amounts at Entabeni on the eastern escarpment (a) and Musina in the Limpopo River Valley (b). The figures above the bars indicate the total number of times these rainfall events have occurred since 1948.

The much higher frequency of occurrence of high rainfall totals at Entabeni compared to Musina is the result of the orographic effect on rainfall of the escarpment at Entabeni. It is clear from Figure 6 that tropical systems cause the majority of extreme 5-day rainfall events at both Entabeni and Musina. During individual years, the contribution to the total rainfall by these systems can also be large. During 2000, for example, tropical systems from the SWIO contributed as much as 36% of the annual rainfall at Musina and 38% at Entabeni.
**Widespread heavy rainfall events**

Three stations were identified in order to consider periods during which precipitation occurred simultaneously over a large area including the escarpment, Limpopo River Basin and eastern Lowveld (the area to the east of the escarpment). These stations are Musina, Pafuri and Entabeni (Figure 1). The area within the triangle connecting these three stations is about 4 400 km². Simultaneous rainfall events at all three of these stations were identified and the relative contribution of tropical systems from the SWIO to such events was calculated. Four definitions were chosen (shown in columns 2 to 5 of Table 3) to identify periods during which moderate to heavy rain occurred over all three stations simultaneously. The first two definitions in Table 3 were chosen to mark periods during which more than 50 mm of rain were recorded at all three stations simultaneously within two (column 2 of Table 3) or three days (column 3 of Table 3). The third definition was chosen to highlight periods during which more than 50 mm occurred on any of three consecutive days at all three stations (column 4 of Table 3). The last column of Table 2 shows the percentage of times during which 5-day total rainfall at all three stations simultaneously exceeded a certain threshold amount for all non-overlapping 5-day rainfall totals calculated at the stations. The values show the percentage of events identified that exceeded the limits shown on the left. The data presented in Table 3 were used to identify widespread heavy rainfall events. The threshold values for widespread heavy rainfall events in the context of the area were calculated by testing several values and extracting any one value occurring between the 95th and 99th percentiles, shown in **bold italics** in Table 3.
Table 3  Widespread heavy rainfall events according to various cut-off values of rainfall occurring simultaneously at all three stations, for total rainfall during a three-day period (column 1), two-day period (column 2), maximum rainfall during a three day period (column 3) or the total rainfall during a five-day period (column 4) exceeding the thresholds as indicated on the left-hand side. (These statistics pertain to all rainfall events, not only those caused by tropical systems, and were calculated for the period 1948 to 2008)

<table>
<thead>
<tr>
<th>Limit</th>
<th>3-Day total</th>
<th>2-Day total</th>
<th>Maximum in 3 days</th>
<th>5-Day total</th>
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<tr>
<td>&gt;20 mm</td>
<td>18.5%</td>
<td>15.1%</td>
<td>11.5%</td>
<td>24.7%</td>
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<tr>
<td>&gt;50 mm</td>
<td>3.4%</td>
<td>2.5%</td>
<td>1.0%</td>
<td>6.4%</td>
</tr>
<tr>
<td>&gt;100 mm</td>
<td>0.4%</td>
<td>0.3%</td>
<td>0.1%</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

Considering widespread, heavy rainfall events, Table 4 puts the contribution of tropical systems into perspective. For only the widespread, heavy rainfall events as identified from the data shown in Table 3 (between the 95th and 99th percentile), Table 4 shows in the first row the total number of occurrences of such events. The second and third rows show what percentage of number of these events occurred during the second part of summer (January to March) and the entire summer (October to March), respectively, while the last row shows what percentage of number of these events was as a direct result of rainfall caused by tropical systems from the SWIO.

Table 4  Occurrence of widespread heavy rainfall events over the eastern parts of the Limpopo Province of South Africa and the contribution of well-defined tropical systems from the SWIO to these events.

<table>
<thead>
<tr>
<th>Definition</th>
<th>Total</th>
<th>3-Day total &gt; 50 mm</th>
<th>2-Day total &gt; 50 mm</th>
<th>Maximum in 3 days &gt;50 mm</th>
<th>5-Day total &gt; 100 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-Mar</td>
<td>55%</td>
<td>58%</td>
<td>89%</td>
<td>86%</td>
<td></td>
</tr>
<tr>
<td>Oct-Mar</td>
<td>82%</td>
<td>79%</td>
<td>89%</td>
<td>86%</td>
<td></td>
</tr>
<tr>
<td>Tropical  system</td>
<td>27%</td>
<td>42%</td>
<td>56%</td>
<td>57%</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 shows that more than half of the widespread heavy rainfall events occurred during the January-March period (row 2) and about 80% or more during the summer half-year (October to March, row 3). The importance of the tropical systems from the SWIO is shown to increase from left to right in row 4, as the definition of widespread heavy rainfall becomes stricter. More than half of all cases where daily total rainfall in excess of 50 mm was reported from all three stations within three days and where more than 100 mm of rain was recorded at all three stations within 5 days were caused by these systems.
**Cycles in the occurrence of landfalling tropical systems and associated rainfall**

Because cycles have been observed in the occurrence of tropical cyclones over various ocean basins (e.g. Goldenberg *et al.* 2001) and knowledge about cyclicity in the landfalling of tropical systems from the SWIO can improve seasonal and decadal forecasting over southern Africa, a Fourier analysis was performed on the station rainfall data in order to establish whether there exists any cyclic behaviour in the occurrence of rainfall caused by landfalling tropical systems over the area of interest, over the period 1948 and 2008.

Figure 7 shows the annual rainfall contributed by tropical systems from the SWIO at four of the weather stations depicted in Figure 1 during the period under consideration. The rainfall values for each station were rescaled to vary between 0 and 1, by dividing the annual rainfall totals caused by tropical systems from the SWIO for each station by the highest annual value caused by tropical systems at that station within the time series.

![Scaled annual rainfall totals](image)

**Figure 7** Scaled annual rainfall totals contributed by tropical systems from the SWIO at four locations over the period 1948-2008 (similar results were obtained for Pafuri and Entabeni).

Based on the graph (Figure 7), the possible existence of cyclic behaviour with peaks indicated by ovals, can be seen in the rainfall contributed by tropical systems from the SWIO over the area of interest.

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Figures 8a and 8b show the periodograms resulting from Fourier analysis for all six stations indicated in Figure 1. On the left-hand side the periodograms for the rainfall caused by tropical systems from the SWIO are shown, while the right-hand side shows the periodograms resulting from Fourier analysis performed on the total annual rainfall at each station. The 90% and 95% confidence levels are also indicated.
Figure 8 a-f  Periodograms obtained for the 5-year moving averages of rainfall caused by tropical systems from the SWIO (left) and for total annual rainfall (right) at Nelspruit (a,b), Villanora (c,d) and Entabeni (e,f). The grey dashed lines indicate the 90% and 95% confidence levels.
Figure 8 g - l Periodograms obtained for the 5-year moving averages of rainfall caused by tropical systems from the SWIO (left) and total annual rainfall (right) at Pafuri (g,h), Musina (i,j) and Makoholi (k,l). The grey dashed lines indicate the 90% and 95% confidence levels.
The Fourier analysis for rainfall caused by tropical systems from the SWIO at stations over the northeastern part of South Africa reveals the largest peak at 18 or 19 years, while the largest peak occurs at 27 years for Makoholi in Zimbabwe. This quasi-18-year oscillation is statistically significant above the 90% confidence level for all the South African stations (all the stations except Makoholi – Figure 1).

While the quasi 18-year cycle dominates the periodograms for rainfall contributed by tropical systems, it also remains the most prominent cycle in the annual rainfall and/or statistically significant above the 90% confidence level for the four stations closest to the centre of the area of interest - Pafuri, Musina, Entabeni and Villanora (Figure 1). It is not present in the data for total annual rainfall at Makoholi in Zimbabwe.

Figure 9 shows the 5-year moving average of rainfall contributed by tropical systems from the SWIO for Musina and Entabeni, as well as the corresponding quasi-18-year wave calculated from the wave coefficients derived from the Fourier analysis.
Figure 9  Five-year moving average of rainfall contributed by tropical systems from the SWIO (solid line) at Musina (a) and Entabeni (b) and the 18.6-year cycle calculated from coefficients resulting from Fourier analysis (dotted line).

For both Musina in the Limpopo River Valley and Entabeni on the escarpment, the 18.6-year cycle contributes about 45% of the variation of rainfall associated with tropical systems from the SWIO, over the period 1948 to 2008. Similar results were obtained for the other three stations in South Africa.

Figure 9 also reveals that the peaks in rainfall due to the westward movement of well-defined tropical systems from the SWIO occurred around 1958, 1977 and 1996. These years correspond to the peaks in the quasi-18-year cycle as noted and predicted by Dyer and Tyson (1977). These peaks are also present in the positive values of the 24-month Standardized
Precipitation Index values calculated for the northeastern interior of South Africa (Rouault and Richard 2003). The quasi-18-year climate oscillation, according to Dyer and Tyson (1977), is confined to the subtropical latitudes south of 15°S and is clearest in the band extending from 20 to 30°S across the subcontinent (Tyson et al. 2002). This is also shown by the weakness of this oscillation in the rainfall time series at Makoholi in Zimbabwe compared to the South African stations.

The question arises to what extent periodicities in the rainfall caused by landfalling tropical systems are responsible for the existence of the quasi-18-year cycle in rainfall over northeastern South Africa (and subtropical Africa in general). Figure 10 shows the 5-year moving average of the total annual rainfall for all six stations displayed in Figure 1, as well as the 5-year moving average calculated for the rainfall caused by landfalling tropical systems (expressed as a percentage of the total annual rainfall).
Figure 10  5-year average total rainfall (solid line) and 5-year average percentage of annual rainfall (stippled line) contributed by tropical systems from the SWIO (secondary axis) for Nelspruit (a), Villanora (b), Entabeni (c), Pafuri (d), Musina (e) and Makoholi (f).
The contribution of tropical systems from the SWIO to total annual rainfall ranges between 0 and 30% when considering the 5-year moving averages. It can also be seen that the influence (relative contribution) of these systems is larger during periods of relatively high rainfall. For the South African stations, three distinct peaks are visible in both annual rainfall and the percentage contribution of landfalling tropical systems to the annual rainfall, with these peaks coinciding with the quasi-18-year cycle of Dyer and Tyson (1977). Figure 11 shows the 5-year moving average annual rainfall averaged over all 6 stations, the 5-year moving average annual rainfall with the rainfall originating from tropical systems subtracted, as well as the 5-year moving average annual rainfall contributed by tropical systems from the SWIO.

![Figure 11](image)

**Figure 11** 5-year moving average rainfall for all 6 stations accumulated (thick solid line), 5-year moving average annual rainfall when the contribution of tropical systems from the SWIO is discarded (thin solid line) and the 5-year moving average annual rainfall contributed by tropical systems from the SWIO (dotted line).

It can be seen that the 18-year oscillation is enhanced by the rainfall contributed by the landfalling systems, but that it persists when the rainfall by these systems is subtracted from the time series. The greatest contribution to rainfall by tropical systems occurred during the three peaks of the quasi-18-year cycle. These results, suggest that during wet periods over
southern Africa within the 18-year cycle, atmospheric circulation patterns enhance the potential of landfalling tropical systems to cause widespread heavy rainfall events over the region, however it is not the rainfall contributed directly by these systems that drives the quasi 18-year cycle.

The larger contribution to rainfall by tropical systems from the SWIO during the peaks of the 18-year cycle is consistent with the fact that La Niña-like conditions are associated with these multi-year periods of above-normal rainfall over the summer rainfall region of South Africa (Reason and Rouault 2002), and that La Niña conditions favour the landfall (Vitard et al. 2003) and westward penetration of tropical cyclones into the southern African subcontinent (Reason and Keibel 2004). The largest contribution to rainfall over northeastern South Africa by tropical systems from the SWIO occurred during the last rainfall peak of the quasi 18-year cycle, between 1995 and 2003. The role that landfalling tropical systems play in contributing to wet years over northeastern South Africa is further illustrated by Figure 12, which shows the difference in the average contribution of tropical systems to total annual rainfall for years with above and below-average rainfall considered for all six stations separately over the entire period.

![Figure 12](image)

**Figure 12** Contribution by tropical systems during above-average rainfall years (black) and during years with below-average rainfall (grey).
It may finally be noted that the 18-year peaks in the rainfall data for South African stations represent the contribution of systems that follow a largely zonal (westward) track, whilst the station in Zimbabwe is also influenced by systems that track more northwesterly. For example, during 1962, 1967, 1969 and 1986, tropical cyclones that made landfall moved westward or northwestward over the central parts of Zimbabwe, causing rain over the northern side of the Limpopo River Basin but no rain on the South African side of the Limpopo River Basin. This may explain the relatively smaller contribution of the 18-year peak in the periodogram for Makoholi in Zimbabwe (Figure 8b). Furthermore, the cycle found in the rainfall contributed by tropical systems from the SWIO over the area is not visible in the actual time series of number of tropical systems making landfall and causing at least some rainfall over the area (Figure 3). This is further evidence that the altered conditions during the peaks of the Dyer-Tyson cycle for the period 1948 to 2008 favoured the more zonal movement after landfall of these systems over the interior of southern Africa.

**Conclusions**

Tropical systems from the SWIO contributed less than 10% of the total rainfall occurring over the eastern interior of southern Africa in the Limpopo River Valley over the period 1948-2008. The percentage contribution of these systems to rainfall is highest over the eastern escarpment, from where it decreases to the south and west. When heavy rainfall events over northeastern South Africa are considered, the contribution of tropical systems is far more significant. These systems contribute more than 50% of multi-day heavy rainfall events occurring in the Limpopo Basin (for example, when more than 100 mm is measured within 5 days, simultaneously at three weather stations over the escarpment and Lowveld area of the Limpopo Province in South Africa). The highest 5-day total rainfall values on record both on the escarpment and in the Limpopo River Basin around 30°E are associated with tropical systems from the SWIO.

The contribution to total annual rainfall by these systems over the eastern interior of southern Africa appears to be of a cyclic nature – Fourier analysis of the 5-year moving average of the rainfall time series for the period 1948-2008 shows a statistically significant quasi-18-year cycle in the rainfall contributed by these systems over the northeastern parts of South Africa. The cycle is in phase with the well-known quasi-18-year Dyer-Tyson cycle (Dyer and Tyson 1977). The quasi-18-year cycle also exists with respect to the total annual rainfall occurring...
at weather stations in northeastern South Africa, and persists to occur when the rainfall contributed by tropical systems is subtracted from the time series. This result indicates that tropical systems from the SWIO do not as such drive the Dyer-Tyson cycle, but rather that the atmospheric and surface conditions leading to wet phases of the Dyer-Tyson cycle also favour the landfall and westward movement of tropical systems from the SWIO over southern Africa – and their eventual contribution to rainfall over northeastern South Africa. Indeed, the relative contribution of tropical systems from the SWIO to annual rainfall over northeastern South Africa is higher during wet periods within the 18-year cycle. Although the study of underlying factors causing the cyclicity during the study period is outside the scope of this paper, these results emphasize that the types of rain-bearing systems occurring over southern Africa differ in frequency of occurrence and tracks followed between the wet and dry phases identified through the Dyer-Tyson cycle. These findings can also contribute to the skill of forecasts on the time scale of decadal predictability.

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References


Synopses

The significance of the rainfall contribution by tropical systems from the SWIO over the Limpopo River Basin has now been demonstrated by a collective study of historical events from available data. Specifically, the important contribution by tropical systems from the SWIO to widespread heavy rainfall events emphasizes the significance of the occurrence of these systems over the region. The importance of these systems in causing widespread heavy rainfall over parts of the basin furthermore underlines the need to understand variability of these systems over the region. A significant bi-decadal (quasi-18-year) variability in the influence of tropical systems from the SWIO over the Limpopo River Basin identified therefore also needs to be investigated in terms of broader climate variability. To this end, a link needs to be established between the bi-decadal variability of tropical systems from the SWIO over the Limpopo River Basin and large-scale or even hemispheric circulation anomalies. This notion will be dealt with in the following section which addresses the second objective of the study.
3. Large-scale circulation anomalies of tropical cyclones over the Limpopo River Basin and decadal scale variability

Preface

This section consists of one peer reviewed paper as follows


In this paper, the link between significant rainfall events associated with tropical systems from the SWIO over the area of interest and large-scale circulation patterns is established. Furthermore, the association of hemispheric circulation patterns with rainfall produced by tropical systems from the SWIO over the Limpopo River Basin is investigated. The paper therefore addresses the second objective of the study and is seen as a necessary step towards potentially being able to provide an understanding of bi-decadal variability of the influence over the area of tropical systems from the SWIO. Towards understanding the variability at hemispheric scale, emphasis is placed on the Southern Annular Mode. Furthermore, consistent with results of the previous section, only the January-March period is considered as these months constitute the period during which tropical systems from the SWIO are responsible for rainfall over the Limpopo River Basin.

My co-authors are WA Landman and FA Engelbrecht. I conceptualized the paper, was responsible for data acquisition, all analyses and also the synthesis of the results.
The bi-decadal rainfall cycle, Southern Annular Mode and tropical cyclones over the Limpopo River Basin, southern Africa

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Abstract

The association between decadal-scale rainfall variability over southern Africa and the rainfall contributed by tropical cyclonic systems from the Southwest Indian Ocean (SWIO) provide a potential means towards understanding decadal-scale variability over parts of the region. A multi-decadal period is considered, focusing on the anomalous tropospheric
patterns that induced a particularly wet 8-year long sub-period over the Limpopo River Basin. The wet sub-period was also characterized by a larger contribution to rainfall by tropical cyclones and depressions. The findings suggest that a broadening of the Hadley circulation underpinned by an anomalous anticyclonic pattern to the east of southern Africa altered tropospheric steering flow, relative vorticity and moisture contents spatially during the sub-period of 8 years. These circulation modulations induced enhanced potential for tropical systems from the SWIO to cause precipitation over the Limpopo River Basin. The same patterns are also conducive to increasing rainfall over the larger subcontinent, therefore explaining the positive association in the decadal-scale rainfall cycle and rainfall contributed by tropical cyclonic systems from the SWIO. The regional circulation anomalies are also explained in hemispheric context, specifically the Southern Annular Mode, towards understanding variation over other parts of the Southern Hemisphere at this time scale.

**Introduction**

Rainfall that occurs in association with landfalling tropical cyclones and depressions (hereafter referred to as tropical systems) from the Southwest Indian Ocean (SWIO) over the Limpopo River Basin in southern Africa vary at a decadal time scale, in phase with a similar cycle noted earlier in the rainfall time series over subtropical southern Africa (Malherbe et al. 2012). The cycle, known as the Dyer-Tyson cycle (Dyer and Tyson 1977, Alexander 1995), has been shown to be a feature of southern African rainfall over a period of at least 600 years (Tyson et al. 2002). The ENSO-rainfall relationship in the region (Ropelewski and Halpert 1987, Nicholson and Kim 1997, Reason et al. 2000, Reason et al. 2005) is altered by this decadal-scale variation (Reason and Rouault 2002) in the regional climate with El Niño and La Niña seasons being wetter/drier during multi-year epochs of above-normal/below-normal rainfall (Kruger 1999). The importance of hemispheric-scale anomalies associated with this cycle is implicated by teleconnections with glacial variation over New Zealand (Tyson et al. 1997) since the early part of the 20th century.

Mason and Jury (1997) reviewed regional circulation anomalies associated with (decadal-scale) climatic variability in the southern African region. These include for wetter periods positive anomalies in the geopotential heights of the lower to mid-troposphere over the mid-to subtropical latitudes, especially towards the southwest of the subcontinent over the Atlantic Ocean, and towards the south (Miron and Tyson 1984, Preston-Whyte and Tyson
Positive anomalies throughout the troposphere towards the southeast and east over the Indian Ocean are also associated with wet conditions (Jury 1996, Jury and Nkosi 2000, Hofmeyer and Gouws 1964, Washington and Preston 2006). This association results from increased easterly flow causing enhanced westward and southwestward advection of moist air from the SWIO (D’Abreton and Lindesay 1993, Matarira and Jury 1992, Jury 1996) and concurrent increase in barotropic instability responsible for a higher frequency and growth rate of tropical disturbances (Mulenga et al. 2003). Furthermore, there is a southward shift in the occurrence of westerly winds (including the Jet stream at 200 hPa) that would advect dry air from the Atlantic Ocean towards the southern parts of the subcontinent if located further north (D’Abreton and Lindesay 1993, Richard et al. 2001, Mulenga et al. 2003). The anticyclonic anomaly to the southeast and east of southern Africa that characterizes wet summer seasons is replaced by a cyclonic anomaly in the same area during dry conditions (Richard et al. 2001). This is the case for non-ENSO-related droughts as well as for ENSO-related droughts (Mulenga et al. 2003, Pezza and Ambrizzi 2003, Richard et al. 2000). To the east of the subcontinent during ENSO warm events, vorticity advection by storms in the westerlies tracking further north is responsible for the development of a Rossby wave to the east of southern Africa (Cook 2000), which could result in anomalously low rainfall over the subcontinent.

The decadal-scale geopotential anomalies over the oceanic regions surrounding southern Africa can be attributed to the influence of planetary standing waves 1 and 3 (Trenberth 1980, Tyson 1981, Jury 1996) which may be modulated by large-scale SST anomalies in the Eastern Pacific (Hurrell and van Loon 1994). The association with planetary standing waves indicates a mid- to high latitude influence on the regional subtropical climate variability (Mason and Jury 1997). The principal mode of variability between the extratropics and high latitudes in the Southern Hemisphere (SH) is the Southern Annular Mode (SAM – Limpasuvan and Hartmann 2000). Positive pressure anomalies over the mid-latitudes throughout the troposphere are more prominent during the positive phase of the SAM. Hence, a positive association between rainfall over much southeastern southern Africa and the SAM exists (Gillett et al. 2006). This positive association of SAM with rainfall is also present at subtropical latitudes of Australia and South America, whilst a negative relationship holds for the southern parts of South America and New Zealand (Gillett et al. 2006) as well as the winter rainfall region of southern Africa (Reason and Rouault 2005). While it is influenced
by ENSO (L’Heureux and Thompson 2006, Gong et al. 2010), the SAM is also positively (negatively) correlated to ENSO cold (warm) event teleconnections towards the high southern latitudes (Fogt et al. 2011).

A higher frequency of tropical systems tracking into the interior over the Limpopo River Basin was responsible for an increase in major flood events (e.g. Crimp and Mason 1999, Dyson and van Heerden 2002, Reason and Keibel 2004) during the 1995-2003 period (Malherbe et al. 2012). This was consistent with a predicted increase in rainfall during this period as per the aforementioned decadal-scale rainfall variation (Dyer and Tyson 1977, Tyson et al. 2002). Large-scale circulation anomalies such as the Pacific-Decadal Oscillation and Atlantic Multi-decadal Oscillation have been shown to cause decadal-scale variability in the tracks of tropical cyclones over the Atlantic and Pacific Oceans (Chu 2002, Liu and Chan 2008, Matsuura et al. 2003, Kubota and Chan 2009, Goldenberg et al. 2001). This happens through forcing of variables important to tropical cyclone tracks such as steering flow (defined to be the weighted average flow between 850 hPa and 200 hPa), moisture availability, SSTs, large-scale vorticity as well as vertical wind shear (Chan 1985, Holland 1982, 1984, Becker et al. 2010). ENSO also affects the tracks of tropical cyclones over all ocean basins through the remote forcing of genesis parameters and circulation patterns (Gray 1984, 1988, Chan 1985, Vitart et al. 1999, Camargo et al. 2007). In the SWIO towards the north of 20ºS in particular, large-scale lower-level vorticity becomes anomalously positive in response to ENSO, diminishing dynamic potential for the development of tropical cyclones in the region (Vitart et al. 1999). In general over the SWIO, a southward shift of upper air westerlies, increased easterly trade winds and a strengthened Hadley circulation are characteristic of summers with more tropical cyclones (Jury 1993). Furthermore, an anomalously strong easterly flow to the east of the subcontinent in the subtropics increases the chance of tropical cyclone landfall (Vitart et al. 2003).

Extensive research has been performed on the influence of SWIO variability on southern African rainfall (e.g. Jury and Nkosi 2000, Reason 2002, Washington and Preston 2006). This paper will describe the synoptic circulation anomalies associated with the most recent surge in direct influence of tropical cyclonic systems from the SWIO on southern Africa, within the context of the maximum in the decadal-scale Dyer-Tyson cycle during the late 1990s. The decadal-scale cycle in the frequency of occurrence of landfalling tropical systems over
southern Africa is also placed within the context of circulation anomalies of the SH, specifically the SAM.

**Data and Methodology**

NCEP Reanalysis I data (Kalnay *et al*. 1996) at a 2.5° spatial and daily temporal resolution for the years 1979 to 2011 are used in the analysis of large-scale synoptic fields over the Area of Interest (AOI – Figure 1). The geopotential heights at 17 standard pressure levels are considered.

![Map of southern Africa and surrounding regions](image)

*Figure 1* Area of interest (the Limpopo River Basin is indicated as well as 6 rainfall stations used later in the analysis).

Data are firstly considered for the period 1979 to 2011 for the analysis of regional anomalies, due to the superior quality of the data since the inclusion of more surface observations over the southern high latitudes since the early 1970s (Hines *et al*. 2000) and inclusion of satellite data from 1979 onwards (Kanamitsu *et al*. 1997, Sturaro 2003, Tennant 2004). Since landfalling systems which cause high rainfall totals over the Limpopo River Basin only occur during the three-month season of January through March (JFM – Malherbe *et al*. 2012), our
study will subsequently focus on this part of the austral summer season. During this period, tropical systems in general control the summer circulation to a large extent (Preston-Whyte and Tyson 2000). Rainfall data for the period, representing parts of the Limpopo River Basin, are considered for six rainfall stations with locations indicated in Figure 1.

The study firstly employs a Self Organizing Map (SOM) analysis (Kohonen 2001) towards understanding synoptic circulation associations with landfall events of tropical systems resulting in rainfall over the Limpopo River Basin. The analysis using SOMPAK 3 (Kohonen et al. 1996) is performed to classify regional synoptic patterns of geopotential heights, for each of the standard atmospheric levels from 1000 hPa to 30 hPa separately. The analysis is performed on the standardized values to compensate for latitudinal difference in magnitude of variation. By studying the synoptic-scale patterns associated with the nodes of the SOM analysis, and taking the error when associating synoptic conditions with the SOM nodes into account, it was decided to use a 25-node 5X5 SOM. The nodes resulting from the SOM analysis are evaluated in terms of the percentage of days with landfalling systems relative to the total number of days represented by that node. The yearly JFM time series of the nodes are considered towards identifying the presence of synoptic-scale variability supporting the prominence of rainfall caused by tropical systems from the SWIO during a sub-period. Any grouping of the resulting SOM nodes is done by classifying the existing 25 nodes resulting from SOM analysis again using the SOM analysis software.

A change-point analysis (Taylor 2000, Cram et al. 2003) is performed on the normalized yearly rainfall contributed by tropical systems from the SWIO at the six stations (Figure 1). Identification of these systems and associated rainfall are detailed in Malherbe et al. (2012). The results of the change-point analysis, supported by the SOM node time series, are used to identify the specific sub-period during which tropical systems from the SWIO contributed significantly more rain than the climatological average. Various tropospheric variables are then considered and contrasted to the rest of the 1979-2011 period. These variables, important to the movement of tropical systems and rainfall over southern Africa, are: low level and upper air geopotential height, 700-500 hPa steering flow, 850-250 hPa wind shear, low level relative vorticity and relative humidity at 600 hPa. Statistical significance is determined by comparison of results to a thousand randomized time series generated through Monte Carlo simulations (Wilks 2011), from the observed annual JFM averages for the same period.
Certain large-scale anomalous circulation features characterizing the wet sub-period are subsequently considered together with the SAM, to identify possible global characteristics of the decadal variation observed in rainfall data. This is done for the entire 1948-2011 period, spanning the period of data availability of NCEP Reanalysis I. Here, the SAM is calculated by taking the difference between the normalized 850 hPa height anomalies per grid point between 40°S and 65°S. These are the same latitudes used by Gong and Wang (1999) in their calculation of the SAM from Sea Level Pressure data. Ho et al. (2012) found the station-based index by Marshall (2003) to be superior to reanalysis-based definitions. For the period of station data availability (1958-2012) for that index, the Pearson correlation between the SAM calculated for JFM in the present study with the station-based index is 0.85.

The study ends with an overview of circulation anomalies over the southern African region during decadal-scale wet and dry epochs over the entire 1948-2011 period. Trends in the average JFM geopotential height as well as U and V vectors during this period are calculated for each gridpoint using the method of pairwise slopes (Lanzante 1996). These trend values are subsequently used to detrend the 1948 to 2011 JFM geopotential, U and V vector values prior to analysis. The detrended data are used to calculate the association between the (detrended) SAM and circulation anomalies in the southern African region. Finally, for each wet/dry epoch, anomalies are calculated relative to the rest of the detrended time series.

The correlation between Austral summer rainfall over the AOI (Figure 1) and ENSO is well established (Ropelewski and Halpert 1987, Nicholson and Kim 1997, Reason et al. 2000, Reason et al. 2005). While no significant correlation exists between the SAM and ENSO during JFM or any of the individual months December through April (Pohl et al. 2010), caution is advised when attributing an apparent correlation between summer rainfall during November-to-February to the SAM while it is in fact a result of ENSO variability. The focus of the current research is decadal scale variability, focusing on circulation patterns in the JFM season. While associations between ENSO and rainfall is expected on inter annual basis, the interest of the current research rather lies in the multi-year variability, noticeable also in the regional anomalies and impact associated with ENSO and which may also be detected in rainfall at a multi-year timescale. An example of a similar situation in the Northern Hemisphere is the modulating effect the North Pacific Oscillation has on the impacts of ENSO over North America (Gershunov and Barnett 1998). A Fourier analysis is therefore
performed for low-frequency (5-year and longer) variability of the JFM SAM, JFM rainfall and the JFM SOI.

**Results and Discussion**

*Synoptic circulation associations with landfalling tropical systems*

The total number of landfalling tropical systems responsible for rain over the area of interest during 1979-2011 is 18 (Malherbe *et al.* 2012). The associated synoptic sequences associated with these systems are represented by 110 days out of a total of 3240 days (90 days per JFM season over 33 years). Based on the percentage representation of these 110 days within each of the 25 nodes, landfall of tropical cyclonic systems causing rainfall over the Limpopo River Basin is found to be associated with very specific anomaly patterns from the 1000 hPa to 100 hPa levels. Above the 100 hPa level, trends in the time series during the study period dominate the results for these levels and are excluded from further analysis.

The results of the SOM analysis for the 850 hPa and 250 hPa levels are shown in Figure 2a and 2b. This provides a summary of the associations found through the troposphere, focusing on favourability of synoptic conditions for landfall and also rainfall contributed by tropical systems over the Limpopo River Basin. The Sammon map is shown for both these levels also with an indication of the extent to which each of the nodes favours the synoptic sequence (landfall, propagation into the subcontinent): darker (lighter) shades indicate more (less) favourable synoptic conditions. The distances between the nodes in the Sammon map is an indication of how much the various synoptic states associated with each node differ from the synoptic states associated with surrounding nodes in terms of spatial distribution and size of anomalies.
Figure 2a SOM based on the standardized values with lighter (darker) shades showing positive (negative) deviations for the 850 hPa level (top), and Sammon map (bottom) showing the concentration of days of landfall events for each of the identified nodes. In the Sammon map, darker shades represent a higher concentration of days with landfall events. Numbers on the Sammon map correspond to the numbers of the nodes in the SOM.
Figure 2b  As for Figure 2a, but for 250 hPa.
Results are more coherent with increasing height from 850 hPa to 100 hPa (not shown), with a more distributed occurrence of favourable versus unfavourable nodes at the lower levels. The following main circulation categories, and their relation to landfall, may be indicated:

The patterns at the 850 hPa to 100 hPa levels that are associated with landfall events are:

- Negative deviations in height to the north of southern Africa associated with weak or strong positive deviations to the south of the country;
- Positive deviations towards the southeast of the subcontinent and negative deviations towards the southwest of the subcontinent.

The patterns at the 850 hPa to 100 hPa levels that are not associated with landfall events are:

A. Positive deviations in height to the north of southern Africa associated with weak or strong negative deviations to the south of the country;
B. Negative deviations towards the southeast of southern Africa.

These SOM results indicate an association in landfall events with anticyclonic anomalies towards the south and southeast of southern Africa and cyclonic anomalies over the subcontinent. These anomalies are also associated with above-normal rainfall over much of southern Africa (Tyson 1981).

Decadal-scale variability of synoptic nodes

Based on the 4 synoptic circulation patterns relevant to landfall of tropical systems from the SWIO and movement into the Limpopo River Basin, as identified above, the 25 SOM nodes at each standard level have been reclassified into 4 groups:

- Negative deviations in height to the north of southern Africa associated with weak or strong positive deviations to the south of the country (subsequently referred to as Pattern A+);
- Positive deviations in height to the north of southern Africa associated with weak or strong negative deviations to the south of the country (Pattern A-);
- Positive deviations towards the southeast of the subcontinent and negative deviations towards the southwest of the subcontinent (Pattern B+);
- Negative deviations towards the southeast of southern Africa (Pattern B-).

Pattern A+ (-) is an indication of positive (negative) anomalies over a wide region to the south of southern Africa, stretching from 20°W to 60°E. Pattern B+ (-) is an indication of positive (negative) anomalies specifically towards the southeast and east of southern Africa,
between 30°E and 60°E. Fig. 3 shows the percentage of days with which tropical systems making landfall and tracking into the Limpopo River Basin are associated within each of the four groups (Pattern A +/- and Pattern B +/-) with height.

![Figure 3](image)

**Figure 3** Variation in concentration within each of the four SOM groups (indicated at the top) of landfall-event days per pressure level. The pressure levels are represented on the vertical from bottom (1000 hPa) to top (100 hPa).

The frequency of occurrence of landfall days is indicated in Figure 3 with higher (lower) concentration shown in darker (lighter) shades. Throughout the troposphere, the positive anomalies in pressure for the entire region to the south of the subcontinent (Pattern A +) or to the southeast only (Pattern B +) are associated with rainfall contributed by tropical systems from the SWIO over the Limpopo River Basin as opposed to the other two patterns. At the lower levels (from 1000 hPa to about 400 hPa), Pattern A is most strongly associated with landfall (largest contrast in concentration found between the far left and far right in Figure 3). From 300 hPa to 100 hPa, the strongest contrast is associated with Pattern B (largest contrast between the middle left and middle right). To summarize, this indicates that while anomalously high pressure towards the southern parts of the region of interest favours landfall and precipitation contribution by tropical systems, positive anomalies towards the
southeast specifically becomes more important with increasing height, indicating (together with lower-level anticyclonic anomalies over the larger region to the south) the presence of a deep anticyclonic anomaly throughout the troposphere in that region. Tropical systems moving into the Limpopo River Basin only occurred on roughly 4% of the total number of days during JFM over the 33-year period, resulting in the seemingly low percentages association with the 4 groups in Figure 3.

Change-point analysis based on the average normalized rainfall at the stations over the Limpopo River Basin (Figure 1) contributed by tropical systems from the SWIO indicates that the period 1995 to 2002 can be considered to be anomalous from the rest of the time series spanning the period 1979 to 2011, with a significance exceeding the 90% level of confidence. The rest of the analysis will focus on this period, based on the altered contribution to rainfall by tropical systems.

As the association of the deep anticyclonic anomaly towards the southeast of southern Africa with tropical cyclone landfall and precipitation over the Limpopo River Basin has now been identified, the variation of this anomaly (occurrence of Pattern B) on all the levels up to at least 100 hPa determined through SOM analysis, is considered. This is done towards understanding the higher concentration of landfall and a larger contribution to rainfall over the eastern parts of the subcontinent during the 1995-2002 period. Figure 4 shows the yearly total rainfall contributed by tropical systems from the SWIO, averaged over the 6 stations in the northeast of South Africa and southern Zimbabwe (Figure 1). Also shown is the time series of the balance of positive and negative occurrences (number of days with positive minus number of days with negative) of Pattern B as averaged over the entire 250-100 hPa depth. El Niño and La Niña events (NOAA Web Page 2012) are also indicated.
The occurrence of anticyclonic anomalies towards the east of the subcontinent (Pattern B+) reaches a maximum during the 1995-2002 period. The variation in time of this pattern (Figure 5) over time is influenced by the occurrence of ENSO, but further also displays a modulation causing it to be more prevalent during La Niña / El Nino events from 1993 to 2002 compared to the rest of the time series. This is not the case for Pattern A (not shown). The variation since 1979 of Pattern B, as an average over all standard pressure levels up to 100 hPa, is also reflected at the individual levels (not shown). Variations in the geopotential pattern are visible throughout the troposphere up to 100 hPa (not shown), with a maximum from 1993 to 2002. This maximum is consistent with the change-point analysis which indicates that much of this period was characterized by enhanced contribution of rainfall by tropical systems from the SWIO. The average low level (850 hPa) and upper air (250 hPa) geopotential height anomalies for the period 1995-2002 relative to the average for the rest of the 1979-2011 period (Figure 5) is a further reflection on the anomalous occurrence of certain nodes as indicated by the SOM time series in Figure 5.
The 850 hPa height anomalies reflect the same patterns as those associated with the earlier multi-year wet periods (Tyson 1981, Reason and Rauoult 2002) and ENSO cold events (Reason et al. 2000). Negative anomalies over the subcontinent and positive anomalies towards the south dominate. At 250 hPa the most outstanding feature is the anticyclonic anomaly to the east of southern Africa as well as negative anomalies towards the southwest of the subcontinent, or Pattern B+ from the SOM analysis, already shown to be more frequent during this period (Figure 4). Positive anomalies in geopotential height towards the eastern parts of the AOI throughout the troposphere occur during years of anomalously easterly flow, associated earlier with positive rainfall anomalies over southern Africa (Jury and Nkosi 2000). Stronger west winds are further located towards the south of this anomaly. Considering now the vertical profile of zonal wind anomalies, for the same sub-period, Figure 6 shows the zonal wind anomalies to the east of southern Africa at 40°E, near the east coast of Africa.
Figure 6  Average zonal wind along 40°E during the 1995-2002 period (solid contours, units: ms$^{-1}$), compared to the rest of the 1979-2011 period (dashed contours) and the difference (shaded).

The zonal flow anomalies during the 1995-2002 period, calculated with respect to the remaining years of the 1979-2011 period, display the following characteristics:

- Intensification of subtropical easterlies in the lower to middle troposphere and intensification of westerlies to the south;
- Southward contraction or weakening of the Jet stream from north of 35°S;
- Stronger upper air Jet stream towards 50°S;
- Stronger Equatorial upper easterly Jet stream;
- Stronger Equatorial westerlies in the lower to middle troposphere.

These zonal anomalies show a broadening in the Hadley cell and a Walker circulation anomaly during this period. This feature in the zonal flow is visible over a wide area surrounding southern Africa. The anomalously easterly flow over the subtropics (40°S to 15°S) and westerlies further south (55°S to 45°S) are visible throughout the column below 100 hPa. The boundary between the relatively westerly flow towards the south and the relatively easterly flow towards the north around 40-30°S throughout the column represents the center of the deep anticyclonic anomaly. In the middle troposphere it is significant above
the 95% confidence level for the 1995-2002 period and above 99% confidence level for the 1993-2000 period (Figure 7).

![Figure 7](image_url)

**Figure 7** Time series of normalized difference in zonal wind (40-15°S minus 55-45°S) at 600 hPa (black solid line), 3-year moving average (broken line) and level of significance (secondary y-axis) exceeding 90% for moving 8-year above-average value (light grey bars) and 8-year below-average value (dark grey bars).

Other features visible in Figure 8 such as the weakening and southward displacement of the upper air subtropical Jet stream with a strengthening towards 50°S as well as the Walker cell anomaly (Figure 6) are also associated with wetter conditions over southern Africa (Tyson 1981, Tyson et al. 1997). These however don’t attain a level of significance exceeding 95% during the sub-period. It is concluded that especially the broadening of the Hadley circulation, associated with the deep anticyclonic anomaly to the east of the subcontinent, defines the contrasting tropospheric conditions within the region during the 1995-2002 period.
Implications of variable synoptic conditions for tropical systems

Steering flow, low-level convergence, mid-tropospheric relative humidity, low level relative vorticity and vertical wind shear are all factors considered important to tropical cyclone tracks and intensity. These will now be considered for the 1995-2002 sub-period relative to the rest of the 1979-2011 period. The 700 hPa to 500 hPa levels have been singled out over the SWIO as important steering flow level for tropical cyclones SWIO (Jury and Pathack 1991). Figure 8 shows the anomalous steering flow during the sub-period.

![Figure 8](image)

**Figure 8** Difference wind vectors (scale shown, units: ms⁻¹) of the 700-500 hPa flow for the period 1995-2002 (difference in zonal component shaded, units: ms⁻¹) compared to the rest of the 1979-2011 period.

Wind vectors over much of the mid-latitudes and subtropics, between 45°S and 15°S, are anomalously east (Figure 8). The strengthened easterlies over the subtropics at these levels indicate an enhanced westward steering flow for tropical systems during the 1995-2002 sub-period into the subcontinent. The mid-level cyclonic anomaly over northern Namibia / southern Angola in Figure 8 represents the deepening of the Angola Low, which is located on the northern flank of the anomalously easterly flow. The strengthened easterly flow is also reflected from the surface to the upper troposphere (not shown). On the northern flanks of enhanced easterlies there is a large elongated area of increased convergence at 850 hPa and

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increase in relative humidity (RH) at 600 hPa (Figure 9), showing a southward displacement of the Inter-tropical Convergence Zone (ITCZ). This is visible over both the subcontinent and SWIO, but most strongly in the area of intensification of the Angola low.

![Diagram of 850 hPa convergence and RH anomalies](image)

**Figure 9**  Difference in 850 hPa convergence (shaded, units: s\(^{-1}\)) and difference in relative humidity at 600 hPa (white contours, units: %). 850 hPa wind vector anomalies for the period 1995-2002 relative to the remaining years in the period 1979-2011 are also indicated (scale shown).

An increase in RH, as seen from the 600 hPa anomaly over much of southern Africa including the Limpopo River Basin (Figure 9), is associated with the enhanced easterly flow in the lower to mid-troposphere into southern Africa together with the southward displacement of lower-level convergence. The anomalous circulation pattern therefore enhances zonal transport of moisture and a southward displacement of the ITCZ over Africa. The increase in RH over Africa and towards Madagascar also indicates increased thermal potential for the development and sustenance of tropical systems over these areas.

The boundary between the increased easterly flow over a large part of the subtropics and anomalously westerly flow towards the north of 15°S (Figure 8) identifies an area of enhanced negative relative vorticity (Figure 10).
Negative vorticity is enhanced in the region of the Angola Low, stretching zonally eastward to northern Madagascar and further east into the SWIO along the northern edge of enhanced easterlies. This region (around 15°S) over the SWIO is important for cyclogenesis and anomalous negative vorticity represents an increase in dynamical potential for development of tropical cyclones, a situation associated with ENSO cold events (Vitart et al. 1999). Furthermore, wind shear between 850 hPa and 200 hPa increases over southern Africa towards the north of 15°S and towards the south of 30°S, with smaller increases over much of the 30-15°S region, and even a decrease over much of the Limpopo River Basin and into the SWIO crossing southern Madagascar. This relative decrease in wind shear and enhanced negative vorticity over much of subtropical southern Africa represent dynamical features conducive to the development of tropical systems over the SWIO and also into the Limpopo River Basin. The intensification of the Angola Low together with increased moisture and low level convergence over much of southern Africa further represent more favourable conditions for rainfall over the Limpopo River Basin and in fact much of southern Africa (Preston-Whyte and Tyson 2000).

Figure 10 Difference in 850 hPa relative vorticity (shaded), winds shear between 850 hPa and 200 hPa (black contours) and wind vectors for the period 1995-2002 relative to the remaining years in the period 1979-2011.
The increase in positive vorticity towards the southeast of the subcontinent where the deep anticyclonic anomaly occurs has important implications for moisture transport and rainfall over the southern African region. It is over this part of the SWIO where negative vorticity advection due to transient eddies in the westerlies, leading to the development of the mid-latitude Rossby wave, has been indicated to enhance dry conditions over the subcontinent during ENSO warm events (Cook 2000). The anticyclonic anomaly over this area therefore represents a modulation in the regional atmosphere important to ENSO teleconnections over southern Africa.

**Decadal-scale variation within context of circulation of the hemisphere**

Over the Southern Hemisphere, the sub-period 1995-2002 is associated with positive geopotential height anomalies over much of the mid-latitudes and negative anomalies over Antarctica, throughout much of the troposphere. While evident throughout much of the troposphere, this is demonstrated for the 500 hPa level in Figure 11.

![Figure 11](image.png)

**Figure 11** Difference in 500 hPa geopotential heights (units: m) for 1995-2002 compared to the remaining years of the 1979-2011 period.
The positive tropospheric anomalies in the southern African sector in the mid-latitudes are reflected across the SH mid-latitudes, indicating a positive SAM relative to the rest of the period. This supports the finding that the rainfall over eastern-southern Africa is positively correlated to the SAM (Gillett et al. 2006). The positive phase of the SAM is further also associated with a southward positioning of the mid-latitude Jet stream (Limpasuvan and Hartmann 2000), noticed also specifically towards the east of southern Africa during this period (Figure 6).

Considering now the period 1948 to 2012, there are indications that similar large-scale features were associated with multi-year wetter periods. These periods were also characterized by more frequent occurrences of tropical cyclones responsible for extensive rainfall over the Limpopo River Basin (Malherbe et al. 2012). The anomalies over the African and New Zealand sectors (Figure 11) are of particular interest. In the region of New Zealand the 1995-2002 positive anomalies in geopotential height over and to the east of the country relative to the full 1979-2011 period are, in correspondence to Tyson et al. (1997), more closely associated with the decadal-scale (18-20 years) retreat of the Franz Jozeph Glacier. These authors also indicated the anomalies surrounding southern Africa (Figure 12) to be associated with wetter conditions over much of the subcontinent. Tyson et al. (1997) further indicated that these multi-year anomalies recurred together on decadal time scale throughout the 20th century up to 1996 and could be related to changes in the amplitude and position of troughs and ridges of SH standing wave 3. The present study shows evidence that this oscillation of anomalies has subsequently persisted until 2011. The glacial advances/accumulation of the Tasmanian Glacier, located relatively close to the Franz Joseph Glacier, has subsequently been shown to have a negative association with the SAM (Purdie et al. 2011) while Gillett et al. (2006) showed these southern areas of New Zealand to be warmer and drier when the SAM is positive. Indications that the variation in JFM rainfall over the Limpopo River Basin varies on 18-20 year time scale with the SAM will therefore be considered in this paper.

During the 1979-2011 period the most recent peak in the rainfall cycle in the decadal range over the Limpopo region is associated with an anticyclonic anomaly to the east of southern Africa. This is detected in the zonal wind anomaly in that region with stronger westerlies towards the south of 45°S and anomalously easterly flow towards the north of 45°S. On hemispheric scale, this is part of a tendency for anticyclonic anomalies over the mid-latitudes,
associated with a positive SAM. Three features of the climate system regionally and on hemispheric scale, that have been considered earlier for the 1979-2011 period, are now considered for the entire period of 1948-2011:

- The geopotential height anomaly at 250 hPa east of southern Africa: (30-70°E, 45-25°S);

- Difference in normalized zonal flow throughout the 700-300 hPa column (30-70°E: 45-15°S minus 55-45°S). Positive values are associated with easterly anomalies towards the north and westerly anomalies towards the south, associated with anticyclonic anomalies throughout the 700-250 hPa column;

- Southern Annular Mode: Difference between normalized height anomalies at 850 hPa between 40°S and 65°S.

The positive trend in the SAM in reanalysis data is a well-known feature (Marshall 2003). Positive linear trends revealed by each of the three time series (listed above) are removed for time series analysis by subtracting the first order polynomial regression equation fitted to each time series. Figure 12 shows the time series of the variation in the SAM and the relative strength of the anticyclone to the east of southern Africa as well as the associated anticyclonic flow anomaly throughout the troposphere, calculated as the difference in normalized tropospheric flow (30-70°E: 45-15°S minus 55-45°S) from 700 hPa to 300 hPa. Rainfall over the region from the continuous dataset for the 6 stations (Figure 1) is also shown.
Figure 12  Top: Detrended time series of the SAM (grey bars), geopotential height anomaly (30-70°E, 45-25°S – solid line) and anticyclonic zonal flow anomaly throughout 700 to 300 hPa (30-70°E: 45-15°S minus 55-45°S – broken line) for the 1948-2012 period. Bottom: 5-year filtered SAM (black line – secondary y-axis), geopotential height anomaly at 250 hPa (dark grey line – secondary y-axis) and zonal flow anomaly throughout 700 to 300 hPa (light grey line – secondary y-axis), 5-year filtered normalized total seasonal rainfall (grey bars – secondary y-axis) and normalized rainfall contributed by tropical systems from the SWIO (black bars – primary y-axis) over stations (Figure 1) in the Limpopo River Basin.

Figure 13 shows the positive association between the SAM and a deep anticyclonic anomaly to the east of southern Africa. This anomaly is associated with multi-year periods with enhanced late summer rainfall and also enhanced rainfall contributed by tropical systems from the SWIO as also indicated in Figure 13. Three multi-year periods of anomalously positive SAM and associated regional circulation features with related above-normal rainfall are centred around 1958, 1976 and 1997, coinciding with the maxima within the decadal-scale rainfall cycle (Dyer and Tyson 1977). Also, from reconstructed SAM indices spanning 53 and 119 years, Yuan and Yonekura (2011) report significant peaks at 16 and 18 years for autumn and at 9 years for summer – both these seasons are considered partially in the JFM time series. The negative association of multi-year rainfall over the eastern parts of southern Africa with glaciation over southern New Zealand (Tyson et al. 1997) can therefore also be attributed to this variation in the SH, as a negative correlation between net accumulation of
glaciers in that region and the SAM exists (Purdie et al. 2011). The correlation between the three time series in the southern African region in Figure 13 is significant (Table 1).

Table 1  Correlation between the SAM, anticyclonic geopotential height anomaly towards the east of southern Africa (30-70°E, 45-25°S) and the anticyclonic zonal flow anomaly (difference in normalized zonal flow throughout the 700-300 hPa column (30-70°E: 45-15°S minus 55-45°S). Significance above the 90% and 95% levels of confidence is indicated by single and double asterisks, respectively. The period 1948-2011 is considered.

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The significant correlations indicated in Table 1 support previous findings over the SWIO and southern African region. The anticyclonic anomaly throughout the troposphere towards the east of southern Africa is associated with above-normal SSTs over this part of the Indian Ocean (Jury and Nkosi 2000), which therefore also have a positive correlation with rainfall over southern Africa (Reason and Mulenga 1999). These positive SST anomalies, when associated with a positive South Indian Ocean subtropical dipole event, are further also suggested to be associated with the SH standing wave pattern and SAM (Hermes and Reason 2005). While the SAM influences the ENSO teleconnection towards high latitudes (Fogt et al. 2011), the correlation between the SAM and anticyclonic anomaly to the east of southern Africa is further evidence for modulation of potential regional responses to ENSO as part of large-scale hemispheric anomalies. The correlation between the SAM calculated at 850 hPa and the 250 hPa height and 700-500 hPa flow anomaly in the southern African region is shown in Figure 13. These variables have all been considered earlier for the 1979-2011 period. Also shown is the result of a Fourier analysis performed on the 5-year moving average JFM rainfall and JFM SAM for the period 1948-2011.
The significant positive correlation between the SAM calculated at 850 hPa and the 250 hPa height anomaly around 40°S is to be expected. More importantly though is the relatively large positive correlation towards 60°E as well as the large extent northward over the SWIO of these positive anomalies. Steering flow trends are easterly throughout most of the region towards the north of 45°S. To the north of this region of anomalously easterly flow, the circulation becomes more cyclonic over the northern parts of Namibia. These trends closely resemble the anomalies observed during the 1995-2002 period relative to 1979-2011
(Figure 5). The Fourier analysis further indicate that the 5-year moving average SAM and JFM rainfall time series both display significant peaks at the ~20-year period.

Figure 14 is a summary of regional 250 hPa height and 700-500 hPa steering flow anomalies over the southern African region from 70°S to 10°S also for the entire 1948-2011 period. Data are subdivided into 9 or 10-year periods, staying with the 18-20 year Dyer-Tyson cycle, supported also by the findings in this paper (Figure 12, 13). It supports the result of the Fourier analysis (Figure 13) and provides further insight into the decadal-scale variability in the SAM and regional anticyclonic anomaly shown in Figure 12.
Figure 14  500-700 hPa steering flow anomaly vectors (scale in ms\(^{-1}\) shown for each map) with U-component shaded (red – positive, blue – negative, units: ms\(^{-1}\)), and 250 hPa height anomalies (contours) for alternating wet (left) and dry (right) multi-year epochs as indicated. Contour intervals are 5 m; dark (light) contours are for negative (positive) anomalies. The positions of prominent ridges at 850 hPa are also indicated (broken black/yellow lines). Inter-quartile ranges for rainfall (units: % of average during JFM) as average for all 8 stations in Fig. 1 and the SAM are indicated per epoch for comparison in box plots. The average annual rainfall contributed by tropical systems (TCR, units: mm) from the SWIO calculated as an average for the eastern stations (dark circles in Fig. 1) is also indicated per epoch.
Figure 14 shows that low frequency, decadal-scale circulation features over the southern African region have alternated between patterns conducive to wet conditions (and increased rainfall contributed by tropical systems from the SWIO) and patterns conducive to drier conditions (with less rain contributed by tropical systems from the SWIO). The wet patterns (left hand side of Figure 14) resemble the correlation map (Fig 13) indicative therefore of features more strongly associated with a positive SAM during JFM. This is also indicated by the inter-quartile ranges of the SAM for each epoch. Most noteworthy is the dominance of westerly anomalies in steering flow towards the south of 40°S and strengthened easterly anomalies to the north of 40°S during the wet epochs. These are reversed during the dry epochs.

Other features of the alternating near-decadal epochs include for wet (dry) conditions:

- Cyclonic (anticyclonic) flow anomalies dominating over the subcontinent to the north of the anomalously easterly (westerly) flow – indicated with “C” (cyclonic) or “A” (anticyclonic);
- Large areas of positive (negative) geopotential height anomalies throughout the troposphere centered near 40°S, between the anomalously westerly (easterly) steering flow to the south and easterly (westerly) flow towards the north.

Considering the steering flow and 250 hPa height anomalies towards the east of southern Africa near 40°S, the wet epochs have always been dominated by deep anticyclonic anomalies and replaced by cyclonic anomalies during the dry epochs. Positive anomalies in this region are also associated with the movement of tropical cyclones and depressions into the Limpopo River Basin (Figure 2 – 4) and therefore further explain the larger contribution to rainfall (Figure 5 and “TCR” in Figure15) by these systems during the wet sub-periods.

**Conclusions**

Several tropospheric anomalies were responsible for higher rainfall and also a larger contribution to rainfall by tropical cyclones and depressions over the Limpopo River Basin during the 1995-2002 period. These circulation anomalies are also associated with ENSO cold events and positive SAM. The main feature of this wet period is a broadening of the Hadley Cell with a deep anticyclonic circulation anomaly (at 40°S) towards the east of the subcontinent. This feature has been shown to be associated with higher tropical cyclone
activity in the SWIO basin (Jury 1993, Jury et al. 1999) and has the following consequences related to tropical systems from the SWIO:

- Enhanced dynamic potential (negative vorticity and relatively smaller vertical wind shear) for the development of tropical systems over the SWIO as well as over the southern African subcontinent (Vitart et al. 1999);
- Enhanced easterly steering flow directing tropical systems towards southern Africa and also responsible for further inland penetration – related also with higher landfall risk (Vitart et al. 2003);
- Increased moisture content of the lower to middle troposphere towards the southern parts of southern Africa due to low-level convergence over the region and stronger subtropical easterlies – increasing the tropospheric potential for tropical systems moving into the subcontinent to be sustained (Mulenga et al. 2003);
- A southward shift in both the upper air Jet stream and upper air troughs east of the subcontinent (west wind trough formation east of South Africa interacts with the vorticity field (Becker et al. 2010) and steering flow of tropical cyclones in the SWIO, thereby inhibiting the westward trajectory towards and into the Limpopo River Basin).

Conditions become favourable for above-normal rainfall over much of the subcontinent as the Angola Low strengthens (Tyson 1981, Cook et al. 2004). This happens in a band of enhanced negative vorticity and low-level convergence on the northern edge of stronger subtropical easterlies with increased moisture advection over the subtropical subcontinent. The result is that the period associated with above-average rainfall as identified by the Dyer-Tyson cycle in the region is also characterized by an increase in tropical cyclones and depressions penetrating the subcontinent (Malherbe et al. 2012) as both result from so-called ENSO-like decadal-scale variability (e.g. Reason and Rouault 2002). The implications are that more tropical cyclones and depressions penetrate the subcontinent during wet summers in multi-year periods with above-normal rainfall when soils are saturated and reservoirs full, enhancing the probability of major flood events in the Limpopo River Basin such as happened in 1996 and 2000.
Since 1948, three wet epochs over parts of southern Africa (1954-1963, 1973-1982 and 1993-2002) were associated with the anomalously anticyclonic circulation east of the subcontinent (throughout the troposphere) and a lower level cyclonic anomaly over much of the subcontinent. The anticyclonic anomaly has been shown to be related to a decadal-scale cycle in the SAM for JFM. This anomaly may contribute to observed ENSO-like decadal to multidecadal variability (Reason and Rouault 2002) in the region. The SAM and associated regional anticyclonic anomaly have varied in tandem since 1948 (the period for which data are available). The regional circulation anomaly provides further insight into the 18-20 year Dyer-Tyson rainfall cycle over parts of southern Africa and associated variation in influence of tropical systems from the SWIO over the Limpopo River Basin (Malherbe et al. 2012). Its association with the SAM also explains the inverse relationship between multi-year wet periods over large parts of the southern African summer rainfall region and glacial advances over southern New Zealand noted earlier (Tyson et al. 1997), a feature that has occurred on an 18-20-year time scale since at least the beginning of the 20th century. It is therefore concluded that the 18-20 year rainfall cycle can be attributed to the low-frequency variation in pressure distribution and (zonal) wind anomalies over much of the mid- and high latitudes of the SH during JFM. This is represented by an oscillation in the SAM with similar periodicity. The associated variation in the Southwest Indian Ocean implies a possible mechanism for an altered regional response to or expression of ENSO, with both warm and cold events being wetter (drier) during the wet (dry) part of the 18-20 year oscillation.

Acknowledgements

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Synopses

The link between significant rainfall events associated with tropical systems from the SWIO over the area of interest and large-scale circulation patterns, specifically circulation anomalies within the mid-latitudes and high latitudes in terms of the SAM, has now been established. Bi-decadal variability of the SAM and associated regional circulation anomalies relevant to the tracks followed by tropical systems from the SWIO has also been identified. The second objective of the study has therefore been addressed and the results provide the possibility to study variability of a large-scale circulation anomaly (the SAM) sensitive to external forcing towards understanding the associated regional variability. In the following section, an external forcing mechanism to the bi-decadal variability of the SAM will be investigated, noting that results are relevant to regional circulation anomalies important to tropical systems from the SWIO over the Limpopo River Basin.
4. Projected decadal-scale variability in the influence of tropical systems from the SWIO and total seasonal rainfall

Preface

This section consists of a published peer reviewed paper:


In this paper, a possible forcing mechanism for the bi-decadal variability identified in previous sections is proposed. The atmospheric response to external forcing is demonstrated at a daily and annual time scale by noting variation in the SAM. The predictability of the SAM by using an index derived from the external forcing mechanism as a predictor is evaluated. As the association between the SAM and regional anomalies relevant to tropical systems from the SWIO has been established in the previous section, this paper addresses the third objective of the study, namely the identification of a possible external forcing mechanism on the variability of the influence of tropical systems from the SWIO over the Limpopo River Basin.

I conceptualized the paper and was responsible for data acquisition and analysis as well as synthesis of results. I obtained the tidal prediction algorithm from the Internet and translated it from the original GW Basic code to Fortran 90.
Response of the Southern Annular Mode to tidal forcing and the bi-decadal rainfall cycle over subtropical southern Africa

Abstract

Synoptic weather data and rainfall records are used to support previous suggestions that the decadal-scale cycle in certain climate records may be attributed to the modulation in tidal forcing related to the 18.6 year lunar nodal cycle. The Southern Annular Mode (SAM) is shown to be sensitive to tidal forcing on a daily time scale. It is subsequently shown that the late-summer SAM can be predicted by consideration of tidal potential. The seasonal response in the SAM is also reflected in sea-surface temperatures. Observed behavior of the atmosphere suggests that changing tidal potential over the lower versus higher latitudinal regions plays a role. The atmospheric response as reflected in the changing SAM affects the daily rainfall variation in certain subtropical parts of southern Africa where rainfall correlates positively with the SAM. The daily rainfall response subsequently accumulates in a bi-decadal rainfall cycle, known over southern Africa as the Dyer-Tyson cycle.

Introduction


Tidal potential at a given location on earth is a function of the position of the moon or position of the moon and sun relative to each other and the location. It is modulated by, amongst other factors, the following (Wood 1986):
- Lunar declination (varying from southern to northern and back to southern maximum lunar declination (MLD) within the lunar nodal period of 27.2 days, causing higher (lower) potential towards high (low) latitudes during MLD.

- Distance between the moon and earth, ranging from minimum of as little as 356,700 km (high potential) at Perigee through maximum of 406,300 at Apogee (low potential) and back to minimum distance within the 27.55-day anomalistic month. These distances vary slightly.

- Alignment of the sun, moon and earth through the 29.5-day synodic month starting at new moon (high potential) through first quarter (low potential), full moon (high potential) and last quarter (low potential) to new moon again.

- Solar declination (23.5° N/S at solstices vs. small declination at equinoxes.

- Solar distance – ranging between the minimum of 147.1 million km during Perihelion on 3 January (high potential) to the maximum distance of 152.1 million km during Aphelion on 4 July (low potential).

Certain aspects of the lunar cycle remain fairly similar from year to year. For example, the occurrence of full and new moon happens close to the MLD near the solstices (with new (full) moon over the summer (winter) hemisphere). During the equinoxes, new and full moon happens at small declinations relative to the equator. This change in declination of new and full moon results in larger potential towards higher latitudes during solstices than during the equinoxes. Other factors vary at inter-annual time scales. One example is the timing of new and full moon relative to Perihelion or Aphelion. Another example of this is the variation within the anomalistic month which changes between years with Perigee and Apogee happening at any position in the synodic or nodal month. Variations such as these are responsible for tidal cycles of several periodicities ranging from daily to millennial scale. The 18.6-year nodal cycle results in variation in the MLD from 28.5° N/S (the major lunar standstill) during the 27.2-day nodal period to as little as 18.5°N/S 9.3 years later (at the minor lunar standstill). This variation in MLD alters the overall north-south movement of the moon relative to a point on earth from 37° to 57° during the 27.2-day nodal period. This change in the size of the north-south movement leads to a variation in tidal potential especially towards the higher latitudes. Depending on ocean basin geometries, certain parts of the ocean have a predominantly diurnal tide while the semi-diurnal tide dominates in other
areas, resulting in tidal variation in some areas associated more strongly with lunar phase and in other areas rather with lunar declination (e.g. Kvale 2006). The increase in bi-weekly MLD from minor to major lunar standstill causes increases of up to 19% in certain diurnal tidal constituents, influencing areas with diurnal and mixed tides (e.g. Haigh et al. 2011, Zetler and Flick 1985).

Decadal to millennium scale climate variability shows an association with tidal forcing (Keeling and Whorf 1997, 2000). The association exists due to the recurrence of strong tides or low beat frequencies between strong tidal harmonics (Munk et al. 2002) and subsequent increase in vertical mixing of oceans influencing amongst others sea-surface temperatures (SSTs). A change in the ratio of tidal forcing between high latitudes versus lower latitudes has specific large-scale atmospheric impacts (Treloar 2002). As changing MLD associated with the 18.6-year nodal cycle has a modulating effect on tidal potential and more specifically the strength of short-term diurnal tides, high-latitude SSTs are influenced due to the stronger tidal mixing (Loder and Garret 1978, Royer 1993, Ray 2007, Yasuda 2009, Osafune and Yosuda 2010). The impacts are noted on global climate and also specifically at high latitudes (Loder and Garret 1978, Royer 1993, Yasuda 2009). Decadal-scale climate variability may therefore be associated with tidal forcing producing significant responses in regional SSTs at this time scale (Loder and Garrett 1978, Parker et al. 1995, Royer et al. 2001, McKinnell and Crawford 2007). The significant responses in SSTs result in atmospheric response and feedback (Tanaka et al. 2012). More specifically, variability associated with changes in tidal potential has been noted in the Southern Oscillation Index (SOI), Interdecadal Pacific Oscillation (IPO - Treloar 2002) and the Arctic Oscillation (Ramos da Silva and Avissar 2005, Yndestad 2006) on decadal scale. At sub-decadal scale, the SOI and Equatorial Pacific temperatures have been shown to respond to tidal potential (Treloar 2002). Another example is the decadal-scale variability of the Pacific Decadal Oscillation that is associated with the 18.6-year lunar nodal cycle (Yusoda, 2009). Here the variability of the PDO results from increased (decreased) tidal mixing due to a larger (smaller) diurnal tides during periods of large (small) MLDs, further enhanced by air-sea interaction over mid-latitudes (Tanaka et al. 2012). As the coastal regions surrounding Antarctica experience relatively large diurnal tides (Ray and Sanches 1989) the effect of changing tidal potential associated with the nodal cycle may play a relatively important role in that area also and subsequently in the Southern Hemisphere (SH) high latitude region.
Furthermore, as an association between the Arctic Oscillation and the lunar nodal cycle has previously been pointed out (Ramos da Silva and Avissar 2005), a similar association in the SH should not be unexpected.

While climate responses at decadal scale are considered to result from modulation of short-term tides (Munk et al. 2002), short-term responses in the atmosphere also occur. In the troposphere, the lunar tide is detected in small variations in pressure (Chapman and Lindzen 1970). The semi-diurnal tide is the most widely studied and included in certain atmospheric models (Pedatella et al. 2012). It reaches a maximum close to the equator and is weaker at higher latitudes. Interaction between the solar and lunar tide is further also responsible for a diurnal tide (Brahde 1988, Hamilton 1984), being stronger at higher latitudes than closer to the equator and also being sensitive to the lunar declination. The atmospheric diurnal tide is also more pronounced when the nodal 18.6-year cycle is closer to its maximum (Brahde 1989).

Responses to lunar tidal potential by air temperature or SSTs have been observed on the bi-weekly and/or interannual time scale over equatorial regions (Ffield and Gordon 1996, Koch-Larrouy et al. 2010) and between polar and sub-polar regions (Kowalik and Proshutinsky 1994, Shaffer et al. 1997, Anyamba and Susskind 2000). On daily to weekly time scales, rainfall, and in particular significant rainfall events, follow full and new moon, when maximum tidal potential is reached within the lunar synodic month (Bradley et al. 1962, Brier 1965, Visagie 1966, Hanson et al. 1987). Such reactions are subsequently also reflected in river flow data (Cerveny et al. 2010). The response in rainfall to the lunar phase is also further enhanced during a new or full moon associated with stronger tidal forcing such as when it coincides with the lunar Perigee (Brier 1965). Cloudiness is significantly correlated with both lunar declination and phase (Pertsevf and Dalin 2010). Whether or not it is a direct tidal forcing on the atmosphere, or a response due to the oceanic tide, atmospheric anomalies associated with lunar declination (the 27.2-day nodal period) are linked to an atmospheric tide that causes changes in global tropospheric circulation over both tropical (Li 2005, Li et al. 2011) as well as mid- and high-latitude regions (Li 2005, Krahenbuhl et al. 2011). During days with smaller lunar declination, the troposphere over lower latitudinal regions thickens (Li 2005). During southern or northern MLD, a change in high latitude circulation is speculated to be associated with a Rossby Wave reaction in response to the tidal forcing, with significant changes noted between the southern and northern MLD (Krahenbuhl et al. 2011).
Over the subtropics, the position of the ridge during Austral summer over Australia has been shown to be modulated in accordance with several cycles of varying tidal potential (Wilson 2012).

The SAM is the principal mode of variability between extra tropical and high latitudes in the SH (Limpasuvan and Hartmann 2000) with subsequent associations in climate (Gillet et al. 2006, Reason and Rouault 2005). It is sensitive to external forcings such as stratospheric ozone concentration, volcanic aerosols, greenhouse gases and solar variability (Kuroda and Kodera 2005, Arblaster and Meehl 2006). The current study aims to present evidence for a lunar tidal forcing of the Southern Annular Mode (SAM) on weekly to decadal scales. The SAM is the principal mode of variability between extra tropical and high latitudes in the SH (Limpasuvan and Hartmann 2000) with subsequent associations in climate (Gillet et al. 2006, Reason and Rouault 2005). Furthermore, evidence is presented that, as the 18.6-year cycle in extreme lunar declination acts as one of the role players in modulating the SAM, the decadal-scale rainfall cycle is also associated herewith over summer rainfall regions of subtropical southern Africa, where a positive correlation between SAM and annual rainfall exists (Gillet et al. 2006).

Whether the responses reported in literature are due to atmospheric tides, an atmospheric response to oceanic tidal mixing, a combination of both or other external factors associated with the position of the moon relative to the earth, is not considered here. However, the findings do suggest that the response noted over the SH atmospheric circulation patterns can be represented by consideration of the tidal potential and specifically how it varies between the lower and higher latitudinal regions. It is also observed that the response in the SAM on daily time scales and subsequently decadal scale is also reflected in daily rainfall variation that ultimately translates to the bi-decadal variability in rainfall over eastern southern Africa. Therefore, over and above the existing body of literature on regional climatological responses at decadal to bi-decadal scale to variation in atmospheric circulation and SSTs (e.g. Tyson 1981, Mason and Jury 1997, Allan et al. 1995, Nicholson 2000), including ENSO-like patterns (Reason and Rouault 2002), the current paper explores the potential role of lunar forcing towards the bi-decadal component over eastern southern Africa. Over these areas, the 18-20 year cycle has been detected intermittently in paleo-climate data for at least 600 years and its persistence has been deemed a striking feature of the southern African climate (Tyson et al. 2002).
Data and Methodology

Daily NCEP Reanalysis 1 synoptic data (Kalnay et al. 1996) for the SH for the period 1948-2012 are used to investigate the possible influence of the lunar tide on circulation patterns focusing on the SAM. Only the 850 hPa level is considered as the SAM is also usually calculated at the lower levels of the troposphere (e.g. Gong and Wang 1999). For the purpose of the study, the daily SAM is calculated by subtracting the normalized 850 hPa height at 65°S from the normalized 850 hPa height at 40°S (Gong and Wang 1999). The Geopotential Heights per latitude are normalized with respect to the long-term 7-day moving average in the time series. Due to the positive trend in the SAM (Marshall 2003), it is also detrended over the 65-year period using a second-order polynomial, selected on the basis of a higher R-squared value as opposed to using only a first-order polynomial.

Previous research has shown that the rainfall during January-March (JFM) over southern Africa exhibits 18-20 year cyclicity in association with the SAM (Malherbe et al. 2013). For this reason, data for the October-March (Austral summer) and JFM periods are analyzed. As the lunar nodal cycle has been postulated to play a potential role in cyclicity at this time scale (e.g. Currie 1984), the correlation between the seasonal average SAM and MLD is explored. To identify any multi-year cycles in the SH that may be associated with the MLD, a two-step procedure is followed. Firstly a trend analysis is performed per NCEP Reanalysis grid point for the 850 hPa Geopotential over the SH for all JFM periods using the method of pairwise slopes (Lanzante 1996). The time series is then detrended per grid point using the trend analysis results, after which the resulting series is rearranged according to increasing MLD per JFM period. The trend analysis is then repeated on the new MLD-related time series peer grid point to identify the trend according to increasing JFM MLD. The Spearman rank correlation coefficient is calculated for the trend and grid points where the trend with increasing MLD is significant above the two-tailed 95% level of confidence are identified. The entire process is repeated for the 1979-2011 period as the data for this period is considered of superior quality due to, amongst other reasons, the inclusion of satellite data (Tennant 2004).

To identify any possible responses of the SAM at daily time scale, data are screened according to three components of the lunar cycle associated with varying tidal potential:
Lunar distance, declination and phase. The SAM is firstly evaluated as a function of lunar declination and distance, and then according to lunar phase and distance. Only data for the Austral summer (Oct-Mar) are taken into account. Daily calculated SAM time series are then considered firstly according to position of the lunar Perigee and Apogee (distance) within the nodal (declination) and secondly according to position of Perigee and Apogee within the synodic (phase) month. It is done separately for periods during which the MLD exceeds 25° (large MLDs) and when it less than 23° (small MLDs), as tidal forcing is expected to differ according to the range in declination over the nodal cycle. These cut-off values are chosen to acquire two datasets of similar size while still allowing some separation between the datasets. While firstly focusing on declination and distance, the effect of the lunar phase is to some extent present by the focus on the Austral summer half year. During Austral summer, new (full) moon occurs with negative (positive) declination relative to the equator. Maps are daily sequences of the SAM in the horizontal, selected in relation to the nodal month. These sequences are then arranged (stacked) according to the position of the lunar Perigee and Apogee. This is done to observe (if present) the effect of changing tidal potential due to interaction between the nodal (declination) and anomalistic (distance) month (arranged in the vertical). In total, 366 (302) sequences are taken into account for large (small) MLDs. The data in each line of the resulting maps represent the time series of 41 daily SAM values for all sequences with Lunar Perigee on a specific day or any of the four adjacent days of the nodal month – therefore, the lunar Perigee can occur on any of 5 days with the day considered being the middle position (Figure 1).
Figure 1  Stacking of daily sequences to identify possible significant deviations in the SAM with lunar distance and declination.

This approach increases the number of sequences represented by each line from the order of 10 to between 50 and 75. The same method is repeated, but with time series stacked to evaluate possible influences of the position of lunar Perigee and Apogee within the synodic (new moon – new moon) month. Here, 376 (326) sequences are taken into account for large (small) MLDs. Significance levels for all four maps per point in each map are determined from 5000 reconstructions of the maps based on randomized series generated through Monte Carlo simulations of the original time series data.

The next step is to relate responses in the SAM to lunar tidal potential instead of separate elements of the lunar cycle. An estimate of tidal potential per 5° latitude is therefore calculated (Ahern 1993) for the period 1910-2013 using the algorithm of Longman (1959) based on the harmonic developments of the solar and lunar tidal constituents by Schureman.
Firstly, the acceleration per hour due to the sun and moon or the moon only is calculated (Ahern 1993). As certain parts of the ocean have a tidal variation rather associated with the declination than the phase of the moon (e.g. Kvale 2006), potential related to the moon only is also considered, together with potential related to the sun and moon. The daily range in acceleration is taken as the tidal potential per day. As the near-equatorial versus high latitude tidal potential may play an important role in the atmospheric responses noted (Krahenbuhl et al. 2011, Li 2005, Li et al. 2011), the low latitude potential (average potential at 0° and 20°S) and high latitude potential (at 65°S) are considered separately. Tidal potential per day per latitude is normalized with respect to the day of year over the entire time series (1910-2013). The normalized tidal potential is used to construct an index to approximate the effect on the SAM as deduced from the previously described screening of daily data. The resulting Tidal SAM Index is therefore a yearly estimate of the seasonal (JFM) average SAM based on the combination of certain normalized tidal potential values during Austral summer.

The initial analysis for identifying a trend in JFM 850 hPa heights per grid point over the SH with increasing MLD is repeated for the Tidal SAM Index. The trend in JFM 850 hPa heights and JFM SSTs with decreasing Tidal SAM Index is evaluated. Here, the sea ice and SST dataset from the Met Office Hadley Centre (HadISST1 - Rayner et al. 2003) is used.

In studying the response of rainfall to the atmospheric anomalies associated with an observed atmospheric response to tidal forcing, a daily rainfall time series covering a period of 104 years (1910-2013) is used. It is for an area over the northeastern South Africa, a summer rainfall region with 18-20 year cyclicity in rainfall (Dyer and Tyson 1977, Tyson et al. 2002) and a positive correlation between rainfall and the SAM (Gillet et al. 2006). The rainfall time series is constructed from the rainfall records for 8 stations (Figure 2), covering the entire period. A wavelet analysis is performed on the 5-year filtered time series to identify significant cycles in the range of the lunar nodal cycle. Significance is calculated by exact repetitions of the analysis on 5000 randomized series generated through Monte Carlo simulations of the original time series data. To establish whether a significant correlation exists, the Spearman rank correlation coefficient is calculated between the rainfall time series and the Tidal SAM Index.
To evaluate whether the occurrence of relatively wet and dry periods on decadal scale may be associated with observed atmospheric responses to tidal forcing on daily time scales, the average daily rainfall values from the same stations (Figure 2) for high and low Tidal SAM Index years, respectively, are arranged according to the 27-day lunar nodal period and compared. All sequences starting in December through March are considered resulting in all JFM periods becoming part of the dataset of complete sequences. The rate of change in cumulative surplus rainfall per day (relative to the nodal period) during high versus low Tidal SAM Index years is evaluated. This rate is calculated as the slope of the trend line of cumulative rainfall surplus over a surrounding 5-day period.

The predictability of the seasonal average JFM SAM using tidal potential (in this case the Tidal SAM Index) as predictor is evaluated by using the Multiple Linear Regression (MLR) option of the Climate Predictability Tool (CPT) of the International Research Institute for Climate and Society (IRI; http://www.iri.columbia.edu) by testing a linear statistical model which relates the Tidal SAM Index with the SAM. The test determines the skill with which the Tidal Sam Index is able to objectively predict the likelihood for a specific phase (positive or negative) at a seasonal time scale (JFM) of the SAM. Prior to creating the MLR model with the CPT software the SAM data are first transformed into an approximate normal distribution. The MLR model is initially trained over a 33-year period from 1948 to 1980. The retro-active forecast option of the CPT is selected with a 1-year model update interval.
and forecast SAM values are subsequently obtained for the 33-year period from 1981 to 2013. Probabilistic retro-active SAM predictions for each of the 33 years are subsequently created from the error variance of the cross-validation procedure (using a 5-year-out window) that precedes each retro-active prediction (e.g. Landman et al. 2012) and evaluated. Using the established relationship between predictor and predictand, a forecast is also generated for the SAM based on the Tidal SAM Index for 2014 to 2050.

Results and discussion

The late Austral summer (JFM) is an important rainfall period over large parts of southern Africa, with rainfall to a large extent associated with the activity of tropical weather systems in the region (Preston-Whyte and Tyson 2000). In previous studies, both seasonal rainfall and rainfall contributed by tropical cyclones over the northeastern parts of South Africa were shown to vary at an 18-20 year time scale and to be positively related to the SAM during JFM (Malherbe et al., 2012, 2013). Consideration of average detrended JFM Geopotential height according to the MLD per year indicates a trend towards a negative SAM with increasing MLD during the 1948-2012 period (Figure 3). This result and others were also obtained when using ECMWF ERA Interim Reanalysis data (Berrisford et al. 2009) for the 1979-2013 period, lending further credibility to the findings of the study.
Figure 3  Trend in the SAM (top, +0.5 and -0.5 standard deviation of SAM time series indicated) with increasing MLD (°) and trend in 850 Geopotential Height (m) per 1° increase in MLD for JFM (bottom) during the 1948-2012 period and the 1979-2012 sub-period (insert) using the method of pairwise slopes. Areas where the trend is significant above the 95% level of confidence according to the 2-tailed test calculated for the Spearman rank correlation are indicated with the solid (for positive trend) and broken (for negative trend) white lines. The latitudes at which the SAM is calculated are indicated by broken black concentric lines.

The downward trend in the SAM exceeds one standard deviation with increasing lunar declination as calculated for 3-month JFM average per year. Results remain consistent for the 1979-2012 period. The finding presents observational evidence for the modulation of the JFM SAM at decadal scale possibly due to variation in diurnal tides towards higher latitudes, associated with the Lunar Nodal Cycle.

To investigate responses of the SAM at daily time scales, Figure 4 shows maps consisting of 41-day sequences of the SAM arranged according to the lunar nodal month and stacked according to the occurrence of lunar Perigee (in the anomalistic month) relative to maximum
southern declination (MSLD) for the Austral summer half year. It is a screening of the data for indications of responses in the SAM that may be attributed to changing tidal potential over different latitudes based only on the declination and distance of the moon. The full period from northern MLD through southern back to northern MLD is approximately 27 days. This is the number of days represented between N (left) and N (right) at the top of each map in Figure 4. The full sequence in the horizontal represented in each map in Figure 4 (left to right) is 41 days. Solid vertical lines indicate lunar transit at northern MLD (N), southern MLD (S) and equator (Eq). Diagonal broken lines indicate the mean position (middle position of 5) of lunar Perigee (black) and Apogee (white) relative to MLD. See also Figure 1 for clarification.

![Figure 4](image)

**Figure 4** Average daily SAM time series (left-to-right) stacked according to position of lunar Perigee (P) and Apogee (A) with respect to Maximum Southern Lunar Declination (MSLD) within the lunar nodal month. The 90 and 95% positive (negative) significance levels are indicated in broken and solid black (white) lines respectively. The map on the left (right) hand side is for data during years with large (small) MLD. Data considered are for Austral summer (October-March).

Significant alterations to the SAM occur, as indicated in Figure 4, at the following areas:

For large MLDs:

- a significant increase (X1) after lunar transit over the equator while distance decreases from Apogee towards Perigee, representing a large increase in tidal potential
a significant decrease in the SAM (Y1) associated with and following extreme declination (N/S)

negative SAM values (Z1) are also associated with Apogee, especially when occurring with MLD (N/S), indicating a negative SAM when tidal potential is at a minimum.

For small MLDs:

- significant decreases in the SAM (Z1) are also associated with Apogee, also more pronounced with MLD (S/N), indicating also a negative SAM when tidal potential (at low latitudes) is at a minimum
- a significant increase in the SAM (X2) with decreasing declination
- a decreasing SAM after equatorial transit (Y2) and also associated with MLD.

Figure 5 shows a similar summary as in Figure 4, but instead of the nodal (declinations) and anomalistic (distance) month, the synodic (phase) and anomalistic months are considered. It is also done separately for large and small MLD, as in Figure 4.

Figure 5  Average daily SAM time series (left-right) stacked according to position of lunar Perigee (P) and Apogee (A) with respect to new moon within the lunar synodic month. Vertical (diagonal) lines indicate the position in the time series of new and full moon (Perigee and Apogee). The 90 and 95% positive (negative) significance levels are indicated in broken and solid black (white) lines respectively. The map on the left (right) hand side is for data during years with large (small) MLD. Data considered are for Austral summer (October-March).
For both small and large MLD, the following observations are made:

- a low SAM (Z1) associated with Apogee, especially during or following maximum tidal potential associated with new moon
- an increase in the SAM with increasing tidal potential towards full moon (X1) and new moon (X2)
- a decrease in the SAM especially after new moon (Y2)
- a tendency for a higher SAM (H) following maximum tidal potential associated with full moon.

These observations also indicate a positive response by the SAM during periods of increasing tidal potential, followed by a decrease. The response in the SAM especially with new moon is therefore more significant with small MLDs (Figure 5). This result could be associated with tidal potential that varies relatively more strongly with phase than declination during smaller MLDs. Conversely, the response associated with changing declination and distance is more strongly demonstrated with large MLDs (Figure 4). This result could be associated with tidal potential that varies relatively more strongly with declination during large MLDs. Concurrently, a lower potential in all cases is associated with lower SAM. Furthermore, from Figure 4, it is concluded that stronger tidal potential at lower latitudes causes a positive response in the SAM, whilst this response is not associated with stronger tidal forcing at high latitudes (MLD). As a first approximation, these findings may be summarized as follows:

The SAM is positively correlated with (the acceleration in) tidal potential at lower latitudes

The two main findings for large and small MLD are summarized in Figure 6a and b respectively.
Figure 6a Normalized Low latitude (average at 0° and 20°S) tidal potential based on lunar declination and distance (broken line, secondary y-axis) and the SAM (solid line, primary y-axis) for cases with Perigee occurring with lunar equatorial passage towards northern MLD (white) and Perigee occurring with equatorial transit towards southern MLD (black). For build-up and break-down events, the percentage of events during which an increase in 5-day average 850 Geopotential Height occurs following maximum tidal potential versus the 5-day average before maximum tidal potential, is shown per NCEP Reanalysis grid point (bottom). Only periods during which MLD is larger than 25° are considered.
While significance for the magnitude of anomalies has already been indicated in Figs 4 and 5, the percentage of events during which an increase in 5-day average 850 Geopotential Height occurs following maximum tidal forcing versus the 5-day average before maximum tidal potential, as shown per NCEP Reanalysis grid point at the bottom of Figure 6a and b, further indicate that the anomalies do not arise due to a small number of extreme values. The build-up (increase) and break-down (decrease) of the SAM is shown here to be related to the increase and decrease in tidal potential at low latitudes for both cases (small and large MLD). The effect on the SAM around extreme southern declination is summarized in Figure 7.
Figure 7  Average daily SAM (normalised) during the Austral summer arranged according to the Lunar nodal cycle for all events (light grey line), during periods when MLD exceeds 23° (dark grey line) and periods when MLD exceeds 23° and extreme southern declination happens within five days of Perigee (black line).

Figure 7 summarizes the tendency towards a negative SAM following maximum tidal potential at low latitudes and increasing tidal potential at higher latitudes due to a large MLD (dark grey line) as opposed to all MLDs (light grey line). When Perigee occurs between the equator and MLD or near MLD (black line), the effect on the SAM is exacerbated resulting in a multi-day period of significant negative values. This represents the case (as in Figure 6a) where a large increase in tidal potential near the equator (around day -7 in Figure 7) is followed by a decrease in tidal potential as lunar declination increases towards day 0 and lunar distance also increases through days 0 to 6. The negative trend in the SAM may be associated with lower potential towards low latitudes during multiday periods with or following high potential at high latitudes and also specifically with larger tidal potential at high latitudes.

All the findings above suggest the following possible tidal influences on the SAM:

1) An increase in tidal potential at lower latitudes results in the SAM increasing. This may also indicate that not only the magnitude, but also the rate of change of tidal potential at lower latitudes has a positive influence on the SAM. This is seen in
increasing tidal potential associated both with lunar distance and declination as well as with phase (towards new or full moon). This also further supports the results of Li et al. (2011) who found that, at intraseasonal time scales, high (low) pressure anomalies at low (high) latitudes are significantly correlated to an increase in the Length of Day which is related to lunar tide raising force. The positive response in the SAM with higher low-latitude tidal potential is a further reflection on the findings in Figure 3, where significant trends associated with an increase in MLD, and thus high-latitude tidal forcing, resulted in a change towards a negative SAM.

2) A significant influence on the SAM when maximum tidal potential occurs between equatorial passage and MLD or close to MLD with higher high latitudinal tidal potential (such as associated with large MLD). During and following such a tidal sequence, the SAM decreases. This may also indicate that not only the magnitude of tidal forcing, but also the rate of change of tidal potential at higher latitudes has a negative influence on the SAM as the rate of increase in tidal potential will be larger if lunar distance decreases while declination increases. The change in the SAM may be due to Rossby wave breaking (Wang and Magnusdottir 2011, Ndarana et al. 2012) associated with MLD as alluded to by Krahenbuhl et al. (2011).

3) A positive influence associated with and following full moon with smaller MLD. Evidence (Figs 5 and 6b) suggests that during Austral summer, a strong low latitudinal tidal forcing associated with full moon has a positive influence on the SAM. The SAM remains positive even after maximum tidal forcing.

4) A decrease in the SAM following new moon. The larger negative effect of new moon as opposed to full moon during Austral summer on the SAM may be associated with the different times of day when maximum tidal potential occurs, resulting in varied responses in the atmosphere related to the thermal tide. Alternatively it may also result from new moon being associated with southern declinations while full moon is associated with northern declinations during Austral summer, further resulting in varied responses (stronger tides with southern declination) such as through the occurrence of tropical tides (Wood 1986).

The difference in behavior of the atmosphere with full versus new moon (Shaffer et al. 1997) and southern versus northern declination (Krahenbuhl et al. 2011) are previous work
supported by these findings (points 3 and 4 above). These earlier findings further warrant the separate consideration of tidal potential associated with new versus full moon or northern versus southern MLD.

Combining the above-mentioned simple rules, an index is approximated for the average JFM SAM from daily normalized tidal potential values by linear combination of four variables. The variables are magnitudes of tidal potential associated with certain characteristics of the lunar cycle occurring through mid- to late summer, shown to cause a reaction in the SAM, as listed above. The first two of these variables (A, B) focus on the lunar tidal potential associated with lunar trajectory towards southern MLD and the subsequent decrease in declination after MLD. The third (C) provides an indication of the average balance in tidal potential, as largely influenced by magnitude of MLD. The fourth (D) considers the low-latitude tidal potential specifically towards the end of the summer season.

A:  Strongest high-latitude tidal potential associated with new moon during Austral mid-summer (December/January)

This is used as a negative input based on evidence of a significant decrease in the SAM with or following strong high-latitude tidal forcing and new moon and southern MLD (point 4 above and Figs 4-7).

B:  Magnitude of the maximum low-latitude tidal potential directly following “A” with lunar passage towards northern MLD

This is a positive input value and is used as an approximation of the potential recovery (increase) of the SAM after tidal event “A”. If the lunar trajectory is such that low-latitude tidal potential decreases more strongly after southern MLD, the earlier evidence suggests that a prolonged period of lower SAM values follow (point 2 above and Figs 4, 6 and 7). It is expressed as the normalized lunar tidal potential based on declination and distance. Essentially, consideration of this variable results in the implicit focus on the strength of the increase in tidal potential during the descending limb of the lunar trajectory towards southern MLD by characterizing the lunar trajectory in terms of declination and distance. This characterization of the lunar trajectory also provides an implicit emphasis on the magnitude of the early summer maximum high-latitude tidal potential associated with new moon/southern MLD, resulting in consideration of possible lagged atmospheric or oceanic responses.
C:  *Average mid-summer (November-February) tidal potential at high latitudes (65°S)*

This provides an indication of the tidal balance between lower and higher latitudes during the period in summer when the largest tidal potential is located towards higher latitudes when new and full moon occur close to MLD. It is closely related to the magnitude of the MLD and is therefore negatively associated with the SAM (Figure 3).

D:  *Strongest low-latitude tidal potential associated with full moon during JFM*

Inclusion of this variable is based on evidence presented in point 3 above. The largest tidal potential considered here will generally be located towards the end of the JFM season as each successive full moon occurs at a smaller declination from mid-summer onwards.

Tidal SAM Index = -A+B-C+D

As a first approximation, equal weights are given to the four components of the index. Figure 8 shows the time series of the Tidal SAM Index and JFM SAM for 1948-2013.

![Figure 8](image)

**Figure 8**  Observed detrended JFM SAM (broken black line) per year for 1948-2013 with 3-year moving average (solid black line). The Tidal SAM Index (solid white line) is also indicated.

The Spearman rank correlation coefficient for the Tidal SAM Index and the SAM is 0.52, which is (over a 65-year period) significant at the 99.9% level of confidence. As the elements within the Tidal Sam Index vary slowly over time and any responses over the ocean or atmosphere may have a lag effect, a higher correlation with the 3-year average JFM SAM of 0.67 is not surprising. This effect can however also be the result of the smoothing itself. Figure 9 shows the areas of significant positive or negative trends per JFM period for 850 hPa heights and SSTs with decreasing Tidal SAM Index on an annual basis. The trend per grid
point is calculated for the yearly JFM averages, similarly as for Figure 3, but instead of increasing lunar MLD, according to decreasing Tidal SAM Index value.

![Grid points where significant (see bar) positive (light shades) and negative (dark shades) trends in JFM 850 hPa heights (left) and JFM SSTs (right) with a decreasing Tidal SAM Index occur. Significance is indicated according to 2-tailed test calculated for the Spearman rank correlation.](image)

The significant negative trends in 850 hPa heights at the mid-latitudes and significant positive trends at high latitudes result in the negative trend in the SAM with decreasing Tidal SAM Index. Significant negative trends over the mid-latitudes occur over more grid points than for the trend analysis results based on MLD (Figure 3). Considering trends in the SSTs with decreasing Tidal SAM Index, significant negative trends are located especially along the mid-latitudes, with positive trends at high latitudes. The high-latitude sea ice distribution and SST gradient is theorized to influence the position and strength of storm tracks and subsequently also of the mid-latitude Jet (Herman and Johnson 1978, Sampe et al. 2010). Lower (higher) SSTs over the mid(high)-latitudes will weaken the gradient, which should result in a weakening and northward displacement of storm tracks in the westerlies as well as the mid-latitude Jet. Moreover, lower SSTs over the mid-latitudes, associated with larger mixing in the ocean due to larger diurnal tides, may result in negative 850 hPa heights at the mid-latitudes, as demonstrated for the southwestern Atlantic (Agosta 2013). Conversely, the SST pattern (Figure 9) also resembles the response to the SAM, shown to occur with a lag of 1 week with respect to atmospheric anomalies (Ciasto and Thompson 2008). Air-sea interactions further have been demonstrated to potentially increase persistence of...
tropospheric SAM anomalies on interseasonal to annual time scales (Sen Gupta and England 2007). The trends visible with decreasing Tidal SAM Index for 850 hPa heights and SSTs are therefore in agreement, even though the observation does not provide insights regarding cause and effect. 850 HPa anomalies in the southern African region with decreasing Tidal SAM Index (Figure 9) include negative anomalies over the oceanic regions towards the southwest and southeast and positive anomalies over the subcontinent. Such anomalies result in a decrease in moisture advection and a decrease in convergence over the southern African interior as well as a northward displacement of the mid-latitude Jet, all of which are associated with a decrease in summer rainfall (e.g. Tyson 1981, D'Abreton and Lindesay 1993). It is therefore anticipated that the rainfall over the summer rainfall region of southern Africa will be positively related to the Tidal SAM Index.

Spectral analyses of 5-year average rainfall from 1910-2013 for 8 locations over northeastern South Africa (Figure 1) indicate the existence of significant periodicity in the 16-20 year band (see also Tyson et al. 2002) for average total annual rainfall and in the 20-27 year band for JFM rainfall (Figure 10).

![Figure 10](image)

Figure 10  Spectral analysis results for 5-year smoothed rainfall (solid line) with 95% significance levels indicated (broken line), for total seasonal rainfall (black) and JFM rainfall (white) over northeastern South Africa.

The Spearman rank correlation coefficient for the total annual rainfall with the Tidal SAM Index, modified to a large extent by the MLD, is -0.25 over a 104-year period (1910-2013), significant at the 99% level of confidence. For JFM, the correlation with the Tidal SAM
Index is 0.21, significant at the 97.5% level of confidence. The relationship is indicated in Figure 11 which shows the 1910-2013 time series of rainfall on the horizontal, resulting from the application of several low-pass filters from 5-year to 25-year range on the vertical.

![Time series of rainfall](image)

**Figure 11**  Time series (shaded) of average percentage deviation of rainfall for 8 rainfall stations (Figure 2), with low pass filters ranging from 5 to 25 years on the vertical for total seasonal rainfall (top) and JFM rainfall (bottom). Broken lines are the Tidal SAM Index (secondary Y-axis).

The time series (Figure 11) substantiates the positive correlation (0.25) between the Tidal SAM Index and low frequency variation of bot total annual rainfall and JFM rainfall. While the correlations are significant, they are still relatively low, emphasizing that the statistical relationship with tidal forcing only explains a fraction of the total variance.

Figs 4 and 6 have shown that there exists a stronger influence at daily time scales on the SAM when maximum tidal potential occurs towards or associated with large absolute MLD. The SAM increases with lunar transit over the equator (build-up) and experiences a sharp decline with the subsequent MLD, followed by multi-day negative values (Figs 6a and 7). The Tidal SAM Index emphasizes this (negative) influence associated with tidal potential on
the daily SAM. When the JFM daily rainfall for 1910-2013 is rearranged according to the 27-day lunar nodal period (for all sequences starting during December through March), the effect of the response in the SAM towards extreme lunar declination is noticeable at daily time scale in an acceleration of the cumulative surplus in the rainfall following MLD in years with a high Tidal SAM Index relative to years with a low Tidal SAM Index (Figure 12). The result in rainfall data is not unexpected, as rainfall over the summer rainfall area of South Africa is positively correlated with the SAM on intra-seasonal basis (Pohl et al., 2010).

![Figure 12](image_url)

**Figure 12**  Average cumulative rainfall difference (bars - high Tidal SAM Index years minus low Tidal SAM Index years) over 30-day periods starting in December through March aligned with the lunar nodal cycle (through southern (S) and northern (N) MLD) at 8 stations over northeastern South Africa (Figure 2). The solid line represents the rate of change (average mm/day over 5-day period – secondary y-axis) of the cumulative rainfall difference. Contributing years are those, as identified through the Tidal SAM Index value, that belong to the upper and lower 50% (light grey line and bars), upper and lower 35% (dark grey line and bars) and upper and lower 20% of years (black line and bars). Data for 1910-2013 are considered.

Figure 12 shows that the largest increase in surplus rainfall recorded during years with a higher Tidal SAM Index occurs during days directly after southern or northern MLD. It indicates that during the years with a lower JFM rainfall associated with a low Tidal SAM Index, the period preceding MLD (days -5 to 0) is relatively wet, followed by drier conditions. It can be seen also in the low values of the trend-line slope before MLD (days -4 to -1) with a strong increase following MLD (days 0 to 3). This result is expected, as the stronger modulation of the SAM (increase followed by sharp fall – Figs 6a and 7) with MLD causes a relatively wet period after lunar crossing of the equator during years with low Tidal
SAM Index values. The multiday period of a low SAM associated with and following MLD during those (low-Index) years, however, causes a relatively dry period over the subtropical regions of South Africa, resulting in the largest gains during years when the Tidal SAM Index is high relative to low-index years to follow MLD (days 1 to 7). This effect is exacerbated with consideration of more extreme values of the Tidal SAM Index (from upper and lower 50/50% through 35/35% to 20/20% years), as shown in Table 1.

Table 1  Total average and percentage of rainfall surplus.

<table>
<thead>
<tr>
<th>Percentage of high and low Tidal SAM Index years considered</th>
<th>Total rainfall difference per (D)JFM</th>
<th>% In 5 days to MLD</th>
<th>% In 9 days following MLD</th>
<th>% Increase in rainfall per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>50/50</td>
<td>38 mm</td>
<td>23</td>
<td>77</td>
<td>44</td>
</tr>
<tr>
<td>35/35</td>
<td>55 mm</td>
<td>20</td>
<td>80</td>
<td>55</td>
</tr>
<tr>
<td>20/20</td>
<td>60 mm</td>
<td>-8</td>
<td>108</td>
<td>109</td>
</tr>
</tbody>
</table>

*Total average rainfall surplus during DJFM seasons associated with high Tidal SAM Index years relative to low Tidal SAM Index years (column 2), the percentage of surplus rainfall occurring during the 5-day period up to MLD (column 3), the percentage of surplus rainfall occurring during the 9-day period following MLD (column 4), and the percentage increase in rainfall surplus per day from the average for the 5-day period up to MLD to the 9-day period following MLD (column 5).*

The average rainfall at the 8 rainfall stations (Figure 2) during the DJFM season is 490 mm. Therefore, on average, there is an 8 to 15% increase in rainfall between years associated with lower and years with higher Tidal SAM Index values (Table 1, column 2). The days immediately before MLD contribute a much smaller percentage per day to this difference than the days following MLD (columns 3 and 4 respectively). Because both southern and northern declinations are considered simultaneously, the total number of days (columns 3 and 4) is 14 but in actual fact represents 27.2 days. Daily cumulative rainfall surplus gains are on average 44% more per day following MLD as opposed to preceding MLD when all years (row 1 – upper 50% and lower 50% of years according to the Tidal SAM Index) are considered. As a smaller proportion of years, represented by more extreme upper and lower values of the index, are taken into account, the contribution to the total surplus during the 5 days prior to MLD diminishes further until 100% is contributed during days following MLD (row 3).

The difference in average seasonal rainfall associated with the decadal rainfall-scale cycle and approximated here through the Tidal SAM Index therefore is associated largely with
multiday periods following extreme lunar declination. These findings remain unchanged when the daily rainfall for the entire year is rearranged according to lunar nodal period for both the Tidal SAM Index as well as when only maximum tidal potential at high latitudes is considered (data not shown). Here too, for example, the rate of increase (slope of trend line) in surplus rainfall more than doubles between 3 days before MLD and 2 days after MLD (data not shown).

Towards evaluating the use of the Tidal SAM Index to predict the JFM SAM, the retro-active forecasts by the IRI CPT for the SAM for the 33-year period 1981-2013, based on the Tidal SAM Index, are shown in Figure 13. Years with the highest contributions to rainfall by tropical systems from the Southwest Indian Ocean over the Limpopo River Basin (Malherbe et al. 2012) are also indicated. Also shown are the upper and lower prediction limits of the Tidal SAM Index based forecast for 2014-2050.

**Figure 13**  Observed detrended JFM SAM (solid black line – primary axis) per year for 1948-2013 and Tidal SAM Index (solid white line – secondary axis) for 1948-2050. The retroactive hindcasts for the SAM for 1981-2013 (thick broken line) and the Tidal SAM Index-based upper and lower prediction limits (error bars associated with verification results) for the SAM for 2014-2050 (thin broken lines) are also shown. The years with highest rainfall contributed by tropical systems from the Southwest Indian Ocean over the Limpopo River Basin (Malherbe et al. 2012) are also indicated on the Tidal SAM Index line (triangles).

The hindcast for 1981-2013 is obtained by the process of retro-active forecasting, based on the relation obtained between the Tidal SAM Index (predictor) and SAM (predictand) during
1948-1980. Similarly, the upper and lower prediction limits for 2014-2050 are obtained from statistics developed over the entire 1948-2013 period. For the verification of the Tidal SAM Index forecast for the JFM SAM, the relative operating characteristic (ROC; Mason and Graham 2002) scores and a reliability diagram (Hamill 1997) are considered for the 33 years of retroactive forecasts. The ROC scores (data not shown) for the positive (high phase) and for the negative (low) phase of the SAM are high (0.85 and 0.78 respectively). The high ROC scores demonstrate that by using the Tidal SAM Index as a predictor in a linear model, the model is able to respectively discriminate positive and negative JFM SAM years from the remainder of the years. Notwithstanding the high ROC scores, the retro-active hindcasts of the SAM are not perfectly reliable since the weighted regression lines associated with the SAM phases are not on top of the diagonal of the reliability diagram (Figure 14).

![Reliability plot](image)

**Figure 14** Reliability plots for above- (>67th percentile – high-phase) and below normal (<33rd percentile – low-phase) SAM retroactive forecasts for 1981-2013 produced by using the Tidal SAM Index.

For the positive SAM predictions (solid lines in Figure 14) the changes in high forecast probabilities slightly underestimate the changes in the observed relative frequencies – the retro-active forecasts of the high-phase is therefore under-confident. In spite of the somewhat poor reliability, the forecasts have high resolution. For the negative SAM predictions (dashed lines in Figure 14), events occur less frequently than predicted since the forecast probabilities
are consistently higher than the observed relative frequencies – the forecast model is over-confident regarding negative SAM predictions. The positive SAM predictions therefore have higher predictability (higher ROC scores and improved reliability), and it is also during seasons with a positive SAM that seasonal total rainfall is higher over northeastern South Africa whilst there is an increased risk of tropical systems such as cyclones and depressions to cause widespread heavy rain and subsequent flooding over the Limpopo River Basin (Malherbe et al. 2013). For the 2012-2050 period, the prediction for tidal influence on the SAM indicates that the periods 2012-2019 and 2032-2038 are more likely to be characterized by a positive JFM SAM.

Conclusion

For the mid-to-late Austral summer period (JFM), the possible sensitivity of the SAM on daily to decadal time scales to tidal forcing has been observed. On both daily and decadal scale, lower (higher) tidal potential towards the equator and higher (lower) potential towards the high latitudes cause the SAM to become anomalously negative (positive). A seasonal index (Tidal SAM Index) to approximate the SAM, based on observed daily-scale responses by the atmosphere to tidal potential, have been demonstrated to predict the seasonal average SAM with high skill.

The atmospheric response at daily time scale to large high-latitudinal tidal potential and small low-latitudinal potential during MLD, associated with years with a low seasonal Tidal SAM Index, results in lower rainfall over the period of several days occurring in parts of the subtropics where rainfall is positively associated with the SAM. These anomalously drier periods associated with and following extreme declination results to a large extent in the bi-decadal rainfall cycle over these regions. These findings are further evidence in support of previous results noting that short-period tides, modulated within the slowly varying 18.6-year nodal cycle may, through changing tidal potential between lower and higher latitudes, result in a climate response at the decadal scale (Ray 2007). The atmospheric response may further not only be present due to long-term 18.6-year variation in oceanic tidal mixing, but also immediate at daily time scales during times of maximum forcing. However, whether the immediate response is the result of ocean-atmosphere interaction or purely atmospheric in nature will be dealt with in modelling studies. The predictability of the SAM due to tidal forcing (such as with a Tidal SAM Index) may further present the potential for decadal-scale
statistical outlooks based on regional association with the SAM. However, even though significant predictability has been demonstrated, tidal forcing is only one of several (external) influences on the SAM and rainfall over the sub-tropics. Significant results obtained nevertheless emphasize the need to investigate, understand and incorporate lunar influences on the climate system in Coupled Global Models.

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Synopses

The third objective of the study, namely the identification of a possible forcing mechanism responsible for bi-decadal variability in the influence of tropical systems from the SWIO over the Limpopo River Basin, has been addressed. While tidal variability associated with the lunar nodal cycle has long been implicated to be responsible for bi-decadal variability within climate records, results obtained have identified sensitivity of a hemispheric circulation phenomenon, namely the SAM, to the changing tidal potential associated with this (lunar) cycle. The results therefore provide an understanding also of regional anomalies associated with the SAM, responsible for bi-decadal variation in climate records. In the southern African region specifically, the variation in the SAM provides an indication of the strength and position of the subtropical high pressure belt towards the south and southeast of the subcontinent and also the position of the westerly Jet, as shown in Section 3. These atmospheric phenomena have consequences for summer rainfall over some parts of the subcontinent as well as the tracks of tropical systems from the SWIO.

This section has concluded the focus on bi-decadal variability in tropical systems from the SWIO over the Limpopo River Basin. The index for seasonal prediction of the SAM and associated circulation anomalies in the southern African region may be considered as a first step towards multi-decadal prediction of bi-decadal variability in the region. It can be evaluated as an indication of the influence of predictable changes in tidal potential on hemispheric to regional circulation anomalies and extended into the future beyond 2050, noting however that tidal forcing is only one of several external factors influencing climate and also neglecting the effects that anthropogenic forcing may have on the potential for tropical systems from the SWIO to influence the Limpopo River Basin.

The effect of anthropogenic forcing on the climatology of tropical systems in the SWIO region is a relevant area of research according to Assessment Report Four (AR4) of the IPCC. Having noted the contribution of tropical systems from the SWIO to significant rainfall events over the Limpopo River Basin and exploring the bi-decadal variation thereof in the region, the focus in the following section will shift to investigation of the projected changes in the climatology and landfall of tropical systems from the SWIO towards the end of the 21st century. Over and above the bi-decadal variability associated with tidal forcing as indicated in Section 4, Section 5 will therefore provide information on the projected trend throughout
the 21\textsuperscript{st} century as associated with the effect of anthropogenic forcing as projected by Assessment Report 4 (AR4) climate models.
5. Projected changes in climatology of tropical systems from the SWIO under anthropogenic forcing towards the end of the 21st century

Preface

While the previous sections focused on variation of tropical systems from the SWIO at bi-decadal scale, the final section consists of a published peer reviewed paper that provides an overview of the anthropogenically induced long-term trends in the climatology of tropical systems in the SWIO-southern African region towards the end of the 21st century:


The paper addresses the fourth and final objective of the study by reporting findings of an analysis of the simulations of multi-decadal climate change over southern Africa with the emphasis on changes projected in the climatology of tropical systems over the Southwest Indian Ocean and associated changes in rainfall over the Limpopo River Basin. A direct approach is followed, whereby tropical cyclone-like vortices (TCLVs) are tracked and Tropical Cyclone Indices are calculated from the simulations of current and future climate produced by an Atmospheric General Circulation Model (AGCM) forced with biased-corrected SSTs and sea-ice of six Coupled Global Climate Models (CGCMs) that contributed to Assessment Report 4. The focus is therefore shifted away from the SAM, which was considered in Sections 3 and 4 towards understanding bi-decadal variability of the influence of tropical systems from the SWIO over the Limpopo River Basin. Instead, the simulated regional circulation anomalies, synoptic weather systems and atmospheric temperature and humidity profiles are considered directly, relying on the AGCM’s ability to simulate regional responses to and interactions with global SSTs and atmospheric circulation patterns.

I conceptualized the paper, performed the analyses and synthesized the results. I analyzed the output of the AGCMs by applying the tracking algorithm (modified in section 2) and also calculating a tropical cyclone genesis potential index. I further adjusted the tracking algorithm used in Section I to distinguish between tropical cyclones and weaker tropical systems.
Projected changes in tropical cyclone climatology and landfall in the Southwest Indian Ocean region under enhanced anthropogenic forcing

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Abstract

The conformal-cubic atmospheric model (CCAM), a variable-resolution global model, is applied at high spatial resolution to perform simulations of present-day and future climate over southern Africa and over the southwestern Indian Ocean. The model is forced with the bias-corrected sea-surface temperatures and sea-ice of six coupled global climate models (CGCMs) that contributed to Assessment Report 4 (AR4) of the Intergovernmental Panel on Climate Change (IPCC). All six simulations are for the period 1961-2100, under the A2 emission scenario. Projections for the latter part of the 21st century indicate a decrease in the
occurrence of tropical cyclones over the Southwest Indian Ocean adjacent to southern Africa, as well as a northward shift in the preferred landfall position of these systems over the southern African subcontinent. A concurrent increase in January to March rainfall is projected for northern Mozambique and southern Tanzania, with decreases projected further south over semi-arid areas such as the Limpopo River Basin where these systems make an important contribution as main cause of widespread heavy rainfall. It is shown that the projected changes occur in relation to larger scale atmospheric temperature, pressure and wind profiles of the southern African region and adjacent oceans.

Key words
Tropical cyclone; Indian Ocean; southern Africa; climate change; landfall; atmospheric model

Introduction

Tropical cyclones of the Southwest Indian Ocean (SWIO) basin make landfall over Madagascar and/or Mozambique about three times per year (Mavume et al. 2009). Apart from the devastation caused by storm surges over coastal regions during landfall, rainfall associated with tropical cyclones can also cause widespread flooding over the eastern parts of the southern African interior including the Limpopo River Basin (Reason and Keibal 2004, Crimp and Mason 1999), a semi-arid region including parts of Mozambique, Zimbabwe, South Africa and Botswana. Tropical cyclones and less intense tropical lows originating from the SWIO are in fact responsible for a large portion of the widespread heavy rainfall events that occur over the eastern parts of southern Africa. Between 1948 and 2008, a total of 45 such systems caused rainfall over the Limpopo River Basin, after making landfall over the southern African subcontinent (Malherbe et al. 2012). Assessment Report Four (AR4) of the IPCC points out that only a small number of studies have to date explored the potential impact of enhanced anthropogenic forcing on the attributes of tropical cyclones over the SWIO (Christensen et al. 2007). Globally, there is evidence that tropical cyclones may be expected to become more intense and cause more extreme precipitation events, notwithstanding a projected possible decrease in the total number of cyclones.

Changes in the frequency, tracks and intensity of tropical cyclones over various parts of the globe during the recorded past have been inferred by the study of historical cyclone track data.
bases and/or datasets of synoptic-scale circulation systems (Nicholls et al. 1998, Klotzbach 2006, Elsner et al. 2008, Mavume et al. 2009). The projections of climate models have additionally been used to gain insight into the potential impact of enhanced anthropogenic forcing on tropical cyclones (e.g. Camargo et al. 2007a, Royer et al. 1998, Sugi et al. 2002, Walsh et al. 2004). The analysis of the future attributes of tropical systems, as projected by atmospheric global circulation models (AGCMs) or by coupled global circulation models (CGCMs), has been performed either by the tracking of simulated tropical cyclone-like vortices (TCLVs) or by inferring whether the simulated large-scale conditions favour tropical cyclone formation and intensity, using indices based on atmospheric and surface variables.

Tracking algorithms of TCLVs follow anomalies in several atmospheric variables associated with tropical cyclones, in time and space. Certain threshold values are used to define the intensity of the system, and to distinguish TCLVs from cold-core lows. The position of the TCLV is determined by the geopotential height anomaly in the lower levels of the atmosphere (Walsh and Watterson 1997) or the sea-level pressure anomaly (Bengtsson et al. 1995, Tsutsui 2002, Sugi et al. 2002) and/or sea-level pressure gradient (Tsutsui 2002) or relative vorticity anomaly (eg. Bengtsson et al. 2007b). The height/pressure anomaly in some algorithms needs to be detected in the vicinity of a vorticity anomaly at the lower levels (Bengtsson et al. 1995, Walsh and Watterson 1997, Camargo and Zebiak 2002, Sugi et al. 2002). Wind speed at the lower levels is sometimes used to ascertain the intensity of the system and needs to exceed a minimum value for the identification of a TCLV (Bengtsson et al. 1995, Nguyen and Walsh 2001, Sugi et al. 2002). Criteria used to identify a system as warm-cored include lower tropospheric wind speed exceeding that in the upper troposphere (Bengtsson et al. 1995, Nguyen and Walsh 2001, Sugi et al. 2002) and/or that the average temperature in the troposphere (at 850, 700, 500 and 300 hPa) in the vicinity of the system needs to be higher than in the surrounding area (Nguyen and Walsh 2001, Sugi et al. 2002) - as also reflected in the thickness of the 700 to 200 hPa level (Tsustui 2002). Finally, the duration of the TCLV also needs to exceed a certain time limit in order to be noted (Bengtsson et al. 1995, Sugi et al. 2002). After identification of a TCLV, several criteria are sometimes relaxed. Threshold values for certain variables are also adjusted according to the resolution of simulated data (Walsh et al. 2007, Sugi et al. 2009, Camargo and Zebiak 2002) and ocean basin (Camargo and Zebiak 2002). For example, for low-level wind speed,
threshold values can range between 11 and 17 m/s, depending on the spatial resolution of the data (Bengtsson et al. 1995, Walsh et al. 2004, Walsh et al. 2007, Sugi et al. 2009).

CGCMs have been used to study the influence of enhanced anthropogenic forcing on tropical cyclones (e.g. Bengtsson et al. 1995, Tsutsui 2002, Bengtsson et al. 2006) even when applied at spatial resolutions too coarse to represent realistically the intensity of tropical cyclone vortices, hence necessitating the relaxation of certain criteria for the identification of TCLVs (e.g. Bengtsson et al. 1995, Camargo and Zebiak 2002, Sugi et al. 2009). High resolution atmospheric global circulation models (AGCMs) and nested or nudged regional climate models (RCMs) have also been used to obtain more detailed projections of the effects of enhanced anthropogenic forcing on tropical cyclone attributes (Walsh and Katzfey 2000, Nguyen and Walsh 2001, Walsh et al. 2004, Sugi et al. 2009, Murakami and Wang 2010). The skill demonstrated by AGCMs of various resolutions in simulating the present day tropical cyclone climatology has however been reported to be low over the southern Indian Ocean, with an equator ward displacement of tropical cyclone tracks over the region (Camargo et al. 2005, Sugi et al. 2009). The topography of the island of Madagascar furthermore influences the low level flow and hence the tropical vortices’ evolution over the SWIO (Landman et al. 2005). This necessitates, in the case of limited-area RCMs, the inclusion of the island in the domain of the regional model. The eastern boundary should be in the region of highest simulated tropical cyclone track densities as simulated by the GCM for tropical cyclones moving into the Mozambique Channel (Landman et al. 2005). Recent years have seen the advent of variable resolution atmospheric global circulation models as an alternative to limited-area models, for the purpose of downscaling the output of CGCMs (Gibelin and Déqué 2003, Terray et al. 2004, McGregor 2005a, 2005b, Engelbrecht et al. 2009). An advantage of this approach is that the spurious reflection of atmospheric waves (and associated spurious vertical velocities), which may occur at the lateral boundaries of limited-area models, is avoided.

The influence of large-scale environmental conditions such as vertical wind shear, steering flow and relative humidity on the occurrence of tropical cyclones (e.g. Gray 1988, Emanuel 1995, DeMaria 1996, Holland 1997) has facilitated the development of several tropical cyclone indices from seasonal averages of atmospheric and oceanic variables (e.g. Gray 1998, Bister and Emanuel 1998, Emanuel and Nolen 2004, Zeng et al. 2007). Such indices
have been used to gain insight into the large-scale background conditions that favour tropical storm genesis (e.g. McDonald et al. 2005).

Several variables thought to reflect whether the large-scale environment favour tropical cyclone development are included in two widely used indices, namely The Tropical Cyclone Seasonal Genesis Parameter (TCSGP, Gray 1998) and the Tropical Cyclone Genesis Potential Index (TCGPI, Emanuel and Nolan 2004):

The TCSGP focuses on the dynamical and thermodynamical properties of the environment. Dynamical variables include the Coriolis parameter, low-level absolute vorticity and tropospheric vertical wind shear, while the thermal variables include two atmospheric components namely relative humidity in the mid-troposphere and difference in equivalent potential temperature between the surface and 500 hPa levels as well as an ocean component where thermal energy (temperature exceeding 26° to a depth of 60 m) is considered. A variation of this index is the Convective Genesis Parameter (CGP), where the thermal component of this index is replaced by the convective potential, which is a scaled representation of the mean convective rainfall (mm/day) for the relevant period (Royer et al. 1998, Caron and Jones 2008). This scale factor is estimated based on the relationship between the CGP and number of tropical cyclones formed over an area of interest. The alteration to the TCSGP index is based on the assumption that the thermal potential within the TCSGP is a representation of the potential for cumulonimbus convection, which is related to the supply of latent heat in the atmosphere (Royer et al. 1998) and which is the main energy source of tropical cyclones.

The TCGPI considers similar dynamic and thermal variables as used in the TCSGP and further also requires the calculation of potential intensity from vertical wind, temperature and humidity profiles. (e.g. Yu and Wang 2009).

The above-mentioned indices have been used successfully to investigate the influence of the El Nino Southern Oscillation (ENSO) phenomenon on tropical cyclone formation (Camargo et al. 2007b) and have also been applied to the output of the CGCMs that participated in the IPCC AR4 CMIP3, to analyze the projected change in the regional characteristics of tropical cyclones under doubling of CO2 concentrations (Caron and Jones 2008, Yu and Wang 2009, Yu et al. 2010). Several of the input atmospheric variables have also been used individually in studies towards explaining the temporal variability in the occurrence of tropical cyclones.

Large-scale circulation patterns over the SWIO that have been linked to deviations in the occurrence of tropical cyclones include upper and lower tropospheric wind anomalies over the subtropics and tropics, and in particular the quasi-biennial oscillation (Jury 1993). The Madden Julian Oscillation and ENSO have also been linked to the track and frequency characteristics of tropical cyclones over the region (Liebmann et al. 1994, Vitart et al. 1999) while the landfall of tropical cyclones have been related to ENSO through an associated increase in the tropical easterlies over the SWIO during La Nina events (Vitart et al. 2003).

Anthropogenically enhanced warming could lead to a worldwide decrease in the frequency of tropical cyclones towards the end of the 21st century (e.g. Bengtsson et al. 2007a, Yoshimura and Sugi 2005, Sugi et al. 2009). However, an increase is expected in the occurrence of the most intense systems (Bengtsson et al. 2007a, Walsh and Ryan 2000, Knutson et al. 2001, Walsh et al. 2004). The decrease in expected frequency of tropical cyclones under enhanced anthropogenic forcing have also been reported for the southern Indian Ocean specifically (Caron and Jones 2008) as well as a slight increase in the maximum wind speed obtainable (Oouchi et al. 2006, Yu et al. 2010). Uncertainty in the projections is reflected to some extent in the finding of Tsusui (2002) reporting an expected increase in the number of days with tropical cyclones over the region.

In a review of trends in tropical cyclone climatology from historical datasets, Knutson et al. (2010) cites data heterogeneity (Landsea et al. 2006) and shortness of reliable data series as problematic when attempting to study the effect of anthropogenic forcing, and also to distinguish such forcing from multi-decadal climate variability (Chan 2006).

Analyses of historical datasets have shown no statistically significant change in the global frequency of tropical cyclones between 1986 and 2005 (which is the period during which a higher reliability of the historical record was achieved through satellite observations) and only a small change in the occurrence of category 4 and -5 hurricanes (Klotzbach 2006). Findings over the Southern Indian Ocean include a lack of any trend in the observed number of tropical cyclones between 1960 and the late 1990s (Henderson-Sellers et al. 1998) and an upward trend in number of most intense systems since the late 1970s into the 21st century.
(Webster et al. 2005; Elsner et al. 2008). Kuleshov et al. (2010) reaffirms these findings for the period 1981-2007 concluding that while no trend exists over this period for all systems with a lifetime minimum central pressure (LMCP) of 995 hPa or lower, the upward trend in systems with a LMCP of 950 hPa or lower is statistically significant. Concerning landfall in the region of the SWIO, a decrease has been observed between 1952 and 2007 (Muvame et al. 2009). However, in an assessment of observed data from 1948 no trend has been found either in landfall occurrences over southern Africa considering all closed warm core tropical low pressure systems originating over the SWIO, or in the rainfall contributed by these systems (Malherbe et al. 2012).

The present study is an evaluation of the simulated current and projected future climatologies of tropical systems over the SWIO under enhanced anthropogenic forcing by a variable-resolution atmospheric model. As these systems have been shown to play an important role in significant rainfall over the eastern parts of the southern African subcontinent, specifically the Limpopo River Basin, the tendency of these systems to make landfall as well as their preferred area of entry and subsequent movement over the southern African subcontinent are also evaluated.

**Materials and Methods**

The conformal-cubic atmospheric model (CCAM), a variable-resolution global model of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research in Australia (McGregor 1996, 2005a, 2005b, McGregor and Dix 2001), is used to perform simulations based on the bias-corrected sea-surface temperatures (Katzfey et al. 2009) and sea-ice simulations of six coupled global climate models (CGCMs) that contributed to Assessment Report 4 (AR4) of the International Panel for Climate Change (IPCC) and the Coupled Model Intercomparison Project (CMIP3) data base. All six CGCMs responded to greenhouse gas forcing as described by the A2 (business as usual) emission scenario of the Special Report on Emission Scenarios (SRES), for the period 1961-2100.

The CGCMs are:
These six models have been shown to simulate average sea-level pressure fields in the Southern Hemisphere and tropical belt (van Ulden and van Oldenborgh 2006), and the Madden Julian Oscillation (Sato et al. 2009) relatively well compared to the full set of CMIP3 models, whilst most members of the set of six models are also superior in simulating the response of rainfall over the Western Pacific to SST anomalies associated with ENSO (Ose and Arakawa 2009).

Downscaling is performed using a multiple-nudging approach. First, CCAM is applied at quasi-uniform C48 resolution (about 2° in latitude and longitude), with forcing from the host models as specified. In a second phase of the downscaling, CCAM is subsequently integrated in stretched-grid mode over southern Africa and the Southwest Indian Ocean, at C64 resolution (Figure 1) and with a Schmidt factor of 2.5 (this provides a resolution of about 60 km over the area of interest, decreasing to about 400 km in the far-field).
Quasi-uniform C48 conformal-cubic grid (Schmidt factor 1) that provides about 200 km resolution in the horizontal (top) and C64 stretched conformal-cubic grid (Schmidt factor 2.5) over southern and tropical Africa (bottom).
The high-resolution grid is chosen to optimize the resolution over the Mozambique Channel and the eastern subcontinent of southern Africa - with the purpose of resolving the influence of westward propagating tropical storms over this region with sufficient detail. The higher resolution simulations are nudged within the quasi-uniform C48 simulations, through the application of a digital filter (Thatcher and McGregor 2009) using a 4000 km length scale. The filter is applied at six-hourly intervals and from 900 hPa upwards. Details of the experimental design, as well as a verification of the CCAM simulations of seasonal rainfall totals over southern Africa, are provided by Engelbrecht et al. (2011). Previous applications of CCAM over southern Africa have illustrated the model's ability to satisfactorily simulate not only the temperature and rainfall climatology over southern Africa (Engelbrecht 2005, Engelbrecht et al. 2009), but also the seasonal circulation and rainfall cycle (Engelbrecht et al. 2009). Recently, the model has been shown to provide realistic simulations of mid-tropospheric closed-low tracks and frequency of occurrence of extreme weather events over southern Africa (Engelbrecht et al. 2012).

The 6-member CCAM-ensemble is used to study the projected changes in the characteristics of tropical systems over the SWIO and their landfall over southern Africa, through the tracking of simulated tropical-cyclone-like-vortices (TCLVs) (here defined as intense warm core closed-low pressure systems of which the simulated maximum wind speed exceeds 13 m/s), and the larger family of warm core closed-low pressure systems (of which the simulated maximum wind-speed do not necessarily exceed the 13 m/s threshold). With the primary focus of the study being the tracking of tropical systems from the SWIO into the eastern parts of southern Africa, the area of interest (Figure 2) has been selected to include Madagascar and the Indian Ocean to the east of the island, to allow the tracking of tropical systems from 80° E westwards into southern Africa. For the purpose of model verification, the simulated 1961-1990 TCLV climatology of the CCAM-ensemble over the SWIO and southern Africa is compared to that of NCEP reanalysis data (Kalnay et al. 1996), after resampling the NCEP data to 2° resolution through bicubic interpolation to obtain data with overlaying grid points.
Figure 2  Area of interest. The Limpopo River Basin is indicated.

The simulation of the current and future warm-core closed-low and TCLV climatologies over the region is first evaluated through the application of an objective closed-low tracking algorithm (Malherbe et al. 2011, Engelbrecht et al. 2012), entailing the identification of geopotential height minima and their tracking in time. For all six ensemble members on the C48 grid, all local geopotential minima (closed-lows) are identified at the 700 hPa pressure level and tracked for every 6-hourly time-step over the entire 140-year period from 1961 to 2100. Because the majority of landfalling tropical storms over southern Africa are confined to the January-to-March period (Malherbe et al. 2011), only these months are considered in the analysis. Geopotential minima are identified by considering the geopotential height at all grid points relative to their surrounding 9-gridpoint stencil on the latitude-longitude grid. In certain cases, it is found that multiple adjacent grid points recorded the same geopotential minimum value at a given time-level. For such cases, the stencil is enlarged and the algebraic average of the longitudinal and latitudinal coordinates of the grid points sharing the geopotential minimum value is taken as the position of the closed-low at that time-level (e.g. Lambert 1988, Blender and Schubert 2000). For each closed-low identified at the 700 hPa
level, the following criteria are used to identify it as a warm-core low pressure system as opposed to other types of closed-low pressure systems, such as cut-off lows (e.g. Taljaard 1985):

- A temperature maximum at 250 hPa overlaying the low pressure system at 700 hPa
- A pressure minimum reflected also at 500 hPa above the 700 hPa low pressure minimum
- A vorticity value lower than \(-0.000035\text{s}^{-1}\) at 700 hPa – this vorticity threshold is identified by visual inspection of several low-pressure systems at 700 hPa from historical records and reanalysis simulations.

A further prerequisite for the identification of TCLVs from this set of closed warm core low-pressure systems is that the maximum 10 m wind speed surrounding the centre of the low at 700 hPa should exceed 13 m/s (Walsh et al. 2007).

The tracking of closed-lows in time is carried out at the 700 hPa level, after identification of a warm cored closed-low in an iterative procedure where all the height minima identified at time \(t\) are subjected to the tracking criteria that entail finding the closest minimum at time \(t+1\) to the minimum found at time-level \(t\). During this procedure, consideration is given to the direction of movement of the minimum being tracked as well as the difference in the height of the minima during time-step \(t\) and \(t+1\). This procedure has been shown to realistically track tropical systems observed over the area of interest (Malherbe et al. 2012). The number of times that the simulated tracks of warm core low-pressure systems migrate through each grid point over the area of interest as simulated by each member of the CCAM ensemble, for the 1961-1990 period as well as those found through the application of the tracking algorithm to the NCEP Reanalysis dataset are recorded. The pattern correlation between these simulated and observed values, as well as the root mean square error and standard deviation of the simulations normalised by the standard deviation of the observations (Taylor 2001) are used as a measure of the CCAM ensemble’s ability to represent the current climatology of tropical systems over the SWIO (including those moving into the subcontinent). Landfall positions are defined within the tracking algorithm by recording the latitude where a tracked low pressure system originating over the SWIO is located over a land point for the first time.
In order to gain insight into certain projected changes simulated in preferred TCLVs and tracks in the region, the Convective Tropical Cyclone Genesis Parameter (Royer et al. 1998) is calculated for the January to March period. The averages of each CCAM ensemble member’s simulated 850 and 200 hPa geopotential heights and wind vectors, relative humidity at 600 hPa and simulated convective rainfall for the January-March period are used for this purpose. The scale factor used to relate the convective daily rainfall to the convective potential is 0.1379. This value was derived from the ERA40 dataset for the approximation of the average observed number of tropical cyclones globally (Caron and Jones 2008).

**Results**

*Simulated versus observed warm core closed-low pressure system and TCLV climatology*

Figure 3 shows the ensemble average of the frequency of occurrence of TCLVs per grid point (top, shaded) for the period 1961-1990 as simulated by the CCAM, and as observed from the NCEP reanalysis data (bottom), as obtained through application of the tracking algorithm. The NCEP analyses data instead of Best Track data are used as a comparison in order to evaluate the CCAM ensemble output to data of similar resolution. The individual TCLV tracks, from which the frequency of occurrence per grid point is calculated, is also shown for the observed tracks (bottom) and one for one of the CCAM ensemble members (top).
Figure 3  
Frequency of occurrence of TCLVs per grid point, as calculated from the ensemble average of the CCAM tracks (top, shaded) and as observed from the NCEP reanalysis data tracks (bottom, shaded). The actual simulated tracks for the CCAM-ECHAM5 ensemble member is indicated (top), and similarly for the reanalysis data (bottom). Units are number of occurrences per grid point over the January to March period.
Figure 4 shows the track frequency per 2° grid point for the period 1961-1990 based on information from the International Best Track Archive for Climate Stewardship (IBTrACS – Knapp et al. 2010) over the SWIO for the January-March period.

![Track Frequency Map](image)

**Figure 4** Frequency of occurrence of tropical cyclones per 2° grid point based on information from the IBTrACS for the 1961-1990 period. Units are number of occurrences per grid point over the January to March period.

The track frequency displayed in Figure 4, based on the IBTrACS data set, represents the tracks of all named storms over the SWIO during the 1961-1990 period. For lack of intensity information for all storms (e.g. Mavune et al. 2009), all named storms are considered irrespective of intensity information. For this reason, and an underestimation of tropical cyclone intensity in reanalysis datasets (Schenkel and Hart 2012), the track frequency in Figure 4 represents a larger number of systems than that tracked from the NCEP reanalysis dataset (Figure 3). It serves however as an indication that the preferred tracks of systems as determined from the tracking algorithm applied to the NCEP data is realistic.

The highest concentration of TCLVs over the SWIO, the movement of systems around the northern edge of Madagascar and their southeastward and southward movement out of the SWIO region, their landfall tendency and westward and northwestward propagation of some
of the systems into the subcontinent as simulated by the CCAM ensemble, are also observed in the NCEP reanalysis dataset over the period 1961-1990 (Figure 3). These characteristics are captured in the simulations of the individual CCAM ensemble members, as shown in Figs.5a and b.
Figure 5a  Frequency of occurrence of TCLVs (shaded) per grid point for the period 1961-1990 as simulated by CCAM-CIROMk3.5 (top), CCAM-ECHAM5 (middle), CCAM-UKHADcm3 (bottom). The actual tracks simulated by each CCAM ensemble member are also indicated.
Figure 5b Frequency of occurrence of TCLVs (shaded) per grid point for the period 1961-1990 as simulated by CCAM-MIROC (top), CCAM-GFDLcm2.0 (middle) and CCAM-GFDLcm2.1 (bottom). The actual tracks simulated by each CCAM ensemble member are also indicated.
The CCAM ensemble members display a high degree of agreement in the simulation of the current distribution of TCLVs over the SWIO, with the ensemble mean showing superior correspondence to observations compared to individual ensemble members, as quantified by the Taylor Diagram (Figure 6). However, the standard deviation of the simulated storms is higher than the variance standard deviation of the reanalysis.

![Figure 6](image)  

**Figure 6**  Taylor diagram showing the statistical comparison of the simulation of TCLVs frequency of occurrence per grid point of the individual CCAM ensemble members (circles) and the CCAM ensemble mean (triangle) over the SWIO with the reanalysis distribution (cross).

The pattern correlation of the individual members range between 0.76 and 0.82, with the ensemble mean having the highest pattern correlation with the observed field. Furthermore, the ensemble mean has the smallest normalised root mean square error when compared to the observed field (owing to the smooth nature of the ensemble field relative to the individual members), and second lowest difference in the normalised standard deviation.

Overall, the main attributes of the tracks of landfalling warm core closed-lows are captured realistically by the ensemble mean (Figure 7).
Figure 7  Average frequency of occurrence of landfalling warm core closed-lows per grid point (shaded), during January to March, as simulated by the CCAM ensemble average for 1961-1990 (top) and as according to NCEP Reanalysis data (bottom).
Considering all simulated warm core closed-low pressure systems making landfall from the SWIO over the southern African subcontinent, the main region of origin of systems to the northeast of Madagascar, the preferred landfall area as well as the main west-northwestward inland track are all represented by the CCAM ensemble (Figure 7). For a further indication of the ability of the CCAM ensemble to simulate landfall of TCLVs (a subset of the larger set of warm core closed-lows) in particular, as well as their propagation into the subcontinent, Figure 8 shows the simulated and observed position of westward propagating systems along the 28th longitude over southern Africa, after making landfall as TCLVs from the SWIO.

![Diagram showing latitudinal occurrence and average frequency of occurrence during January to March, of TCLVs from the SWIO moving across 28°E over the period 1961-1990, as observed in NCEP reanalysis (black) and as simulated by individual CCAM ensemble members (thin lines) as well as the CCAM Ensemble mean (thick grey line).](image)

The number of systems moving into the subcontinent as simulated by the CCAM ensemble mean represents the observations realistically, except for a systematic northward displacement of the preferred westward path. All the ensemble members show the peak latitude of landfall to the north of the observed, except for the CCAM-GFDLcm2.0 simulation that indicates the preferred latitude to be 18 degrees S - as observed. The ensemble member that seems to displace the preferred tracks along this longitude furthest to the north is CCAM-CSIROmk3.5 downscaling. The north-south envelope within which westward propagation of tropical systems occurs over the interior, however, is an accurate representation of the observed. It can therefore be concluded that the CCAM ensemble is able
to satisfactorily simulate the occurrence of warm-cored closed lows over the SWIO and over the southern African subcontinent after landfall.

**Projected changes**

The 75th, 50th and 25th percentiles projected change in the frequency of occurrence of TCLVs and all warm core closed-low pressure systems per grid point, as represented in the simulated CCAM tracks, are shown in Figure 9. While the entire period for November-to-April was considered, the changes during the January-March period are more pronounced than for the rest of the season (not shown) and there is no indication of a shift in the landfall season towards the early or late tropical cyclone season from the January-to-March period. Changes are shown for the January-to-March season, for the period 2071-2100 relative to 1961-1990.
Figure 9  
75th (top), 50th (middle) and 25th (bottom) percentiles of projected change in number of average January to March occurrences per grid point of TCLVs (left) and warm-core low pressure systems (right) as simulated by the CCAM ensemble for the 2071-2100 period relative to 1961-1990.
The median of the CCAM ensemble indicates a general decrease in the number of TCLVs over much of the region, and a decrease of all warm core closed-low pressure systems over the southern parts of the Mozambique Channel and the southern parts of the IO in general (Figure 9). Increases in the frequency of occurrences of warm-core closed lows are projected to occur in a zonal band over and to the north of northern Madagascar. The 25th and 75th percentiles of the projected changes provide some insight into the uncertainty range described by the projections. The 75th percentile in fact is indicative of a potential increase in the frequency of closed-lows not only within a zonal band over and to the north of Madagascar, but also over large parts of the southern Indian Ocean. TCLVs specifically are consistently projected to decrease over the southwestern parts of the SWIO. Considering only landfalling systems, a decrease is simulated to occur in the landfall of TCLVs from the SWIO, but an increase is simulated for all tropical warm-core closed-lows with the preferred latitude of landfall shifting somewhat northward (Figure 10).

![Figure 10](image)

Figure 10  Average number of warm core lows (top) and TCLVs (bottom) per 2° latitude interval making landfall over southern Africa from the SWIO as simulated for the 1961-1990 (black) and 2071-2100 (grey) periods by the CCAM ensemble. Lines representing the moving averages are also indicated.
Figure 10 shows that the CCAM ensemble average indicates a general reduction in the number of landfalling TCLVs over most of the southern African coastline. This is also the case for all warm core lows, except over the northern parts (north of 18°S), where an increase in the frequency of occurrence of such systems is projected. Consistent with the projected decrease in the landfall of all tropical systems over the southern parts of the coastline, the ensemble average projects a decrease in simulated rainfall over these areas for January to March rainfall (Figure 11).

![Figure 11](image)

**Figure 11**  CCAM ensemble average projected change in January-March rainfall between the 1961-1990 and the 2071-2100 periods.

The environmental steering flow for TCLVs is considered to be the weighted average of the wind vectors from 700 hPa to 500 hPa (Franklin et al. 1996, Jury and Pathack 1991), whilst the large-scale circulation anomalies at 700 hPa have been associated with cyclone track characteristics (Harr and Elsberry 1991). To gain insight into how the projected change in the tracks of warm core closed-lows and TCLVs in particular is brought about by changes in the regional circulation in the region, Figure 12 shows the projected change in average January-March heights of the 700hPa level, for all of the CCAM ensemble members.
The general simulated increase in the height of the 700 hPa level is due to general warming of the troposphere in the greenhouse gas warmed climate, resulting in the increase in 700 hPa geopotential heights through the hydrostatic relationship (e.g. Engelbrecht et al. 2009). The one member that is different in this respect is CCAM-MIROC, which shows a decrease in the 700 hPa geopotential height over a large region to the east of Madagascar, with a concurrent decrease in rainfall over the eastern parts of Madagascar. This change can be related to a large increase in the occurrence of tropical cyclones over this region, from 55°E eastward and south of 15°S, by this particular ensemble member (not shown). Five of the six ensemble members agree broadly about the change in the average 700 hPa height over southern African
and the SWIO region. This general pattern involves a relatively larger increase in the geopotential heights over the northern parts of the subcontinent, in some cases extending eastwards over the Mozambique Channel. Relatively smaller increases are simulated further to the south over the subcontinent and the IO. Towards the east of Madagascar, geopotential heights are projected to increase relatively more than the surrounding areas. Five ensemble members also project larger increases in geopotential over the subcontinent than over the adjacent SWIO, the only exception being the CCAM-CSIROmk3.5. All members further project an increase in the rainfall over the SWIO surrounding the northern parts of Madagascar and a decrease further south towards southern Mozambique. These findings suggest that the simulated mechanism for the northward shift in the preferred tracks of tropical systems from the SWIO may be related to a relatively larger strengthening in the subtropical ridge over the northern to eastern parts of the southern African subcontinent and towards the Mozambique Channel, causing tropical systems to move into the continent further northward around the strengthened anticyclonic circulation over these areas.

Apart from a northward displacement in the tracks of tropical systems over the SWIO and adjacent southern African subcontinent, the simulated decrease in TCLVs and also all tropical warm core closed-lows over the areas to the east of South Africa and to the east of Madagascar requires further investigation. To this end, the Convective Tropical Cyclone Genesis Parameter (Royer et al. 1998) provides an indication of the large-scale mechanisms responsible for this decrease. The index gives an estimation of the expected frequency of formation of tropical cyclones per $5^\circ$ grid point over a period of about 20 years.
Figure 13  Number of occurrences per grid point of TCLVs (top) as simulated by CCAM-MPI (Unit: total number of tropical cyclones passing per 2° grid point over a 30-year period) and CTCGP (Unit: approximate average twenty-yearly total number of tropical cyclones formed per 5° grid point) calculated for CCAM-MPI for the 1961-1990 period.
The CTCGP estimate is consistent with the calculations of Caron and Jones (2008) based on IPCC AR4 CGCMs. Even though there should be a direct relationship between the number of systems formed and the number of tracks passing a point, the number of systems formed should be lower as indicated. The index identifies the tropical cyclone areas and is further investigated to provide information on possible mechanisms for the change observed through tracking. The changes in this index from the 1961-1990 period to the 2071-2100 period per grid point as simulated by the ensemble members have been ranked and the 25th percentile, median and 75th percentile values are indicated in Figure 14.
Figure 14  75th (top), 50th (middle) and 25th (bottom) percentiles of the change in the Convective Tropical Cyclone Genesis Parameter (Unit: approximate average twenty-yearly total number of tropical cyclones formed per 5° grid point) as calculated from the ensemble of CCAM members for the period 2071-2100 relative to 1961-1990.
Figure 14 shows that the findings deduced from the tracking of simulated TCLVs are supported by averages of the large-scale seasonal atmospheric variables utilised in the CTCGP. The two areas where a decrease in both TCLVs and tropical warm core closed-lows are consistently simulated (Figure 9) by the various ensemble members, namely the southern parts of the Mozambique Channel and the southern IO between 60° and 80° E, are also indicated by the index as areas of reduced capability of the large-scale environment to support the development of tropical cyclones. The areas around northern Madagascar, where the tracking of TCLVs suggested less tropical cyclones, but an increase in the total number of all warm core closed-lows is simulated, are shown to become more favourable for cyclone genesis. Uncertainty in the tracking results however over this area specifically is displayed by the relatively large positive value indicated by the 75th percentile of simulated change.

Several factors are responsible for the decrease in conditions that favour the development of tropical cyclones over large parts of the SWIO, specifically over the southern parts of the Mozambique Channel and east of Madagascar towards the end of the 21st century under enhanced anthropogenic forcing. Figure 15 shows that both the dynamic and the convective (as proxy for the thermal) components of the CTCGP index are implicated in the diminishing potential for tropical cyclone development over the southern parts of the Mozambique Channel, while decreases towards the east of Madagascar are more clearly associated with dynamical component only.
Figure 15  75th (top), 50th (middle) and 25th (bottom) percentiles of the change in the dynamic (left) and convective (right) components of the Convective Tropical Cyclone Genesis Index as calculated from the ensemble of CCAM members for the period 2071-2100 relative to 1961-1990.
The convective component of the index is conducive of a decrease in tropical cyclones over especially the southern part of the Mozambique Channel, but indicates a potential for an increase in such systems to the north (where an increase in warm-core tropical lows is in fact projected). It is this component of the index that results in the overall indication of the potential for an increase in the number of tropical cyclones over the northern parts of the area of interest. It has been noted that (convective) rainfall over the southern African subcontinent is overestimated by CCAM (Engelbrecht et al. 2009, Engelbrecht et al. 2011). A potential overestimation of the future increase in convective rainfall in the CCAM simulations, may explain the inconsistency of the median of ensemble members projecting a decrease in the frequency of occurrence of TCLVs across the IO, whilst the median of the projections of change in the CTCGP indicate more favourable conditions for TCLV occurrence in a zonal band stretching around northern Madagascar. Indeed, most ensemble members project increases in rainfall over and to the north of the Mozambique Channel in the order of 30%, with increases in the order of 20% over the remainder of the SWIO, for the period 2071-2100 relative to 1961-1990 (Engelbrecht et al. 2011). The rainfall that occurs over this region is mostly of a convective nature (rather than of stratiform nature). These strong increases in convective rainfall are consistent with the convective component of the index indicating an increased potential for tropical cyclone occurrence. However, the projected increase in total number of tropical warm core closed-lows in this region (Figure 9) indicates that there is indeed an increase in favourability of the environment for the development of tropical systems but with 10 m wind not exceeding the theoretical 13 m/s threshold. We conclude therefore that the convective component of the index might lead to a possible overestimate of tropical cyclone genesis over the northern areas in future and will therefore consider the thermal atmospheric components of the CTCGP later also to further investigate this.

The dynamic component of the CTCGP decreases over a large part of the SWIO, especially over the area towards the south of the central Mozambique Channel and vast areas towards the east of Madagascar. Dynamic mechanisms therefore seem to be the most important factor responsible for the projected decrease in the favourability of tropical cyclone occurrence over these regions. Similarly over the North Pacific, changes in atmospheric dynamics have been found key in driving changes in that region’s tropical cyclone climatology (Chan and Liu 2004). The dynamic component of the CTCGP consists of absolute vorticity at 850 hPa and the wind shear between the 850 hPa and 200 hPa levels. Figure 16 shows that these
components both play a role in the decrease in the genesis potential over the southern parts of the Mozambique Channel and the areas towards the east of Madagascar.
Figure 16  75th (top), 50th (middle) and 25th (bottom) percentiles of the change in the average wind shear (ms$^{-1}$/600 hPa) between 800 and 200 hPa (left) and the change in vorticity (10$^{-6}$s$^{-1}$ -right) as calculated from the ensemble of CCAM members for the period 2071-2100 relative to 1961-1990.
South of about 20°S, an increase in average wind shear between 850 hPa and 200 hPa is simulated, whilst the 850 hPa vorticity is projected to increase (decrease in cyclonic vorticity), especially over the southern parts of the Mozambique Channel and also east of 50° E, between 10° and 20°S. These are the two main areas showing a projected decrease in TCLVs and tropical warm core closed-lows. The increase in low level vorticity adjacent to southern Africa is related to a relatively larger increase in geopotential heights relative to the surrounding areas, as described earlier.

While the thermal convective component of the CTCGP is calculated from the simulated convective rainfall, the two atmospheric components of the original TCSGP are the relative humidity at 600 hPa and the gradient of the potential temperature between the surface and 500 hPa. The projected change in the averages of these variables is shown in Figure 17.
Figure 17  75th (top), 50th (middle) and 25th (bottom) percentiles of the change in the gradient of potential temperature (10⁻⁸°C) between the surface and 500 hPa (left) and the change in Relative Humidity (%) at 600 hPa (right) as calculated from the ensemble of CCAM members between the 1961-1990 and the 2071-2100 periods.
The gradient of the potential temperature between the surface and 500 hPa is negatively related to tropical cyclone genesis (Gray 1998, Bengtsson et al. 2007a). The projected steeper gradient in potential temperature is an indication of an increase in static stability of the atmosphere over large parts of the SWIO by the end of the 21st century under enhanced anthropogenic forcing and may therefore be related to the overall decrease in simulated tropical cyclone frequency. Relative humidity in the mid-troposphere, however, is expected to increase over most regions, counter balancing the effect of the increase in static stability on tropical cyclone genesis as used in the CTCGP, except over the areas adjacent to southern Africa over the Mozambique Channel (Figure 17) where the majority of ensemble members indicate a decrease in this variable. These findings suggest that the future thermal properties of the atmosphere also play a role in the simulated decrease in tropical cyclone activity towards the southern parts of the Mozambique Channel and into the southeastern parts of southern Africa but to a lesser extent over the rest of the area, especially towards the north.

The projected reduction in the occurrence of tropical cyclones over parts of the SWIO, especially near southern Africa over the central and southern parts of the Mozambique Channel, can therefore be related to a change in the large-scale circulation patterns as well as a change in the vertical temperature and moisture profiles of the atmosphere.

**Discussion**

The 6-member CCAM ensemble has captured the general spatial characteristics of the occurrence of warm core closed-lows and TCLVs over the SWIO and into southern Africa realistically, as quantified by a high pattern correlation between simulated and observed fields for the 1961-1990 period. The observed preferred tracks of tropical cyclones over the SWIO, landfall positions as well as westward penetration into the subcontinent have been resolved by the simulations forced by the bias-corrected SSTs and sea-ice simulations of 6 AR4 models for that period.

Projections of the CCAM ensemble based on the business as usual SRES scenario indicate that under enhanced anthropogenic forcing a general decrease in the frequency of tropical cyclones may occur towards the end of the 21st century over most of the SWIO region, even though the total number of warm core closed-lows over the region are projected to increase. The projected increase in the total number of warm core closed-lows in a zonal band over and
to the north of northern Madagascar is associated with increasing favourability in thermal and
dynamic features of the atmosphere, while the projected decrease in TCLVs over the southern
areas is related to a projected change mainly in the dynamic properties of the atmosphere
(over the southern Mozambique Channel, the thermal properties are also conducive to a
decrease in TCLVs). Apart from an increase in static stability in the lower to middle
troposphere in agreement with earlier findings over the Northern Hemisphere ocean basins
(e.g. Bengtsson et al. 2007) and a decrease in relative humidity over the southern parts of the
Mozambique Channel, the general circulation patterns are also conducive to an enhancement
of vertical wind shear between the lower and upper levels of the troposphere, a phenomenon
which have been related to a projected decrease in Atlantic Ocean Hurricane activity (Garner
et al. 2009). An increase in vorticity in the lower levels over especially the regions of the
SWIO close to the southeastern parts of southern Africa where the strengthening of the
subtropical high pressure is expected to be larger than over the surrounding areas is also
indicated. Such an increase in low-level vorticity over parts of the SWIO has been linked to
reduced tropical cyclone genesis over the SWIO during El-Nino years (Vitart et al. 1999).

A projected decrease in the occurrence of TCLVs is indicated in particular over the southern
parts of the Mozambique Channel and the adjacent southern Africa, whilst an increase in the
number of tracks of the larger family of warm core lows are projected for most of the
northern regions of the southern African coast (northern Mozambique and southern
Tanzania). This northward shift in the tracks of tropical systems from the SWIO over
southern Africa is also the result of a relatively larger strengthening in the subtropical high
pressure system over the northern to eastern parts of southern Africa relative to the areas
surrounding that. Concurrently there is also a related decrease in total rainfall over much of
the eastern parts of southern Africa including most of the Limpopo River Basin where the
decrease in passage of tropical systems from the SWIO is projected to occur. The decrease in
the simulated future occurrence and intensity of tropical systems from the SWIO moving into
the Limpopo River Basin under enhanced anthropogenic forcing can have serious impacts on
the water balance of this region with a largely rural population dependent on agriculture as
such weather systems have been associated with the largest rainfall events as well as the most
extensive flood events there at least since 1948.
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References


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Synopses

The effect of anthropogenic forcing on the climatology of tropical systems in the SWIO region towards the end of the 21st century has been investigated, addressing the final objective of the study. Over and above the bi-decadal variability associated with tidal forcing as indicated in Section 3 and 4, findings reported in Section 5 indicate that regional circulation anomalies and atmospheric temperature and humidity profiles may result in a trend towards a northward displacement of tropical systems moving into the southern African subcontinent and in fact a reduction in the tendency towards strengthening of tropical systems over large parts of the SWIO into tropical cyclones. A concurrent decrease in the rainfall during JFM over the Limpopo River Basin is indicated towards the end of the 21st century. Understanding bi-decadal variability of tropical systems from the SWIO over the Limpopo River Basin towards the middle of the 21st century together with information on the trends of these systems in the region as projected towards the end of the 21st century, provides potentially valuable information for decadal to longer-term planning in fields such as agriculture and hydrology.
6. Summary and Conclusions

While there have in the past been several accounts of disasters over southern Africa and in particular the Limpopo River Basin related to the influence of tropical systems from the SWIO, the current study provided a collective historical account of the climatological impacts of these systems during the era of meteorological data availability over the interior of the basin (northeastern South Africa, southern Zimbabwe). Additionally, it has also provided new insight into climate variability and drivers thereof in the region, whilst giving an indication of the projected change towards the end of the 21st century in the climatology of tropical systems from the SWIO in the region.

Considering synoptic weather systems of a specific type historically instead of only total rainfall have yielded new discoveries about the climate system and its decadal-scale variability in the region. Moreover, identification of Hemispheric anomalies with which the regional anomalies are associated has shed more light on a previously noticed teleconnection between climate variability over southern Africa and New Zealand at bi-decadal scale. The identification of an external forcing mechanism with statistically significant atmospheric circulation responses not only at bi-decadal scale but also at daily time scales, has given direction to a large area of potential further climate research that can feed into the improvement of Earth System Models. The study further provided information on projected change in the region, with reference to general atmospheric circulation patterns and impacts on extreme events, by the end of the 21st century. This new knowledge about the bi-decadal variability in the region can be used together with multi-decadal projections towards the end of the 21st century to support planning at decadal to multidecadal scale.

Major results of the study are summarized as follows:

- Regarding the collective influence of tropical systems from the SWIO over the Limpopo River Basin:
  - The rainfall resulting from these systems over the Limpopo River Basin is confined to the January-March period, with a maximum around early February.
  - Less than 10% of the average annual rainfall can be attributed to these systems.
o Notwithstanding, widespread heavy rainfall events are mostly the result of these systems.

o The rainfall associated with these systems over the region varies with a bi-decadal cycle, in phase with the Dyer-Tyson cycle.

- The multiyear variation in the influence of these systems over the Limpopo River Basin is related to decadal time scale changes of:
  o The Southern Annular Mode (SAM).
  o Occurrence of an anticyclonic anomaly to the southeast of southern Africa related to a lower to mid-tropospheric ridge separating tropical systems from the westerlies to the south in the region.
  o The strength of the subtropical easterlies.
  o Vorticity ad convergence along 15°S, including the area of the Angola Low.

- The regional atmospheric circulation anomalies with which the increase in the contribution to rainfall in the Limpopo River Basin is associated are also conducive to above-normal rainfall over much of southern Africa, therefore explaining the positive association with the Dyer-Tyson cycle.

- While circulation anomalies relevant to tropical systems from the SWIO during JFM over the Limpopo River Basin is significantly associated with the SAM, variation in the SAM at daily to bi-decadal time scale seems to be strongly associated with lunar tidal forcing during JFM.

- The variation in the SAM is also noticeable at daily to bi-decadal time scale in the rainfall records over northeastern South Africa (including parts of the Limpopo River Basin), where rainfall is positively associated with the SAM.

- Towards the end of the 21st century, the influence of tropical systems from the SWIO over the Limpopo River Basin is expected to decrease under enhanced anthropogenic forcing due to the following:
  o The intensification of the subtropical high pressure systems over the northern and eastern parts of the southern African subcontinent, responsible for steering tropical systems further north, where an increase in occurrence of such systems is simulated.
Thermal and dynamical properties of the troposphere over the southern parts of the SWIO are expected to cause a decrease in the occurrence of tropical cyclones and also a decrease in the landfall of these systems.

- Total JFM rainfall is expected to decrease over the Limpopo River Basin towards the end of the 21st century in response to the change in tracks of the systems from the SWIO and the strengthening of the subtropical ridge across the region.

- Multi-decadal projections of bi-decadal variability, based on forcing of the SAM by the tidal component only, suggests that the periods 2012-2019 and 2032-2038 are more likely to be characterized by a positive JFM SAM. A higher JFM SAM is strongly linked to anomalously high rainfall and larger contribution by tropical systems from the SWIO over the Limpopo River Basin. Similar multi-year periods with a larger contribution to rainfall by tropical systems form the SWIO over the Limpopo River Basin will also occur towards the end of the century. However, climate change projections analysed suggest a trend towards a decrease in the contributions by tropical systems from the SWIO over the basin and lower seasonal total rainfall towards the end of the 21st century over and above bi-decadal variability.

Several new findings regarding climate variability and climate change in the SWIO has emerged during the study, and the following key recommendations are made with the view on future research:

- The bi-decadal cycle needs to be investigated through an Earth System Model approach. The inclusion of a tide model in a Coupled Global Climate Model, such as already done over the Pacific (Tanaka et al. 2012), needs to be configured for the Southern Hemisphere. The current observations regarding tidal forcing and the SAM may in turn provide a benchmark for verification of the simulation by a physical model of bi-decadal variability at hemispheric to regional scale.

- There is still very little known about the effect of other external forcing mechanisms, such as solar variability and large volcanic eruptions, over the southern African region. Similar approaches as followed in the current study may yield further observational evidence for the effect and mechanism of such forcing on regional climate impacts.
• The section regarding climate change impacts on the regional climate can be repeated for the new suite of climate model projections of the COordinated Regional climate Downscaling EXperiment (CORDEX). Such follow-on studies may substantiate findings emanating from the AR4 and be used for further testing of the theory.

• The large impact of decadal-scale circulation anomalies in the region emphasizes the need to test the effect of external forcing through Earth System Models. While the bi-decadal variation may in some cases exceed the projected change related to anthropogenic forcing, it may prove useful to supply additional information for practical planning purposes towards the end of the 21st century whilst possibly extending the anticipated envelope of extremes for which planning needs to be done.
References


Appendix 1  Rainfall across South Africa during periods of influence of tropical systems from the SWIO from 1948 to 2012
Figure A1  Total rainfall in South Africa during inland passage of a tropical cyclone in 1948 (top left), tropical cyclone “A” in 1956 (top right), tropical cyclone Astrid in 1958 (bottom left) and tropical cyclone Bridget in 1960 (bottom right)
Figure A2: Total rainfall in South Africa during inland passage of tropical cyclone Claude in 1966 (top left), tropical cyclone Caroline in 1972 (top right), tropical cyclone Eugenie in 1972 (bottom left) and tropical cyclone Danae in 1970 (bottom right).
Figure A3 Total rainfall in South Africa during inland passage of tropical cyclone Emile in 1977 (top left), tropical cyclone Domoina in 1984 (top right), a tropical depression in 1995 (bottom left) and tropical cyclone Bonita in 1996 (bottom right).
Figure A4: Total rainfall in South Africa during inland passage of a tropical depression in 1996 (top left), a tropical depression in 2000 (top right), tropical cyclone Eline in 2000 (bottom left) and tropical cyclone Japhet in 2003 (bottom right).
Figure A5 Total rainfall in South Africa during inland passage of tropical cyclone Faylo in 2007 (left) and tropical depression Dando in 2012 (right)