An investigation into the relative contributions of ENSO, Benguela Niño and the sub-tropical Indian Ocean dipole on summer rainfall over southern Africa

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Dedication

This thesis is dedicated to my sisters, Tiisetso, Malenka and Kekeletso and to my nephew Mori. To my parents Tlalane and Thabo, ke leboha tshehetso le boitelo ba lona thutong ya ka.

Ho wena modimo, ke lebisa tlotla le hlompho ho wena hobane ke ka mohau wa hao ke fihliletseng sena.

Plagiarism declaration

I know the meaning of plagiarism and declare that all the work in the dissertation, except for that which is properly acknowledged is my own.

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Abstract

The region below the 5°S latitude is defined here as southern Africa. This region is subject to high inter-annual rainfall variability attributed to the local and remote SST fluctuations. The main purpose of this study is to investigate the unique impact that SST conditions related to ENSO, Benguela Niño and subtropical Indian Ocean Dipole (SIOD) has on summer rainfall over southern Africa. To achieve this, a partial correlation method was employed to analyse the possible relationship between rainfall variability and interannual SST variability in the Niño3.4 index, Angola-Benguela front and SIOD index for the climatological period between 1950 and 2010. The results revealed ENSO as a prime mode of rainfall variability in southern Africa. The ENSO-rainfall relationship in the central region of southern Africa tends to be modulated by the Benguela Niño and SIOD signal. In the west coast region of Namibia and Angola, the Benguela Niño was found to be strongly linked to rainfall variability. However, this Benguela Niño-rainfall relationship tends to weaken when the effect of ENSO and SIOD is removed. The SIOD impact on the rainfall was found to be dependent on ENSO.

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1. Introduction

The global oceans cover approximately 70% of the earth's surface and act as prime moisture source for the continental areas. Over the years scientists have taken an interest in understanding the role of oceanic areas on continental climate variability. The inter-annual variations of SSTs in the tropical Pacific Ocean related to the El Niño Southern Oscillation (ENSO) are known to be the major climate mode of variability globally. Over much of southern Africa, the most severe droughts and flood conditions in the historical record of rainfall data tend to occur with El Niño and La Niña events respectively (Lindesay, 1988; Reason et al., 2000; Dube, 2002; Rouault & Richard, 2003).

On the regional scale, Jury (1996) showed that the Indian and Atlantic Oceans despite their temperature difference effectively impact on the climatic patterns in various countries in southern Africa. Previous studies have also shown that SST anomalies in these regional oceanic areas may potentially add to or abate the impact of ENSO in southern Africa (Nicholson, 2003). The Indian and Atlantic Ocean basins are locations of two other important climate modes of variability, Subtropical Indian Ocean Dipole (SIOD) and Benguela Niño respectively.

In its positive (negative) phase, the SIOD has been proven to enhance (deplete) rainfall in the southern Africa (Behera & Yamagata, 2001; Reason, 2001, 2002; Hermes & Reason, 2005). During a Benguela Niño, above normal warm SSTs occur near the Angola-Benguela frontal zone and tend to induce above average rainfall in coastal Angola and north-western Namibia (Florenchie, et al., 2003; Rouault, et al., 2003). A detailed discussion on the physical processes that drives the formation and climatic impacts of each of these modes of variability to southern Africa is presented in the next chapter.

A large fraction of the population in southern African countries lives in rural areas and depends on rain-fed agriculture, a positive or a negative departure of seasonal mean rainfall is a vital factor in determining crop yields and food security. Moreover, severe flooding events pose a risk on life of people in this region and may cause damage to infrastructure.

Although, there is a great wealth of literature on how ENSO, Benguela Niño and SIOD affect inter-annual variations of rainfall, there is less knowledge of how each of these modes impacts rainfall when the effect of two other modes in removed. Therefore, this study aims to further refine the current understanding of how ENSO, Benguela Niño and SIOD affect climate in southern Africa by exploring the contribution of each of the climate modes of variability in the climate pattern of southern African particularly over the summer period, the main rainfall season. In the following chapter a general review of the climate system in southern Africa with particular emphasis on the summer is presented. The review chapter discusses factors driving and modulating rainfall patterns in southern Africa from synoptic weather systems to global modes of climate variability. The third chapter addresses the analytical approach and data used in this study. The results obtained are demonstrated in chapter 4, discussed in chapter 5 and overall summary is given in chapter 6.

2. Literature review

Introduction

Southern Africa is defined here Africa south of 5°S and contains a range of climates. Most of the region experiences summer rainfall except the south coast which is an all-season rainfall region, south-western South Africa which is a winter rainfall region, and the northern part of Tanzania/Kenya which is bimodal. Rainfall is a commonly used element to identify the climate system of a region, thus it is imperative that the underlying factors that drive rainfall events and the rain-modulating factors are well understood. In this review these factors are discussed in detail in the context of Southern African continent in section 2.2 and 2.3. In section 2.4, the important modes of climate variability which influence the inter-annual rainfall are explored. The review is concluded in section 2.5 where the gaps in current understanding of the climate system over southern Africa are highlighted and a brief discussion on how this study aims to fill that void are presented.

Prominent rain-bearing weather systems in summer

Tropical temperate troughs

Tropical temperate troughs (TTTs) are known to be the main rain-producing systems over subtropical southern Africa during the austral summer (Harrison, 1984; Reason et al, 2006). Their total contribution has been suggested to be between 30-60% (Pohl, et al., 2008). Recently, Hart, et al. (2010), found that a 7-day wet spell that occurred during 1-7 January 1998 was a result of rapid succession of two TTT events and contributed over 40% of the November-to-January season's rainfall widely across South Africa. TTTs manifest themselves as the cloud bands in a north east to south west direction stretching from a disturbance or heat low (e.g., the Angola Low) over the tropical landmass to a mid-latitude disturbance passing south of South Africa. TTTs are channels for the large-scale transfer of heat and moisture flux from the tropics to the extra-tropical regions to the south. The Angola low, a semi-permanent feature of circulation during summer over the tropical southern Africa (Reason, et al., 2006) often acts as the source region for TTTs; others are troughs in the Mozambique Channel or east of Madagascar (Usman and Reason, 2004; Fauchereau et al., 2009).

Cut-off lows

Cut-off lows (COLs) are closed, upper-level low-pressure areas that have been detached from the polar or the subtropical jet streams. Fuenzalida et al., (2005) conducted a study to understand the climatology of COLs in southern hemisphere and found these systems to be clustered around the three continents with a low frequency of occurrence over the oceans. The distribution of these weather systems highlights their significance over the continental areas. As the COLs move over a region they tend to produce intense rainfall in short span of time (~ 24hr) and well exceeding the monthly mean. For example, the case of March of 2003 in Montagu (a town situated ~100km north of south coast in South Africa) where close to 200mm of rain was recorded one day compared to climatological mean of March of just 19.5mm (Singleton & Reason, 2007a). This is due to the deep moist convective processes associated with these systems. Singleton and Reason (2007a, 2007b) found that over the subtropical southern Africa on average, 11 cut-off low events occur per year and are common in late summer to autumn. With this annual frequency and the intensity of the rain induced these systems, one can infer that they may have considerable impacts on the seasonal rainfall over South Africa, particularly the southern half. Although they do also sometimes impact on countries further north (e.g., Singleton and Reason, 2007b, Muller et al, 2008), they are less important than TTTs to regional rainfall. COLs also play a role in the exchange of radiative flux between stratosphere and troposphere which in turn has implications for the radiative forcing of global climate (Ndara & Waugh, 2010).

Tropical cyclones

Tropical cyclones (TC) are warm core low pressure systems with very strong winds above a certain magnitude depending on the ocean basin where they are generated. In the Atlantic, they are known as hurricanes and typhoons in the Pacific. These very powerful systems develop from an intensifying tropical disturbance over ocean areas with SSTs above 26-27^{o}C. These high SSTs and low vertical wind shear are important in the development of TCs. These systems are accompanied by organised convection and a well defined cyclonic surface wind circulation. Here the attention is focused on the TC forming in the South Indian Ocean which frequently impact on Madagascar and Mauritius and sometimes on Mozambique and north-eastern South Africa. In rare cases, TC can lead to substantial rainfall well inland from the Mozambique Channel (e.g., TC Eline in February 2000 – Reason and Keibel, 2004). The period between September and April represents a typical season of TC activity in this region (Vitart, et al., 2003). Generally, the TC tracks tend to follow a path in a southwest direction then veer to southeast as the system approaches Madagascar. However, results found by (Vitart, et al., 2003) indicated that TC tracks from one season to the other vary significantly. There are also rare cases whereby TC will cross into or develop in the Mozambique Channel move southwards before re-curving in a south-eastwards manner into the open ocean. The 50-year climatological observations reveal that less than 5% of the TCs events in this region actually make a landfall in the east coast of southern Africa (Reason & Keibel, 2004). The landfall may result in heavy flooding with devastating socio-economic impacts (e.g., Eline and TC Favio in 2007 – Klinman and Reason, 2008).

Meso-scale rain-producing systems

The meso-scale rain-producing weather systems include thunderstorms, tornadoes and meso-scale convective complexes (MCC). In Southern Africa, the eastern and south-eastern regions are more prone to these systems as characterised by low-level radiative heating during summer and their proximity to the warm Indian Ocean which act as source of moisture (Tyson & Preston-Whyte, 1988). Blamey and Reason (2012, 2013) were able to identify 70 MCCs that occurred the period between 1998 and 2006 and suggested that these systems contributed 20% of the rainfall during summer months (November to February). MCCs appeared to be most frequent in November and December. These systems, in common with thunderstorms and tornadoes are associated with severe-weather patterns which lead to devastating socio-economic impacts (Goliger, et al., 1997). The very same severe-weather-producing systems often turn out to be important in the semiarid areas as they provide a significant rainfall amount to the seasonal mean (Dyson & van Heerden, 2001; Blamey & Reason, 2012).

Modulating factors

The main emphasis in the previous section was on the predominant systems that produce rainfall during summer. Although the distribution and rainfall contribution of these systems is spatially heterogeneous over the region, their formation and persistence depends on two paramount elements: sufficient low-level moisture and uplift triggering mechanisms. The oceanic areas have high moisture content as compared to the continental areas and inland water bodies (i.e. rivers, lakes etc.) thus act as the prime moisture sources in the global climate regime. Southern Africa is bounded by the Indian and the Atlantic Oceans in the east and west respectively. Both oceans have great impact on the moisture input over the subcontinent. However, the extent to which moisture is advected inland may be limited by the regional topography. In this section, the influence of these surrounding oceans on rainfall is explored. Also discussed here is the effect of orography on rainfall.

Surrounding oceans and southern African rainfall

Depicted in figure 1 from Reason et al. (2006) is the mean seasonal SST variation overlaid with vertically integrated moisture flux in February, May, August and November representing the core of summer, winter, autumn and spring respectively. The contrasting surface temperature observed all year round between the Indian and Atlantic Oceans plays a role in modulation of the moisture content that reaches the continental landmass. The South Indian Ocean has warm SST attributed to pole ward transport of warm tropical waters by the Mozambique channel eddies and the Agulhas current system. In a study to investigate the evolution of the severe storm that arose in December of 2008 over the south coast of South Africa, Rouault, et.al, (2002) found that near-surface onshore moisture from Agulhas current region greatly influenced the development of that particular storms event. Modelling studies have shown further how moisture evaporated off the Agulhas Current region may contribute significantly to the development of COLs (Singleton and Reason 2006, 2007a), MCCs (Blamey and Reason, 2009) and seasonal rainfall in general (Crimp et al., 1998; Reason, 2001).

The Atlantic Ocean has relatively cooler SST and, as a result, the air that is transported inland is cool and dry which help explains the location of arid areas in the western parts of the southern African region. As evident in figure 1 the seasonal SST variation in the Atlantic Ocean is much more defined mainly due to the seasonal latitudinal shift of the south Atlantic high pressure system and the inter-tropical convergence zone (Tyson & Preston-Whyte, 1988; Reason et al., 2006). Furthermore the seasonal shift of South Atlantic High is also closely related to the changes in surface winds which drive the upwelling of cold nutrient water to the surface along the west coast of southern Africa and in the equatorial cold tongue during the boreal summer. Generally, there has been less work done to understand the role of the Atlantic Ocean in southern African climate variability during summer as compared with the influence of Indian Ocean and the Pacific Ocean. This imbalance may be because most of the rain-producing systems come in from the east and/or are linked to the moisture flux from the Indian Ocean. On the other hand, the tropical Pacific Ocean has been proved to have significant impacts on climate variability on a global scale, primarily via ENSO. In the later section, the relationship between the SST anomalies and the implication of thereof is explored in detail.

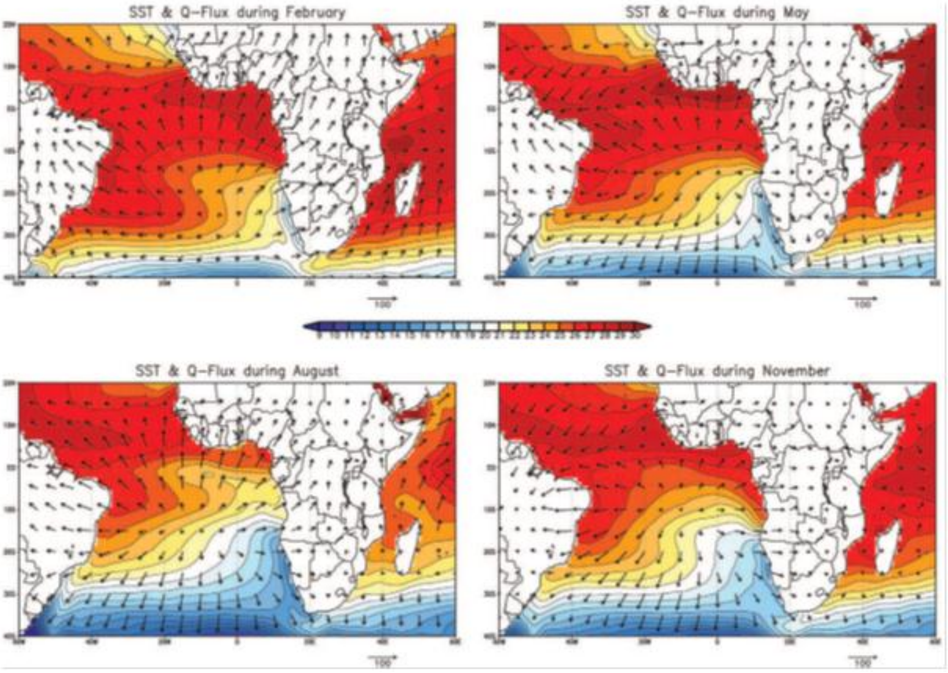


Figure 1: The SST overlaid with the vertically integrated moisture flux for February, May, August and November based on the 6-hourly reanalysis data for the period 1979-2003. (Reason, et al., 2006)

Topography and southern Africa

The effect of topography on the climate of any particular region operates through presenting a barrier to incident airflow which either goes around the obstacle if the air-mass is stable, or over the top if this air-mass is sufficiently unstable leading to the possibility of orographic rainfall. Thus, the stability of incident air-mass and the dimensions and orientation of the mountain barrier can play an important role in regional rainfall and wind characteristics. The slope and relative relief are particularly essential on a regional scale with mountain gradient and aspect greatly responsible for the differentiation of local climate. For example, the semi-desert climate near Oudtshoorn is separated from the relatively high rainfall climate of George by a few tens of kilometres due to the rain-shadow effect of the Outiniqua Mountains. Barry (2008) provides a detailed description of the topographic influences on regional meteorology and climate.

Singleton and Reason (2006, 2007b) and Blamey and Reason (2009) have used numerical models to show how topography influences the amount of rainfall produced in particular storm systems over southern and eastern South Africa. Rouault, et al., (2012) found that in the late afternoon to early evening, the interior of South Africa tends to receive its maximum rainfall whereas along the east to south coast as well as the north-eastern region of the country the time for maximum precipitation is midnight to early morning. These findings suggest that topography together with local surface radiation flux determines the spatial and diurnal variation of rainfall events over South Africa.

Climate modes of variability

ENSO

The El Niño Southern oscillation (ENSO) is the dominant mode of inter-annual climate variability impacting on most regions throughout the world. It involves a large-scale oscillation of atmospheric and upper-ocean circulation and properties in the tropical Indo-Pacific Oceans. When anomalously warm (cold) SSTs are observed in the equatorial central and eastern Pacific region, such an event is defined as an El Niño (La Niña). El Niño can be further classified into three types; namely warm pool El Niño and cold tongue El Niño, these are presented in figure 2 (Kug, et al., 2009) as well as El Niño Modoki (Ashok, et al., 2007). The latter is associated with irregular occurrences of anomalous SST warming in the central equatorial Pacific resembling a horseshoe-like pattern, bordered on both sides along the equator by anomalously cooler SST. This phenomenon is similar to El Niño but its global climate implications are different from the conventional El Niño hence the name 'Modoki' derived from Japanese meaning 'a similar but a different thing'. Lian and Chen (2012) questioned the physical existence of El Niño Modoki after a thorough statistical analysis of the rotated Emperical orthogonal function (REOF) against the conventional EOF method which Ashok, et al., (2007) used to identify the El Niño Modoki. The cold tongue El Niño is characterised by relatively large SST anomalies in the region bounded by 5° latitudes (North and South) and 150-90° W longitudes whereas the warm pool El Niño tend to have SST anomalies confined in the [5°N-5°S, 160-150°W] domain. Furthermore Kug, et al., (2009) showed that the precipitation, atmospheric convection and surface zonal wind anomalies associated with both El Niño types differs. Therefore, it is necessary that when measuring the intensity of an El Niño event that both indices are used. It is because of this reason that many studies when analysing ENSO uses the SST anomalies in the [5°N- 5°S, 120°- 170° W] region known as the Niño3.4 index. This index comprises of both warm pool and cold tongue El Niño regions.

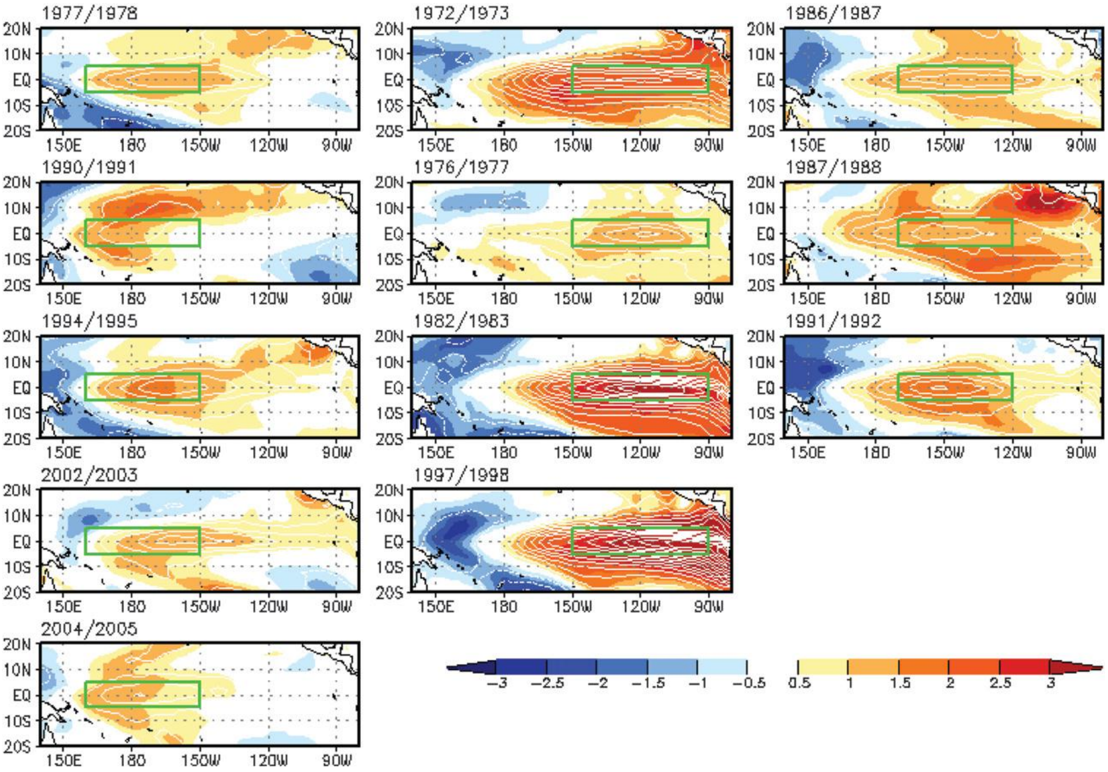


Figure 2: SST anomalies of El Niño events that occurred between 1970 and 2005 period. The events are classified into (left) warm pool El Niño, (middle) cold tongue El Niño and (right) Mixed El Niño. The green boxes in the right panel indicate the Niño3.4 region. (Kug, et al., 2009)

When it comes to forecasting ENSO, a detailed understanding of the physical mechanisms forcing an ENSO event is important. It is suggested that the development of El Niño is as a result of a Bjerknes feedback, a positive interaction between ocean and atmosphere linking the strength of trade winds to the slope of the thermocline and to the SST in the tropical Pacific Ocean (Bjerknes, 1966). A relaxation of the trade winds in the west leads to a downwelling equatorial Kelvin wave that changes the slope of the thermocline and leads to warm SST anomalies in the central and eastern parts of the basin. This re-distribution of SST and upper ocean heat content leads to changes in atmospheric convection and hence rainfall. These wind and thermocline anomalies tend to force a near-surface response that reinforces the initial SST anomaly. In due course this positive loop leads to an El Niño event, which normally reaches its maturity peak in austral summer (Izumo, et al., 2010). In a modelling study that was carried out in the early 1990s in an attempt to understand the physics underlying ENSO the results were comparable to the Bjerkes feedback mechanism (Barnett, et al., 1991).

The eastward shift of atmospheric convection following the shift of warm SST anomalies also has an impact on the Walker circulation, a large-scale atmospheric circulation over the tropical Pacific Ocean whose main function is to balance and transport momentum, heat and moisture flux in the tropical region thereby modifying the local climate. As a result, instability of SSTs in the tropical Pacific is linked to global climate variability. However the impacts vary from one region to the other.

In the African continent, a number of empirical studies revealed a significant relationship between ENSO and rainfall over various parts of Africa (Ropelewski & Halpert (1989); Lindesay & Vogel, 1990; Reason et al., 2000). However the relationship in the Sahel region is not as robust as in the other sectors (Nicholson & Kim, 1997). Over East Africa, above (below) average rainfall tends to occur during the OND "short rains" season of an El Niño (La Niña) event (Ogallo, 1988) whereas over much of southern Africa, the major impact occurs during DJF or JFM with below (above) average rainfall during El Niño (La Niña) (Lindesay, 1988; Reason et al 2000; Rouault and Richard, 2003; Kijazi and Reason 2005). The historical rainfall anomalies taken for the period between 1921 and 2001 indicates that the droughts events in the sub-tropical southern Africa since the 1960s are more often linked to El Niño events whereas above normal wet conditions were associated with La Niña (Rouault & Richard, 2003).

Sub-tropical Indian Ocean Dipole

Using a simple EOF method Behera and Yamagata (2001) were the first to show the dipole SST pattern in the South Indian Ocean. This dipole pattern is termed subtropical Indian Ocean dipole (SIOD) in the some literature it is named Indian Ocean South Dipole (IOSD), however here it is refer to as the SIOD. Behera and Yamagata (2001) constructed the dipole index by computing the SST anomaly difference between the western pole [55-65°E, 27-37°S] and eastern pole [90-100°E, 28-18°S]. It has been shown that SIOD significantly influence the inter-annual rainfall over a large part of southern Africa (Behera & Yamagata (2001); Reason (2001, 2002). This mode of variability fluctuates in between two phases: The positive phase is characterised by anomalously warm (cold) SST in the south-eastern (south-western) Indian Ocean. The negative phase is defined when the reversed SST anomalies are observed in the southeast and southwest regions in the Indian Ocean.

Many studies have been attributed the formation of SIOD to the change in position and intensity of the Mascarene High (Behera & Yamagata, 2001; Reason, 2001; Hermes & Reason, 2005). The results from these studies suggest that during a positive SIOD, the Mascarene high shifts southwards and strengthens thereby inducing the dipole pattern of the latent heat flux which in turn generates the SST anomalies east and west poles. Recently, Morioka et al., (2010) revealed that the latent heat flux does not directly influence the SST anomalies and that the mixed layer depth is important in the evolution of the SST dipole pattern. Figure 3 below shows a schematic representation of the formation of the positive SIOD event as described by Morioka et al., (2010). The advection of moist (dry) air over the western (eastern) pole leads to less (more) latent heat loss. This change in latent heat flux causes the mixed layer in the western pole to shoal and deepen in the eastern pole. The mixed layer depth and shortwave radiation play an important role in the growth of the SST anomalies. The sea surface warming in the west (east) pole is enhanced (suppressed) owing to the thickness of the mixed layer. Hermes and Reason (2005) found the large-scale atmospheric circulation in the extra-tropics in the Southern Hemisphere, specifically the wavenumber 3 and 4 pattern, also plays a role in the formation of SIOD events. Most recently Morioka et al., (2012) discovered similar results from the performed model experiments.

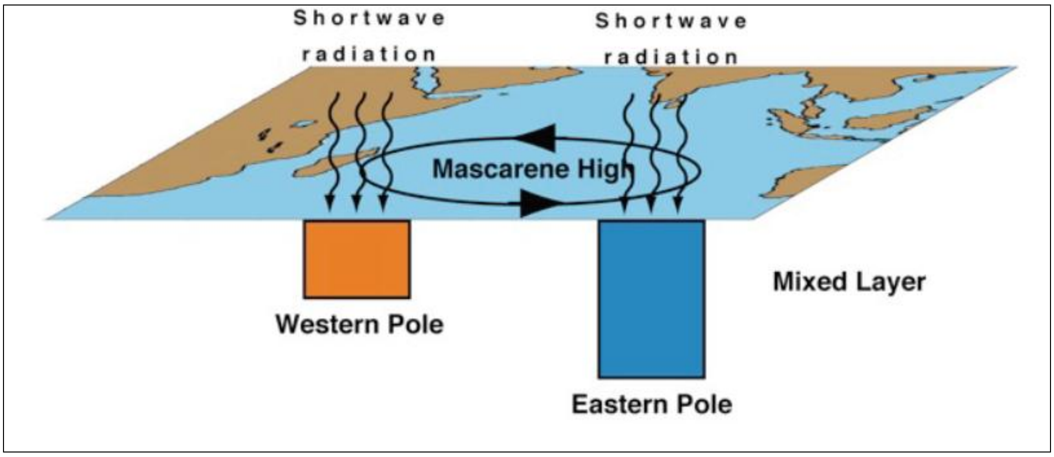


Figure 3: Shematic representation of the process the leads to the positive phase of SIOD. Morioka et al., (2010)

Benguela Niño

During a Benguela Niño event, warm SST anomalies are observed in the area near the Angola Benguela frontal zone and extending north along the Angola coast (Shannon et al., 1986; Florenchie et al, 2003, 2004). These warm events got their name by analogy with their counterparts in the tropical Pacific Ocean (Shannon et al., 1986).

Benguela Niño events are intermittent, usually peaking in late summer and may persist for period of months (Florenchie et al., 2003, 2004). Such events tend to enhance rainfall over the adjacent landmass (Rouault et al, 2003) and are also attributed to drastic reduction of local fish catch [*Boyer et al., 2001* cited in (Rouault, 2012)]. The 1984 and 1995 Benguela Niño episodes were the most intense (Reason, et al., 2006). Florenchie et al. (2003, 2004) showed how relaxation of the trade winds over the western tropical Atlantic led to the generation of warm SST anomalies there which propagated to the east as a Kelvin wave and then south along the Congo and Angolan coastlines. As the thermocline shoals towards the surface near the ABFZ, it is this region where the largest SST anomalies tend to be observed a few months after the trade wind relaxation. Thus, in the area between 10-20 °S and from 8° E stretching onto the continent, (Florenchie, et al., 2004) found maximum SST deviations from the mean. Rouault (2012) showed that this intrusion of warm tropical waters in the Angola-Benguela region occurs twice in year: in the late summer and late spring. Consistent with Florenchie et al. (2003), (2004), Rouault (2012) also suggested that Benguela Niños are remotely forced by the weakening trades in the western tropical Atlantic. In addition, the local net heat fluxes at the air-sea interface and local wind stress may also have significant role in SST anomalies offshore of the southern Angola and Northern Namibia respectively.

Summary

The intention behind this review was to assemble current knowledge of climate dynamics in southern Africa with emphasis on the role that ocean surface temperature has in regulating climate. Southern African rainfall is subject to high degree of inter-annual variation of rainfall linked to the climate modes of variability. The discussion in the previous section on climate modes of variability provided a platform from which gaps in the existing literature could be identified. Often in the comprehensive study of certain process in the earth system, for simplification scientists tend to examine that process in isolation. However, that is not the case in reality. Thus far, with all the all studies undertaken to investigate and understand the impacts of Benguela Niño, ENSO and SIOD on southern African rainfall equips us with the necessary tools to advance into the next level of understanding. In attempt to refine knowledge on how Benguela Niño, ENSO and SIOD impacts on southern African climate, the following research questions are investigated:

1. Is there a significant relationship between summer rainfall in the southern African region and each of the climate variability modes? Are these relationships stable through the record or do they change from one decade to the next?

2. What is the unique (independent of the two other modes) rainfall impact over the region contributed to by each mode? Do the spatial patterns of rainfall impact of each mode and their seasonality differ?

3. Data and Methods

3.1 Data

The approach taken in the present study involves usage of the Global Precipitation Climatology Centre (GPCC) data set (Schneider, et al., 2013). It is monthly gridded (0.5° x 0.5° resolution) rainfall data available from 1901 until 2012. The data was extracted for the region within 5- 35°S and 6-43° E spatial range. The global monthly dataset of National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed Sea Surface Temperature version 3b (ERSST.v3b) (Smith, et al., 2008) is also used in the study. This data is obtainable from 1854 to the present and has a 2° x 2° spatial resolution. All datasets used here cover the period from 1950 to 2010. Post-1950 data are used as they are likely to be more reliable than that collected in the first half of the last century.

3.2 Methods

Indices of climate modes of variability

The ENSO analysis is based on SST data extracted in the Niño3.4 domain which is defined for the [5°N- 5°S, 120°- 170° W] range in the equatorial Pacific Ocean. The SST anomaly in this area is the accepted indicators for El Niño and La Niña events (Barnston et al., 1997). The Angola-Benguela area (ABA) index, defined as the JFM SST anomaly averaged over the box 8-15E, 10-20S (Florenchie et al., 2004), determines whether a Benguela Niño or Niña event occurs in a particular season if the index exceeds 3°C and below 3°C respectively. The subtropical index is defined as JFM SST difference between the western pole [28-38°S, 54-64°W] and eastern pole [18-28°S, 90-100°E] in the South Indian Ocean (Behera and Yamagata, 2001). If the SST anomaly is above (below) 1°C the climatological mean, then the SIOD event for a given season is defined as a positive (negative) event.

Statistical methods employed

This study is based on the assumption that SST and rainfall time series follow a normal distribution curve. Hence making the assumptions that linear relationship exists between these two variables is appropriate (von Storch & Zwiers, 1999). It is because of this reason that throughout the analysis when linking these two parameters (i.e. SST and rainfall) the Pearson correlation method is being used.

a. EOF analysis

The method of Empirical Orthogonal Functions (EOF) (Pearson, 1902; Hotelling, 1935) is a statistical analysis technique that is grounded on the basic matrix operations. It is frequently used in the earth science to analyse the variability in data set of a given geophysical field. EOF analysis provides a description of spatial and temporal variability of field data in terms of modes that explain the greatest amount of variance in the data. Each mode of EOF has a time series associated with it and it known as the principal component (PC). It is important to note that EOF is just a statistical method and without a prior understanding of the climate dynamics, one can easily misinterpret the results. In order to avoid misinterpretation of the results, Behera, et al. (2002) suggested two steps: (1) A thoroughly look at the raw data to identify the real phenomenon, (2) Preparation of composite maps to describe the manner in which the phenomenon evolves. This two-step process was undertaken in this study and the comparison between the composites and the EOF loadings favoured the use of EOF to statistically represent what is known about the physical variation of the SSTs over time with particular interest in the equatorial Pacific, south-east Atlantic and south-west Indian Ocean. The first and second EOF modes are considered here to find the possible connection between the interannual variations of SSTs and rainfall. The results are then compared to those obtained when correlating the SST indices (i.e. Niño 3.4, SIOD and Benguela Niño) with rainfall to find out which EOF mode best represent ENSO, SIOD and Benguela Niño.

b. Running correlation: sliding window method

A sliding window correlation is a useful technique for qualitatively evaluating the time pattern of change in strength of relationship between two variables. In climate studies, this has been used to examine inter-decadal changes (Chiang, et al., 2000; Yan, et al., 2013). Here this method is applied using a 21-year widow to investigate the inter-decadal stability of the relationship between summer (JFM) rainfall and SSTs in the ENSO, SIOD and Benguela domain respectively. Sliding window correlation is computed as follows:

xycorr W (i)= corr(X(i:i+(w-1)),Y(i:i+(w-1)))
Where w= sliding window width
i= time step
X and Y = correlated time series (i.e. rainfall and SSTs)

c. Partial correlation

A first step towards assessing the independent influence of ENSO; Benguela Niño and SIOD on summer rainfall over southern Africa is obtained by employing a statistical partial correlation method (e.g., Saji and Yamagata, 2003). In this case, four variables are involved: Rainfall; ENSO; Benguela Niño and SIOD. Given that only the relationship of rainfall with a single climate mode is examined at a time, the effect of two variables has to be removed. Thus a second order partial correlation is applicable and its algorithm is shown below.

For example, let's consider variables: p, q, r and s. The unique relationship between p and q adjusted for r and s is given by:

$$r_{pq.rs} = \frac{r_{pq.r} - r_{ps.r} r_{qs.r}}{\sqrt{1 - r_{ps.r}^2}\sqrt{1 - r_{qs.r}^2}}$$

Where *rpq.r* is the correlation of *p* (say, rainfall) with *q* (say, Benguela Niño) while taking out the effect of *r* (say, ENSO). Similarly, *rps.r* and *rqs.r* represent the relationship between *p* and *q* with *s* (say, SIOD) adjusted for the effect of *r* respectively. The terms in the denominator subtract the total variance explained by the exclusive relationship between *p* and *s* also between *q* and *s*.

4. Results

The impact of SST variability on rainfall

a. Oceanic variability: EOF analysis

An EOF analysis was performed on the seasonal (JFM) mean of the SST anomalies in the tropical Pacific Ocean [10°S-10°N, 180-90°W], South Atlantic Ocean [0-40°S, 70°W-14°E] and in the South Indian Ocean [0-40°S, 30-100°E]. The SST anomalies were computed over the climatological period between 1950 and 2010. The first two EOF modes collectively account for about 84%, 57% and 67% of the summer SST variance in the Pacific, Atlantic and Indian Ocean respectively. In the Pacific region the first (second) EOF mode explains 72.18% (11.81%) of SST variability. About 42.93% (13.88%) of the explained SST variance in the Atlantic region corresponds to the first (second) EOF mode. In the southern Indian Ocean the first and second EOF modes account for about 48.2% and 18.88% of the total SST variance respectively.

The time series of expansion associated with these EOF modes (depicted in figures 5 and 7) are correlated with time series of SST anomaly on each grid point to get the SST spatial patterns illustrated in figure 4 and 6 corresponding to the first and second EOF modes. Squaring the correlation coefficient yields the local variance explained. In all three Oceanic areas, the first EOF mode demonstrates a monopole SST pattern (see figure 4). In the Pacific Ocean, the highest local variance explained is seen in the domain covering the Niño3.4 region [5°N-5°S, 120°-170°W] and is reminiscent of an El Niño pattern. In the Atlantic and Indian Ocean, the highest local variance tends to be mostly confined in the tropical area. In both cases, the spatial patterns are reminiscent of the mature phase of ENSO in these basins (Reason et al., 2000; Colberg et al., 2004). Along the coast of Namibia and Angola, the local SST variance explained ranges between 4 to 16%. The SST variability in this area is located in the region where the Benguela Niño signal is strongest.

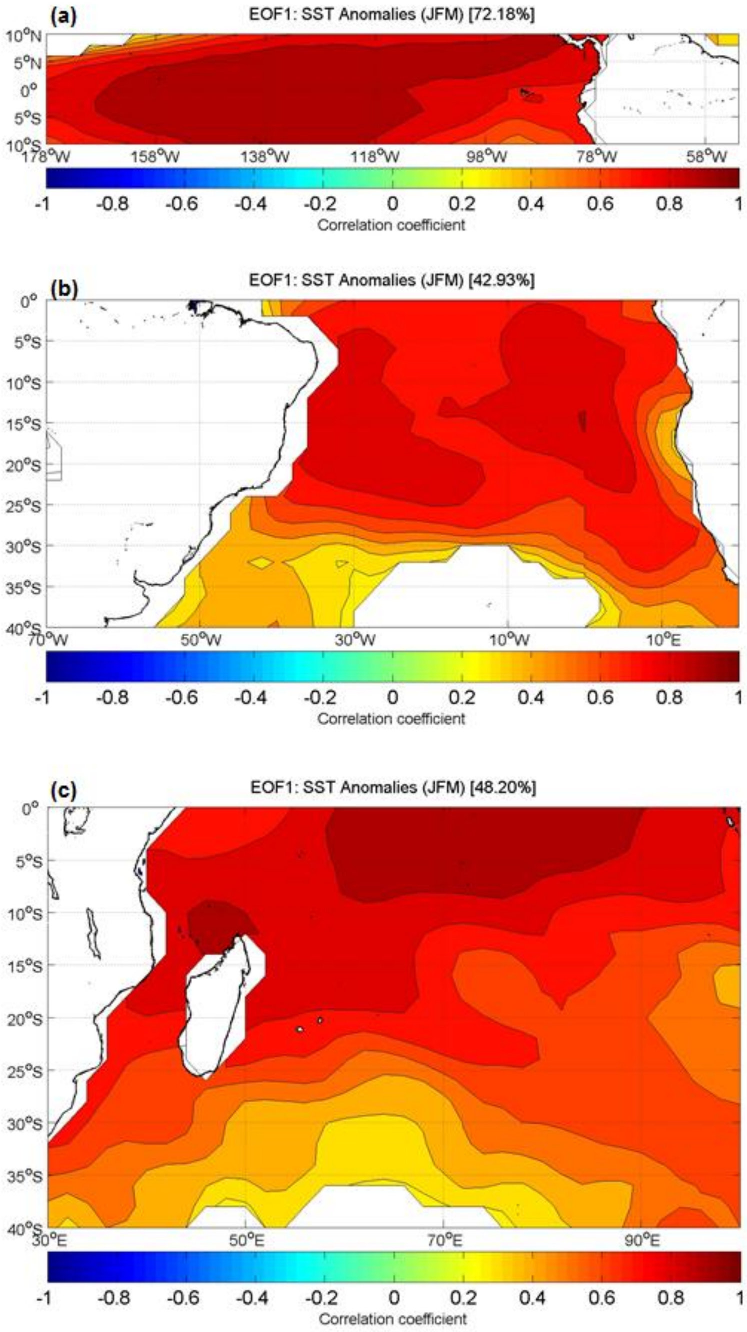


Figure 4: Spatial patterns of the first mode of SST in **(a)** Pacific; **(b)** Atlantic and **(c)** Indian Ocean. The spatial patterns are presented as correlation maps. The value at each grid point is the correlation coefficient between the principal components of Figure 5 and the SST anomaly at that grid point. Only correlations significant at 95% level are shown.

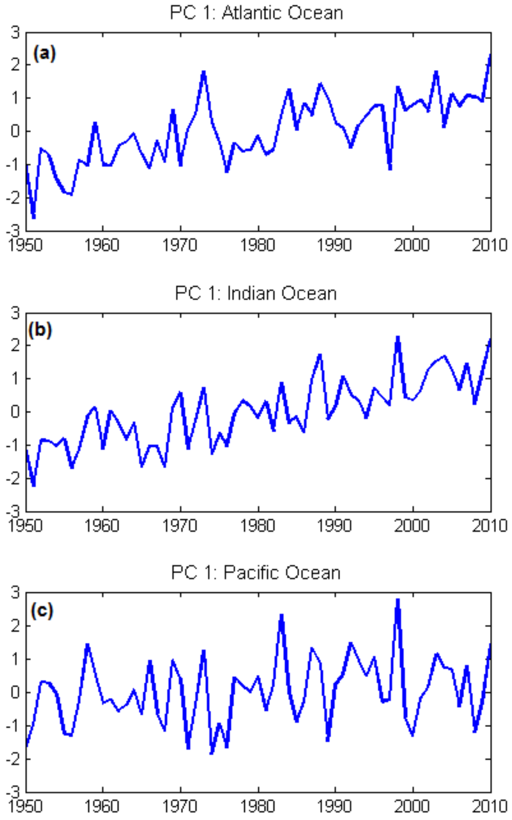


Figure 5: Principal components of the first EOF mode of SSTs in the **(a)** South Atlantic; **(b)** South Indian and **(c)** tropical Pacific Ocean. X and Y-axis denotes time in years and standardized SST anomalies respectively.

Figure 6 shows the field correlation of the second EOF mode with the SST anomalies in the same oceanic areas as in the figure 4. Following the orthogonal principle involved in the computation of EOF the second EOF resulted in a dipole pattern. The second mode in the Pacific (figure 6a) reveals an out-of-phase relationship between SST anomalies in the eastern and western tropical Pacific Ocean. The associated time loading is shown in figure 7c and tended to correlate positively with SST in the NIÑO3.4 index (see table 1). The dipole configuration seen in the Atlantic and Indian Ocean displays an east-west unsynchronised relationship between SST anomalies and the time series of expansion extracted for this mode. At the 95% confidence level, the SST anomalies in the south-west (south-east) Atlantic tend to be inversely (directly) linked to the time loading of EOF 2 (figure 6b). Reminiscent of the Atlantic, the Indian Ocean displays a slanted east-west dipole pattern that is similar to the subtropical dipole of Behera and Yamagata (2001). The correlation value between of time loading in figure 7b with SIOD index reveals a proportional link between the two (see table 1).

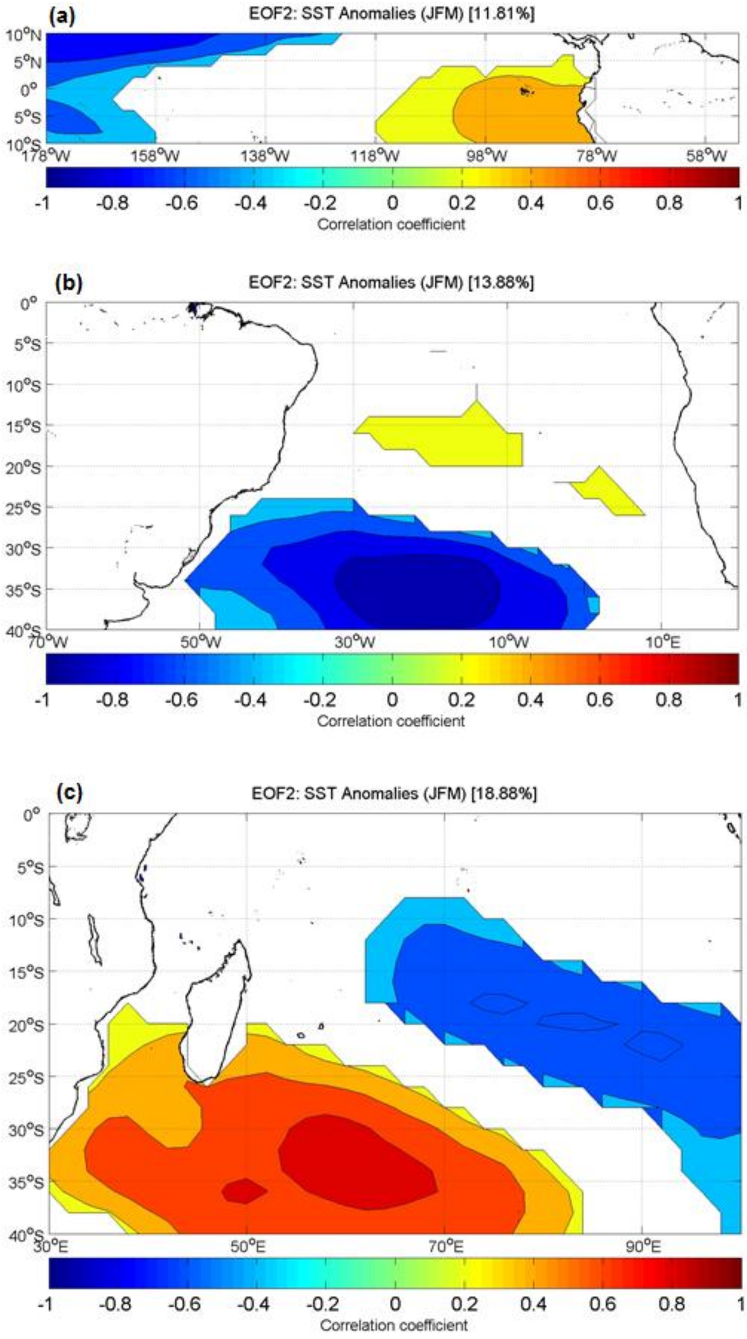


Figure 6: Spatial patterns of the second mode of SST in **(a)** Pacific; **(b)** Atlantic and **(c)** Indian Ocean. The spatial patterns are presented as correlation maps. The value at each grid point is the correlation coefficient between the principal component of Figure 7 and the SST anomaly at that grid point. Only correlations significant at 95% level are shown.

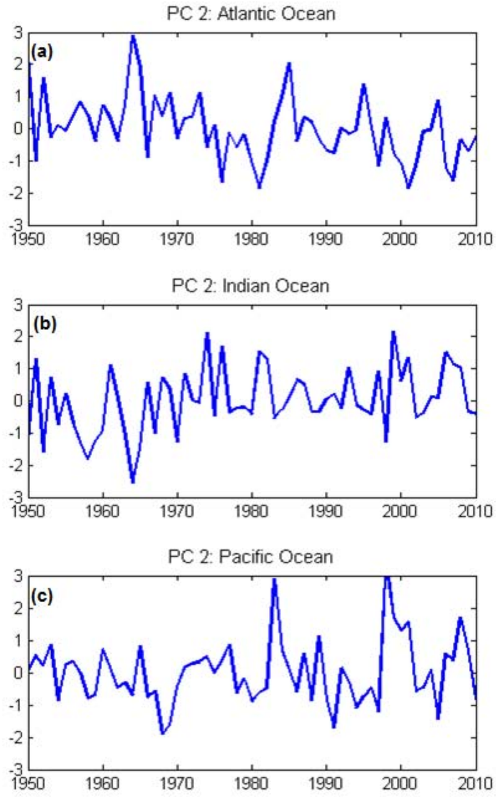


Figure 7: Principal components of the second EOF mode of SSTs in the **(a)** South Atlantic; **(b)** South Indian and **(c)** tropical Pacific Ocean. X and Y-axis denotes time in years and standardized SST anomalies respectively.

b. Relating SST modes to southern African rainfall

To investigate a possible link between oceanic variability and rainfall over southern Africa, time series corresponding to EOF modes 1 and 2 were correlated with rainfall anomalies over southern Africa. Figure 8 shows the results attained when these time series were projected onto rainfall anomalies over southern Africa based on the 1950-2010 climatological period. The values displayed in figure 8a represent a significant correlation pattern between the de-trended principal component of the first EOF mode (PC 1, in figure 5c) and de-trended rainfall anomalies at each grid point. Detrending was done to remove any secular change and to focus on climate variability patterns. The observations show that large parts of sub-tropical southern Africa are negatively associated with the first EOF mode of SST in the equatorial Pacific Ocean. This relationship suggests that about 20-50% of the variance in the rainfall from 1950 to 2010 may be related to SST variability in the Pacific. Figure 8b in which the rainfall anomalies on each grid point are correlated with de-trended PC 2 of figure 7c, indicates only a few patches of significantly positive relationship between second EOF mode of SST and rainfall. This EOF mode only explains about 20% of the rainfall variability from 1950 to 2010.

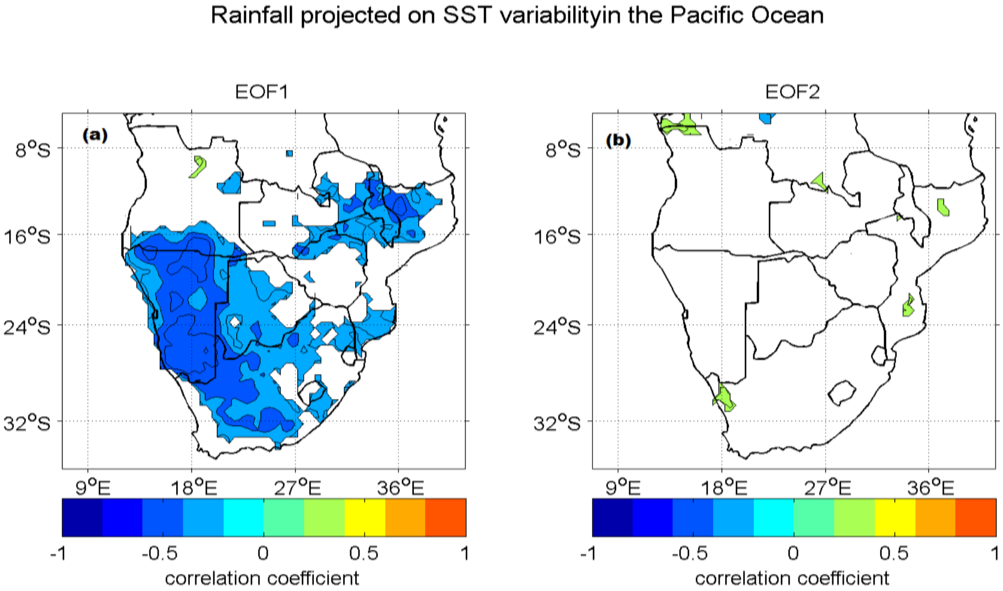


Figure 8: Spatial correlation between de-trended standard anomalies of the time series of Figure 5c and Figure 7c and rainfall anomalies computed for a 61-year climatology [1950-2010]. **(a)** correlation of rainfall anomalies with first EOF mode of SST in the Pacific Ocean. **(b)** correlation of rainfall anomalies with second EOF mode of SST in the Pacific Ocean. Only areas which are statistically significant above 90% are plotted.

Similar to figure 8 are the figures 9 and 10 for the Atlantic and Indian oceans respectively. The first EOF mode of SST in the Atlantic Ocean correlates significantly with rainfall in the northern coastal region of Angola and north-eastern Namibia (figure 9a). The variation of rainfall over the latter region is linked negatively with first EOF mode whereas in the former area rainfall anomalies are directly related to first mode. Figure 9b shows that rainfall over a large part of central southern Africa is negatively correlated with the second Atlantic SST mode. About 20% of local the rainfall variance can be accounted for by this relationship. There is also a small area of northern Angolan coastal rainfall that is linked with this mode.

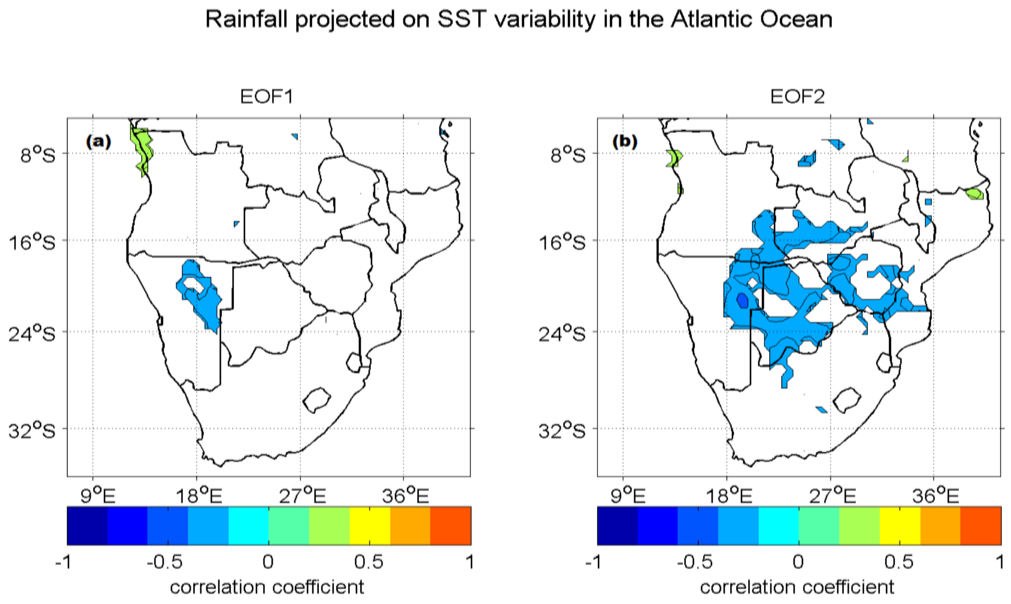


Figure 9: Spatial correlation between de-trended standard anomalies of the time series of Figure 5a and Figure 7a and rainfall anomalies computed for a 61-year climatology [1950-2010]. **(a)** correlation of rainfall anomalies with first EOF mode of SST in the Atlantic Ocean**. (b)** correlation of rainfall anomalies with second EOF mode of SST in the Atlantic Ocean. Only areas which are statistically significant above 90% are plotted.

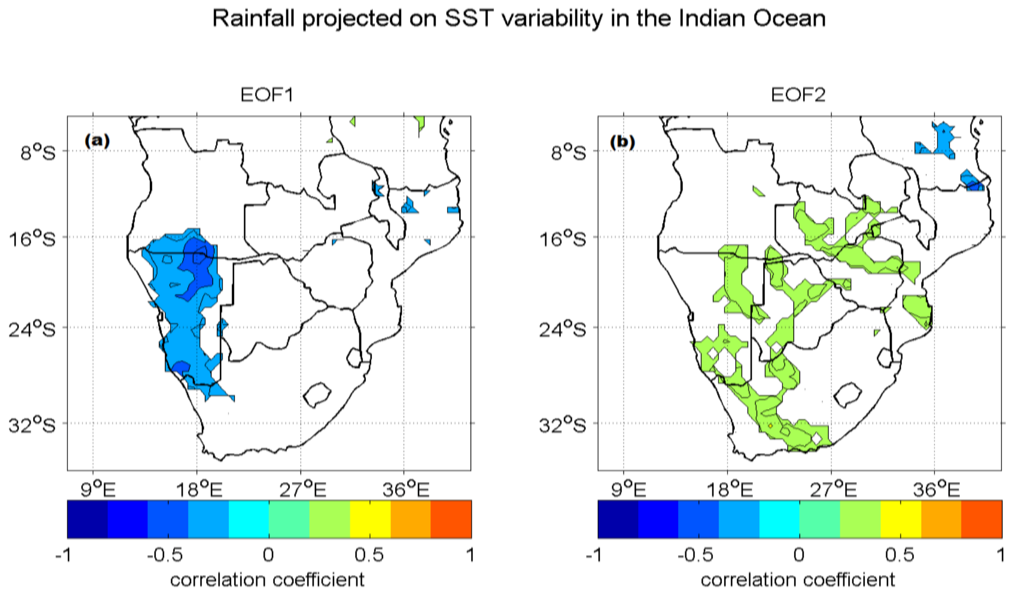


Figure 10: Spatial correlation between de-trended standard anomalies of the time series of Figure 5b and Figure 7b and rainfall anomalies computed for a 61-year climatology [1950-2010]. **(a)** correlation of rainfall anomalies with first EOF mode of SST in the Indian Ocean. **(b)** correlation of rainfall anomalies with second EOF mode of SST in the Indian Ocean. Only areas which are statistically significant above 90% are plotted.

For the Indian Ocean, figure 10a shows that rainfall over much of Namibia and the far south of Angola are negatively correlated with the first mode. About 20-56% of the overall variance of rainfall in Namibia and southernmost region of Angola is explained by first EOF mode. The relationship of the second EOF mode of SST variability with rainfall indicates a significantly positive correlation between these variables in south-west, central north and east of southern Africa, and a small area of negative correlation over Tanzania. Close to 20% of rainfall variance in these regions related to the second EOF mode of Indian Ocean SST.

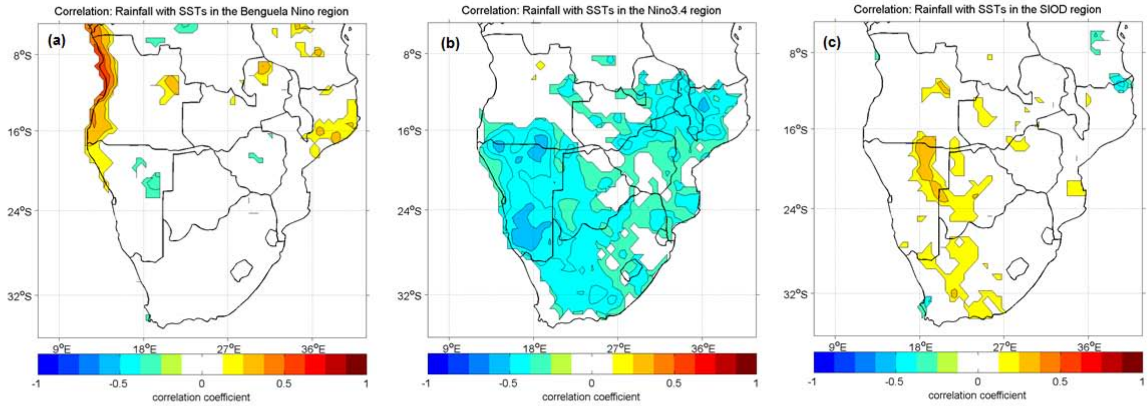


Figure 11: Correlation map representing the relationship between rainfall and the **(a)** Benguela Niño index, **(b)** the Niño3.4 index and **(c)** the subtropical Indian Ocean dipole (SIOD) index. Only areas that are statistically significant above 90% are plotted.

The main focus of this study is to investigate the climatic patterns over southern Africa related to the Benguela Niño in the tropical South East Atlantic, the South Indian Ocean subtropical SST dipole to ENSO. A simple zero-lag correlation with southern Africa summer (JFM) rainfall for the 61-year period is illustrated figure 11. For the Benguela Niño, figure 11a shows that coastal rainfall in Congo, Angola and northern Namibia is significantly correlated with this mode. This correlation corresponds to between 5 and 50% of the variance in this region. There is also statistically significant relationship between the Benguela Niño and rainfall in some other parts of southern Africa (Zambia, northern Mozambique and Tanzania). Rouault, et al., 2003 and Hansingo and Reason (2009) both showed evidence of some Benguela Niño relationships with rainfall over other parts of southern Africa besides western Angola and Namibia.

Figure 11b depicts the relationship between ENSO and rainfall indicating that almost all of subtropical southern Africa as well as parts of Zambia, northern Mozambique and northern Zimbabwe) tend to experience drier (wetter) than average conditions during El Niño (La Niña) events similar to the findings of (Ropelewshi & Halpert, 1989; Lindsay & Vogel, 1990; Nicholson & Kim, 1997; Reason et al. 2000). Between 9% and 36% of JFM rainfall variance across southern Africa is related to ENSO. The correlation between rainfall and the SIOD index (figure 11c) reveals a significantly positive correlation between SIOD and rainfall in a NW-SE oriented band stretching from central Angola towards the Eastern Cape. In addition, there are small areas of positive (negative) correlation in Zimbabwe and Mozambique (Tanzania and far northern Mozambique). This pattern is similar to that found by Behera and Yamagata (2001).

Table 1: Shows the correlation coefficient computed between each of the first two EOF modes in the Atlantic, Indian and Pacific Ocean and ENSO (Niño3.4), Benguela Niño (BN) and SIOD index. The values printed in bold represent statistically significant correlations at 95% confidence interval.

	1st EOF MODE				**2nd EOF MODE**		
	Nino	BN	SIOD		Nino	BN	SIOD
Atlantic	0.232	**0.494**	-0.344		0.200	**0.323**	**-0.629**
Indian	**0.680**	-0.015	**-0.480**		**-0.432**	-0.161	**0.944**
Pacific	**0.982**	-0.070	**-0.422**		-0.147	0.210	0.022
	Significance level at 95%			±0.252			

Visually, the spatial patterns of figure 11b and 11c representing the relationship of rainfall with ENSO and SIOD are similar to the rainfall projections on the first EOF mode in the tropical Pacific Ocean and the second mode EOF in the Indian Ocean respectively. This result is consistent if much of the SST variation in the tropical Pacific Ocean is due to the ENSO related SST changes and, for the South Indian Ocean, most of the second SST EOF mode is represented by the SIOD. Further statistical results are given in table 1 where the correlation coefficients between EOF modes in all three ocean basins and climate modes of variability are shown. Table 1 indicates that 86% of the total inter-annual variance in the second EOF mode of SSTs in the South Indian Ocean is accounted for by SIOD. In the tropical Pacific Ocean, first EOF mode incorporates most of the ENSO signal as reflected by the correlation coefficient of 0.98 between ENSO and that mode. In the case of the South Atlantic, it is less obvious as to which of the two EOF modes best represent the Benguela Niño related fluctuations. Comparing figure 11a and figure 9, and the correlation values in table 1, it seems that both the SST modes in the South Atlantic Ocean are important with the first mode being slightly stronger linked with the Benguela Niño pattern. A statistically significant inverse relationship exists between SIOD and second EOF mode in the Atlantic which together with the modelling results of Hansingo and Reason (2009) implies that there may be modulation of the rainfall anomalies due to Benguela Niño by the anomalies in the south-west Indian Ocean (Hansingo & Reason, 2009).

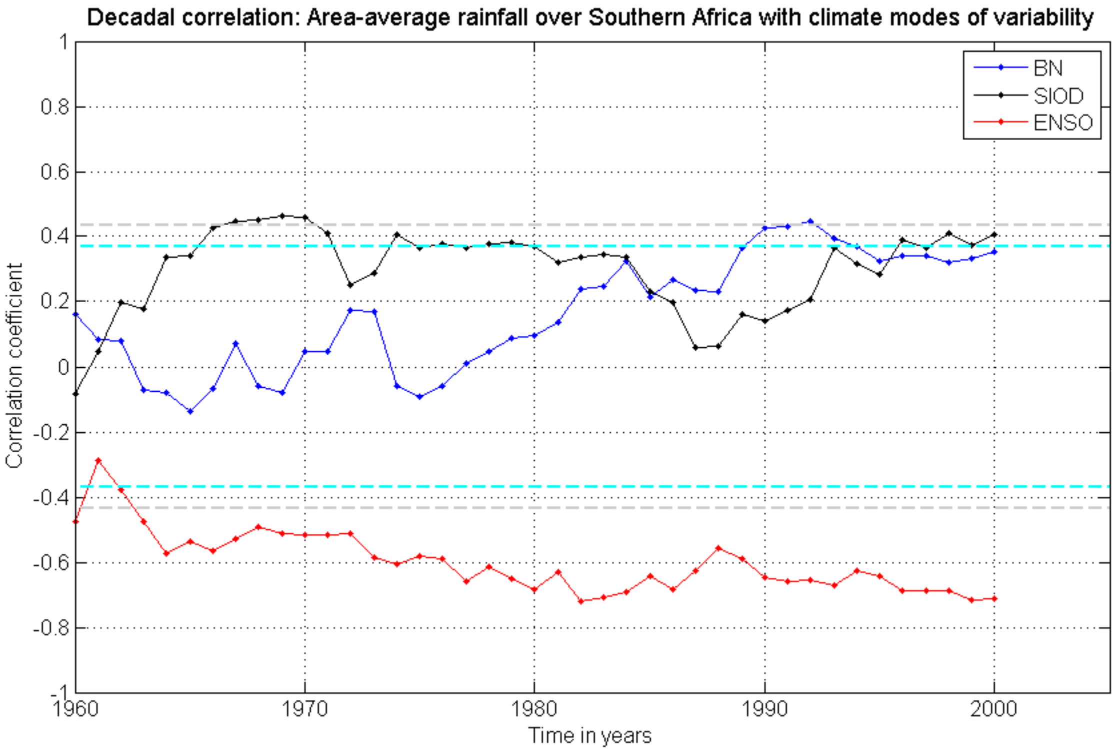


Figure 12: A 21-year running correlation of area-averaged rainfall over Southern Africa with SSTs in the: Benguela Niño (BN) index demarcated in black; Niño 3.4 index (ENSO) represented by red line and Sub-tropical Indian Ocean dipole (SIOD) index in blue. The years on x-axis denote the centres of sliding windows (i.e. 1960 represent the correlation in the 21-year sliding window of 1950–1970). The cyan (grey) dashed lines indicate the 90% (95%) statistical significance level.

Decadal stability of established relationship between rainfall and climate modes of variability

The results presented in the previous section suggested that there are statistically significant relationships between summer rainfall in various regions of Africa south of about 5°S and three modes of climate variability (ENSO, the Benguela Niño, and the South Indian Ocean subtropical dipole).To investigate whether these relationships are stable throughout the record a sliding correlation window method was employed with a 21-year width. Previous studies relating South Indian Ocean SSTs, ENSO and rainfall have used bandpass filter techniques with this time scale (Allan et al., 1995, 2003; Reason and Mulenga, 1999). Figure 12 shows the resulting sliding correlation coefficients between area-averaged rainfall over southern Africa and Benguela Niño; SIOD and ENSO (shown in blue, black and red respectively). The years on the x-axis indicate the midpoint of the sliding window width. Thus, the value for 1960 represents the correlation value computed over the years ranging from 1950 to 1970.

For the SIOD, significant positive correlations with area-averaged rainfall of about 0.4 occur during the periods centred on the mid-1960s to early 1970s, the mid-1970s to about 1980, and about 1995-2000. Weak correlations exist in the periods centred from about 1960-1965 and the mid-1980s to the mid-1990s implying that there is decadal variability in the relationship between the SIOD and summer rainfall.

The Benguela Niño also shows decadally varying positive correlations but these are all relatively weak until the period centred on the late 1980s to 2000. There are also periods centred in the mid- to late 1960s and the mid-1970s when the relationship changes sign. This behaviour suggests that the Benguela Niño may have a less stable relationship with rainfall than does the SIOD. Evidently so, the SST anomalies in the Angola-Benguela frontal zone from 1980 to 2003 had positive impact on rainfall. This relationship accounts for about 20% of the decadal rainfall variance. At the same period, 40-45% of southern African rainfall variance was accounted for by ENSO which is negatively related to rainfall. Throughout the record, ENSO-rainfall relationship has strengthened from one decade to the other with the exception of the 1976-1996 to 1978-1998 21-year periods (located at 1986 and 1988 x-axis points in figure 12) where weakening corresponding to a decrease from 40 to 31% of the total explained rainfall variance.

Although there are indications of variability in the ENSO-rainfall links, this mode shows a much more stable relationship which, with the exception of a brief period centred in the early 1960s, always shows a statistically significant negative relationship with rainfall. However, there are still decadal variations in the strength of this relationship through the record as well as a tendency for the correlation to have gradually increased from about -0.5 to -0.6 in the early part to about -0.7 in the periods centred on the 1990s decade.

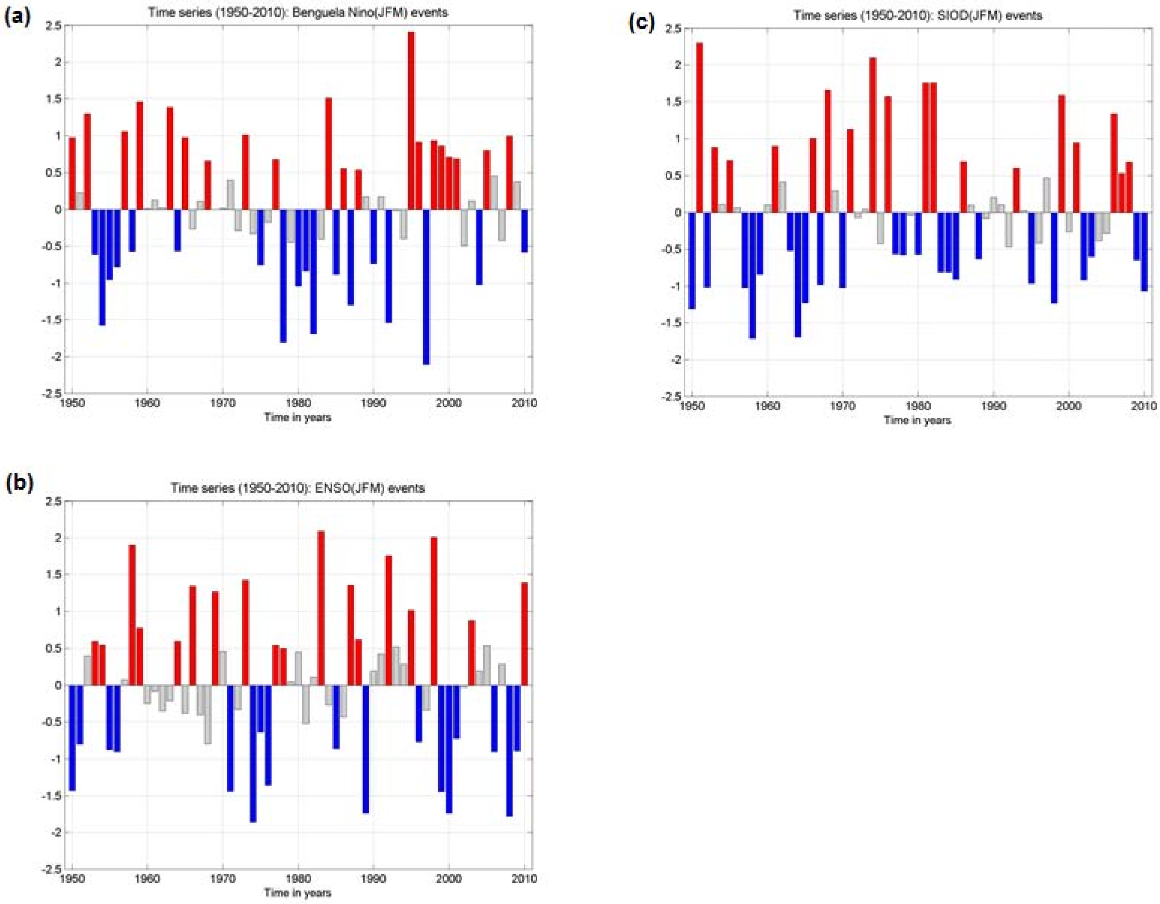


Figure 13: Time series for (a) Benguela Niño index, (b) Niño 3.4 index and (c) SIOD index. The red bars represent positive phases, blue represent negative phases, and grey bars indicate weak or neutral phases of these modes.

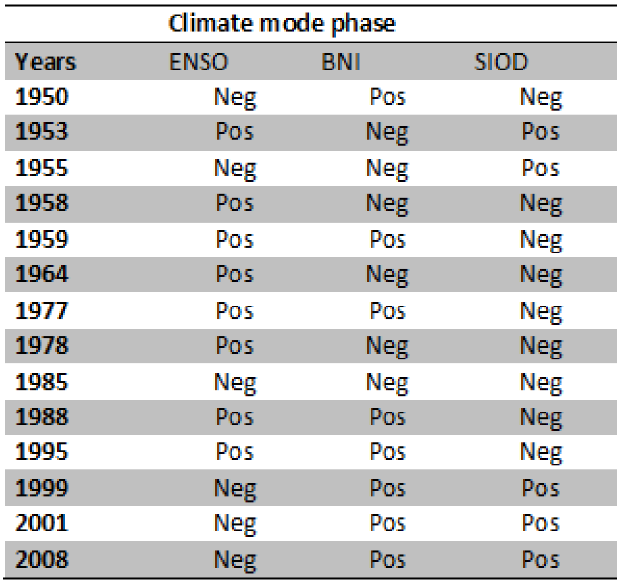
Historical periodicities of ENSO, Benguela Niño and SIOD

Time series of the indices for ENSO, Benguela Niño and SIOD events are presented in figure 13. The events are classified into three phases: positive, negative and weak or neutral, and are demarcated in red, blue and grey respectively. The positive (negative) phases are defined when the value of the standardised JFM SST anomaly is at least 0.5 (less than -0.5). Weak or neutral phases are characterised by an absolute standardised SST anomaly value less than 0.5. Twenty Benguela Niño events (1950, 1952, 1957, 1959, 1963, 1965, 1968, 1973, 1977, 1984, 1986, 1988, 1995, 1996, 1998, 1999, 2000, 2001, 2005 and 2008) and 18 cold Benguela Niño events, also known as Benguela Niñas (1953, 1954, 1955, 1956, 1958, 1964, 1975, 1978, 1980, 1981, 1982, 1985, 1987, 1990, 1992, 1997, 2004 and 2010) were identified in the 61-year period from 1950 to 2010. The most intense positive

Benguela Niño event occurred in 1995 and preceded the 1997 strongest negative event (Shannon, et al., 1986; Rouault, et., 2003).

The analysis of the climatological ENSO periodicity displayed in figure 13b indicates that out of 18 El Niño events (1953, 1954, 1958, 1959, 1964, 1966, 1969, 1973, 1977, 1978, 1983, 1987, 1988, 1992, 1995, 1998, 2003 and 2010) that occurred between 1950 and 2010, the 1983 and 1998 events had standardised SST anomalies exceeding 2 standard deviations (Lyon & Mason, 2007). Note that the JFM season considered here refers to the mature phase of the ENSO event which begins in the preceding year. Thus, more correctly, the ENSO events should be referred to as 1982/83 and 1997/98 etc. In the same 61-year period, 17 mature phase La Niña events were identified (1950, 1951, 1955, 1956, 1971, 1974, 1976, 1985, 1989, 1996, 1999, 2000, 2001, 2006, 2008 and 2009). Of these, four (1974; 1989; 2000 and 2008), had standardised SST anomalies over 1.5 standard deviations (Washington & Preston, 2006). For the SIOD, the positive events exceeding 1.5 on the intensity scale were observed in 1951; 1969; 1974; 1976; 1981; 1982 and 1999 (figure 13c) The most intense negative SIOD events occurred in 1958 and 1964.

Table 2: Years in which Benguela Niño, SIOD and ENSO co-occurred and the corresponding their phases. Neg and Pos represent negative and positive phases respectively.



	Climate mode phase		
Years	ENSO	BNI	SIOD
1950	Neg	Pos	Neg
1953	Pos	Neg	Pos
1955	Neg	Neg	Pos
1958	Pos	Neg	Neg
1959	Pos	Pos	Neg
1964	Pos	Neg	Neg
1977	Pos	Pos	Neg
1978	Pos	Neg	Neg
1985	Neg	Neg	Neg
1988	Pos	Pos	Neg
1995	Pos	Pos	Neg
1999	Neg	Pos	Pos
2001	Neg	Pos	Pos
2008	Neg	Pos	Pos

It has been suggested that the SST fluctuations in the Benguela Niño, SIOD and ENSO domain may occur independently (Nicholson, 2003). On the other hand, the years within the study period in which all climate mode co-occurred are shown in table 2 along with their respective phases. To examine the rainfall patterns resulting from the event when all these modes are significantly active, the normalised rainfall anomalies computed for the 14 years in table 2 are presented in figure 14. At first glance, figure 14 suggests little commonality in rainfall anomaly patterns for the 14 JFM seasons. However, it appears that 5 of the seasons (1953, 1955, 1977, 1978, 1988) show a broadly similar NW-SE oriented band of wetter conditions across subtropical southern Africa, albeit that this band shifts slightly. Another 7 (1958, 1959, 1964, 1985, 1995, 1999, 2001), shows dry conditions across most of the southern half of the domain. A further similarity of wet anomalies somewhere in western Angola and Namibia is evident in 1950, 1959, 1995, 2001, and 2008. Figure 14 also indicates that the impact of the three climate modes on rainfall combines non-linearly.

An alternative approach is to consider that there are 3 climate modes which for any given season can combine in 24 ways based on each mode being either in negative or positive phase and equally likely to occur. For example, a season can be defined as class NPP if ENSO is in negative (La Niña) phase, the Benguela Niño is positive, and the SIOD is also in positive phase (e.g., 1999, 2001, 2008). However, for the 1950-2010 climatology as depicted in table 2 only 7 climate mode configurations (NPP, PNP etc) were distinguished.

When comparing the rainfall deviation from the climatology for the years that experienced a similar climate modal pattern, it is evident in figure 14 that there is a significant difference from one year to the next. The number of events in all seven climate modal patterns suggested in the present study is insufficient to compute unbiased composite analysis for the years that correspond to each of the phase configuration of climate modes. Thus, to further examine the distinctive contribution of Benguela Niño, ENSO and SIOD over southern Africa data from 1950 to 2010 is the most effective way to extricate the impacts of the individual modes.

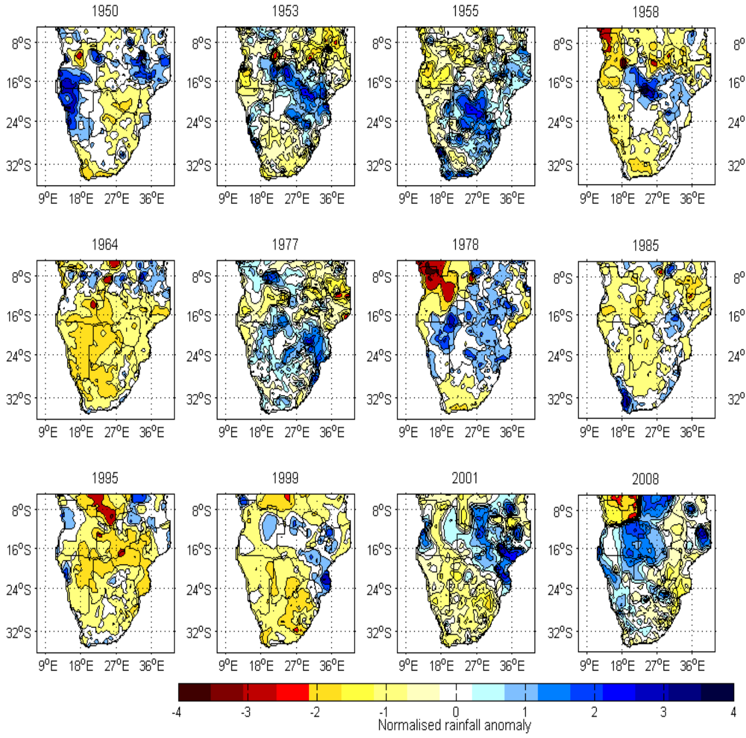


Figure 14: Normalised rainfall spatial patterns based on the 1950-2010 climatological period. Shows rainfall patterns for the years in which Benguela Niño, SIOD and ENSO events coincided.

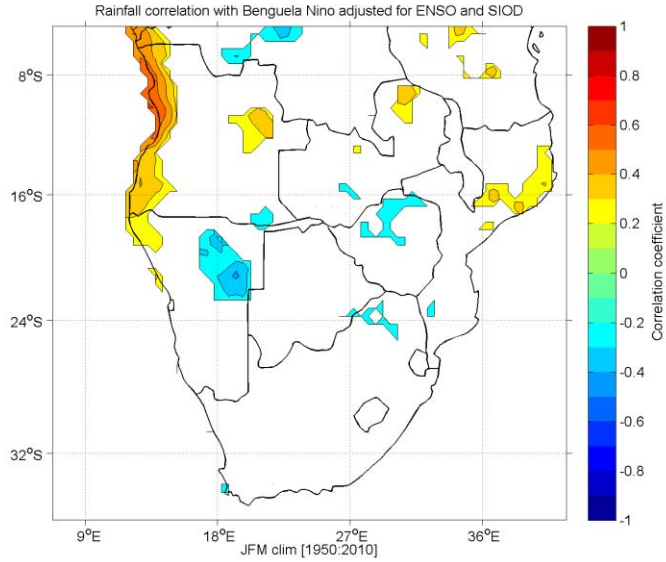


Figure 15: Correlation map. The coefficient value at each grid point represents the relationship between rainfall and Benguela Niño when the effect of ENSO and SIOD is removed. Only regions with 90 % significance are plotted.

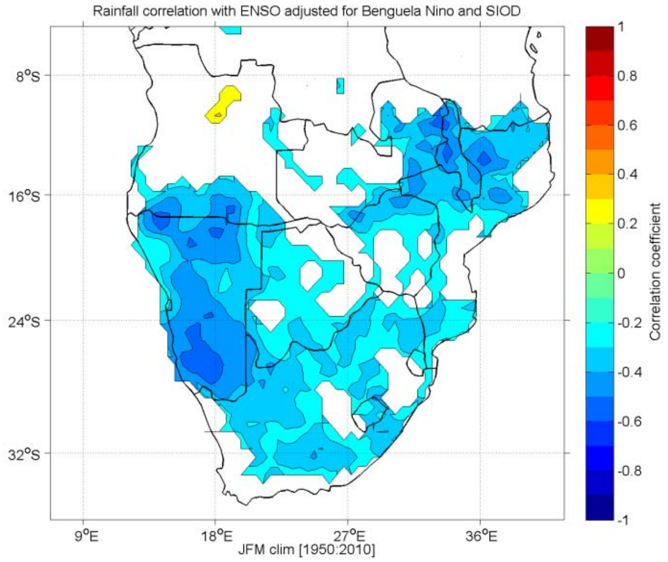


Figure 16: Correlation map. The coefficient value at each grid point represents the relationship between rainfall and ENSO when the effect of Benguela Niño and SIOD is removed. Only region with 90% Significance are plotted.

Unique role of ENSO, Benguela Niño and SIOD to inter-annual rainfall variation

The second order partial correlation method was employed on the 1950-2010 climatology data so as to try and assess the individual rainfall impacts associated with ENSO, Benguela Niño and SIOD. Figure 15 demonstrates the correlation of rainfall with Benguela Niño adjusted for ENSO and the SIOD. Rainfall along the Angolan and northern Namibian coasts correlates positively with the Benguela Niño index. In these areas, rainfall variance in the range 4-36% is accounted for by the fore-mentioned direct Benguela Niño-rainfall association. A similar relationship is seen further inland over north-eastern Angola; northern Mozambique and northern Zambia. Some small areas in central southern Africa and in the south-west of South Africa display a significant inverse relationship between rainfall and Benguela Niño. Compared to the raw correlation in figure 11, figure 16 suggests that the Benguela Niño relationship with Angolan and northern Namibian coastal rainfall is only weakly contributed to by ENSO or the SIOD.

Figure 16 shows the ENSO-rainfall relationship when the effect of SIOD and Benguela Niño is removed. About 4-64% of the rainfall variance over large parts of southern Africa is connected to the ENSO events. Comparison with figure 11 indicates that the individual ENSO impact is generally strengthened when Benguela Niño and SIOD links are removed via the partial correlation technique.

The SIOD effect on rainfall when the influences of ENSO and Benguela Niño are removed is presented in figure 17. The results show a statistically significant positive correlation SIOD and rainfall in the areas in parts of south coast; central-east interior of Angola and the region in the north-western province of Zambia. On the other hand, areas in the north-eastern part of southern Africa, the South Western Cape and north-eastern Free State in South Africa suggest that rainfall is linked negatively with SIOD. By contrast with ENSO and the Benguela Niño, the partial correlation technique significantly weakens any direct impact of the SIOD on southern African rainfall.

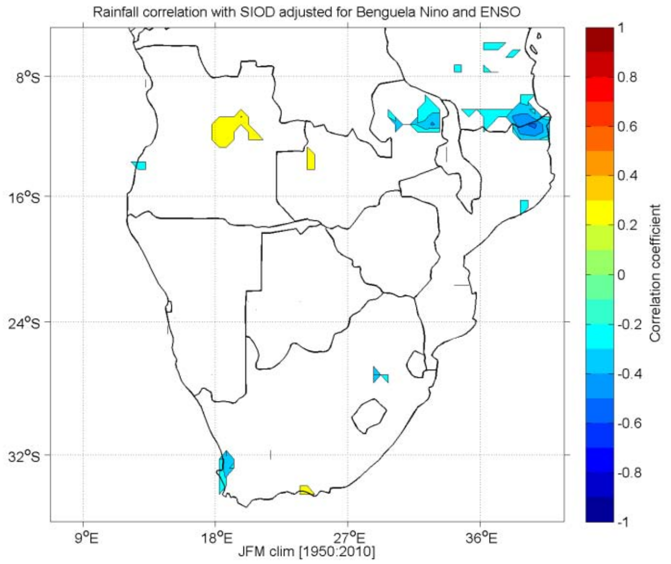


Figure 17: Correlation map. The coefficient value at each grid point represents the relationship between rainfall and SIOD when the effect of ENSO and Benguela Niño is removed. Only regions with 90% significance are plotted.

5. Discussion

An EOF method applied here allowed for the identification of prominent modes of variability of SSTs in the tropical Pacific, South Indian and Atlantic Ocean. These modes of variability each have different impacts on rainfall variability across southern Africa. The projection of rainfall on EOF modes revealed that most of the ENSO related SST fluctuations in the tropical Pacific Ocean are clearly captured by the first mode. This mode showed a significantly negative correlation with southern African rainfall particularly in the north-eastern and subtropical regions of southern Africa consistent with previous work showing ENSO impacts over the region (Lindesay, 1988; Lindesay & Vogel, 1990; Nicholson & Selato, 2000; Reason et al., 2000). The spatial correlation pattern observed for the rainfall projections on the first EOF mode matches up with those attained when SSTs in the Niño3.4 region were correlated with rainfall (see figure 8a and 11b). These results corroborate with previous findings that warm (cold) ENSO event tend to bring anomalously dry (wet) conditions in greater part of southern Africa (Ropelewski & Halpert,1989; Nicholson & Kim, 1997); Richard, et al., 2000;Reason, et al., 2000; Philippon, et al., 2011).

The Benguela Niño, as represented in figure 11a, is positively linked to rainfall along the coast of Angola and northern Namibia and in small parts in the interior of southern Africa. Rouault, et al., (2003) related the above average rainfall events along the west coast of Namibia and Angola to the occurrence of anomalously warm events in the Angola-Benguela frontal zone and also showed the regional atmospheric circulation anomalies play a vital role as to how far inland the Benguela Niño-related rainfall anomalies extend. This influence of regional atmospheric circulation was confirmed by model experiments carried out by Hasingo and Reason (2009). The correlation between the principal component of the first EOF mode in the Atlantic with SSTs in the Benguela Niño region (as defined in the methodology section) suggest that close to 25% of the total summer variance in the Atlantic Ocean is explained by inter-annual variability of SSTs in the Benguela Niño domain (see table 1). On the other hand, correlation with the second EOF mode reveals that about 10% of variance is accounted for by Benguela Niño.

The results presented in figure 10b and the correlation coefficient between the SIOD index and the second EOF mode in table 1 confirm the findings of Behera & Yamagata (2001) that SST variations according to the second EOF mode in the South Indian Ocean represent a significantly large fraction of SST variability related to SIOD. The overall results presented in this study associate rainfall anomalies in the south-west central region of southern African directly to SIOD events. Reason (2001, 2002) and Behera & Yamagata (2001) found that the presence of anomalously warm (cold)

SST in the south-west Indian ocean during a positive (negative) SIOD event tend to induce above (below) average rainfall conditions in the central subtropical region of southern Africa.

ENSO, Benguela Niño and SIOD each have a distinct and significant relationship with rainfall in various parts of southern Africa. To examine the decadal stability of these relationships, a sliding correlation of 21-year width between southern African area-averaged rainfall and each of the climate modes of variability was employed and the results shown in figure 12. The results for the ENSO-rainfall analysis suggest strengthening of the ENSO-rainfall relationship since the 1960s. According to Richard et al., (2000), before 1970 rainfall over southern Africa was mostly influenced by regional SSTs and only after 1970 did the ENSO impact became significant. An alternative possibility is that there are ENSO-like modes occurring on the decadal to multi-decadal time scales that are sometimes in and out of phase with each other (Allan et al., 1995; 2003). If that is the case, assuming that SST anomalies in the South Indian Ocean were insignificant then the observed ENSO-rainfall relationship strengthening in the 1960s can either be explained by magnitude and or the intensity of ENSO episodes that occurred in the 1970s relative to the 1960s events. As evident in figure 13b, there were more instances of ENSO in the 1970s than in 1960s. However, given the occurrence of some strong events of ENSO in the 1970s (i.e. 1974 and 1976 La Niña), it is difficult to disregard the impact of intensity on the ENSO-rainfall decadal relationship stability. For further exploration of the factors modulating decadal ENSO-rainfall relationship stability, the period between 1976 and 1999 during which the relationship weakened, is examined. The strong ENSO events of figure 13b are defined when standardized SST anomalies are about or greater than one standard deviation. The 1976 to 1999 period consists of four sliding decades (i.e. 1976-1996; 1977-1997; 1978-1998 and 1979-1999) defined on a 21-year time frame. A common thread among these decades is that at least 10 to 11 out of 21 years were identified as ENSO events. What may modulate the ENSO-rainfall relationship is the number and measure of strong events. The observations at the beginning of the historical record considered here offer supplementary evidence to the theory proposed above. The first three decades: 1950-1970; 1951-1971 and 1952-1972 are distinct from those in between 1979 and 1999 in that they displayed a much weaker ENSO-rainfall relationship. The moderate ENSO events during the early-1950s and early-1970s are equivalent to that seen over 1979 to 1999 but the magnitude of the strong events is relatively low. However it is important to note that this theory holds if the effect of the neighbouring oceans is assumed insignificant. It must also be noted that the very strong 1997/98 El Niño had much weaker rainfall impacts than expected (Reason & Jagadheesha, 2005; Lyons & Mason, 2008).

The existing literature identified Benguela Niño events in 1934, 1963, 1984 (Shannon, et al., 1986) and also in 1959, 1965, 1986, 1995, 1998, 1999, 2001and 2006 (Rouault, et al., 2003; Grimm & Reason, 2011). The Benguela Niño events identified in this study are the same as those identified in the previous researches. The 2009 event which was specified here as non-Benguela Niño event resulted in extreme flooding over most parts of Angola and Namibia (see appendix A.1). This inconsistency between the observed anomalies in the Benguela Niño domain and the intensity and the spatial distribution of the resultant rainfall anomalies might be attributed to regional low-level atmospheric circulation anomalies over southern Africa when there are also sizeable SST anomalies in the south-western Indian Ocean (Rouault, et al., 2003; Hansingo & Reason, 2009).

When the decadal relationship of Benguela Niño and rainfall area-averaged over the entire Southern African landmass was examined, the relationship was found to be statistically significant during the four successive 21-year periods: 1980-2000; 1981-2001; 1982-2002 and 1983-2003 (figure 12). A gradual increase was observed for the first three decades with a decline in the last decade. Since 1980 and 2002 period includes the 1984, 1986, 1995 and 2001 Benguela Niños which had severe impacts on fisheries and rainfall along the west coast, it is possible that these events had an important influence on Benguela Niño-rainfall relationship. The correlation field plot of figure 11a indicated that Benguela Niño mostly modulates rainfall in the north-western coastal parts of Southern Africa. Therefore, the Benguela Niño impact is likely to be underestimated when the whole of southern African region is averaged into single homogeneous area. Thus, the southern African region was divided into six regions (the results are no shown here): North-west; North-east; central-west; central-east; south-west and south-east. The northern regions reveal a statistically significant Benguela Niño-rainfall decadal relationship at the 90% confidence level. The north-east region area-averaged over the [26-41°E; 5-15°S] domain displayed a similar decadal relationship as for the analysis of entire southern Africa post-1980s. The north-west region [12-26° E; 5-15°S] showed a significant decadal relationship earlier in the record which was not observed when the whole southern African area was considered in the analysis. The frequency of cold and warm events in the Angola-Benguela frontal zone is insufficient to explain the inter-decadal stability of the Benguela Niño-rainfall relationship. For further understanding of the relationship, not only the regional atmospheric circulation but also the possible co-occurrence of ENSO and the Indian Ocean SST anomalies needs to be considered. On the other hand, the SIOD-rainfall decadal relationship showed a much more variable inter-decadal relation in the central-west [12-26°E; 15-25°S] and south-west [15-26°E; 25-35°S] regions than when analysed for the entire area of southern Africa as illustrated in figure 12. It is interesting to see that despite its proximity to the Indian Ocean, the eastern regions are statistically less affected by the SIOD.

Thus far the influence of ENSO, Benguela Niño and SIOD on southern Africa rainfall was investigated disregarding the possibility of inter-linkage among these climate modes of variability. Given that in reality, ENSO, Benguela Niño and SIOD events may occur simultaneously, the result from the previous studies revealed that the anomalies in the two other oceanic areas remote from the domain of the climate mode of variability that is being analysed may act to reinforce or oppose the impact of that particular phenomenon (Rocha & Simmonds, 1997b; Hansingo & Reason, 2009; Rouault, et al., 2003). Table 2 presents the years during the 1950 and 2010 period when climate modes co-occurred along with their respective phases. The standardised rainfall anomalies for those particular years are depicted in figure 14. It is no surprise that each year had a distinct rainfall pattern. However, one would expect to find clusters of rainfall patterns for the years in which similar phases for each climate mode occurred, but that is not the case. The length of time series for this study constrained the employment of the composite analysis of the climate mode phase clusters to explore the unique contribution of each of the climate modes. Therefore, the partial correlation of South African rainfall with respect to ENSO, Benguela Niño and SIOD was examined for the entire study period.

Excluding the contribution of ENSO and SIOD, the Benguela Niño tends to regulate inter-annual rainfall along the north-western coast of southern Africa and some inland areas (see figure 15). The spatial pattern presented in figure 15 is similar to that illustrated in figure 11a (where a simple correlation between Benguela Niño and rainfall is represented) but slightly weaker correlation coefficients. Since the South-western Cape in South Africa receives little or no rainfall during summer (Tyson & Preston-Whyte, 1988), the negative relationship found between rainfall in this region and Benguela Niño events suggest that during a Benguela Niño event, rainfall can be enhanced in this region. The spatial patterns remain the same when the Benguela Niño-rainfall relationship is adjusted for either ENSO or SIOD. However, the maximum percentage fraction of the variance in rainfall explained by this relationship decreases from 49% to 36%. These results imply that 13% of the total rainfall variance along the Angola-Namibian coast may relate to the tropical Pacific and South Indian Ocean SST anomalies.

The unique coefficient of correlation between ENSO and southern African rainfall are relatively greater in the central-west and north-east areas of south Africa and slightly less in the interior, south and eastern regions (figure 17) compared to when either the effect of SIOD or Benguela Niño is omitted for the ENSO-rainfall analysis (not shown). The contribution of ENSO is found to be modulated by SIOD and Benguela Niño.

The SIOD-rainfall relationship adjusted for ENSO and Benguela Niño is statistically insignificant except for the small and spatially scattered regions in the South Africa, Angola, Zambia, Mozambique and Tanzania. It is evident that the tropical Pacific SST anomalies are pertinent to the SIOD-rainfall relationship for when just the effect of Benguela Niño is removed (not shown), the resultant spatial correlations resembled those illustrated in figure 10b and 11c.

6. Conclusion

In southern Africa, the SST variability in both the remote and adjacent oceans leads to strong inter-annual to inter-decadal rainfall variability. Much research has concentrated on how a particular climate mode of variability affects rainfall across the region.

This study was based on two hypotheses:

i. ENSO, SIOD and Benguela Niño have some influence on the inter-annual summer rainfall over Southern Africa
ii. The degree to which these modes impact on southern African summer rainfall may be different.

Following these statements, the research questions were formulated and various statistical methods were applied to address them. In this final chapter, the important findings of chapter 4 are summarised. For recollection, the main research questions are repeated below.

- **Is there a significant relationship between summer rainfall in the southern African region and each of the climate variability modes? Are these relationships stable through the record or do they change from one decade to the next?**

- **What is the unique (independent of the two other modes) rainfall impact over the region contributed to by each mode? Do the spatial patterns of rainfall impact of each mode and their seasonality differ?**

Statistical EOF techniques were used to analyse the effect that SST variations in Indian, Atlantic and Pacific Ocean have on inter-annual rainfall variability over southern Africa. It was found that the first EOF mode in Pacific Ocean comprises of most of the ENSO signal. In the Indian Ocean, the second EOF mode clearly represented the inter-annual dipole-like SST anomalies. As for the Atlantic Ocean, there is not a clear indication as to which of the two EOF modes best represent the SST fluctuations in the Angola-Benguela frontal zone. Given that the domain in which the EOF analysis was computed is large compared to where Benguela Niño actually occur, it could be that the phenomenon could not be well resolved and also that the signal from other climate modes such as the dipole event in the south Atlantic may have been captured in the EOF.

SIOD was found to be positively related to rainfall events in the south-central regions of southern Africa based on the 1950 to 2010 time series. When the relationship was adjusted for ENSO and Benguela Niño the area of significant relationship was very much reduced. However, removing just the effect of the Benguela Niño in the SIOD-rainfall analysis spatial pattern matched the typical SIOD-rainfall relationship pattern (i.e. direct relationship with rainfall in the central west areas in southern Africa. See figure 11c). Therefore, the SST conditions in the tropical Pacific Ocean seem to have a considerable influence on spatial extent of the SIOD related impacts on rainfall in southern Africa. The most significantly stable inter-decadal relationship between SIOD and rainfall was observed for the period between late 1950s and 1980.

The inter-annual SST variations in the Benguela Niño region were shown to be positively linked to rainfall mostly along Angolan and northern Namibian coast. The most significant decadal relationship between rainfall over southern Africa and SST fluctuations in the Angola-Benguela frontal zone were evident during the 1980s and afterwards. Removing the ENSO and SIOD impacts, the spatial patterns of Benguela Niño-rainfall relationship remains the same but are slightly weaker in correlation intensity. ENSO remains a prime climate mode of variability in large part of southern Africa and it is associated negatively with rainfall variability in the region. Throughout the study period, the ENSO-rainfall decadal relationship was found to be gradually strengthening.

The results of this study further develop the current understanding of the implications of ENSO, Benguela Niño and SIOD on southern African climate. Moreover, the newly established knowledge of how each climate mode of variability contributes to changes in rainfall pattern from one year to the other will enable us to have a better idea of the socio-economic impact which could be potentially caused by the current state of ENSO, Benguela Niño and SIOD during a particular summer season.

A major limitation faced in this study was the lack of available observations in order to examine the mean atmospheric conditions associated with different coexisting phases of all climate modes of variability simultaneously. For future studies, we propose that climate model experiments be conducted to simulate and investigate the impacts that climate mode phase configuration has on regional atmospheric circulation thereby driving rain-producing weather systems.

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