Revisiting the links between the Southern Annular Mode and rainfall over the Western Cape region of South Africa

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Plagiarism declaration

I understand the nature of plagiarism and I understand the University's policy on this. The content of this thesis represents my own opinions and not necessarily of the University of Cape Town.

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Abstract

The winter rainfall region of South Africa displays considerable interannual variability and prevalence to prolonged dry periods. Although not completely understood, a wide range of factors have been highlighted to contribute to this interannual variability. The relatively poor understanding of rainfall variability in this region is of concern considering the low rainfall received in 2015-2017, resulting in the City of Cape Town enforcing severe water restrictions due to dam levels falling dangerously low. The focus of this thesis is on the influence of the Southern Annular Mode (SAM) on rainfall over the region, the possible influence of El Niño Southern Oscillation (ENSO) is also considered. To achieve this, a correlation analysis was conducted using the Marshal (2003) SAM index and station rainfall anomalies over the region for the period 1979 to 2016.

The results show that five (three) of the six driest (wettest) years were associated with a positive (negative) SAM phase. However, the relationship is found to be statistically insignificant at a 95% significance level. The relationship is also found to show spatial variability, with strong negative correlations over the West Coast, while a weak positive correlation is observed over the South Coast. Furthermore, a decadal analysis in the relationship found it to be statistically insignificant (at the 95th significance level) for most of the study period, with an exception of the early winter over the West Coast which shows a strong negative correlation after 2015. A composite analysis showed that dry (wet) winters tend to be associated with a positive (negative) SAM pattern superimposed with a wave number 3 anomaly. In addition, there are La Niña (El

Niño) – like SST anomalies in the tropical Pacific. These circulation and SST patterns are more or less observed during the generally dry 2015-2017 winters except that winter 2015 shows an El Niño SST anomaly.

Table of Contents

Figures captions and tables:

List of acronyms and abbreviations:

CoLs	Cut-of lows
CP	central Pacific
ENSO	El Niño Southern Oscillation
EOF	Empirical Orthogonal Function
EP	eastern Pacific
ERSST	Extended Reconstructed Sea Surface Temperature
MSLP	Mean Sea Level Pressure
NCAR	National Centre for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	**National** Oceanic and Atmospheric Administration
OISST	Optimum Interpolation Sea Surface Temperature
SAHP	South Atlantic Subtropical High Pressure
SAM	Southern Annular Mode
SAWS	South African Weather Services
SICZ	South Indian Convergence Zone
SSTs	Sea Surface Temperatures
SW Atlantic	South West Atlantic
TTTs	Tropical Temperate Troughs

1. Introduction

The southwestern tip of South Africa receives rainfall during austral winter (May-September), while the rest of the country is mostly categorised as a summer rainfall region. This winter rainfall region is semi-arid, with the relatively wet coastal region separated from the dry interior by the Cape Fold Mountain range and the Great Escarpment. The region receives its rainfall mostly through cold fronts associated with extratropical cyclones and occasionally cut-off lows (Reason and Rouault, 2005; Blamey and Reason, 2007). Despite this part of the country being a major contributor to high quality agricultural production and home to the country's second largest city, little research has been done on its climate variability. The winter rainfall displays considerable interannual variability and prevalence to dry periods. Although not completely understood, a wide range of factors have been highlighted to contribute to the interannual variability, ranging from the influence of sea surface temperatures (SSTs) in the South Atlantic (Reason *et al*., 2002; Reason and Jagadheesha, 2005), sea ice anomalies in the Atlantic sector of the Southern Ocean (Blamey and Reason, 2007), to large scale modes of variability, such as the El Niño Southern Oscillation (ENSO) and Southern Annular Mode (SAM) (Reason *et al*., 2002; Philippon *et al*., 2012).

The relatively poor understanding of rainfall variability in this region is of concern considering the low rainfall received in 2015-2017, resulting in the City of Cape Town enforcing severe water restrictions due to dam levels falling dangerously low (City of Cape Town, 2017). Rainfall variability for the summer rainfall region is relatively well understood. Here, wet and dry years are strongly correlated with ENSO. Different studies have shown that La Niña (El Niño) years tend to be associated with wet (dry) conditions, although the relationship is found to be nonlinear (Mulenga *et al*., 2003). El Niño dry conditions essentially occur due to modulations in the local walker circulation and SST in the neighbouring tropical Indian and Atlantic oceans (Ropelewski and Halpert 1987; Kruger 1999; Reason *et al*., 2000; Mulenga *et al*., 2003). During ENSO there is an offshore shift of the ascending branch of the local circulation, which lies over the western Indian Ocean instead of southern Africa (Reason *et al*., 2000). This shift displaces the South Indian Convergence Zone (SICZ) which is an expression of the Tropical Temperate Troughs (TTTs) (Reason *et al*., 2000). During an El Niño the SICZ shifts northeastward and lies over the Indian Ocean, resulting in dry conditions over southern Africa (Mulenga *et al*., 2003; Blamey and Reason, 2012).

By contrast, ENSO does not have the same influence over the winter rainfall region. In this region El Niño events are associated with positive anomalies in winter (May-July) rainfall amounts caused by longer wet spells that bring more rainfall, this is proposed to be caused by the northward shift of rain systems during El Niño (Philippon *et al.*, 2011). It is thought that the SAM plays a bigger role as it is the dominant mode of tropospheric circulation variability in the Southern Hemisphere (Hartman and Lo, 1988; Thompson and Wallace, 2000; Reason and Rouault, 2005; Abram *et al*., 2014). A few studies have investigated the SAM influence on rainfall over different parts of the globe (Silvestri and Vera, 2003; Rouault *et al*., 2005; Gillet *et al*., 2006). Gillet et al. (2006) conducted a study for the Southern Hemisphere, which showed that over the western tip of South Africa, a negative response in precipitation was observed associated with a one standard deviation positive anomaly of the SAM. Reason and Rouault

(2005) is the only study which focuses specifically on the southwestern region of South Africa. In their study, they analysed the rainfall response to SAM and found that the wettest (driest) winters over the region between 1948 and 2004 occurred during a negative (positive) SAM phase. It must be noted that both these studies run their analysis up to the early 2000's.

Given the availability of new observation datasets and a longer time frame, it presents an opportunity to revisit the findings of both Reason and Rouault (2005) and Gillet *et al.* (2006). The SAM and ENSO phenomena have been shown to have a strong teleconnection at the interannual scale (Pohl *et al*., 2010), with El Niño (La Niña) events corresponding to a negative (positive) SAM phase. L'Heureux and Thompson (2006) further show that 25% of the SAM variance linearly relates to the ENSO state and that the SAM variability is also shown to be forced by ENSO anomalies. SAM has been showing to have a positive polarity in recent decades, which has been largely attributed to stratospheric ozone depletion (Abram *et al*., 2014).

In this study, the relationship between the SAM and winter rainfall over the Western Cape is revisited to investigate whether it has changed in recent decades. This analysis will investigate whether the observed changes in the winter rainfall could be explained by the changes in the SAM trend in recent years, which was described earlier. The influence of ENSO on SAM is also considered in this study. This is useful for a better understanding of rainfall variability, which will in turn help in planning and decision making on proper water usage to supply the need of the rapidly growing population in this region.

The thesis is divided up into the following sections: Section 2 highlights the relevant literature on this topic. The methods and datasets used are described in Section 3, while results are presented in section 4. Sections 5 and 6 contain the discussion and conclusions, respectively.

2. Literature review

2.1 Rainfall regimes in South Africa

Rainfall and temperature patterns of South Africa are generally moderated by the surrounding oceans and topography. The country is surrounded by a strong western boundary current to the east (Agulhas Current) and an intense eastern boundary current (Benguela Current) to the west (Griffiths *et al.*, 2010). The South African Weather Services (SAWS) divides the country into 93 rainfall districts, with the 93 districts being part of 8 climatic areas which are based on cluster analysis of rainfall in the country (Rouault and Richard, 2003). These climatic regions can be further classified into either winter, summer or an all year round rainfall region, which is defined by the month the area receives its maximum rainfall. For instance, the north-western Cape has very little rainfall and has its maximum rainfall in June (~30mm), while the south-western Cape also receives its maximum rainfall in June but has a maximum of 70mm (Rouault and Richard, 2003). Both these two areas fall under the winter rainfall region. Areas along the Southern Cape coast receive rainfall all year round, while the rest of the country falls under the summer rainfall region. The southern interior and western interior has maximum rainfall in March; and the central interior, KwaZulu-Natal and north-eastern interior receives a maximum rainfall in January (Rouault and Richard, 2003).

Rainfall generally increases from the west to east coast, with warm SSTs and the orographic effect on the eastern side of the Drakensberg playing a key role. The contrast in rainfall between the summer and winter rainfall regions is also notable in the different time scales of variability and potential factors contributing to rainfall variability. Therefore, when considering weather events each rainfall region should be considered separately as different systems contribute to rain formation and annual variability.

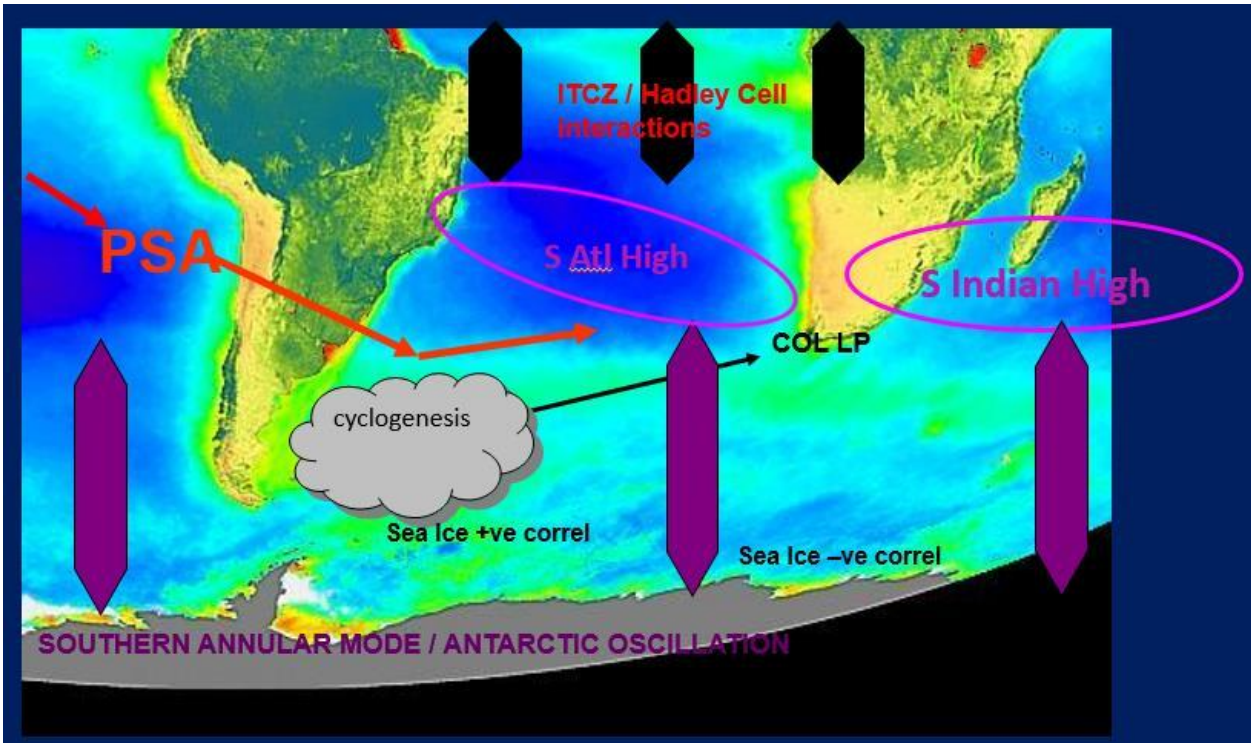

Figure 1**:** A Schematic showing the main circulation features important for rainfall over the winter rainfall region. © Prof. Chris Reason, 2018

2.1.1 The winter rainfall region

As introduced above, the Western Cape region of South Africa is primarily a winter rainfall region, which is characterized by wet winters and dry summers. This region receives rainfall during the austral winter months (May to August) and most of the rainfall is produced by cold fronts and associated, extratropical cyclones and the occasional westerly cut-off low (CoLs)(**Fig.1)** (Singleton and Reason, 2006; Philippon *et al*., 2012). This type of climate is described as a Mediterranean climate and it is caused by the location of the subcontinent relative to the South Atlantic Subtropical High Pressure (SAHP) and the low pressure systems of the circumpolar trough between 40° and 60°S (Midgley *et al*., 2005). During the winter season, the westerly wind belt shifts equatorward and the associated circumpolar trough in the Southern Ocean also shifts northwards bringing rainfall to the southwestern tip of the country. In contrast, during the summer months the westerlies retreat poleward as the SAHP shifts southeastwards. This shift in position of these circulation systems brings dry conditions over the Western Cape during this season.

There is a high occurrence of CoLs in austral spring and autumn (Singleton and Reason, 2006) as well as a possible relationship with increased CoL frequency over South Africa during La Niña years. CoLs are middle/upper tropospheric features produced when pre-existing cold troughs extending equatorward are cut off from their high-latitude source region, leaving a closed cyclonic vortex (Singleton and Reason, 2006). When a CoL is confined in the middle and upper troposphere (cold pool) it causes strong instability and hence thunderstorms, strong winds and heavy precipitation may occur. CoLs can also be produced from deep lows extending towards the lower troposphere forming surface lows; these are associated with widespread precipitation and strong winds (Favre *et al*., 2012).

CoLs are quasi-stationary in nature which could lead to two to three days of heavy rainfall over the same region, increasing chances of flooding. Favre *et al*. (2012) suggest that they contribute between 25 to 35% of the annual rainfall accumulation between the summer and winter rainfall regions, making them a vital part of the climate of the region. Furthermore, Favre *et a*l. (2012) presents evidence of a 25% increase in the frequency of CoLs rainy days for the last three decades of the period 1979 to 2006. These changes are evident in the south and east coast of the country during the spring-summer seasons, and this is favoured by the reinforcement of temperature/pressure meridional gradients between high and midlatitudes due to large Southern Hemispheric modes of variability (i.e. positive SAM) (Farve *et a*l., 2012).

Extratropical cyclones also play a dominant role in determining local weather along the midlatitudes therefore having a strong influence on precipitation. This is due to their role in the general atmospheric circulation through their influence of heat, moisture and momentum exchange; and interaction with large scale atmospheric patterns (Simmonds and Keay, 1999; Bengtsson and Hodges, 2005). The location and orientation of baroclinic zones, and Sea Surface Temperature (SST) gradients determine the distribution of extratropical cyclones. The climatology of extratropical cyclones over the Southern Hemisphere derived by Jones and

Simmonds (1993) highlights the south west (SW) Atlantic as an important area for cyclogenesis (Reason *et al*., 2002). Anomalous warm (cold) SSTs in this region favour an increase (decrease) in cyclogenesis upstream of the South Western Cape region. In the central South Atlantic cool (warm) SST anomalies reduce (enhance) the tropical-midlatitude meridional gradient, thereby weakening (strengthening) weather system moving towards the Western Cape region (Reason *et al*., 2002). Therefore, warm (cool) SST anomalies near the coastal areas of Western Cape are favourable (unfavourable) for local intensification leading to increased (decreased) rainfall (Reason *et al*., 2002).

The Western Cape has a high interior plateau (1-2 km) and steep topography near the coast which leads to strong topographic gradients and a variety of topographically forced weather systems. These climatic gradients include an east-west rainfall seasonality gradient with increased summer rainfall towards the east (**Fig. 1**), and a very steep south-north aridity gradient (Midgley *et al*., 2005). Orography therefore plays a huge role, particularly the Cape Fold Mountains which extend northward along the west coast and east-west to the south which favour high (low) rainfall on their seaward (landward) side (Philippon *et al*., 2012). Strong SST gradients which result from coastal upwelling along the West and South Coast and the presence of the strong western boundary current (the warm Agulhas) have an influence on the atmospheric circulation and rainfall over the winter rainfall region of South Africa (Philippon *et al*., 2012).

2.2 Global modes of variability

Climate modes of variability are recognised patterns or phenomena that originate in particular regions of the Earth and have an impact on a global scale. Most modes (e.g. ENSO) have a well-defined index time series that can be used to monitor their presence and intensity. Regional climates over particular areas of the Earth may be sensitive to one or more large scale climate modes. For example, the summer rainfall regions of southern Africa may be sensitive to both ENSO and the South Indian Ocean subtropical dipole (Lindesay, 1988; Reason et al., 2000; Behera and Yamagata, 2001; Reason, 2001). These climate modes influence the net transport of heat, momentum and moisture into a region, therefore, influencing local and regional climate (Christensen *et al.*, 2013). The next few sub-sections present some of the key modes of variability that impact the Western Cape.

2.2.1 El Niño Southern Oscillation

The ENSO phenomenon accounts for approximately 30% of rainfall variability over the summer rainfall region of South Africa (Tyson & Preston-Whyte, 2000; Gosling *et al*., 2011) but has less of an impact on the winter rainfall region. As alluded to previously, El Niño events are typically associated with drought over the summer rainfall region and La Niña associated with wet conditions (Tyson & Preston-Whyte, 2000; Gosling *et al*., 2011), although the relationship is found to be nonlinear (Meque and Abiodun, 2013). Recent studies (Rouault *et al*., 2010;

Philippon *et al*., 2012) suggest that ENSO may also have an impact on the climate of the South Western Cape and nearby SSTs (Colberg *et al*., 2004), but predominantly during the summer months. In this region the prevailing summer wind is a southeasterly and it drives upwelling on the West Coast. During an El Niño (La Niña) event the wind speed is weaker (stronger) than normal which leads to positive (negative) SST anomalies. Negative (positive) SST anomalies may occur when rainfall is above (below) normal over the winter rainfall region (Rouault *et al*., 2010). Philippon *et al*. (2012) used a high density daily rainfall dataset and reanalysed climate data to show how seasonal rainfall amounts and wet spells are modulated during El Niño events. The results of their study illustrated positive anomalies in winter (May-July) rainfall amount during El Niño events caused by longer wet spells, thus producing more rainfall. The proposed mechanism behind the increase in rainfall is the northward shift of rain systems during El Niño.

2.2.2 The Southern Annular Mode

The Southern Annular Mode (SAM) is the fundamental pattern of tropospheric circulation variability in the mid- and high latitude Southern Hemisphere, influencing rainfall distribution and temperatures from the subtropics to the South Pole (Hall and Visbeck, 2001; Reason and Rouault, 2005; Abram *et al*., 2014). The SAM is barotropic in nature, revealed as being the leading empirical orthogonal function (EOF) in many atmospheric fields, including surface pressure, geopotential height, surface temperature, and zonal wind over the Southern Hemisphere south of about 20°S (Marshall, 2003). It is characterized by opposing pressure anomalies of different signs between the Antarctic and midlatitudes near 40° – 50°S. The positive phase of the SAM is associated with negative pressure anomalies over the polar cap, positive pressure anomalies over the midlatitudes, resulting in the strengthening and poleward shift in storm tracks (Gillett *et al*., 2006). Conversely, during a negative SAM phase there is an expansion in the westerly wind belt towards the equator, which allows storm passage and increased rainfall over the land. The SAM signals can be found throughout the year, with the possibility of a seasonal peak in December (Silvestri and Vera, 2003; Pohl *et al*., 2010).

A few studies have been done to investigate the impact of the SAM on climate in specific countries. Gillet *et al*. (2006) considered its influence on SSTs and rainfall over the entire Southern Hemisphere region, in this study they found that a positive SAM phase was associated with significant cooling over Antarctica and Australia, and a significant warming over the south of New Zealand, Argentina, Tasmania and the Antarctic Peninsula. Furthermore, anomalously dry conditions were also found to be associated with the positive SAM phase over New Zealand, southern America and Tasmania; and anomalously wet conditions over most of Australia and South Africa (see **Figure 1** of Gillet *et al*., 2006). Another study by Silvestri and Vera (2003) on the SAM signal on rainfall anomalies over southeastern South America found that the SAM influence is particularly strong in winter and late spring, although in opposite signs (see **Figures 1** and **2** of Silvestri and Vera, 2003). In spring the positive (negative) SAM phase is associated with intense upper level anticyclonic (cyclonic) anomalies, weakened (stronger) convergence and decreased (increased) rainfall over southeastern South America (Silvestri and Vera, 2003).

Rouault *et al*. (2005) also found evidence of significant changes in the climate over Marion Island. These changes include reduction in precipitation and number of rainy days, increase in pressure, increased temperatures and coastal SSTs.

Reason and Rouault (2005) is the only study that explicitly considers the impact of SAM on rainfall over the west part of South Africa. In their study they found that the wettest (driest) winters over the region between 1948 and 2004 occurred during a negative (positive) SAM phase (see **Figure 1** of Reason and Rouault, 2005). This was shown to be due to the weaker than normal westerly winds, which are caused by the shift of the westerly wind belt towards Antarctica. High pressure anomalies over the landmass were unfavourable for rain-bearing frontal systems to reach the region (Reason and Rouault, 2005). A negative SAM event may be associated with low pressure anomalies over western South Africa as well as over the SW Atlantic. The two phases of the SAM can also be linked to the shifts in the subtropical jet, during wet winters the jet shifts equatorward bringing stronger storm tracks and westerly troughs while during dry winters there is a slight southward shift of the jet leading to the dry conditions on land (Reason and Rouault, 2005, Gillet *et al*., 2006).

2.2.3 SAM and ENSO

The SAM and ENSO have been shown to have a strong teleconnection at the interannual scale, El Niño (La Niña) events corresponding to a negative (positive) SAM phase (Pohl *et al*., 2010).

L'Heureux and Thompson (2006) show that 25% of the SAM variance linearly relates to the ENSO state, the SAM variability is also shown to be forced by ENSO anomalies (Pohl *et al.*, 2010). Yu *et al.* (2015) found that ENSO forcing only became significant after the 1990s and suggested it to be related to the change in the ENSO type from being mostly of the eastern Pacific (EP) to a central Pacific (CP) type. The two types differ in their longitudinal position; CP ENSO develops and decays in the central equatorial Pacific, while the EP develops near the South American coast and has its SST anomalies centred over the eastern equatorial Pacific (Yu *et al.*, 2015). The shift in the longitudinal position of ENSO SST variability therefore has implications on the observed climate over the adjacent land masses. CP ENSO is suggested to induce the SAM through an eddy-mean flow interaction mechanism in the stratospheric and tropospheric mechanism pathways (Yu *et al.*, 2015). During an El Niño event, an increased meridional temperature gradient associated with tropospheric warming produces a strengthening and equatorward displacement in the subtropical jet. This strengthening affects the propagation of transient eddies due to changes in the location of eddy momentum flux convergence (Yu *et al.*, 2015). An acceleration of westerly (easterly) anomalies occurs on the equatorward (poleward) side inducing a negative SAM phase (Yu *et al.*, 2015). Silvestri and Vera (2003) found that the relationship between SAM and ENSO was only significant during austral spring. Thompson and Wallace (2000) suggest that this is associated with the significant cooling (warming) of the tropopause at polar (tropical) regions which trigger SAM fluctuations during the spring season.

Although there is some literature on SAM and its teleconnections, there is still a knowledge gap on how it interacts with other local scale synoptic weather patterns that are known to influence rainfall over the winter rainfall region. This is due to inconsistencies in the literature on how SAM is defined, the index used to represent SAM and the data used to calculate the SAM index (Ho *et al*., 2012). This makes it difficult to approximate and classify SAM for impact analysis on rainfall over the region.

2.3 Regional factors influencing the winter rainfall

Rainfall variability in the South Western Cape has also been identified to be influenced by local features within the South Atlantic basin. One such feature is the strong SST gradients which result from coastal upwelling along the West and South Coast and the presence of the strong western boundary current (the warm Agulhas) which has an influence on the atmospheric circulation or rainfall over the winter rainfall region of South Africa (Philippon *et al*., 2011). The South Atlantic basin experiences variability on an interannual to multidecadal scale and is impacted by ENSO (Colberg et al, 2004). ENSO is shown to be a possible forcing to SST variability and in turn the summer climate of the Western Cape region. Rouault *et al*. (2010) found a negative correlation between rainfall anomalies and SST anomalies, negative (positive) SST anomalies were recorded when rainfall was above (below) normal inland.

Changes in winter sea-ice over Antarctic (**Fig.1**) have also been identified as a contributing factor to rainfall variability over western South Africa (Blamey and Reason, 2007). A composite analysis of the relationship between the anomalies in winter sea-ice over the South Atlantic sector of Antarctica and the winter rainfall over western South Africa suggests that a positive (negative) correlation exists between the rainfall and sea-ice concentration in the Weddell Sea. The correlation was found to be stronger in early (May to July) and mid-winter (June to August) compared to late winter (July to September). Out of 23 years of data, 19 winters show an opposite anomaly between sea-ice concentration and winter rainfall which suggest that the rainfall anomaly is not always strongly related to sea ice but other factors such as SST anomalies in the South Atlantic come into play (Blamey and Reason, 2007). The relationship through which sea-ice concentration and rainfall are linked seems to also involve shifts in the subtropical jet and midlatitude storm tracks which change low level vorticity, convergence and uplift over the west coast of South Africa (Blamey and Reason, 2007).

The South Atlantic subtropical high pressure (SASH) is also an important regional system that influences rainfall along this region. The mechanisms that underlie the development of subtropical anticyclones are still not fully understood. Rodwell and Hoskins (2001) suggest that the seasonal cycle is mainly controlled by convective heat sources over southern Africa and South America and by interaction between the orography and the trade easterlies and midlatitude westerlies. It is also influenced by remote cross-hemispheric effects of heat sources located in the

Northern Hemisphere (Seager *et al*., 2003). These fundamental mechanisms in turn lead to the observed stronger SASH in austral winter compared to austral summer. In austral summer, the anticyclone is predominantly a response to heating over the adjacent land masses while in austral winter the Northern Hemispheric heat sources are responsible for the strengthening of the anticyclone (Seager *et al*., 2003). The subtropical surface pressure over the ocean maximizes at the end of winter when the Hadley cell and midlatitude westerlies are at their strongest. Furthermore, the westerly wind belt shifts northward and the SASH system with it, bringing rainfall to the south-western part of the country (Jury, 1987), as this shift allows passage to more cold fronts moving over the southern part of the country. The anticyclone tends to be displaced poleward in La Niña years when the SAM is in its positive phase which restricts passage to cold fronts that bring rainfall into the region (Sun *et al*., 2017).

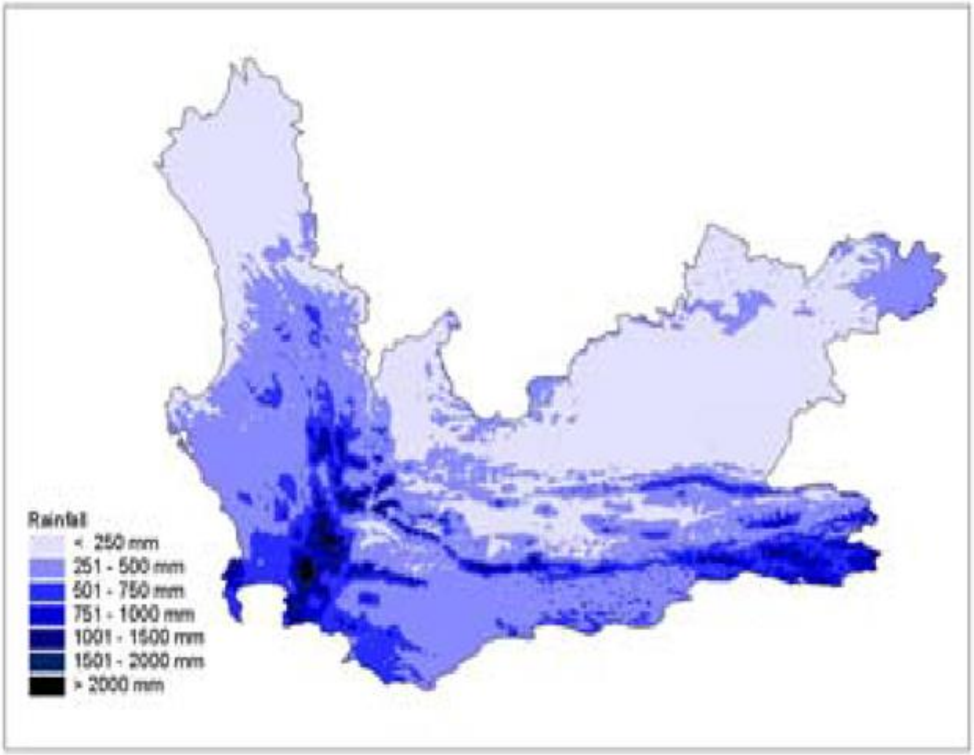

***Figure 2**:* Mean annual rainfall used to illustrate rainfall gradient of the Western Cape region of South Africa (Midgley *et al*., 2005).

2.4 Summary

This review has highlighted that rainfall variability over the winter rainfall region of South Africa is complex and its response to climate modes of variability (i.e. ENSO) differs from the summer rainfall region. It has also highlighted that there is paucity in knowledge on the links between this rainfall and climate modes of variability as only a few studies have focused explicitly on this region. ENSO and SAM are the two global modes of variability that have previously been suggested to influence the region. However, their impacts on the region and the associated mechanisms are not particularly well understood. The perceived increased occurrence of dry periods over the region highlights a need to revisit and refine knowledge on how these modes of variability influence rainfall. The SAM is thought to have the largest influence over the region as it is the largest mode of tropospheric circulation variability over the mid- to high latitude Southern Hemisphere where the cold fronts that bring the winter rainfall emanate from. Therefore, this study aims to revisit the SAM-rainfall relationship over the winter rainfall region and the following research questions will be addressed:

1. Has the relationship between SAM and rainfall changed in recent years, and has its teleconnection with ENSO changed?
2. Is the relationship also stable throughout the record?

3. Can the dry conditions in the past three years be explained using the SAM trend in recent years?

3. Data and Methodology

3.1 Rainfall data

Monthly rainfall station data for the Western Cape region were provided by the SAWS for the period April 1979 to June 2017 (**Fig. 2** shows stations location). Due to the strong spatial variability in rainfall, linked to topography, four domains are also selected to further investigate the rainfall patterns (see **Fig. 1**; Midgley *et al*., 2005). The location of the domains represent; **A** the northwest coast (17 stations), **B** south west coast (28 stations), **C** South Coast (13 stations) and **D** the inland (44 stations) domain (**Fig. 2)**. The number of stations in each domain is not the same due to the paucity of stations in some parts of the region. Standardized anomalies were computed per station and averaged for the full Western Cape and sub-domains:

$$\text{Standardized anomaly} = \frac{seasonal\ average - long\ term\ mean}{standard\ \ deviation} \qquad (1)$$

Equation (1) was used to calculate standardized anomalies for the full winter period and different winter trimesters in each spatial domain i.e. for the complete winter (April to September), early winter (April to June), mid-winter (June to August) and late winter (July to September). It should be noted that only the early winter period includes data for the 2017 season.

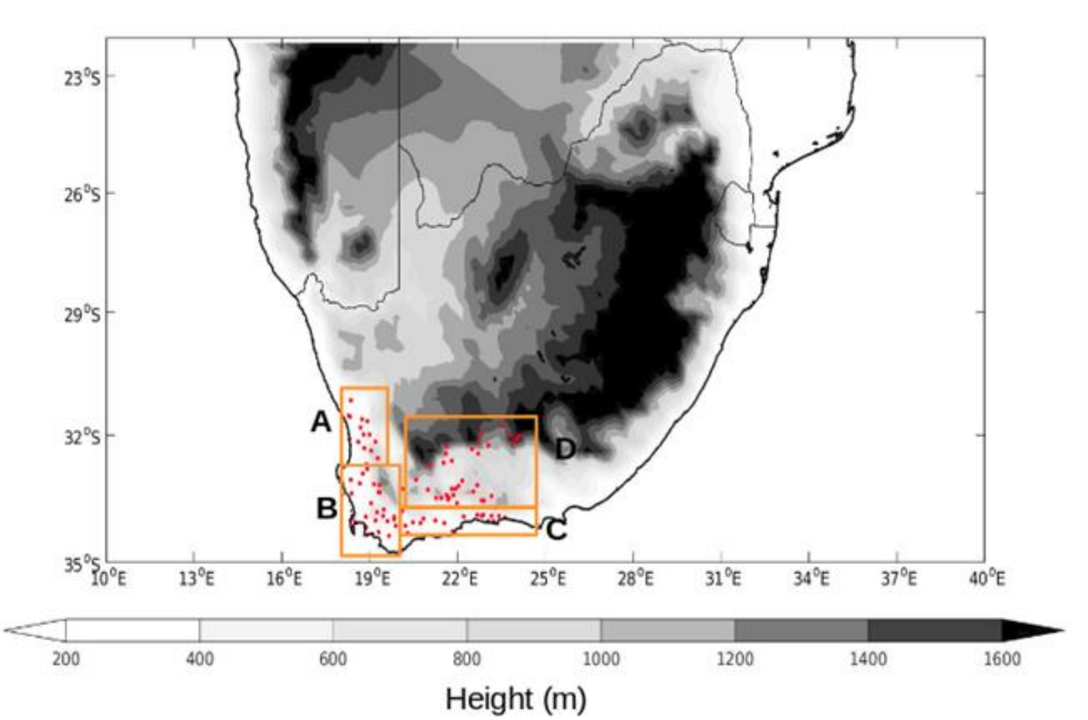

Figure 3: Topography map showing the location of the SAWS stations used for this study. The four domains used to analyse rainfall patterns over the region are also shown. **A** represents the north west coast, **B** south west coast, **C** South Coast and **D** the inland domain.

3.2 SAM and ENSO index

There are a variety of sources of data and methods that can be used to derive the SAM index. For the purpose of this study, the Marshall (2003) SAM index is used to analyse the SAM trend in recent years. This index uses monthly mean differences between the mean sea level pressure (MSLP) anomaly at six stations close to 40°S and six stations close to 65°S. Ho *et al*. (2012) conducted a comparison of different SAM indices in representing the influence of SAM on Australian rainfall. In their study they found that despite representing the same physical process, differences exist in the various indices used to represent SAM, and these are due to the differences in sources of data used, method and variable used. The Marshal index used in this study uses station data, eliminating the influence introduced by changes in observational coverage which results in spurious trends being observed in indices using reanalysis data. Although using reanalysis data has a broader spatial coverage advantage, Marshall (2003) warns that the observed trends in reanalysis strengthen SAM signals by a factor of two or three. The Marshall index is developed using Gong and Wang (1999)'s empirical definition shown in equation (2) and was obtained from the Climate Explorer website[1] available from 1957 to present.

$$\mathrm{SAM} = P^*_{40^\circ S} - P^*_{65^\circ S} \qquad (2)$$

Where $P^*_{40^\circ S}$ and $P^*_{65^\circ S}$ are normalized monthly zonal MSLP at 40° and 65°S, respectively (Marshall, 2003). The index is used to determine winters with a positive or negative SAM phase and correlation coefficients are used to evaluate the strength of the relationship between the two series (rainfall standardized anomalies and SAM index).

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[1] https://climexp.knmi.nl/start.cgi

The ENSO analysis is based on the Nino 3.4 index, also obtained from the Climate Explorer website[1] available from 1856 to present. The Nino 3.4 index is based on the Extended Reconstructed Sea Surface Temperature (ERSST) dataset from the domain 5°N- 5°S, 120°- 170° W in the equatorial Pacific Ocean. The study assumes that both indices (SAM and Nino 3.4) and rainfall are normally distributed making it possible to conduct a Pearson correlation between the two series (i.e. SAM and rainfall). A 10 year running correlation is also conducted between SAM and rainfall to qualitatively evaluate the decadal change in strength of relationship between the two variables.

Geopotential heights at 500 hPa and 850 hPa from the National Centres for Environmental Prediction-National Centre for Atmospheric Research (NCEP-NCAR) reanalysis dataset (Kalnay *et al*., 1996) are used to compute monthly anomalies for the 2015 and 2016 winter season. Although it is not regarded as the most advanced reanalysis product currently available, it produces an adequate reconstruction of South Africa historical climate and is widely used in climate research. Composites for the six driest years in each period are also obtained to investigate associated anomalies in the regional circulation patterns. The 2015 and 2016 winter seasons are investigated separately to determine whether they show similar patterns. The National Oceanic and Atmospheric Administration (NOAA) 1/4° daily Optimum Interpolation Sea Surface Temperature (OISST) is obtained and monthly averages are computed to obtain seasonal anomalies. This dataset is available from 1981 to present (Reynolds *et al*. 2007).

4. Results

4.1 Rainfall variability

The SAWS station data shows a considerable interannual variability in winter rainfall over the Western Cape region (**Fig. 4**). Standardized anomalies are used as a measure of the departure from the mean for rainfall that fell for (a) the whole winter, (b) early winter, (c) mid-winter and (d) late winter for each year for the period 1979 to 2016 (2017 for b, the early winter). **Table 1** shows the six driest (< -1 standardised anomalies) and six wettest (> 1 standard standardised anomalies) for each time period. There are persistent periods of dry conditions between 1996 and 2000 for the complete and mid- and late winter over the full domain. The early winter (**Fig. 4b**) shows a similar period of consecutive dry years between 1999 and 2005. Notable the last three years have received lower than average rainfall (2015 to 2017) for the early winter. Overall, **Fig. 4** highlights that there is no uniformity in rainfall conditions in the same winter year for the different timescales (complete winter, early winter, mid-winter and late winter). For instance, the complete and early winters of 2015 received below average rainfall while mid and late winter in the same year shows above average rainfall. However, it is reminded that these figures are produced from all the stations within the domain, including the Southern Cape (domain **C** in **Fig. 3**), which tends to get more rainfall during the autumn / spring period.

The sub-domains highlight a high degree of temporal variability in winter rainfall over the region. Although all these domains (see **Fig. 3** for location) form part of the Western Cape region, they demonstrate a high level of spatial variability in the region. There is generally no uniformity in rainfall received in the same winter year at different domains. For instance, for the full winter in 2015, below average rainfall was received over the southern part of the West Coast (**Fig. 5a**) while the South Coast domain (**Fig. 6a**) received above average rainfall in the same year.

Most notable, all domains show considerable intraseasonal variability, i.e. the early winter is wet compared to the mid-winter and late winter over the South Coast (**Fig. 6**). The severity of the dryness or wetness in these domains also differs and this displays the rainfall gradient that exists in the winter rainfall region as highlighted by Midgley *et al*. (2005). The station data also reveal that the South Coast (mid and late winter) shows a persistent pattern of below average rainfall since the 1990's. All domains show persistent periods of dry conditions between 1995 and 2000.

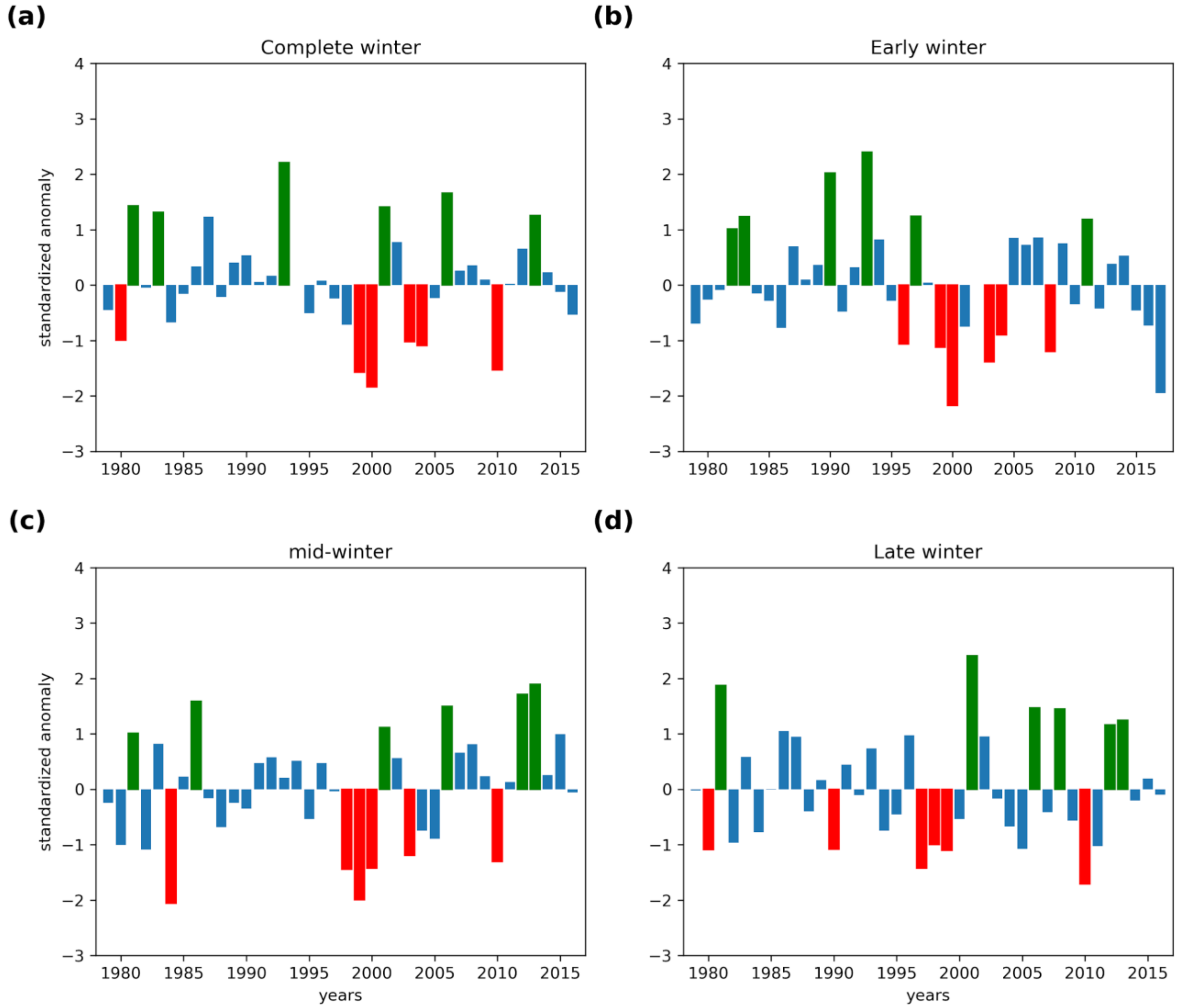

Figure 4: Winter rainfall standardized anomalies (bars) of the full Western Cape region during 1979 to 2016 for the (a) complete winter, (b) the early winter (c) mid-winter, (d) late winter periods. Note that only (b), the early winter, contains rainfall data for 2017. The six driest (red) and wettest (green) winters are highlighted for each period.

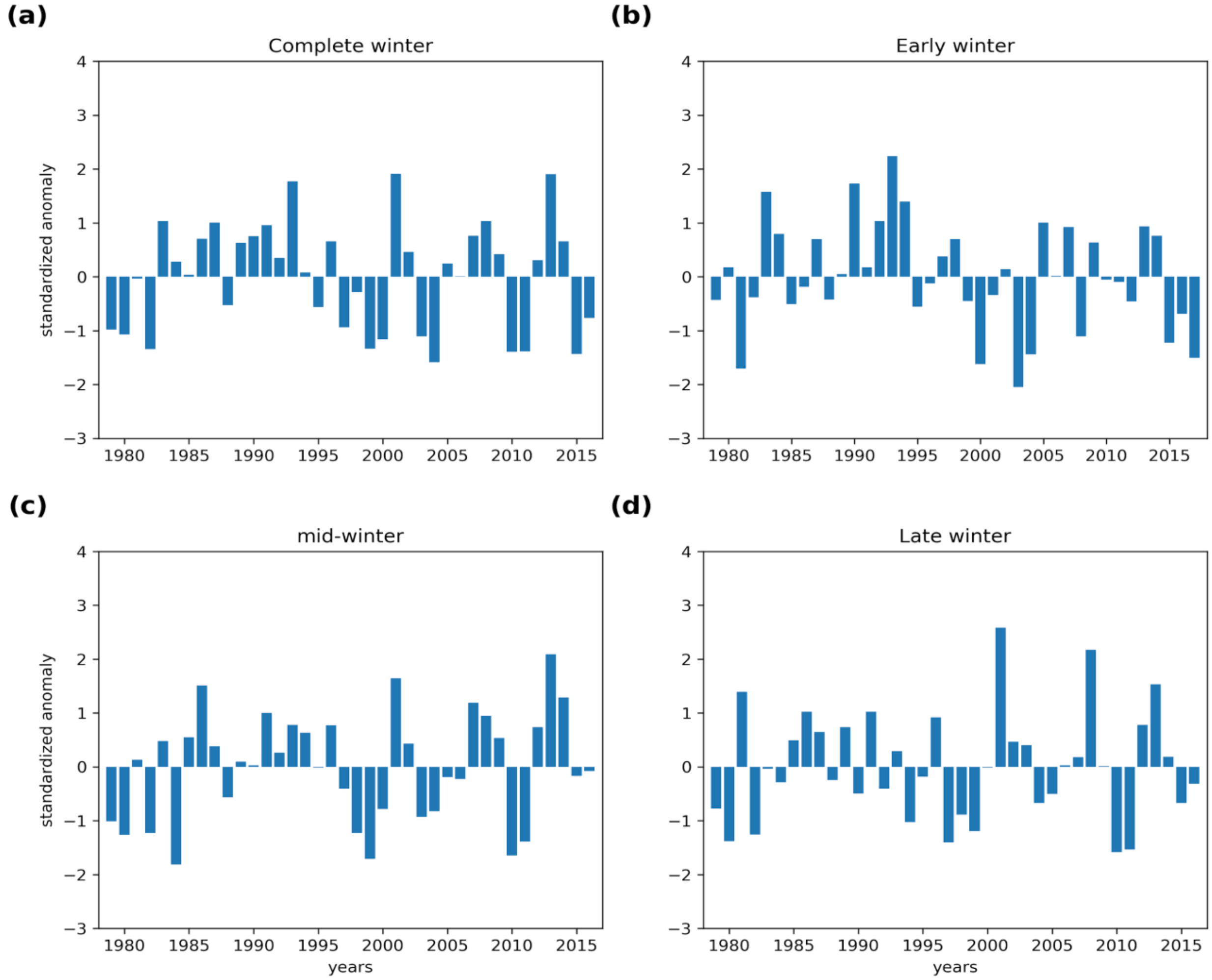

Figure 5: Same as **Fig. 4,** but for the southern West Coast (domain **B**).

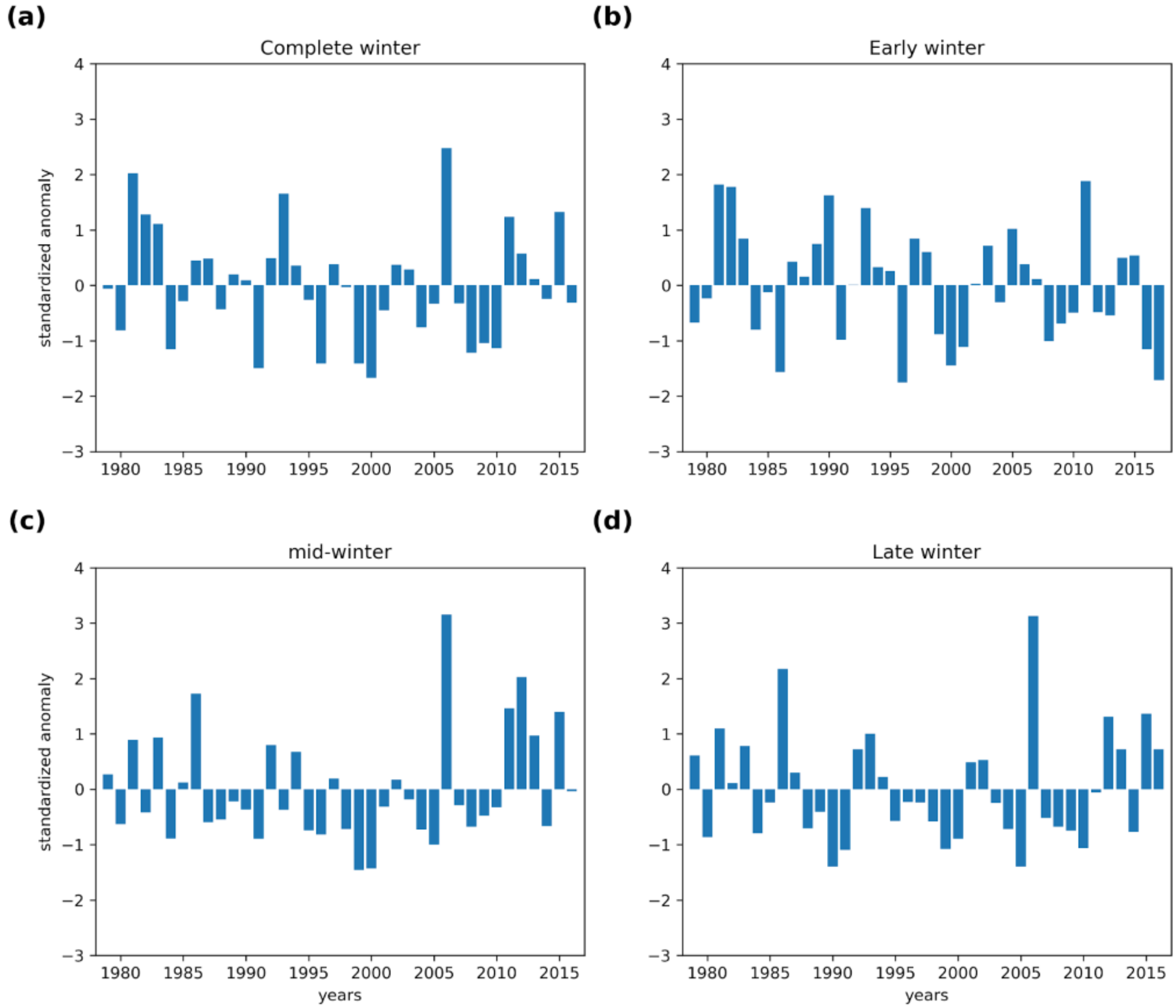

Figure 6: Same as **Fig. 4,** but for the South Coast (domain **C**).

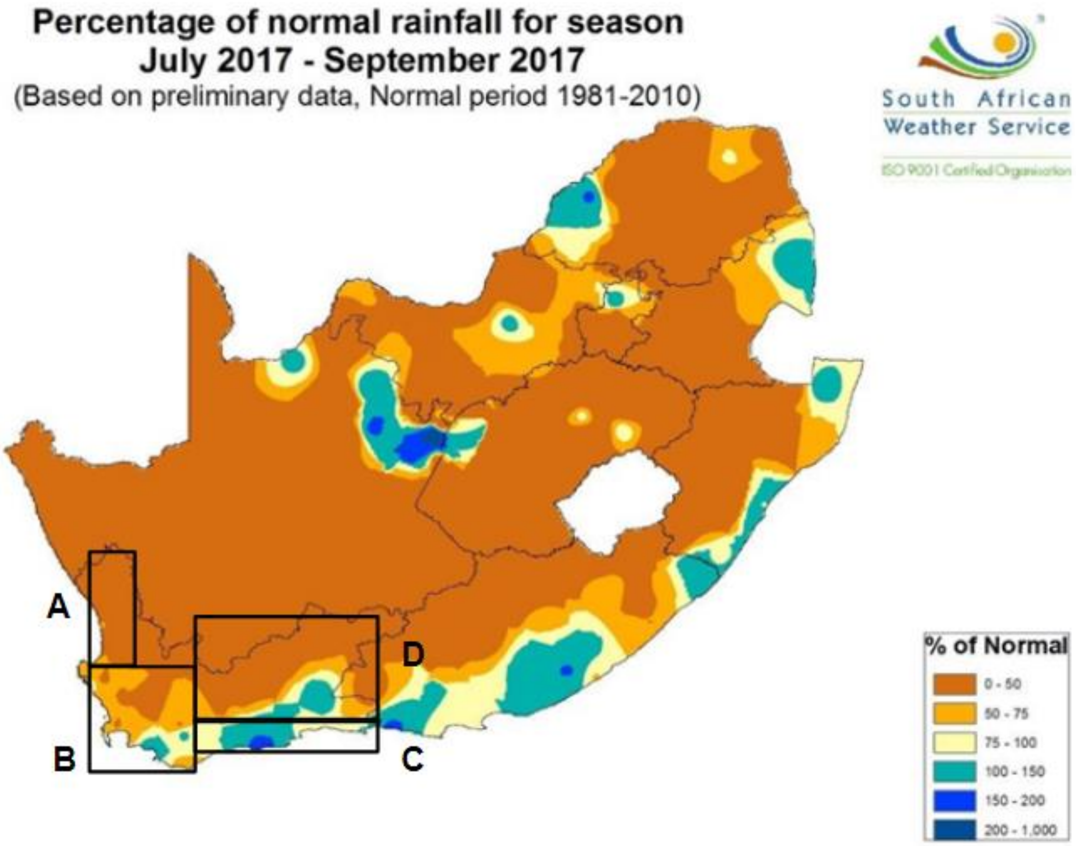

Figure 7: Spatial rainfall distribution shown as a percentage of normal rainfall (shaded) for the late winter period (July to September 2017). Provided by SAWS (website accessed on 05/02/2018).

Table 1: The six wettest and driest years for each time period

Winter Period	Top 6 Dry Years	Top 6 Wet Years
Full	1980, 1999, 2000, 2003, 2004, 2010	1981, 1983,1993, 2001, 2006, 2013
Early	1996, 1999, 2000 2004, 2010, 2017	1982, 1983, 1990, 1993, 1997, 2011
Mid	1984,1998,1999, 2000, 2003, 2010	1981, 1986, 2001 2006, 2012, 2013
Late	1980, 1990, 1997 1998, 1999, 2010	1981, 2001, 2006, 2008, 2012, 2013

The Western Cape region experienced dry conditions over the past three years (2015 to 2017). Unfortunately, SAWS station data was not received in time to provide a complete analysis of the entire 2017 winter and hence **Fig. 7** was downloaded from the SAWS website to show conditions for July-September 2017. In general, the results show that although the rainfall anomalies differ between the domains, each was affected during some parts of the winter periods during 2015-2017. The start of the rainy season (April to June) was the second driest in 2017 over the full domain (**Fig. 4**). The sub-domains demonstrate spatial variability. For example, the 2017 early winter was dry in all domains, 2015 was dry over the southern part of the West Coast, South Coast and inland domains (shown in appendix) , while 2016 was dry over all regions with an exception of the northern part of the West coast. The dry conditions persisted throughout the full winter period over the West Coast domains (**Figs. 5** and **7**) while the South Coast (**Figs. 6** and **7**) and inland received some rainfall relief during the mid and late winter. It is also evident that this is not the longest period of dry conditions over the South Coast domain. Similar conditions have been observed for the early winter between 1998 and 2005.

4.2 Rainfall and the SAM

The Marshall (2003) index and standardized rainfall anomalies are shown in **Fig. 8** for the full Western Cape domain, the correlation at zero lag between the two series is shown for each season. Five of the six dry years for the complete winter occurred during a positive SAM phase and three of the six wet years occurred during a negative SAM. The series also shows that SAM has mainly been in the positive phase since 1995, particularly during the early winter trimester. Consecutive dry years are identified to be associated with the protracted positive SAM conditions. There tends to be a better link between dry conditions to a positive SAM compared to wet winters to the negative SAM phase. The winter of 1993 for instance is the wettest winter in record for the full winter period and its associated with a positive SAM phase, other factors like the strong El Nino event experienced over the region during this season could have contributed to the observed wet condition. A statistical analysis on the rainfall anomalies and SAM index series shows that a positive correlation exists between rainfall and SAM in winter (complete winter) over the full domain (**Fig. 8a**). The correlation between the two series is found to be stronger for the early winter (-0.180) in comparison to the mid (-0.060) and late winter (-0.072); however, none of these are statistically significant at 95%.

The sub-domains show spatial variations in the SAM - rainfall relationship, for the northern West Coast (**Fig. 9**), the relationship is found to be anti-correlated and stronger for the late winter (-0.306) than for the early winter (-0.176) and mid-winter (-0.191). The South Coast (**Fig. 10**) and inland domains (in appendix) show a positive correlation between SAM and rainfall. A stronger correlation is observed in late winter over the South Coast domain. Rainfall and SAM are found to be strongly correlated over the West Coast for the full winter (-0.3) compared to the south coast and interior (0.2) regions. The SAM and rainfall standardized anomalies series highlights intraseasonal and spatial variations in the strength of the relationship.

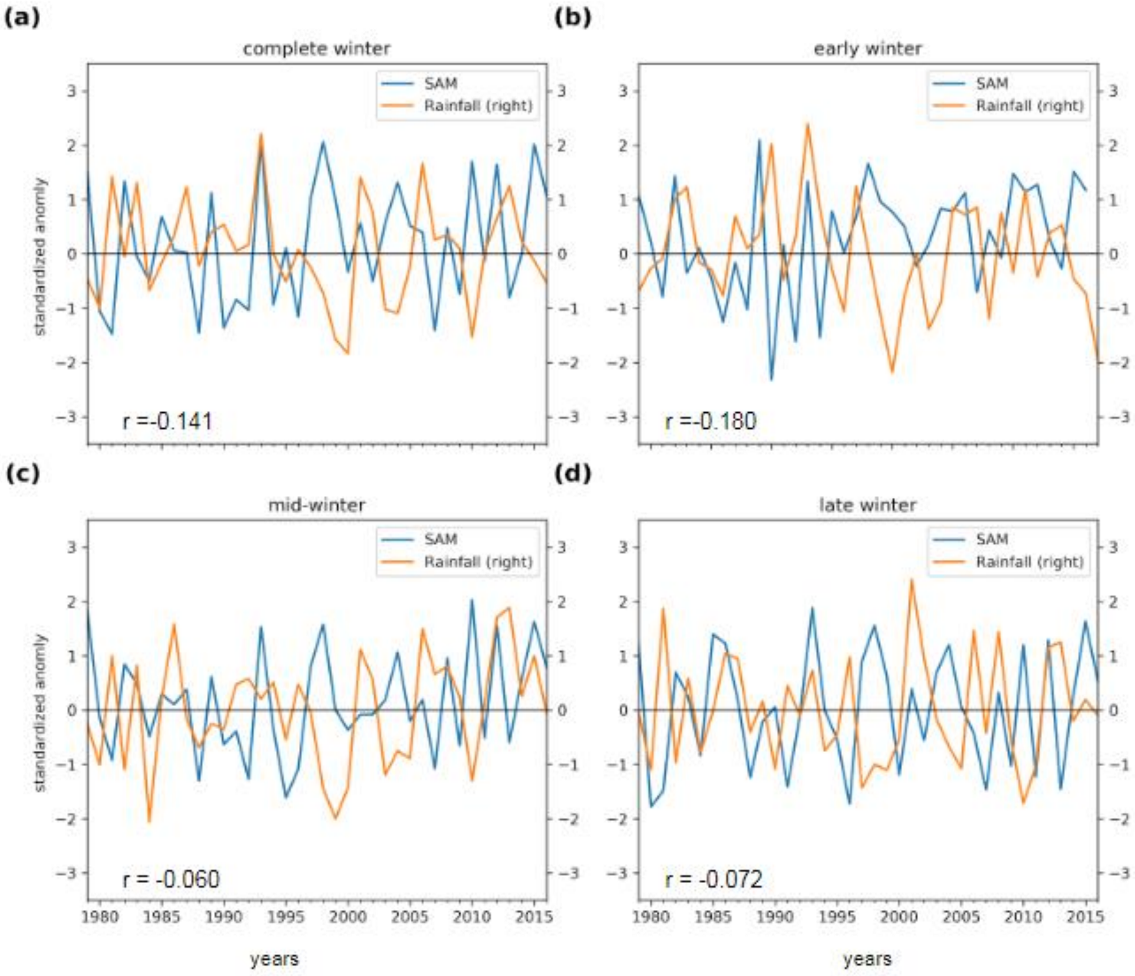

Figure 8: Rainfall anomalies for the winter season over the full Western Cape domain (orange) during 1979 to 2016, and the SAM index (blue) for the same period. The panels illustrate series for (a) the complete winter, (b) early winter, (c) mid-winter and (d) late winter period. The correlation coefficient (r) between the two indices is given for each panel in the bottom left corner.

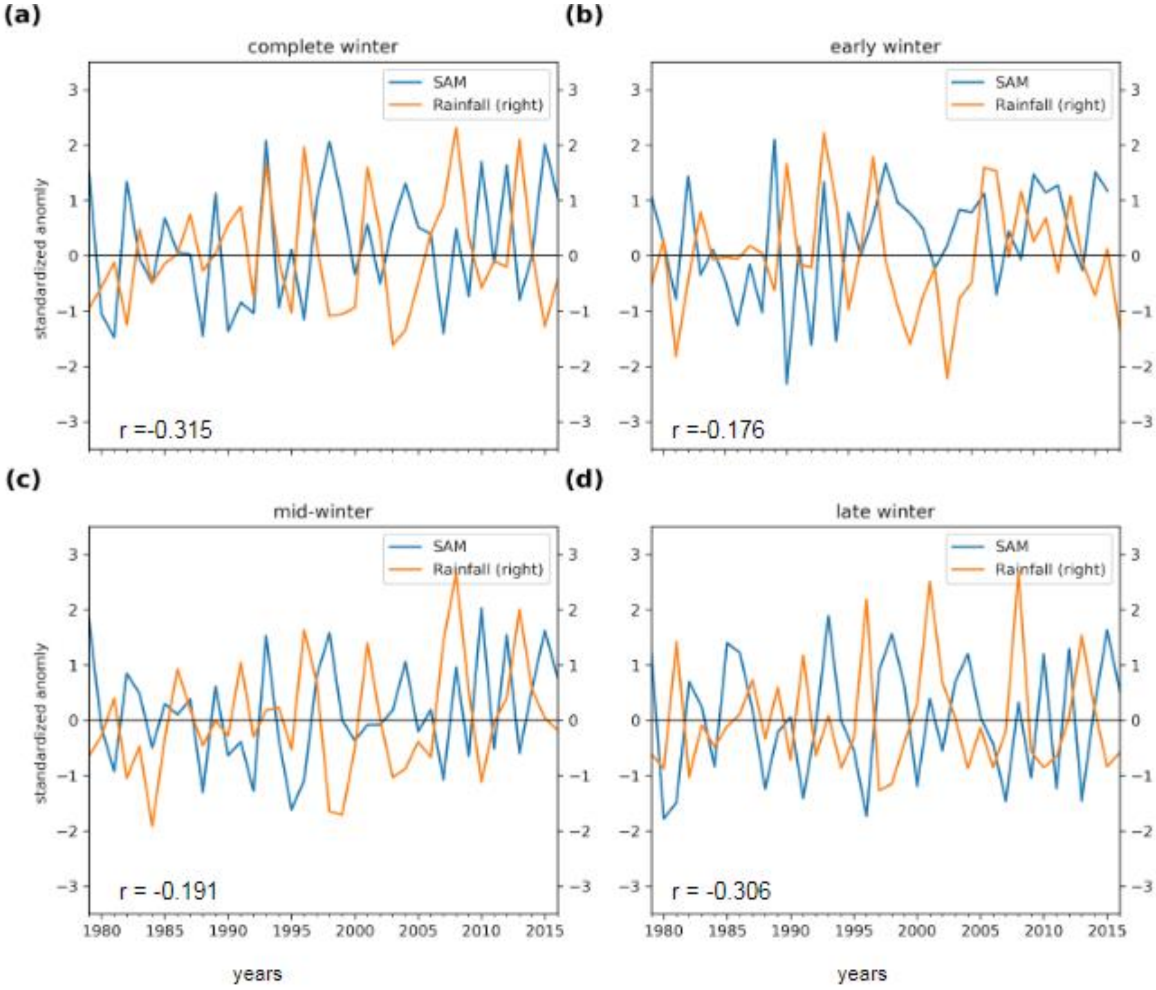

Figure 9: Same as **Fig. 8,** but for the northern Western Cape domain (domain **A**).

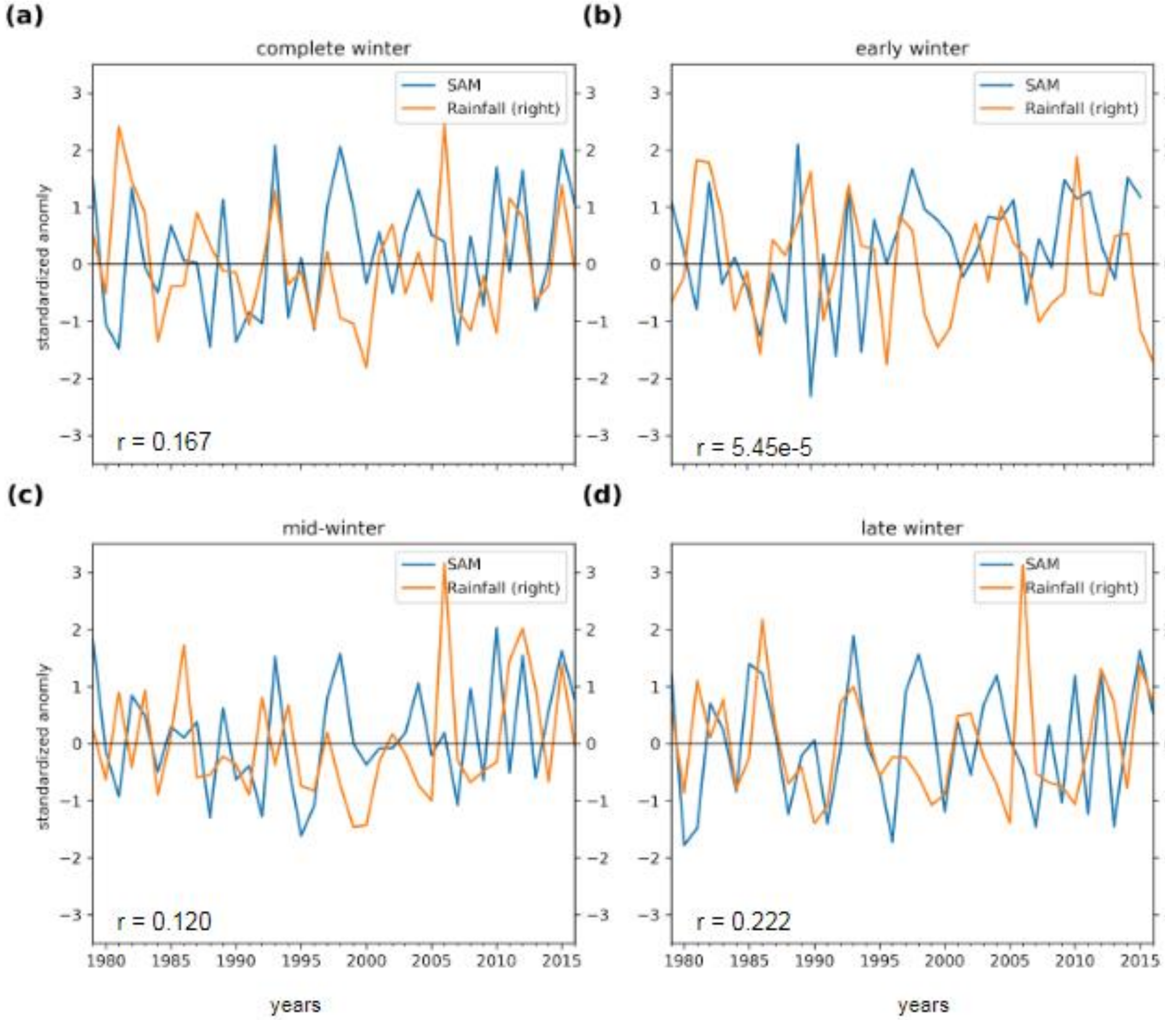

Figure 10: Same as **Fig. 8**, but for the South Coast domain (domain **C).**

4.3 Decadal relationship between rainfall and SAM

The previous section highlighted the intraseasonal and spatial variation in the relationship between the SAM and winter rainfall. To investigate the decadal variations in the SAM - winter rainfall relationship, a running correlation method was employed with a 10-year window. A two-paired student t-test was conducted to test whether the relationship is statistically significant at the 95% significance level only. The resulting running correlation coefficients between rainfall standardized anomalies and SAM for the full Western Cape domain, south West Coast and South Coast are illustrated in **Figure 11**. The years indicated on the x-axis show the last year of the running correlation width. Therefore, the value 1990 on the horizontal axis represents the correlation value computed over the years ranging from 1981 to 1990. The early winter for the full domain (**Figure 11a)** shows the correlation for the full winter was low before the early 1990s, then it increased rapidly to positive 0.7 between 1994 and 1998, and thereafter it decreases drastically. In the early 2000s, it became negative reaching values of about -0.4 after about 2008. Thus, the decadal relationship between SAM and rainfall for the complete winter is not stable over the full domain and has changed from strongly positive in the early period to moderate to strongly negative in the latter part of the period. Only during 1994-1998, does the relationship become statistically significant at the 95% level. For the shorter winter periods, the correlation values also vary and change sign but never reach significance (**Figs. 11b-d**).

Over the southern West coast for the complete winter, the relationship changes are similar as that seen above for the full domain (full domain vs southern West coast). Again, there are changes for the shorter winter periods but none of the correlations are ever significant at 95% (**Figs. 11b-d**). Taken over the complete winter, the South Coast (**Fig. 11a**) shows a positive correlation between SAM and rainfall for most of the period but weakens to almost zero during 2007-2013. Only around the late 1990s does it become significant. A short period around 1995 also shows a significant correlation for the late winter (**Fig. 11d)** but otherwise there are generally weak correlations which change sign for the other winter periods (**Fig. 11b-d**).

Thus, the relationships are found to be statistically insignificant for most of the sub-domains, with an exception of the early winter over the southern part of the West Coast which shows a strong anti-correlation of 0.7 after 2015. A positive correlation between SAM and rainfall is observed over the South Coast and inland domains for the winter period, while the SAM and rainfall relationship is found to be anti-correlated over the West Coast. Furthermore, the relationship is found to be stronger for the late winter (0.4) in comparison to the early and mid-winter (0.2) in recent decades for the South Coast and inland domains, while the West coast domains show a stronger relationship during the early winter (-0.6) compared to the mid and late winter.

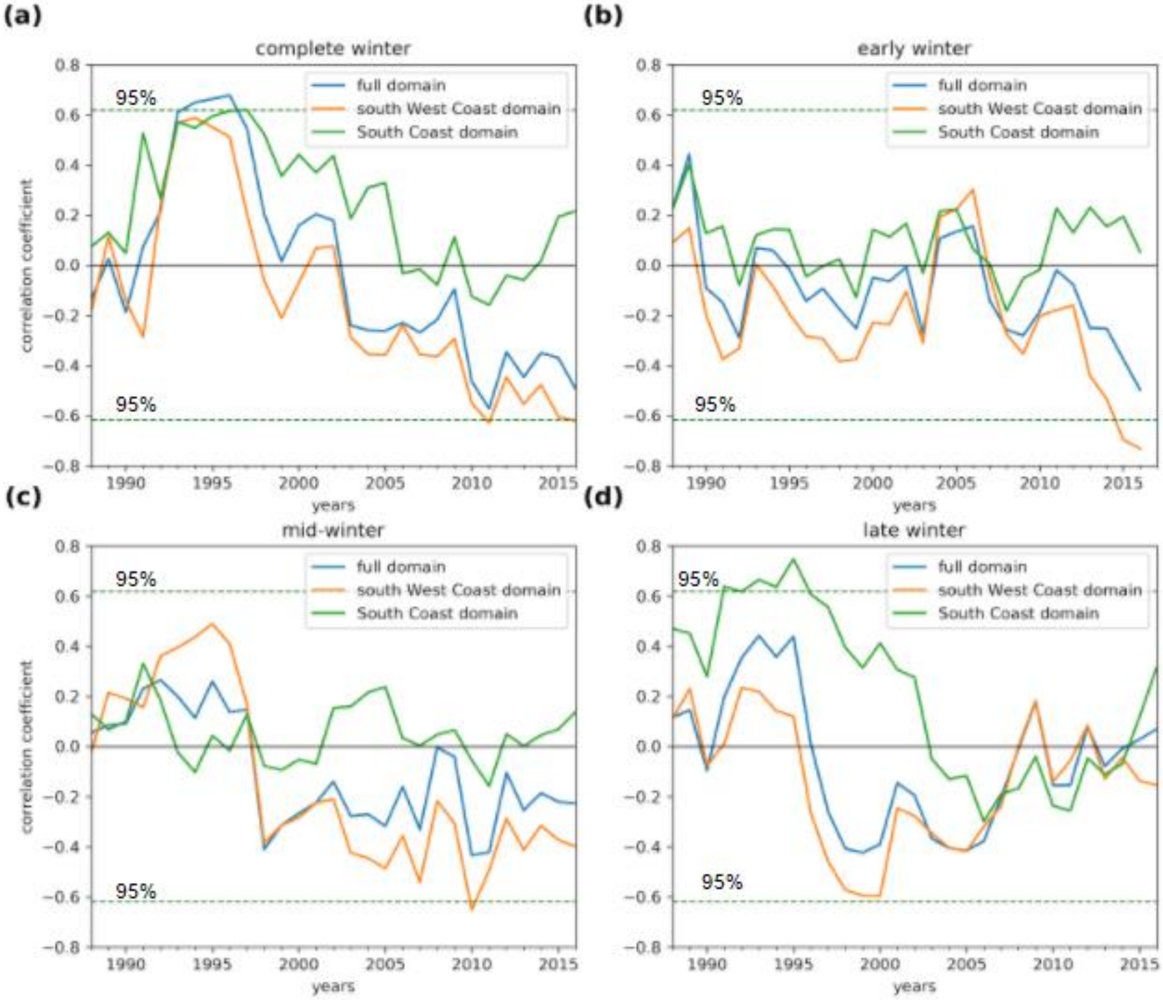

Figure 11: The 10 year running correlation coefficients between the SAM and rainfall for the Western Cape region (blue), south west coast (orange) and south coast (green) during 1979 to 2016. Panels illustrate (a) the complete winter, (b) early winter, (c) mid-winter and (d) late winter series. The dashed horizontal lines represent the confidence intervals using a two-tailed Student’s t test.

4.4 Rainfall and ENSO

The Nino 3.4 index and standardized rainfall anomalies are shown in **Fig. 12** for the full Western Cape domain, the correlation at zero lag between the two series is shown for each season. The strongest (> 2 standardised anomalies) El Niño events occurred during 1983, 1992, 1998 and 2015, while the most intense La Niña events occurred during 1989, 2000 and 2008. Two of the four strongest El Niño events are found to have a positive rainfall response, and one of the three strongest La Niña events are found to have a negative rainfall response. A correlation analysis between the two series shows they are negatively correlated during the mid and late winter over the full domain and a positive correlation is observed for the early winter. The relationship is found to be strong during the early winter for the full domain. The sub-domains illustrate spatial variability on the ENSO influence on rainfall. The West Coast shows (**Fig. 13**) a negative correlation between ENSO and rainfall, with an exception of the early winter over the northern part of the West Coast. The relationship is slightly stronger for the late winter (-0.29) compared to the early and mid-winter. A positive correlation between rainfall and ENSO is observed for the South Coast (**Fig. 14**). Overall the correlation between ENSO and winter rainfall is seen to be very weak.

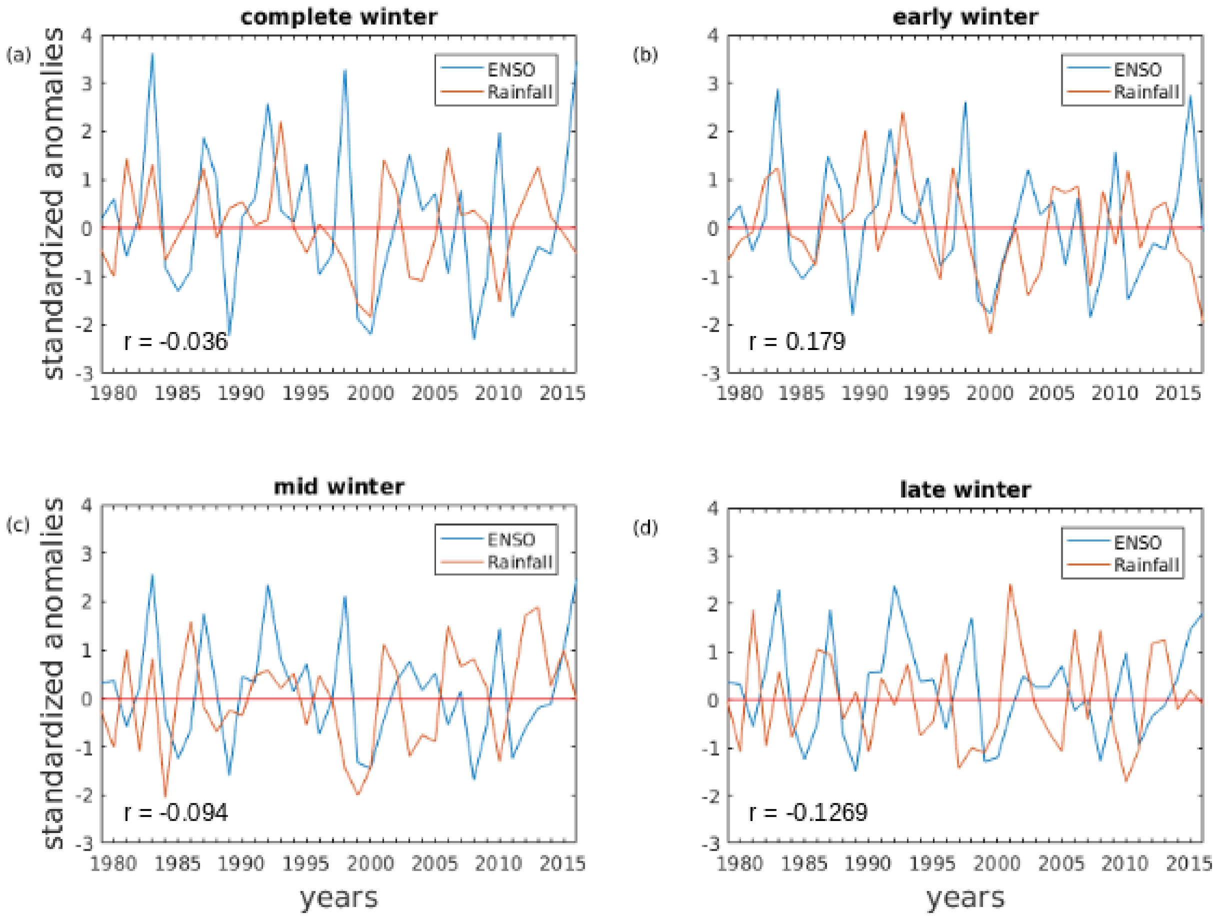

Figure 12: Rainfall anomalies over the full Western Cape domain (red, secondary y-axis), and the Nino 3.4 index (blue, primary y-axis) for the (a) complete winter, (b) early winter, (c) mid-winter and (d) late winter period. The analysis period is 1979 to 2016 for the complete, mid-winter and late winter, and 1979 to 2017 for the early winter. The correlation coefficient (r) between the two indices is given for each panel in the bottom left corner.

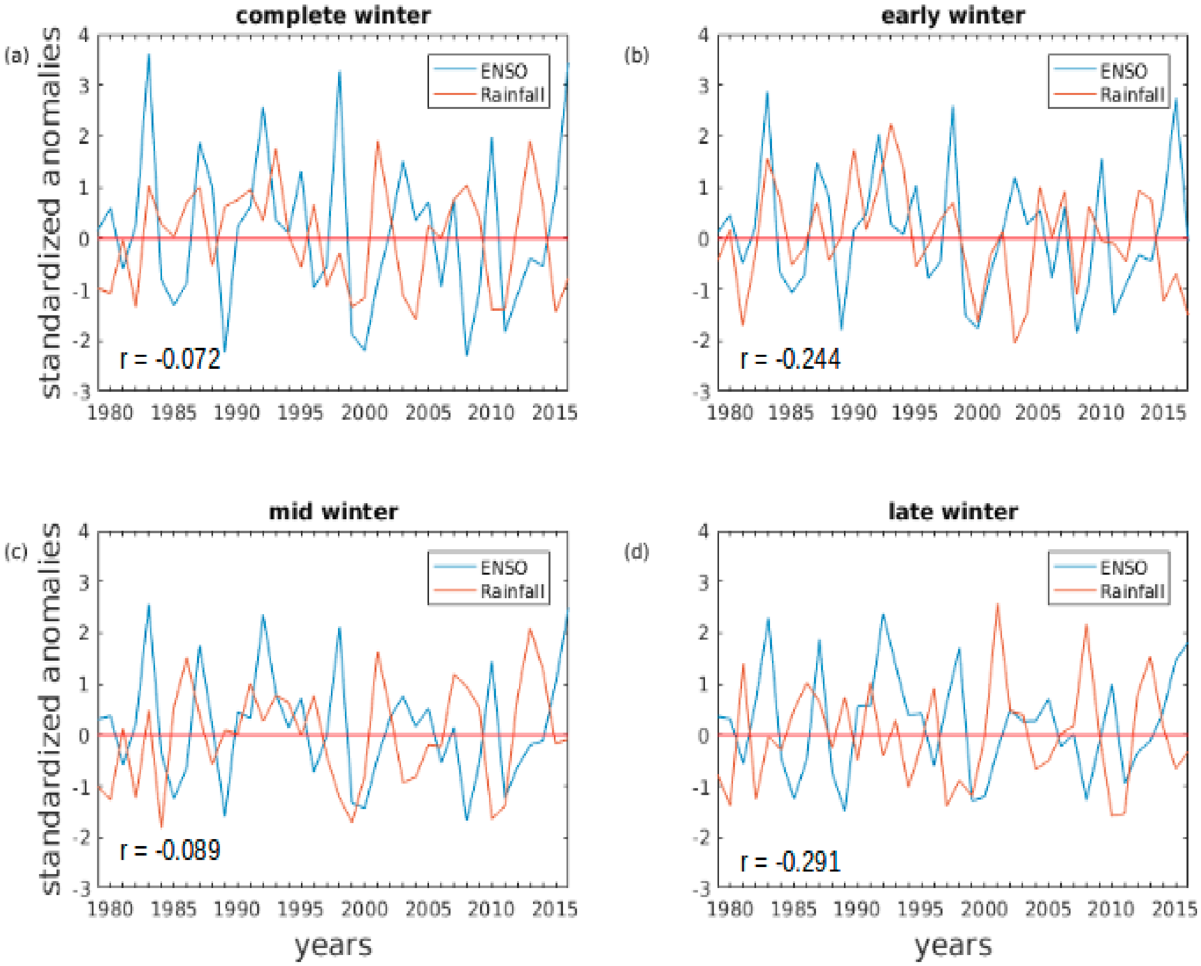

Figure 13: Same as **Fig. 12,** but for the southern West Coast domain.

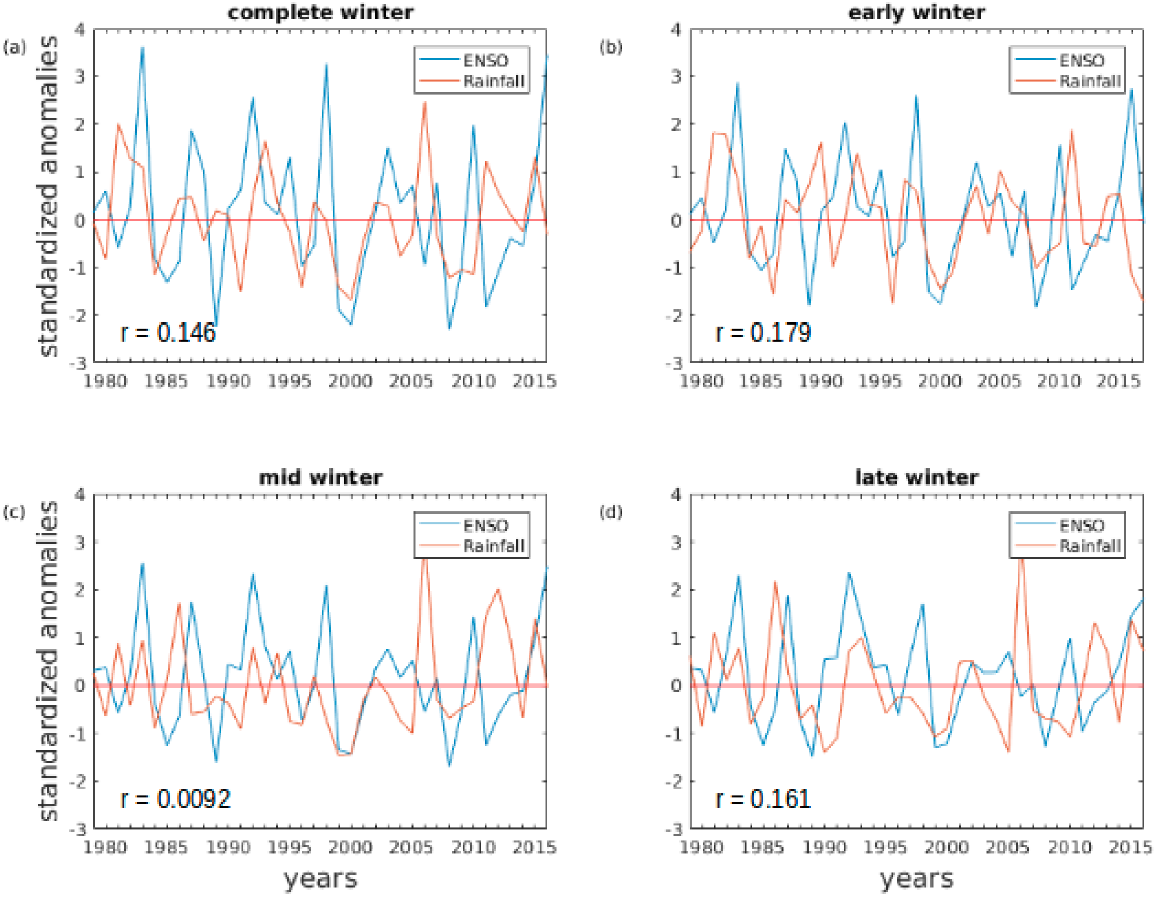

Figure 14: Same as **Fig. 12,** but for the South Coast domain.

Tables 3 and **4** shows the six driest and wettest years, respectively, for the full domain. The SAM and ENSO phase for each year is also shown. Pohl *et al*. (2010) show that El Niño (La Niña) events tend to correspond to a negative (positive) SAM phase, leading to an increase (decrease) in rainfall. Furthermore, these authors suggest that this relationship is statistically significant when seasonal mean fields are averaged for November to February. The results here suggest a weak correspondence between SAM and ENSO for the winter season. The winter of 1999 and 2017 show similar conditions of the six dry years, while of the six wet years 1983 corresponds to the SAM and ENSO suggested by Pohl *et al.* (2010). This highlights a weak correspondence between the SAM and ENSO teleconnections.

Table 2: Dry years and their corresponding SAM and ENSO state. "+ve" and "-ve" represent a positive and negative phase, respectively.

Dry years	SAM	ENSO
1998	+ve	+ve
1999	+ve	-ve
2000	-ve	-ve
2004	+ve	+ve
2010	+ve	+ve
2017	+ve	-ve

Table 3: Wet years and their corresponding SAM and ENSO state. “+ve” and “-ve” represent a positive and negative phase, respectively.

Wet years	**SAM**	**ENSO**
1981	-ve	-ve
1983	-ve	+ve
1993	+ve	+ve
2006	+ve	-ve
2012	+ve	-ve
2013	-ve	-ve

4.5 Circulation patterns

The SST composites for the six driest (wettest) winters were analysed (**Fig. 15**)**.** The winter SST composite shows that, dry (wet) conditions over the Western Cape region are associated with negative (positive) SST anomalies over the Equatorial Pacific and positive (negative) SST anomalies over the West Coast of South Africa. Rouault *et al*. (2010) shows that during La Niña (El Niño) events the wind speed over the West Coast is stronger (weaker) causing the observed SST anomalies over the region. Furthermore, Reason and Jagadheesha (2005) show that the atmospheric circulation is sensitive to SST changes over the South Atlantic during the winter season. The atmospheric response is associated with changes in the strength and position of the westerly wave, convergence of moisture and latent heat flux, and relative vorticity which leads to changes in rainfall over the Western Cape region (Reason and Jagadheesha, 2005).

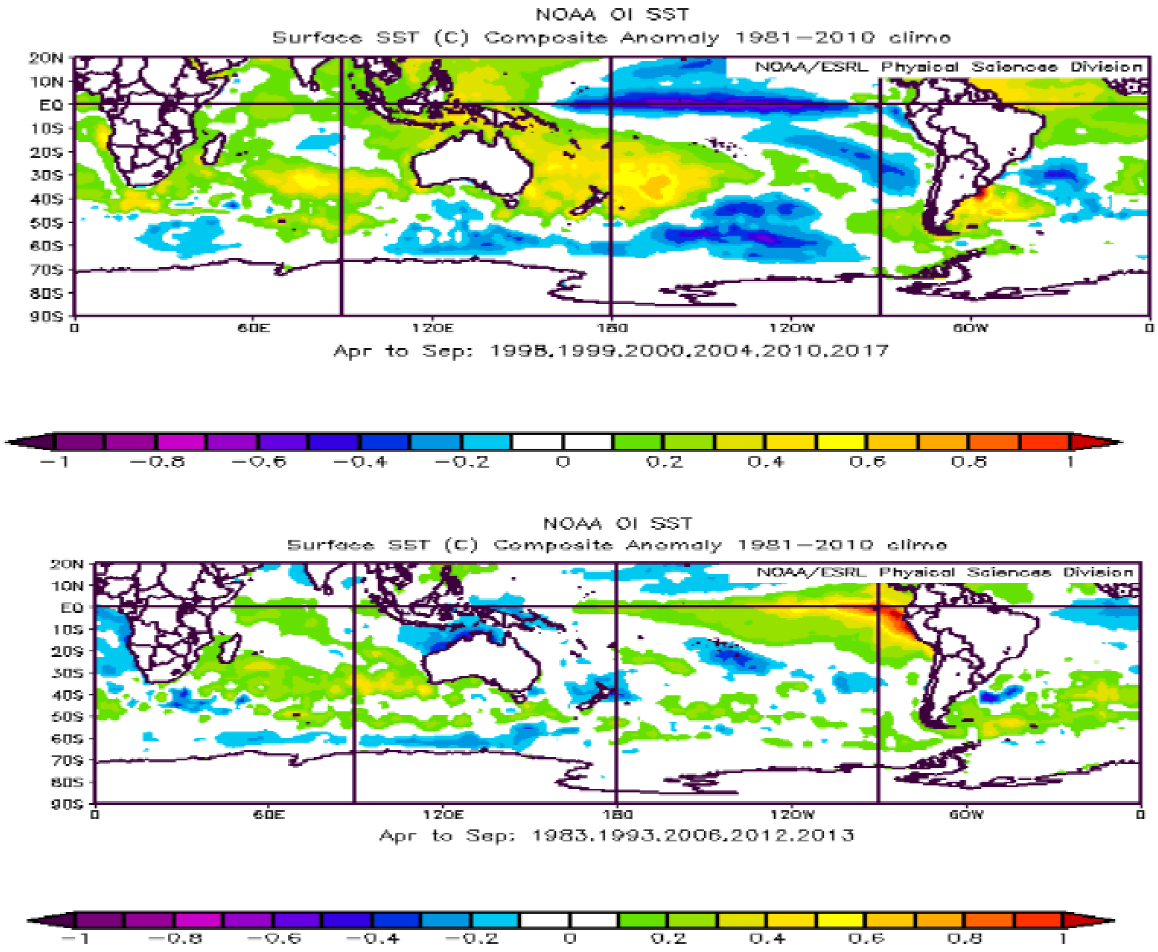

Figure 15**:** SST composite anomalies for the six driest (top) and the six wettest (bottom) winters, the full winter period is shown. The NOAA OISST dataset is used.

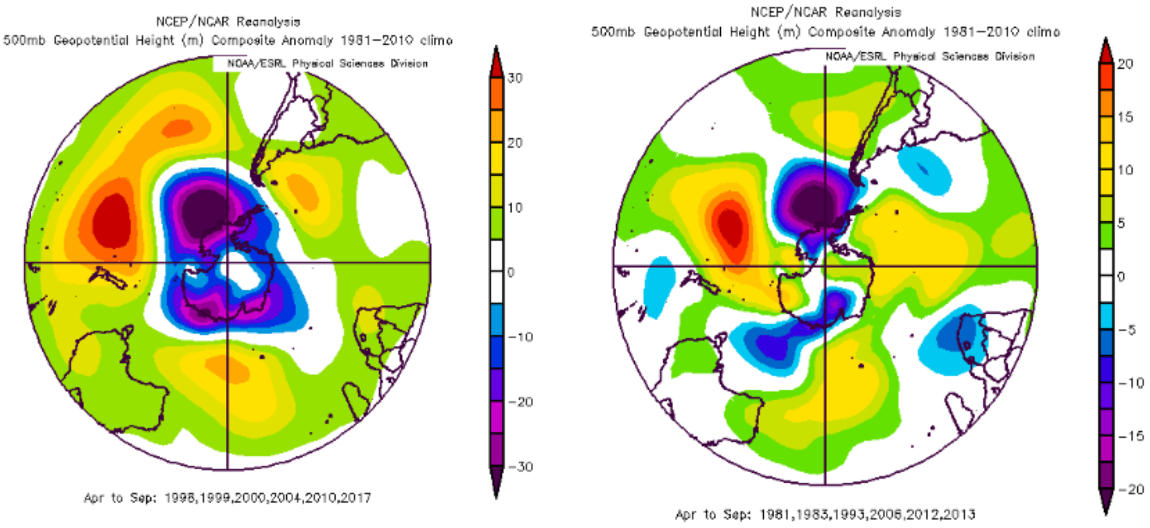

***Figure 16*:** Geopotential height composite anomalies for the full winter (April to September) at 500 hPa, for the six driest (left panel) and wettest (right panel) winters.

The composite dry and wet winter 500 hPa geopotential height anomalies over the Southern Hemisphere are shown in **Fig. 16**. The dry winter composite shows negative (positive) geopotential heights over the polar caps (midlatitudes), these conditions are typical of a positive SAM phase. Furthermore, there are positive pressure anomalies over the south West Coast which causes increased subsidence blocking frontal systems from reaching the land. The wet winter composite is characterised with negative pressure anomalies over the SW Atlantic an important area for cyclogenesis. The West Coast of South Africa also associated with cyclonic anomalies which, due to the decreased, subsidence allows passage of frontal systems (Reason *et al*., 2002).

4.6 Evaluating the 2015 to 2017 dry conditions

The SAWS data shows that the full Western Cape domain (**Fig. 4**) has had consecutive years of dry conditions in the past three years. These dry conditions are found to be severe during the early winter trimester in comparison to the mid and late winter. Of the three years, 2017 was the driest and is recorded as the second driest year for the early winter (over the past 38-year period). The sub-domains illustrate spatial variability; there is no uniformity in rainfall conditions on the same year. The West Coast domains (**Fig. 5**) received below average rainfall for the three years during the early winter trimester while the South Coast shows below average rainfall for the last two years. The dry conditions persisted for the full winter period over the West Coast while the South Coast received some rainfall relief during the mid and late winter (**Fig. 6**). The South Coast is also influenced by summer rainfall which could be the contributing factor to the rainfall relief. Rainfall is mostly brought by cold fronts over the region, Midgley *et al*. (2012) projected a drying trend in winter rainfall over the Western Cape region from west to east, associated with a weakening in winter rainfall and an increase in summer rainfall over the eastern part of the province (Midgley *et al*., 2012). The findings in this study shows that the West Coast is wet compared to the South Coast. The South Coast is found to be prone to protracted periods of dry conditions, particularly during the mid- and late winters.

The past three years are associated with a positive SAM phase which, as highlighted earlier, is typically characterised by dry conditions over the region. An analysis of the SST conditions for the surrounding and Equatorial Pacific oceans was conducted for the early, mid and late winter for the last three years (**Fig. 17** to **19**). The results show strong positive SST anomalies over the Equatorial Pacific throughout the winter season in 2015, which was associated with a strong El

Niño event. Negative SST anomalies are observed over the West Coast in the same year. A negative correlation has been found to exists between rainfall and SST anomalies over the West Coast, negative (positive) SST anomalies are recorded when rainfall was above (below) normal on land (Reason and Jagadheesha, 2005; Rouault *et al.*, 2011). This suggests that the above average rainfall received during the year 2015, particularly over the South Coast was due to the ENSO influence on local SST. The winters of 2016 and 2017 were associated with negative SST anomalies over the Equatorial pacific for the mid and late winter and positive SST anomalies over the West Coast. Furthermore, the South Atlantic shows negative SST anomalies during these two years, and as alluded to previously, this region is important for cyclogenesis. Positive (negative) SST anomalies favour an increase (decrease) in cyclogenesis which leads to an enhancement (decrease) in rainfall over the region (Reason *et al.*, 2002).

The atmospheric circulation patterns along the midlatitudes are shown to respond to SST changes over the Atlantic. Geopotential height anomalies at 500 hPa (**Fig. 20**) shows similar patterns observed during dry periods over the Southern Hemisphere. Negative pressure anomalies lie over Antarctica while positive pressure anomalies are observed over the midlatitudes. During wet winters the pressure anomalies are thought to cause an equatorward shift in the jet bringing stronger storm tracks and westerly troughs while during dry winters there is a slight southward shift of the jet leading to the dry conditions on land (Reason and Rouault, 2005, Gillet *et al.*, 2006).

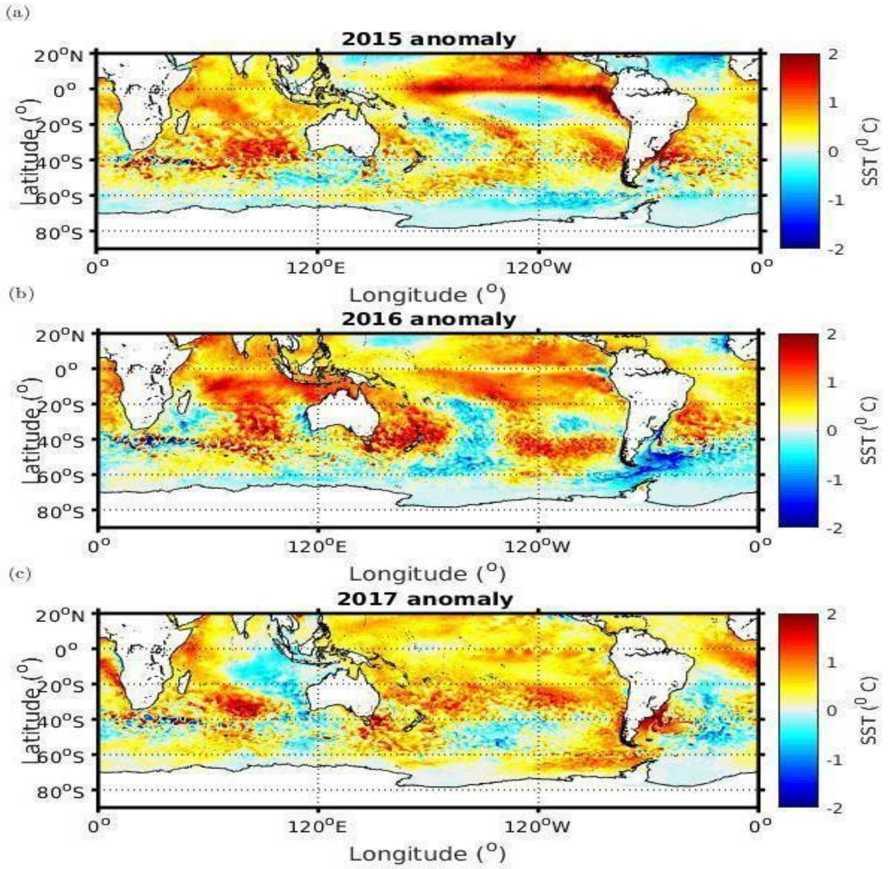

Figure 17: Global SST anomalies for the early winter (April to June) for (a) 2015, (b) 2016 and (c) 2017. The NOAA OI SST dataset was used.

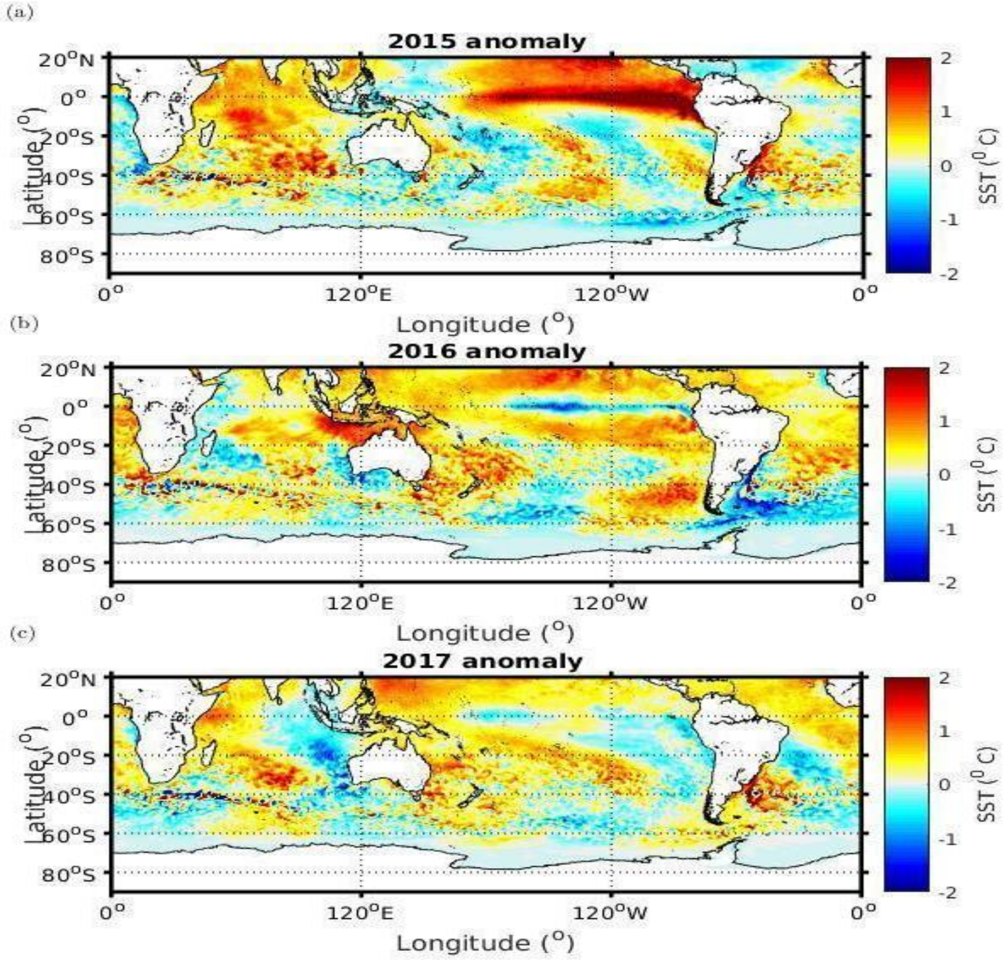

Figure 18: Same as **Fig. 17**, but for the mid-winter (June to August).

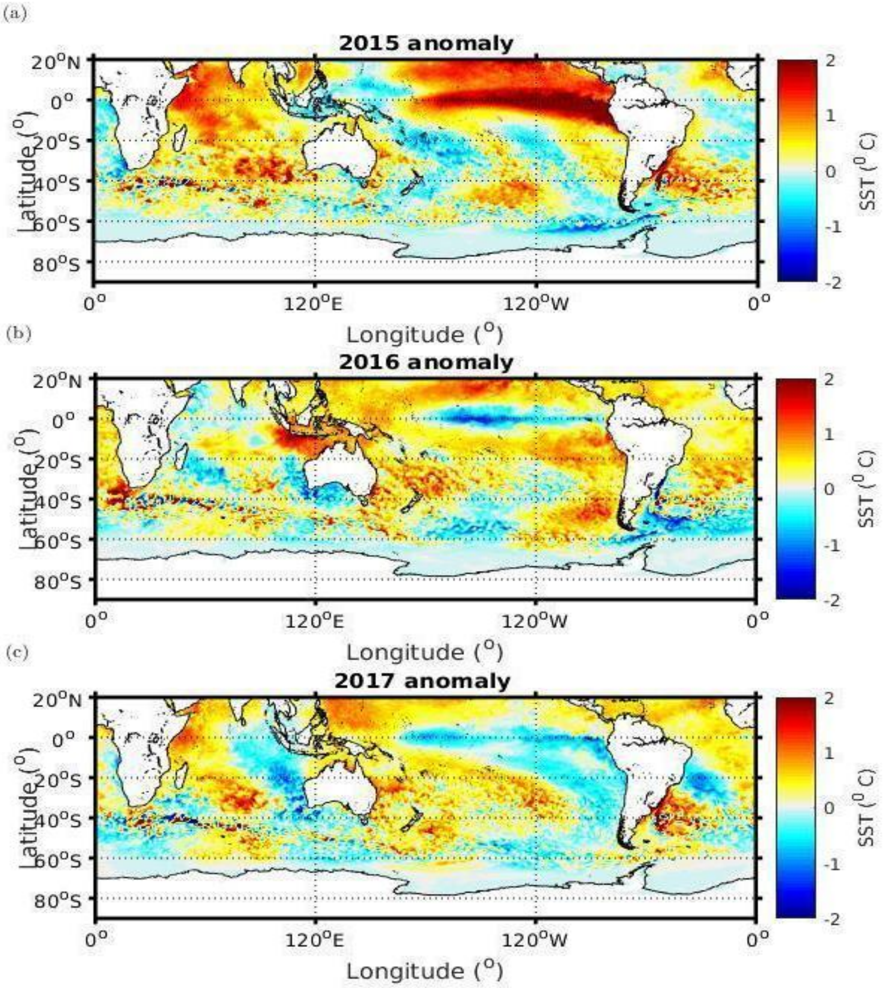

Figure 19: Same as **Fig. 17**, but for the late winter (July-September).

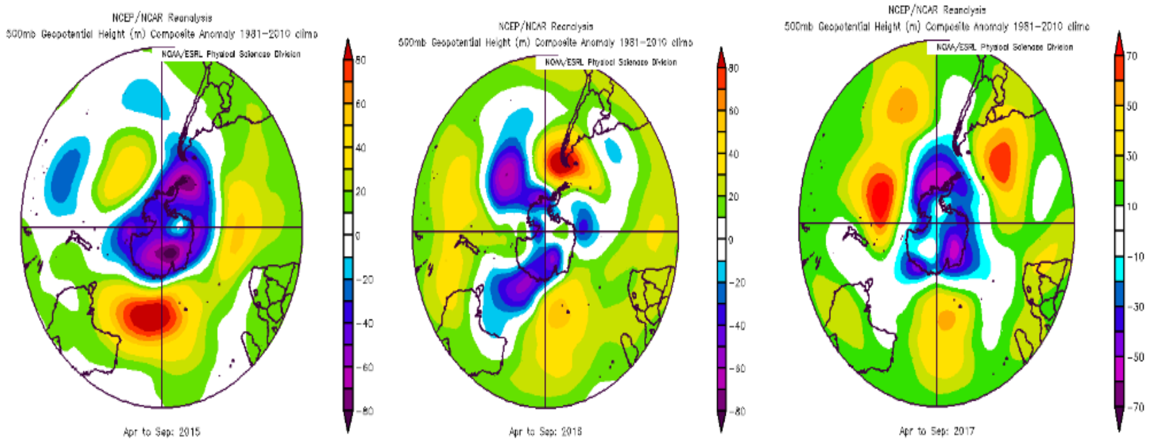

Figure 20**:** Geopotential height anomaly for the winter (April – September) of 2015 (left panel), 2016 (middle panel) and 2017 (right panel).

5. Discussion

The station data used in this study shows considerable spatial and intraseasonal rainfall variability during the winter half of the year over the Western Cape region. The west coast domains (north west coast and south west coast) are generally wetter in winter compared to the rest of the region, particularly during the mid-winter period (June to August). The South Coast and inland domains can show a prevalence to dry conditions lasting up to six consecutive years, particularly during the mid- and late winter trimesters. These observations are consistent with findings by Midgley *et al*. (2005) who notes that very distinct rainfall gradients exist over the region. Furthermore, the intraseasonal variations are due to the differences in the months at which the different regions receive maximum rainfall as highlighted by Rouault and Richard (2003). The northern and southern West Coast both receive their rainfall maximum in June, which is evident in the data as the mid-winter period is the wettest in these domains. The western interior receives its maximum rainfall in March and is dry for most of the winter season. The spatial variability in rainfall over the region suggests a rational representation could be misleading (Rouault and Richard, 2003).

The SAM and rainfall time series shows that SAM has an influence on rainfall over the Western Cape region. Earlier work showed that a positive (negative) SAM phase is associated with dry (wet) winters over western South Africa region (Reason and Rouault, 2005) and that SAM also influences rainfall during some parts of South Africa during summer (Gillett *et al*., 2006). Using SAWS station data since 1979, it is found here that five (three) of the driest (wettest) winters over the full domain are associated with a positive (negative) SAM phase. However, the relationship between the two series is found to be statistically insignificant for the full winter period over the entire region. For the sub-domains the relationship is found to be different between the two West Coast domains where SAM and rainfall are found to be anti-correlated, and the South Coast and Inland domains which show a positive correlation between SAM and rainfall anomalies. Furthermore, the correlation between the two series is found to be weak compared to the findings by Reason and Rouault (2005). In this study, the correlation between the two series for the full Western Cape domain during the mid-winter (**Fig. 8a**) trimester was -0.060 whereas Reason and Rouault (2005) found a stronger correlation 0.3 for 1948 and increasing to 0.4 for 1965-2004. The differences in the results between the two analyses could be due to the differences in the analysis period, our study was conducted for the period 1979 to 2016 while the study period for the later was 1948 to 2004. Different SAM indices were also used for the analysis, in this study the Marshal (2003) index was used, while Reason and Rouault (2005) defined the SAM using the leading mode of 850 hPa geopotential height south of 20° S (the Antarctic Oscillation Index (AAO) of NOAA Climate Prediction Centre). Ho *et al*. (2012) highlights that the use of different indices in analysing relationships with precipitation could yield different results and these are due to the differences in sources of data used, method and variable used to compute the indices. The AAO index is calculated using NCEP-NCAR re-analysis data, Marshall (2003) warns that the observed trends in reanalysis data strengthen SAM signals by a factor of two or three. This could potentially contribute to the higher correlation obtained by Reason and Rouault (2005). In addition, the leading mode also contains a signature of the wave number 3 within it (and hence a modulation of the South Atlantic Anticyclone) so it is not purely annular mode.

The SAM has been shown to have a positive polarity in recent decades particularly during the austral summer (December to February) and autumn (March to May) (Christensen *et al.*, 2013; Abram *et al*., 2014). A positive trend is observed in this study since 1995 during the early winter trimester. This has been largely attributed to stratospheric ozone depletion (Christensen *et al*., 2013; Abram *et al*., 2014). Christensen *et al*. (2013) suggests that as the ozone hole recovers it is likely that SAM could be driven to the opposite direction, particularly during austral spring and summer where ozone depletion has had its greatest influence on SAM. An equatorward shift in the jet position is also projected for these seasons (Christensen *et al*., 2013), which could enable storm passage and increased rainfall over the region. This shift may suggest an increase in summer rainfall as projected by Midgley *et al*. (2012). Although the SAM - rainfall relationship is found to have stronger decadal correlations, these are found to be statistically insignificant (at the 95th significance level) for most of the analysis period. This result implies that there may be a weak decadal variability in the relationship between SAM and rainfall. The running correlation analysis found was to be significant between 1994 and 1998.

An analysis of geopotential heights anomalies at 500 hPa for the six driest and wettest years was conducted (**Fig. 16**) to investigate the regional atmospheric circulation patterns. A wave number 3 pattern is observed between the polar cap and midlatitudes. The dry (wet) winter composites show positive (negative) pressure anomalies over the midlatitudes and negative (positive) pressure anomalies over the polar cap. The cyclonic patterns over the midlatitudes during the wet winters are favourable for the formation of strong depressions which bring rainfall over the region (Reason and Rouault, 2005). The dry winter’s composite shows anticyclonic conditions over the midlatitudes particularly the SW Atlantic and over the West Coast which increases subsidence over the region preventing frontal systems from reaching the land. These conditions are associated with a positive SAM phase (high pressure anomalies over much of the midlatitudes and low pressure anomalies over the Antarctic). Although a relatively coherent positive SAM pattern is seen for the dry winter composite, the opposite is not clear evident for the wet winter composite for which a cyclonic anomaly over the Western Cape / adjacent ocean region and the wave number 3 pattern is much more obvious.

SST changes over the South Atlantic during the winter season are shown to trigger an atmospheric response associated with changes in the strength and position of the westerly wave, convergence of moisture and latent heat flux, and relative vorticity which leads to changes in rainfall over the Western Cape region (Reason and Jagadheesha, 2005). The study shows that negative (positive) SST anomalies over the West Coast of South Africa correspond with the cyclonic (anticyclonic) conditions at 500 hPa. The decrease (increase) in subsidence leads to a strengthening (weakening) of fronts reaching the region during wet (dry) winters. For the composites shown here, there tends to be a cool-warm pattern across the western and central subtropics / midlatitudes of the South Atlantic for the wet winters and more or less the reverse for the dry winters. However, the signal immediately upstream of the Western Cape in the South East Atlantic, as well as the region to the south of South Africa does not appear to show a consistent or coherent anomaly pattern.

Pohl *et al*. (2010) highlights that SAM and ENSO are teleconnected at interannual scales, with El Niño (La Niña) events corresponding to a negative (positive) SAM phase. Our analysis shows that of the six driest years two exhibit the conditions suggested by Pohl *et al.* (2010). The global SST anomaly patterns are La Niña (El Niño) – like for the dry (wet) composite. Variability in SAM is related to ENSO during austral summer (Pohl *et al.,* 2010), which could explain the low correspondence observed in our analysis. ENSO and rainfall are also found to be anti-correlated over the West Coast while a positive correlation is observed over the South Coast. Similar findings were made by Philippon *et al.* (2010) for the late winter trimester (July to September) during 1950-1999. Although there is some literature on SAM and its teleconnections with ENSO, there is still a knowledge gap on how it interacts with other synoptic weather patterns known to influence rainfall over the winter rainfall region. For example, Singleton and Reason (2007) showed evidence that cut-off lows over South Africa tend to be more frequent during La Niña than during El Niño years but they did not consider the possible influence of the SAM on this relationship. In general, most studies evaluate the influence of these two modes of variability separately; and there are also inconsistencies in the literature on how SAM is defined. This makes it difficult to fully understand the teleconnections of SAM and its impact on rainfall over the region.

6. Conclusion

The aim of this study was to investigate the SAM and winter rainfall relationship over the Western Cape region of South Africa. The study analysed winter rainfall anomalies for the study period (1979-2017) over the full Western Cape domain. Due to the strong rainfall gradient observed over the region (Midgley *et al*., 2005), four sub-domains were chosen to further investigate the spatial influence on this SAM/rainfall relationship. The results show that rainfall displays interannual variability with frequent dry periods over the region in the past 38 years. The winter season was also divided into three trimesters, the early winter (April - June), mid-winter (June - August) and late winter (July - September). The study shows that local rainfall displays intraseasonal variability; there was no uniformity in rainfall conditions for the different trimesters. Furthermore, the sub-domains demonstrate spatial variability over the region. The south West Coast is found to be wetter in comparison to the South Coast which shows periods of protracted dry conditions lasting up to six consecutive years (between 1998 and 2005).

In terms of the SAM and rainfall relationship, a negative correlation (r = -0.3) exists over the West Coast while the correlation is found to be positive (r = 0.17) over the South Coast. Five (three) of the six driest (wettest) years are found to be associated with a positive (negative) SAM phase. All the correlations are statistically insignificant at a 95% significance level in all trimesters. As highlighted in the literature, the SAM is shown to have been in a positive phase since 1995 particularly during the early winter which is unfavourable for rainfall. A decadal analysis of the statistical relationship between SAM and rainfall shows that the relationship is also not significant at a 95% significance level for most of the winter period. It is only found to be significant during the early winter over the West Coast in about the last decades.

A composite analysis of the six dry (wet) winters shows that circulation patterns observed at 500 hPa are suggestive of positive (negative) SAM conditions but with a wave number 3 pattern superimposed, particularly for the wet case. These anomalous SAM patterns cause shifts in the subtropical jet, and an equatorward (poleward) shift in storm tracks leading to wetter (drier) than average conditions over the Western Cape region.

Reason and Jagadheesha (2005) suggested that the winter rainfall is also influenced by anomalies in the subtropical - midlatitude South Atlantic SSTs (Reason and Jagadheesha, 2005). Here, the composites suggested a possible relationship with SST in some parts of the South Atlantic but there seems to be a more obvious link with La Niña (El Niño) – like SST anomalies in the tropical Pacific during dry (wet) conditions over the Western Cape region.

The most recent three winters (generally dry) were also evaluated in this study. The start of the rainy season (April to June) in 2017 was the second driest since 1979 over the full domain. In general, the dry conditions of 2015-2017 are found to be associated with the positive SAM phase. This SAM association is also evident in the circulation pattern analysis, which shows similar conditions to those observed during a positive SAM. The year 2015 was associated with a strong El Niño, the South Coast of the region received above average rainfall for this year. Although the patterns were weak, both 2016 and 2017 showed La Niña – like SST anomalies in the tropical Pacific which the composite analysis indicated was associated with dry winters.

The circulation composites and the results for 2015-2017 suggest that SAM may have an influence on winter rainfall over the Western Cape region of South Africa. However, the relatively weak correlation values and their change through the 1979-2017 periods indicate that this influence is subtle and inconsistent at times. The SAM relationship here appears weaker than that found by Reason and Rouault (2005); however, it must be noted that these authors used a different definition of the SAM to this study as well as a different period of data (1948-2004). Thus, perhaps at best, SAM can be considered as one of the diagnostic tools for attributing rainfall changes over the region.

This thesis has also highlighted that spatial variability within the Western Cape should be considered when analysing the influence of modes of variability on the winter rainfall region. The presence of strong topographic gradients over the land and marked SST gradients in the nearby oceans likely influences the tracks and intensity of rain-bearing weather systems (mainly cold fronts and cut off lows) over the Western Cape. The complex regional topography and oceanic environment together with the subtle SAM and ENSO influences therefore pose great challenges for fully understanding the climate variability of the winter rainfall region let alone predicting it on seasonal to decadal time scales.

Finally, it needs to be noted that there is still a knowledge gap in how the SAM and ENSO teleconnections to South Africa may interfere, oppose or reinforce each other and, more generally, how the generation and the evolution of these modes may influence each other. One possible avenue for future work on Western Cape rainfall would be to separately analyse the influence of SAM and ENSO by means of partial correlations in order to investigate the linear influence of each mode of variability independently.

References

Abram, N.J., Mulvaney, R., Vimeux, F., Phipps, S.J., Turner, J. and England, M.H., 2014. Evolution of the Southern Annular Mode during the past millennium. *Nature Climate Change*, *4*, pp.564-569.

Behera, S.K. and Yamagata, T., 2001. Subtropical SST dipole events in the southern Indian Ocean. *Geophysical Research Letters*, *28*(2), pp.327-330.

Bengtsson, L., Hodges, K.I. and Roeckner, E., 2006. Storm tracks and climate change. *Journal of Climate*, *19*(15), pp.3518-3543.

Blamey, R. and Reason, C.J.C., 2007. Relationships between Antarctic sea-ice and South African winter rainfall. *Climate Research*,*33*(2), pp.183-193.

Blamey, R.C. and Reason, C.J.C., 2013. The role of mesoscale convective complexes in southern Africa summer rainfall. Journal of climate, 26(5), pp.1654-1668.

Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W. Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B. Stephenson, S.-P. Xie and T. Zhou, 2013: Climate Phenomena and their Relevance for Future Regional Climate Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

City of Cape Town 2017, *Water restrictions*, viewed 9 September 2017, < http://www.capetown.gov.za/Family%20and%20home/residential-utility-services/residential-water-and-sanitation-services/make-water-saving-a-way-of-life>.

Colberg, F., Reason, C.J.C. and Rodgers, K., 2004. South Atlantic response to El Niño–Southern Oscillation induced climate variability in an ocean general circulation model. *Journal of Geophysical Research: Oceans*, *109*(C12).

Favre, A., Hewitson, B., Lennard, C., Cerezo-Mota, R. and Tadross, M., 2013. Cut-off lows in the South Africa region and their contribution to precipitation. *Climate dynamics*, *41*(9-10), pp.2331-2351.

Fogt, R.L., Bromwich, D.H. and Hines, K.M., 2011. Understanding the SAM influence on the South Pacific ENSO teleconnection. *Climate Dynamics*, *36*(7-8), pp.1555-1576.

Gillett, N.P., Kell, T.D. and Jones, P.D., 2006. Regional climate impacts of the Southern Annular Mode. *Geophysical Research Letters*, *33*(23).

Gong, D. and Wang, S., 1999. Definition of Antarctic oscillation index. *Geophysical research letters*, *26*(4), pp.459-462.

Gosling, S.N., Dunn, R., Carrol, F., Christidis, N., Fullwood, J., Gusmao, D.D., Golding, N., Good, L., Hall, T., Kendon, L. and Kennedy, J., 2011. Climate: Observations, projections and impacts. *Climate: Observations, projections and impacts*.

Griffiths, C.L., Robinson, T.B., Lange, L. and Mead, A., 2010. Marine biodiversity in South Africa: an evaluation of current states of knowledge. *PloS one*, *5*(8), p.e12008.

Hall, A. and Visbeck, M., 2002. Synchronous variability in the Southern Hemisphere atmosphere, sea ice, and ocean resulting from the annular mode. *Journal of Climate*, *15*(21), pp.3043-3057.

Hartmann, D.L. and Lo, F., 1998. Wave-driven zonal flow vacillation in the Southern Hemisphere. *Journal of the Atmospheric Sciences*, *55*(8), pp.1303-1315.

Ho, M., Kiem, A.S. and Verdon-Kidd, D.C., 2012. The Southern Annular Mode: a comparison of indices. *Hydrology and Earth System Sciences*, *16*(3), p.967.

Jones, D.A. and Simmonds, I., 1993. A climatology of Southern Hemisphere extratropical cyclones. *Climate Dynamics*, *9*(3), pp.131-145.

Jury, M. R., 1987. Aircraft observations of meteorological conditions along Africa's west coast between 30-35 S. J.Clim.Met, 26(11), pp. 1540-1522.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J. and Zhu, Y., 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American meteorological Society*, *77*(3), pp.437-471.

Kruger, A.C., 1999. The influence of the decadal-scale variability of summer rainfall on the impact of El Niño and La Niña events in South Africa. Int J Climatol 19:59–68.

L'Heureux, M. L. and Thompson, D. W. J., 2006. Observed Relationships between the El Nino Southern Oscillation and the Extratropical Zonal-Mean Circulation. J. Climate, 19, pp.276–287.

Marshall, G.J., 2003. Trends in the Southern Annular Mode from observations and reanalyses. *Journal of Climate*, *16*(24), pp.4134-4143.

Lindesay, J.A., 1988. South African rainfall, the Southern Oscillation and a Southern Hemisphere semi-annual cycle. *International Journal of Climatology*, *8*(1), pp.17-30.

Meque, A. and Abiodun, B.J., 2015. Simulating the link between ENSO and summer drought in Southern Africa using regional climate models. *Climate Dynamics*, *44*(7-8), pp.1881-1900.

Midgley, G.F., Chapman, R.A., Hewitson, B., Johnston, P., de Wit, M., Ziervogel, G., Mukheibir, P., van Niekerk, L., Tadross, M., van Wilgen, B.W., *et al*., 2005. A status quo, vulnerability and adaptation assessment of the physical and socio-economic effects of climate change in the Western Cape. *Report to the Western Cape Government, Cape Town, South Africa. Stellenbosch, CSIR Report No. ENV-S-C 2005–073.*

Mulenga, H.M., Rouault, M. and Reason, C.J.C., 2003. Dry summers over northeastern South Africa and associated circulation anomalies. Climate Research, 25(1), pp.29-41.

Philippon, N., Rouault, M., Richard, Y. and Favre, A., 2012. The influence of ENSO on winter rainfall in South Africa. *International Journal of Climatology*, *32*(15), pp.2333-2347.

Preston-Whyte, R.A. and Tyson, P.D., 1988. *Atmosphere and weather of southern Africa*. Oxford University Press.

Pohl, B., Fauchereau, N., Reason, C.J.C. and Rouault, M., 2010. Relationships between the Antarctic oscillation, the Madden–Julian oscillation, and ENSO, and consequences for rainfall analysis. *Journal of Climate*, *23*(2), pp.238-254.

Reason, C.J.C., Allan, R.J., Lindesay, J.A. and Ansell, T.J., 2000. ENSO and climatic signals across the Indian Ocean basin in the global context: Part I, Interannual composite patterns. *International Journal of Climatology*, *20*(11), pp.1285-1327.

Reason, C.J.C., 2002. Sensitivity of the southern African circulation to dipole sea- surface temperature patterns in the south Indian Ocean. International Journal of Climatology, 22(4), pp.377-393.

Reason, C.J.C., Rouault, M., Melice, J.L. and Jagadheesha, D., 2002. Interannual winter rainfall variability in SW South Africa and large scale ocean–atmosphere interactions. *Meteorology and Atmospheric Physics*, *80*(1), pp.19-29.

Reason, C.J.C. and Jagadheesha, D., 2005. A model investigation of recent ENSO impacts over southern Africa. *Meteorology and Atmospheric Physics*, *89*(1-4), pp.181-205

Reason, C.J.C. and Jagadheesha, D., 2005. Relationships between South Atlantic SST variability and atmospheric circulation over the South African region during austral winter. *Journal of Climate*, *18*(16), pp.3339-3355.

Reason, C.J.C. and Rouault, M., 2005. Links between the Antarctic Oscillation and winter rainfall over western South Africa.*Geophysical Research Letters*,*32*(7).

Rodwell, M.J. and Hoskins, B.J., 2001. Subtropical anticyclones and summer monsoons. *Journal of Climate*, *14*(15), pp.3192-3211.

Ropelewski CF, Halpert MS (1987) Global and regional scale precipitation and temperature patterns associated with El Niño/Southern Oscillation. Mon Weather Rev 115:1606–1626

Rouault, M. and Richard, Y., 2003. Intensity and spatial extension of drought in South Africa at different time scales. *Water SA*, *29*(4), pp.489-500.

Rouault, M., Mélice, J.L., Reason, C.J. and Lutjeharms, J.R., 2005. Climate variability at Marion Island, Southern Ocean, since 1960. *Journal of Geophysical Research: Oceans*, *110*(C5).

Rouault, M., Pohl, B. and Penven, P., 2010. Coastal oceanic climate change and variability from 1982 to 2009 around South Africa. *African Journal of Marine Science*, *32*(2), pp.237-246.

Reynolds, R.W., Smith, T.M., Liu, C., Chelton, D.B., Casey, K.S. and Schlax, M.G., 2007. Daily high-resolution-blended analyses for sea surface temperature. *Journal of Climate*, *20*(22), pp.5473-5496.

Seager, R., Murtugudde, R., Naik, N., Clement, A., Gordon, N. and Miller, J., 2003. Air–sea interaction and the seasonal cycle of the subtropical anticyclones. *Journal of climate*, *16*(12), pp.1948-1966.

Silvestri, G.E. and Vera, C.S., 2003. Antarctic Oscillation signal on precipitation anomalies over southeastern South America. *Geophysical Research Letters*, *30*(21).

Simmonds, I. and Keay, K., 2000. Mean Southern Hemisphere extratropical cyclone behavior in the 40-year NCEP–NCAR reanalysis. *Journal of Climate*, *13*(5), pp.873-885.

Singleton, A.T. and Reason, C.J.C., 2006. Numerical simulations of a severe rainfall event over the Eastern Cape coast of South Africa: sensitivity to sea surface temperature and topography. *Tellus A*, *58*(3), pp.355-367

Sun, X., Cook, K.H. and Vizy, E.K., 2017. The South Atlantic Subtropical High: Climatology and Interannual Variability. *Journal of Climate*, *30*(9), pp.3279-3296.

Thompson, D.W. and Wallace, J.M., 2000. Annular modes in the extratropical circulation. Part I: Month-to-month variability. *Journal of climate*, *13*(5), pp.1000-1016.

Tyson, P.D. and Preston-Whyte, R.A., 2000. *weather and climate of southern Africa*. Oxford University Press.

Yu, J.Y., Paek, H., Saltzman, E.S. and Lee, T., 2015. The early 1990s change in ENSO–PSA–SAM relationships and its impact on Southern Hemisphere climate. *Journal of Climate*, *28*(23), pp.9393-9408.

Appendix

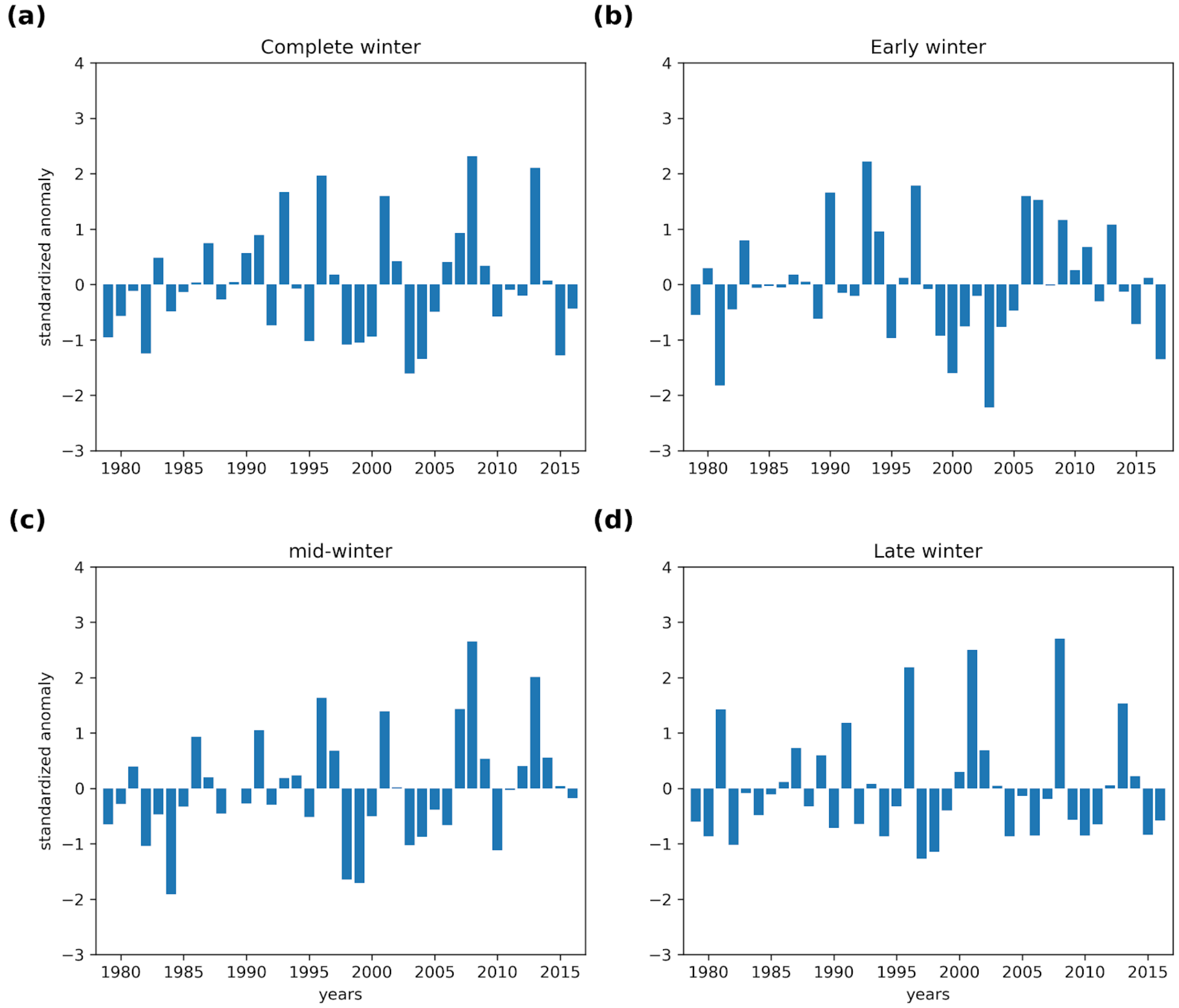

Figure 21: Same as **Fig. 4,** but for the northern West Coast domain (domain **A).**

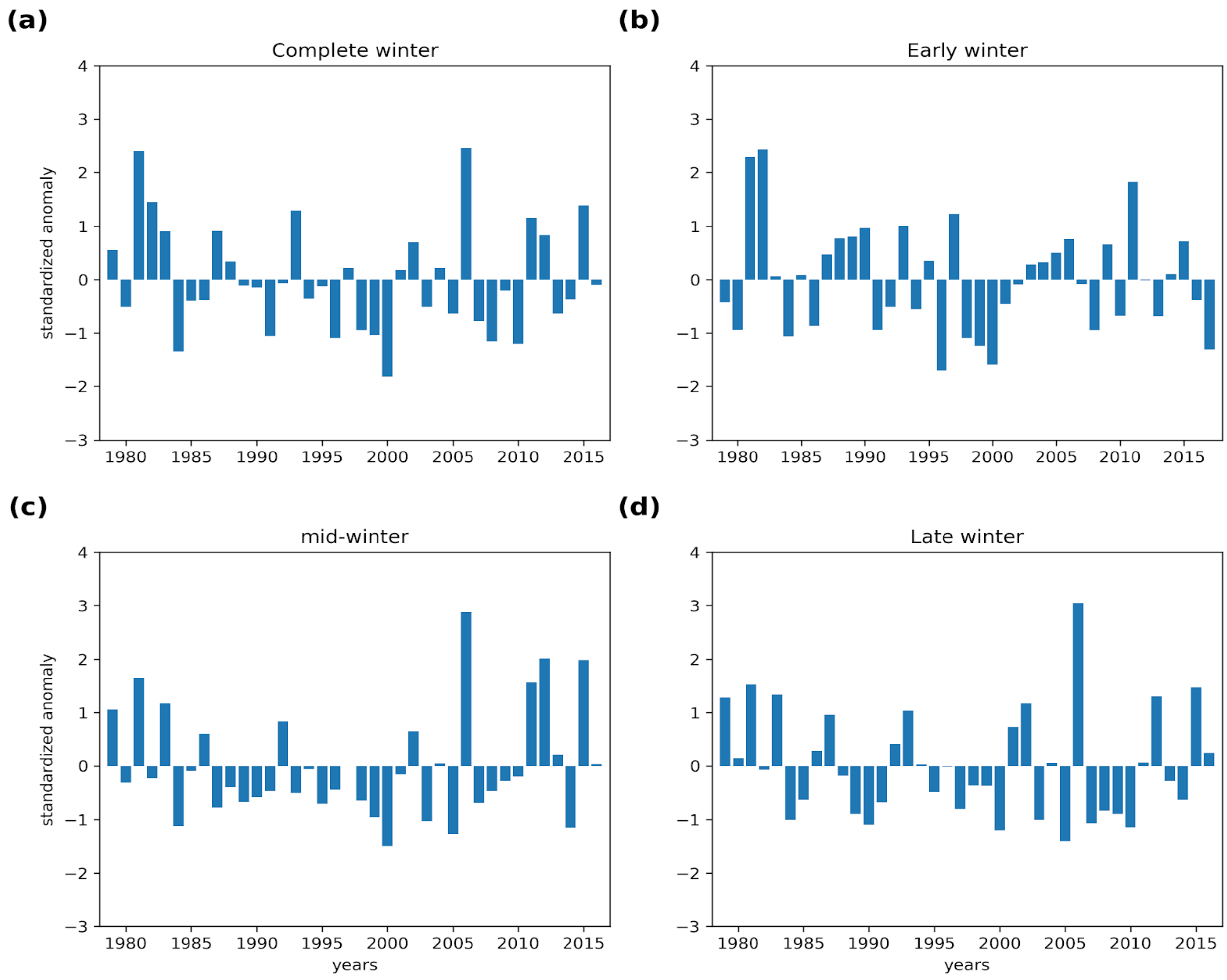

Figure 22: Same as **Fig. 4,** but for the inland domain (domain **D**).

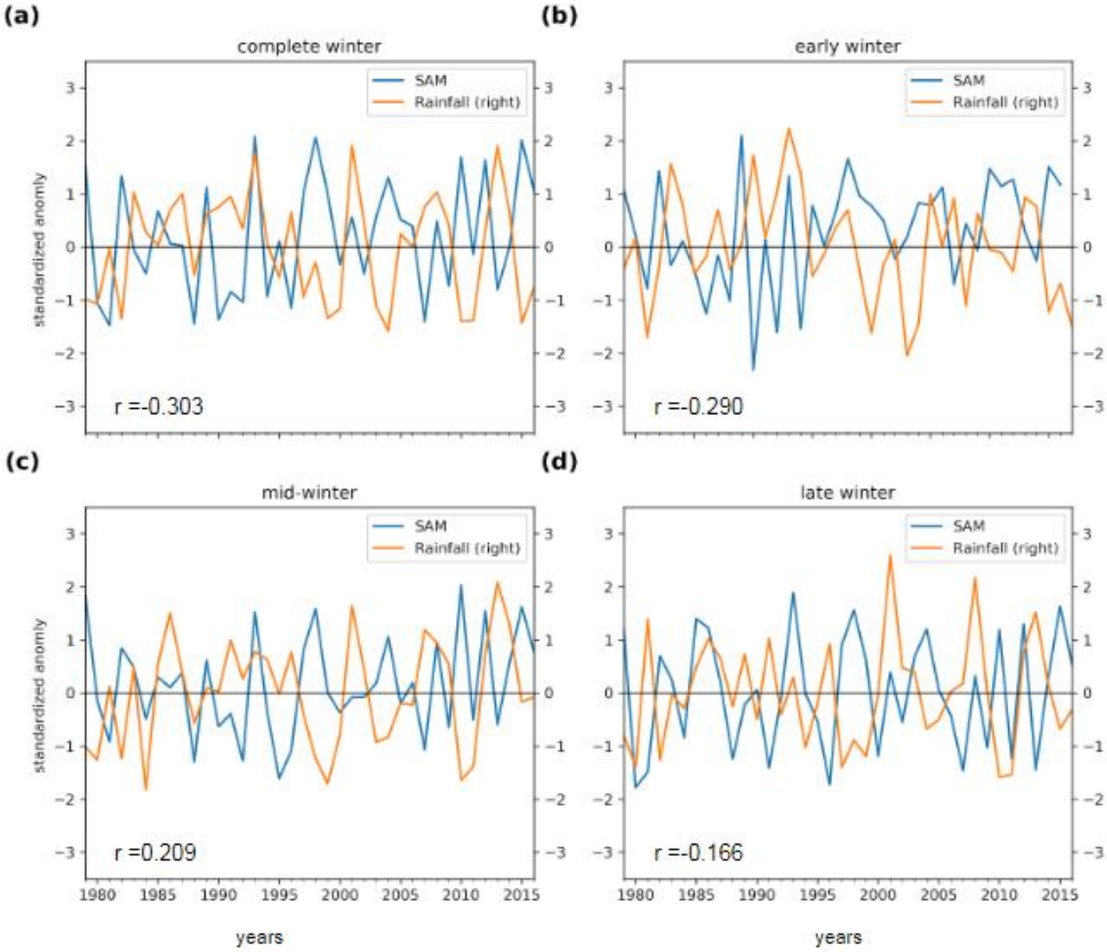

Figure 23**:** Same as **Fig. 8**, but for the southern Western Cape domain**.**

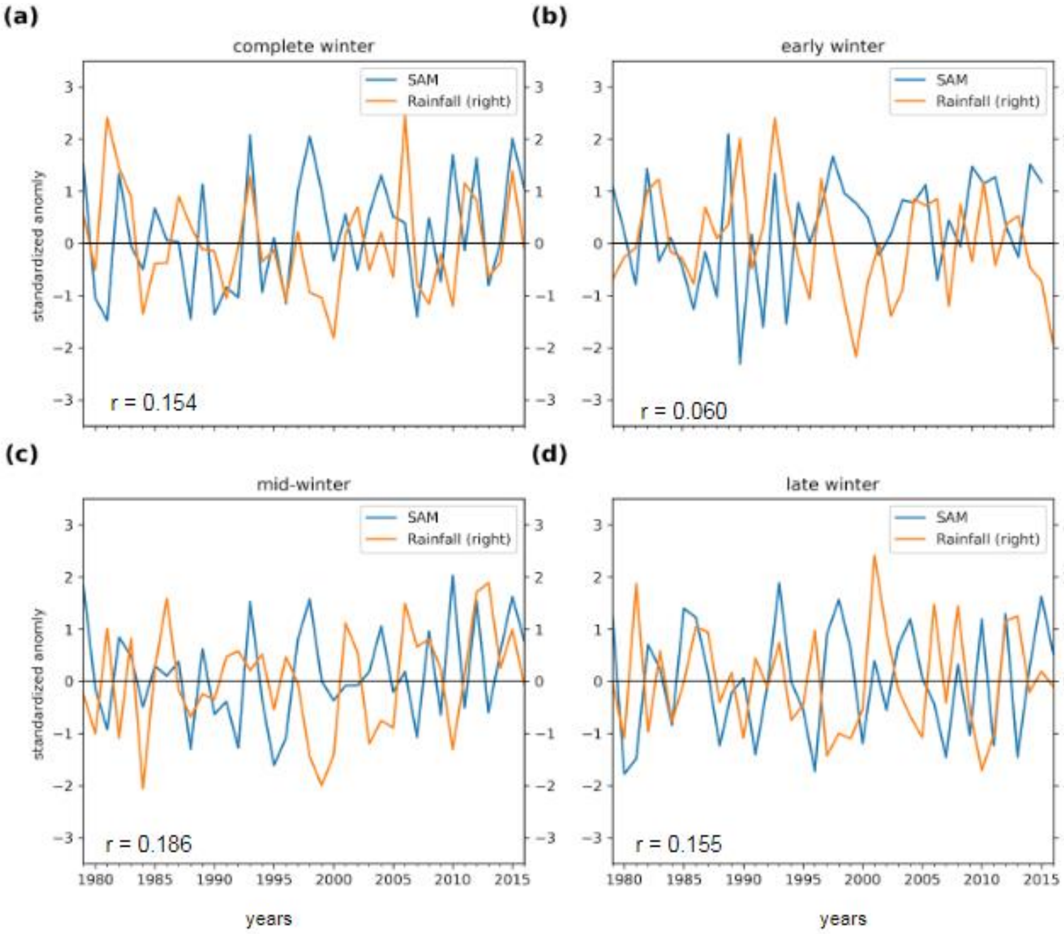

***Figure 24*:** Same as **Fig. 8,** but for the inland domain.

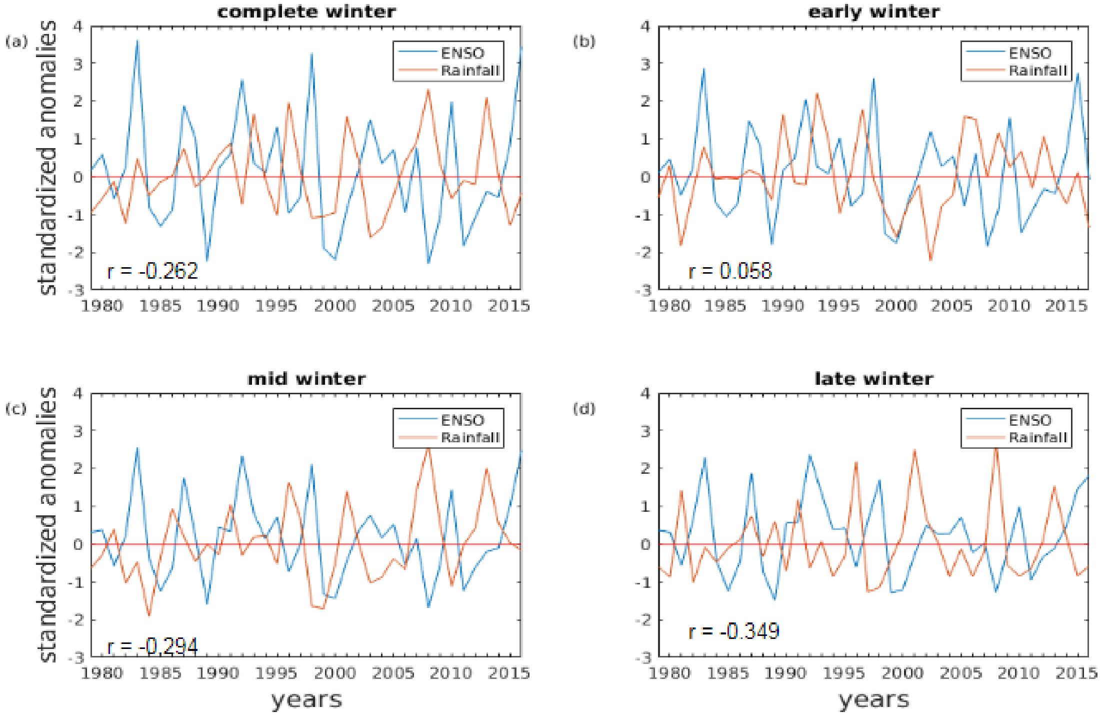

Figure 25: Same as **Fig. 12,** but for the northern West Coast domain.

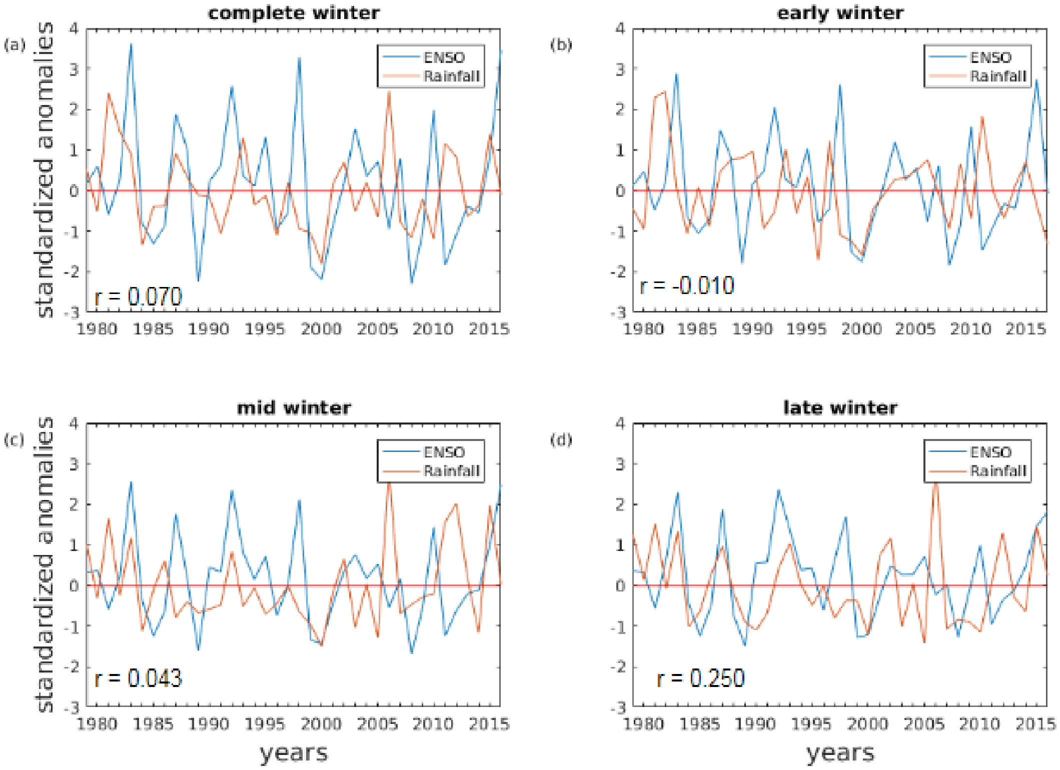

Figure 26**:** Same as **Fig. 12**, but for the inland domain**.**

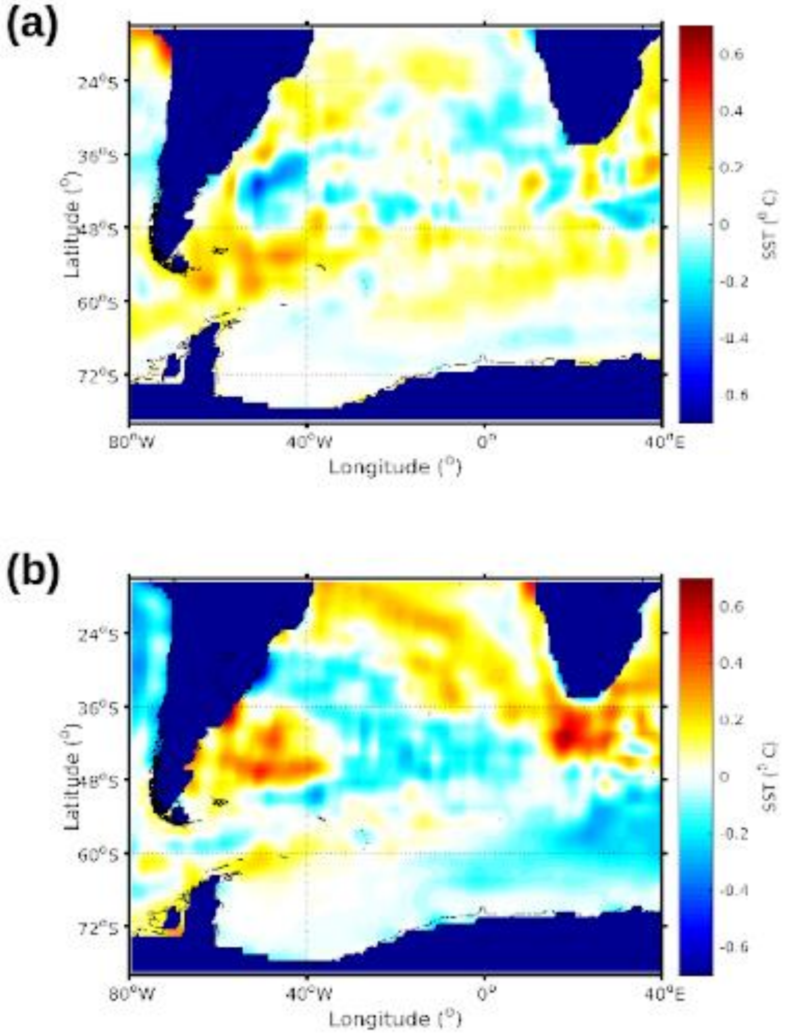

Figure 27**:** Same as **Fig. 15**, but for the South Atlantic and South West Indian domain.

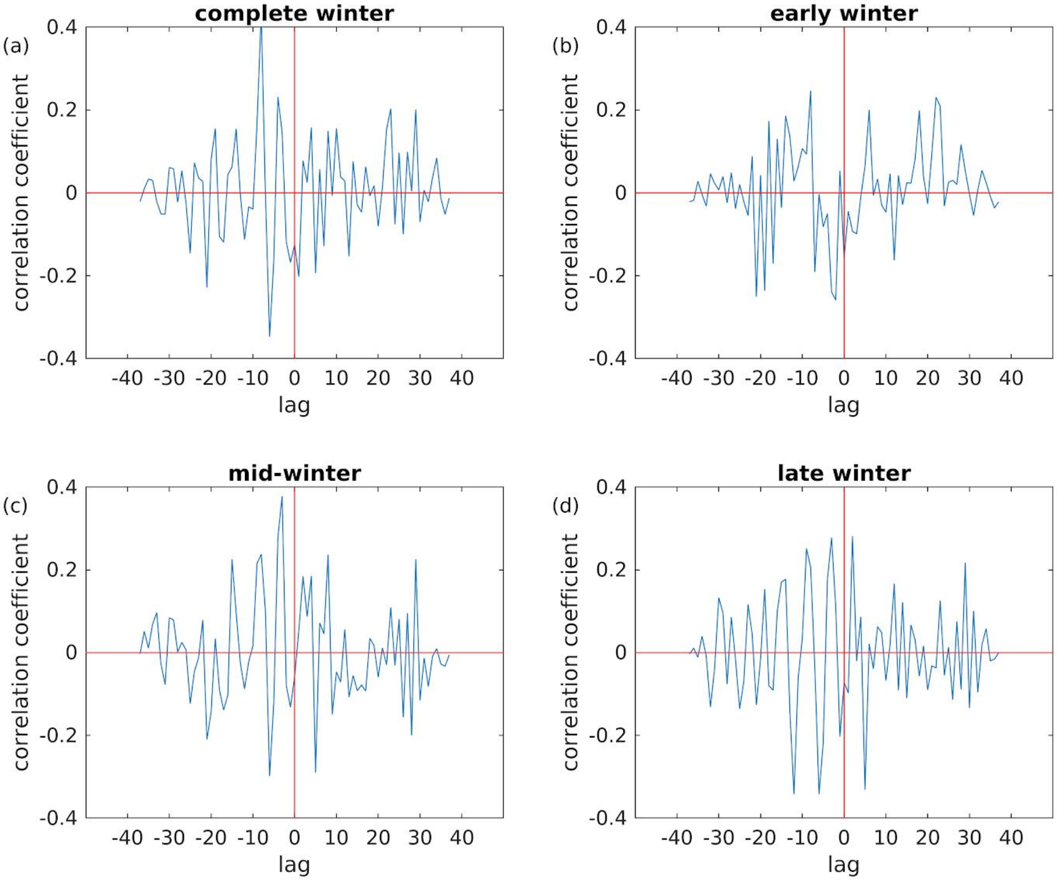

Figure 28: The correlation coefficient between SAM and rainfall anomalies over the full Western Cape domain at different lags. Panels illustrates correlations between the two series for (a) the complete winter (b) early winter (c) mid-winter and (d) late winter periods.