



Southern Africa Climate Over the Recent Decades: Description, Variability and Trends

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Abstract

South of 15°S, southern Africa has a subtropical climate, which is affected by temperate and tropical weather systems and comes under the influence of the Southern Hemisphere high-pressure systems. Most rainfall occurs in austral summer, but the southwest experiences winter rainfall. Much of the precipitation in summer is of convective origin forced by large-scale dynamics. There is a marked diurnal cycle in rainfall in summer. The El Niño Southern Oscillation (ENSO) influences interannual rainfall variability. In austral summer, drought tends to occur during El Niño, while above-normal rainfall conditions tend to follow La Niña. During El Niño, higher than normal atmospheric pressure anomalies, detrimental to rainfall, occur due to changes in the global atmospheric circulation. This also weakens the moisture transport from the Indian Ocean to the continent. The opposite mechanisms happen during La Niña. On top of the variability related to ENSO, the Pacific Ocean also influences the decadal variability of rainfall. Additionally, the Angola Current, the Agulhas Current, the Mozambique Channel and the southwest Indian Ocean affect rainfall variability. Over the last 40 to 60 years, near-surface temperatures have increased over almost the whole region, summer precipitation has increased south of 10°S, and winter precipitation has mostly decreased in South Africa. Meanwhile, the

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G. P. von Maltitz et al. (eds.), *Sustainability of Southern African Ecosystems under Global Change*, Ecological Studies 248, https://doi.org/10.1007/978-3-031-10948-5_6

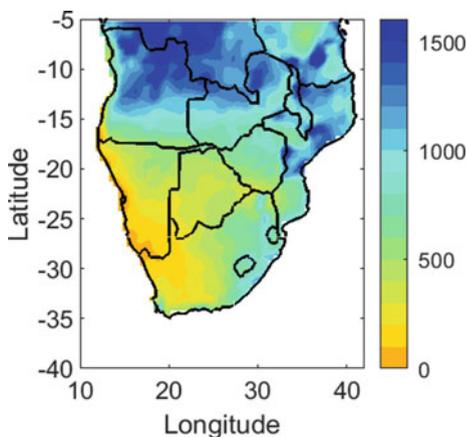
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Agulhas Current and the Angola Current have warmed, and the Benguela Current has cooled.

6.1 Annual Cycle of Rainfall in Southern Africa

Climatologically speaking, sub-Saharan Africa can be divided into four regions: (i) West Africa, a classic monsoon climate; (ii) East Africa, fed by an intense flux of moisture coming from the Indian Ocean; (iii) Central Africa, which has a tropical climate, hot and wet with rainfall maximum following an annual latitudinal pattern and (iv) southern Africa, a relatively dry and hot climate that can be found south of 15°S to 20°S depending on longitude (Fig. 6.1). Therefore, in this chapter, we will define southern Africa as the continental areas south of 15°S. While there is a high range in annual rainfall and timing at the regional scale, southern Africa is characterized by distinct summer and winter rainfall regions (Figs. 6.2 and 6.3). There is also a region where rainfall is almost equal all year long to the far south. The longitudinal rainfall variation is due to a warm ocean to the east composed of the Agulhas Current, the Mozambique Channel and the southwest Indian Ocean. The longitudinal variation is also due to the South Atlantic high-pressure system's influence on the west, creating subsidence and preventing rainfall. The subsidence created to the east by the South Indian high-pressure system is offset by east-to-west moisture flux from the ocean to the continent and the presence of a convergence zone leading to air uplift and rain. Figure 6.2 shows the spatial distribution of the wettest month of the year in southern Africa. The red and blue domains are the area used to calculate the summer and winter rainfall total presented in Fig. 6.3 by averaging all grid points of each domain. It is also used to calculate the summer Standardized Precipitation Index (SPI) and calculate the Summer Rainfall Index (SRI), as was done by Dieppois et al. (2016, 2019).

Fig. 6.1 Mean 1950–2016 Global Precipitation Climatology Centre (GPCC) January to December annual total rainfall (mm) for southern Africa



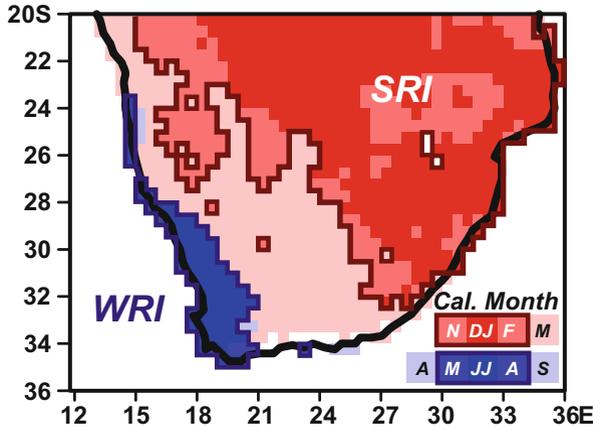


Fig. 6.2 Spatial distribution of southern Africa’s wettest month of the year (calendar month: red, summer: November to March; blue winter: April to September). Lines and colors delineate the area used to calculate summer and winter rainfall averages and indices (SRI and WRI)

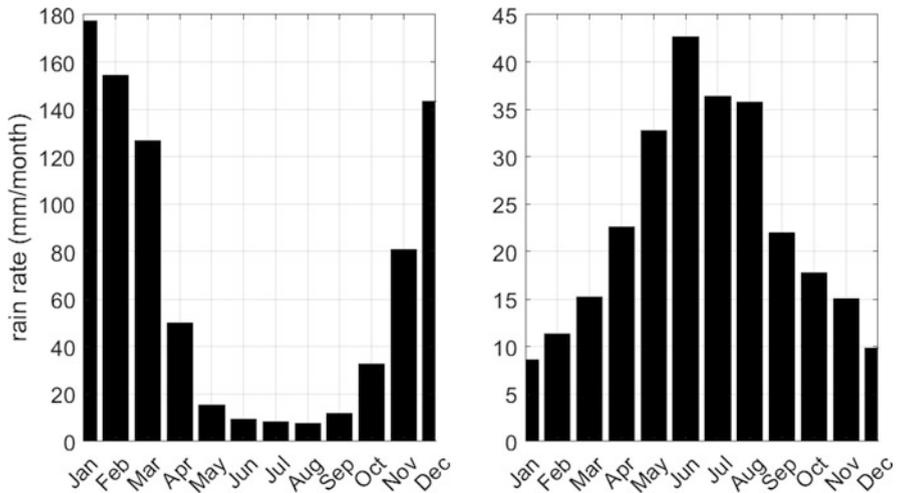


Fig. 6.3 Mean 1950–2016 annual cycle of rainfall in mm/month for southern Africa’s southwest winter rainfall region (left) and summer rainfall region (right) as defined in Fig. 6.2

The greatest precipitation rate and maximum timing range are especially marked in South Africa. South Africa is divided into eight climatic regions by the South African Weather Service (Rouault and Richard 2003). The North-Western Cape has very little rainfall, with a winter maximum in June of 30 mm. The Southwestern Cape also has a maximum in June but differs with a maximum of 70 mm. Both regions constitute the winter rainfall region. The South Coast, which encompasses most of the Garden Route, experiences regular rainfall all year long, from about

30 mm to 40 mm per month, reaching about 100 mm in places over the Tsitsikamma region during October and November. There are even substantial spatial variations in rainfall within a region. For instance, Philippon et al. (2012) show that maximum monthly rainfall can vary from 240 mm to 30 mm per month for the Western Cape, primarily due to orography. The following five regions are part of the southern Africa summer rainfall region and have a maximum at different summer months. The Southern Interior has its maximum rainfall in late summer, March, with about 60 mm. The Western Interior has its rainfall maximum in January, with about 130 mm, but part of that region has a maximum in March (Dieppoiss et al. 2016). The Central Interior, KwaZulu-Natal and the North-Eastern Interior have maximum rainfall in January. KwaZulu-Natal is the wettest region, with a maximum in January of 130 mm. The North-Eastern Interior has the most significant difference between summer and winter. A comprehensive study of the annual cycle, regional differences and timings can be found in Favre et al. (2015). It indicates that while a rainfall deficit of 10 mm for a given month could be considered a drought in one region, it is not in another. Furthermore, the onset and demise of the rainy season are different for the eight areas making water management and mitigation of agricultural or hydrological drought difficult.

6.2 Synoptic Drivers of Rainfall

In southern Africa, much of the precipitation received in summer is of convective origin and forced by large-scale dynamics (Tyson and Preston-White 2000). Southern Africa has a subtropical climate and is affected by temperate and tropical weather systems. The country comes under the influence of the Southern Hemisphere high-pressure systems, but a heat low is found over the subcontinent in summer. This helps break the subsidence associated with high-pressure systems that prevent rain from occurring, allowing a diurnal cycle of rainfall to exist (Rouault et al. 2013). Most of the interior lies on an elevated plateau, and orography plays an important role in rainfall (Tyson and Preston-White 2000). The southwest region and the west coast receive most of their precipitation in austral winter through temperate systems such as cold fronts and cut-off lows, while the rest of the country gets most of its rainfall in austral summer. Summer rainfall is caused by large-scale synoptic systems leading to convection, but the diurnal cycle of rain has a substantial effect in the interior and along the East Coast. Such large rain-bearing systems include Tropical Temperate Troughs (TTTs; Chikoore and Jury 2010; Vigaud et al. 2012; Hart et al. 2012; Macron et al. 2014), Cut Off Lows (Favre et al. 2013), Mesoscale Convective Cloud systems (Blamey and Reason 2013) and occasionally tropical cyclones or tropical low-pressure systems associated with easterly waves (Malherbe et al. 2012). A substantial amount of rainfall in the summer rainfall region of southern Africa is due to TTTs and attendant cloud bands. The relative contribution of TTTs to rainfall during the summer ranges from 30% to 60%. While the annual cycle is dominant over southern Africa, intraseasonal rainfall oscillations occur with spectral peaks around 20 and 40 days associated with TTTs

(Chikoore and Jury 2010). The Madden-Julian Oscillation also affects rainfall on a 40–60 days' timescale (Pohl et al. 2007). Over the South Coast, nearly half of the annual rainfall is due to ridging anticyclones (Engelbrecht et al. 2015). The South Indian Anticyclone over the southwest Indian Ocean, Mozambique Channel and the Agulhas Current also plays an essential role in the source of moisture transported onto the interior plateau (Rapolaki et al. 2020; Imbol et al. 2021). Severe weather and flooding can occur due to cut-off lows, especially when the South Indian Anticyclone is quasi-stationary or blocking. Cut-off lows contribute significantly to rainfall over South Africa, especially along the south and east coasts and the Karoo regions (Favre et al. 2013). With some regional exceptions, spring is the season of the most substantial contribution by cut-off lows to annual rainfall. Over the Kalahari region, the most considerable contribution by cut-off lows to rainfall occurs during late summer. In contrast, the coastal regions, particularly the south coast, receive the most considerable cut-off low contribution to rainfall during the winter season (Favre et al. 2013). Over the south coast, cut-off lows have been associated with the autumn rainfall peak (Engelbrecht et al. 2015). For South Africa, the standardized amplitudes, indicative of the strength of the diurnal cycle across a region, are most substantial over the interior and along the East Coast, with up to 70% explained variance of hourly rainfall associated with the diurnal cycle (Rouault et al. 2013). The time of maximum precipitation is late afternoon to early evening in the interior and midnight to early morning along the Agulhas Current and inland in the northeast of the country (Rouault et al. 2013). In general, annual mean rainfall is overestimated by the regional climate model in South Africa (Favre et al. 2015), and also ocean–atmosphere global climate models (Dieppois et al. 2015, 2019). However, despite these general overestimations of rainfall totals, regional climate models have been demonstrated to simulate the main features of the annual cycle in circulation patterns and rainfall realistically across the southern African region (Engelbrecht et al. 2015).

6.3 Interannual Variability

The climate of southern Africa is highly variable and vulnerable to extremes such as droughts and floods. During the last decades, much has been gained on how the oceans can influence the climate of southern Africa on interannual scale (Richard et al. 2000, 2001; Fauchereau et al. 2003, 2009; Pohl et al. 2010; Cr  tat et al. 2012).

ENSO is the primary driver of southern Africa's rainfall interannual variability. Figure 6.4a shows the average normalized sea surface temperature and rainfall anomalies during the mature phase of El Ni  o in austral summer since 1982. This would be the average difference from normal during a typical El Ni  o event in austral summer. The normalized anomaly, which is presented in Fig. 6.4a, is a departure from the mean of November to March divided by the corresponding climatological standard deviation for 11 El Ni  o events. For instance, for values superior to one mean the anomaly is above one standard deviation. Roughly 66% of the values are between -1 and 1 standard if the data is normally distributed.

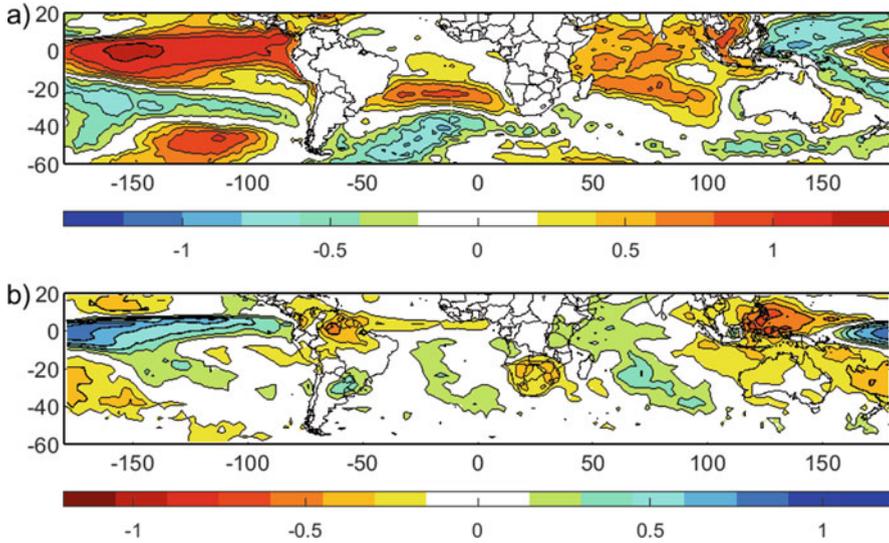


Fig. 6.4 (a), top: Average November–March sea surface temperature seasonal standardized anomalies during the mature phase of El Niño in austral summer (anomaly from the mean of November to March divided by the climatological corresponding standard deviation for 11 El Niño events). Blue/green is colder than normal; yellow/red is warmer than normal. (b), bottom: Average November–March rainfall seasonal standardized anomalies during the mature phase of El Niño in austral summer. Blue/green is wetter than normal; yellow/red is dryer than normal

As shown in Fig. 6.4a, most sea surface temperature anomalies are due to changes in global atmospheric and regional oceanic circulation, which are associated with El Niño. The impact of ENSO on sea surface temperature, land temperature, wind speed and rainfall offers predictability at the seasonal scale. This is because ENSO events’ starting months precede the southern African rainy season, and atmospheric models relatively well reproduce this lagged relationship.

Note that we use the Oceanic Niño Index (ONI) provided by the Climate Prediction Center to detect El Niño and La Niña years on Figs. 6.4 and 6.5. In addition, in Fig. 6.4b, the precipitation rate is estimated from satellite remote sensing using the 2.5-by-2.5 degrees resolution Global Precipitation Climate Project dataset available since 1979. For sea surface temperature, we use the 1-by-1-degree resolution Reynolds SST Optimally Interpolated, available only since 1982. For that reason, we have selected the following 11 El Niños, 1982/1983, 1986/1987, 1987/1988, 1991/1992, 1994/1995, 1997/1998, 2002/2003, 2004/2005, 2006/2007, 2009/2010 and 2014/2015.

Although early works suggested that there were no strong relation between the strength of El Niño and the intensity and spatial extension of the southern African drought (Rouault and Richard 2003, 2005), Ullah et al. (2023) highlight significant statistical relationships between El Niño and large-scale extreme rainfall events. Indeed, seven of the ten strongest droughts since the 1950s happened during the

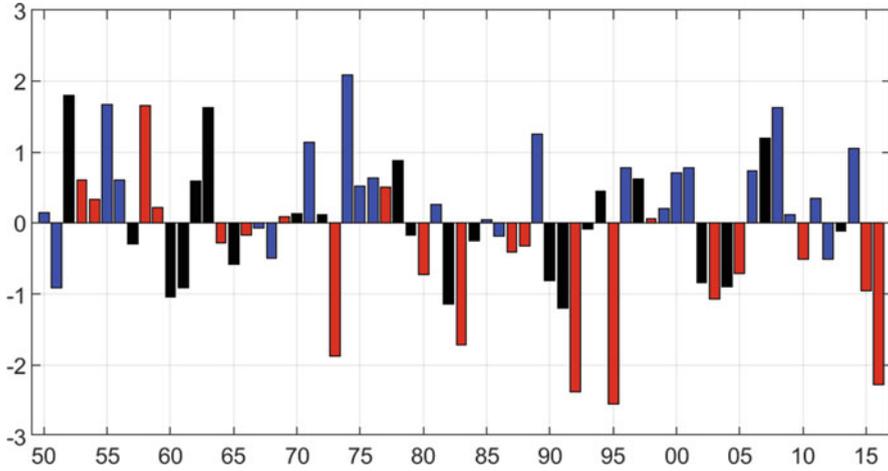


Fig. 6.5 November to March southern Africa summer rainfall Standardized Precipitation Index from 1950 to 2016. Red bars denote El Niño, and blue bars denote La Niña austral summers according to the ONI

mature phase of El Niño (Fig. 6.5), this provides ample early warning for drought monitoring. Droughts lasting two seasons always involve El Niño (Rouault and Richard 2003, 2005). The relationship between El Niño and drought occurrence has been particularly strong since the late 1970s (Fauchereau et al. 2003; Richard et al. 2000, 2001). However, this statistical relationship is not linear. For instance, the 1997/1998 strong El Niño did not lead to widespread drought (Lyon and Mason 2007), and severe drought can occur during a weak El Niño (Rouault and Richard 2005). Such nonlinear behavior in the El Niño-rainfall teleconnection has a significant impact on seasonal forecasts built on linear statistical models or in coupled or noncoupled general atmospheric circulation models, which, therefore, tends to be overconfident in predicting drought when El Niño occurs (Landman and Beraki 2012). Nevertheless, it may be noted that seasonal forecasts are skillful over the summer rainfall region of southern Africa during periods exhibiting significant ENSO forcing, even more so during La Niña, while forecasts are generally not skillful during neutral years (Landman and Beraki 2012).

The mechanisms linking the Pacific and southern Africa climate are relatively well understood and reasonably well simulated in state-of-the-art climate models (Dieppois et al. 2016, 2019). During El Niño events, near-surface divergence, detrimental to rainfall, is observed over southern Africa due to changes in the Walker and Hadley circulations. Along with the anomalous near-surface divergence, high-pressure anomalies (Fig. 6.6) over the landmass during El Niño also reduce the maritime moisture transport from the Indian Ocean to southern Africa.

A mid-tropospheric anticyclone becomes established and persistent during El Niño leading (not shown) to the anomalies presented in Fig. 6.6. Large-scale mid-troposphere disturbances (around 5000 m) are present globally during the mature

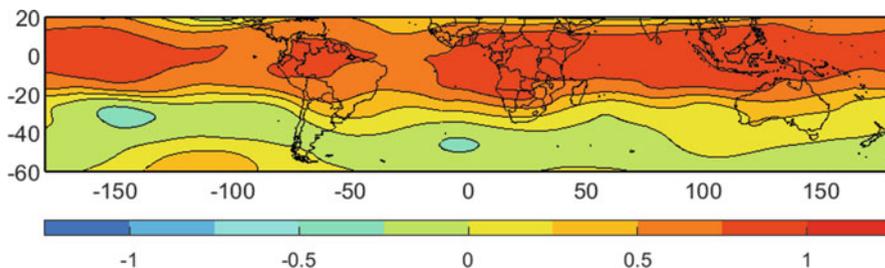


Fig. 6.6 Average December–February standardized El Niño normalized anomalies of the 500 hPa geopotential height in austral summer indicating global anomalies of atmospheric circulation in the mid-troposphere

phase of El Niño. There is a significant positive correlation between geopotential height anomalies over southern Africa at 500 hPa and the ONI Index. A more robust than normal Botswana high-pressure system causes enhanced subsidence for prolonged periods over much of the subcontinent. Moreover, El Niño is associated with extratropical atmospheric Rossby waves propagating poleward, influencing the southern hemisphere mid-latitude storm track (Fig. 6.6), and that could be responsible for an eastward shift of the South Indian Convergence Zone (Cook 2000, 2001). The eastward shift of the South Indian Convergence Zone is visible in Fig. 6.4b (bottom), where most of the large-scale synoptic-scale rain-bearing systems that affect southern Africa, such as Tropical temperate Troughs, preferably develop. The Indian Ocean warming during El Niño (Fig. 6.4a) also shifts atmospheric convection and rainfall eastward above the ocean, increasing subsidence above southern Africa and reducing the maritime moisture flux to the continent. During La Niña, a low-pressure anomaly is found over southern Africa, which favors the transport of moisture into southern Africa from the Indian Ocean, and consequently, rainfall is enhanced. Cut-off lows occur more frequently in a latitudinal band situated at lower latitudes during the La Niña years compared to El Niño years, during which these systems are located too far south of the country to contribute to seasonal rainfall amounts (Favre et al. 2012). El Niño and La Niña also change the wind strength along the coast and influence the ocean. In the upwelling system of the West Coast of South Africa, the Southern Benguela Current, El Niño often triggers lower than normal wind, weaker upwelling and warmer sea surface temperature due to the mid-latitude low-pressure anomalies shown in Fig. 6.6 (Rouault et al. 2010; Dufois and Rouault 2012; Tim et al. 2015; Blamey et al. 2015) and the opposite effect happens in the Northern Benguela (Rouault and Tomety 2022). During La Niña, the opposite occurs. Refer to Chap. 9 in this volume for more information on the northern and southern Benguela systems. El Niño also impacts the Western Cape rainfall and wind patterns in winter (Philippon et al. 2012).

Other modes of climate variability have been correlated to southern African rainfall, such as the Antarctic Annular Oscillation in winter, which is also called Southern Annular Mode (Reason and Rouault 2005; Malherbe et al. 2016) and the

Table 6.1 NDJFM synchronous cross-correlation between Summer Rainfall Index Standardized Precipitation Index (SRI SPI), ONI, South Indian Ocean Subtropical Dipole (SIOD) and Antarctic Annular Oscillation (AAO). In bold are correlations significant at the 95% confidence level

	SRI SPI	ONI	SIOD	AAO
SRI SPI	1	-0.67	0.42	-0.03
ONI		1	-0.45	-0.1
SIOD			1	0.16
AAO				1

South Indian Ocean Subtropical Dipole in summer (Behera and Yamagata 2001; Hoell et al. 2017).

Table 6.1 shows the correlation between the southern rainfall summer Standardized Precipitation Index, ONI, SIOD and AAO for austral summer (November to March). The strongest correlation, -0.67 , is between ONI and SRI. There is a weaker correlation, 0.42 , between SIOD and SRI but there is also a correlation of the same magnitude, -0.45 , between ONI and SIOD, which means that the SIOD does not necessarily impact southern African rainfall directly but could be a symptom of the effect of ENSO on both the Indian Ocean and southern African rainfall although Hoell et al. (2017) proposed that the phase of the SIOD can disrupt or augment the southern Africa precipitation response to ENSO.

Next, we investigate the impact of ENSO on Water Management Areas and stream flow of South Africa, focusing on the seasonal average measured flow of water in all rivers of a specific Water Management Area. Observed stream flow monthly time series data were summed in summer from November to March per Water Management Areas from 1969 to 2004. The most striking result is that for Water Management Areas of South Africa situated in the summer rainfall region (Fig. 6.2), flows are between 1.6 and 2.8 times higher during La Niña years than during El Niño years (Rouault 2014). This confirms and extends the findings of Landman et al. (2001). For instance, from the 1970s, for WMA 6, Usutu Mhlathuze Swazi WMA (including the following major rivers: the Usutu River, Pongola River, Mhlathuze River, Mfolozi River and Mkuze River and covers the Oedertrouw dam and the am Mhlathuze River dam; Fig. 6.7), the five driest years are all El Niño years

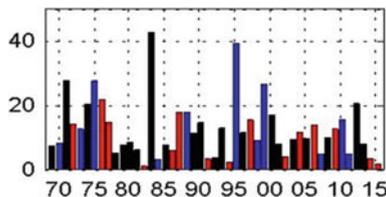


Fig. 6.7 Total summer stream flow volume averaged for all stations of the Water Management Area 6 (Usutu Mhlathuze Swazi). El Niño years are in red, and La Niña years are in blue. Stream flow is summed from November to March

(2015/2016, 1982/1983, 1994/1995, 2014/2015 and 1991/1992), and four out of five wettest years are La Niña years (1983/1984, 1987/1988, 2000/2001, 1988/1989 and 2010/2011). Four of the five lowest stream flow volume summer seasons occurred during El Niño (1982/1983, 2015/2016, 1994/1995, 1984/1985 and 1991/1992), although one occurred during la Niña. Three out of five of the highest stream flow volume years happened during La Niña.

Regional oceanographic and atmospheric features that have been reported to influence the southern African climate are the Agulhas Current (Jury et al. 1993; Nkwinkwa Njouodo et al. 2018; Imbol Nkwinkwa et al. 2021), the Angola Current (Rouault et al. 2003; Desbiolles et al. 2020; Koseki and Imbol Koungue 2021), the Mozambique Channel (Barimalala et al. 2020), the Angola low-pressure system (Crétat et al. 2019; Desbiolles et al. 2020) and the Botswana high-pressure system (Driver and Reason 2017). The Southern Annular Mode (Reason and Rouault 2005; Malherbe et al. 2016), the South Indian Ocean Dipole (Behera and Yamagata 2001; Hoell et al. 2017; Dieppois et al. 2016, 2019; Ullah et al. 2023) have also been linked to climate variability in southern Africa.

6.4 Decadal Variability of Southern Africa's Climate

As illustrated in Fig. 6.8, while interannual variability (2–8 years) mainly related to ENSO explains approximately 70% of the total rainfall variance on average over southern Africa, a third of rainfall variability is explained by variations on quasi-decadal (8–13 years) and interdecadal timescales (15–23 years; Dieppois et al. 2016, 2019). In addition, we note that the amplitudes of those decadal variations strengthen and weakened over the twentieth century in summer and winter rainfall areas (Dieppois et al. 2016). Teleconnections with global sea surface temperature, in particular, the Pacific Ocean and atmospheric circulation anomalies, reminiscent of the impact of ENSO, were shown to impact southern Africa's summer and winter rainfall at the interdecadal and quasi-decadal timescales (Dieppois et al. 2016, 2019). This could help understanding why, during some periods, ENSO does not strongly influence southern Africa as a cold or warm sea surface temperature background in the Pacific could make the impact of ENSO on the atmosphere weaker or stronger (Fauchereau et al. 2009; Pohl et al. 2018). This might also help understand the development of various ENSO flavors and their contrasted effects on southern Africa (Ratnam et al. 2014; Hoell et al. 2017). Indeed, the development of ENSO flavors might partly result from interactions between Pacific SST anomalies occurring on different timescales (e.g., Pacific Decadal Oscillation SST anomalies influencing ENSO anomalies). In austral summer, on interdecadal timescales, decadal ENSO-like forcing of the Pacific Decadal Oscillation (PDO) decadal variance indeed leads to shifts in the Walker circulation. At the regional scale, it contributes to ocean-atmosphere anomalies in the South Indian Ocean to shift the South Indian Convergence Zone toward the continent. According to Dieppois et al. (2016, 2019), combinations of ENSO forcing and ocean-atmosphere anomalies in the South Indian Ocean are thus needed in the relationship between Pacific Decadal

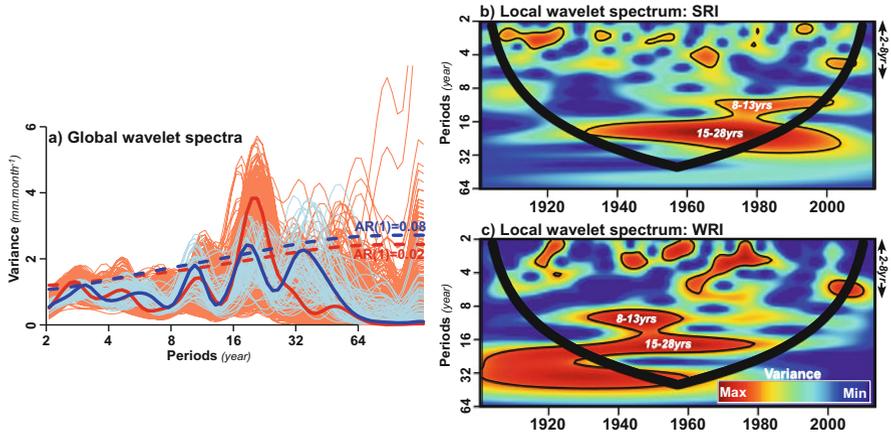


Fig. 6.8 Timescale patterns of variability for summer (SRI) and winter (WRI) southern African rainfall index (a) Global wavelet spectra of the SRI (red) and the WRI (blue), and of every grid-point used for their calculations (light red and blue). The dashed blue and red lines indicate the red noise spectra (b–c) Continuous wavelet power spectrum of the SRI and the WRI. Bold lines delineate the area under which power can be underestimated due to edge effects, wraparound effects and zero padding; thin contour lines show the 95% confidence limits. Note that SRI and WRI variability could be poorly represented from the mid-1990s due to a deficient number of rain gauges available in the Climatic Research Unit (CRU TS version 3.23) precipitation and temperature dataset that could substantially reduce interannual to interdecadal variability

Oscillation and southern African rainfall. The Interdecadal Pacific Oscillation (IPO) also drives such anomalies at the quasi-decadal timescale. At each timescale, colder or warmer Pacific SSTs result in changes to the Walker circulation: these interact with ocean-atmospheric modifications in the South Indian Ocean, which act together with varying degrees of importance to alter the intensity and longitudinal location of the South Indian Convergence Zone and, thus, to modulate the Tropical Trough developments and deep-convection over southern Africa (Dieppois et al. 2016, 2019; Pohl et al. 2018). The influence of tropical Pacific Ocean climate variability on austral winter southern African rainfall variability is almost negligible over the twentieth century. However, according to Philippon et al. (2012), the influence of tropical Pacific climate variability may have become more important since the 1970s. Decadal winter rainfall variability is strongly related to regional changes in the Southern hemisphere’s subtropical high-pressure system and, thus, mid-latitude westerly low-pressure activity (Dieppois et al. 2016). This corroborates previous findings by Reason and Rouault (2005), highlighting that the Southern Annual Mode (SAM) influence is strong in austral winter.

6.5 Current Climate Trends

The increase in the concentration of atmospheric greenhouse gases is causing a global rise in temperatures and possibly also trends in precipitation, as the content of water vapor in the atmosphere has increased. However, regional climate change may be somewhat different from the global picture, since regional orography, proximity to water masses and atmospheric circulation may also modulate regional climate trends. In the following paragraphs, we present a summary of temperature and precipitation trends in southern Africa over the last decades, as these two variables are probably the most important for stakeholders. However, one should bear in mind that trends in water availability for societal needs may also be impacted by nonclimatic management decisions (Muller 2018), so water scarcity maybe not always linked to climate trends. In addition, and as discussed in the previous section, precipitation in southern Africa is prone to significant natural decadal variations (Dieppois et al. 2016, 2019; Mahlalela et al. 2019), so trends derived over the recent decades may result from the impact of greenhouse gas forcing but may also reflect shorter natural swings. Disentangling both, i.e., unambiguously attributing recent observed trends to anthropogenic climate forcing, requires a detailed analysis of observations and model simulations. In that sense, only a few studies highlighted an increase in the likelihood of extreme climate conditions, notably drought and fire-prone weather, in the southwestern regions of southern Africa (Otto et al. 2018; Zscheischler and Lehner 2022; Liu et al. 2023). In addition, according to climate future projections, Pohl et al. (2017) highlighted that southern Africa could expect fewer rainy days and more extreme rainfall by the end of the twenty-first century. This is also consistent with recent analyses identifying an increased severity of drought in South Africa from the mid-1980s (Phaduli 2018; Jury 2018). Therefore, an ongoing analysis of all available data sets to identify long-term trends in societal climate impacts due to climate change or other human impacts is paramount.

Beyond South Africa, southern Africa is not as densely covered by a net of meteorological stations as western Europe or North America, so estimating long-term climate trends from point observations may provide only a partial illustration of regional climate trends. Previous studies focusing on long-term trends were mainly based on meteorological stations' data (Jury 2018; Kruger and Nxumalo 2017; Ullah et al. 2021). Here, we use climate reanalysis and observations.

The reanalysis is essentially a retrospective hindcast using weather prediction models that incorporate the information from available meteorological observations. The trends in precipitation and air temperature over the last decades are shown here with the global reanalysis data sets, ERA5, of the ECMWF (European Centre for Medium-Range Weather Forecasts, Hersbach et al. 2020) and the observational data set CRU (Climate Research Units gridded time-series data set; Harris et al. 2020). Both are analyzed over the period 1979–2020. In Fig. 6.9, the trends in precipitation of the two data sets are shown for the two rainfall seasons, winter rainfall in June–August (JJA) and summer rainfall in December–February (DJF). The summer rainfall zone (SRZ) covers most of southern Africa, and the winter

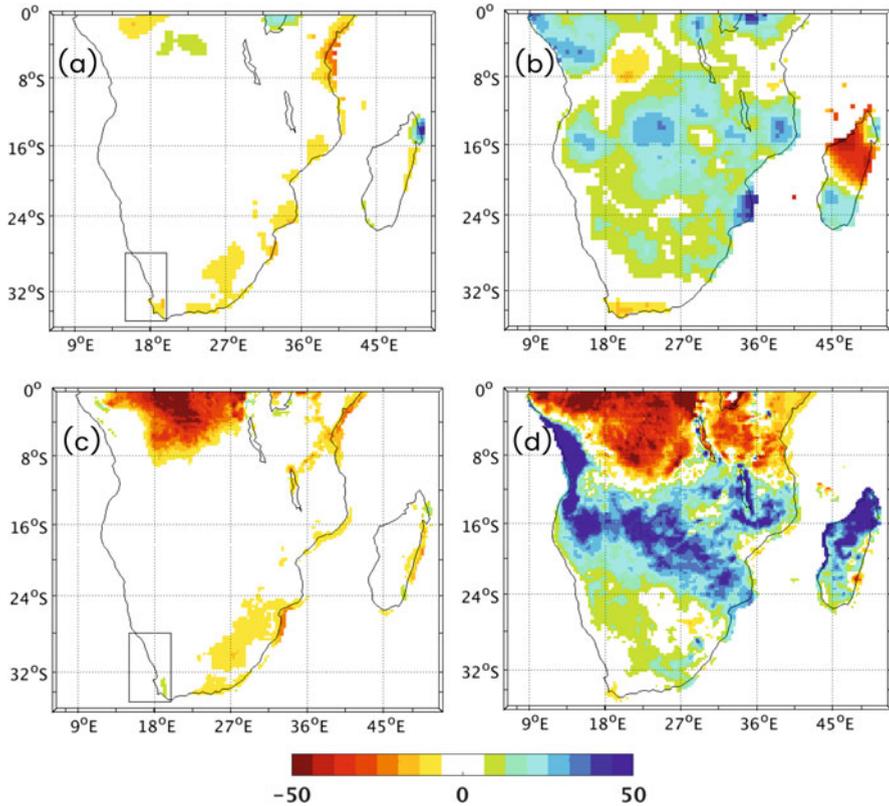


Fig. 6.9 Precipitation trends of CRU (a, b) and ERA5 reanalysis (c, d). Subfigures a, and c, left, are for the winter rainfall season (June–July–August), and subfigures b and d, right, are for the summer rainfall season (December–January–February). The winter rainfall zone is marked with black rectangular. Trends are given in mm/decade for the period 1979–2020. Based on typical standard deviation, trends of (a) 0.77, (b) 15.76, (c) 2.14 and (d) 31.8 mm/decade and larger are significant at a 95% level

rainfall zone (WRZ, black box in Figure 6.9a and c) covers the cape region in the southwest of South Africa.

For the winter rainfall zone, CRU and ERA5 provide somewhat different results. CRU shows a slight decrease in precipitation (Fig. 6.9a), while ERA5 shows an increase in the southwest of the winter rainfall zone (Fig. 6.9c), which has been found previously by Onyutha (2018) and MacKellar et al. (2014a, 2014b). In DJF in the summer rainfall zone, the precipitation has increased in most parts of southern Africa (Fig. 6.9b, d, Onyutha 2018; MacKellar et al. 2014a, 2014b; Kruger and Nxumalo 2017). Ullah et al. (2021) found a significant trend in the intensity of wet spells from 1965 to 2015 using daily observation and ERA5. Both CRU and ERA5 data sets show a drying at parts of the South African coast, which has also been found at the southeast coast by Jury (2018). Thus, the precipitation has

mainly increased in the SRZ and decreased in the winter rainfall zone over the last 40 years. It must also be considered that the assessment provided by the sixth IPCC assessment report does not differentiate between summer and winter precipitation (Ranasinghe et al. 2021), so it is not directly comparable with the assessment provided here. Also, the available precipitation data sets do not always agree in this region, illustrating their inherent uncertainty.

Air temperature trends near the surface are shown in Fig. 6.10. The temperature has risen along the coast in both seasons. This has also been found in station data sets (Jury 2013) and in the pace of record-setting temperatures (McBride et al. 2021). In addition, ERA5 shows an area in central southern Africa where cooling or no trend occurred in DJF over the analyzed period. An even more pronounced cooling has been detected in other reanalysis data sets (e.g., ERA-Interim and JRA-55) and has also been found in annual mean trends by Jury (2013). Further analysis of the

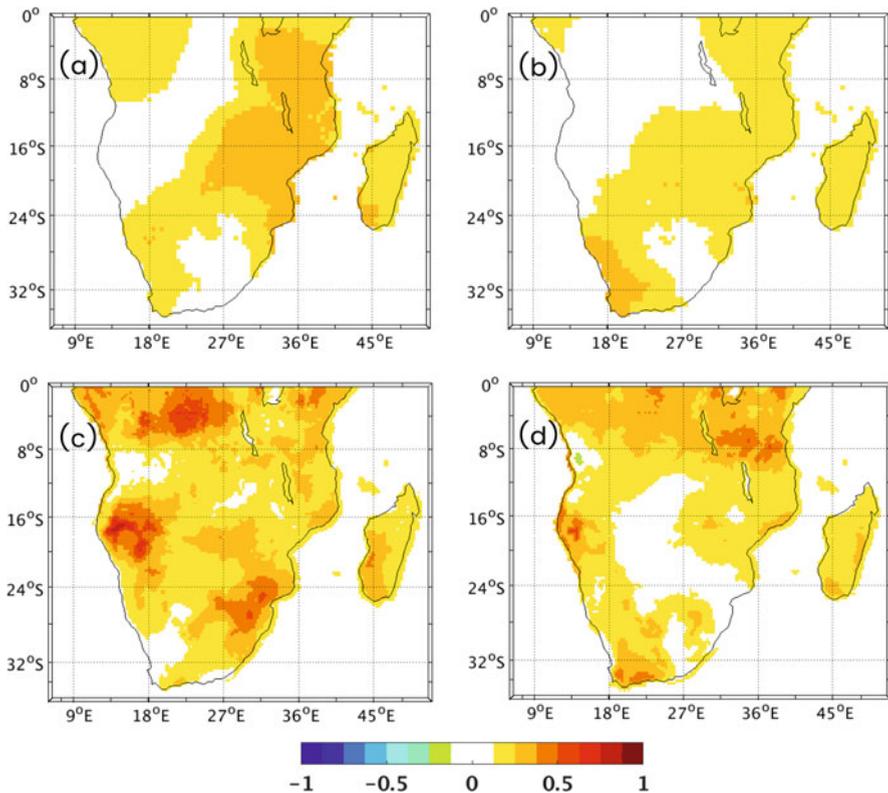


Fig. 6.10 2 m air temperature trends of CRU (a, b) and ERA5 reanalysis (c, d). Subfigures a, and c, left, are for winter (June–July–August), and subfigures b and d, right, are for summer (December–January–February). Trends are given in $^{\circ}\text{C}/\text{decade}$ for the period 1979–2020. Based on typical standard deviation, trends of (a) 0.09, (b) 0.11, (c) 0.19 and (d) 0.16 $^{\circ}\text{C}/\text{decade}$ and larger are significant at a 95% level

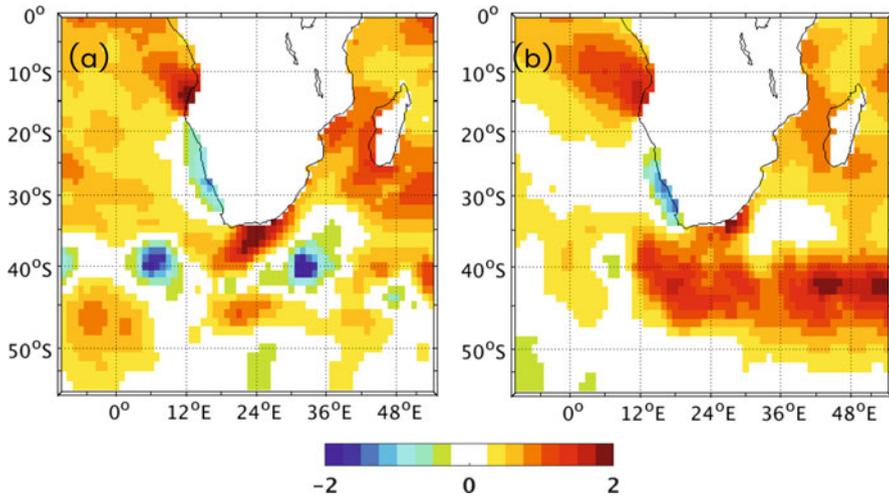


Fig. 6.11 Sea surface temperature (SST) trends of HadISST1, (a, left) for winter (June–July–August), (b, right) for summer (December–January–February). Trends are given in °C/period, which is 1958–2019. Based on typical standard deviation, trends of (a) 0.17 and (b) 0.35 degree/period and larger are significant at a 95% level

JRA-55 data set has shown that this cooling trend is likely an artifact of the data assimilation procedure. Fewer observational data can be assimilated in earlier years, and the introduction of increasingly more data can lead to this false-negative trend. The warming along the coast is accompanied by the warming of the adjacent oceans. The trends of sea surface temperature, as shown in Fig. 6.11, have been calculated using the interpolated observational data set, HadISST1 (Rayner et al. 2003). SSTs in the Agulhas Current and in the retroflexion, the region where the Agulhas Current turns eastward, have increased (Fig. 6.11 and Rouault et al. 2009), while SSTs in the Benguela Current have decreased (Fig. 6.11).

This warming in the Agulhas Current along the African coast of the Indian Ocean is upwind of the African continent. It may contribute to the positive trend in precipitation as the sea surface temperature of the Agulhas Current system influences southern Africa's rainfall (Nkwinkwa Njouodo et al. 2018; Imbol Nkwinkwa et al. 2021). The warming of the ocean off Angola could also have contributed to increased inland rainfall due to more significant atmospheric water content and subsequently increased moisture flux from the tropical Atlantic (Rouault et al. 2003).

To sum up, as found in basically all data sets analyzed here, the Agulhas Current, the Angola Current, the tropical Atlantic and the Indian Ocean have warmed, near-surface air temperatures along the coasts have risen, and rainfall has increased over large parts of the summer rainfall zone of southern Africa during austral summer while it has decreased over coastal areas of South Africa in both rainfall seasons of the last few decades.

6.6 Further Research Questions

Over the last ten years, much progress has been made in understanding the climate and weather of southern Africa, which has led to a significant number of publications in peer-reviewed journals, and which our paper cannot pay homage due to their sheer numbers. Seasonal forecasts of rainfall are used in the region and are more reliable during El Niño and La Niña. It is essential to maintain the precipitation and temperature observing system in South Africa and develop it in the other countries of southern Africa especially because we want to precisely quantify the effect of global climate change in southern Africa. It would also be essential to foster transdisciplinary studies involving social and economic sciences. Questions, which must be further explored in the future, remain, e.g.,

- What are the exact drivers of the annual cycle of rainfall?
- If the Pacific influences southern African climate at the interannual and decadal scale, can it influence the annual cycle?
- How do the annual cycle and interannual variability of climate impact regional processes relate to agriculture, water resources, management of cities and harbors, or any other relevant societal matter?
- Why do the maxima of summer rainfall happen in different months across the SRZ?
- Is there a climate fluctuation in the probability of extreme events?
- What are the drivers of the Hadley circulation, Walker circulation and the temperate circulation, and what are their roles in the annual cycle of rainfall and temperature?
- What is the role of the oceans and land feedback on the annual cycle of precipitation and temperature?
- Does the extratropical ocean affect the atmospheric circulation of South Africa?
- What is the contribution of the different synoptic systems and the diurnal cycle of rainfall to the annual cycle of precipitation and temperature?
- Why is the timing of the maximum of the diurnal cycle at a different time of the day in southern Africa?
- Why are the onset and demise of the rainy season occurring at different times of the year?
- Why is there no robust relationship between the strength of El Niño or La Niña and their impact on the intensity and spatial extent of southern African rainfall and temperature?
- Why is La Niña better correlated with southern African rainfall than El Niño?
- What exact mechanisms link El Niño and La Niña to southern African rainfall?
- Why is ENSO not related to the southern African climate for some decades?
- What is the role of the adjacent ocean, namely the Agulhas Current, the Mozambique Channel and the Benguela Current, on the southern African Climate?
- What is the role of the Indian Ocean and the tropical Atlantic Ocean?
- Are all relevant processes included in the models used for seasonal rainfall and temperatures forecasts or for future climate projections for southern Africa?

Acknowledgments This work was supported by the NRF SARCHI chair on “modeling ocean-atmosphere-land interactions,” the SPACE 2 project, the Nansen Tutu Centre, the EU H2020 TRIATLAS project under the grant agreement 817578, the Belmont Forum project EXEBUS and the PECO2 project. We like to thank NOAA for the NOAA OI V2 SST *data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA*. We also thank Copernicus and ECMWF for making the ERA5 dataset easily accessible.

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