CLIMATE
RISK AND VULNERABILITY

A HANDBOOK FOR SOUTHERN AFRICA

Second Edition

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CHAPTER 1:
OBSERVED TRENDS IN CLIMATE OVER SOUTHERN AFRICA

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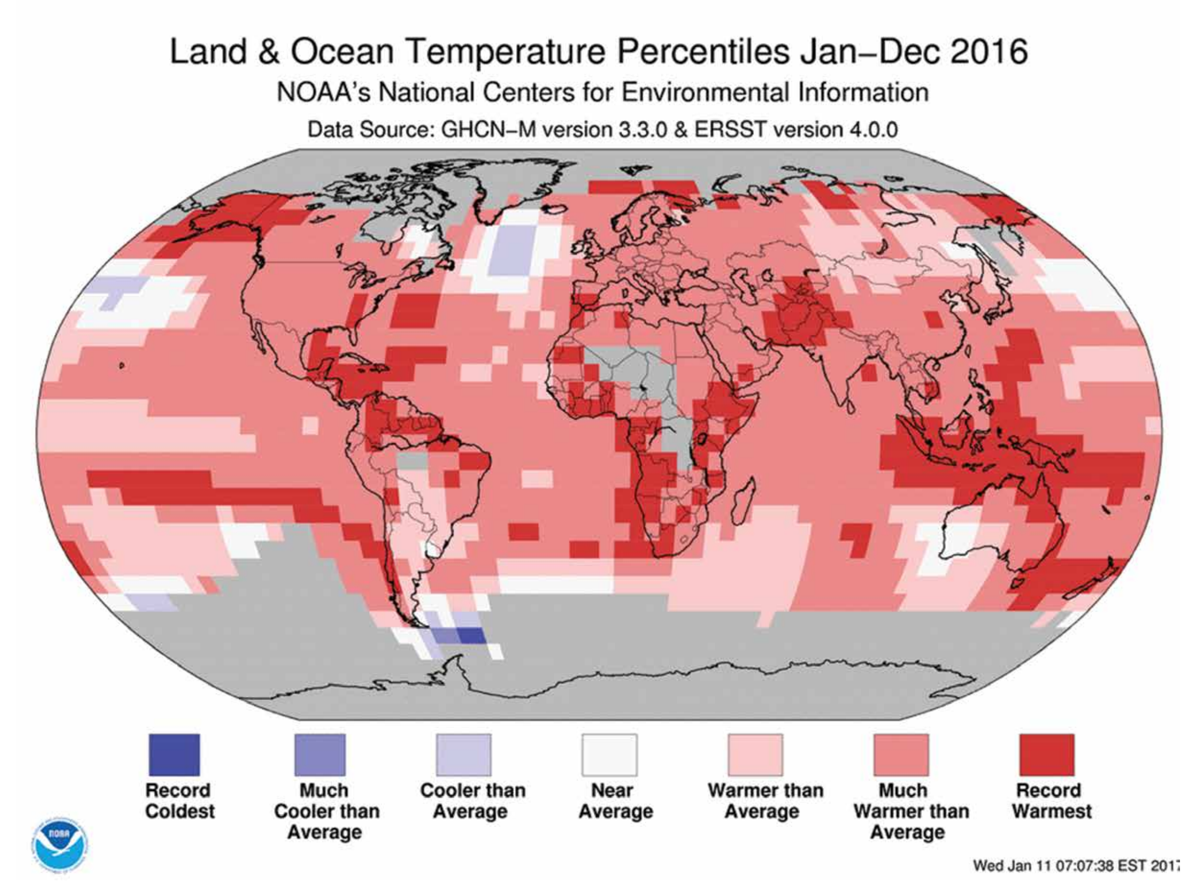
Southern Africa has been warming significantly over the last century. For the period 1961 to 2014, temperatures over the region have increased at a rate of 0.4 °C per decade. Historical rain patterns are characterised by strong inter-annual and inter-decadal variability and there is little evidence for a substantial drying or wetting over the region.

1.1. Introduction

The body of work on historical climate trends has been steadily increasing during the last decade. Global mean annual temperatures have increased by 0.85°C since 1880 and are projected to increase by 0.3 to 2.5 °C by 2050, relative to the 1985-2005 climatological average (Stocker et al., 2013). Along with 1998 and 2010, 2014, 2015 and 2016 are widely recognised as the warmest years on record. The regional distribution of temperature increases is not uniform, however, and some regions have experienced greater change than others.

For the African continent, the recent studies of Jones et al. (2012) and Engelbrecht et al. (2015) are indicative of drastic increases in surface temperature (in the order of twice the global rate of temperature increase). Over southern Africa a decrease in late summer rainfall has been reported over the western regions including Namibia and Angola (Niang et al., 2014). Where records are of sufficient length, there have been detectable increases in average rainfall intensity and the length of the dry season (New et al., 2006; Tadross et al., 2009). Recent studies for South Africa have detected decreases in rainfall and the number of rainfall days over parts of the country (MacKellar et al., 2014). There is also evidence from other studies which shows that inter-annual rainfall variability over southern Africa has increased since the late 1960s and that droughts have become more intense and widespread in the region (Fauchereau et al., 2003).

2016 was the warmest year on record, continuing the long-term warming trend (Source: NOAA)



This chapter presents:

- An analysis of observed trends in land- and sea-surface temperatures as well as rainfall across southern Africa over the last five decades using gridded climate products (CRU TEMv4, CRU TS 3.2, and HadSST);
- Estimates of the rate of relative sea level rise around the southern tip of Africa.

Evidence for recent changes in climate presented here, provides a context for the projections of future regional climate change and changes in climate extremes provided in later chapters.

1.2. Overview of the climate of southern Africa

Southern Africa has a warm climate, with the greater part of the region experiencing an average annual temperature above 17°C (Figure 1.1). In summer, temperatures are highest over the desert regions of Namibia and Botswana and exceed 40 °C during the day. In winter there is a latitudinal gradient, where temperatures decrease southwards and are coldest in the high-altitude regions of South Africa, Lesotho and Zimbabwe. Summer is from December to February (DJF), autumn from March to May (MAM), winter from June to August (JJA), and spring from September to November (SON).

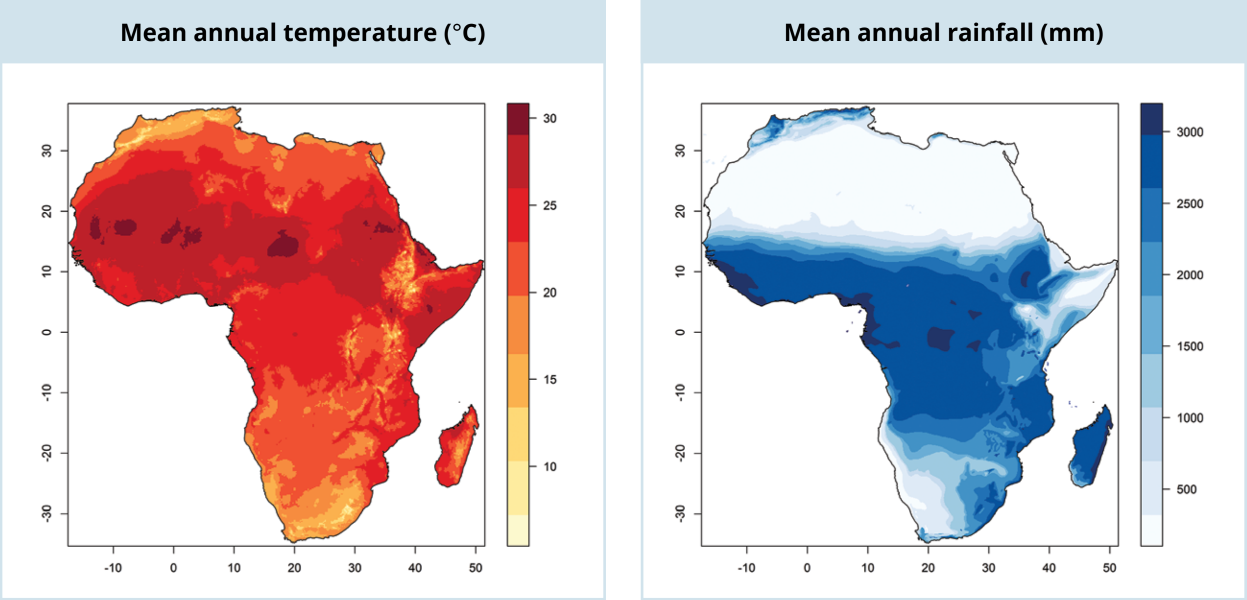
There is a high degree of spatial variation in rainfall across southern Africa due to the influence of the ocean currents and prevailing winds. The highest amount of rainfall occurs in the tropics towards the equator and in eastern Madagascar, which can receive up to 3 100 mm per year (Figure 1.1).

The majority of southern Africa has two distinct rain seasons – a wet season in the summer half of the year from roughly November to March and a dry season during winter from April to October. Areas around the equator and eastern Madagascar experience rainfall all year round, the Cape region of South Africa experiences winter rainfall due to the influence of mid-latitude cyclones, and areas in Tanzania have two rainy seasons — one from March to May and another lighter one from November to January (Hobbs et al., 1998). Tropical cyclones occasionally make landfall on the Mozambican and South African coastlines, bringing significant rainfall and associated flooding to Mozambique, the northern parts of South Africa, western Madagascar, and Zimbabwe.

Part of the reason for the diversity in southern Africa's climate is the dependence on a wide range of distinct climate systems. The average climate is strongly determined by four main factors (Nicholson, 2000):

i) The position of the subcontinent in relation to the major circulation patterns of the southern hemisphere (quasi-stationary high-pressure systems);
ii) The migration of the Inter-Tropical Convergence Zone (ITCZ), which affects the timing and intensity of rainfall;
iii) The complex regional topography (ranging from sea level to a plateau at 1 250 m, and mountains exceeding 3 000 m); and
iv) The influence of the warm Indian Ocean on the east coast and the cold Atlantic Ocean on the west coast – which leads to higher and lower rainfall respectively.

These factors interact to produce a wide variety of climate zones within the region: arid coastal desert from about 32 degrees of latitude to the border of Namibia with Angola, a semi-arid temperate climate over the interior central plateau, a humid subtropical climate over the low-lying coastal regions of the south-east, and a Mediterranean climate in the southern part of South Africa. Superimposed upon the subregional diversity of climate is the role of inter-decadal patterns of natural variability, notably El Niño-Southern Oscillation (see Box 1.1), the Indian Ocean dipole, and the inter-decadal Dyer-Tyson system.



Mean annual temperature (°C)

Mean annual rainfall (mm)

Figure 1.1: (a) Average annual and seasonal temperatures (°C) over Africa (Source: Hijmans et al., 2005) and (b) Mean annual and seasonal rainfall expressed as millimetres (mm) (Source: FAO/Agrhymet Network and ESRI).

Box 1.1: El Niño-Southern Oscillation (ENSO)

The El Niño-Southern Oscillation (ENSO) is a recurring natural climate phenomenon that has important consequences for weather, with extreme events (floods and droughts) occurring in various locations around the world. While largely unpredictable at long time ranges (initiation is observable up to six months before), it occurs approximately every two to seven years (Schreck & Semazzi, 2004).

The ENSO cycle is characterised by spatially coherent and strong variations in sea-surface temperature (SST), rainfall, air pressure and atmospheric circulation across the equatorial Pacific. El Niño refers to the warm phase of the cycle, in which above-average SSTs develop across the east-central tropical Pacific Ocean and below-average SSTs occur across the western Pacific Ocean, due to a change in wind patterns. The opposite state is called La Niña; the cold phase of the ENSO cycle. Each phase lasts approximately one to two years, with some events being larger in amplitude and lasting longer than others.

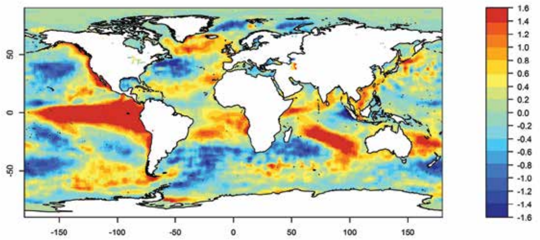
Over southern Africa, El Niño conditions are generally associated with below-average rainfall years over the summer rainfall regions, while La Niña conditions are associated with above-average rainfall conditions (see figure below). For example, in 1982/83 and 2015/16 below-average rainfall and droughts in many parts of the region coincided with strong El Niño events. Recent evidence suggests that ENSO also modulates rainfall in the winter rainfall region of South Africa, with El Niño (La Niña) years being associated with higher (lower) than normal rainfall amounts in May, June and July (Philippon et al., 2011).

The size, duration and intensity of El Niño are not well correlated with the intensity and spatial extent of drought. A large El Niño event does not necessarily result in a larger impact as other factors such as land-surface temperatures, availability of food, political stability (among others) affect the vulnerability of a region to drought.

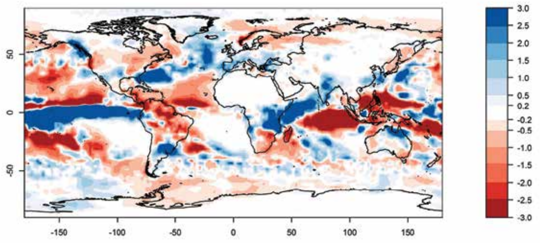
Example of average SST and rainfall anomalies during an:

El Niño Year

Average change in SST (°C)

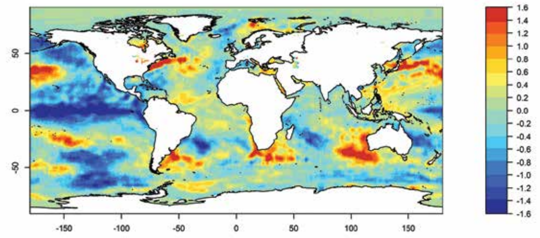


Average change rainfall (mm/day)

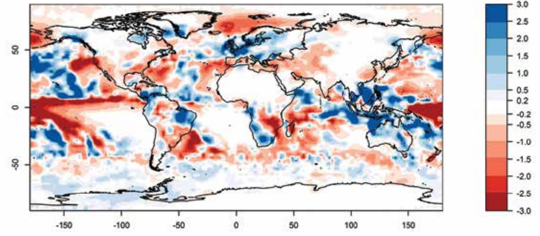


La Niña Year

Average change in SST (°C)



Average change rainfall (mm/day)



1.3. Analysis of observed trends in climate over southern Africa

One way to investigate how regional climate could change in future is to examine how it has changed in the past. As described in the introduction, observational records have already provided evidence of a changing global climate over the last century. Reconstructions of past climatic fluctuations and evidence of more recent changes, based on available observational records together with scientific research about the drivers of change can help scientists understand how greenhouse gas induced climate change has already influenced regional climate (particularly for changes in temperature). For details on the methodology and trend assessment techniques used here, see Section 1 of the Supplementary Information.

1.3.1. Land-surface temperature

The CRUTEM4 (Climatic Research Unit Temperature, version 4) land-surface temperature data set (Jones et al., 2012; Osborn & Jones, 2014) was used to assess changes in temperature over Africa.

There is strong evidence that the average land-surface temperature has increased across Africa over the last century (Figure 1.2), and that this warming has been particularly marked since the 1970s with the decade of the 2000s being the warmest (Figure 1.4). The regional distribution of temperature increases is uneven and some regions have experienced greater change than others. The largest trends, of 0.4 °C per decade, are observed over subtropical southern Africa, subtropical North Africa and parts of central Africa (Figure 1.2). Temperature trends across seasons show a slightly larger warming in summer (DJF) and autumn (MAM) compared with the other seasons (Figure 1.3 and Figure 1.5). Analysis of other data sets (refer to Figure S.1 through to Figure S.4) supports this trend.

The rate of change in temperature over Africa is more than twice the global estimates of temperature increase of 1.12 per century and 0.42 per century for the northern and southern hemispheres respectively (Jones et al., 2012; Osborn & Jones, 2014). These trends are consistent with detected increases in regional temperatures since 1900 (Niang et al., 2014; MacKellar et al., 2014; Engelbrecht et al., 2015). Projections of future temperature change for Africa (refer to Chapter 2) indicate that temperatures are expected to continue to increase. Associated with these increases are increases in evapotranspiration across the region, which have important implications for water stress (Niang et al., 2014; Matsoukas et al., 2011).

Spatial differences between the data sets occur in areas (see Box 1.2) where observational sampling is geographically incomplete, for example areas in Tanzania and Botswana. This suggests that the confidence in the finer spatial detail of the trends is lower in these regions. Temperatures also exhibit substantial decadal and inter-annual variability, where two different periods may exhibit different spatial patterns and differing magnitudes of warming. Differences between the data sets are larger in earlier periods (for example 1900-1960) due to the lack of observational records: this is true globally, but is particularly evident over Africa (Stocker et al., 2013a).

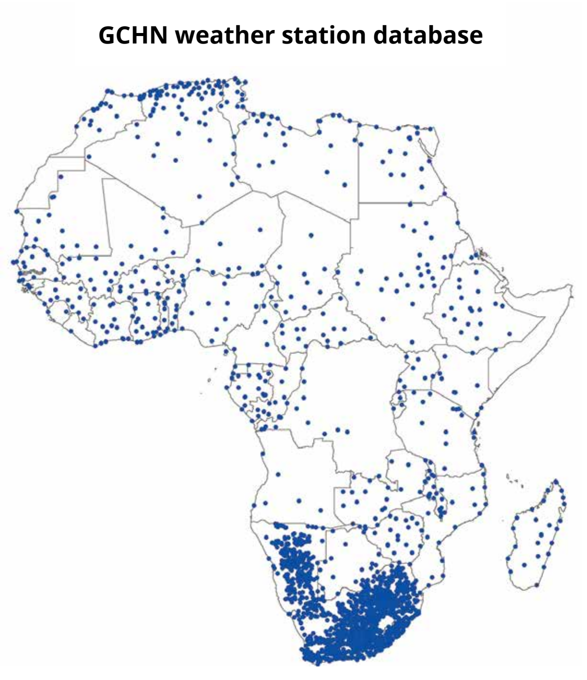
Evidence from some studies in the region (for example New et al., 2006) have demonstrated that minimum temperatures are increasing at a faster rate than maximum temperatures across the interior southern Africa. This has resulted in a decrease in the diurnal temperature range (DTR) for many parts of the globe. Two recent studies in South Africa (Kruger & Sekele, 2013; MacKellar et al., 2014) found no clear consistent pattern with regards to changes in DTR and suggested, along with the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (hereafter referred to as the IPCC AR5), that this topic requires further exploration and research.

Box 1.2: Data-related challenges

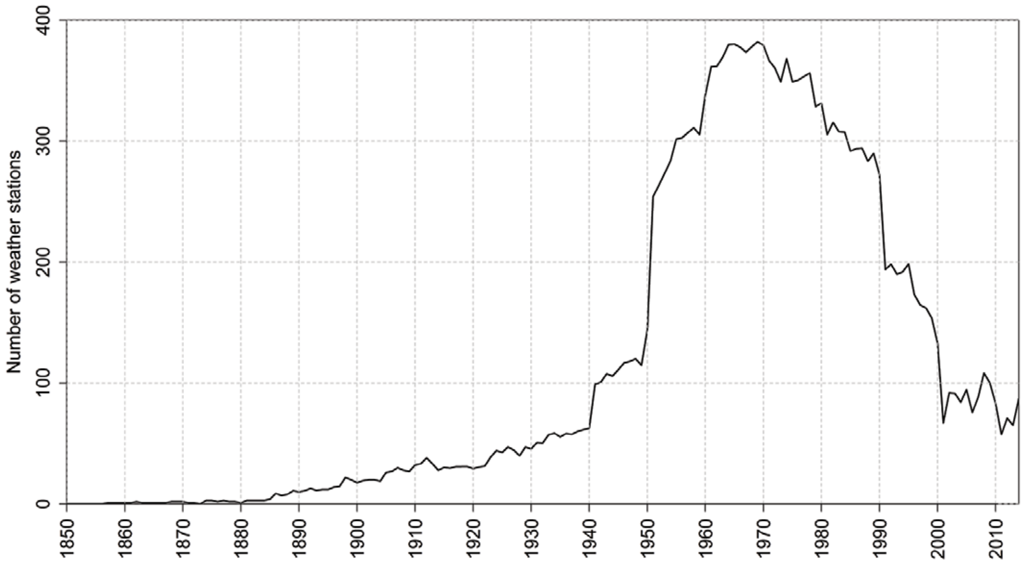
Detecting and attributing regional climate trends in Africa is subject to challenges of data availability. Firstly, there is a lack of an accurate, long-term, well-maintained and dense spatial network of observational stations. Since each station represents only a single point, the information collected may not be adequately representative of the surrounding region. Furthermore, the number of weather stations across southern Africa has decreased drastically since the 1980s, meaning that there are relatively few stations available that have sufficient data for analysis spanning several decades.

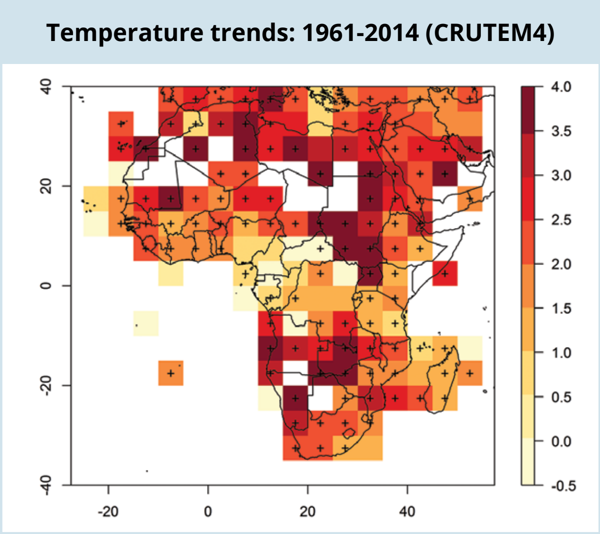
Secondly, in southern Africa many climate variables, particularly those related to rainfall, exhibit very high variance on time scales ranging from daily through to multi-decadal (see Box 1.1 on the influence of ENSO). Climate change is superimposed on this variability, which makes it challenging to understand how the regional climate is changing. Scientists are seeking to understand how climate change interacts with these natural drivers to influence southern African climate, but this is very challenging given limited data availability.

The location of NOAA's Global Historical Climate Network (GHCN) weather stations, as used by CRU, across Africa.



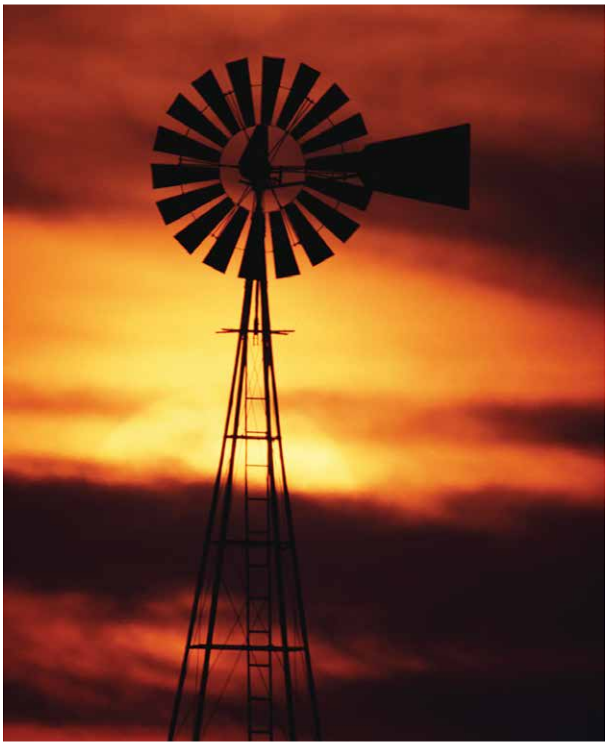
The number of weather stations collecting daily temperature records across southern Africa from 1850 to 2014 used in the gridded CRUTEM4 product. Station density increased consistently from the start of the 20th century and peaked in the 1970s, after which it began to decline.





Temperature trends: 1961-2014 (CRUTEM4)

Figure 1.2: Observed trends in annual average near-surface temperature (°C per decade) over Africa for the period 1961-2014 based on CRUTEM4v data. Crosses indicate grid boxes where the trend is statistically significant. White areas indicate incomplete or missing data.



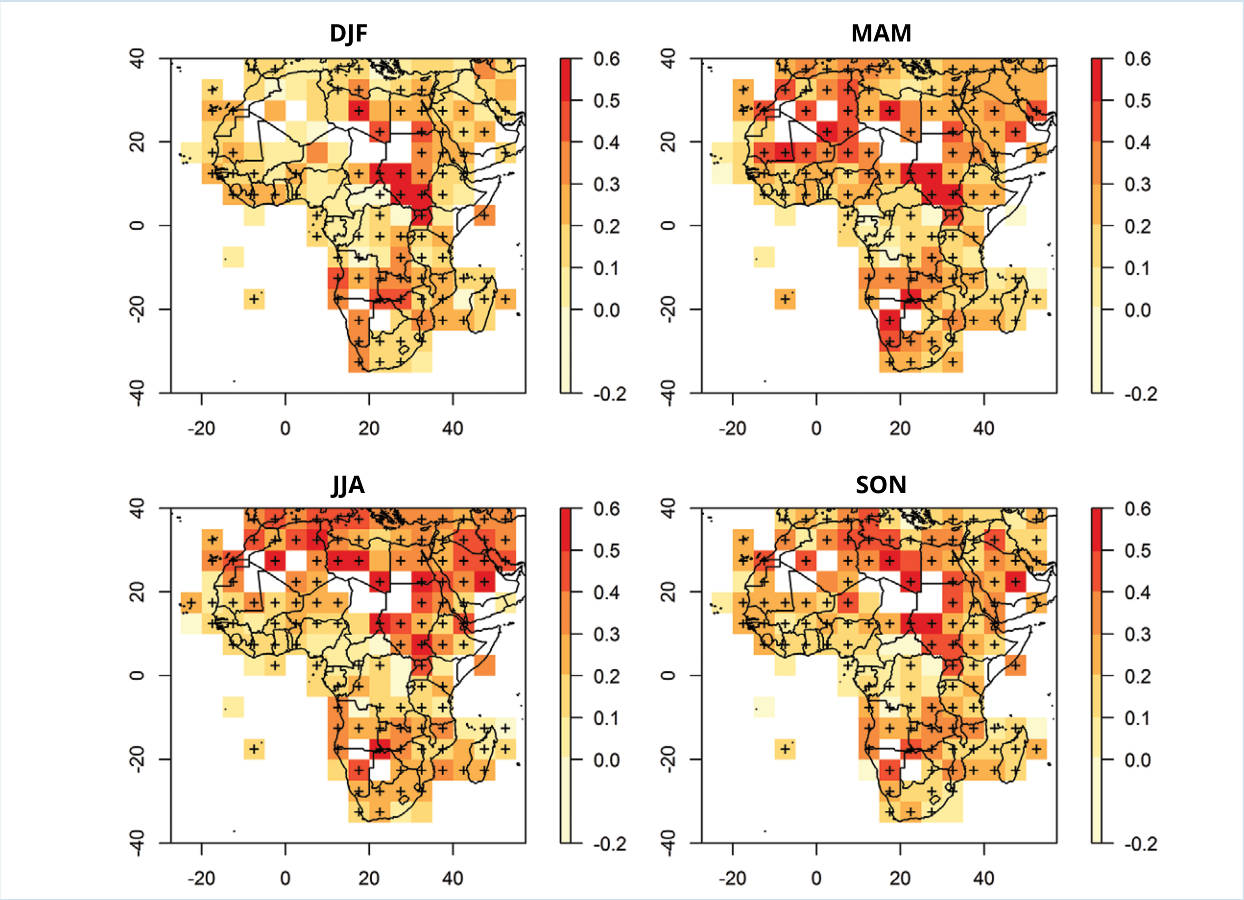


Figure 1.3: Observed trends in seasonal average near-surface temperature (°C per decade) over Africa for the period 1961-2014 based on CRUTEM4v data. Grid boxes where the trend is statistically significant are indicated by crosses. Seasons are given as summer (December-January-February), autumn (March-April-May), winter (June-July-August), and spring (September-October-November). White areas indicate incomplete or missing data.

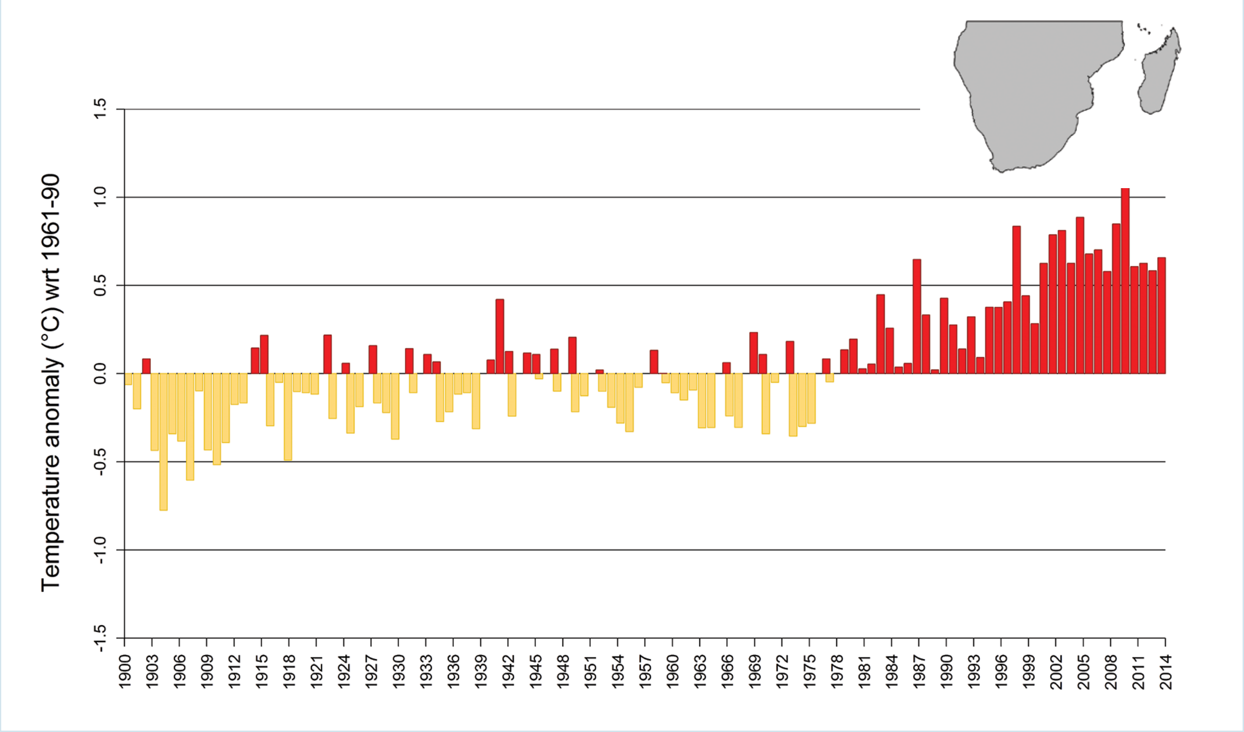


Figure 1.4: Mean annual temperature anomaly (°C) over southern Africa from 1901 to 2014 with respect to the long-term average climatology 1961-1990; based on the gridded CRUTEMv4 data set. Red represents a positive anomaly and yellow a negative temperature anomaly.

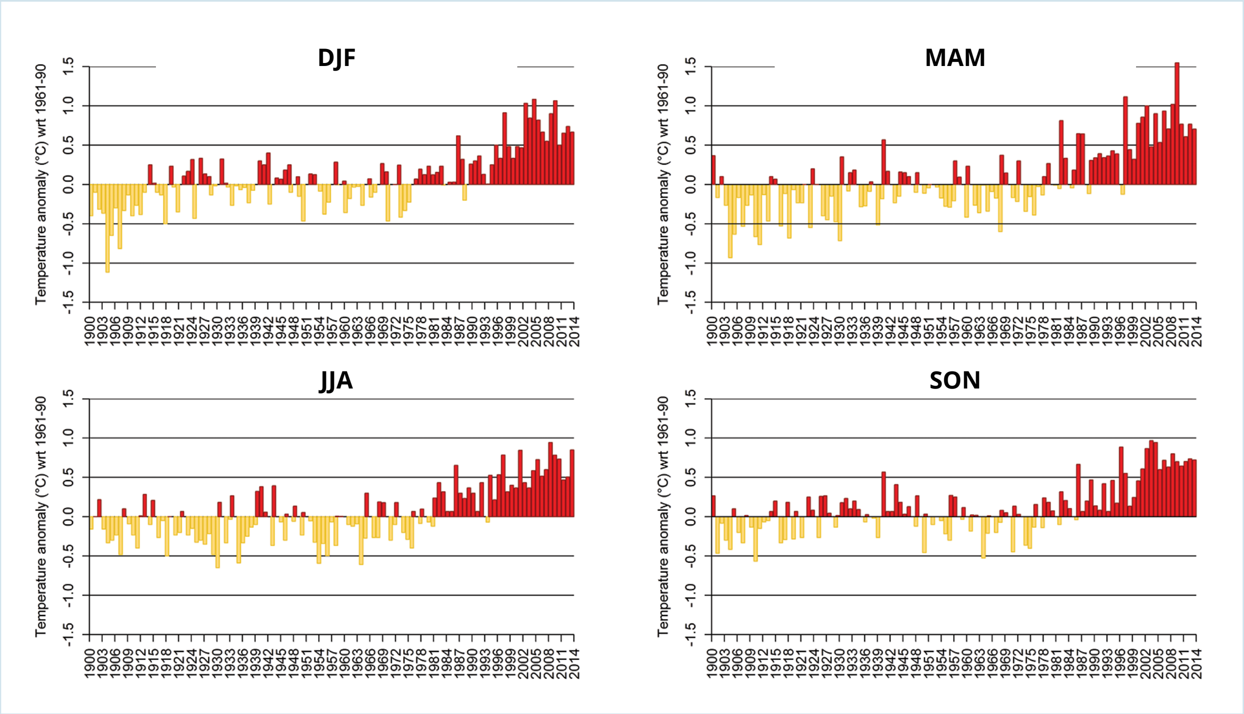
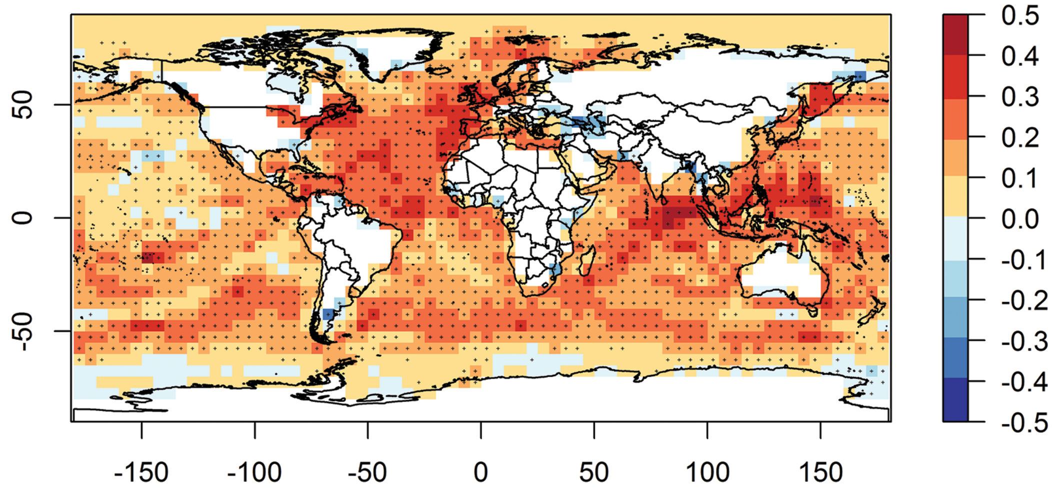


Figure 1.5: Seasonal temperature anomalies (°C) over southern Africa from 1901 to 2014 with respect to the long-term average climatology 1961-1990; based on the gridded CRUTEMv4 data set. Red represents a positive anomaly and yellow a negative temperature anomaly. Seasons are given as summer (December-January-February), autumn (March-April-May), winter (June-July-August), and spring (September-October-November).

1.3.2. Sea-surface temperature

Trends in sea-surface temperature (SST) demonstrate warming at all latitudes along the entire African coastline (Figure 1.6). The highest increases in SST are observed in the northern Atlantic and the north-west and south-west Pacific. Increasing SSTs are also observed over the Indian Ocean. Noting some differences between data sets (see Figure S.5 in the supplementary information), negative or lower magnitude positive trends are observed in the eastern Pacific along the coastlines of the Americas. These trends are consistent with those reported elsewhere (Strong et al., 2000; Good et al., 2007; Stocker et al., 2013a; Roxy et al., 2015), and which are expected to continue with climate change. Changes in SST have important implications for the upwelling strength in the Benguela Current system as well as the Agulhas Current, both of which are important drivers of climate for southern Africa.



SST trends (Tau): 1961-2014 (HadSST3))

Figure 1.6: Observed trends in sea-surface temperature based on the Mann-Kendall test[3] for the period 1961-2014 based on HadSST 3.1.1.0 data set. Grid boxes where the trend is statistically significant are indicated by crosses.

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[3] Values refer to Mann Kendall's correlation coefficient , which ranges from 1 to +1 where a value of +1 indicates a trend that consistently increases and never decreases. The opposite is true of a value of -1. A value of 0 indicates no consistent trend.

1.3.3. Observed changes in relative sea-level rise

Global sea-level rise (SLR) over the last decade has been 3.3 ± 0.4 mm/year (Rahmstorf et al., 2007). The IPCC AR5 (Stocker et al., 2013a) concludes that anthropogenic global warming and sea-level rise will continue for centuries due to the timescales associated with climate processes and feedbacks, even if greenhouse gas concentrations are stabilised or reduced (Figure 1.7).

The geological environment of the oceans and coasts is also important when definitions of SLR are made. If the SLR is measured with respect to the Earth's centre, it is called *eustatic* or *absolute* sea-level change and refers to climate-related global changes (Bollmann et al., 2010). If the vertical movements of the Earth's crust are taken into account, it is called *relative* sea-level change (Bosboom & Stive, 2015). Relative SLR is the combined effect of both absolute SLR and land subsidence or uplifting and is thus the locally perceived sea-level change (Bosboom & Stive, 2015). Limited research has been done in southern Africa regarding SLR. Some literature regarding the topic may be found in Brundrit (1984), Hughes et al. (1991; 1995), Mather (2008); Mather et al. (2009), and Mather & Stretch (2012).

The west, south and eastern coast of southern Africa can expect different rates of relative sea-level rise when vertical local movements of the Earth's crust are considered, as well as the recorded changes in atmospheric and barometric pressure (Mather et al., 2009).

Both crust movements and barometric pressure varied around the southern tip of Africa, resulting in a varying *relative sea-level* rise of:

- +1.87 mm/year for the South African west coast (based on intermittent data from 1959 to 2006);
- +1.48 mm/year for the South African south coast (based on intermittent data from 1957 to 2006); and
- +2.74 mm/year for the South African east coast (based on intermittent data from 1967 to 2006).

The absolute sea-level rise values predicted by Mather (2007) compare well with global value predictions (Bollmann et al., 2010; Stocker et al., 2013a).

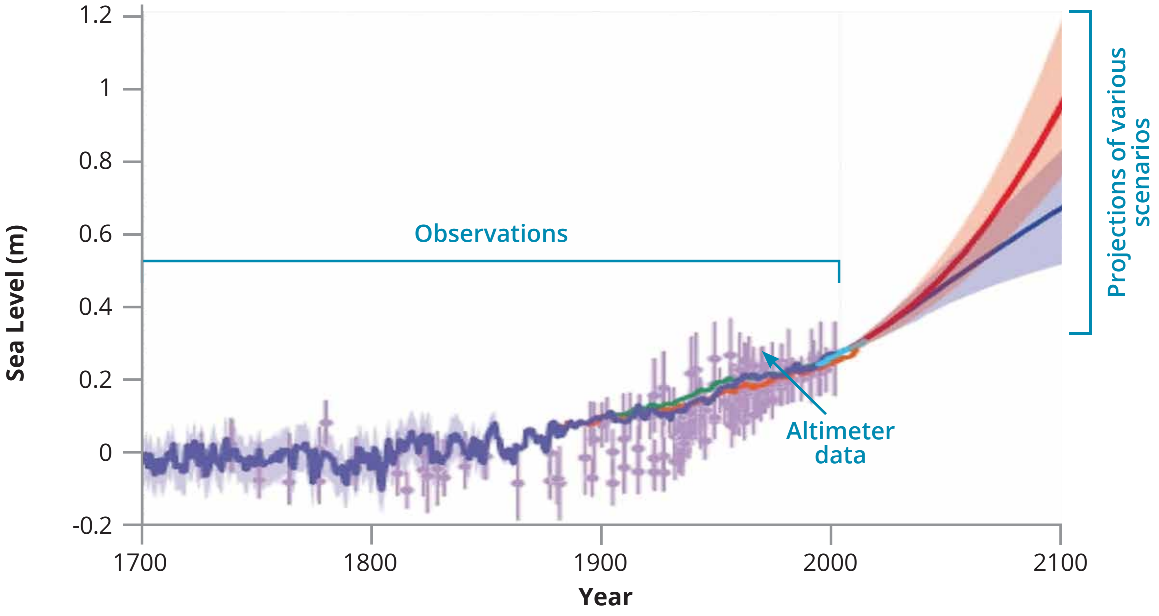

Figure 1.7: Example of measured and projected sea-level rise adapted from IPCC AR5 (Stocker et al., 2013a). The measurements are a compilation of paleo sea-level data (purple), tide gauge data (blue, red and green), and altimeter data (light blue). The projections of the absolute mean sea-level rise over the 21st century relative to 1986–2005 formulated on process-based models together with the error ranges are indicated in the shaded areas and the corresponding mean value as a solid horizontal line (Stocker et al., 2013a). All these values are relative to the pre-industrial values.

1.3.4. Rainfall

Changes in rainfall are typically harder to detect because compared with temperature, rainfall has higher variability, both spatially and from year to year (Fauchereau et al., 2003). Trends in rainfall across Africa need to be treated with caution as most of the continent lacks sufficient observational data to draw robust conclusions on the trends over the past century.

The CRU TS 3.23 (Climatic Research Unit time series version 3) dataset for the period 1900 to 2014 (Harris et al., 2013) was used to assess changes in rainfall over Africa.

For southern Africa, the rainfall time series (Figures 1.8 and 1.9) is characterised by strong inter-annual and inter-decadal variability with periods of above and below average rainfall, for example 1973–1976 and 1993 respectively. The alternating patterns of above normal/below normal rainfall periods clearly illustrate the rainfall cycles prevalent in southern Africa where extreme wet and dry years have been recorded, which resulted in floods and droughts (refer to Chapter 3). There is little evidence from the CRU TS 3.23 time series of a substantial overall wetting or drying trend over the period. Furthermore, trends are not consistent across different observed precipitation data sets and any signals of change are weak and statistically insignificant. Box 1.3 highlights the results of country-specific studies on rainfall trends.

The multi-decadal variability in rainfall over southern Africa is explored further in Figure 1.10. The decade 1960-1969 was characterised by below-normal rainfall over most of the region, except for Angola, Malawi, Zambia, Democratic Republic of Congo and Tanzania. Later in the 1970s this rainfall anomaly pattern was reversed, with parts of southern Africa experiencing above-normal rainfall. Southern Africa was considerably drier in the 1990s compared with the other decades, likely owing to the 1991/1992 drought. The 2000s were wetter for most of the region except for the countries along the south-western coast of Africa and eastern coastline of Tanzania.

CRU TS 3.23: Rainfall over southern Africa

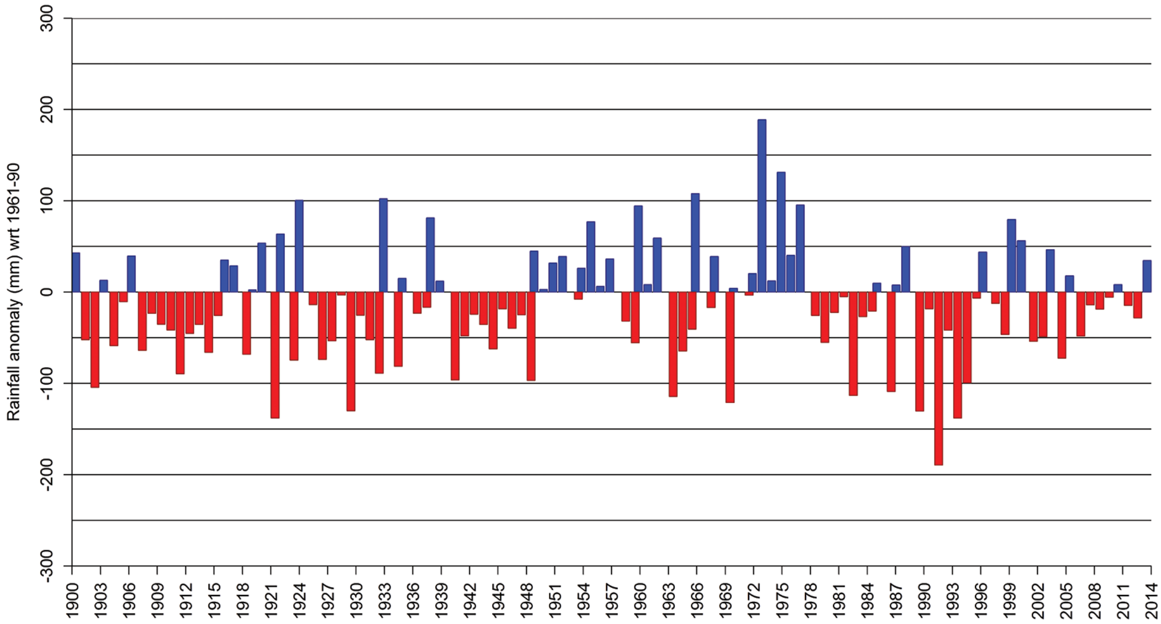

Figure 1.8: Mean annual rainfall anomaly (mm) over southern Africa from 1901 to 2014 with respect to the long-term average climatology 1961-1990; based on the gridded CRU TS 3.23 data set. Red represents positive anomaly and blue a negative anomaly in temperature.

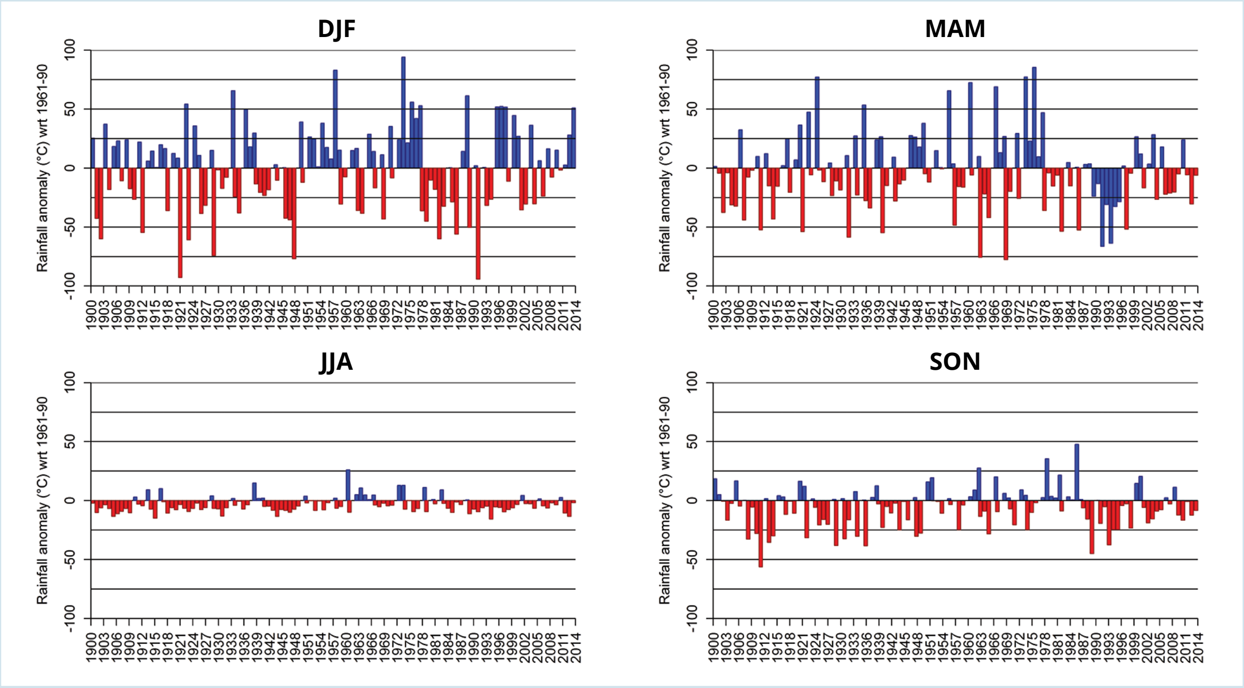

Figure 1.9: Seasonal rainfall anomalies (mm) over southern Africa from 1901 to 2014 with respect to the long-term average climatology 1961-1990; based on the gridded CRU TS 3.23 data set. Red represents positive anomaly and blue a negative anomaly in temperature. Seasons are given as summer (December-January-February), autumn (March-April-May), winter (June-July-August), and spring (September-October-November).

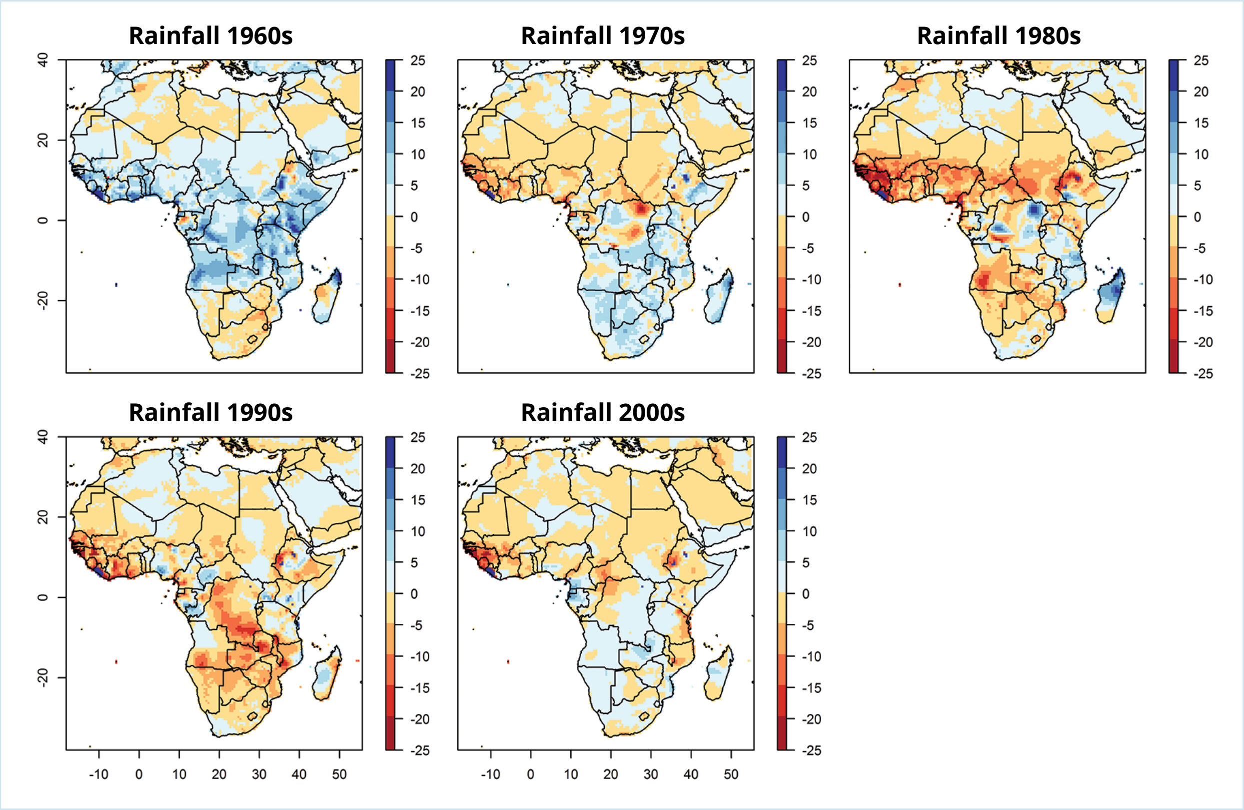

Figure 1.10: Decadal anomalies in rainfall with respect to the long-term average climatology 1961-1990; based on CRU TS 3.23 data.

Box 1.3: Country-specific rainfall trends in southern Africa

South Africa	• Between 1960 and 2010 decreases in rainfall and the number of rainfall days have been observed over parts of the country (MacKellar et al., 2014) • Positive trends in annual rainfall totals over the southern interior of the country and a drying trend in the north and north-east were observed over the period 1921 to 2015 (Engelbrecht et al., 2016, in press).
Botswana	• Rainfall data between 1975 and 2005 indicate a trend towards decreased rainfall and the number of rainy days throughout the country (Batisani & Yarnal, 2010).
Zimbabwe	• Some studies have concluded that average rainfall has declined (for example Unganai, 1996), but more recent studies using weather station records ranging from 1941 to 2000 from across the country have not found significant trends (Mazvimavi, 2010; Mapurisa & Chikodzi, 2014).
Mozambique	• Analysis of weather station data between 1960 and 2005 shows indications of a later start date of the rainfall season by up to 45 days in some areas (Tadross, 2009). • Decrease in mean annual rainfall between 1960 and 2006 due to a decrease in summer rainfall totals (McSweeney et al., 2010). • Increase in high-intensity rainfall events between 1960 and 2006, with the largest increases observed in summer (McSweeney et al., 2010).
Malawi	• Inter-annual rainfall variability is very strong and studies have found no evidence from rainfall records (1960-2000) of a change in rainy season totals, season length or duration of dry or wet spells (McSweeney et al., 2010; Vincent et al., 2014; Sutcliffe et al., 2016).
Namibia	While data from 1901 to 2000 show no directional change, trends based on rainfall station data between 1960 and 2006 have indicated (DRFN, 2008): • Shorter rainfall seasons in most regions of the country; • A decrease in the number of consecutive wet days; and • An increase in measures of rainfall intensity.
Angola	• Decrease in rainfall between 1960 and 2006 due to decreases in autumn rainfall (McSweeney et al., 2010).
Zambia	• Decline in rainfall between 1960 and 2006 over the country largely due to decrease in summer rainfall (McSweeney et al., 2010; Phiri et al., 2013).
Tanzania	• Significant decline in annual rainfall between 1981 and 2014, with greatest decreases observed in the southern region of the country (McSweeney et al., 2010; Harrison, 2015).
Madagascar	• Rainfall is highly variable particularly as a result of single extreme rainfall events due to tropical cyclones. • Total rainfall as well as the length of dry spells during winter and spring has been steadily decreasing between 1961 and 2005 (Tadross et al., 2008).
Mauritius	• There is no trend in annual rainfall evident between 1960 and 2006 (McSweeney et al., 2010). • Decline in rainfall over October-November-December between 1960 and 2006 (McSweeney et al., 2010).
Democratic Republic of Congo (DRC)	• Insufficient data to conduct analysis of changes in annual, seasonal or daily rainfall characteristics.

1.3.5. Extreme events

Sparse operational records in southern Africa (refer to Box 1.2) limit the ability to detect trends in extremes with sufficient confidence. Some changes are more evident with clear long-term trends (e.g. higher frequency of hot days), while changes in other smaller-scale events are more difficult to detect (e.g. thunderstorms).

There is strong evidence to suggest that the number of hot extremes have increased and the number of cold extremes have decreased, which is consistent with the global warming trend (Field, 2012; Stocker et al., 2013). Low temperatures, including the number of frost days, have decreased in frequency and are expected to become less frequent in the future (New et al., 2006).

The analysis of HadGHCNDEX data (refer to Figure S.6) reveals statistically significant increases in the following indices:

- Percentage of days when TX 90th percentile of the baseline average (TX90p)
- The number of days when TX>25 °C (SU25)
- Annual count days with at least six consecutive days (WSDI)

Some studies have shown that an increase in both maximum and minimum temperatures has resulted in a decrease in the DTR in many parts of the globe (Blunden et al., 2012; Easterling et al., 1997; Karl et al., 1993). Two recent studies in South Africa (Kruger and Sekele, 2013; MacKellar et al., 2014), on the other hand, found no clear consistent pattern with regards to changes in DTR and suggest that this topic requires further exploration and research in the southern African context.

Changes in extreme rainfall events are harder to detect because rainfall demonstrates a high degree of spatial and temporal variability (Fauchereau et al., 2003; Field et al., 2014; Stocker et al., 2013). Evidence suggests that the frequency of dry spells as well as daily rainfall intensity has increased (New et al., 2006). Climate change is expected to alter the magnitude, timing, and distribution of storms that produce flood events (Engelbrecht et al., 2013; Fauchereau et al., 2003; Stocker et al., 2013).

There is some evidence to suggest that droughts have become more intense and widespread over southern Africa (Fauchereau et al., 2003; Hulme et al., 2001; Masih et al., 2014; New et al., 2006), but more recent evidence is lacking. An increased frequency in droughts is projected due to the projected increases in temperature combined with a decrease in rainfall in parts of southern Africa (Engelbrecht et al., 2015; Shongwe et al., 2011; Stocker et al., 2013).