

**An analysis of heavy rainfall events over the Limpopo River Basin
in southern Africa, their moisture sources and pathways**

by

Ramontsheng Sakia Rapolaki



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Oceanography, University of Cape Town**

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I would like to dedicate this thesis to my parents (Sankinyane “Polaki” Rapolaki and Mmajane “Mmathebe” Rapolaki), my siblings (Thebe, Gooiman, Konoswane, and Jemina), and my nieces (Freddelin and Joy). In memory of my brother, Mohlolo Rapolaki, and grandmother, Dineo Ntama. Keya leboha!

Supervisors

Prof. Chris Reason

Department of Oceanography, University of Cape Town, South Africa

Assoc/ Prof. Juliet Hermes

South African Environmental Observation Network (SAEON), South Africa

Department of Oceanography, University of Cape Town, South Africa

Dr. Ross Blamey

Department of Oceanography, University of Cape Town, South Africa

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Signature:

Signed by candidate

Date: 10 February 2020

Student Name: Ramontsheng Sakia Rapolaki

Student Number: RPLRAM001

Abstract

Severe flooding events in subtropical southern Africa are not uncommon and can cause damage to infrastructure, lead to huge economic losses, and fatalities. Although extreme rainfall events can have far-reaching negative consequences, they can also provide large amounts of freshwater within a short time span, which supports the rain-fed farming upon which much of the population depends. However, the mechanisms through which extreme rainfall is produced in southern Africa are still not well understood. In particular, relatively little is known about where the moisture, a key ingredient in the rainfall, is sourced and how it is transported into the region. This thesis aims to address some of the gaps in this understanding by examining the moisture sources and subsequent moisture transport moisture into one of the key river basins in southern Africa, the Limpopo River Basin (LRB). The LRB, located in eastern southern Africa and spanning four countries, has experienced a number of extreme flooding events over the last three decades.

Using CHIRPS satellite merged rainfall data for 1981-2016, the thesis identified the top 200 heavy extreme rainfall events in the LRB and the associated weather systems. It was found that tropical-extratropical cloud bands account for almost half of the events and tropical lows are responsible for just over a quarter. The remaining quarter of the events are associated with mesoscale convective systems and cut-off lows, the latter more important during transition seasons. Most of the events occur in the late summer when tropical lows and cloud bands are more common. Some relationships between the frequency of heavy rainfall events over the LRB and interannual climate modes of variability such as ENSO, SIOD, and SAM were found.

Having examined the annual cycle of the top 200 heavy rainfall events, the analysis then applied the Lagrangian trajectory model HYSPLIT, with NCEP II reanalysis data as input, to backtrack air parcels from the LRB to their moisture source on seasonal scales and in terms of the types of weather systems involved. The resulting trajectories show that the seasonal transport of moisture over the LRB originates from seven moisture source regions; namely, local continental, tropical southeast Atlantic Ocean, midlatitude South Atlantic Ocean, tropical Northwest Indian Ocean, tropical southwest Indian Ocean, subtropical southwest Indian Ocean, and the Agulhas Current. Important differences in moisture source regions and pathways exist between early (October-December) and late (January-April) summers, with the tropical northwestern Indian Ocean and the northern Agulhas Current sources more prominent during JFMA than OND. Generally, moisture

source regions and transport pathways for LRB tend to be influenced by both the regional summer season circulation and the synoptic systems involved. Thus, it was found that cloud band and tropical low events within the top 200 tend to have the Congo Basin as an important moisture source whereas this source is less evident for cut-off low events.

To help assess the robustness of the composite synoptic approach, the final part of the thesis applied the Lagrangian analysis to the most severe case in the top 200 events over the LRB (11-21 January 2013). It was found that this case was largely linked to three main moisture sources: (1) tropical northwest Indian Ocean, (2) the Agulhas Current / Mozambique Channel, subtropical Southwest Indian Ocean, and (3) continental sources over the Congo Basin and northern Tanzania. Generally, the moisture source regions and pathways for the January 2013 event agreed with the climatological moisture source regions over the LRB, apart from the obvious absence of the tropical southeast Atlantic source in this case.

In general, the thesis has provided a better understanding of the characteristics of heavy rainfall events over the LRB in terms of their associated weather systems, seasonality, interannual variability, and moisture source regions and trajectories.

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Chapter 1: Introduction

1.1 Background

Precipitation is one of the most important factors for proper planning and management of water resources, especially in semi-arid and arid regions like the Limpopo River Basin (LRB) in southern Africa. The scarcity of water within the basin may affect the livelihoods of local subsistence farmers and the diverse ecosystems in this region. Therefore, it is important to understand from where the water vapor responsible for the precipitation over this region originates, the various pathways which it travels along from these sources to the LRB, and how it may be distributed by the associated weather systems during heavy rainfall events. Such an understanding will then help with the seasonal forecasting of anomalously wet or dry seasons and in assessing how the regional water cycle may behave in the future climate.

The LRB is located in southeastern Africa covering southern Mozambique, northern South Africa, southern Zimbabwe and southeastern Botswana (the brown polygon in **Figure 1.1**). Topography within the basin varies significantly from less than 100 m over the Mozambican flood plains near the coastal town of Xai-Xai to above 1600 m in the Drakensberg Mountains of northern South Africa. There is a large variation in mean annual precipitation across the LRB (160 - 1103 mm; Mosase and Ahiablame, 2018) with the western parts of the basin typically much drier than those nearer the coast or on the windward side of topography. Topographic variations have been shown to influence the spatial distribution of precipitation during heavy rainfall events over LRB (Rapolaki et al., 2019). On average, most of the precipitation over the LRB occurs during the summer half of the year (January typically being the wettest month) with tropical-extratropical cloud bands (Harrison, 1984; Reason et al., 2006; Hart et al., 2010, 2013; Manhique et al., 2011) playing an important role. In addition to cloud bands, tropical lows and sometimes ex-tropical cyclones (Dyson and van Heerden, 2001; Reason and Keibel, 2004; Malherbe et al., 2012, 2014; Fitchett and Grab, 2014), and mesoscale convective systems (Blamey and Reason, 2012, 2013) can make significant contributions to seasonal rainfall as can random air-mass thunderstorms. Occasionally, cut-off lows (Taljaard, 1985; Singleton and Reason, 2007a; Farve et al., 2012) may also produce significant rainfall, especially during the transition months (October and April). Onshore flow associated with ridging anticyclones along the east coast of South Africa may also lead to rainfall over the coastal region of the LRB or near the windward slopes of the topography

but this precipitation tends to be lighter than that associated with cloud bands, tropical lows, mesoscale convective systems or cut-off lows.

The population of the LRB is projected to grow in the future, increasing strain on the already scarce water resources is likely (Mosase and Ahiablame, 2018). Clearly, a better understanding of all aspects of the hydrological cycle and the water resources in the region is a high priority. Therefore, in this thesis, focus is placed on the atmospheric components of the regional cycle over the LRB; namely the sources of moisture for its precipitation, the various pathways this moisture takes to reach it and the characteristics of heavy rainfall events occurring over it for the summer rainy seasons during 1981-2016. To date, very few studies have explicitly considered the sources of moisture and its subsequent transport paths towards this region further reinforcing the need for this study whose specific aims are given below.

1.2 Aims

The main aim of this thesis is to better understand the characteristics of heavy rainfall events over the LRB, their associated moisture sources and pathways, and their variability both within the extended summer rainfall season (October – April) and on interannual time scales. To achieve this aim, the following questions are addressed:

Chapter 4:

- What are the dominant weather systems through which heavy rainfall is produced in the LRB and do these differ between the early and late summer?
- Are there any relationships between the number of heavy rainfall events and seasonal rainfall anomalies over the LRB?
- Are there any relationships between heavy rainfall events over the LRB and interannual climate modes such as ENSO, SIOD, and SAM?

Chapter 5:

- What are the main sources of moisture leading to heavy rainfall events over the LRB?
- What are the relative contributions of the different branches of moisture transport towards the LRB?
- What are the main characteristics of these identified branches of moisture?

Chapter 6:

- How did the moisture sources and pathways for the heavy rainfall event of January 2013 over the LRB compare to the seasonal and composite weather system characteristics derived in **Chapter 5**?
- Did moisture originating from the southeast Atlantic Ocean make a substantial contribution to the heavy rainfall event of January 2013 over the LRB?

Note that some parts of this thesis have already been published (**Chapters 4** and **5**) or in preparation for journal submission (**Chapter 6**). Following the literature review (**Chapter 2**) and Data and Methodology (**Chapter 3**), the thesis is presented in journal paper format. To preserve the fidelity of the papers, some repetition of the material may occur in the thesis.

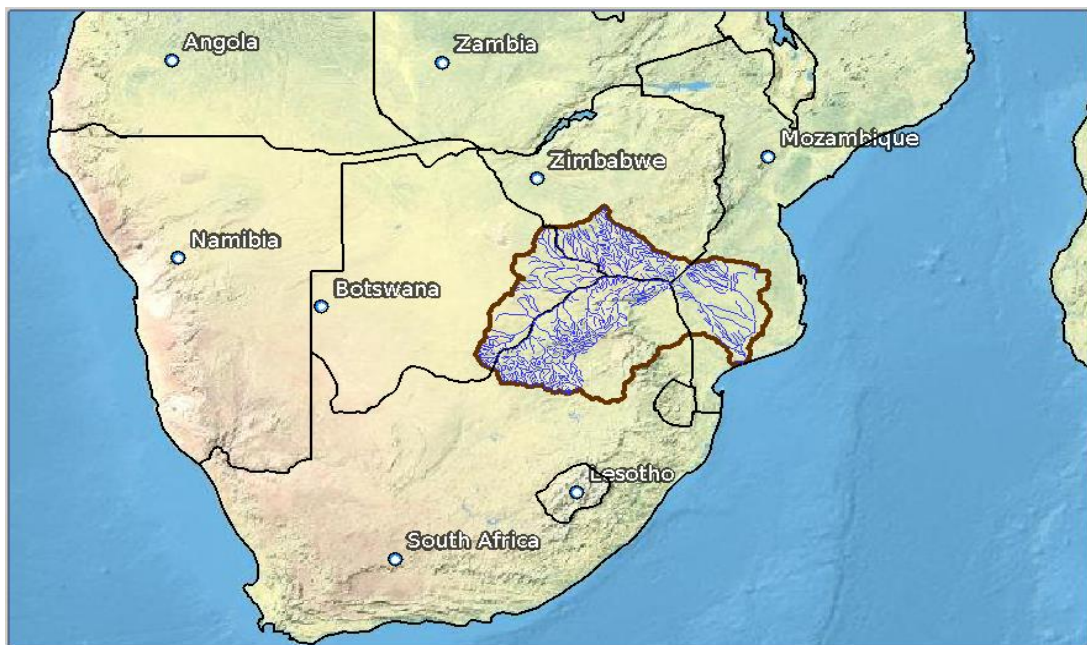


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Chapter 2: Literature Review

It is well known that the climate and weather patterns of subtropical southern Africa display significant spatial and temporal variability with floods and droughts a common occurrence (e.g., Mason and Jury, 1997; Reason et al., 2006). Multiple factors, which include topography, geographic location between the tropics and the midlatitudes with their associated circulation systems, regional oceanic conditions, and large-scale ocean-atmosphere interactions processes in all three basins, contribute to this variability and lead to the climate system of southern Africa being rather complex.

Generally, subtropical southern Africa is characterised by warm and rainy austral summers (December-February; DJF) and cool and dry winters (June-August; JJA). Exceptions are the southwestern region which is characterised by rainy winters and dry summers, and the south coast where rainfall can occur throughout the year (Weldon and Reason, 2014; Engelbrecht et al., 2016). The main circulation features that control the climate of this region are the semi-permanent anticyclonic circulation over the subtropical South Atlantic and Indian Oceans, the Circumpolar Trough and the Inter-Tropical Convergence Zone (ITCZ; Reason et al., 2006).

Due to its geographical location, interannual rainfall variability over subtropical southern Africa is influenced by sea surface temperature (SST) in the Atlantic, Indian, and the Pacific Ocean, with the El Niño Southern Oscillation (ENSO) tending to be the most important climate mode (Lindesay, 1988; Nicholson and Kim, 1997; Reason et al., 2000). However, there is evidence that the subtropical South Indian Ocean Dipole (SIOD; Behera and Yamagata, 2001; Reason, 2001, 2002; Hermes and Reason, 2005), the Southern Annular Mode (SAM; Gillett et al., 2006; Malherbe et al., 2014) and the Benguela Niño (Rouault et al., 2003; Hansingo and Reason, 2009) can also exert substantial influences on interannual scales over certain parts of the region.

2.1 Regional atmospheric circulation and rainfall producing systems over southern Africa

Southern Africa is influenced by the position and strength of the semi-permanent South Atlantic High Pressure (SAHP) and South Indian High Pressure (SIHP) systems. On average, the SAHP shifts 6° meridionally and about 13° zonally between summer and winter (Tyson and Preston-Whyte, 2000). This anticyclonic feature leads to upwelling favourable alongshore southerly winds throughout the year along the Namibian coast but only in summer along the west coast of South Africa. The intensification and zonal shift of the SAHP towards western South Africa during the summer is linked to the development of a coastal low-level jet along the coast of Namibia (Nicholson, 2010; Lima et al., 2018). On long time scales, the tendency towards a southward shift of the SAHP and the SIHP together with positive SAM phase have been identified as the key factors leading to poleward migration of moisture corridors, and thus drying conditions over the southwestern region of South Africa (Sousa et al., 2018; Mahlalela et al., 2019). On synoptic scales, ridging anticyclones along the south and east coasts are important for rainfall in summer not just at the coast but also inland and, under certain circumstances, can be associated with cut-off low development (Taljaard, 1985; Singleton and Reason, 2007b).

Compared to the SAHP, the SIHP shifts a much greater distance zonally between summer and winter (24°) (Tyson and Preston-Whyte, 2000). During the latter season it extends over southeastern Africa, helping to keep this region dry whereas in summer it moves well east over the South Indian Ocean as well as several degrees further south. This shift is then favourable for frontal systems to track closer towards the southeast coast of South Africa and their linkage with tropical convection over the far interior, leading to the development of tropical-extratropical cloudbands (Harrison, 1984; Hart et al., 2010; 2012). The SIHP is associated with the easterly or southeasterly flow of warm, moist marine airmasses towards southeastern Africa and the potential for rainfall there. Northwestward migration of the SIHP coupled with the Mozambique Channel Trough (MCT; Barimalala et al., 2018) can lead to easterly wave flow into South Africa and Mozambique during summer. On interannual time scales, the SIHP is modulated by both ENSO and the SIOD with their associated rainfall impacts over southern Africa (Reason et al., 2000; Behera and Yamagata, 2001; Hermes and Reason, 2005).

North of the SIHP, the ITCZ tends to lie somewhere between $15\text{--}20^{\circ}\text{S}$ over the western South Indian Ocean in summer with its southernmost position being over central Madagascar and

northern Mozambique in February. Associated with the ITCZ is a low-level convergence of warm moist air from the Indian Ocean over southern Malawi, northern Mozambique, and central Madagascar. A more southward located shift of the ITCZ may be associated with wet summers over southern Africa while dry summers may result if the ITCZ is weaker or located further north than average (Cook et al., 2004). Starting in March or April, the ITCZ shifts northwards over the western Indian Ocean to become situated over northern India during the height of the South West Monsoon in July and August. However, on the Atlantic seaboard of Africa, the ITCZ does not move as much meridionally and, in fact never reaches south of the equator in summer, instead being located somewhere slightly inland of the Gulf of Guinea (coast) of West Africa. Between these two locations, there are two convergence zones in summer, a meridional branch extending through the Congo Basin and a secondary branch stretching from the southern part of this meridional feature southwestwards towards the Angola Low.

The Angola Low (denoted L in **Fig. 2.1**) is a lower to mid-troposphere cyclonic feature which develops during austral summer over southeastern Angola / northeastern Namibia (Mulenga, 1999; Mulenga et al., 2003; Reason et al., 2006; Munday and Washington, 2017; Cretat et al., 2019). Its characteristics during the first half of summer tend to be like a heat low whereas later in summer, it is more like a tropical low (Munday and Washington, 2017). As the Angola Low develops during the early summer with strong surface heating there and further south over the Kalahari Desert, the temperature contrast between it and the cooler neighbouring South Atlantic helps to enhance the pressure gradient across Botswana and Zimbabwe facilitating inflow of moist Indian Ocean air towards the interior. In particular, the Angola Low often acts as the source region for tropical-extratropical cloud bands (also known as tropical temperate troughs or TTTs) (Harrison, 1984; Fauchereau et al., 2009; Hart et al., 2010, 2013; Manhique et al., 2011; Cretat et al., 2012; Macron et al., 2014).

Most of the southern African summer rainfall is produced through a variety of convective systems, ranging from short-lived single cell thunderstorms, to large-scale TTTs. The TTTs are cloud bands that result from tropical-extratropical (TE) interactions (Hart et al., 2010) between tropical convection over the southern African/ South West Indian Ocean region and a midlatitude disturbance, typically a cold front). According to Harrison (1984) and Hart et al. (2010), TTTs are the primary rain bearing weather systems during austral summer over subtropical southern Africa. They are characterised by a band of clouds that extends in a (NW-SE) direction either from the

Angola Low (as indicated in **Fig. 2.1**) or from tropical convection further east to the mid-latitudes, and which transport moisture and heat southeastwards over the subcontinent (Harrison, 1984; Todd and Washington, 1998; Reason et al., 2006; Hart et al., 2010).

Additional systems that often lead to heavy rainfall over southern Africa are mesoscale convective systems (MCSs), cut-off lows and tropical lows. MCSs are characterised by an organised group of thunderstorms acting as coherent systems, which include mesoscale convective complexes (MCCs) and squall lines (Blamey and Reason, 2012). The timespan of a single MCC can be more than 12 hours. Blamey and Reason (2012) showed that on average, about nine MCC events occur over southern Africa annually, contributing up to 20% of summer rainfall over the southeastern part of southern Africa. However, their contribution decreases to less than 6% over the western interior. Previous studies (Blamey and Reason, 2009) have shown that an individual MCS event can produce more than 100 mm of rainfall within a day. Similarly, a single MCS event can produce about a third of the monthly total rainfall during summer. However, the mechanisms through which MCCs form over southern Africa are still not well understood, including their contribution to extreme rainfall in Limpopo.

Cut-off lows (denoted COLs in **Fig. 2.1**) also significantly contribute to rainfall over South Africa (Singleton and Reason, 2006, 2007a; Nieto et al, 2008; Favre et al., 2013; Molekwa et al., 2014) and the eastern parts of the LRB, particularly during the transition seasons. Cut-off lows are defined as cold cored systems that have been cut-off from the main westerly flow and displaced equatorward of the polar jet stream (Taljaard, 1985; Singleton and Reason, 2007b; Nieto, et al., 2008; Farve et al., 2012). A major characteristic of cut-off lows is that their development is strongly linked to the occurrence of a strong ridge of high pressure located south of South Africa over the South Atlantic Ocean. Furthermore, these systems are often associated with intense rainfall and stratosphere-troposphere exchange (Barsby and Diab, 1995; Singleton and Reason, 2006, 2007ab; Nieto et al, 2008). Taljaard's (1985) ten-year (1973-1982) study of cut-off lows over the South African region bounded between 20° and 38°S indicated that on average, eleven cut-off lows occurred over South Africa per year confirmed in the 30 year study of Singleton and Reason (2007a). On occasion, these systems can produce more than 100 mm of rainfall in 24 hours (Tyson and Preston-Whyte, 2000; Singleton and Reason, 2007b).

Tropical depressions, storms, and cyclones (denoted TC in **Fig. 2.1**) in the regional context are low-pressure systems mainly originating in the tropical Indian Ocean south of the ITCZ (Tyson

and Preston-Whyte, 2000). Usually, between six and twelve TCs are recorded in the South Indian Ocean every year, with the southwest Indian Ocean tropical cyclone season occurring between November and April (Mavume et al., 2009; Malherbe et al., 2012; Malan et al., 2013). Although some tropical cyclones are generated in the Mozambique Channel, not many of these make landfall, instead they tend to track south through the channel (Reason, 2007). A prominent recent exception was TC Idai in March 2019, one of the deadliest cyclones in the Southern Hemisphere. Of those generated in the southwest Indian Ocean, about 5% make landfall on the southern African mainland (Reason and Keibel, 2004; Nash et al., 2015). Mavume et al. (2009) showed that about 48 of 64 TCs occurring during the period 1980 to 2007 made landfall over Madagascar, thus making this region the most vulnerable to southwestern Indian Ocean tropical cyclones. Malherbe et al. (2012) indicated that the contribution of tropical systems to annual rainfall over the southern interior of southern Africa is less than 10%, but when they occur, they are often associated with extreme, devastating floods such as during February 2000 (largely due to TC Eline).

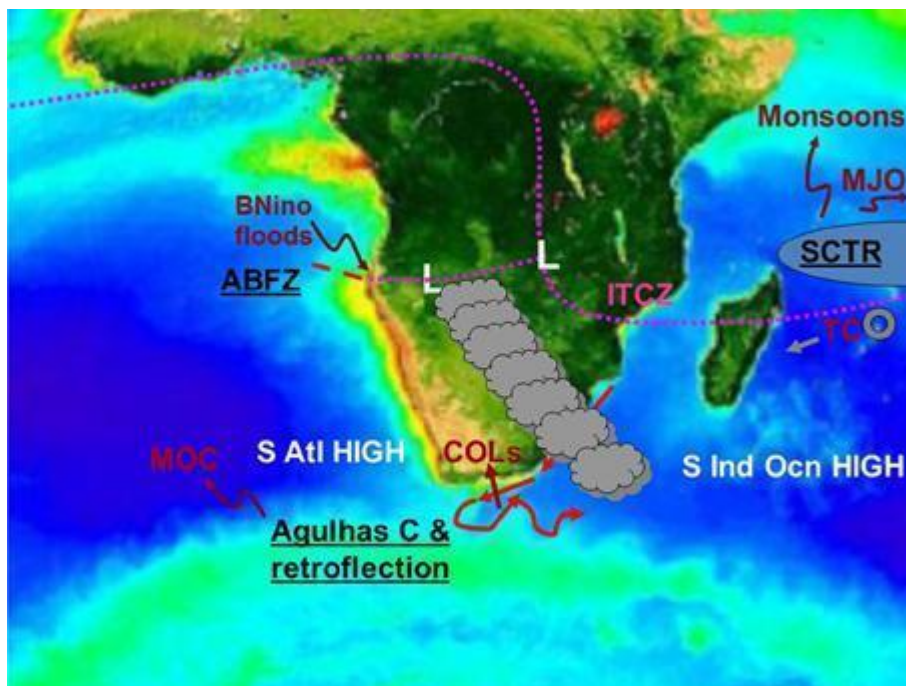


Figure 2.1 Schematic showing important regional oceanic and atmospheric features for summer rainfall over southern Africa. The symbol COLs denote cut-off lows, L indicates the Angola Low near the source region of the cloud band, TC indicates tropical cyclone, B Niño denotes Benguela Niño. The dotted purple line represents the position of the ITCZ during summer. S Atl HIGH and S Ind Ocn HIGH indicate the semi-permanent South Atlantic High Pressure and South Indian High Pressure respectively. Also shown are the Agulhas Current and retroflection region. Source: Reason and Smart (2015).

2.2 The role of adjacent oceans on southern African rainfall

Historically, more work has been done on the South Indian Ocean as a source of moisture for rainfall over the subcontinent (Walker, 1990; Mason, 1995; Reason and Mulenga, 1999); hence, less is known about the influence of the South Atlantic Ocean. More recent studies (Rouault et al., 2003a; Cook et al., 2004; Hansingo and Reason, 2009; Manhique et al., 2015; Reason and Smart, 2015) have indicated the tropical South East Atlantic (north of the Angola Benguela Frontal Zone) as another source of moisture associated with rainfall over southern Africa. Cook et al. (2004) provided evidence that both anomalously wet summers and synoptic wet spells over South Africa were associated with transport of low level moisture from the tropical South East Atlantic. Moisture transport from this region was also associated with the devastating flood event of January 2013 over central and southern Mozambique by Manhique et al. (2015) as well as more generally with several anomalously wet summers over large parts of Mozambique. However, the most well known example of moisture transport into southern Africa from the tropical South East Atlantic tends to occur during Benguela Niño events (Rouault et al., 2003; Hansingo and Reason, 2009; Reason and Smart, 2015) in late summer when SST anomalies off the coast of Angola and northern Namibia can be several degrees above average with associated well above average rainfall there, and in several cases, over large parts of southern Africa.

On the other hand, a significant amount of work has been done on the influence of the Indian Ocean on the climate and weather of southern Africa (Walker, 1990; Mason 1995; Reason and Mulenga, 1999; Behera and Yamagata, 2001; Reason, 2001, 2002; Washington and Preston, 2006). The semi-permanent South Indian Ocean anticyclone positioned east to southeast of South Africa in summer, advects moisture towards the east coast (Tyson and Preston-Whyte, 2000). Further south, large amounts of heat are released to the overlying atmosphere above the Agulhas Retroflexion and Agulhas Return Current, which may strengthen cold fronts tracking here and help form the midlatitude component of the TTTs or cloud bands (Walker and Mey, 1998; Reason, 2001; Rouault et al., 2003b).

The subtropical Indian Ocean Dipole (SIOD; Behera and Yamagata, 2001) which is defined as the difference in SST anomalies between a pole over the southwestern Indian Ocean south of Madagascar and another one over the southeastern Indian Ocean near Western Australia, has been shown to influence rainfall over southern Africa. When the SIOD occurs, it tends to be strongest in January or February and can be associated with above average summer rainfall when in its

positive phase (warm pole in the west, cool in the east) and below average during its negative phase (Behera and Yamagata, 2001; Reason, 2001, 2002). The relationship between the SIOD and ENSO is not completely understood (Hermes and Reason, 2005) but can reinforce or oppose the associated rainfall anomalies (Hoell et al., 2017), as can be the case with the Benguela Niño (Reason and Smart, 2015).

The Southern Annular Mode (SAM) is the leading mode of variability over the mid- and high latitudes in the Southern Hemisphere (Hall and Visbeck, 2001; Marshall, 2003; Gillett et al., 2006). The positive phase of the SAM is associated with negative geopotential height anomalies over polar latitudes and positive geopotential height anomalies over the mid-latitudes near about 40° which leads to easterly wind anomalies, east and southeast of South Africa, (Thompson and Wallace, 2000). This easterly flow inhibits the advection of maritime air onto the coastal regions of southwestern South Africa in winter and weakens approaching cold fronts typically leading to reduced winter rainfall over western South Africa (Reason and Rouault, 2005). However, a positive SAM is associated with an increase in summer precipitation south of 25°S where more moisture is advected off the South Indian Ocean (Gillett et al., 2006).

2.3 El Niño Southern Oscillation and southern Africa rainfall

On interannual timescales, the regional circulation of southern Africa is strongly influenced by ENSO (Lindesay, 1988; Nicholson and Kim, 1997; Reason et al., 2000). ENSO leads to widespread rainfall and temperature anomalies over most parts of the world at various times of the year during a particular episode (Roplewski and Halpert, 1987). However, in southern Africa, it most obviously impacts on the summer rainfall region during the so-called mature phase of the ENSO event. In general terms, El Niño (La Niña) summers tend to be anomalously dry (wet) over southern Africa but the relationship is nonlinear with some strong events (e.g., 1997/98) not leading to the expected rainfall anomalies (Reason and Jagadheesha, 2005; Lyon and Mason, 2007; Blamey et al., 2018). Widespread drought did not occur over subtropical southern Africa during this El Niño event because the Angola Low did not weaken as expected and thus tropical convection was not as suppressed as it often is during other strong events such as 1982/83 and 2015/16 (Blamey et al., 2018). This lack of a weakening in the Angola Low and less severe drought also occurred during the moderately strong 2009/10 El Niño event (Driver et al., 2019).

In terms of rainfall producing weather systems, Singleton and Reason (2007a) found evidence of La Niña conditions tending to favour COL events over subtropical southern Africa. La Niña is also often associated with favourable conditions in the upper level jets and cloud band development over southern Africa (Hart et al., 2013, 2018). Vitart et al. (2003) indicated a tendency to an increased number of landfalling tropical cyclones over Mozambique although there have also been cases of landfalling strong cyclones during El Niño seasons (Klinman and Reason, 2008).

2.4 From evaporation to precipitation: a review on moisture transport

In general, the atmosphere contains a very small fraction of the global water compared to the ocean basins, but it is still a crucial part of the hydrological cycle. The atmosphere acts as a bridge connecting moisture sources (typically parts of the oceans) with sinks (typically continental landmasses) (Gimeno et al, 2014). Many parts of the ocean are regarded as moisture sources because of the positive net rate of evaporation (E) over the oceans, particularly in the subtropics, as illustrated in **Figure 2.2**. On the other hand, over the continents, the rate of precipitation is higher than the rate of evapotranspiration, and thus the continental landmasses represent a net sink region. However, the supply and transport of moisture from oceanic sources to continental sinks is not straightforward due to regional and global circulation features. For example, southern Africa is bounded by the South Atlantic Ocean in the west and the South Indian Ocean in the east, but the air mass that contributes to its net precipitation has been shown to originate primarily from the Indian Ocean and the Agulhas Current regions (Stohl and James, 2005; Gimeno et al., 2012) (**Fig. 2.3**). In addition to southern Africa, the Indian Ocean is also the main moisture source for other neighbouring land masses (Australia, South Asia and East Africa) (Gimeno et al., 2012).

As alluded to earlier, the Atlantic has historically been viewed as a less important moisture source for southern Africa. More generally, the South Atlantic is an important moisture source for both the West African monsoon and for South America, particularly for Argentina and eastern Brazil (Drumond et al., 2008). North of the equator, the North Atlantic Ocean contributes moisture to the east coast of North America throughout the year, and western Europe (Gimeno et al., 2012). The subtropical part of this ocean is also of importance for precipitation across Eurasia and Mexico (Drumond et al., 2011; Gimeno et al., 2010) while the Mexican Caribbean Sea region supplies moisture for precipitation over the Caribbean Islands as well as Central and North America. **Fig. 2.3** illustrates the location of these oceanic moisture source regions in relation to the landmasses.

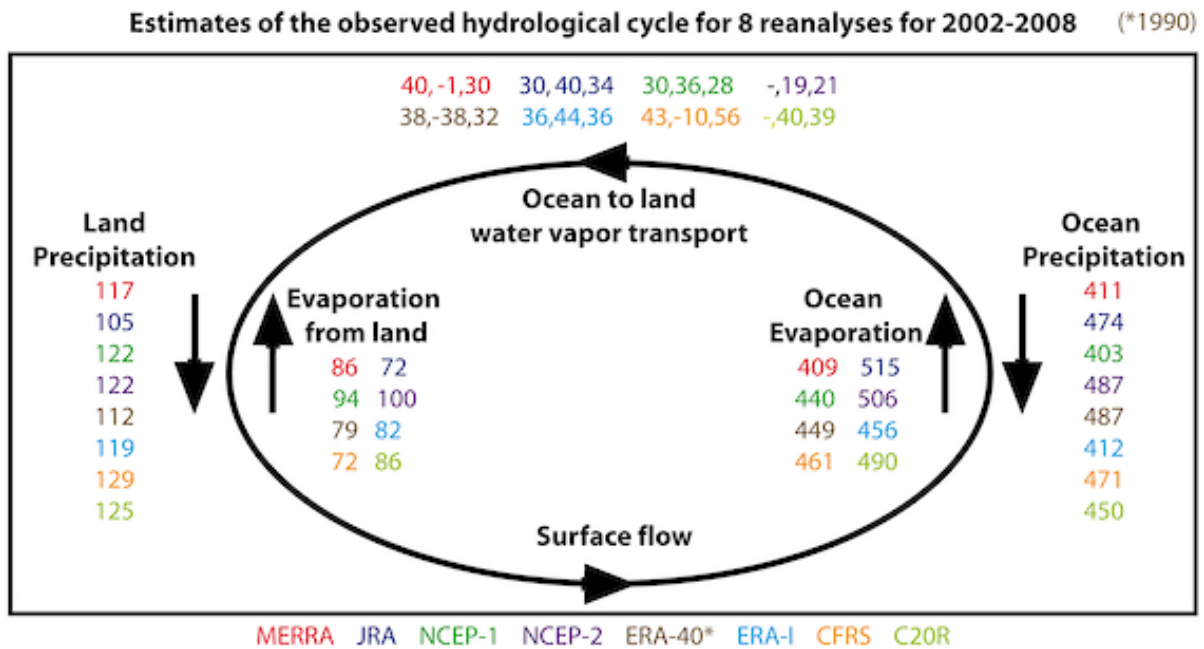


Figure 2.2: Estimated values of the observed hydrological cycle using eight reanalyses datasets for 2002-2008, with the exception of ERA-40, which starts from 1990 (colour coded as given at the bottom of the figure). Source: Gimeno et al. (2012).

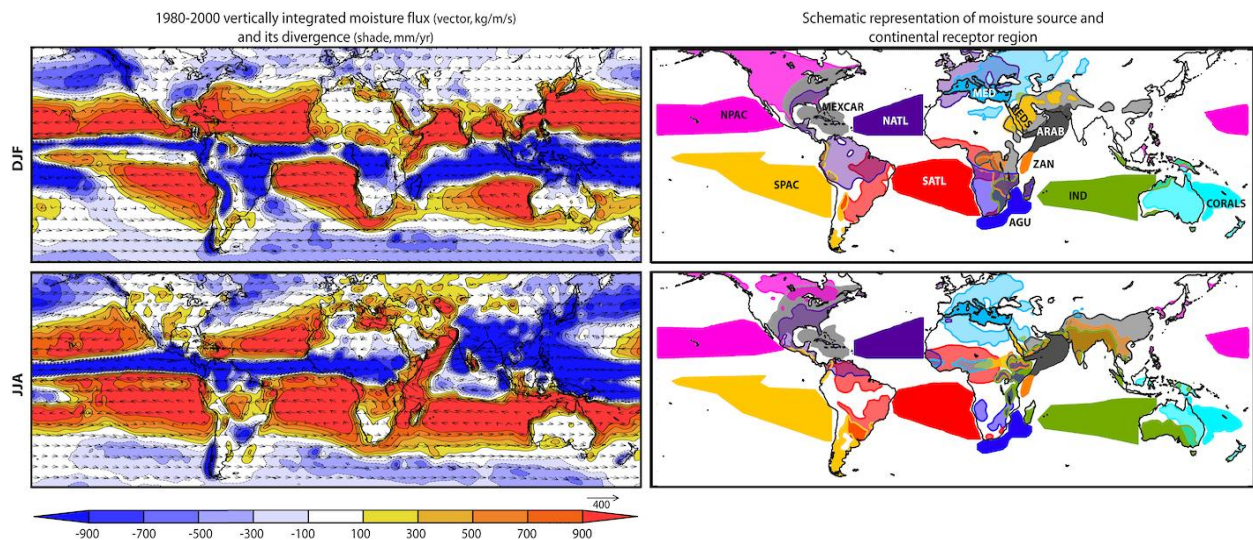


Figure 2.3: Vertically integrated moisture flux and its divergence (left) for DJF (top) and JJA (bottom panel). Also illustrated are the global moisture source regions (right). Source: Gimeno et al. (2010).

2.4.1 Atmospheric moisture transport mechanisms

Atmospheric Rivers (ARs) and Low-Level Jets (LLJs) are two large-scale meteorological phenomena primarily responsible for moisture transport from oceanic source regions towards the landmasses (Gimeno et al., 2014, 2016). LLJs are important in tropical and subtropical regions while ARs are more confined to extratropical regions (Gimeno et al., 2014). A distinction between the moisture transport of ARs and LLJs is evident through the sheer size of such features. ARs are long (~2000km), narrow (~300-500 km in width) and shallow (1-2.5 km) channels in the atmosphere along which the atmospheric water vapour is transported in the extratropical regions (Gimeno et al., 2016). Typically, an AR is found within the warm conveyor belt in the pre-cold front area of an extratropical cyclone (Gimeno, 2014). They are characterised by high-water vapour content, strong wind at low levels (an LLJ) and low level potential instability accompanied by a region of subsidence in the leading edge of the system (Gimeno, et al., 2014). Due to high moisture content ARs are associated with heavy precipitation that often leads to devastating floods especially in regions where they impinge on mountain terrains (e.g. Neiman et al. 2002; Ralph et al. 2004; Rutz et al. 2014).

Globally, a notable number of extreme rainfall events have been linked to ARs over western Europe (Lavers et al., 2011) and the western United States (Dettinger et al., 2011). In the case of southern Africa, Blamey et al. (2018) found that ARs account for most of the heavy rainfall events during winter (April-September) over the Western Cape. Additionally, Gimeno et al. (2016) have indicated the possible occurrence of ARs over the southeastern part of southern Africa including Madagascar.

A LLJ is a mesoscale flow feature that is characterised by a wind-speed maximum profile within the lowest few kilometres (1.5 km) of the atmosphere (Zunckel et al., 1996; Ranjha et al., 2013; Gimeno et al., 2016; Nicholson, 2016). The horizontal along-jet extent of LLJs can exceed hundreds of kilometres, whereas their vertical extent is relatively small, often only a few hundred metres (Ranjha et al., 2013; Gimeno et al., 2016; Nicholson, 2016). These phenomena are driven by various mechanisms depending on whether they are coastal or interior jets (Nicholson, 2016). Coastal LLJs are generally in geostrophic balance and are associated with the daily cycle of land-sea contrast and topography (Zunckel et al., 1996; Anderson et al., 2001; Pomeroy and Parish, 2001; Gimeno et al., 2016; Nicholson, 2016). On the other hand, the interior jets are generally driven by inertial and/ or topographical effects or may form from secondary circulations associated

with upper-level flows (Parish, 2000; Gimeno et al., 2016; Nicholson, 2016). LLJs act as the corridors through which much moisture is transported from warm oceans toward land areas.

Strong easterly jets transporting moisture from areas of the warm South Indian Ocean, including the southern Agulhas Current, have often been implicated in heavy rainfall events over the southern part of South Africa such as cut-off lows (Stensrud, 1996; Singleton and Reason, 2006, 2007b). Furthermore, Stensrud (1996) noted that LLJs are found to be present in most cases of large storm complexes (MCCs). However, to date, rather little work has been done on understanding these jets, despite their contribution to rainfall over southern Africa having been implicated in previous studies. Elsewhere, LLJs have been observed in Australia, Antarctica, Asia, East Africa, North America, and South America (Ranjha et al., 2013).

Summary

This chapter has reviewed the background literature on the climate variability of the LRB and the broader southern African region as well as the weather systems that bring about most of the rainfall over the region. Most of the rainfall occurs during the austral summer half of the year, being linked to cloud bands, tropical lows, mesoscale convective systems, and occasionally cut-off lows. Moisture into subtropical southern Africa has historically been thought to originate primarily over the tropical and subtropical South Indian Ocean, with the southeast Atlantic Ocean occasionally also contributing. Although the main source regions for southern Africa are known to a certain extent, their actual contribution to the total summer rainfall, and particularly heavy rainfall events, remain unquantified. Thus, following the data and methodology discussion (presented next in **Chapter 3**), the remainder of this thesis addresses heavy rainfall events over the LRB, their moisture sources and pathways as well as their seasonality and interannual variability.

Chapter 3: Data and methodology

This chapter mainly describes the moisture tracking software HYSPLIT as well as the data sets used in **Chapter 5**. Data and methodology used in each individual results chapter are described in detail in those chapters (i.e., **Chapters 4, 5, and 6**).

3.1 HYSPLIT model and NCEP/NCAR II

The Lagrangian particle dispersion model HYSPLIT (Draxler and Hess, 1998) was used to produce backward trajectories of moisture into the LRB. HYSPLIT calculates trajectories of a large number of the particles (small air parcels) to describe the transport and diffusion in the atmosphere. HYSPLIT uses gridded reanalysis data, such as the Global Forecast System (GFS), Climate Forecast System Reanalysis (CFSR), and the European Centre for Medium-Range Weather Forecasts (ECMWF) Era-Interim as input data. The Weather Research and Forecasting (WRF) model output may also be used for the regional moisture tracking.

The advantage of Lagrangian particle dispersion models (LPDMs), such as the HYSPLIT, is that they allow for tracking the source of moisture that reaches a specific area which makes it possible to track changes in the specific humidity along the trajectories over time. Although the Lagrangian methods do not provide the large-scale atmospheric circulation linked to moisture transport like the Eulerian methods, they are suitable for this study since they can provide the geographical origin of moisture that reaches the LRB (Gimeno et al., 2012).

Another advantage of the HYSPLIT model is that it can be used forward in time to simulate the dispersion of moisture from its source. This allows the study of future projections of moisture transport over the LRB and the broader southern Africa. However, it should be considered that, like other Lagrangian models, HYSPLIT is also susceptible to computation biases.

In this thesis, six-hourly National Center for Environmental Prediction (NCEP) / DOE NCEP II Reanalysis data (Kanamitsu et al., 2002) were used to provide boundary conditions for the HYSPLIT model. NCEP II data are available on the global grid with 17 vertical levels from the surface to the model top at 0.1 hPa on a $2.5^{\circ} \times 2.5^{\circ}$ (~ 250 km) horizontal grid.

3.2 Climate Research Unit (CRU)

The gridded $0.5^{\circ} \times 0.5^{\circ}$ resolution Climate Research Unit (CRU) TS4.02 (Harris et al., 2014) potential evapotranspiration data were used to calculate the annual cycle of evaporation over the LRB in **Chapter 5**. CRU is available for the period 1901-2017 and contains monthly time series of precipitation, potential evapotranspiration, temperature, and other variables. The data are based on analysis of meteorological variables collected from over 4000 weather station records from land areas excluding Antarctica. The CRU allows studies of Evaporation (*E*)- Precipitation (*P*) fluxes over the land masses which are often restricted by lack of evapotranspiration.

3.3 Climate Hazards Infrared Precipitation with Stations (CHIRPS)

The daily Climate Hazards Infrared Precipitation with Stations (CHIRPS) version 2 (Funk et al., 2015) data with a 0.05° (~ 5 km) spatial resolution were used to identify extreme rainfall events over the LRB during the 1981-2016 period, and to examine the relationships between extreme events and large-scale modes of variability, specifically ENSO, SIOD and SAM in **Chapter 4**. Due to an insufficient number of meteorological station (gauge) surface rainfall data over the LRB, excepting over the South African part of the basin, the rainfall analyses in this study was done solely using CHIRPS. Other similar higher resolution gridded datasets such as the Tropical Rainfall Measuring Mission (TRMM; Huffman et al., 2007) and Multi-source Weighted-Ensemble Precipitation, version 1 (MSWEP-V1) were considered for the analysis in addition to CHIRPS. However, TRMM could not be used due to its shorter temporal time scale (1998 to near present). Although MSWEP-V1 is available from 1979 to 2017 and it covers the entire study period (1981-2016), preliminary analysis indicated erroneous values in the daily maximum rainfall. However, a similar comparison has not been done with MSWEP-V2 (Beck et al., 2019) as it was not available when the study started, and the analysis could indicate a different result. CHIRPS data were downloaded freely from Climate Hazards Center (CHC) website (<https://www.chc.ucsb.edu/>) over Africa for the period 1980-2017.

3.4 Gridded Satellite (GridSat-B1)

The Gridded Satellite data (GridSat-B1; Knapp et al., 2011) was used to subjectively identify weather systems linked to the top 200 extreme rainfall events over the LRB discussed in **Chapter 4**. The data are available at 0.07° (~ 8 km) spatial resolution on equirectangular (70°N to 70°S) grid, for the period 1981 to near present. Both relatively high spatial and temporal resolutions of GridSat-B1 data makes it suitable to analyse and track a wide range of synoptic systems which

could last for a few hours to days or weeks. These data are derived from the International Satellite Cloud Climatology Project- B (ISCCP B; Knapp, 2008). GridSat-B1 is available freely and easily accessible from the NOAA National Centers for Environmental Information (NCEI; <https://www.ncdc.noaa.gov/gridsat/>)

3.5 International Best Track Archive for Climate Stewardship

The International Best Track Archive for Climate Stewardship (IBTraCS; Knapp et al., 2010) data are compiled from a non-exhaustive list of multiple sources described in Knapp et al. (2009), which gives the intensity and locations/position of past tropical storms in different basins since 1982. The IBTraCS data have a spatial resolution of 0.1° (~ 10 km) on an equirectangular (70°N to 70°S) grid interpolated to three hourly intervals. The data are available freely online (<http://www.ncdc.noaa.gov/oa/ibtracs/>).

The next chapter will analyse the weather systems responsible for the heavy rainfall events over the LRB, their seasonality and interannual variability.

Chapter 4: Heavy rainfall events over the Limpopo River Basin in southern Africa

This chapter addresses the following questions listed below. The work is presented as the paper published in *Climate Dynamics*:

*R.S. Rapolaki, R.C. Blamey, J.C. Hermes, and C.J.C. Reason, 2019: A synoptic classification of synoptic weather patterns linked with extreme rainfall events over the Limpopo River Basin in southern Africa, *Climate Dynamics*, 53, 2265-2279*

- What are the dominant weather systems through which heavy rainfall is produced in the LRB and do these differ between the early and late summer?
- Are there any relationships between the number of heavy rainfall events and seasonal rainfall anomalies over the LRB?
- Are there any relationships between heavy rainfall events over the LRB and interannual climate modes such as ENSO, SIOD, and SAM?

Abstract

In the last few decades, the Limpopo River Basin (LRB) has experienced a number of extreme rainfall events which were responsible for considerable socio-economic and environmental impacts. Most of the population here is poor and dependent on rain-fed agriculture. In order to better understand these events over the LRB, CHIRPS, 0.05° gridded rainfall data are used to identify the daily extreme events, analyse their interannual variability and examine relationships with large scale climate modes over the 1981-2016 period.

Analysis of the top 20 events suggests a pattern with rainfall generally decreasing from the eastern to western parts of the basin. Typically, the highest rainfall amounts occur over the regions where there are steep topographical gradients between the mountainous regions of northeastern South Africa and the Mozambican floodplains. Almost half of the top 200 extreme events are associated with tropical extra-tropical cloud bands (48%), with tropical low-pressure systems (28%), Mesoscale Convective Systems (14%), and cut-off lows (10%) in the mid-upper atmosphere, also making sizeable contributions. The monthly distribution of the events showed that most of the events occurred during the late summer months (January-March) when tropical lows and cloud bands are more common. On interannual time-scales, most of the summers with above average number of events coincide with La Niña conditions and, to lesser extent, a positive subtropical South Indian Ocean Dipole.

4.1. Introduction

Located centrally within subtropical southern Africa, defined here as Africa south of 15°S, is the Limpopo River Basin (LRB; **Fig. 1.1**), an important region locally due to its agriculture output, rich biodiversity and tourism. The LRB, mostly consisting of a rural population, extends about 1770 km across four countries (southeastern Botswana, southern Zimbabwe, northeastern South Africa) to southern Mozambique where the Limpopo River flows into the southwest Indian Ocean near the town of Xai-Xai. The altitude of the LRB ranges from less than 200 m over the Mozambican floodplains to higher than 1600 m over mountainous regions of South Africa. The rainfall season occurs between October and April (Mosase and Ahiablame, 2018) with largest precipitation during the late summer months (January-March) and greatest evaporation losses during the early summer (October-December). Both severe drought and extreme rainfall events are common over the LRB (Mulenga et al., 2003; Usman and Reason, 2004; Reason et al., 2005; Malherbe et al., 2014; Manhique et al., 2015).

During the austral summer, southern Africa may experience extreme precipitation events associated with convective storms, ranging in scale from single cell storms through to organised systems such as mesoscale convective complexes (Blamey and Reason, 2012, 2013), squall lines (Rouault et al., 2002) and tropical storms (Reason and Keibel, 2004; Reason, 2007; Malherbe et al., 2012, 2014; Rapolaki and Reason, 2018). The dominant rainfall producing systems over the region are synoptic scale cloud bands, known locally as tropical-temperate-troughs (TTTs; Harrison, 1984; Reason et al., 2006; Hart et al., 2010, 2013; Manhique et al., 2011). Cut-off lows (COLs) can also lead to extreme rainfall in the region (Taljaard, 1985; Singleton and Reason, 2006, 2007a; Favre et al., 2012). Many of these heavy rainfall events are associated with major socio-economic impacts, including sometimes loss of life. For example, tropical cyclone Eline caused severe flooding over the basin when it tracked across Zimbabwe in February 2000 after making landfall near Beira on the central Mozambican coast (Dyson and van Heerden, 2001; Reason and Keibel, 2004). About 1000 people were killed as a result of Eline. Another notable flood event occurred in January 2013 which Manhique et al. (2015) suggested was related to an intense and long lasting cloud band. The flood left approximately 200 000 people homeless and led to more than 100 deaths in central and southern Mozambique (Manhique et al., 2015). More recently, tropical storm Chedza caused severe flooding in Mozambique in 2015, with more than 20 000 displaced and 75 deaths reported in Madagascar (Rapolaki and Reason, 2018).

On interannual time-scales, rainfall over the LRB, like much of southern Africa, is strongly impacted by El Niño-Southern Oscillation (ENSO; Lindesay, 1988; Nicholson and Kim, 1997; Reason et al, 2000; Washington and Preston, 2006). Typically, El Niño (La Niña) conditions are associated with dry (wet) summers here. However, the relationship between the strength of ENSO events and rainfall over southern Africa is non-linear, i.e. not every El Niño corresponds to dry conditions over the region (e.g. Reason and Jagadheesha, 2005). For example, widespread below average dry conditions failed to materialize over southern Africa during the strong 1997/98 El Niño (Lyon and Mason, 2007; Blamey et al., 2018). In contrast, the weaker 1991/92 and 2002/03 El Niño events were linked with severe summer droughts over a large part of southern Africa. Reason and Jagadheesha (2005) showed that the 1997/98 drought was less intense because the Angola Low was not anomalously weak unlike during 1991/92 and 2002/03. Another example of a relatively strong El Niño for which the Angola Low did not weaken much and hence the expected severe drought did not occur was in 2009/10 (Driver et al., 2019). In that study, experiments with a 0.5° resolution stretched grid global model provided further evidence for the importance of the strength of the Angola Low for summer rainfall variability over the region. The significance of the Angola Low is that it tends to act as the source region for the cloud bands that bring much of the summer rainfall (Harrison, 1984; Hart et al., 2010, 2013).

On a regional scale, SST modes such as the subtropical South Indian Ocean Dipole (SIOD) (Behera and Yamagata, 2001; Reason, 2001, 2002) may also influence summer rainfall over the region and can reinforce or oppose the ENSO signal if they occur at the same time. Hoell et al. (2017) presented evidence that when a La Niña and a positive phase SIOD co-occur, the precipitation anomaly over southern Africa is increased relative to when La Niña co-occurs with a negative phase SIOD. Climate modes may influence the rainfall of the LRB via inducing anomalies in regional circulation over southern Africa, which then modify the low level moisture fluxes and uplift. For example, during El Niño there tends to be anticyclonic circulation anomalies over southern Africa with increased subsidence and the reverse during La Niña. On average, most of the moisture flowing into subtropical southern Africa during summer originates from the western Indian Ocean (D'Abreton and Tyson, 1995) but the tropical southeast Atlantic can also make important contributions (Cook et al., 2004; Reason et al., 2006; Manhique et al., 2015). Thus, anomalously warm conditions in the tropical southeast Atlantic (Rouault et al., 2003; Hansingo and Reason, 2009) or in the southwest Indian Ocean (Walker, 1990; Mason, 1995; Reason, 1998, 1999; Reason and Mulenga, 1999) during summer have been associated with increased transport

of moist marine air towards southern Africa and hence increased rainfall. Although the relationship between seasonal rainfall patterns and modes of variability over southern Africa has been established to some degree, there has been less focus on how these modes of variability impact extreme rainfall events over Limpopo although work has been done of relationships between ENSO and the numbers of dry spells during the rainy season (Reason et al., 2005). There is also some evidence that the Southern Annular Mode (SAM) may influence rainfall over parts of South Africa during summer (Gillett et al., 2006; Malherbe et al., 2014) although its influence may be stronger in winter (Reason and Rouault, 2005).

To date, there are very few studies that have investigated variability in daily extreme precipitation events over the Limpopo region. Given its vulnerable and poor rural population, largely dependent on rain-fed subsistence agriculture, a better understanding of the nature of rainfall extremes in the LRB is crucial for decision-makers, disaster management and seasonal forecasters. To help obtain a better understanding of the relationships between extreme rainfall events over the LRB during summer, this study considers the synoptic weather types associated with the events, how they may vary through the summer, and whether there are any relationships between them and climate modes of variability such as ENSO, SIOD and SAM. An improved understanding of these events and their variability should then help with their forecasting as well as with seasonal rainfall outlooks over subtropical southern Africa.

4.2. Data and methods

a. Merged precipitation data

Extreme rainfall producing systems can evolve and dissipate within the span of a few hours, days or weeks, and are difficult to study with monthly averages. Thus, analyses of these events over a longer period, prior to 1996, have been limited by a lack of high-resolution ground-based precipitation data over southern Africa. However, various satellite-derived rainfall products such as the Tropical Rainfall Measuring Mission (TRMM; Huffman et al., 2009), with higher temporal resolution (3-hourly to daily) have been developed based on ground-based observations and using satellite-based algorithms to estimate rainfall (e.g. Huffman et al., 2009; Maidment et al., 2014). Given that many of these products rely on satellites they tend to only cover the recent period (typically the last 30 years or so), thus making it difficult to investigate decadal variability of rainfall patterns over southern Africa.

In this study, Climate Hazards Infrared Precipitation with Stations (CHIRPS) version 2 (Funk et al., 2015), daily data are used to identify daily extreme rainfall events over the basin. The CHIRPS data set combines multiple data, including gauges and satellite imagery, to provide the best estimates of rainfall. Furthermore, CHIRPS was developed to monitor drought conditions over places with complex topography, as well as deep convective precipitation, such as Ethiopia (Funk et al., 2015), which makes it appropriate for the LRB which is also dominated by steep topography and convective rainfall. CHIRPS are available at 0.05° (~5 km) spatial resolution on a quasi-global (50°S-50°N) grid, for the period 1980 to near-present which makes it suitable for this study. Daily rainfall totals were obtained for the region extending from 0° to 50°E and 0° to 40°S, with data falling outside the LRB being masked out as depicted in **Figure 1.1**.

b. Extreme Rainfall Events identification and ranking

The method for identifying and ranking daily extreme rainfall events used here was first proposed by Hart and Grumm (2001) and later modified by Ramos et al. (2014, 2017) for the Iberian Peninsula. The choice of this method is that it takes into consideration both the spatial extent (i.e. an area affected by the event) and the intensity of rainfall over the basin. The 95th percentile is calculated for each grid point. Only grid points with rainfall amounts above 1 mm / day (wet days) for the extended austral summer season (October- April) are considered. Following this, a 7-day running mean (μ) is applied to the 95th percentile for each grid point to smooth the daily climatological noise. The anomalies (N) are then calculated by subtracting the smoothed 95th percentile (μ) values from daily rainfall totals as follows:

$$N = precip_{c,i,j} - \mu_{c,i,j} \dots \dots \dots (4.1)$$

The extreme events are then ranked based on the magnitude (R) of each event given by an index that is obtained after multiplying:

$$R = N \times M \dots \dots \dots (4.2)$$

- 1) The percentage of grid points that have anomalies (N) above a certain threshold (95th of the long-term climatology) by
- 2) The mean (M) values of the anomalies over this percentage.

c. Synoptic Classification

A key component of this study is to understand the dominant mechanisms through which extreme rainfall is produced in the LRB. As such, a combination of products is used to subjectively identify the type of rainfall producing system/ dominant synoptic setting through which the top 200 extreme events were produced. These include mesoscale convective systems (MCS) and COLs which were identified subjectively using Gridded Satellite (GridSat-B1) data (Knapp et al., 2011), South African Weather Service (SAWS) synoptic weather maps, and NCEP/NCAR reanalysis data (Kalnay, 1996). Tropical low-pressure systems (depressions, storms, and cyclones) were identified from the International Best Track Archive for Climate Stewardship (IBTrACS) data (Knapp et al., 2010) and from SAWS synoptic maps. Cloud bands were identified objectively using the output provided by Hart et al. (2012).

To investigate the relationship between the number of events and the seasonal rainfall anomalies, the standardized precipitation anomalies for each year X_i for the short seasons (October-December, January-April) and the extended summer season (October-April) were calculated as follows:

$$X_i = \frac{P_i - \bar{P}_i}{\sigma_i} \dots\dots\dots (4.3)$$

Where P_i is the seasonal rainfall; $\bar{P}_i$ is the seasonal rainfall mean for the period 1981-2016 for the entire basin; σ_i is the standard deviation of seasonal rainfall totals during the same period for the entire basin.

As alluded to in the Introduction, summer rainfall in South Africa is modulated by numerous large-scale modes of variability. To assess the potential links between some of the dominant large-scale climate modes of variability and the occurrence of extreme rainfall events in the LRB, the results were correlated with SIOD, ENSO, and the SAM indices. The Niño 3.4 index used in this study is based on the Group for High Resolution Sea Surface Temperature (GHR SST) anomalies in the Niño 3.4 box (190°E-240°E; 5°S-5°N). The seasonal (OND / JFMA) averages in the Niño 3.4 SST index above (below) 0.5°C (-0.5°C) are defined as El Niño (La Niña), while the averages between -0.5°C and 0.5°C are defined as neutral. The Behera and Yamagata (2001) SIOD index defined as the difference in SST anomalies between the eastern Indian Ocean (90°E-100°E; 28°S-18°N) and the southwestern Indian Ocean (55°E-65°E; 37°S-27°S) was used. The SAM index used in this study is that of Marshall (2003), which is a monthly mean difference between the mean sea level pressure (SLP) anomalies at six stations close to 40°S and six stations close to 65°S.

4.3. Results

a. Synoptic weather types and spatial distribution of extreme rainfall

In this section, the focus is on all synoptic weather systems linked to extreme rainfall events over the LRB. For the purposes of the analysis, two categories of the rankings are shown; namely, the top 20 and the top 200. Each of the top 200 events was then classified into one of the four main rainfall producing systems; (i) cloud bands, (ii) tropical lows (depressions, storms, and cyclones), (iii) MCS, or (iv) COLs. **Table 4.1** lists a rank of maximum daily rainfall and the associated rainfall producing system for each of these top 20 events. Of these 20 events, 45% were associated with cloud bands (9), 45% with tropical lows (9), and 10% linked to MCSs (2). For the top 200 events, the proportions remained similar with 48% of events classified as cloud bands (96), just over 28% as tropical lows (57), about 14% as MCS (27), and 10% as COLs (20). It should be noted that the method used in this study identifies and ranks daily precipitation extremes (i.e. heavy rainy days), and thus several events listed in **Table 4.1** (and in the top 200) can be linked to a single multi-day event.

Figure 4.1 shows spatial rainfall distributions and the synoptic system linked with the top 20 events over the entire basin. The transition zone between the steep topographical areas over northeastern South Africa and the floodplains in southeastern Mozambique generally received higher rainfall amounts compared to the northern and western parts of the basin (southern Zimbabwe and south-eastern Botswana respectively). Heavy rainfall linked to tropical lows (depressions, storms, cyclones) was primarily confined to the eastern parts of the basin with the maximum amounts over the steep topographic regions (**Fig. 4.1**). No discernible difference could be found with regards to the total spatial coverage of rainfall between the different rainfall producing systems in the top 20 events. Furthermore, the maximum daily rainfall received at a particular point in the LRB varies from one event to the other, and ranges from 61 mm (event ranked #6) to 188 mm (event ranked #14).

Table 4.1: The ranking of the top 20 daily events over the Limpopo River Basin and the accompanying daily maximum rainfall total and synoptic weather type as determined by analysis of SAWS synoptic charts, IBTrACS data, and OLR. The ranking of an event is based on the percentage area of grid points that have rainfall anomalies above the 95th percentile of the long term climatology multiplied by the mean values of the anomalies over this percentage. It should be noted that several daily events can be linked to a single multi-day event.

Rank	Event	Rainfall (mm)	Synoptic weather type
1	20-Jan-13	133	Tropical low
2	05-Mar-97	167	Tropical low
3	24-Feb-00	176	Tropical low
4	09-Jan-91	116	Cloud band
5	27-Jan-96	105	Cloud band
6	17-Dec-07	61	Cloud band
7	23-Feb-00	114	Tropical low
8	06-Feb-00	133	Tropical low
9	28-Mar-06	130	MCS
10	10-Feb-96	113	Tropical low
11	03-Mar-06	164	Cloud band
12	01-Dec-89	97	MCS
13	05-Mar-99	122	Tropical low
14	08-Feb-85	188	Cloud band
15	04-Mar-04	169	Tropical low
16	31-Jan-81	129	Cloud band
17	22-Mar-84	66	Cloud band
18	19-Apr-86	66	Cloud band
19	17-Jan-00	121	Tropical low
20	18-Feb-91	125	Cloud band

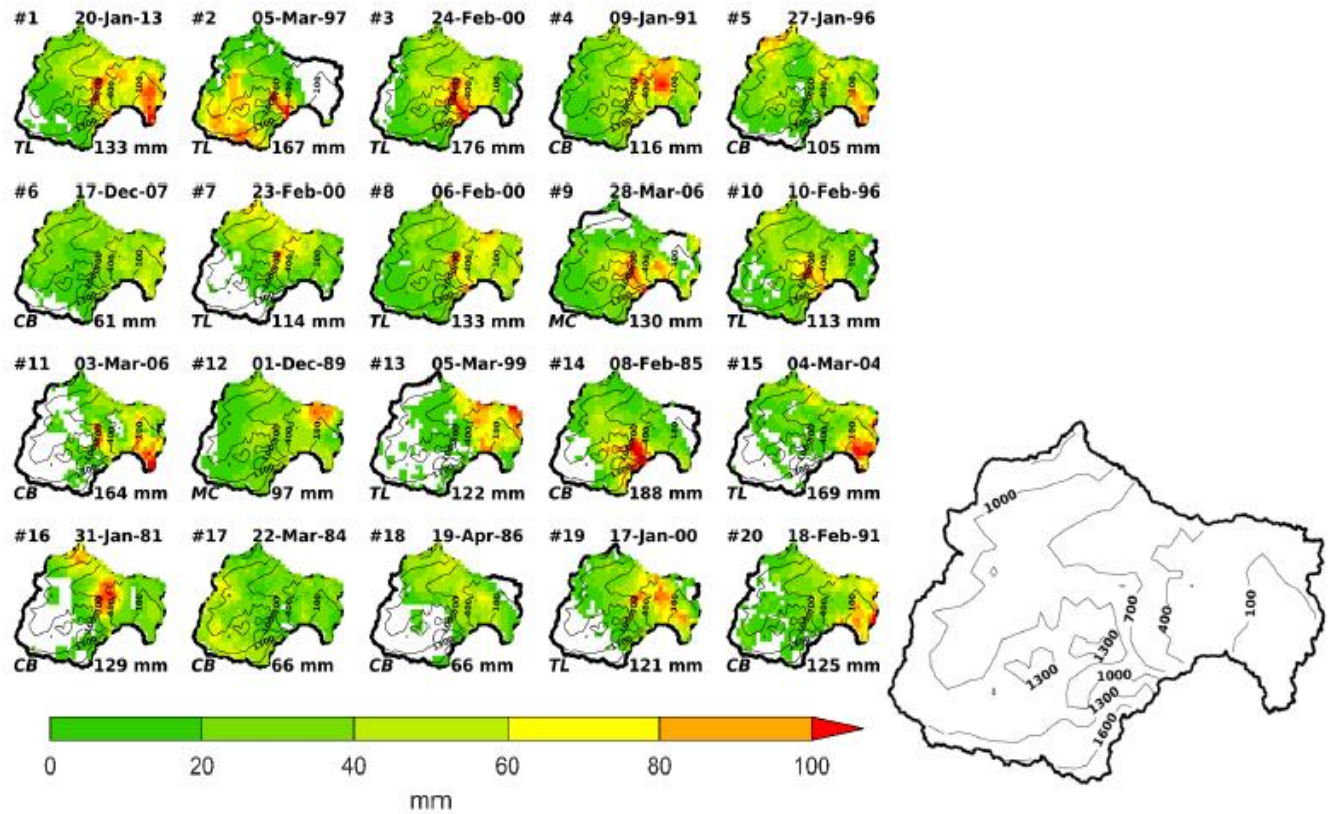


Figure 4.1: Daily rainfall (shaded; units are in mm) of the top 20 ranked extreme rainfall events over the Limpopo River Basin. The contours in the panels represent the local topography, while for clarity a zoomed topography map is inserted in the bottom right. Symbols CB, TL, and MC in the bottom left corner of each panel denote the different rainfall mechanism associated with each event (CB- cloud band, TL- tropical low, MC- mesoscale convective system). The maximum rainfall during each event is given in the bottom right-hand corner.

b. Monthly distribution of heavy rainfall events and synoptic weather types

Figure 4.2a shows the monthly distribution of extreme events in the two categories, showing that for the top 20, there is an increase from December through to a maximum in February/March and then a sharp decrease in April. For the top 200 case, there are substantial numbers in all months from October to April but with an obvious increase in January and a maximum in March. Thus, the second half of summer tends to show more events for both categories. The monthly breakdown of each rainfall producing type for the top 200 extreme events is provided in **Figure 4.2b**. Apart from COLs, the seasonal cycle of each weather system contributing to extreme rainfall is similar to that described above, with the largest number of events occurring during the late summer months (January to March), and the least number of events during early summer months (October to

December). The COL timing in **Figure 4.2b** is consistent with Singleton and Reason (2007b) who found that these systems are most common over subtropical southern Africa in the transition seasons.

Over the 7-month period, the number of cloud band related events per month in the top 200 (**Fig. 4.2b**) ranged from 9 to 20, increasing from a minimum in October to a maximum in February with a sharp decline in April, broadly consistent with Hart et al. (2013). Tropical low numbers also generally increase through the summer (from November) but have a later maximum (March) than cloud bands, and again decrease rapidly in April. For MCS, the monthly frequency is variable through the summer but with a peak in January. However, it is not uncommon for MCSs to be embedded within cloud bands and thus the analysis may underestimate the role of such systems in extreme rainfall events in the region.

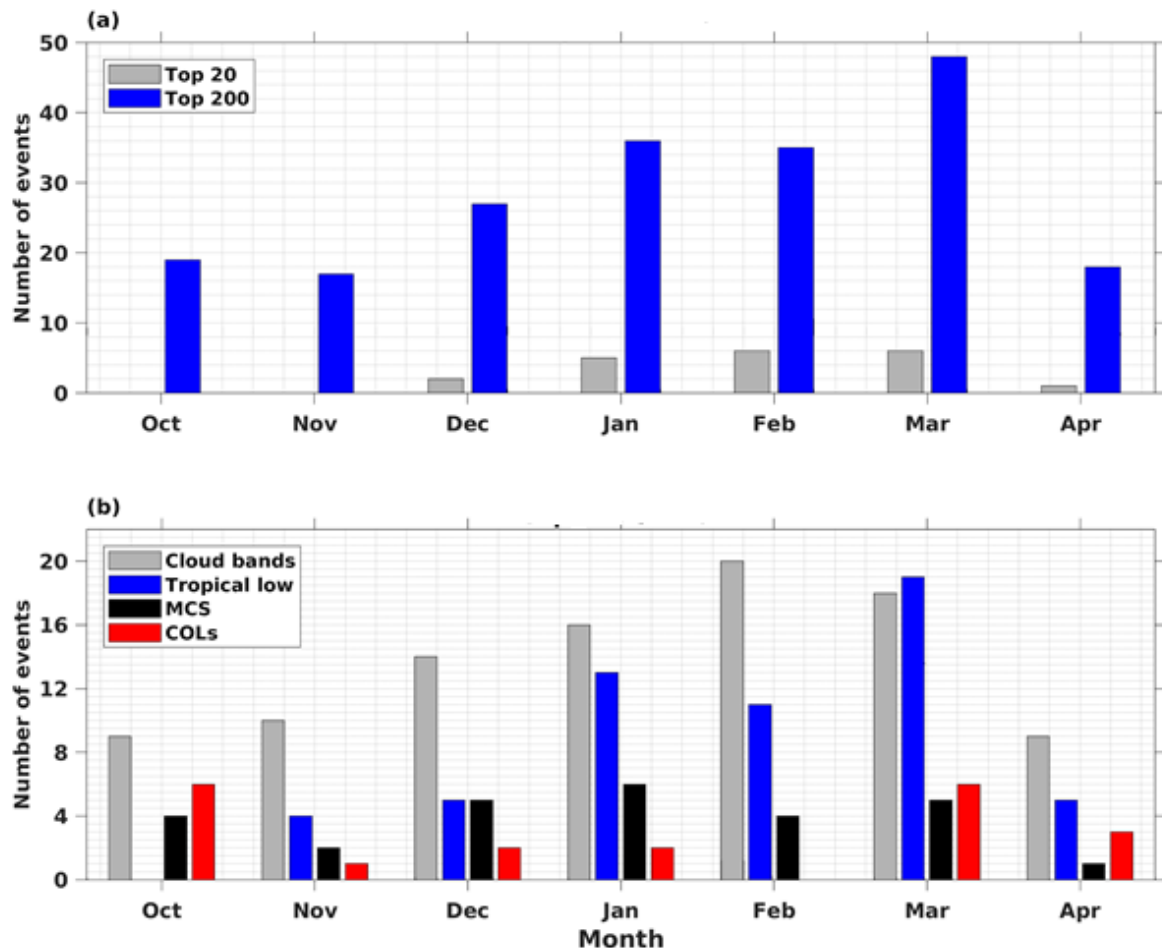


Figure 4.2: (a) The monthly distribution of extreme rainfall events over the Limpopo River Basin during the austral summer months for the period 1981-2016. The top 20 events are represented by grey bars, while the top 200 are in blue bars. (b) Monthly distribution of rainfall

producing systems leading to extreme rainfall over Limpopo for top 200 heavy rainfall events (Cloud bands are in grey, Tropical Lows in blue, MCS in black and COLS in red).

c. Interannual variability of extreme rainfall

To help understand if extreme rainfall events have an impact on the summer rainfall variability over the basin, standardized rainfall anomalies of the LRB were compared to seasonal totals of the top 200 rainfall extremes (**Fig. 4.3**). The summer season was divided into two seasons, early summer (OND, **Fig. 4.3a**), and late summer (JFMA, **Fig. 4.3b**). On average, four events (two) occurred during late (early) summer months, as a result of the increasing frequency of tropical lows and cloud bands from January onwards (**Fig. 4.2**). Substantial interannual variability is evident in both cases but the years of anomalously low or high frequency in OND are, in general, not followed by a similar pattern in JFMA so that for the summer, as a whole, the frequency anomalies may cancel out to some extent.

During JFMA, years with the largest number of events tend to have extremely wet seasons - the ten late summers with above average number of events (1981, 1991, 1995, 1996, 2000, 2004, 2006, 2011, 2013 and 2014) experienced positive anomalies in rainfall (**Fig. 4.3b**). The same does not hold for OND; for example, 2007 had the largest number of events but the rainfall anomaly was barely above average, while 1999 was the wettest season but no high ranking extreme events occurred (**Fig. 4.3a**). Out of 20 summers with above average number of events (i.e. more than two events per year), only 11 experienced wet conditions (**Fig. 4.3a**). Furthermore, only OND 2016 had an anomalously large number of events corresponding with a very large positive anomaly in rainfall.

To further examine the relationship between the top ranked extreme events and seasonal rainfall totals, the number of rain days over the LRB is also computed for the full summer period. Two categories of thresholds were used to define moderate rain (>10 mm/day) and heavy rainfall days (>25 mm/day). The number of rainy days was determined by calculating a percentage of grid points which exceeded a threshold in each category within the basin. Days with at least 10% of grid cells exceeding the respective thresholds were retained for analysis. Seasons with strong positive anomalies in summer rainfall totals (i.e. above one standard deviation; **Fig. 4.4a**) had above average number of wet days (1987/88, 1995/96, 1999/00, 2005/06; **Fig. 4.4b**), as well as above average number of extreme events (**Fig. 4.4c**), except for 1987/88 which had a slightly

below average number of events. Similarly, dry seasons (1981/82, 1982/83, 1991/92, 2002/03, 2011/12) with anomalies over one standard deviation below average (**Fig. 4.4a**), had below average number of wet days (**Fig. 4.4b**) and extreme events (**Fig. 4.4c**). Interannual variability in the frequencies of the events falling within the top 200 (**Fig. 4.3a and b**) does not necessarily reflect in the seasonal totals (**Fig. 4.4a**). However, this disparity is not surprising as Dyson (2009) showed that the northeastern parts of South Africa are typically wet with a high number of rain days during January-March. Anomalously wet seasons coincided with those seasons with the most rainy days. These results suggest that the anomalously wet seasons over the LRB are due both to more rainy days and to more extreme rainfall events (i.e., increase in rain day frequency and intensity).

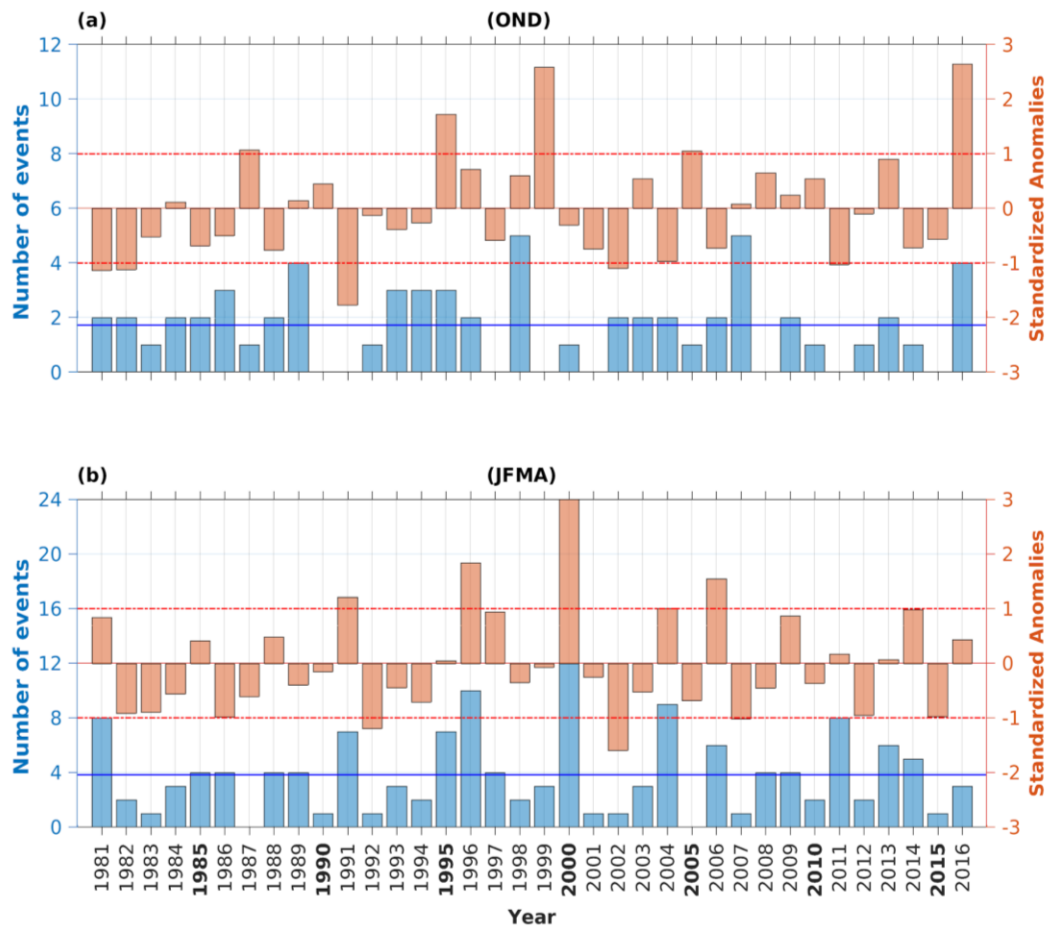


Figure 4.3: 1981-2016 total number of events in the top 200 for (a) October-December (early summer, in blue) and the standardized rainfall anomalies in red, (b) same as subplot a, but for January-April (late summer). Dashed lines are ± 1 STD. The solid line in panels a and b denotes the average number of extreme events.

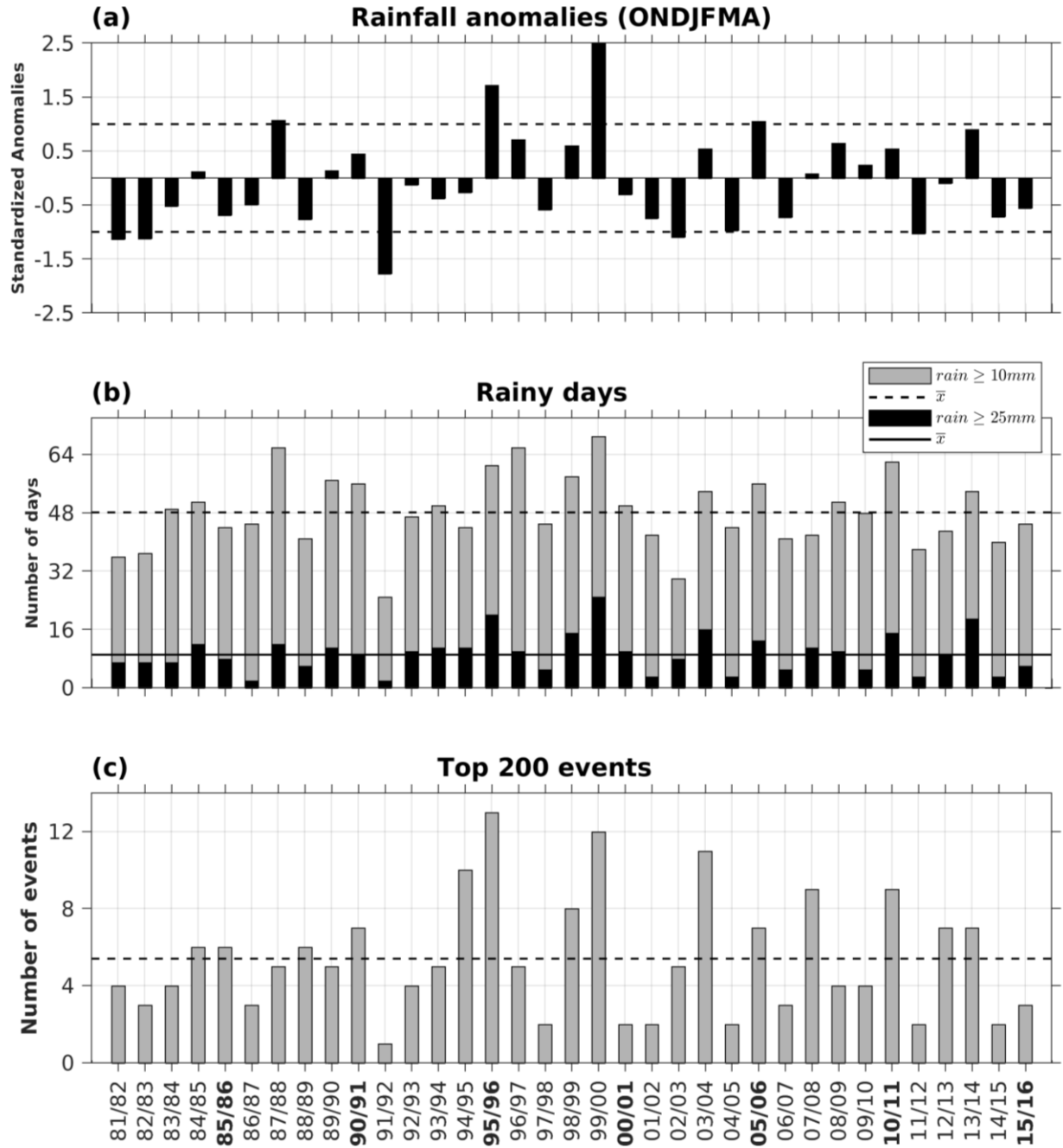


Figure 4.4: Comparison of (a) standardized rainfall anomalies over the basin (October-April), dashed lines are ± 1 STD; (b) number of days where rainfall amounts exceeded 10 (25) mm for at least 10% grid points within the LRB in grey (black) bars with the mean showed as the dashed (solid) lines; (c) the occurrence of the top 200 events for the entire basin, during the period 1981-2016, average number of events shown as dashed line.

d. Extreme events and large-scale modes of climate variability

Here, the possible relationships of rainfall extremes over the LRB with large scale climate modes such as ENSO, SIOD and SAM are considered. The annual distribution (season totals) of the events, standardized anomalies, SIOD, Niño 3.4 index, and the SAM index for the late summer season (JFMA) are shown in **Figure 4.5**. Over the period 1981-2016, 10 (out of 36) late summers (1981, 1991, 1995, 1996, 2000, 2004, 2006, 2011, 2013, 2014) experienced an above-average number of extreme events (i.e. more than 4 events per season) (**Fig. 4.5a**), 4 of which occurred during La Niña events (**Fig. 4.5d**). Of the remaining 6 seasons, 5 were associated with neutral ENSO conditions and 1 was an El Niño summer. All of these 10 seasons experienced wetter than normal conditions (**Fig. 4.5b**). In addition, the number of extreme events is significantly negatively correlated with ENSO ($r = -0.47$, $p < 0.05$). This suggests a close relationship between ENSO and the number of extreme rainfall events over the LRB, at the interannual time-scale during JFMA.

For the SIOD, there were 5 out of these 10 late summers with above average number of extreme events when this mode was in its positive phase. The ENSO – SIOD phase combination shows that 8 out of 10 seasons with above average number of events occurred when ENSO and the SIOD were in opposite phases. However, the SIOD positive correlation with the number of extreme rainfall events is not statistically significant ($r = 0.12$, $p > 0.1$, respectively) while there is no correlation with SAM ($r = 0.03$).

During the early summer (OND, **Fig. 4.6a**) over the same period, 20 summers had above average number of extreme rainfall events (i.e. more than 2 events per season). As already mentioned, this average of 2 events per season is half the average number occurring during the late summer. Although several of these OND seasons of above average numbers of extreme events occur during La Niña (**Fig. 4.6d**), the negative correlation with ENSO is not statistically significant ($r = -0.25$, $p > 0.1$). Thus, ENSO appears to have a weaker relationship with the number of extreme rainfall events over the LRB during the early summer than in the late summer, which is consistent with findings that ENSO has a stronger association with anomalies in rainfall totals over subtropical southern Africa in JFM than in OND (e.g., Reason et al., 2000). For the SIOD, the positive correlation with the number of extreme events is stronger than that for JFMA but again, it is not statistically significant ($r = 0.25$, $p > 0.1$). However, unlike for JFMA, the SAM exhibits a weak negative correlation ($r = -0.12$) with the number of extreme events. These results therefore suggest

that the number of extreme rainfall events over the LRB is not strongly influenced by the SIOD or SAM but does have a significant relationship with ENSO.

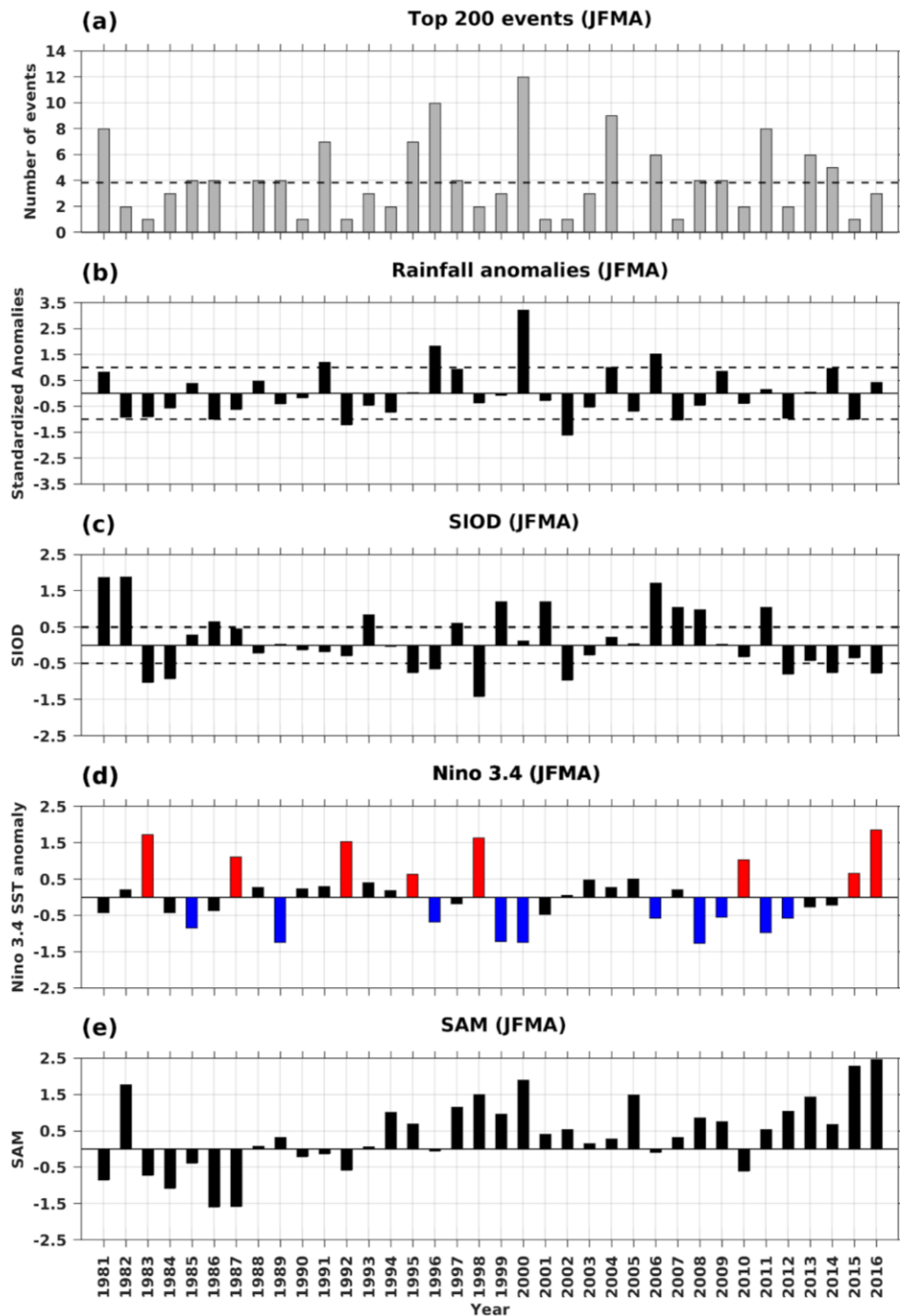


Figure 4.5: (a) The number of the top 200 extreme precipitation events during each extended summer (JFMA), and the corresponding (b) standardized rainfall anomalies, (c) SIOD index, (d) Niño 3.4 index, and (e) SAM index. The dashed line in panel a denotes the austral summer mean of the number of events. Red, blue and black bars in panel d denote El Niño, La Niña, and neutral phases of ENSO respectively. The y-axis range differs between subplots.

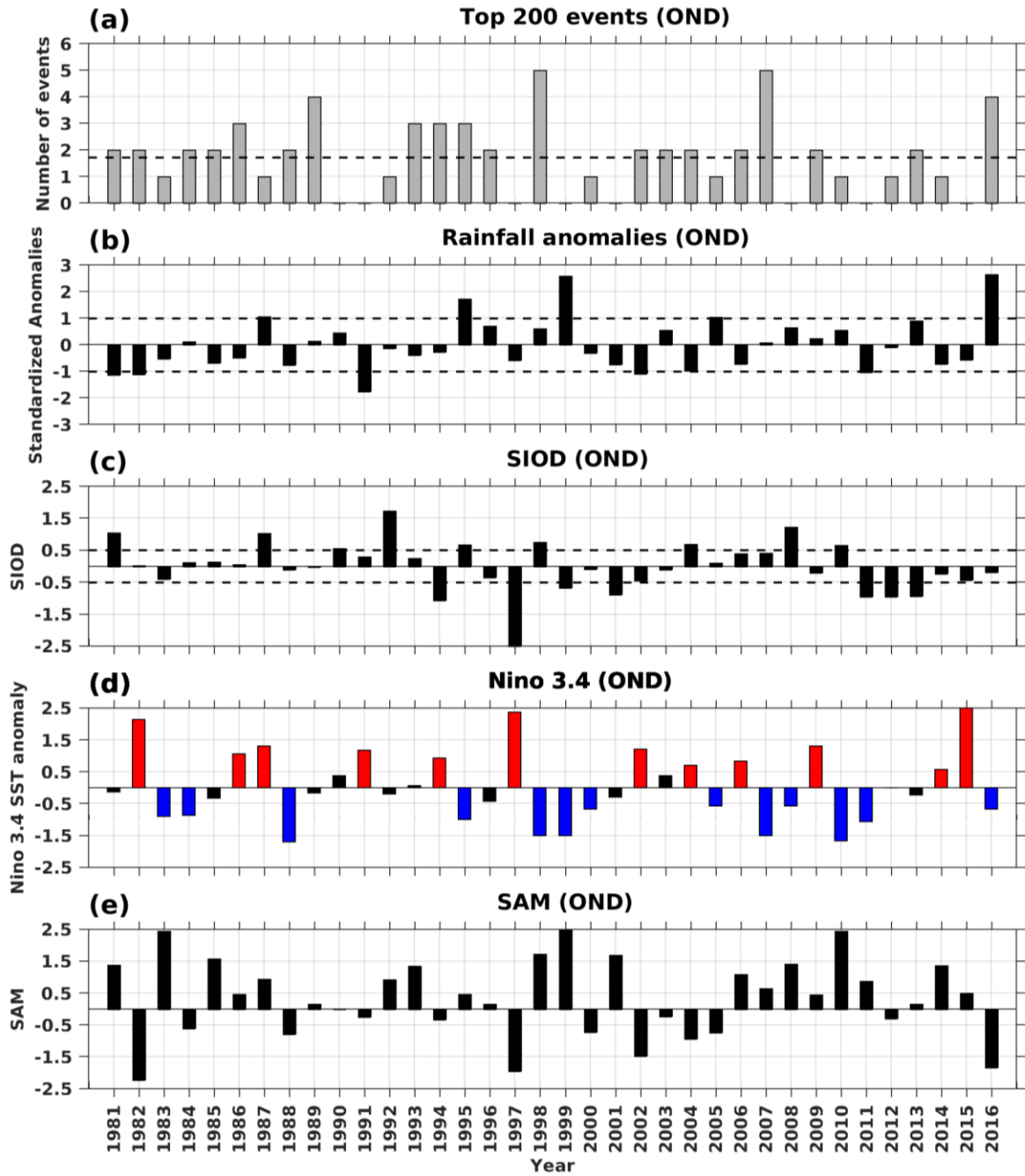


Figure 4.6: Same as Figure 4.5, but for OND.

e. Circulation anomaly patterns linked with above-average number of extreme rainfall events during ENSO-neutral and neutral SIOD phase

Although there is a significant statistical correlation with ENSO, **Figures 4.5 and 4.6** suggest that there are also other factors that contribute to the interannual frequency of extreme rainfall events over the LRB. Similarly, Muñoz et al. (2015) indicated that the relationship between ENSO and the interannual frequency of extreme rainfall events over southern South America can be explained

by other factors in addition to ENSO. Here, those ENSO-neutral and neutral (weak) SIOD late summers of 1991, 2004, 2013, 2014 which had an above average number of extreme events (7, 9, 6, and 5 respectively) are considered.

Before examining circulation anomalies for each of these four seasons, it is useful to consider **Figure 4.7** which displays the seasonal climatology (1981-2016) of the vertically integrated (850-500 hPa) moisture flux for JFMA. In general, the climatological moisture sources for southern Africa are the northeasterly monsoonal flux from the tropical western Indian Ocean and the easterly flux from the southwestern Indian Ocean. These two circulations converge over southern Africa near southern Zambia/ northern Zimbabwe. Previous studies (Cook et al., 2004; Driver et al., 2019) have also shown a westerly moisture flux at 850 hPa from the tropical southeast Atlantic Ocean which is not visible in the vertically integrated plot. This flux is closely related to the near-surface Angola Low which is strongly expressed at 850 hPa. Another noticeable feature in the climatology is the Mozambique Channel Trough (MCT; Barimalala et al., 2018). These authors have shown that variations in the MCT can impact the moisture transport coming from the southwest Indian Ocean into mainland southern Africa and hence precipitation over the landmass. A weaker (stronger) MCT leads to more (less) moisture advecting into southern Africa and hence enhanced (reduced) precipitation over the landmass (Barimalala et al., 2018).

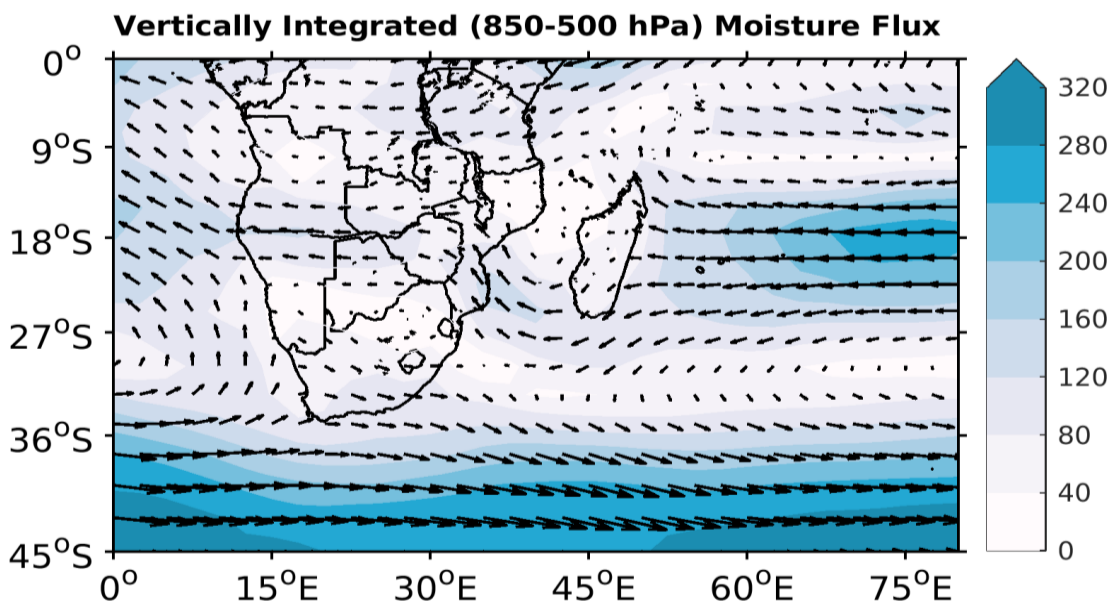


Figure 4.7: Climatology of vertically integrated low-level (850-500 hPa) moisture flux anomalies ($\text{kg m}^{-1} \text{s}^{-1}$), over the period 1981-2016 for JFMA. Based on NCEP/NCAR reanalysis data.

The JFMA moisture fluxes during the four ENSO-neutral and neutral (weak) SIOD events are now considered. For 1991, there were easterly moisture flux anomalies (integrated from 850-500 hPa) across Madagascar and the northern Mozambique Channel as a result of a strong anticyclonic anomaly southeast of Madagascar (**Fig. 4.8a**). Over northern Madagascar and the northern Channel, these represented an enhanced moisture flux towards Mozambique / southern Tanzania from the tropical western Indian Ocean (cf. **Figure 4.7**). There was also a cyclonic anomaly in the southern part of the Mozambique Channel which resulted in more moist marine air being transported into southern Mozambique and the eastern LRB. SST anomalies (not shown) in this region were positive during this season. Thus, both climatological sources of moisture flux into southeastern Africa from the tropical and subtropical western Indian Ocean respectively (D'Abreton and Lindesay, 1993; Reason et al., 2006) were enhanced. Another favourable feature was a cyclonic anomaly over Angola / Namibia and Botswana which, firstly acted to reduce the climatological export of moisture from western southern Africa out over the southeast Atlantic (cf. **Figure 4.7**), and secondly, favoured strengthening of the Angola Low and hence cloud band development. Such westerly flux anomalies from this part of the Atlantic have previously been associated with intraseasonal wet spells over South Africa (Cook et al., 2004). Over the LRB, anomalies in vertical velocity were weak although there was strong relative uplift over its eastern margins and particularly over the Mozambique Channel (**Fig. 4.9a**), which would have been favourable for tropical low development during this season (two of the six events). The other four events were cloud bands.

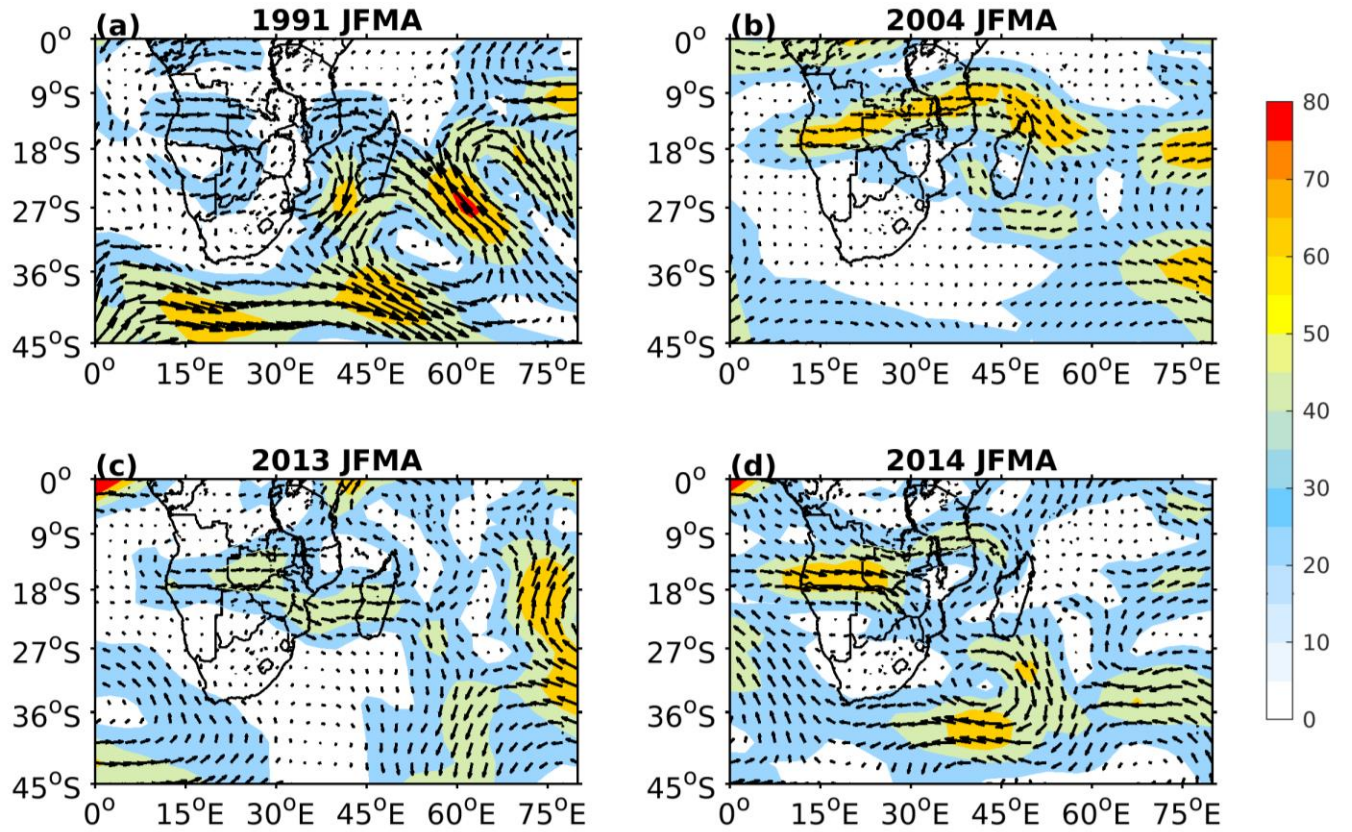


Figure 4.8: Vertically integrated low-level (850-500 hPa) moisture flux anomalies ($\text{kg m}^{-1} \text{s}^{-1}$) over southern Africa JFMA of (a) 1991, (b) 2004, (c) 2013, (d) 2014.

For 2004, there were also westerly flux anomalies from the tropical southeast Atlantic towards the northwestern LRB (**Fig. 4.8b**). However, westerly anomalies extended right across to the northern Mozambique Channel implying increased convergence over northern Mozambique and eastern Zambia with the climatological northeasterly flux (**Fig. 4.7**) from the tropical western Indian Ocean. Such convergence is favourable for increased rainfall events. There were also enhanced southeasterlies in the southern Mozambique Channel leading to increased onshore flow of moist marine air towards the eastern LRB. SST anomalies (not shown) were also slightly positive in the Mozambique Channel. Unlike in 1991, a noticeable region of enhanced uplift was evident over all southern Africa, which was favourable for rainfall (**Fig. 4.9b**). Similar to 1991, most events in 2004 were associated with cloud bands. This season also experienced a tropical low that was one of the top 20 events (**Table 4.1**).

Both JFMA 2013 and 2014 were characterised by enhanced westerly flux anomalies from the tropical southeast Atlantic Ocean; particularly the latter year (**Figs. 4.8c and d**). These westerly

anomalies split over Zambia into a northern branch that opposes the mean (**Fig. 4.8**) northeasterly flux from the tropical western Indian Ocean and a southern branch that opposes the mean easterly flux over central and southern Mozambique. Thus, increased low level moisture convergence is implied over these regions, favourable for the development of heavy rainfall. JFMA 2013 was dominated by tropical lows, including the top ranked event in January (**Table 4.1**) which led to over 100 deaths in southern Mozambique (Manhique et al., 2015). Previously, Manhique et al. (2015) attributed the January 2013 event (#1) to a long lasting cloud band. These authors used multi-day averages to study this event, and as a result, the movement of the tropical low over the land together with frontal passage south of South Africa resembled a large cloud band. However, a detailed daily analysis of this event indicates an eastward moving tropical low tracking over southern Africa rather than a persistent cloud band was present. Similar to 2013, JFMA 2014 was also dominated by tropical lows. A region of strong relative uplift was noticeable over the southeastern parts of southern Africa (Botswana, Mozambique and northeastern South Africa) during 2014 as well as the Mozambique Channel consistent with tropical lows being important in this season. In 2013, there was relative uplift over the southern part of the LRB but weak positive anomalies over the northern part and stronger positive anomalies further west (**Figs. 4.9 c and d**).

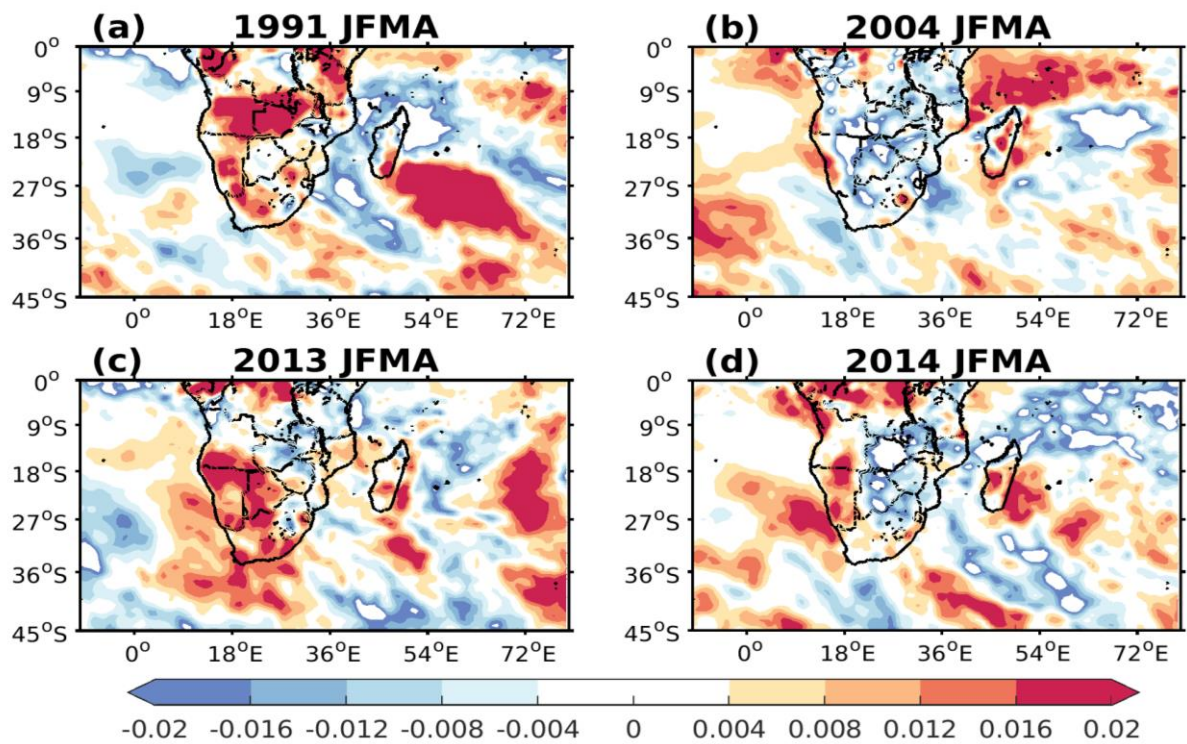


Figure 4.9: 500 hPa NCEP/NCAR vertical velocity anomalies (m s^{-1}) over southern Africa during (a) 1991, (b) 2004, (c) 2013, (d) 2014 JFMA.

In summary, although there are differences in the moisture flux anomaly patterns for each of these four summers, a common feature is strong westerly moisture flux anomalies from the tropical southeast Atlantic. Such anomalies have previously been identified as important for intraseasonal wet spells during summer over South Africa (Cook et al., 2004) and for the January 2013 flooding event in the eastern LRB (Manhique et al., 2015) because they reduce the export of moisture away from western southern Africa over the tropical Atlantic. In three of the four summers, westerly anomalies extend right across southern Africa, opposing the mean easterly flux from the western Indian Ocean across the entire landmass. As a result, these anomalies lead to increased low level moisture flux convergence over the LRB region. Such convergence was accompanied by strong relative uplift over the LRB in 2004 and 2014 further enhancing the favourable conditions. The westerly anomalies over Angola in each of the four ENSO-neutral seasons with above average number of events is reminiscent of the La Niña composite (Fig. 4.10); La Niña summers are generally associated with wetter than average conditions and with more extreme rainfall events over the LRB.

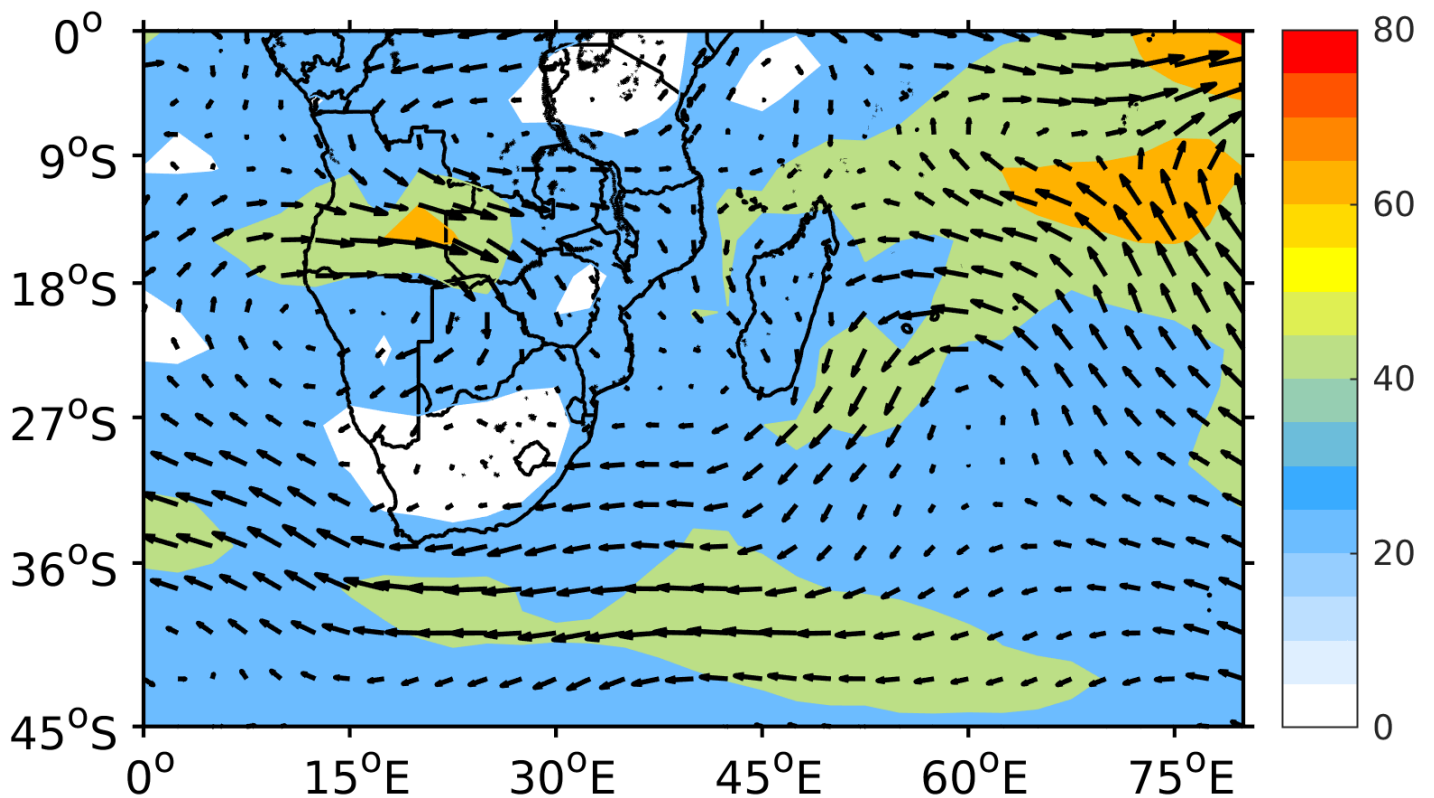


Figure 4.10: La Niña composite anomalies of vertically integrated (850-500 hPa) moisture flux ($\text{kg m}^{-1} \text{s}^{-1}$) over southern Africa during JFMA. Based on NCEP/NCAR reanalyses data.

4.4. Discussion and conclusion

This study set out to identify and classify rainfall producing systems linked to extreme rainfall events over the LRB in southeastern South Africa during the period 1981-2016. Long-term studies of extreme weather events over southern Africa are limited by a lack of high spatial and temporal observation data. However, satellite-derived rainfall estimates with a higher temporal and spatial coverage have been invaluable in providing “observations” in data poor regions. In this study, CHIRPS rainfall data was used to identify extreme rainfall events over the LRB.

It is found that the spatial distribution of rainfall associated with extreme rainfall events is not uniformly distributed over the basin, with a bias of more extreme rainfall towards the eastern half. This east-west gradient in extreme rainfall events is consistent with the annual and seasonal rainfall mean patterns (Mosase and Ahiablame, 2018). An obvious characteristic is the spatial pattern of rainfall maximum over areas with a steep topographic gradient between the mountainous (e.g. Drakensberg Mountain) areas of northeastern South Africa where the altitude rises above 1300m and the Mozambican floodplains. Although this study does not specifically focus on the topographic effects on rainfall over the LRB, the local topography is known to have important consequences for rainfall over southern Africa (Dedekind et al., 2016). Furthermore, there is evidence that the coastal mountains of eastern and southern South Africa have resulted in extreme rainfall during COL and mesoscale convective events (Singleton and Reason, 2006, 2007a; Blamey and Reason, 2009). East of the topography in the LRB, the Mozambique floodplains also tend to receive high rainfall amounts, likely due to its immediate proximity to the relatively warm waters of the Mozambique Channel where tropical storms, and occasionally tropical cyclones develop. Such storms, when they make landfall on the mainland, tend to do so either near the far eastern LRB or a bit further north along the Mozambican coast. Their intensity tends to weaken substantially as they track further inland and thus the eastern LRB is more likely to receive more rainfall from them than the rest of the LRB.

The classification of the top 200 extreme rainfall events suggests that most events over the basin are associated with cloud bands (48%) and tropical lows (28%), with MCS (14%) and mid-to-upper level COLs (10%) making up the remaining quarter. The fact that most events in the top 200 are associated with cloud bands is in agreement with previous studies (Harrison, 1984; Reason et al., 2006; Hart et al., 2010, 2013; Manhique et al., 2011) which further indicates their importance for rainfall over southern Africa. The monthly distribution of COLs over the basin agrees with the

findings of Taljaard (1985), Singleton and Reason (2007b) and Favre et al. (2012), in which they showed that COLs over southern Africa occur mostly during transition seasons and that they are important contributors of early and late summer rainfall.

Monthly distribution of the events showed that the late summer months (January-March) had the highest number of the top 200 events. Approximately 60% of these extreme events occurred during JFM, a time when convective processes dominate over the southern African summer rainfall region (Tadross et al., 2005). Blamey et al. (2017) found marked differences between the early and late summer over northern South Africa in severe convective environment characteristics such as Convective Available Potential Energy and Deep-Layer Wind Shear. Mason and Jury (1997) demonstrated that during late summer (January-March), tropical convection migrates southward to about 20°S over the subtropics linked with the formation of the cloud bands, which create favourable conditions for rainfall over the LRB. Dyson et al. (2015) indicated that the atmospheric conditions over the north eastern parts of South Africa evolve from an extra-tropical nature in early summer to a more tropical nature in late summer.

On longer time-scales, the period 1981 to 1993/94 was characterized by fewer events as compared to the second part of the 1981-2016 period. Several studies have highlighted this period as being dry over southern Africa relative to the late 90s / 2000s (Malherbe et al., 2014; Reason, 2016). Moreover, Mosase and Ahiablame (2018), showed statistically significant increasing trends in rainfall over the LRB between 1979 and 2013. It is known that ENSO events have an impact on southern African seasonal rainfall amounts (Lindesay, 1988; Reason et al., 2000); however, it remains unclear how this mode influences extreme rainfall events over the LRB. There is evidence that La Niña conditions tend to favour COL events over subtropical southern Africa (Singleton and Reason, 2007b) as well as cloud band occurrence over the landmass rather than further east over the Mozambique Channel or Madagascar (Hart et al., 2018). For tropical cyclones, Vitart et al (2003) showed that landfall over Mozambique tended to be more common during La Niña although there have also been cases of strong cyclones making landfall in El Niño summers (Klinman and Reason, 2008). In general, the cyclonic (anticyclonic) low level circulation anomalies and relative uplift (subsidence) that tend to occur over southern Africa during La Niña (El Niño) are more (less) favourable for convective rainfall over the land.

Although an inverse relationship appears to exist between the number of extreme events and the Niño 3.4 index, it remains a challenge to disentangle the impacts of ENSO from other modes of

variability on southern African climate such as the SAM or the SIOD. For example, the 1991/92 summer experienced the smallest number of extreme rainfall events and severe drought, during the 1981-2016 period. A combination of a negative SIOD, El Niño, and a negative SAM occurred during this summer, all unfavourable for summer rainfall over the region. Overall, the majority of the events that occurred during the anomalously wet summers were associated with positive SIOD and La Niña conditions as listed in **Table 4.2**. Positive SIOD is associated with warmer than normal SSTs in the southwest Indian Ocean and anticyclonic anomalies there (Behera and Yamagata, 2001; Hermes and Reason, 2005), which leads to enhanced moisture flux into southeastern Africa (Reason, 2001, 2002) and hence the LRB during the events. The impact of the SIOD on extreme events over the basin seems to be a compound effect to that of ENSO.

Table 4.2: Combinations of ENSO and SIOD phases for October-April during the period 1981-2016 (similar to Hoell et al., 2017). The years with an above-average number of extreme rainfall events are in blue font.

	El Niño	La Niña	Neutral
Negative SIOD	1982-1983; 1991-1992	1983-1984; 1995-1996	2001-2002; 2012-2013
	1994-1995; 1997-1998	1999-2000; 2011-2012	2013-2014
	2002-2003; 2009-2010		
	2014-2015; 2015-2016		
Positive SIOD	1986-1987; 1987-1988	1984-1985; 1988-1989	1981-1982; 1985-1986
	2004-2005; 2006-2007	1998-1999; 2000-2001	1989-1990; 1990-1991
		2005-2006; 2007-2008	1992-1993; 1993-1994
		2008-2009; 2010-2011	1996-1997; 2003-2004

Furthermore, on average, a positive SAM index is associated with wetter than normal summers over the basin. The number of events shows significant peaks during strong positive SAM summers, especially from the early 1990s to near present. A positive phase of the SAM is associated with increased geopotential height over the mid-latitude ocean (near about 40°S; southeast of southern Africa) (Malherbe et al., 2014) which can affect the number and tracks of mid-latitude cyclones passing to the southeast of South Africa. Changes in the frequency and tracks

of these cyclones may influence cloud band development across the LRB since these cloud bands need strong midlatitude troughs over and south of South Africa in order to develop (Harrison, 1984; Hart et al., 2010). Increased geopotential height over the southwest Indian Ocean to the east of South Africa can increase the southeasterly moisture flux towards the eastern LRB, particularly when SIOD phases are positive, associated with above average rainfall.

In summary, the results presented here showed that the majority of extreme events over the LRB occurred during the late summer months and are mainly due to strong cloud bands or to tropical lows. Large-scale modes of climate variability showed a link with the number of extreme events at the interannual time-scale. Consequently, monitoring the state of ENSO, SIOD, and SAM in the late austral spring / early summer may give indications of the likelihood of the rest of the summer experiencing an above or below average number of extreme rainfall events over the LRB. Given the fact that SIOD, ENSO, and SAM can occur concurrently, they may act to strengthen or weaken the impact of each other on extreme rainfall events. Therefore, seasonal forecasting of extreme rainfall events over the LRB should take into account all three climate modes. At present, such efforts in the region tend to focus mainly on ENSO state which the results presented here suggest is insufficient.

Following on from this analysis of the heavy rainfall events over the LRB, Chapter 5 now considers the moisture sources and pathways associated with summer rainfall over the LRB

Chapter 5: Moisture sources associated with heavy rainfall over the Limpopo River Basin, southern Africa

This chapter addresses the following overarching question and subsidiary questions listed below. The work is presented as the paper published in *Climate Dynamics*:

*R.S. Rapolaki, R.C. Blamey, J.C. Hermes, and C.J.C. Reason, 2020: Moisture sources associated with heavy rainfall over the Limpopo River Basin, southern Africa, *Climate Dynamics*, 55, 1473–1487.*

- What are the main sources of moisture leading to heavy rainfall events over the LRB?
- What are the relative contributions of the different branches of moisture transport towards the LRB?
- What are the main characteristics of these identified branches of moisture?

Abstract

Moisture sources and pathways over the Limpopo River Basin (LRB) in southern Africa were identified using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model applied to NCEP II ($2.5^{\circ} \times 2.5^{\circ}$) reanalysis data for 1981-2016. The 10-day air parcel backward trajectories were produced for the extended wet season (October-April) as well as the early and late summer. Analysis of a 36-year climatology of air parcel trajectories indicated seven moisture source regions for the LRB; namely, local continental, tropical southeast Atlantic Ocean, midlatitude South Atlantic Ocean, tropical Northwest Indian Ocean, tropical southwest Indian Ocean, subtropical southwest Indian Ocean, and the Agulhas Current.

The results have shown that important differences in moisture source regions and pathways exist between early (October-December) and late (January-April) summers, with the tropical northwestern Indian Ocean and the northern Agulhas Current sources more prominent during JFMA than OND. On interannual time scales, there are notable differences in moisture source regions between anomalously wet and dry summers, with the South Indian Ocean moisture contribution and transport over the LRB smaller during dry summers than wet summers. Changes in specific humidity for trajectory linked to heavy daily rainfall events (defined from CHIRPS data) showed that subtropical South Indian Ocean source is more extensive for the heavy rainfall than for the moderate case. Generally, moisture source regions and transport pathways for LRB tend to be influenced by both the regional summer season circulation and the synoptic setting.

5.1. Introduction

The Limpopo River Basin (LRB; **Fig. 5.1**) in southern Africa is a semi-arid to arid region prone to frequent droughts and occasional devastating flooding events whose causes are still not well understood. It contains a relatively poor rural population many of whom depend directly on rain-fed sources for farming and drinking water. Although there is some large-scale irrigated agriculture, subsistence farming is common in the region. In addition, there are important national park and conservation areas in various parts of the LRB. While drought is common (Mulenga et al., 2003; Reason et al., 2005), the LRB sometimes experiences flooding events during the summer rainy season (October-April), due to various synoptic weather systems (Rapolaki et al., 2019). These systems include cloud bands (Harrison, 1984; Washington and Todd, 1999; Reason et al., 2006; Hart et al., 2010, 2013; Manhique et al., 2011, 2015), tropical low-pressure systems (Dyson and Van Heerden, 2001; Reason and Keibel, 2004; Malherbe et al., 2012, 2014; Fitchett and Grab, 2014; Rapolaki and Reason, 2018; Rapolaki et al., 2019), mesoscale convective systems (MCS; Blamey and Reason, 2012), and cut-off lows (COLs; Taljaard, 1985; Singleton and Reason, 2007; Favre et al., 2012). The mean annual precipitation ranges between about 160 mm and 1100 mm, with higher rainfall amounts occurring over the eastern parts of the basin (Mosase and Ahiablame, 2018; Rapolaki et al., 2019). Most rainfall occurs during late summer months (January to March), a period when heavy rainfall events are also most frequent. To date, little is known about where moisture for these heavy rainfall events originates or how it is transported to the LRB.

Rainfall occurring over a region generally results from three main water vapour sources; remote moisture transported by the atmosphere, local evaporation mainly through evapotranspiration, and the water vapour already contained in the atmosphere (Trenberth, 1999; Trenberth et al., 2003). These authors have also shown that heavy rainfall is generally linked to moisture travelling long-distances from a remote source rather than local evaporation, whereas light and moderate rainfall is generally linked to local evaporation.

There are three common methods used to identify the source and transport of moisture for a particular region. This entails either using box models (Budyko and Drozdov, 1953; Dominguez et al., 2006), numerical water vapour tracers (D'Abreton, and Tyson, 1995; Stohl and James, 2005; Viguad et al., 2009), or oxygen isotopes analysis (Gat et al., 1970; Coplen et al., 2008). Gimeno et al. (2012) have provided a comprehensive review of the advantages and disadvantages of each

method. It is through such methods that one can establish the source and pathway of moisture into a particular region needed for the rainfall.

Here the focus is on the numerical water vapour tracers which include Eulerian and Lagrangian approaches, and particularly the latter. Globally, numerous moisture source-regions have been established using Lagrangian methods (Stohl et al., 2005; Drumond et al., 2008; Gimeno et al., 2010; Chen et al., 2012; Viste and Sorteberg, 2013; Chen and Luo, 2018). Over Africa, similar moisture transport studies have been conducted for Kenya (Gatebe et al., 1999, 2001), southern Africa (D'Abreton and Tyson, 1996; Nyanganyura et al., 2008), and for the Ethiopian highlands (Viste et al., 2013). D'Abreton and Tyson (1996) focused mostly over the interior of South Africa for short periods of interest in particular years (1980, 1981, 1991) whereas Nyanganyura et al. (2008) considered a northern Zimbabwe region. Although the Nyanganyura et al. (2008) analysis was for a longer period (1994-1999), it is still too short to examine variability in moisture transport over the subcontinent. Moreover, their region has a mostly humid tropical wet-dry climate dominated by the ITCZ in summer whereas the more southward located LRB is arid to semi-arid and can be influenced by both midlatitude and tropical weather systems.

An Eulerian analysis (Benton and Estoque, 1954; Koster et al., 1986; D'Abreton and Lindesay, 1993; Viguaud et al., 2009) is another common method adopted for the identification of moisture transport, but it does not allow one to trace the moisture-laden air over the rainfall region back to its source (Stohl and James, 2004; Gimeno et al., 2012; Drumond et al., 2019). Using such methods, previous studies have suggested that the main moisture sources for subtropical southern Africa during summer are associated with the northeast monsoon across the tropical western Indian Ocean (**Fig. 5.1**), south-easterly flow from the southwest Indian Ocean (SWIO), or northwesterly flow from the tropical southeast Atlantic Ocean (Cook et al., 2004; Reason et al., 2006; Rapolaki et al., 2019). These studies have tended to imply that the latter source is less important than those from the Indian Ocean on seasonal scales. However, there are specific summers, typically associated with anomalously warm SST off the coast of Angola and northern Namibia, when westerly moisture flux anomalies from the tropical southeast Atlantic have led to rainy conditions over large parts of southern Africa (Rouault et al., 2003; Hansingo and Reason, 2009; Reason and Smart, 2015) including the eastern LRB (Manhique et al., 2015). These westerly anomalies are thought to prevent the export of moisture away from the western subcontinent and act to oppose the mean easterly flow from the SWIO, leading to moisture convergence over the LRB (Rapolaki et al., 2019).

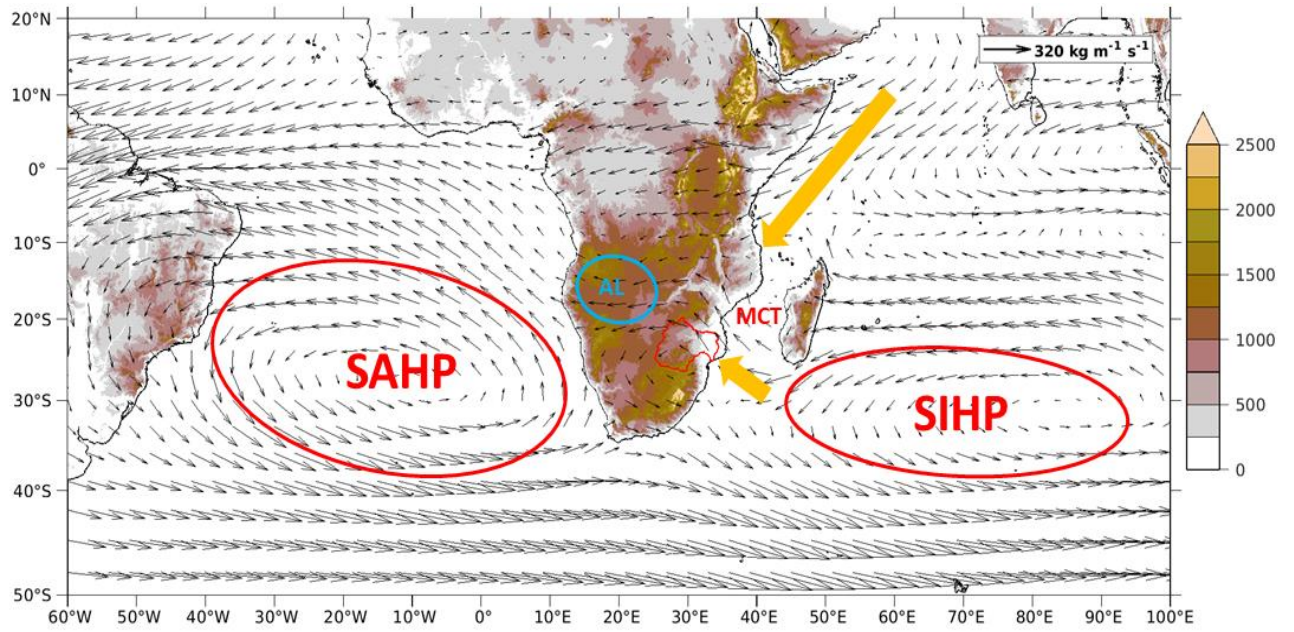


Figure 5.1: Elevation map (shading; m) with mean ERA-Interim climatological vertically integrated water vapour transport (vectors; $\text{kg m}^{-1} \text{s}^{-1}$) from the surface to 200 hPa in the austral summer period (October-April) from 1981-2016. The red polygon over southern Africa denotes the Limpopo River Basin. The abbreviations AL, SAHP, SIHP, and MCT denote the Angola Low, South Atlantic High Pressure, South Indian High Pressure, and the Mozambique Channel Trough respectively. Orange arrows indicate predominant moisture flow paths into southern Africa during the summer months based on previous studies.

Ultimately, moisture flux into the LRB varies significantly due to the regional prevailing circulation patterns, and large-scale climate modes of variability. The recent studies by Barimalala et al. (2018, 2020) showed that a stronger Mozambique Channel Trough (denoted MCT in **Fig. 5.1**) tends to lead to less moisture transport into southern Africa. The Angola Low (AL; **Fig. 5.1**) can be associated with increased local convection over the continental local source, and stronger westerly moisture fluxes from tropical southeast Atlantic Ocean (Reason et al., 2006; Munday and Washington, 2017). Other important circulation features which may lead to variations in moisture transport into the LRB are the South Atlantic High Pressure (SAHP) and the South Indian High Pressure (SIHP) systems. As a result, the amount of moisture leading to rainfall over the LRB and its transport pathways from the various source regions have not been completely quantified. Thus, the aim of this study is to identify and quantify the main moisture source regions into the LRB during the austral summer months with a focus on those associated with heavy rainfall events as defined in Rapolaki et al. (2019).

5.2. Data and methods

a. Precipitation and Potential Evapotranspiration data

In this study, the gridded $0.5^{\circ} \times 0.5^{\circ}$ resolution Climate Research Unit (CRU) TS4.02 (Harris et al., 2014) data were used to calculate the annual cycle of potential evapotranspiration and precipitation over the LRB. CRU is available for the period 1901-2017 and contains monthly values of precipitation, potential evapotranspiration, and temperature. These data are available for all continental areas, excluding Antarctica. The CRU data allows for studies of Evaporation (E) - Precipitation (P) fluxes over the land masses which are often restricted by lack of evapotranspiration. Due to the lack of high-resolution long-period station data over southern Africa, including the LRB, gridded data such as CRU provide a viable alternative for establishing the annual cycle of evapotranspiration and precipitation and their variability.

b. HYSPLIT model and input data

Lagrangian particle dispersion models (LPDMs) such as the HYSPLIT (Draxler and Hess, 1998) or FLEXible PARTicle (FLEXPART; Stohl et al., 2005) allow for tracking changes in specific humidity along trajectories over time and for determining the sources of moisture that reach a specific area. However, unlike Eulerian methods, they do not provide the large-scale atmospheric circulation linked to moisture transport. The HYSPLIT model has been used extensively to establish moisture source-receptors relationships in various regions of the world (e.g., Jorba et al., 2004; Brimelow and Reuter, 2005; Bracken et al., 2015; Li et al., 2016; Jiang et al., 2017; Chen and Luo, 2018; Jana et al., 2018; Zhang et al., 2019) and is used in this study for the LRB region.

To determine moisture sources and trajectories flow linked to the heavy rainfall events, HYSPLIT was run for a 36-year period (1981-2016) using the National Center for Environmental Prediction (NCEP) / DOE NCEP II Reanalysis data (Kanamitsu et al., 2002). A similar approach has been adopted in other studies (e.g. Chen and Luo, 2018; Chu et al., 2019; Zhang et al., 2019). NCEP/NCAR data are available on the global grid at 2.5° spatial resolution with 17 vertical levels, from 1979 to near present. The focus of the analysis here is on the extended austral summer (October-April) as a whole as well as separately for the early (OND) and late summer (JFMA). Splitting the summer into two components was done since midlatitude systems to the south of the continent tend to be more important in OND than in JFMA in terms of moisture transport

(D’Abreton and Lindesay, 1993; Cook et al., 2004) and the development of suitable convective environments over subtropical southern Africa (Blamey et al., 2017).

Due to the relatively high southern African interior plateau, all HYSPLIT trajectories were initiated at 1500 m above sea level (~850 hPa), four times a day (six hourly), and tracked backwards at an hourly interval for 240-hours (10 days). The 10-day period is considered the average residence time for moisture in the atmosphere (Viste and Sorteberg, 2013; Ciric et al., 2016; Chu et al., 2019; Nieto and Gimeno, 2019). At the upper levels, the model was restricted to 12 000 m (~ 200 hPa), or near the top of the troposphere. The “particles” representing air parcel trajectories were released from three locations within the LRB in the eastern (22°S, 33°E), central (22°S, 30°E) and western (22°S, 27°E) parts of the basin.

For this study, only trajectories initiated from the central location (22°S, 30°E) within the basin are analysed. Comparison of trajectories from the three initiation points show a similar spatial distribution, however, for the eastern (22°S, 33°E) site, most trajectories tend to originate over the South Indian Ocean (*not shown*). For the middle (22°S, 30°E) and the western (22°S, 27°E) sites, trajectories emanate from both the Atlantic and Indian Ocean, with only minor differences between them. Although there are minor differences, trajectories from the central site are most representative of the LRB as a whole and hence were chosen for the analysis.

c. Air parcel trajectories clustering and moisture transport identification

The Curve Clustering Toolbox (Gaffney, 2004) was used to cluster all air parcel trajectories into the LRB using the method of Dorling et al. (1992) in which Euclidean distances between corresponding coordinates of individual trajectories are minimised (i.e. the differences within a cluster are minimised but maximised between the clusters). In addition to the clusters, trajectories were gridded onto a 1°×1° grid, and the total number (density) of trajectories was counted at each grid point to show spatial distribution of all air parcels, similar to Jiang et al. (2017) and Chu et al. (2019).

Moisture uptake or loss by the air parcel can be identified by calculating changes in specific humidity (Δq) with time (t)

$$\Delta q = q_t - q_{t-1} \dots\dots\dots (5.1)$$

where q_t and q_{t-1} are the specific humidity at the time t and $t-1$ respectively, along the air parcel trajectory (Chen and Luo, 2018). $\Delta q > 0$ and $\Delta q < 0$ values indicate moisture gain and loss regions

respectively. Thereafter, all $\Delta q > 0.1 \text{ g kg}^{-1}$ values on each $1^\circ \times 1^\circ$ grid box were summed to obtain moisture source regions. Identifying the location along the air parcel trajectory where maximum specific humidity (Q_{max}) occurred can indicate where the parcel gained the greatest moisture, which is indicative of its moisture source region, similar to Bracken et al. (2015). In this study, both approaches were explored, and the results are presented in subsequent sections. The seasonal summer climatology trajectories and those linked to the anomalously wet and dry OND and JFMA, including heavy rainfall events over the LRB described in Rapolaki et al. (2019), during the period 1981 to 2016 were selected for analysis. The seasonal trajectories were analysed for the extended summer as well as the early and late summer.

5.3. Results

a. Moisture transport in the LRB

On the seasonal time-scale, the climate of the LRB is considered arid to semi-arid. This basin is dominated by high potential evapotranspiration rates throughout the year. Since these rates easily exceed those in rainfall during the extended rainy season (October-April; **Fig. 5.2a**), it appears that rainfall over the LRB is more likely linked to remote moisture sources. Over the oceans, the ERA-Interim Evaporation-Precipitation ($E-P$) data (**Fig. 5.2b**) indicates five possible oceanic moisture source regions ($E-P > 1$) for southern Africa. These are: (1) tropical western Indian Ocean, (2) southwest Indian Ocean which includes the southern part of the Mozambique Channel, the Agulhas Current and its retroflection, (3) subtropical South Indian Ocean to the east of Madagascar, (4) tropical southeast Atlantic Ocean off the coast of Angola and northern Namibia, and (5) subtropical South Atlantic Ocean. However, $E-P > 1$ diagnostics alone do not show how moisture laden air is transported from these source regions over the LRB. Therefore, the possible links between these moisture source regions and moisture transport pathways into the LRB are investigated using HYSPLIT Lagrangian software. This analysis is presented for the extended summer as a whole as well as separately for the early (OND) and late summer (JFMA).

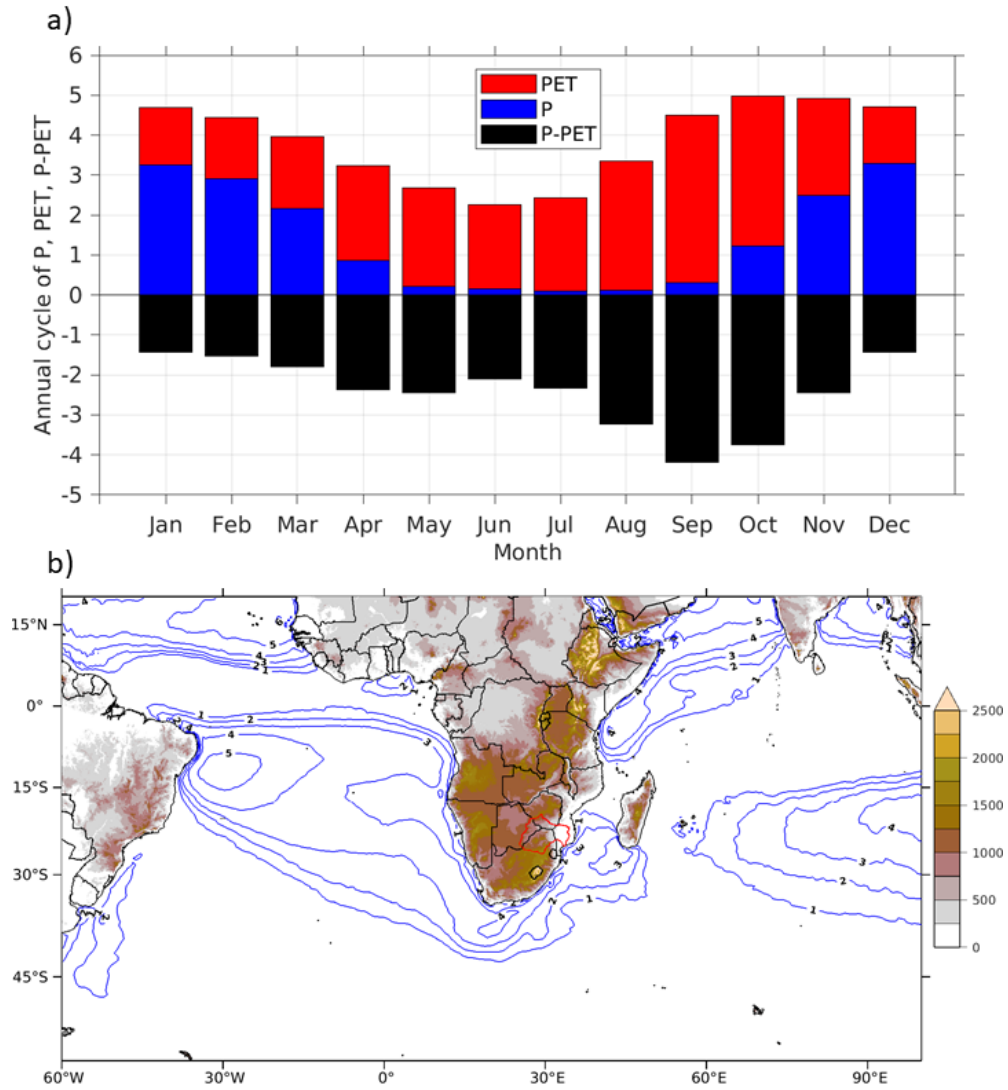


Figure 5.2: (a) Climatological annual cycle of CRU potential evapotranspiration (PET), precipitation (P), and their differences (P-PET), averaged over the Limpopo River basin during 1981-2016 period. All units are in mm/day. Panel b shows the ERA-Interim climatology of Evaporation (E) - Precipitation (P) for the austral summer months (December-February). Only $E-P > 1$ values (blue contours) are shown to indicate moisture source regions around tropical and subtropical Africa.

b. Air parcel origin and trajectory pathways into the LRB

The cluster mean climatological air parcel trajectories into the LRB are shown in **Figure 5.3** for the extended (ONDJFMA), early (OND), and late summer (JFMA) to illustrate the movement of air parcels into the basin regardless of changes in specific humidity. Over the extended summer, most of the branches (four out of seven) reaching the LRB originate from the southeast Atlantic

Ocean or the southwest Atlantic (**Fig. 5.3a**). These branches account for only 49% of all the air parcels into the basin. Of the four Atlantic branches, the southeast Atlantic pathway (dark green) contains a mainly continental trajectory and accounts for about 31% of the air parcels into the LRB and is therefore by far the most important of the Atlantic cases. Although only three out of seven of the branches reach LRB from the South Indian Ocean, they account for slightly over half of the air parcels (51%). It should be noted that the tracks from the southeast Atlantic Ocean and the southwest Atlantic Ocean enter the LRB from mid-to-upper atmospheric levels, whereas, the southwestern Indian Ocean air parcels originate from the lower atmospheric levels (*not shown*).

In the early summers (OND; **Fig. 5.3b**), the main branches are similar to those in the extended summer (ONDJFMA) except that the northeasterly branch curves further eastward over northern Madagascar (magenta) and over the Indian Ocean at about 15°S as well as a more westward extending branch (dark green) over the subtropical South Atlantic. There is a localised component to the trajectories, with almost half the air parcels (45%) reaching the LRB from the northern Agulhas Current / southern Mozambique Channel. Apart from the northern Madagascar branch, it appears fairly few trajectories originate from the southwest Indian Ocean (to the east and southeast of Madagascar).

For the late summer (JFMA; **Fig. 5.3c**), the midlatitude branches over the southwest Atlantic are very similar to the extended summers. However, the continental branch (dark green) does not stretch from the southeast Atlantic, unlike the extended summer, and instead mostly originates over the Namibian / western South African border. Interestingly, there is very little evidence of a northern Madagascar branch (magenta) in the late summer months, with most trajectories originating more from the southern part of the island (accounting for 26% of the air parcels). The southwest Indian Ocean cluster (red) now contains a more central South Atlantic origin point and is the second largest contributor at 21%. Although only a few air parcels originate over the Agulhas Current region, most of the branches from the midlatitude South Atlantic Ocean and the subtropical southwest Indian Ocean tend to cross over some part of this current. As they do so, these branches often gain moisture as they are at low levels and the surface waters of the Agulhas Current tend to be warmer than the air masses above them.

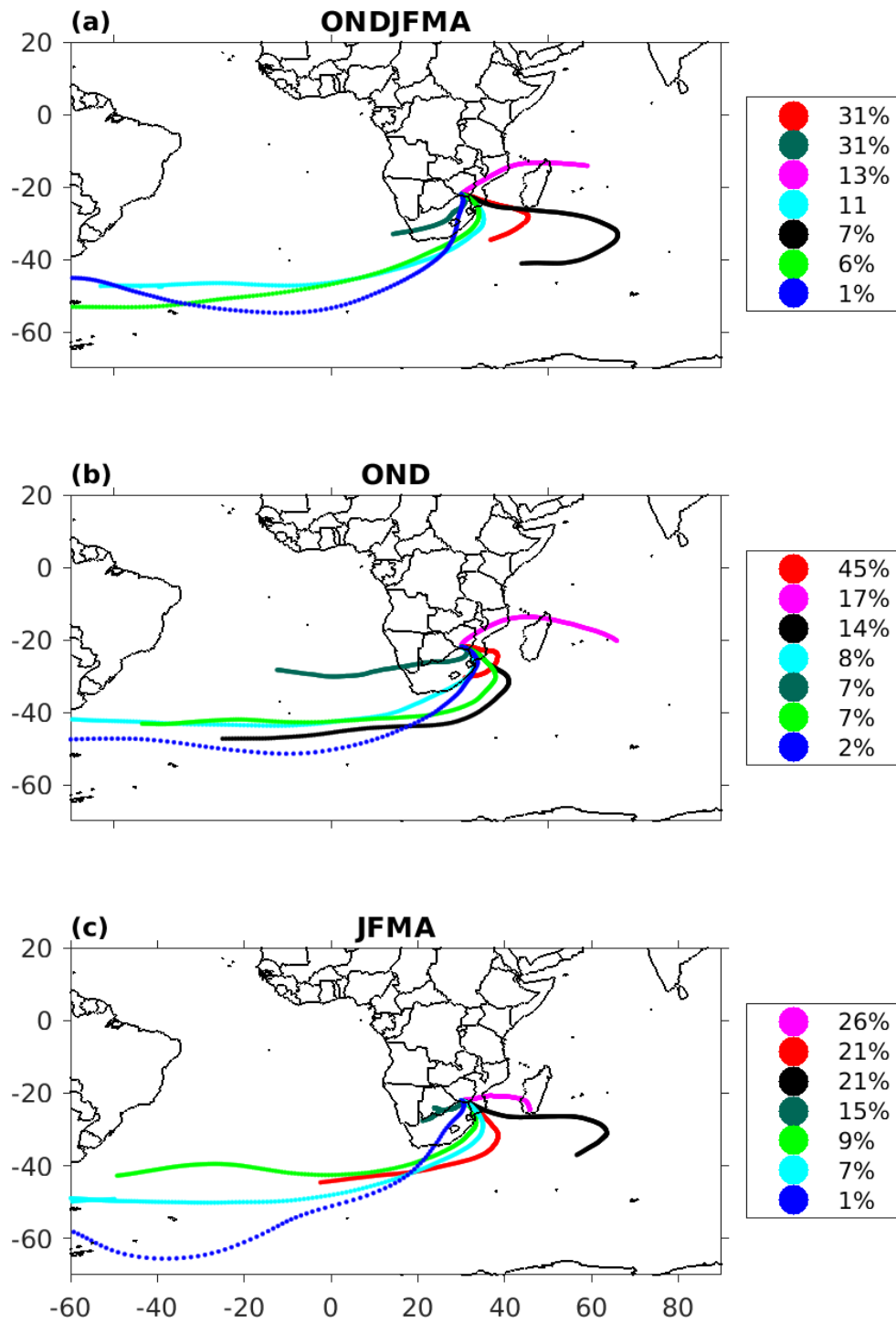


Figure 5.3: Mean groups of air parcel clusters into the LRB for the (a) extended summer, (b) early summer, and (c) late summer months, during 1981-2016 period. The percentage contribution of each trajectory to the LRB is provided in the legend.

Generally, the main branches can be related to some aspects of the general atmospheric flow for southern Africa depicted in **Figure 5.1**. Thus, (1) the easterly trade wind flow around the northern margins of the South Indian Ocean anticyclone (Mascarene High) can be associated with the Madagascan branch which moves further south in late summer (**Fig. 5.3b and c** - magenta); (2) ridging anticyclones along the south and southeast coast of South Africa may be linked to the southwest Indian Ocean branches, particularly in late summer (**Fig. 5.3b and c** – red); (3) mid- and upper level westerly flow across the South Atlantic (blue, green and cyan in **Fig. 5.3b and c**). Note that on seasonal scales, air parcels associated with the northeasterly monsoon flow into tropical southeastern Africa do not reach the LRB as this region lies south of the ITCZ. Also lacking on seasonal scales is any clear evidence of westerly branches from the tropical southeast Atlantic and Angola Low region which is not surprising since previous studies (e.g. Cook et al., 2004; Manhique et al., 2015; Rapolaki et al., 2019) have indicated that these moisture flows towards subtropical southern Africa tend to be associated with anomalous synoptic and intraseasonal wet spell events, which are explored further in subsections 5.3.2 to 5.3.4.

The mean climatological spatial distribution of air parcel trajectories counts into the LRB during October-April (ONDJFMA), October-December (OND), and January-April (JFMA) are shown in **Figure 5.4**. The count of air parcel trajectories (**Fig. 5.4 a-c**) shows three prominent pathways into the LRB. Firstly, there is a pathway from the southwest Indian Ocean extending over southern Mozambique. A second path extends from the western tropical Indian Ocean through Mozambique and Malawi, while the third stretches from the southeast Atlantic Ocean across northern Botswana and Zimbabwe. Less prominent is a path stretching from the midlatitude South Atlantic Ocean, then along the east coast of South Africa, to enter the LRB through southern Mozambique, after traversing the Agulhas Current. The latter path also receives a few parcels which originate in the southeast Pacific Ocean. The sources for all air parcel trajectories are similar for both summer seasons although the western tropical Indian Ocean one becomes more prominent in late summer as does the northern Agulhas Current.

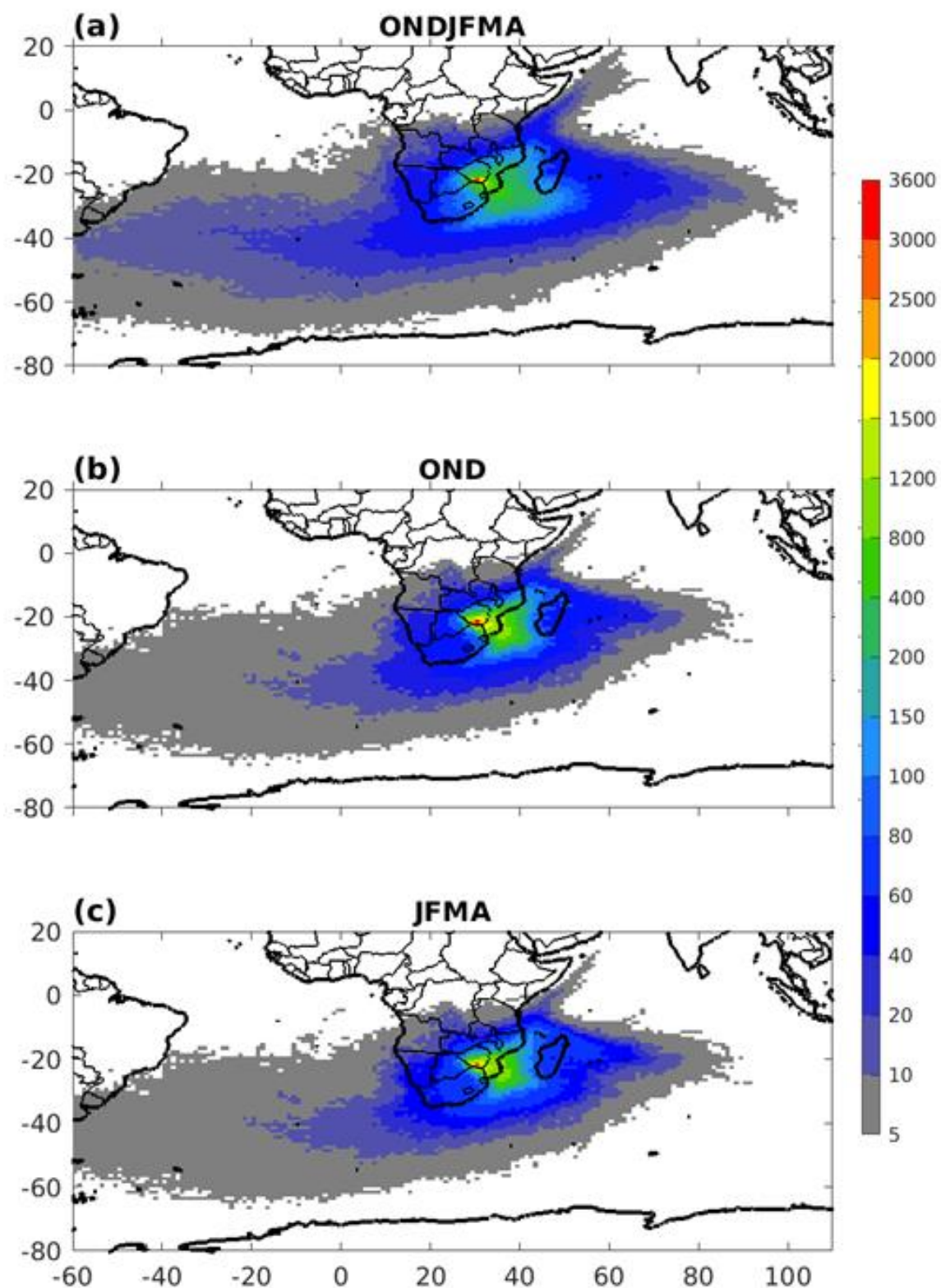


Figure 5.4: Spatial distribution ($1^\circ \times 1^\circ$ bin count) of air parcel backward trajectories into the LRB in (a) extended summer, (b) early summer, and (c) late summer. All based on the period 1981-2016.

c. Origin of moisture and its transport into the LRB

Examining the changes in specific humidity along the trajectories can indicate any regions where the trajectories gained significant moisture before reaching the LRB. **Figure 5.5a-c** shows a climatology of moisture source trajectories for the extended, early and late summers based on the weighted moisture $\Delta q > 0.1 \text{ g kg}^{-1}$ values (*see methods section*). Analysis of $\Delta q > 0.1 \text{ g kg}^{-1}$ counts along the air parcel trajectories indicates maximum density over the southwest Indian Ocean (southern part of the Mozambique Channel and northern Agulhas Current) in all three cases, and high densities further north off the coasts of northern Mozambique and Tanzania. All three cases also show relatively high densities over and just east of Madagascar. The densities decrease substantially as one moves southwards and westwards away from the LRB / southern Mozambique Channel region. The JFMA case (**Fig. 5.5c**) shows a larger region of relatively high densities over the southwest Indian Ocean than that for OND (**Fig. 5.5b**). This difference may be related to the southward shift of easterly integrated moisture transport over the South Indian Ocean in JFMA relative to OND (*not shown*).

Note that the flow of moisture over the basin may be inferred from air parcel trajectories in **Figures 5.3 and 5.4**. Sources over tropical southern Africa are northwesterly to westerly in direction into the LRB. From the subtropical South Atlantic Ocean and the Atlantic sector of the Southern Ocean sources for the LRB are southwesterly to westerly, becoming southeasterly off the east coast of South Africa near 30°S , 35°E . It is noticeable that these westerly – southwesterly flows reside at mid- or upper tropospheric levels, above 3000 m.a.g.l. ($\sim 700 \text{ hPa}$) (*not shown*), as compared to their South Indian and tropical southeast Atlantic Oceans counter parts.

Figure 5.6 shows moisture trajectory counts based on the maximum ($Q_{\max}$) specific humidity along the air parcel trajectories. Compared to Δq (**Fig. 5.5**), $Q_{\max}$ shows more localised moisture source regions, with the southwest Indian Ocean and Mozambique Channel regions as most important together with the LRB itself for all three seasons (**Fig. 5.6a-c**). For the late summer (**Fig. 5.6c**), high counts extend further east into the southwest Indian Ocean south of Madagascar than for the early summer.

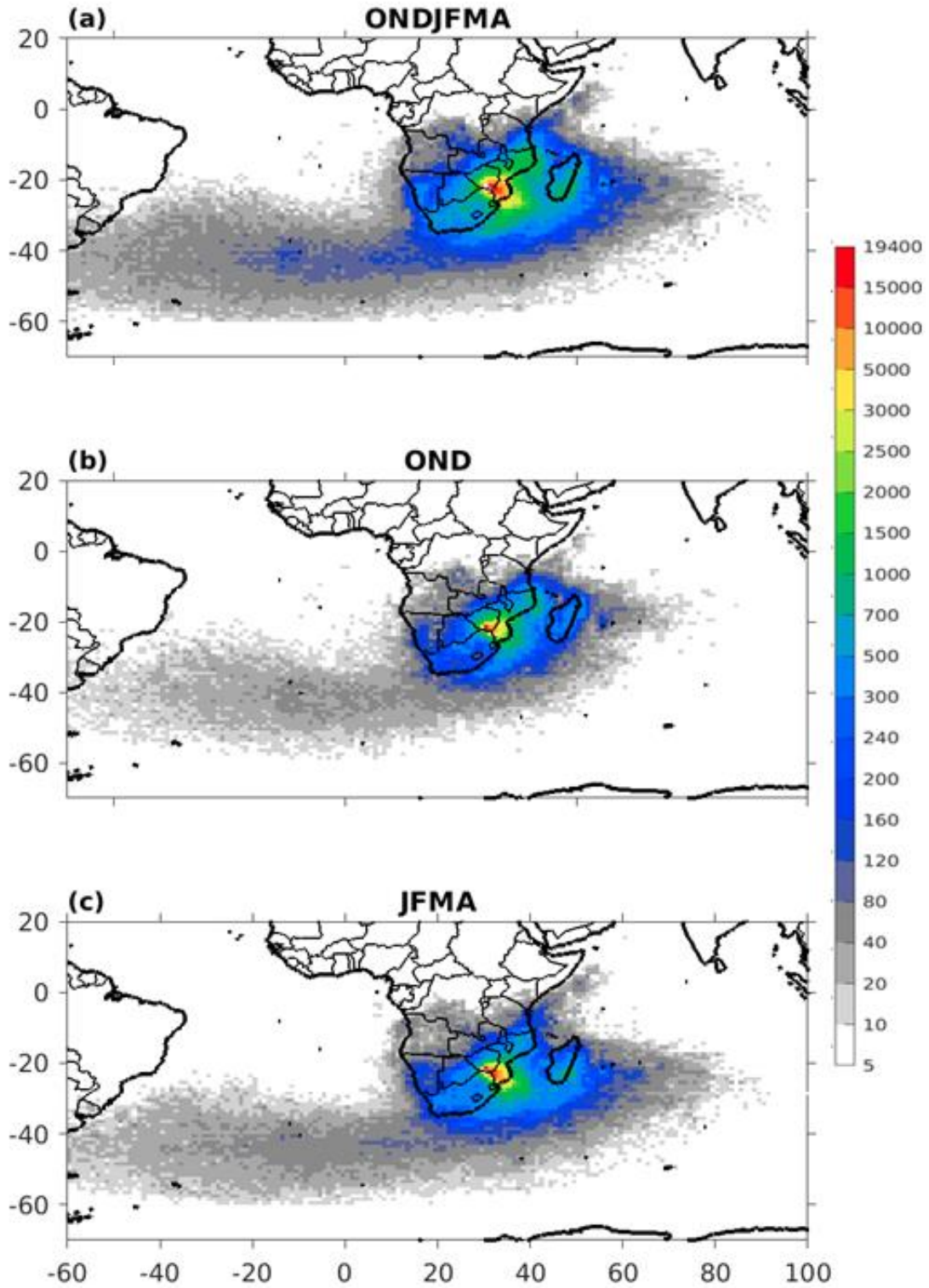


Figure 5.5: Moisture trajectory counts for change is specific humidity values greater 0.1 g kg^{-1} (binned onto a $1^\circ \times 1^\circ$ grid) for (a) extended summer (ONDJFMA), (b) early summer (OND), and (c) the late summer (JFMA), during 1981-2016 period.

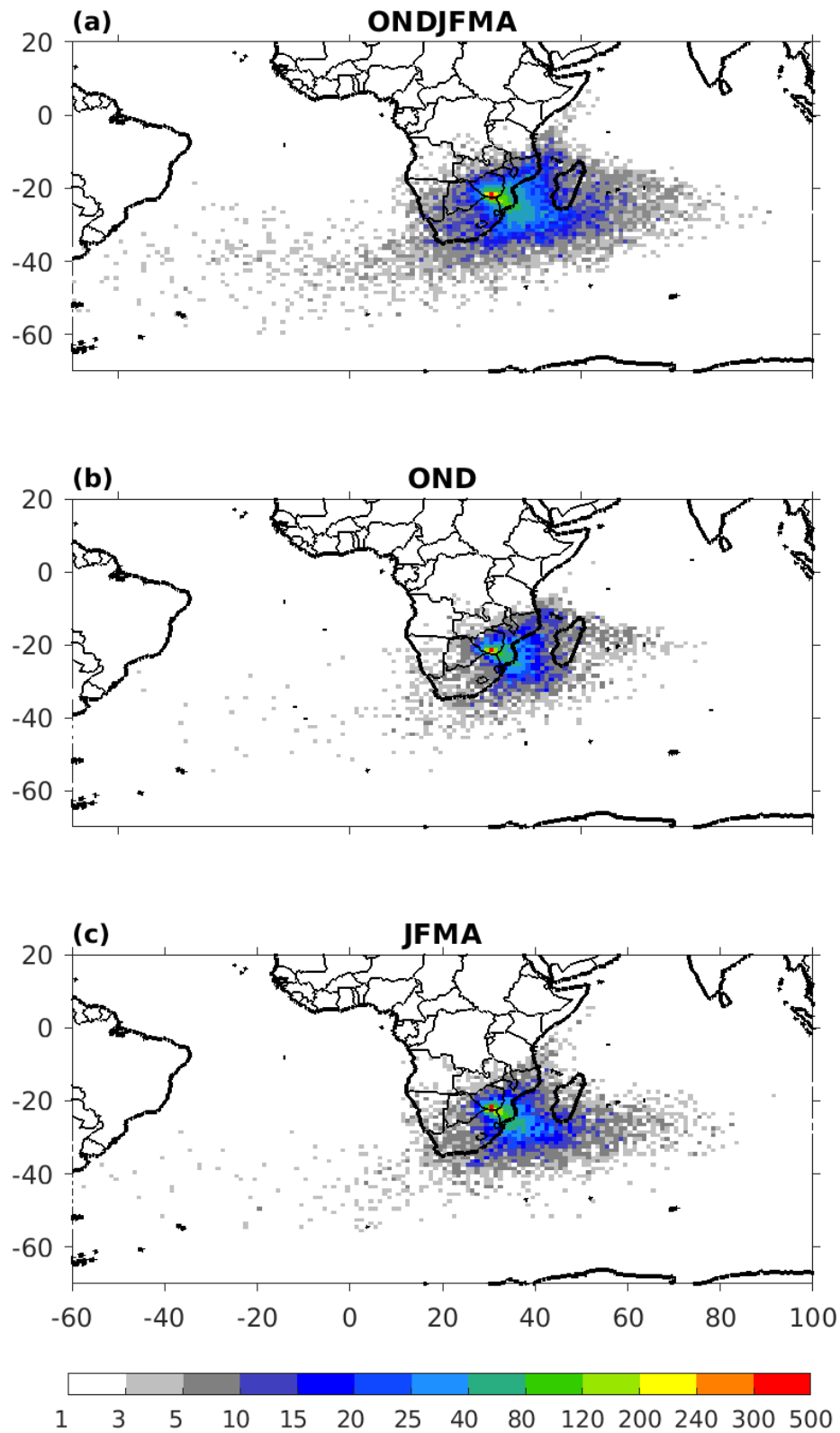


Figure 5.6: The total number of times each bin ($1^\circ \times 1^\circ$) contained the maximum specific humidity along the track for (a) extended summer, (b) early summer and (c) late summer, during 1981-2016 period.

d. Moisture transport during wet and dry summers

Figure 5.7 shows the air parcel trajectories linked to early (OND) and late (JFMA) summers which are either anomalously wet or dry over the LRB. The four wettest and driest seasons out of the 36-year period were chosen such that their standardised rainfall anomaly was at least (± 1) and are listed in **Table 5.1**. Note that the Climate Hazards Infrared Precipitation with Stations (CHIRPS) version 2 data were used instead of CRU to calculate standardised rainfall anomalies because of its higher resolution 0.05° ($\sim 5\text{km}$), and because it has been shown to represent southern African summer rainfall well compared to the other products (Funk et al., 2015).

Table 5.1: Standardised rainfall anomalies averaged over the Limpopo River Basin for the early (OND) and late (JFMA) summers. The seasonal (OND/JFMA) anomalies equal or above (below) 1 (-1) are defined as wet (dry) seasons.

(a) Early wet summers (OND)			
1995	1999	2005	2016
1.80	2.70	1.00	2.50
(b) Early dry summers (OND)			
1981	1982	1991	2002
-1.10	-1.10	-1.90	-1.10
(c) Late wet summers (JFMA)			
1991	1996	2000	2006
1.20	2.00	2.80	3.20
(d) Late dry summers (JFMA)			
1992	2002	2012	2015
-1.30	-1.70	-1.00	-1.00

During the early (OND) wet summers (**Fig. 5.7a**), five out of seven air parcel branches were associated with southerly flow into the LRB, with one northeasterly and one easterly flow respectively. Of the southeasterly branches which make up 40% of the total, 21% originated over the central midlatitude South Atlantic Ocean (green), 11% from the southwest Atlantic (magenta), 4% from the southeast Pacific Ocean (red and cyan), and 4% from the southwest Atlantic Ocean

(black). Most of the 60% coming from the Indian Ocean originates from the northern Agulhas Current (dark green 45%) with the remaining 15% coming from the subtropical South Indian Ocean (blue). Although only two out of the seven branches originate over the South Indian Ocean, their net contribution is much higher than those from the Atlantic regions. For early (OND) dry summers (**Fig. 5.7b**), all of the branches except one were linked to southeasterly flow and South Atlantic trajectories. The Indian Ocean path across Madagascar is located further south than for the wet summers and has a much shorter trajectory. Note that the 7th branch in **Figure 5.7b** lies closer to other southeasterly branches and thus it is not clearly visible.

For the late (JFMA) wet summers (**Fig. 5.7c**), only three out of seven branches originated over the Atlantic sector (cyan and red: 18%) or crossed it after exiting the southeast Pacific Ocean (black: 5%). Unlike for the early summers, there is now also a westerly branch emanating from the land (southern Namibia - green: 21%). The Indian Ocean branches are made up of a north-easterly flow across the Mozambique Channel (blue: 29%), and easterly flows across the southern Mozambique Channel (dark green and magenta: 27%). The dry late summers (**Fig. 5.7d**) also contain a trajectory originating from the land (light green) but starting further south (central South Africa) than for the wet late summers. Elsewhere, the trajectories are similar to those for the wet case except that the northeasterly branch across the northern Mozambique Channel is now missing (**Fig. 5.7c-d**). It is possible that the smaller number of South Indian Ocean branches in the dry than the wet summers may be related to a stronger Mozambique Channel Trough and its associated cyclonic flow in the channel which tends to lead to a weaker moisture inflow into the LRB (Barimalala et al., 2018, 2020).

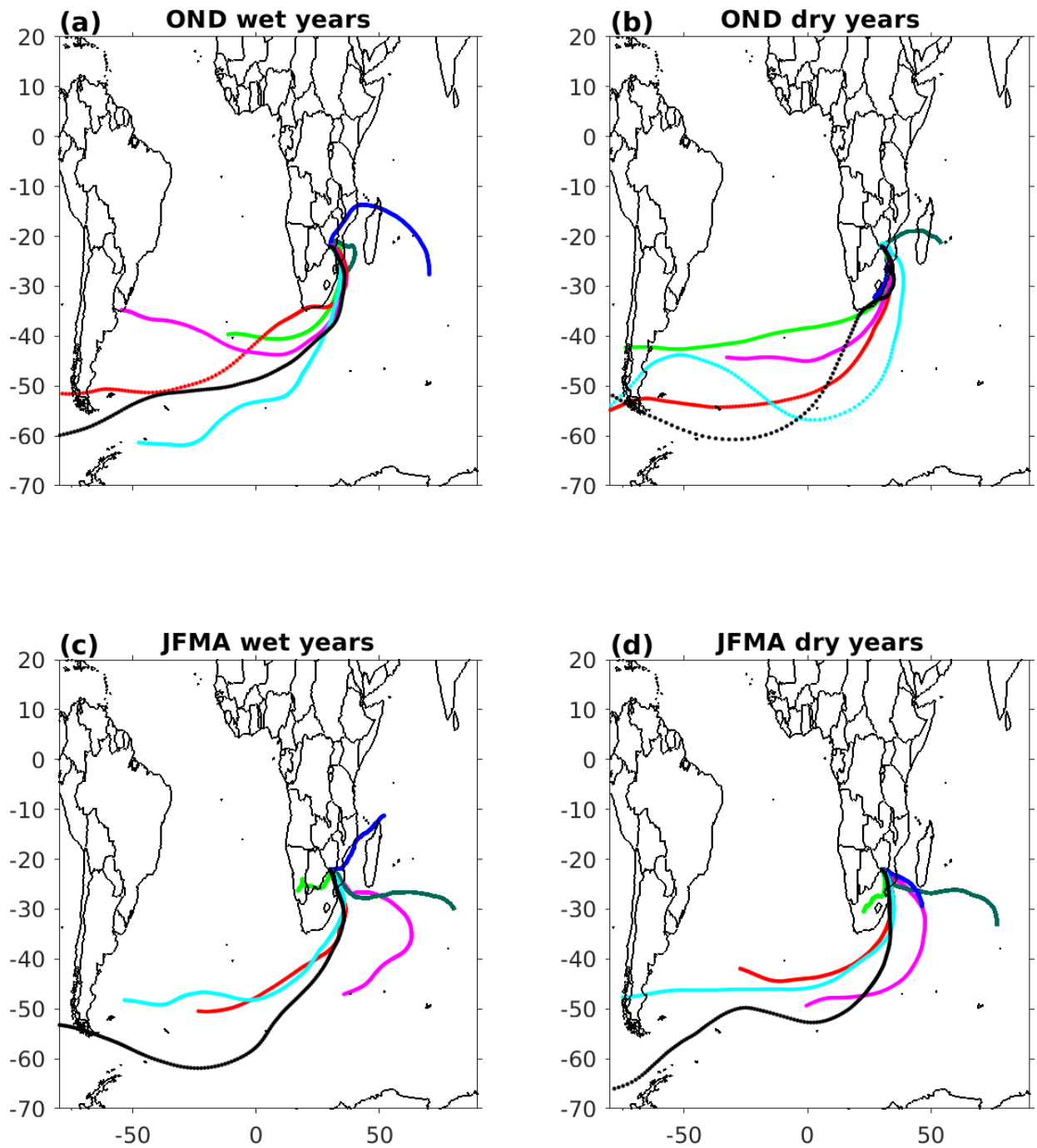


Figure 5.7: The key trajectory groups (different colours used to denote different paths with their percentage contributions explained in the text) of air parcel backward trajectories into the Limpopo River Basin for (a) wet OND, (b) dry OND, (c) wet JFMA, (d) dry JFMA. Wet (dry) OND/JFMA seasons are based on rainfall standardised anomalies above (below) 1 (-1) and are provided in Table 5.1.

e. Moisture sources linked to rainfall events

To extend the analysis beyond seasonal anomalies to the event scale, moisture trajectory counts (Q_{max}) for moderate (> 10 mm per day) and heavy (> 25 mm per day) rainfall events over the LRB were calculated (**Fig. 5.8**). For moderate events (**Fig. 5.8a**), the highest moisture gain occurred locally over Mozambique and the adjacent Channel. Considerable moisture gain is also evident east/south east of Madagascar.

For heavy rain days (**Fig. 5.8b**), the source regions are similar to those for the moderate case except that there is a larger region of high gain over the northern Agulhas Current / southern Mozambique Channel and southern Mozambique. The area of relatively large uptake in the Indian Ocean now also extends much further north and east.

It is also of interest to consider the moisture trajectories and uptake for particular extreme events where the daily rainfall totals are well in excess of 25 mm per day. For example, some wet summers may be dominated by a few intense rainfall events which can make a larger contribution to seasonal totals than many days of moderate rainfall. Using the results of Rapolaki et al (2019), **Figure 5.9a** plots backward trajectories along with specific humidity values for the top 200 daily extreme rainfall events which occurred over the LRB during 1981-2016. Points on the trajectories with specific humidity greater than 15 g kg^{-1} are likely to be moisture source regions for the events. Of these 200 events, about half were characterised as being due to cloud bands with the remainder being associated with tropical lows and to lesser extent mesoscale convective systems and cut-off lows.

For those events due to cloud bands, **Figure 5.9b** shows that specific humidity values greater than 15 g kg^{-1} mainly occur over the tropical western Indian Ocean (TSI source) and the southwest Indian Ocean (SWI source) with smaller contributions originating from the tropical southeast Atlantic (SEA source) and continental areas (western Tanzania and locally) (LC source). For tropical lows, (**Fig. 5.9c**) suggests similar source regions except that there is a greater LC contribution (mainly the southern Congo Basin). Both mesoscale convective systems and cut-off lows (**Figs. 5.9cd**) tend to show relatively little contribution from either the SEA or the LC source. In general, the values are smaller everywhere than for the cloud band or tropical low events. This is particularly true for the cut-off low events (**Fig. 5.9d**) which are mainly confined to October and March-April (Rapolaki et al., 2019).

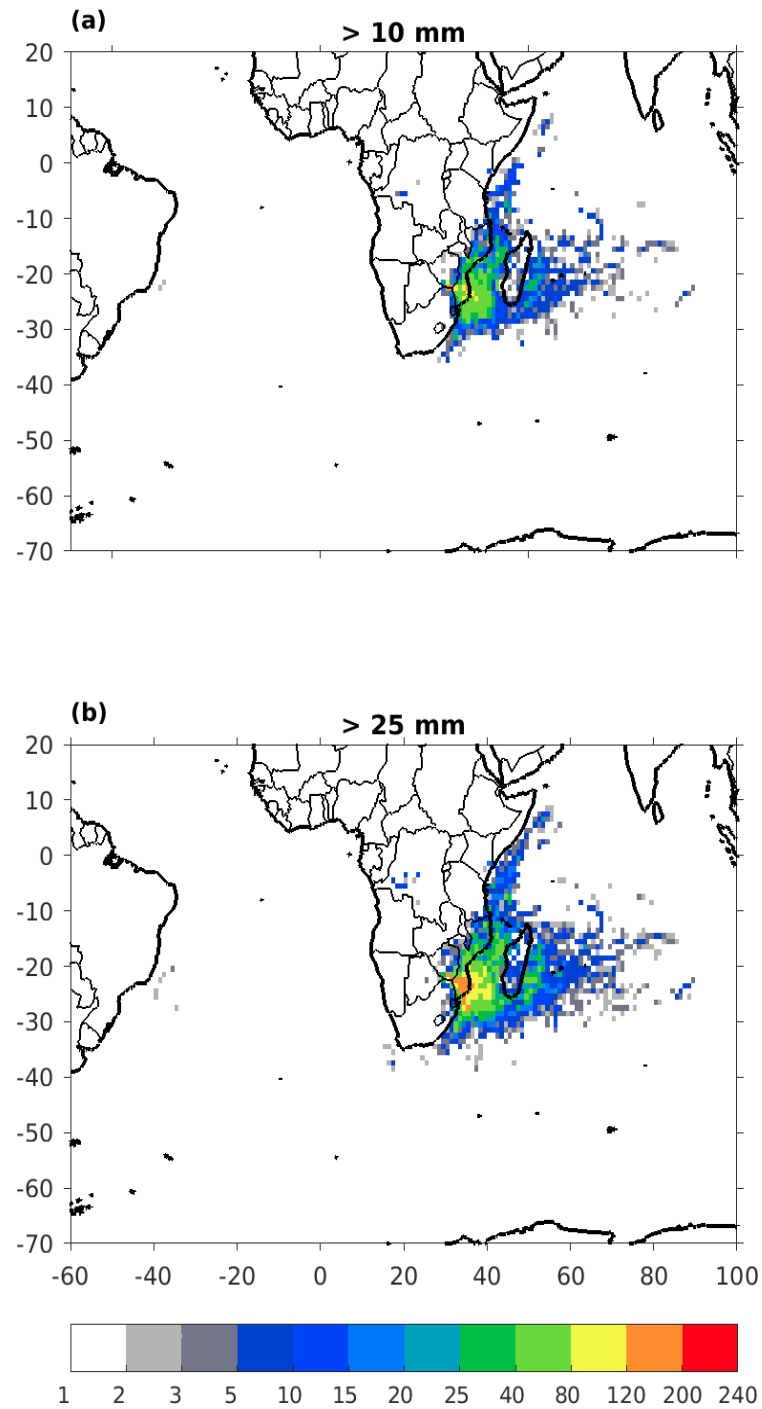


Figure 5.8: Moisture trajectory counts (binned onto a $1^\circ \times 1^\circ$ grid) for rainy days where rainfall was greater than (a) 10 mm and (b) 25 mm over LRB. These rain days were considered only when at least 10% of the CHIRPS grid points in the LRB exceeded the given threshold.

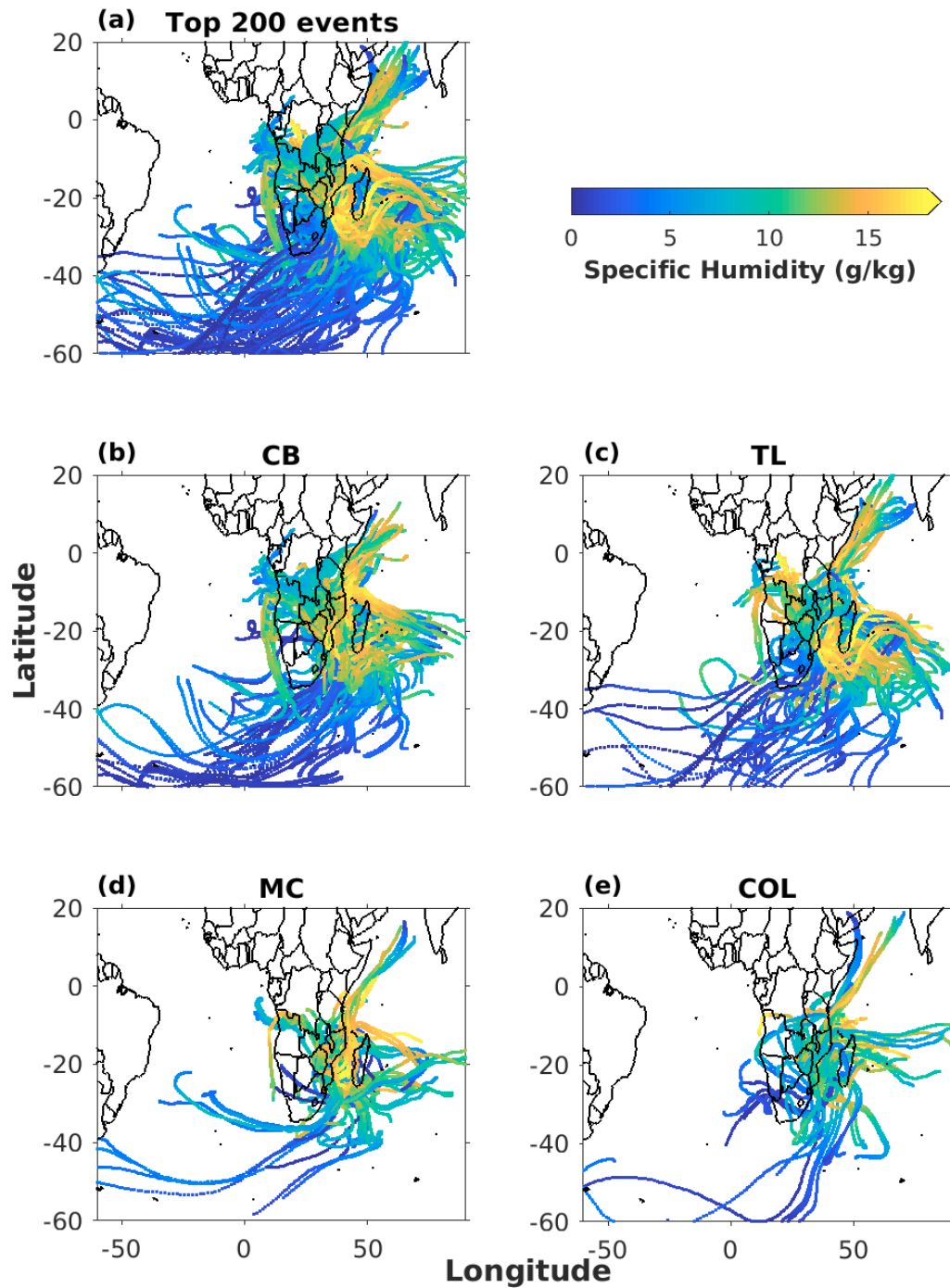


Figure 5.9: (a) Top 200 extreme rainfall (1981-2016) events' backward trajectories for the Limpopo River Basin with the specific humidity (shading; g kg^{-1}) values along the track. Blue values indicate low specific humidity while yellow values indicate high specific humidity. The abbreviations (b) CB, (c) TL, (d) MC, and (e) COL denotes cloud bands, tropical lows, mesoscale convective systems, and cut-off lows synoptic systems respectively.

In summary, although most of the air parcel branches reaching the LRB originate from the Atlantic sector, their contribution to moisture content over the LRB is much lower than those trajectories coming from the Indian Ocean or land sources. In the Atlantic branches, the specific humidity values are typically less than 10 g kg^{-1} whereas it is often above 15 g kg^{-1} for the Indian Ocean and land branches. The latter branches also typically occur at much lower levels than those for the Atlantic (*not shown*). This is consistent with organised convection over the LRB typically resulting from warm moist low level air masses originating from the Indian Ocean or tropical land mass overlain by cooler, drier Atlantic air masses transported over the LRB by the subtropical jet and associated upper level westerly waves.

5.4. Discussion and conclusion

Sources of moisture for the LRB on seasonal scales and for heavy rainfall events were identified using HYSPLIT Lagrangian software. The advantage of Lagrangian methods is that they allow one to identify the origin of moisture reaching the LRB, thus making it possible to examine changes in the specific humidity along the air parcels trajectories over time. Although HYSPLIT trajectories do not provide the large-scale atmospheric circulation linked to moisture transport like the Eulerian methods, it was found suitable since it provides the geographical origin of moisture that reaches the LRB.

Analysis of 10-day backward trajectories has been conducted for the air parcels arriving at 22°S and 30°E , for a 36-year period (1981-2016). It should be noted that trajectories were also initiated from the western and the eastern parts of the basin; however, the results showed negligible differences in the spatial distribution of air parcels between all three locations. Therefore, for simplicity, the central location was considered as representative of the entire basin for this purpose.

During extended summers, the results showed that the Indian Ocean contributed more air parcels flowing into the LRB than did continental or southeast Atlantic sources. Of the former, the Mozambique Channel, northern Agulhas Current and waters south and east of Madagascar are the most important. For the early summers (OND), when mid-latitude circulation patterns are still important over subtropical southern Africa (D'Abreton and Tyson, 1995), the contribution of each source region is similar to the extended summer, but with Indian Ocean source regions slightly enhanced. However, in the late summers (JFMA) when circulation conditions over the LRB become more dominated by tropical systems (Walker 1990; Cook et al., 2004), the contributions

from the Indian Ocean sources decrease slightly, while the continental source increases. This seasonal change is consistent with a build-up of warm moist air masses over tropical southwestern Africa in the later summer as the low-level Angola Low strengthens and the mid-level Botswana High moves further south over Namibia (Reason, 2016; Driver and Reason, 2017). Typically, continental air parcels arriving over the LRB are, like those from South Indian Ocean sources, at low levels whereas those coming from the South Atlantic are found at mid-tropospheric levels and have a lower moisture content.

By examining changes in specific humidity for backward trajectories, seven moisture source regions have been established for the extended summer: local continental, tropical northwest Indian Ocean, tropical southwest Indian Ocean, subtropical southwest Indian Ocean, Agulhas Current, tropical Southeast Atlantic Ocean and the midlatitude South Atlantic Ocean. Of these, the tropical northwest and subtropical southwest Indian Ocean sources tend to dominate, consistent with previous work based on Eulerian methods (Walker, 1990; D'Abreton and Lindesay, 1993; Mason 1995; Reason and Mulenga, 1999; Cook et al., 2004; Reason et al., 2006). While the tropical southeast Atlantic source is relatively minor on average on seasonal scales, it can become very important for intraseasonal or synoptic wet spells over subtropical southern Africa (Cook et al., 2004; Manhique et al., 2015) as well as for some summers where there are anomalously warm SST conditions off the coast of Angola / northern Namibia (Rouault et al., 2003; Hansingo and Reason, 2009; Reason and Smart, 2015). About 7% of the air parcels reaching the LRB originate from the midlatitude South Atlantic, a source region which has not been previously noted in any detail, possibly due to Eulerian methods being used rather than the Lagrangian approach adopted here.

When the extended summer is broken up into the early (OND) and late (JFMA) summers, differences in moisture source regions for the LRB are found, consistent with D'Abreton and Lindesay (1993). During JFMA the northwestern tropical Indian Ocean and the northern Agulhas Current sources are more prominent than during OND. On interannual time scales, there are notable differences in moisture source regions between anomalously wet and dry summers. The late dry summers tend to be characterised by a westerly branch of moisture arising from inland over southern Namibia which is absent during early summers. In contrast, the absence of the westerly branch or continental source during dry summers may be due to a stronger or more spatially extensive Botswana High which tends to occur in dry summers (Cook et al., 2004; Reason 2016; Driver and Reason, 2017). The northeasterly branch across the northern Mozambique

Channel is absent during the late dry summers and in some cases may be related to a stronger Mozambique Channel Trough (Barimalala et al., 2018, 2020). Generally, the South Indian Ocean moisture contribution and transport over the LRB is smaller during dry summer than wet summers.

Moisture sources for moderate ($>10 \text{ mm day}^{-1}$) and heavy rain ($>25 \text{ mm day}^{-1}$) events were also examined. The results indicated that moisture sources for moderate rainfall days lie closer to the LRB than is the case for heavy rain events. In the former case, the Mozambique Channel, east of Madagascar, and the tropical northwest Indian Ocean are important together with land sources in Mozambique. For the heavy rainfall days, there is also some moisture originating from the midlatitude South Atlantic and a more remote land source from the western Congo Basin as well as within the LRB itself. The subtropical South Indian Ocean source is also more extensive for the heavy rainfall than for the moderate case. Heavy rainfall events are likely to arise from strong cloud bands, tropical lows or mesoscale convective systems needing more intense moisture input than for moderate rainfall days as well as the development of deep convection; hence the more spatially extensive moisture sources are not unexpected.

In addition to continental moisture sources, examination of humidity changes along the trajectories indicated that there can be an increase in humidity over the LRB itself, which suggests the potential importance of locally recycled moisture. **Figure 5.2a** showed high potential evapotranspiration over the LRB and some of this evaporated moisture may contribute to rain-producing weather systems over the region and hence be recycled. Some of this recycled moisture may feed into the air parcels arriving from the South Atlantic since it was observed that the specific humidity on these trajectories increased over land as well as over the Agulhas Current before reaching the LRB. These Atlantic air parcels start out at mid- and higher levels and are relatively dry but descend and increase in moisture content as they approach the LRB. Thus, although some air parcels reaching the LRB originate very far away, they tend to gain most of their moisture when travelling at lower levels over the warm waters in the Southwest Indian Ocean and Agulhas Current consistent with Gimeno et al. (2012).

On seasonal scales, four moisture paths which originate from seven source regions can be identified for the LRB (**Fig. 5.10**). These are: (1) northeasterly flow arising from the tropical northwest Indian Ocean and the tropical southwest Indian Ocean (sources A and B in **Fig. 5.10**); (2) southeasterly flow which originates from the subtropical southwest Indian Ocean, the northern Agulhas Current/ southern Mozambique Channel, or the Agulhas Current Retroflexion region

(sources C, D, E), (3) northwesterly from the tropical southeast Atlantic Ocean (source G), and (4) southwesterly/ westerly flow from the South Atlantic Ocean and locally inland (source F). Local recycling of moisture over the LRB can also make an important contribution and there may also be inflows from the southern Congo Basin. The latter become more obvious for the top 200 extreme rainfall events over the LRB, particularly in the cases due to cloud bands or to tropical lows.

This study has provided an overview of moisture sources and pathways for the LRB on seasonal time scales as well as for heavy rainfall events, and thus may provide a basis for future research over the broader southern African region. Given that the LRB contains a large rural population spanning four countries, several important conservation and wilderness areas as well as the second largest river on the Indian Ocean seaboard of Africa, it is very important to better understand its rainfall variability. However, despite it receiving moisture from a variety of sources, the LRB still remains a relatively dry region due to the frequent presence of mid-level anticyclonic conditions such as the Botswana High and to its location relative to that of Madagascar (Barimalala et al., 2018). While this study has focussed on synoptic to interannual time scales, further research is needed to investigate potential long-term changes in moisture source regions and transport paths, including their likely impacts on extreme rainfall over the LRB.

Having discussed moisture sources and pathways into the LRB on seasonal scales and for synoptic systems in a general sense, the next chapter considers the specific heavy rainfall event of January 11-21, 2013. This event was ranked as the top event in **Chapter 4** and it is of interest to determine how its moisture characteristics compare to the more general results obtained in this Chapter.

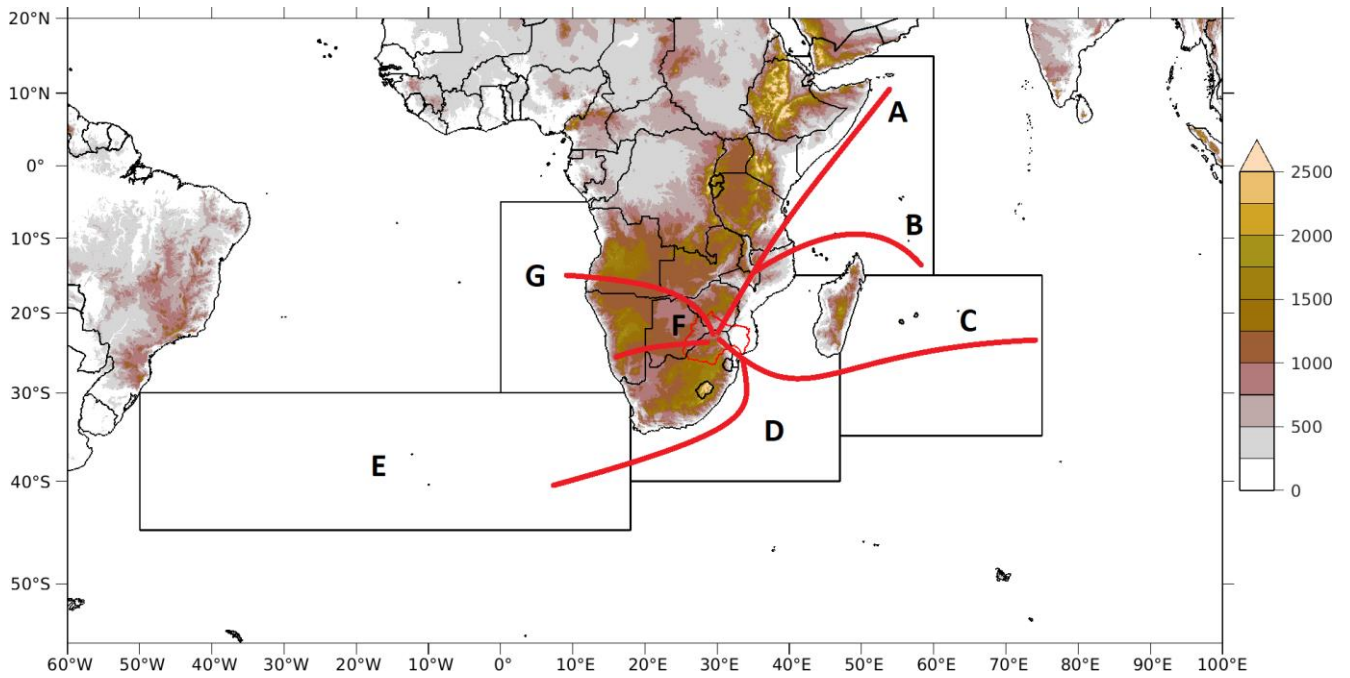


Figure 5.10: Summary schematic of main source regions for LRB, which are: A- tropical Northwest Indian Ocean, B- tropical southwest Indian Ocean, C- subtropical southwest Indian Ocean, D- Agulhas Current/ Mozambique Channel, E-midlatitude South Atlantic Ocean, F- local continental, and G- tropical southeast Atlantic Ocean. The red lines indicate main moisture paths over the LRB. Also shown is the topography of the region (shaded; m).

Chapter 6: Case study of 11-21 January 2013 heavy rainfall event over the Limpopo River Basin

This chapter addresses the following questions.

- How did the moisture sources and pathways for the heavy rainfall event of January 2013 over the LRB compare to the seasonal and composite weather system characteristics derived in Chapter 5?
- Did moisture originating from the southeast Atlantic Ocean make a substantial contribution to the heavy rainfall event of January 2013 over the LRB?

Abstract

Lagrangian air parcel trajectories were determined for the heavy rainfall event of 11-21 January 2013 over the Limpopo River Basin (LRB), using the HYSPLIT model forced with NCEP II (2.5°×2.5°) reanalysis data. This event was chosen as it led to devastating floods over the eastern LRB and southern Mozambique and because previous observational work that was based on Eulerian analyses suggested that moisture emanating from anomalously warm waters off the Angolan coast played an important role in its evolution.

Examination of specific humidity along the respective trajectories showed that the local northwest Congo Basin and tropical southwest Indian Ocean were the most important sources for heavy rainfall. However, some of the mid-tropospheric level moisture trajectories originated over the mid-latitude South Atlantic Ocean. SAWS synoptic maps and NASA satellite images indicate that a tropical low was largely responsible for the devastating floods which occurred over the LRB, particularly between 17 and 21 January. This system drew moist air from the tropical northwest Indian Ocean over Tanzania, Zambia and Zimbabwe into the basin. Other important sources were continental; namely, the northwestern Congo Basin and northern Tanzania, during the mid-stages of the event. However, during the early stages (11 - 13 January), moisture originating from the Agulhas Current and the Mozambique Channel was dominant.

6.1 Introduction

This chapter focuses on the origins and pathways of moisture associated with the extreme rainfall event of 11-21 January 2013, that occurred over the LRB and which was ranked top in **Chapter 4** and Rapolaki et al. (2019). The event was associated with devastating flooding which led to more than 100 deaths and over 150,000 people displaced in southern Mozambique (Manhique et al., 2015). However, there appears to be some uncertainty regarding the responsible weather systems associated with the flooding since Manhique et al. (2015) suggested that a long-lasting cloud-band was responsible whereas Wiston and Mphale (2019) attributed the floods to a mesoscale convective system. On the other hand, Rapolaki et al. (2019) suggested that the flooding mainly resulted from tropical low-pressure systems. Therefore, due to a lack of consensus regarding the synoptic systems which led to this flooding event, further research is warranted.

Moreover, it is as yet still unclear what the main origins of the moisture associated with this event were. Manhique et al. (2015) suggested the moisture originating from the anomalously warm water in the tropical southeast Atlantic Ocean off Angola was the most important for this Mozambican flooding event. However, their study was based on Eulerian methods which only indicated the direction from which moisture originated into the LRB. Thus, the main aim for this Chapter is to apply the Lagrangian methodology used in the previous chapter to better understand the moisture sources and pathways for this event, to see whether the tropical southeast Atlantic was indeed a major factor in its evolution, and to further investigate the responsible synoptic systems. Furthermore, an assessment of how the major moisture sources and pathways compare to the climatology described in **Chapter 5** is given.

6.2 Data and methods

a. Rainfall and satellite data

High resolution 5 km (0.05°) Climate Hazards Infrared Precipitation with Stations (CHIRPS) data were used to show the spatial distribution and the intensity of rainfall during 11-22 January 2013. The CHIRPS data have been shown to better represent rainfall over southern Africa as compared to other similar gridded rainfall products. To show the evolution of the rainfall systems, hourly National Aeronautics and Space Administration (NASA) infrared satellite

imagery were used together with the South African Weather Service (SAWS) daily synoptic charts. The satellite images were obtained from the University of Albany radar system <http://www.atmos.albany.edu/student/ppapin/mapdisco/20130201/>. Note that SAWS charts are shown for selected days only, to indicate the major evolution stages of surface synoptic conditions and not for the entire duration of the event. However, **Appendix A** contains charts for the other days.

b. HYSPLIT model and NCEP II data

Six hourly backward trajectories were produced using the HYSPLIT model (Draxler, 1998) based on the National Center for Environmental Prediction (NCEP)/ DOE NCEP II Reanalysis data (Kanamitsu et al., 2002). The trajectories were initiated at 22°S, 30°E from 1500 m (~850 hPa). The specific humidity, position (latitude and longitude), and the altitude of each trajectory were recorded at a six-hourly interval for a period of ten-days. HYSPLIT has been used previously to establish sources and tracks of moisture (e.g., Jorba et al., 2004; Brimelow and Reuter, 2005; Bracken et al., 2015; Li et al., 2016; Jiang et al., 2017; Chen and Luo, 2018; Jana et al., 2018; Zhang et al., 2019). The origin of moisture was determined by examining changes in specific humidity along the air parcel trajectories.

6.3 Results

a. Moisture origins, pathways, and rainfall

The air parcel trajectories for 11 to 22 January 2013 are shown in **Figure 6.1** with the altitude as a function of time (hours) profiles for each trajectory shown in **Figure 6.2**. For each trajectory, the blue colour denotes low specific humidity (less than 6 g kg⁻¹), whereas the orange-yellow colours denote high humidity (16-20 g kg⁻¹) and green are intermediate values. The air parcels may lose and gain moisture along their paths due to either evaporation or precipitation. On the 11th of January (**Fig. 6.1a**), all air parcel trajectories can be tracked to the mid-latitude South Atlantic Ocean. These trajectories moved northeastward over the mid-latitude Atlantic and along the east coast of South Africa at mid-levels (**Fig. 6.2a**), before curving northwestward across the northern Agulhas Current at low tropospheric levels, and finally ascending over the basin from the southeast. Examination of specific humidity along each trajectory indicates an increase in moisture over the Agulhas Current and locally over the eastern part of the basin. A tropical low was situated over Zimbabwe (**Fig. 6.3a**) on this day

with a ridging anticyclone along the east coast of South Africa, facilitating the moisture inflow across the northern Agulhas Current into the LRB leading to widespread rainfall (**Fig. 6.5a**). The infra-red satellite image for this day (**Fig. 6.4a**) suggests strong convection over eastern Zimbabwe and central Mozambique as well as a cloud band like a feature extending from northern Namibia, over northern South Africa and out over the mid-latitude South Indian Ocean.

On the 12th (**Fig. 6.1b**), the mid-latitude South Atlantic Ocean source maintained its contribution but there was now also a strong source from the tropical northwest Indian Ocean. The latter moisture trajectory entered the LRB from a northeasterly direction after tracking over the Mozambique Channel. Unlike the mid-latitude South Atlantic, the tropical northwest Indian Ocean trajectories occurred throughout at low tropospheric levels (**Fig. 6.2b**) and had higher specific humidity. The mid-latitude Atlantic trajectories tend to travel in the south-westerly direction along the east coast of South Africa before curving north-westwards near 25°S, 40°E at lower levels, where they tend to gain moisture, arriving over the basin from the southeast, consistent with the ridging anticyclone (**Fig. 6.3a**). This flow then merges over southern Mozambique with that from the tropical western Indian Ocean. Tropical lows were situated over southern Angola/ northern Namibia and Zimbabwe (*not shown*). Rainfall over the LRB was confined to the eastern parts on this day (**Fig. 6.5b**) near where the two moisture pathways merge.

On January 13th, there are only trajectories from the equatorial western Indian Ocean whereas on the 14th, only trajectories from the northern Mozambique Channel and northern Madagascar are apparent (**Fig. 6.1c-d**) with both entering the LRB from the east. Notably, all trajectories tend to ascend over the last 24 hours before arrival over the LRB at the initiation point (22°S, 30°E) with an obvious decrease in moisture. Rainfall on both days occurred over the basin but mainly to the east of this initiation point in the LRB (**Fig. 6.5c-d**) consistent with the moisture decrease over the last 24 hours of the inflow. The rainfall and moisture pathways over the eastern LRB were associated with a weak tropical low there and a trailing anticyclone south of Madagascar (**Fig 6.3b**). A cold front was situated south of South Africa, to the west of this anticyclone, and there was a heat low over central South Africa to the southwest of the tropical low over the eastern LRB. As a result, a cloud band like feature is evident in the satellite imagery stretching from the convection over the eastern LRB southeast over the southwest Indian Ocean (**Fig. 6.4c-d**).

Unlike the previous days, in which air parcel trajectories originated over either the mid-latitude South Atlantic or the western Indian Ocean, January 15-16 were characterised by continental sources, either the Congo Basin (southern on the 15th or northwestern on the 16th) and northern Tanzania on the 15th (**Fig. 6.1e-f**). As for the tropical Indian Ocean sources on January 13-14 (**Fig. 6.2c-d**), their altitude profiles (**Fig. 6.2e-f**) were also low level. The tropical low over the LRB strengthened (**Fig. 6.4e-f**) with deep convection apparent there as well as over northern Angola and parts of the Congo Basin. As a result, there was heavy rainfall over the LRB (> 100 mm in some parts) during 15-16 January (**Fig. 6.5e-f**). A weak cloud band like feature was still evident on the 15th but the connection between the tropical convection and the eastward moving cold over the midlatitude South Indian Ocean had broken on the 16th (**Fig. 6.4e-f**).

The tropical low, which was situated over southern Zimbabwe on 16 January, moved westward over Botswana on the 17th (**Fig. 6.4g**) while two additional surface lows were situated over the southern part of the Mozambique Channel and east of South Africa (near 33°S, 35°E), respectively (*not shown*). **Figure 6.1g** indicates that the tropical low over Botswana drew moisture into the LRB from the eastern Congo Basin but more so from the tropical northwest Indian Ocean and across Tanzania / Zambia. However, **Figure 6.2g** suggests that much of this moisture rained out before it actually reached the LRB since maximum humidity occurred four or more days before reaching the LRB initiation site. Moderate rainfall (> 20 mm) occurred over the northwestern, and to lesser extent, the southwestern parts of the LRB on this day (**Fig. 6.5g**).

Over the following three days, the tropical northwest Indian Ocean moisture source (and subsequent flow across Tanzania/ Zambia maintained its contribution (**Fig. 6.1h-j**) but some of this moisture precipitated out before reaching the initiation site (**Fig. 6.2h-j**). Meanwhile, the tropical low which had been located over Botswana moved eastwards to lie over the LRB during 18-20 January (**Fig. 6.3c**) with convection strengthening there, and particularly on the 19th and 20th (**Fig. 6.4i-j**). Heavy rainfall (> 100 mm) occurred over the central and eastern LRB (**Fig 6.5i-j**) as this tropical low moved south-eastward during 18-20 January (**Fig. 6.4h-j**).

On the 21st, all air parcel trajectories originated from the southwest Indian Ocean south or southeast of Madagascar (**Fig. 6.1k**) as the tropical low moved offshore into the southern

Mozambique Channel (**Fig. 6.3d**). Low level moisture then fed into the LRB from the southwest Indian Ocean around the southern half of this low (**Figs. 6.1k, 6.2k**) leading to widespread moderate to heavy rainfall (20-80 mm) over the eastern half of the LRB. The heavy rainfall days (on the 11th, 15th, 16th, 18th, 19th, and 20th) can be matched with regions of low-level moisture convergence (**Fig. 6.6a-f**) and uplift (**Fig. 6.7a-f**).

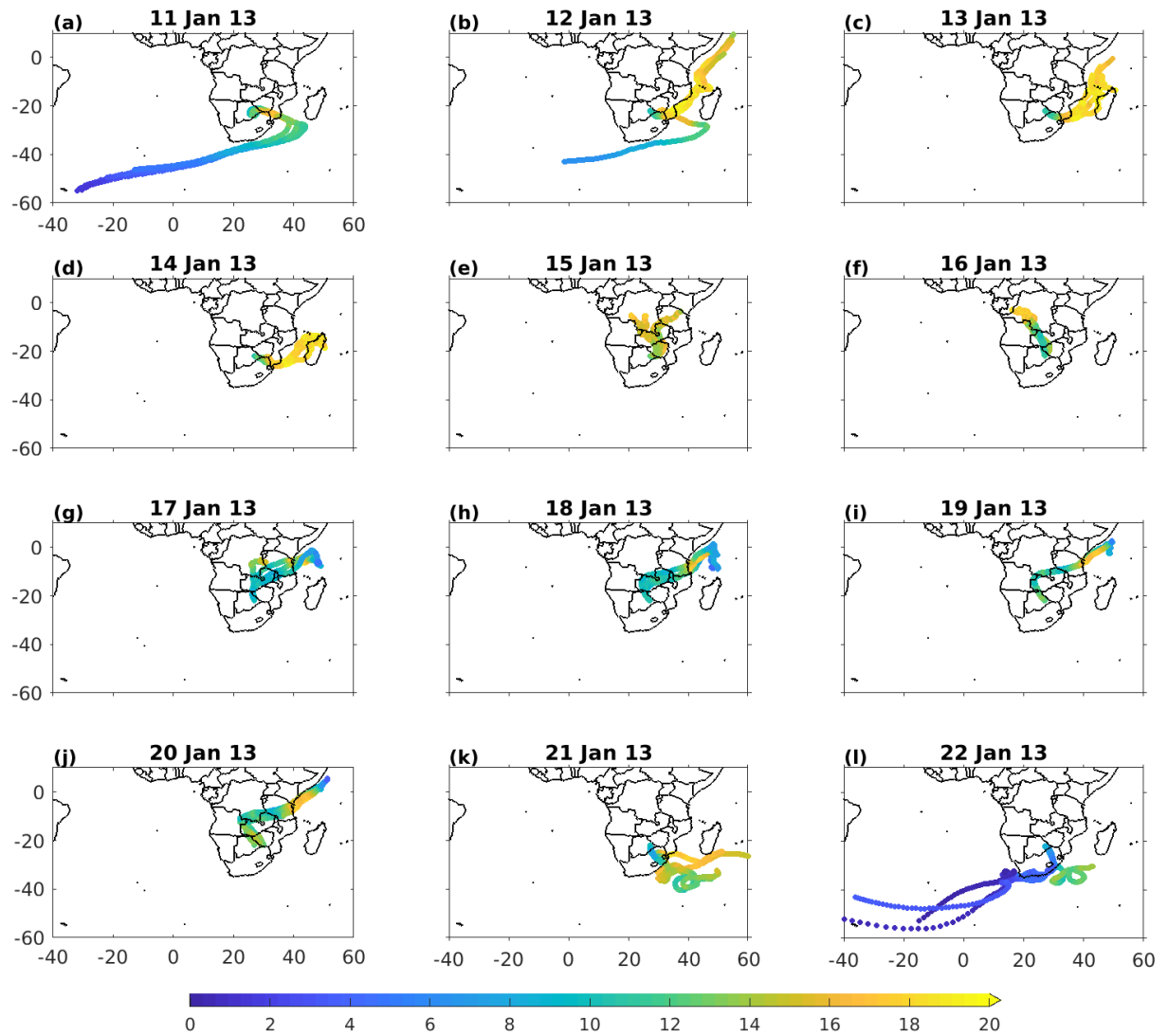


Figure 6.1: 10-day backward trajectories started at 22°S and 30°E for from (a) 11 to (l) 22 January 2013. The yellow colour indicates high specific humidity (g kg^{-1}) while low specific humidity values are shown by the blue colour.

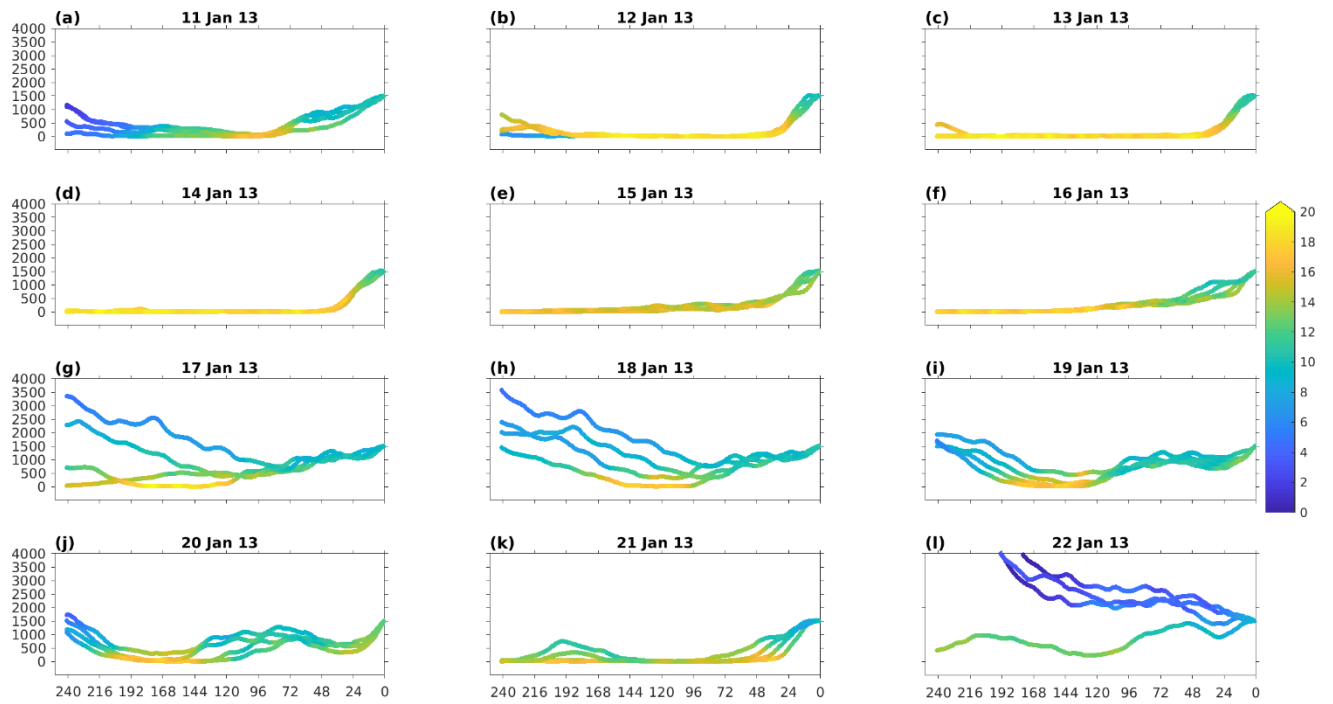


Figure 6.2: The trajectory altitudes as function of time for 11-22 January 2013 (a-l). The yellow colour indicates high specific humidity (g kg^{-1}) while low specific humidity values are shown by the blue colour.

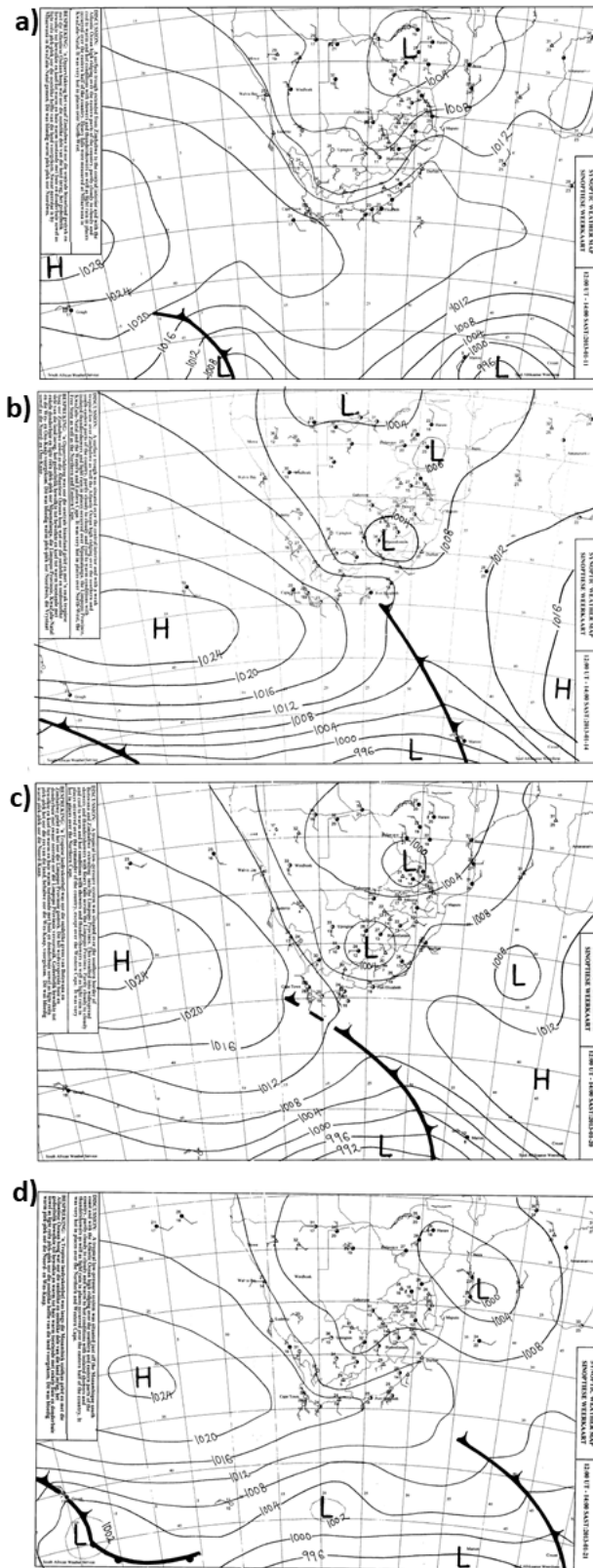


Figure 6.3: SAWS synoptic charts showing surface condition over southern Africa for (a) 11, (b) 14, (c) 20, and (d) 21 January 2013 (all times are for 12h00 UTC).

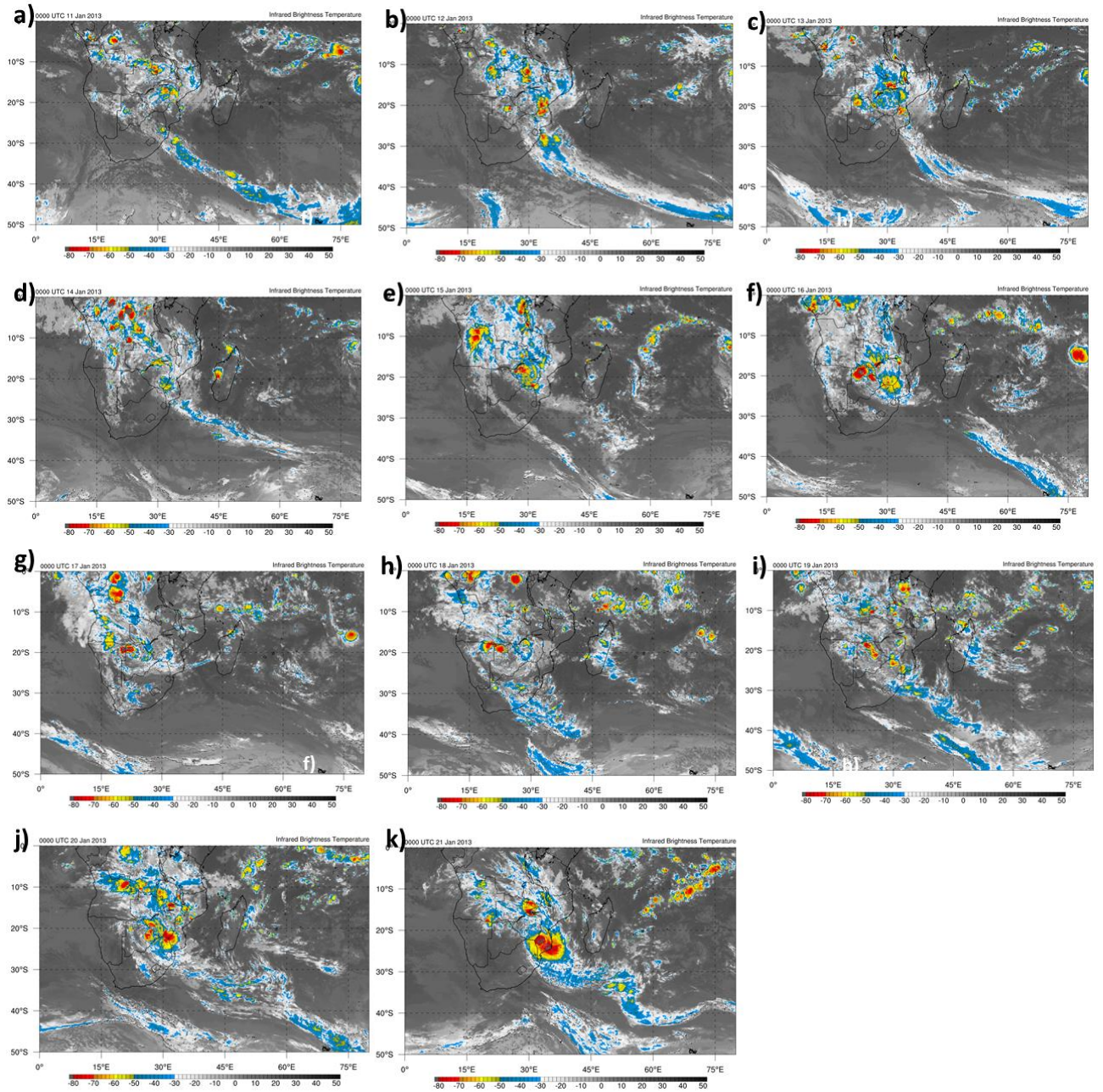


Figure 6.4: Infrared (IR) brightness temperature (°C) imagery from (a) 11 to (k) 21 January 2013. At image times are at 00h00 UTC.

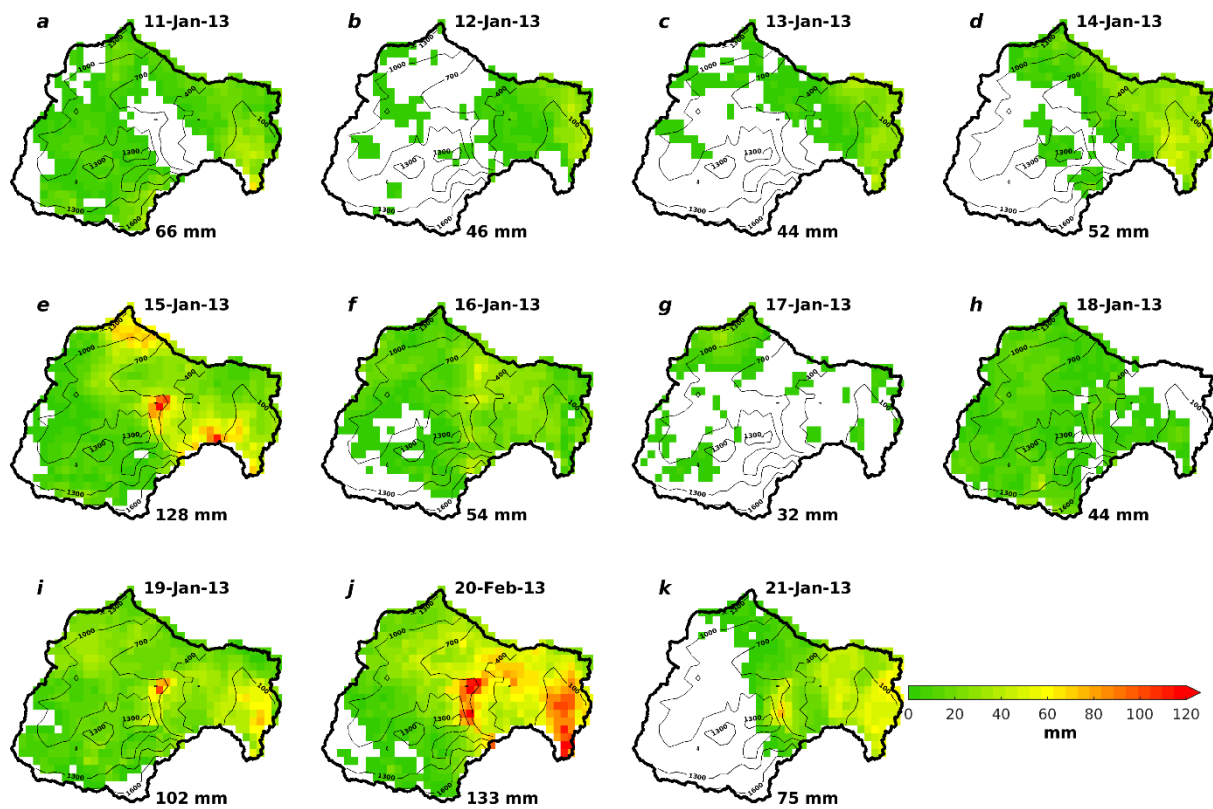


Figure 6.5: CHIRPS daily rainfall (mm) over the Limpopo River Basin for (a) 11 – (k) 21 January 2013.

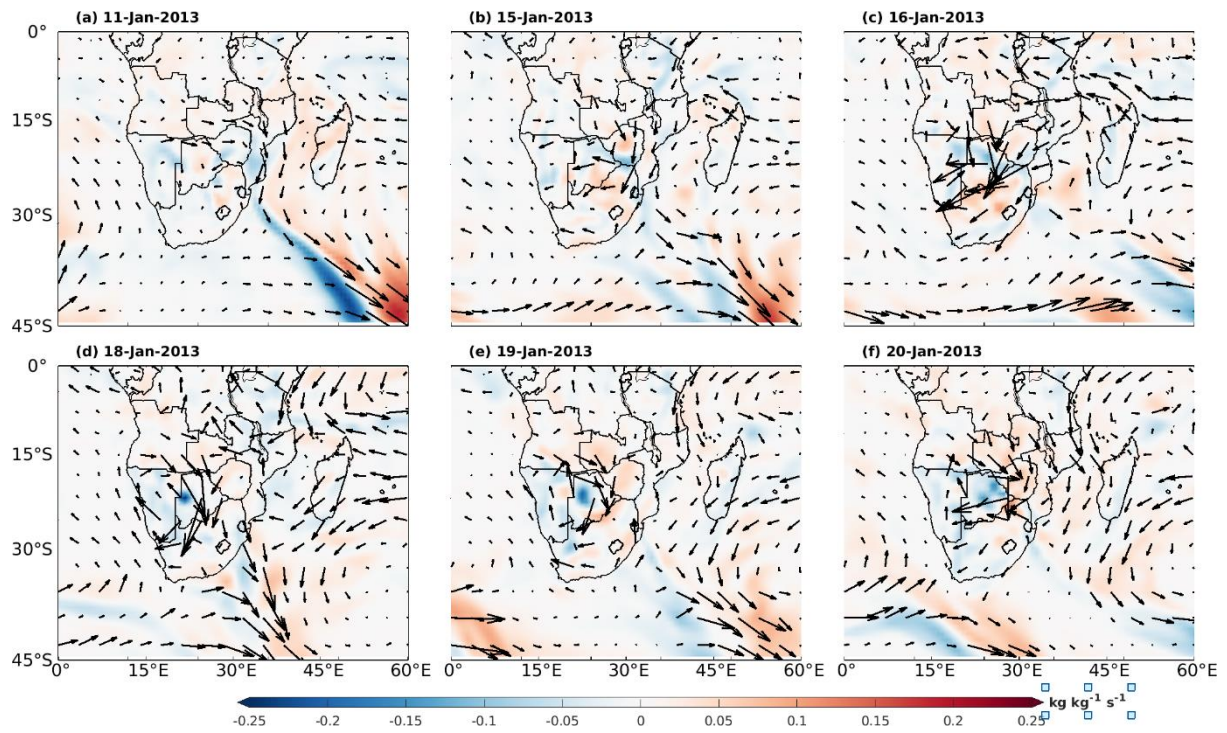


Figure 6.6: NCEP reanalysis 850 moisture flux and its convergence ($\text{kg kg}^{-1} \text{s}^{-1}$) for the heavy rainfall days for (a) 11, (b) 15, (c) 16, (d) 18, (e) 19, and (f) 20 January, during the event. Positive (negative) values denote divergence (convergence).

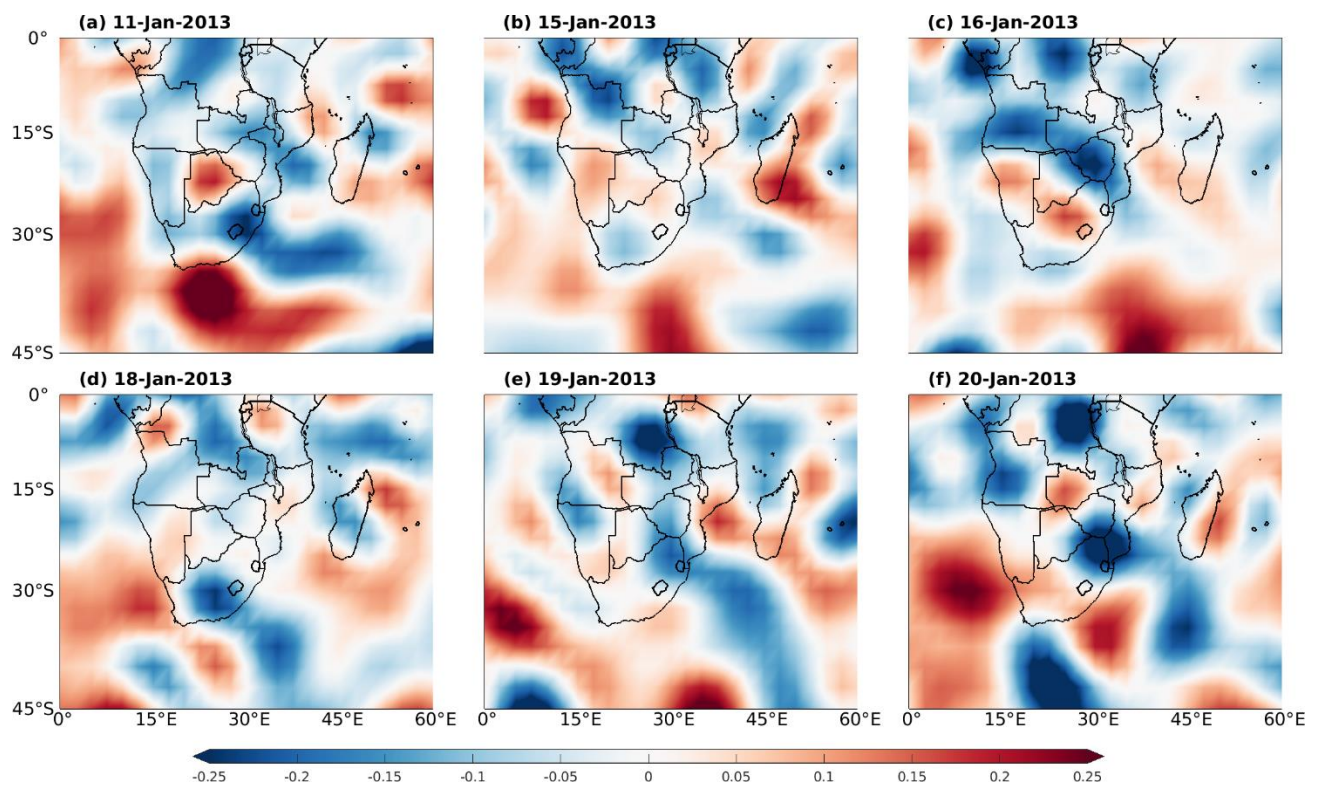


Figure 6.7: NCEP reanalysis 500 hPa omega (kg m s^{-1}) for the heavy rainfall for (a) 11, (b) 15, (c) 16, (d) 18, (e) 19, and (f) 20 January, during the event. Negative values denote uplift.

b. The 11-21 January event and climatology

To see how anomalous the moisture sources and pathways are for the January 2013 event, **Figures 6.1-2** can be compared to the summer mean trajectories schematic (**Fig. 5.10**) developed in **Chapter 5** as well as with the top 200 events trajectories (**Fig. 5.9**). As described above, the early part of the event (11-12 January 2013) indicated moisture trajectories from both the midlatitude South Atlantic (trajectory **E** in **Fig. 5.10**) and the western tropical Indian Ocean (trajectory **A** in **Fig. 5.10**). During 13-14 January, trajectory **A** was important as well as one from near northern Madagascar (somewhat like trajectory **B** in **Fig. 5.10**). However, tropical continental sources became important on January 15-16 and these trajectories are well north of the continental source in the climatology (trajectory **F** in **Fig. 5.10**) although they are like the typical tropical low events in the top 200 (about 25% of the total events) (**Fig. 5.9c**). Most of the remaining days reverted to a tropical western Indian Ocean source like trajectory **A** in **Figure 5.10** and then to a southwest Indian source like trajectory **C** in **Fig. 5.10** which is typical of tropical lows, cloud bands or mesoscale convective systems (**Fig. 5.9b-d**). However, most obviously missing from the January 11-21 event is any clear inflow from the tropical southeast Atlantic (trajectory **G** in **Fig. 5.10**) although it could be argued that the pathway of **G** over land has some elements similar to the Congo Basin trajectories on 15-16 January (**Fig. 6.1e-f**).

The absence of a tropical southeast Atlantic source contrasts with the suggestion in Manhique et al. (2015) about its importance. However, that suggestion was based on Eulerian analyses and a dekad as opposed to a daily examination of the fields, reinforcing the importance of rather using daily data for better understanding the evolution of these extreme weather events. Nevertheless, the synoptic charts and satellite imagery (**Figs. 6.3, 6.4**) indicate that this is a complex event with several weather systems contributing to the moisture fluxes and resulting rainfall. Although tropical lows seem to be the most important contributors, there are also cloud band like features on several days as well as the possibility of a MCS embedded within the larger area of convection on the 16th and 20th January (**Figs. 6.4f, j**).

6.4 Discussion and conclusion

This chapter has identified the moisture source regions and pathways associated with the heavy rainfall event of 11-21 January 2013 over the LRB, using the HYSPLIT model with NCEP II

reanalyses as input. The HYSPLIT trajectory analysis indicated three moisture source regions linked to the event: (1) tropical northwest Indian Ocean, (2) the Agulhas Current / Mozambique Channel, subtropical southwest Indian Ocean, and (3) continental sources over the Congo Basin and northern Tanzania. Although some air parcel trajectories originated over the mid-latitude South Atlantic Ocean (on the 11th, 12th), they were mostly at the middle tropospheric levels and had low specific humidity. Subsequently, these moisture trajectories descended and gained moisture over the warm waters of the Agulhas Current.

Generally, during the early stages of the event, moisture originated from the Agulhas Current region, the Mozambique Channel, and locally over and near the LRB itself. This was followed by an unusually strong continental moisture source from the Congo Basin and northern Tanzania. During the later stages of the event, moisture from the tropical northwest Indian Ocean became dominant and contributed to heavy rainfall on the 20th of January.

In terms of flood impacts, the Limpopo River level at Chokwe started rising significantly on January 16 (Manhique et al., 2015) following the first day of widespread heavy rainfall over the LRB on the 15th (**Fig. 6.5e**). The peak in river level occurred on January 23 (Manhique et al., 2015) following the heaviest rainfall in the LRB on the 20th (**Fig. 6.5j**) as the tropical low tracked southeastward over the LRB into the southern Mozambique Channel and the tropical western Indian Ocean moisture source replaced the tropical continental source as the most important.

Although it is difficult to see any obvious tropical southeast Atlantic moisture source, it is possible that the moisture originating from the Congo Basin on January 15-16 may have merged in with flow from this ocean region. It is also important to note that the analysis here is based on an initiation site in the central LRB and that had a site over southern or coastal Mozambique been chosen, then it is possible that a more obvious input from the tropical southeast Atlantic could have emerged from the analysis. The January 2013 event is a complex one with cloud band like features and possibly an MCS also contributing to the main tropical low system that was identified in **Chapter 4** and Rapolaki et al. (2019). Another important aspect of this event is the important contribution from tropical continental moisture sources (particularly 15-16 January) which were not identified by the commonly used Eulerian approach of Manhique et al. (2015). Compared to the climatology, the main difference in this event is this apparent absence of the tropical southeast Atlantic Ocean and a less obvious

tropical southwest Indian Ocean (trajectory **B** in **Fig. 5.10**) although part of the pathways on January 14 is similar to a shortened and slightly southward located version of trajectory **B**.

In summary, the results indicate the advantages of the Lagrangian approach for better understanding the moisture sources and pathways of heavy rainfall events over southern Africa.

Chapter 7: Summary and conclusions

The main aim of this thesis has been to investigate heavy rainfall events over the LRB in southern Africa, their associated weather systems, and their moisture sources and pathways. Given that this region experiences a long dry season during austral winter and receives the vast majority of its rainfall during summer, the analysis has focussed on the extended summer months (October-April).

Extreme rainfall identification and classification remains a challenge for most parts over southern Africa due to a lack of long-term high-resolution station data. In cases where the data are available, they often come from inconsistent rainfall station over time. As a result, many recent studies have focussed on seasonal rainfall anomalies and pentads analyses (e.g. Cook et al., 2004; Reason et al., 2005) or specific cases of events of interest (Reason and Keibel, 2004; Manhique et al., 2015). Moreover, all previous climatological studies which characterised heavy rainfall over southern Africa often considered a specific extreme rainfall producing system such as cut-off lows, tropical-extratropical cloud bands, mesoscale convective systems or tropical lows (e.g. Singleton and Reason, 2007b; Hart et al., 2013; Blamey et al., 2012; Malherbe et al., 2012; Favre et al., 2013; Molekwa et al., 2014).

To better understand rainfall extremes over the LRB, this thesis presented an analysis of the daily rainfall events in **Chapter 4** derived from high resolution CHIRPS gridded data. Using the methodology of Ramos et al. (2014), the top 20 and top 200 heaviest rainfall events were identified for the LRB, over a 36-year period. Unlike other methodologies (e.g. Brooks and Stensrud, 2000; Konrad, 2001) which use thresholds (e.g. 25 mm h^{-1}) approach to define heavy rainfall, the current methodology considered both the intensity and spatial extent of the rainfall. Knowing both rainfall distribution and intensity could help develop more accurate daily forecasts which are better tailored to the needs of various stakeholders.

A classification of the top 200 extreme rainfall events presented in Rapolaki et al. (2019) and as **Chapter 4**, suggests that most events over the LRB are associated with cloud bands (48%) and tropical lows (28%), with MCS (14%) and mid-to-upper level COLs (10%) making up the remaining quarter. In general, the results agreed with previous studies (Harrison, 1984; Reason

et al., 2006; Hart et al., 2010, 2013; Manhique et al., 2011), that cloud bands are responsible for most summer rainfall over subtropical southern Africa reinforcing the need to better understand the evolution and rainfall patterns associated with these systems. Furthermore, the monthly distribution of COLs agreed with the earlier findings of Taljaard (1985), Singleton and Reason (2007b) and Favre et al. (2012) who showed that COLs over southern Africa occur mostly during transition seasons and that they are important contributors of early and late summer rainfall.

Chapter 4 also found some relationships between the frequency of heavy rainfall events over the LRB and interannual climate modes of variability such as ENSO, SIOD, and SAM. Consequently, monitoring the state of ENSO, SIOD, and SAM in the late austral spring / early summer may give indications of the likelihood of the rest of the summer experiencing an above or below average number of extreme rainfall events over the LRB. However, it must be noted that the SIOD, ENSO, and SAM can occur concurrently, and thus they may act to strengthen or weaken the impact of each other on these rainfall events. Therefore, seasonal forecasting of extreme rainfall events over the LRB should take into account all three climate modes. At present, such efforts in the region tend to focus mainly on the ENSO state which the results presented here suggest is insufficient.

Following on from this analysis of the weather systems responsible for the heavy rainfall events, **Chapter 5** considered the moisture sources and pathways associated with summer rainfall over the LRB. Unlike most previous studies (e.g., Walker, 1990; D'Abreton and Lindesay, 1993; Mason 1995; Reason and Mulenga, 1999; Cook et al., 2004; Reason et al., 2006) which are based on the Eulerian methods, **Chapter 5** used a Lagrangian approach so that moisture received at a particular point in the LRB can be traced back to its various sources. This chapter represents the first climatology of moisture sources and transport for the LRB using Lagrangian methods (in this case the HYSPLIT model with NCEP-II reanalyses as input data) as well as for the top 200 heavy rainfall events identified in **Chapter 4**.

On seasonal time scales, **Chapter 5** showed seven moisture source regions for the LRB which converge into four main pathways nearer the LRB. This result is a more nuanced version of the traditional Eulerian-derived view which generally refers to the western tropical Indian Ocean, the southwest Indian Ocean and the tropical southeast Atlantic as the main moisture sources for subtropical southern Africa. For example, **Chapter 5** finds that the western tropical Indian

Ocean source should rather be thought of as the northwestern Indian Ocean and western tropical South Indian Ocean, and that the southwest Indian Ocean source contains one originating from well east of Madagascar and one from the midlatitude South Atlantic that then flows along the Agulhas Current before merging with the source east of Madagascar as a southeasterly branch towards the LRB. Additionally, a continental source over western southern Africa was found. When the analysis is applied to the subsets of weather systems responsible for the top 200 rainfall events, it was found that tropical continental sources (parts of the Congo Basin and Tanzania) become important, particularly for the cloud band and tropical low events. While these results suggest a deeper and more detailed understanding of moisture sources and pathways, there are some important caveats. Firstly, the accuracy of the Lagrangian derived results depends on the ability of the NCEP-II reanalyses to adequately represent the weather systems and circulation patterns of the region. Depending on the application, some reanalysis datasets do appear to perform better than others over southern Africa (Zhang et al., 2013; Moalafhi et al., 2016). Although NCEP-II is not regarded as the most advanced reanalysis product currently available, it produces an adequate reconstruction of southern Africa historical climate and is widely used in climate research. Secondly, although in general the results did not appear to differ much when a western or eastern initiation point was used instead of the central LRB site (22°S, 30°E), it is possible that there may be some differences in the exact locations of the moisture sources and trajectories, particularly for some of the heaviest rainfall events. Also, had a longer dataset been available, some differences from the results presented in **Chapter 5** could emerge.

As a first step towards seeing how robust the results might be for an individual case, **Chapter 6** analysed the heavy rainfall event of 11-21 January 2013. This event was not only ranked first in its rainfall impact (**Chapter 4**) but also had rather complex circulation aspects. Previous work has suggested that a long-lasting cloud band was responsible for the Mozambique flooding during this event (Manhique et al., 2015) or a mesoscale convective system (Wiston and Mphale, 2019). However, the analysis presented in **Chapter 4** indicates that a tropical low was the main rainfall producing system, although there were several days during the period when aspects of an embedded mesoscale convective system and a cloud band like feature were present.

Chapter 6 showed that this event was largely linked to three main moisture sources: (1) tropical northwest Indian Ocean, (2) the Agulhas Current / Mozambique Channel, subtropical

Southwest Indian Ocean, and (3) continental sources over the Congo Basin and northern Tanzania. Unlike the suggestion of Manhique et al. (2015) that moisture originating from the tropical southeast Atlantic Ocean made a substantial contribution to the heavy rainfall, this source was not obviously present on any of the days. **Chapter 6** further showed that there were trajectories coming from the northwest (western Congo Basin) on two of the heavy rainfall days over the LRB which the Eulerian analysis of Manhique et al. (2015) could then infer as a tropical southeast Atlantic source instead of the tropical continental source identified in this thesis. However, it is possible that had an initiation site been chosen over the far eastern LRB or neighbouring southern Mozambique (focused on in Manhique et al., 2015), then a tropical southeastern Atlantic source could have emerged. Compared to the climatology, the main difference in the January 2013 event was the apparent absence of the tropical southeast Atlantic Ocean source and a less obvious tropical southwest Indian Ocean source (trajectory **B** in **Fig. 5.10**) although some of the pathways on January 14 were similar to a shortened and slightly southward located version of trajectory **B**.

Although Lagrangian models such as HYSPLIT are computationally efficient and moisture budgets can be traced along the trajectories, the reliability of the trajectories depends on the quality of meteorological input data (Ciric et al, 2016). Therefore, the trajectories may change from those obtained in this thesis with NCEP II reanalyses if a finer resolution data set such as 0.75° ERA-Interim (Dee et al., 2011) had been used. To fully understand the effects of different spatial meteorological input data on moisture source-sink relationships over the LRB, a comparative study between NCEP II and ERA-Interim will be done in the future to indicate which data set provides better results. Moreover, Nieto et al. (2019) have shown that the backward derived from Lagrangian models are sensitive to the integration time. Although a 10-day period is considered the average residence time of moisture in the atmosphere (Trenberth, 1999), this choice may have led to an over- or underestimation of moisture sources over the LRB, particularly the westerly branch which extends from over Namibia (trajectory **F** in **Fig. 5.10**) where the integration period may be as short as 1-2 days (Nieto et al., 2019). Therefore, future studies should use different integration times following the recent methodology established in Nieto et al. (2019) to help establish the optimal residence times for the LRB.

Given that the LRB contains a large rural population spanning four countries, several important conservation and wilderness areas as well as the second largest river on the Indian Ocean

seaboard of Africa, it is very important to better understand its rainfall variability. However, despite it receiving moisture from a variety of sources, the LRB still remains a relatively dry region due to the frequent presence of mid-level anticyclonic conditions such as the Botswana High (Reason, 2016; Driver and Reason, 2017) and to its location relative to that of Madagascar (Barimalala et al., 2018). While this thesis has focussed on synoptic to interannual time scales, further research is needed to investigate potential long-term changes in moisture source regions and transport paths, including their likely impacts on extreme rainfall over the LRB.

In conclusion, this work has helped improve understanding of the atmospheric branch of the hydrological cycle of the Limpopo River Basin. The results presented here provide a basis for future research on atmospheric moisture sources and pathways and their impacts on rainfall and water resources on both seasonal and event time scales for the LRB and the broader southern African region.

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Appendices

Appendix A- SAWS synoptic charts for 10-21 January 2013

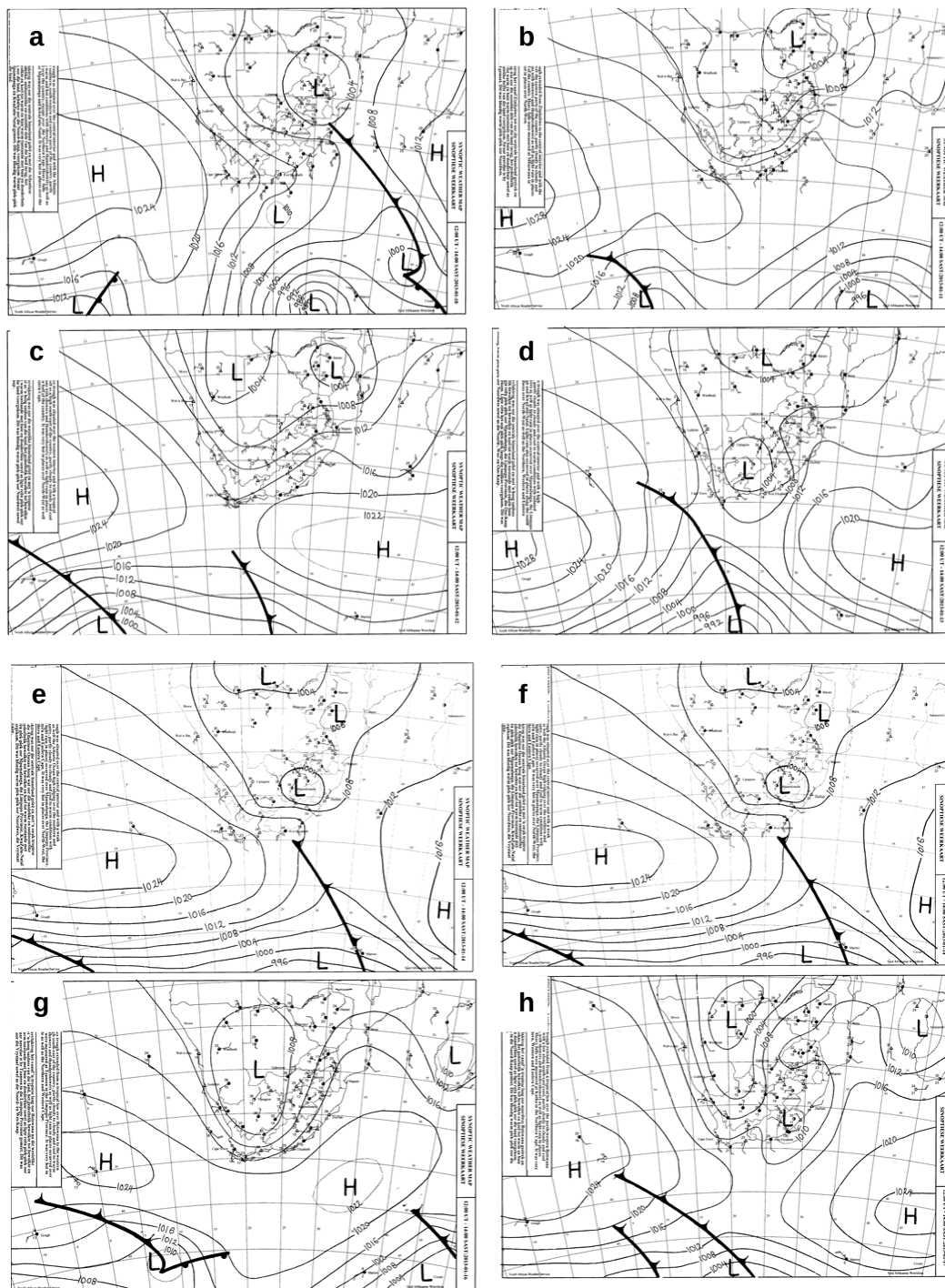


Figure A5.1: SAWS charts showing surface conditions over southern Africa for (a) 10- (l) 21 January 2013 (*continued next page*).

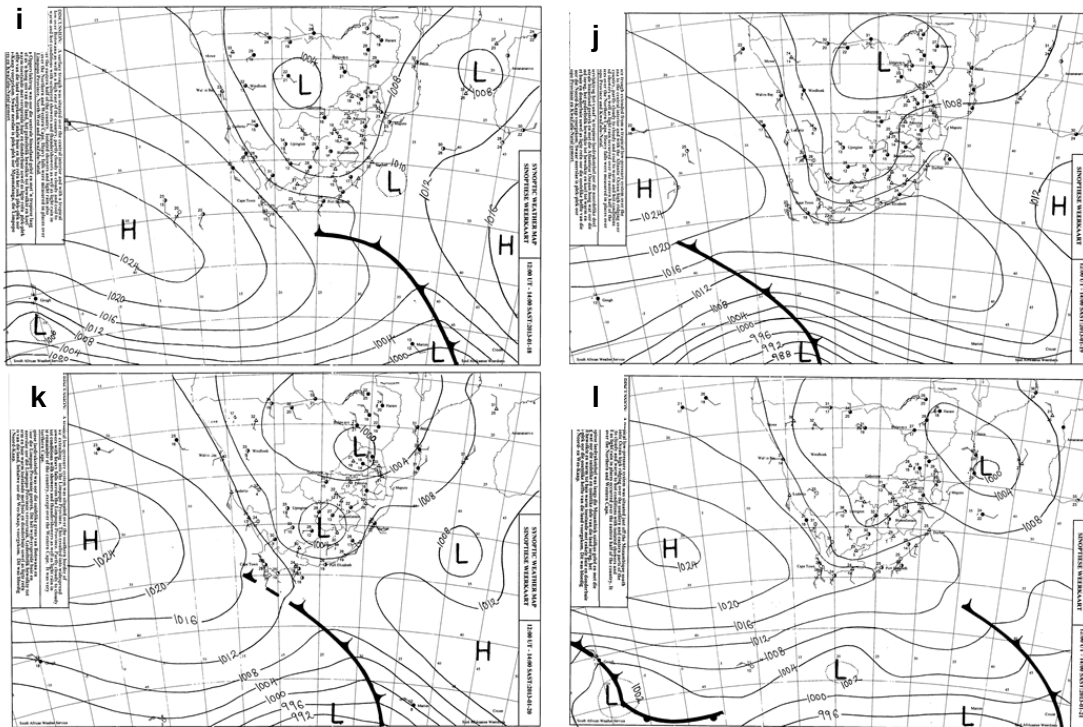


Figure A5.1: (continued) SAWS charts showing surface conditions over southern Africa for (a) 10- (l) 21 January 2013.