RAINFALL VARIABILITY IN SOUTHERN AFRICA, ITS INFLUENCES ON STREAMFLOW VARIATIONS AND ITS RELATIONSHIPS WITH CLIMATIC VARIATIONS

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PATRICK VALIMBA

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ABSTRACT

Hydrological variability involving rainfall and streamflows in southern Africa have been often studied separately or have used cumulative rainfall and streamflow indices. The main objective of this study was to investigate spatio-temporal variations of rainfall, their influences on streamflows and their relationships with climatic variations with emphasis on indices that characterise the hydrological extremes, floods and droughts.

It was found that 60-70% of the time when it rains, daily rainfalls are below their long-term averages and daily amounts below 10 mm are the most frequent in southern Africa. Spatially, climatologies of rainfall sub-divided the southern African subcontinent into the dry western/southwestern part and the “humid” eastern and northern part. The daily amounts below 20 mm contribute significantly to annual rainfall amounts in the dry part while all types of daily rainfall exceeding 1 mm have comparable contributions in the humid part. The climatologies indicated the highest likelihood of experiencing intense daily events during the core of the wet seasons with the highest frequencies in central Mozambique and the southern highlands of Tanzania. Interannual variations of rainfall indicated that significant changes had occurred between the late-1940s and early-1980s, particularly in the 1970s. The changes in rainfall were more evident in the number of daily rainfall events than in rainfall amounts, led generally to increasing early summer and decreased late summer rainfall.

It was also found that intra-seasonal dry day sequences were an important parameter in the definition of a rainy season’s onset and end in southern Africa apart from rainfall amounts. Interannual variations of the rainy season characteristics (onset, end, duration) followed the variations of rainfall amounts and number of events. The duration of the rainy season was affected by the onset (Tanzania), onset or end (tropical southern Africa - southwestern highlands of Tanzania, Zambia, northern Zimbabwe and central Mozambique) and end (the remaing part of southern Africa).

Flow duration curves (FDCs) identified three types of rivers (ephemeral, seasonal and perennial) in southern Africa with ephemeral rivers found mainly in the dry western part of the region. Seasonal streamflow patterns followed those of rainfall while interannual streamflow variations indicated significant changes of mean flows with little evidences of high and low flow regime changes except in Namibia and some parts of northern Zimbabwe. It was, however, not possible to provide strong links between the identified changes in streamflows and those in rainfall.

Regarding the influences of climate variability on hydrological variability in southern Africa, rainfall variations in southern Africa were found to be influenced strongly by ENSO and SST in the tropical Indian ocean and moderately by SST in the south Madagascar basin. The influence of ENSO was consistent for all types of daily rainfall and peaks for the light and moderate (< 20 mm) events in the southern part and for the intense events in the northern part. SST in the tropical Indian ocean influence the light and moderate events while SST close to the region influence the heavy events. However, the relationships experienced significant changes in the mid-1950s and in the 1970s. The former changes led to improved associations while the latter deteriorated or reversed the relationships. The influences of climatic variables on streamflows and rainy season characteristics were inferred from the rainfall-streamflow and rainfall-climatic variables relationships.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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DECLARATION AND COPYRIGHT

I, Patrick VALIMBA, declare that this thesis is my original work and that it has not been presented and will not be presented to any other university for a similar or any other degree award.

Signature

CHAPTER 1

INTRODUCTION

1.1. Introduction

Surface water resources in southern Africa are declining leading to growing conflicts between different competing users such as agriculturalists, hydropower plants and water suppliers. Declining river flows and dam levels are the evidences of declining surface water resources in the region. Dam levels have been reported to decline since the mid 1970s in Namibia (Jury and Engert, 1999), in South Africa since the early 1980s as a reflection of prolonged rainfall deficit in the 1980s and early 1990s (Mason, 1996). Berhanu (1999) and Berhanu *et al.* (2001) found a recent decrease in mean annual runoff in southern African catchments that occurred since 1975, particularly marked in Zambia, Angola, Mozambique and the South African High Veld. The decline is attributed mainly to declining and unreliable rainfall, population increase and changing landuse and water use patterns.

It is plausible to hypothesize that identified changes in southern African surface water resources are reflected from changes in rainfall as observed in West Africa (Mahé and Olivry, 1991; Olivry, 1993; Olivry *et al.*, 1993; Servat *et al.*, 1997b) and their severity is increased by human-related influences. Past studies had identified a mixture of increasing and decreasing annual and seasonal rainfall amounts in some parts of southern Africa (Tyson, 1986; Smakhtina, 1998; Mason *et al.*, 1999; Mkhandi and Ngana, 1999; Mutua, 1999) while studies which used regional indices concluded that there is no strong evidence of declining or increasing trends in southern Africa rainfall amounts.

There is evidence, however, of increasing frequency of high rainfall events in some parts of southern Africa. A modeling study of Mason and Joubert (1997) under a doubled-CO_2 scenario and the studies of Smakhtina (1998) and Mason *et al.* (1999) which used observed records had further identified increased frequency and magnitude of high rainfall and rain rates in southern Africa. Such changes in rainfall alone could have serious negative consequences to water resources, the population and properties. The possibilities of collapse of small dams and reservoirs are likely to increase which means flood risks to the population and properties in the flood plains are similarly increased. Consequently, frequent floods have been reported in recent decades in the humid as well as in the dry parts of the region (e.g. the 1984 floods in the dry Namibian coast; the February 2000 severe floods which hit

Mozambique, Zimbabwe and northeast South Africa; the November-December 1997 floods in east Africa).

The risks of flooding are further increased by human-related activities. The southern African population is mostly rural and agriculture, predominantly traditional rainfed type, is its main economic activity. The population is dynamic and has been growing rapidly in recent decades with the highest population densities and growth rates characterising the humid eastern part and the fertile land. Owing to its rapid growth and limited fertile land, the southern African population is constantly displaced into marginal, low-productivity areas looking for areas for settlement and cultivation. Increasing exploitation of these marginal areas have been observed in different parts of the region (e.g. Yanda, 2002). Limited land and increased water demand from the growing population have led to changes in the landuse and water use patterns in the region. Traditional farming and pastoralism have changed into irrigation and plantation agriculture mixed with modern animal husbandry. More land therefore is cleared to accommodate these activities, leading to reduced land cover and modified soil surface properties. Consequently large land areas become exposed to actions of the weather. The changes at the soil surface may result in increased frequency and/or volumes of flash floods due to poor infiltration. Insufficient groundwater recharge due to poor infiltration during the wet season may further lead to declining dry season flow and hence the danger of severe streamflow droughts. Identified declining annual flows, therefore, may be caused by prolonged periods of low flows.

Floods and drought events in southern Africa have been further linked to extreme oceanic and atmospheric conditions in the surrounding Atlantic and Indian oceans as well as to the remote influence of the Pacific ocean. The 1997 floods in east Africa (including Tanzania) were differently linked to Indo-Pacific El Niño/Southern Oscillation (ENSO) and to sustained high sea surface temperatures (SST) in the Southwest Indian Ocean. The 1984 floods along the Namibian coast were associated with extremely warm SST in the Angola/Benguela Front region typical of the Benguela Niño while the 2000 floods which hit Mozambique, eastern Zimbabwe and northeast South Africa could have been influenced by the tropical-temperate troughs (TTTs) which have been previously linked to high rainfall intensities in these parts. Moreover, severe storm and flooding rainfall events along the southern coast of South Africa have also been linked to warmer than normal SST in the Agulhas Current which flows off the South African southeast coast. Droughts in most of the southern part of southern Africa, on the other hand, have been linked to SST variations in tropical Indian ocean (TIO) and to ENSO. Warmer conditions in TIO and/or in the Pacific or low phase of the southern oscillation (SO), typical of the warm ENSO, correspond to reduced rainfall in the southern part of the region and rainfall increase in the northern part, particularly in northern Equatorial Tanzania.

However, the relationships between southern African rainfall and climatic variables are dynamical, seasonally variable and have undergone significant changes in the 1970s reflecting changes that occurred in the background climatic variables in that decade. Significant changes in SST have been identified in the 1970s, warming in the tropical Indian and Pacific Ocean basins in the late-1970s and in Southwest Indian Ocean basins in early-1970. According to Stephens (1990) and Zhang (1993), an increase in SST causes a non-linear increase in the amount of water precipitated from an oceanic vertical column of air. Since the Indian Ocean is the main source of moisture, which is advected into southern Africa, the warming in this Ocean may have enhanced convection and consequently rainfall in southern Africa becomes more convective leading to reduced frequency of light rainfall events while enhancing heavy rainfall events. The results of Mason and Joubert (1997), Smakhtina (1998), Mason *et al.* (1999) and Richard *et al.* (2000) agree with enhanced SST although the annual timescale used in the latter three studies usually masks the patterns at lower timescales (seasonal, monthly). Recent floods in southern Africa are more severe while recent droughts are both severe and widespread.

The changes towards increased frequency and magnitude of high rainfall identified at the annual timescale, while suggesting increased flood risks during the wet season, are not very useful in the management of floods as the dates when the risks are highest are still not provided. Intense rainfall events are often observed during the core of the rainy seasons at the time when soil moisture is high due to early season rains. Flood flows are usually short-lived and correspond to such similarly short-lived intense rainfall events on moist soils. Better management of floods and their associated risks, therefore, requires knowledge of the period when high rainfall events are more likely to occur during the wet season, their frequency, intensity and duration of the individual events and the soil moisture conditions before the time of these high rainfalls. This therefore requires analyses of short-duration (e.g. daily) records of rainfall and streamflows at intra-annual timescales to better understand hydrological variability at lower timescales (monthly, seasonal), which are most appropriate in water resources planning and management.

It is therefore the *time* scale that is important in the management of water resources, which includes management of floods and droughts. Short-duration records are more informative and indices derived from these short-duration records are therefore useful. Since southern African rainfall is variable between the seasons of the year and across the region, it is necessary to perform analyses at monthly or seasonal timescales rather than at the annual timescale. For example, the identification of periods in which floods are most likely involves studying characteristics of daily rainfall and streamflows within the year and for different years of the records across the region. No studies have yet characterised spatio-temporal patterns of daily rainfalls, the relationships between different types of daily rainfall and climatic variables and their links to streamflow variations in southern Africa. Such studies are expected to improve our understanding of hydrological variability in the southern African region.

Our better understanding of spatio-temporal variations of rainfall in southern Africa is highly dependent on how well we understand the variations of the dynamic background climatic variables with respect to their influences on different types of rainfall events in the region. The use of total amounts, for example, may hamper advancement of our understanding of relationships between southern African rainfall and climatic variables. It would be appropriate then to classify daily rainfall events into classes and thereafter seek to understand how rainfall amounts and number of rainfall events in each of the classes are related to climatic variables. Emphasis should, therefore, be given to links between indices derived from short-duration observations and climatic variables. Better understanding of the relationships between types of daily rainfall and climatic variables is expected to be useful in improving the prediction skills of the operational general circulation models (GCMs) on one hand and on the other, it will be possible to predict different types of daily rainfall given that climatic variables are successfully predicted well in advance. Consequently, the impacts of floods and droughts can be significantly reduced.

Despite past efforts at studying different characteristics of rainfall, most of the previous studies analysed rainfall and streamflows separately and those which used observed records were mainly concentrated in different parts of the region, notably South Africa. It was not possible, therefore, to obtain a regional interpretation of the results. More often, studies of rainfall and those of streamflows were concentrated in different areas making it difficult to relate variations of the two variables.

1.2. Thesis organisation

This thesis is broadly intended to investigate spatio-temporal variations of rainfall in southern Africa, their relationships with climatic variables and their influences on the rainy seasons characteristics and streamflow variations. The main interest is on the identification of drought and flood prone areas in the region on one hand and on the other, the identification of periods during the wet season when risks of flooding are high. Using indices that appropriately characterise flood and deficit streamflows, interannual variability of corresponding rainfall indices are related to interannual variability of these indices of streamflows. They are both then linked to interannual variations of climatic variables.

The entire study is therefore divided into five main parts, specifically designed to achieve the three main objectives of the study. Part I, which comprises five chapters, introduces the study in general (chapter 1), presents the objectives of the study (chapter 2), introduces the study region (chapter 3) and reviews the literature (chapter 4) and describes the data sets that were used (Chapter 5). Chapters 6, 7 and 8 form Part II, which investigates rainfall variations in the region. Chapters 6 and 7 describe respectively the spatial variations and interannual variability of southern African rainfall while chapter 8 investigates spatial and interannual variations of the rainy season characteristics in southern Africa. Seasonal and interannual streamflow variations are presented in chapter 9, the only chapter in the Part III, while Part IV investigates relationships between interannual variations of rainfall and interannual variations of climatic variables (chapter 10). The general conclusions are given in chapter 11 (Part V).

CHAPTER 2

THE STUDY OBJECTIVES

2.1 Introduction

From the introductory chapter, it is clear that there are potential problems with the management of surface water resources in southern Africa, which are partly caused by climate-related rainfall variations and partly by human activities. Despite various past studies aimed at understanding the hydrological variability in the region, efforts are still needed to improve our understanding of the hydrological variability particularly in relation to flow extremes, droughts and floods. The availability of good quality and long daily records of rainfall and streamflows makes studies of hydrological variability using indices derived from these short-duration observational records more appropriate now than before.

This chapter presents, using a list of questions, key issues that, when better understood and resolved, are considered to improve our ability to manage the surface water resources in the southern African sub-continent. The objectives are then stated in the form of responses to formulated questions.

2.2 The importance of the study

In this section, a set of questions, which form the basis of the present study, is presented. Questions regarding rainfall variability, flow variability, inter-relationships between interannual variations of rainfall and flow indices and their relationships to climatic variables are formulated. With respect to rainfall variability in southern Africa, a number of important key issues have been grouped into 5 categories: rainy season, rainfall amounts and number of daily rainfall events, extreme rainfall, other derived rainfall indices and links between rainfall variations and climatic variables at both regional and global scales. Since rainfall is the main forcing factor for streamflow and several characteristics of the rainfall affect the resulting patterns of streamflow, therefore different characteristics of rainfall are addressed while only a few of streamflow are studied.

2.2.1 Rainfall

2.2.1.1 Rainfall amounts and number of daily rainfall events

Rainfall amounts have been and are being extensively investigated although a few recent studies have analysed the number of rainfall events as well. The annual timescale has been preferred by most researches although some have used seasonal and monthly timescales. Despite such efforts devoted to studying the variability of rainfall amounts, there are still a lot of unanswered questions.

- What temporal patterns of variability do time series of annual rainfall amounts and number of rainfall events display? Are they uniform in space?
- Are spatio-temporal patterns of rainfall variability at the annual timescale identical to those at seasonal and monthly timescales? Do certain seasons dominate variations observed in annual rainfall amounts and number of rainfall events?
- How does this dominance vary both in time and in space? Do rainfall amounts co-vary with number of rainfall events at both annual and seasonal timescales?

2.2.1.2 Rainy and dry seasons

It is well known that there exists no global definition of the rainy season. This fact may be caused by the lack of a precise way of defining important characteristics of the rainy season: onset and cessation, hence the duration of the season. A high degree of spatial and temporal variability of rainfall may be contributing to this problem. This study will not provide precise definitions of rainy seasons. It will rather tackle the problem through analysis of daily as well as monthly rainfall amounts and number of rainfall events in separating wet (rainy) seasons from dry season. The following questions are relevant:

- Is it possible to characterise wet and dry seasons in southern Africa with regard to sequences of wet and dry days? What can be said about dry days and their sequences during the wet seasons in the region?
- Can existing definitions of rainy seasons adequately define the rainy seasons in southern Africa? If not, then how can the start and the end of the rainy seasons in different parts of southern Africa be defined?
- What spatial patterns of variations are shown by the rainy season characteristics (onset, end and duration) in southern Africa? Are there any significant changes of

these rainy season characteristics over time? Are there any interrelationships between interannual variations of the rainy season characteristics?

- On average, what proportions of annual rainfall amounts and number of rainfall events are observed during the rainy seasons? Are rainfall amounts received during the rainy season dependent on onset, end, duration or both?

2.2.1.3 Types of daily rainfall events

Apart from rainfall amounts and number of rainfall events, indices defining rainfall extremes are of great importance in water resources management and in hydrological risk assessment. Unfortunately, they and their spatio-temporal patterns of variability have not yet been fully explored. Problems posed by extremely high, as well as low, rainfall intensities are well known. Apart from maximum intensities, which have been often studied, interannual variability of other rainfall intensities is worth investigating. Then,

- How effectively can daily rainfall intensities be classified (It is the problem of defining objectively the limits that appropriately distinguish between different classes of daily rainfall intensities)?
- Once classes of daily rainfall intensities are established, which classes contribute the most to the seasonal and annual amounts and number of rainfall events? What are the spatio-temporal patterns of variability of rainfall amounts and number of rainfall events in each of the defined classes? Are the patterns of interannual variability similar between the classes and between classes and overall amounts and number of rainfall events?

2.2.2 River flows

In most cases, seasonal streamflow variations respond to rainfall variations. Long term flow variations, on the other hand, are affected by a combination of rainfall variations and human-related changes such as changing water use and landuse patterns. Changes in these background factors have different effects on various streamflow characteristics. For example, depleted land cover can significantly affect both low and high flows in such a way as to cause substantial flood volumes during the wet period and reduced flows during the dry period. The following questions can be asked:

- What seasonal patterns do flow records display across southern Africa? Are the patterns uniform across the region irrespective of basin (catchment) size, geographical location in the region and physiographical differences?
- Do flow peaks lag behind rainfall peaks substantially? If yes, do these lags remain practically unchanged over the years? If changes were observed, then when and do they manifest as trends or discontinuities?
- Are mean monthly and seasonal flows displaying discontinuities or significant trends? Are patterns of interannual variability of mean monthly and seasonal flows comparable to those of mean annual flows?
- Can flood and deficit (drought) flows adequately be separated using existing techniques such as the flow duration curves (FDCs) or statistical frequency distributions? Once successfully separated, have flood flows and deficit flows become more severe and/or more frequent in recent decades than before? If trends and/or discontinuities were identified in mean flows, are they caused by similar trends and/or discontinuities in low flows, high flows or both?
- In relation to rainfall variability, are seasonal and interannual patterns of streamflow variability resembling those of rainfall? If not, do common periods exist in which both streamflow and rainfall indices show similar interannual patterns of variability? Are there any links between various rainfall and streamflow indices? What may be the probable causes of deviations observed in the other periods?

2.2.3 Linking interannual variations of rainfall and streamflows to climatic variations

Past efforts have been devoted to understanding the nature of the relationship between interannual variations of climatic variables and variations of overall rainfall amounts and to some extent variations of mean streamflow. Some contradictory results have been reported in the case of rainfall (see e.g. Lanzante, 1996; Janicot *et al.*, 1996, 1999). These contradictions may be arising from the fact that background climatic variables are dynamic and their influences on rainfall are similarly changing over time. The following questions can be asked:

- Are SST changes in the key oceanic basins, that have been identified to influence southern African overall rainfall amounts, influencing rainfall amounts and number of rainfall events in each class of daily rainfall similarly?

- Which ocean basins have dominant influences and on which classes and where in southern Africa? What is the nature of the relationships between SST variations in the different ocean basins and rainfall amounts and number of rainfall events in each class?
- What relationships exist between ENSO and rainfall amounts and number of rainfall events in each class of daily rainfall? Are the relationships stronger for certain classes and in certain parts of southern Africa than in others?
- Are the relationships between classified rainfall amounts and number of rainfall events and ENSO indices/SST seasonally variable? Are they dynamic over time?
- What are the possible responses of streamflow to varying climatic background? Are low flows, mean flows and high flows responding similarly? Do high and low flow indices undergo any significant temporal modifications as a result of changes in the climatic variables?

2.3 Study objectives

The fundamental objective of this study is to explore spatio-temporal variability of various rainfall and flow indices in the southern African subcontinent, investigating their interrelationships and how they are influenced by climatic variations. More specifically, this general objective has been divided into four sub-objectives, which correspond to the anticipated outputs:

2.3.1 Sub-objective 1: Variability analysis of rainfall indices

Fundamentally, this objective investigates spatio-temporal variability of various rainfall indices in southern Africa. The analysis of spatial rainfall variations in the region aims at delineating the southern African region into dry and humid sub-regions using different rainfall indices derived from daily rainfall. Characteristic daily rainfall intensities of the two sub-regions are then related to overall seasonal and annual rainfall amounts and number of rainfall events. Interannual variability analysis is used to investigate the temporal evolution of indices of rainfall amounts and number of rainfall events. Hence this broad sub-objective specifically involves

- Defining appropriate seasons for the entire southern African region and establishing time series of overall rainfall amounts and number of rainfall events at monthly, seasonal and annual timescales at each rainfall station.
- Establishing limits that appropriately define classes of daily rainfall intensities. Time series of monthly, seasonal and annual rainfall amounts and number of rainfall events in each of the defined classes are then established at each rainfall station.
- Spatial investigation of rainfall seasonality in southern Africa using monthly rainfall amounts and number of rainfall events in each of the established classes as well as using overall rainfall amounts and number of rainfall events.
- Establishing appropriate definition(s) of the start and end of the rainy seasons in southern Africa. Using the established definition(s), time series of the onset, end and duration of the rainy seasons and of the amounts of rainfall received during the rainy seasons are established at each station.
- Investigating temporal evolution of the established rainfall indices at annual and seasonal timescales. This is done using both standardized rainfall anomalies and statistical change-point and linear trend analyses.

2.3.2 Sub-objective 2: Variability analysis of flow indices

This objective fundamentally aims at investigating seasonal and interannual streamflow variations in southern Africa and their relationships to rainfall variations. This involves:

- Investigation of seasonal characteristics of river flows in southern Africa. The emphasis is on mean monthly flows, maximum flows and minimum flows and on the identification of months of high and low flows.
- Establishment of time series of mean, maximum and minimum flows at monthly, seasonal and annual timescales.
- Defining threshold flows that approximately distinguish flood and drought flows from normal flows. Using the defined thresholds, time series of monthly, seasonal and annual excess and deficit flow volumes and frequencies are established.
- Investigating the temporal evolution of the established flow indices at monthly and seasonal timescales. This is done statistically using change-point and linear trend analyses.

- Investigating interrelationships between monthly and seasonal flow indices and catchment areal average rainfall indices. This is performed only for selected catchments.

2.3.3 Sub-objective 3: Linking interannual rainfall and flow variations to climatic variations

This sub-objective intends to broadly investigate the influences of interannual variations of climatic variables on interannual variations of rainfall amounts and number of rainfall events and of river flows. The influences of climatic variables on river flows are inferred from rainfall-flow relationships. The relationships between climatic variables (southern oscillation index (SOI), sea surface temperatures (SST) and atmospheric fields (winds and geopotential heights)) and southern African seasonal rainfall as well as classified seasonal amounts and number of rainfall events are statistically explored and no numerical model experiments are performed. More specifically, this sub-objective concerns:

- Identification of key oceanic basins in the Atlantic and Indian oceans in which interannual variability of their SST affects significantly interannual variability of rainfall in southern Africa.
- Investigation of the relationships between interannual variability of areal average SST indices in these key oceanic regions and interannual variability of rainfall amounts and number of rainfall events in southern Africa. Overall and classified seasonal rainfall indices are used while both seasonal and monthly SST indices are used.
- Investigation of the relationships between interannual variability of ENSO indices (SOI is used) and seasonal rainfall amounts and number of rainfall events in southern Africa.
- Assessing the dynamic nature of the relationships between overall and classified rainfall amounts and number of rainfall events in southern Africa and climatic variables.

2.4 The study hypotheses

In southern Africa not much has been done with regard to hydrological variability, although devastating floods and prolonged droughts have been observed in the region. Hence the present study hypothesizes that

- There have been significant rainfall decreases in some parts of southern Africa and increases in other parts at all timescales. The rainfall changes are shown by changing characteristics of the rainy seasons, changing number of rainfall events and intensities of daily rainfall as well as changing frequencies and lengths of dry episodes within the rainy seasons.
- Rainfall changes in recent decades are caused by observed changes in climatic variables including warming in the tropical Indian and Pacific Oceans, warming in the Southwest Indian Ocean and changing ENSO characteristics.
- Recent changes in rainfall patterns induce similar changes in the streamflows.

CHAPTER 3

THE SOUTHERN AFRICA SUBCONTINENT

3.1 Introduction

The southern African region lies in the tropics in the southern hemisphere, between latitudes 0° and 35°S and longitudes 13°E and 41°E. The region is surrounded by the Atlantic Ocean (west), Indian Ocean (east), the southern Oceans (south) and continental central and eastern Africa to the north (Fig.3.1). The region comprises the 11 countries; Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe.

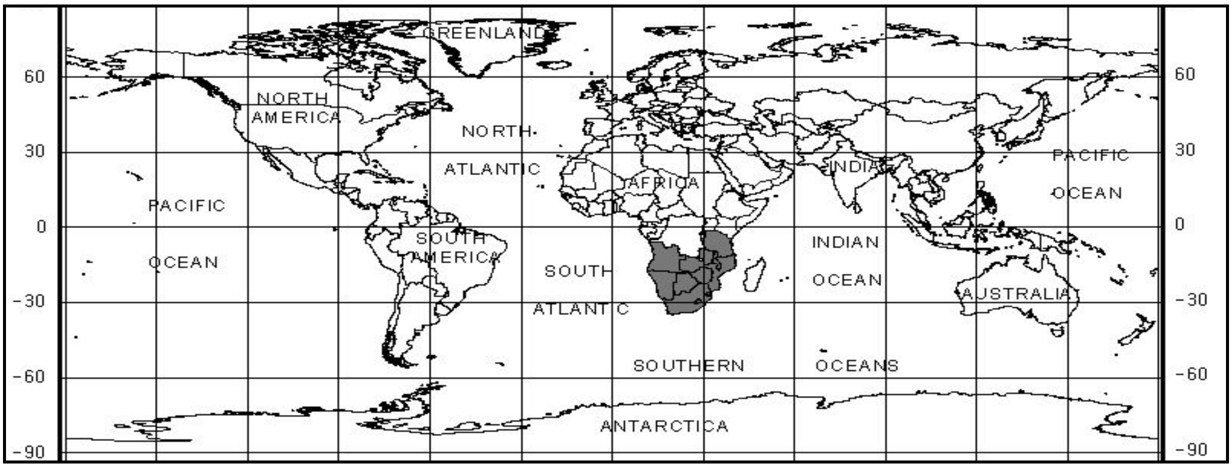

Fig.3.1: Southern Africa subcontinent (shaded region).

The introduction includes a general overview of the wetland systems and the climate of the region with emphasis given to rivers, the river network and rainfall. Factors that affect spatio-temporal variations of rainfall and streamflows and consequently the surface water resources in southern Africa are briefly discussed. They include, among others, topography, soils and aquifer characteristics, vegetation and the influences of the oceans and atmosphere.

3.2 Climate of southern Africa

The equatorial-tropical extent of the southern Africa region and the range of different landforms, including high mountains and large inland lakes, make the regional climate highly variable. The climate of southern Africa varies from arid (tropical dry) to humid tropical and subtropical (Fig.3.2) and can be broadly divided into 7 zones. In a broad sense, the region is dry as indicated by the dominance of tropical dry/wet-dry climates, with characteristic annual rainfall amounts below 1 000 mm. The driest conditions with annual rainfall amounts typically below 500 mm are observed in the deserts of Namib and Kalahari, which occupy most of Botswana and some parts of Angola, Namibia and South Africa.

Different climatic zones are mainly observed in Angola and South Africa. Northern Angola lies on the boundaries of the tropical (Congo) rainforest climate while the southern coast experiences arid conditions. Rainfall is abundant in the north (1 500 mm annual average) and lowest on the southern coast (340 mm), and typically about 50 mm in the Namib Desert.

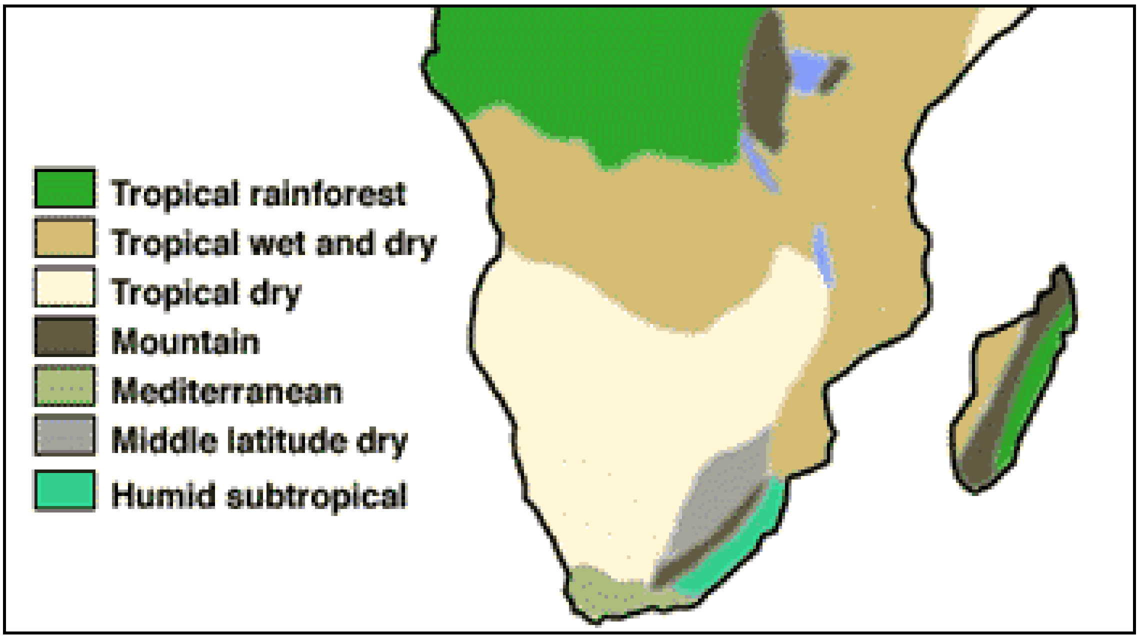

Fig.3.2: Climatic zones of southern Africa (Source: Natural History Museum of Los Angeles County Foundation, 1997).

South Africa experiences 5 different types of climates. Its southern/southwestern part experiences a Mediterranean climate, the northwest part lies within the tropical dry climate, while the east coast has a humid subtropical climate. Areas inland of the east coast (in the Drakensburg Mountains) experience both midlatitude and mountainous climates. A midlatitude climate is considered to be a transition between the humid subtropical climate in the lowveld and the mountainous climate in the higher Drakensburg.

Despite such diverse climatic zones, rainfall in southern Africa is mainly observed during the austral summer between October and May. Rainfall in May is observed in northern Tanzania. Southwest South Africa (Western Cape Province) receives most of its annual rainfall during the austral winter (May – September). There are areas such as western Lake Victoria and the Usambara Mountains in Tanzania and the southern coast of South Africa which receive rainfall throughout the year, although the rainfall amounts and characteristics during the main wet seasons and the intermediate season are significantly different.

3.3 Geology, topography and soils

3.3.1 Geology and geological background

The continent of Africa is made up of a very old and vast stable crystalline rock basement, mainly of Precambrian age. Superimposed on this basement are later, largely flat-lying cover successions; along the east, north and west coasts there are sediments of Mesozoic and Tertiary age, deposited in marginal marine basins.

The Precambrian basement can be divided into three large masses (cratons), the Kalahari, Congo, and West African cratons. They are separated from each other by a number of mobile belts active in late Precambrian and early Palaeozoic times.

A number of well-defined mobile belts became established in the continent in late Precambrian times. They are the two well-defined Mozambique and Katanga belts and two other less well-defined belts running through the Cape Province and along the west Zaire (Democratic Republic of Congo, DRC) coast. The Mozambique belt stretches north-south along the eastern side of the continent from Egypt to Mozambique whereas the Katanga belt runs east-west between the Congo and Kalahari cratons. At this late Precambrian-early Palaeozoic time Africa was joined to the other southern continents as part of the super-continent of Gondwanaland. Evidence of these late Precambrian belts is found in the other continents.

Towards the end of the glaciation time (Upper Palaeozoic), new basins of deposition were initiated within the continent and on its margins. This phase began with a widespread glaciation in Permo-Carboniferous times. Huge thicknesses of glacial deposits (tillites, varved clays, and sandstones) were laid down. The Dykwa glacial sequence of the Karroo basin is 800-900 m thick, suggesting a lengthy glaciation. The Cape fold belt in the southwest of Africa was another feature of Palaeozoic times.

Sedimentation in the continental Karroo basin continued without interruption through Permian, Triassic, and Jurassic times. The Permian glacial deposits were closely followed by the deposition of coal measures, followed in turn by shales, sandstones, and finally the Karroo basalts. Large volumes of plateau basalts, up to 1 000 m thick, poured out in late Triassic and Jurassic times, marking the beginning of the splitting up of the Gondwanaland continent.

During the initial phases of continental disruption in late Jurassic and early Cretaceous times, narrow marine troughs developed at the sites of the future continental margins, and faulting and flexing in the basement brought about the formation of the east African rift system. This system came into existence in its southern part in the late Mesozoic, and was associated with voluminous igneous activity. It is part of a 5 000 km fracture zone extending from the Limpopo valley in the south to the Jordan valley in the north. At the same time, basic and alkaline igneous activity was widespread with further extensive igneous activities in the Tertiary to recent volcanics of the northern part of the rift. Fault movement forming the rift valley took place mainly in Miocene and Pleistocene times, and the area is still marked by seismic activity, volcanism, and high heat flow through the crust. Since mid-Cretaceous times, the continents began to move apart. This movement is believed to have displaced Africa by about 15-18^{o}N north to its present position.

In general, the topograhy, aquifer systems and soils in southern Africa correspond to these past geological activities. There are 6 major aquifer systems in the region (Fig.3.3), namely Fold system, Precambrian crystalline ridges system, Central African/Sahara Sedimentary system, Coastal Sedimentary system, Infra-Cambrian and Paleozoic cover and Volcanic effusions.

The Precambrian crystalline ridges system is the largest, extending from Tanzania to northeast South Africa. It covers most of Tanzania and Zimbabwe, the whole of Malawi, northern central Mozambique and northern South Africa. Precambrian crystalline ridges also occupy most of Angola and northwest and southeast parts of Namibia.

The Central Africa/Sahara Sedimentary system occupies almost the whole of Botswana, the eastern half of Angola, northeast Namibia, southwest Zambia and central South Africa (highveld). The Coastal Sedimentary system covers much of Mozambique while the fold system extends along the whole South African coastline. The Infra-Cambrian/Paleozoic cover is observed usually between the Precambrian and Sedimentary systems.

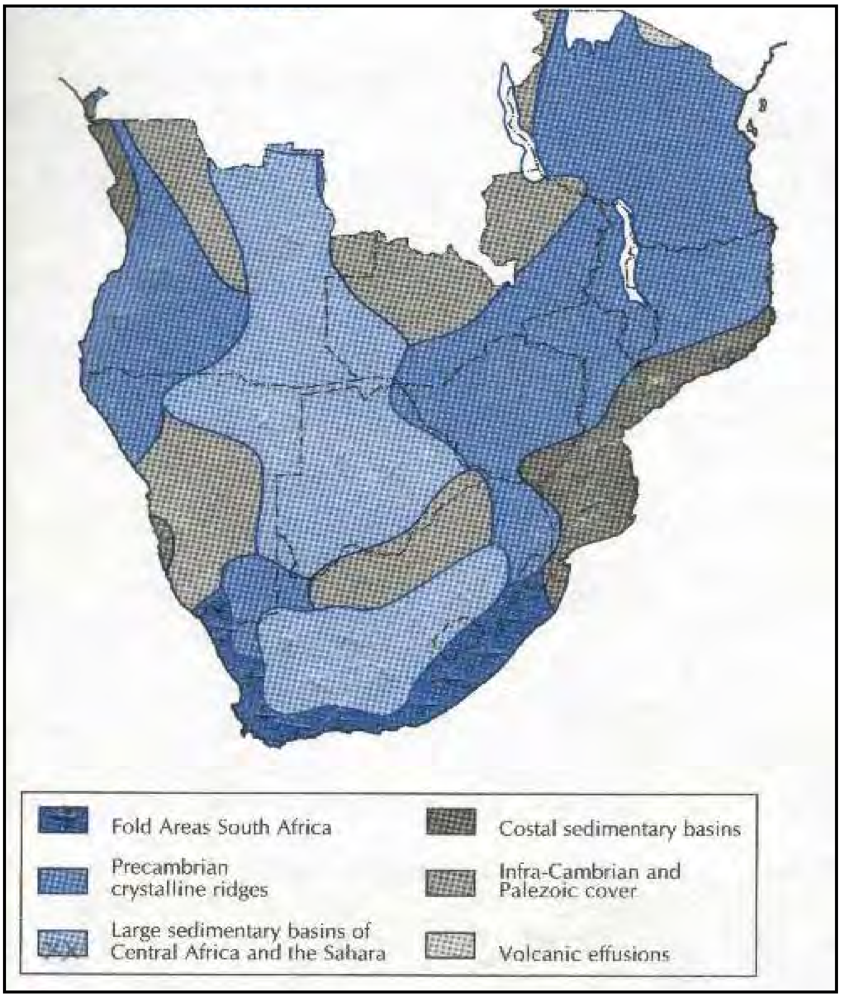

Fig.3.3: Major aquifer systems of southern Africa (Source: Chenje and Johnson, 1996).

3.3.2 Topography

There are three basic landforms in southern Africa, the low-altitude coastal plain; the mountain systems and the elevated interior (or central) plateau. The low-altitude coastal plain is wider in central and southern Mozambique than elsewhere (Fig.3.4). The mountain systems in southern Africa can be divided, according to their location in the region, into eastern and western mountain systems. The eastern mountains of southern Africa are part of the east coast mountain system of Africa, extending between Ethiopia in the north and South Africa in the south (Fig.3.4). The southern part of the east coast system is divided into

- The southern section, containing the Drakensberg with its highest peak Thabana Ntlenyana (3482 m), the Randberg with Stritzkop (2286 m) and the Neuveld with

Compass Berg (2440 m). Also there are the Manicaland (Eastern) Mountains in Zimbabwe with their highest peak Inyangani (2593 m) and the Sapitwa peak (3002 m) in southern Malawi in the Mulanje Mountains.

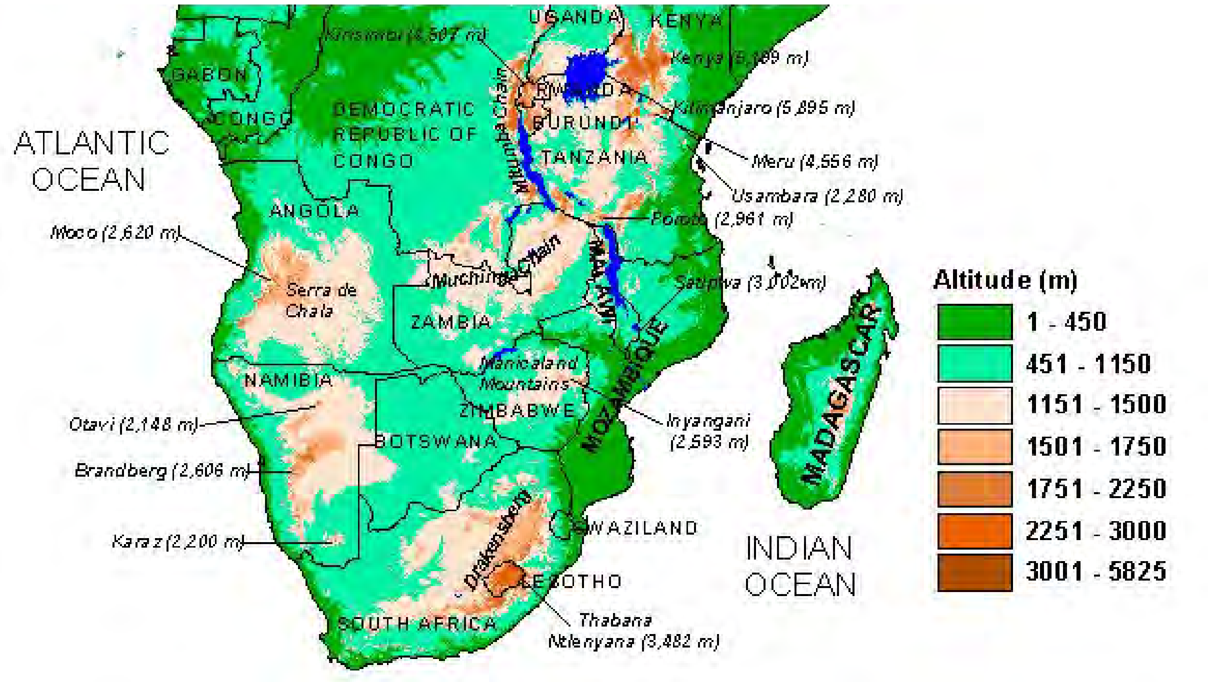

Fig.3.4: Major topographical features and lakes in southern Africa.

- The section between the Zambezi and Ethiopia, containing the highest peaks in Africa. Kilimanjaro (5895 m) and Mount Kenya (5199 m) are extinct volcanic peaks while Mount Meru (4556 m), west of Mount Kilimanjaro, is a non-volcanic peak. The highest peak of the Usambara Mountains located southeast of Mount Kilimanjaro and near the Indian Ocean coast is 2280 m.

  Central Tanzania is characterized by hilly ground of which the Sekenke hills are a part. To the south, there are the southern highlands of Tanzania with their highest peak Poroto (2961 m) and the Muchinga chain occupying most of northeast Zambia. The Mitumba chain, situated on the western border of Tanzania, extends from northwest Zambia to northwest Uganda (Fig.3.4). Its highest peaks are Kirisimbi (4507 m) in Rwanda, the Ruwenzori Range or 'Mountains of the Moon' (4880 m) situated between Lake Mobutu and Lake Edward and Mount Mfumbiro (3355 m) situated between Lake Mobutu and Lake Victoria.

Two main mountain ranges are found on the western mountain system of the southern Africa sub-continent. They are the Namib Desert chain in central Namibia with its highest peak the Brandberg (2606 m) and the central Mountains occupying most of central and southern Angola, with Môco (2620 m) the highest peak.

The interior plateau of southern Africa, situated to the west of the eastern mountains, is part of the elevated central and southern African plateau. It lies, on average, between 900 m and 1500 m above mean sea level. It is said to have resulted from uplift of the central plateau in the late Miocene (10 million years BP).

3.3.3 Soils

Soils originate from weathered rocks. They derive most of their characteristics from their parent rock materials. According to FAO's soil descriptions and the soil map of Africa[1], the southern African region is dominated by 4 types of soils, sandy soils, soils with clay increasing at depth (Luvisols, Nitisols, Planosols), soils with low nutrient holding capacity (Ferralsols and Acrisols) and shallow stony soils (Lithosols, Leptosols, Xerosols, Yermosols) (Fig.3.5). Further, Cambisols and Gleysols/Histosols cover considerable areas of Tanzania and Angola respectively.

Sandy soils occupy much of the interior western part of southern Africa. They are a characteristic of deserts and tropical dry climates. They cover about two thirds of Angola and Botswana and are found in northeast Namibia as well, the southern half of Mozambique, northwest South Africa and some parts of western Zambia and Zimbabwe. They are wind/water deposits in deserts or residues of weathering of quartz-rich rocks in tropical and subtropical regions. Sandy soils are very permeable with low water holding capacity within the root zone and low fertility.

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[1] FAO soil map of Africa. Available online in September, 2003 at http://www.devecol.org/DevHelp/Soil%20Group%20Descriptions.htm

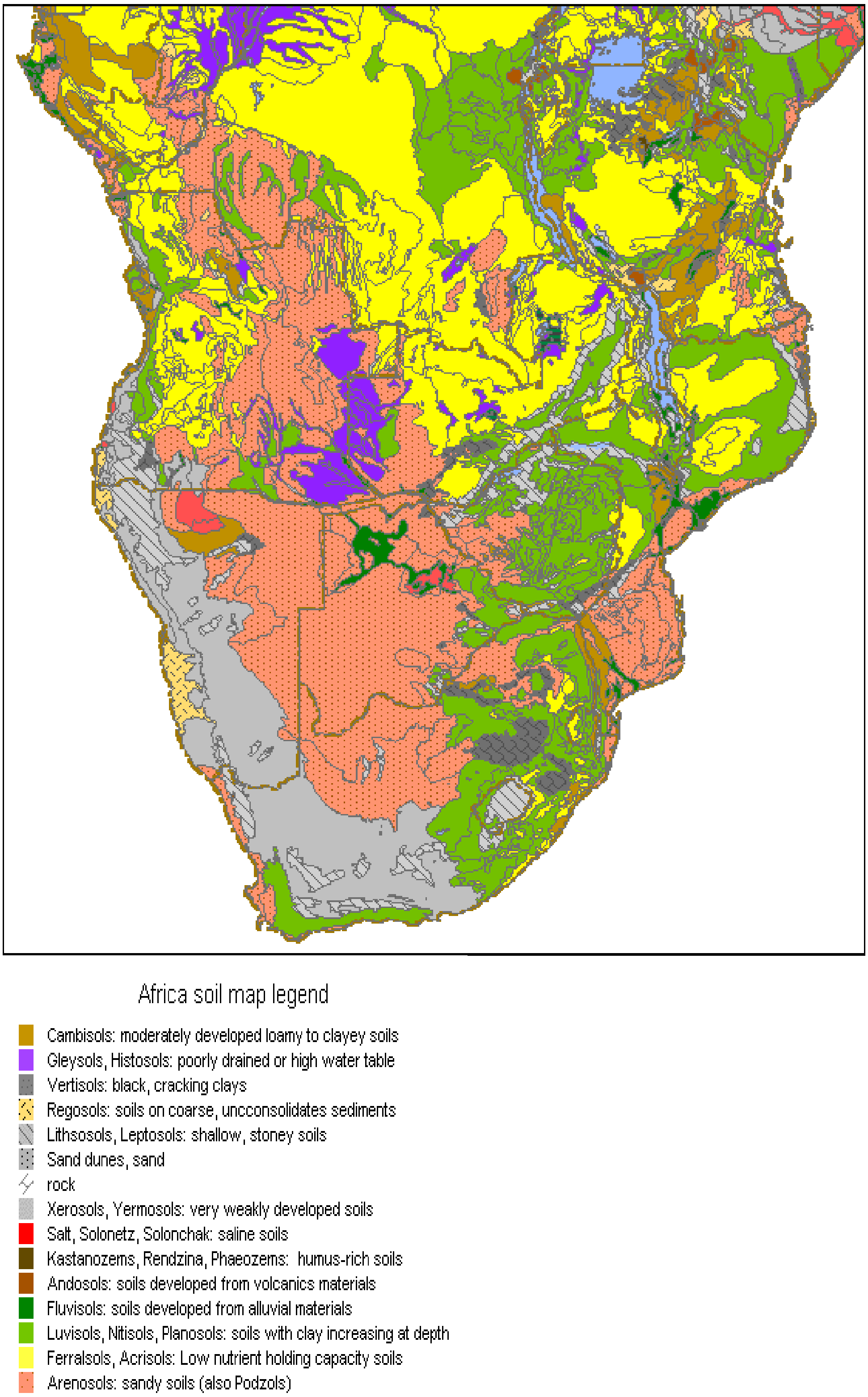

Fig.3.5: Major soils of southern Africa. (Data Source: FAO; Prepared by Development Ecology Information Services, DEVECOL (USA)).

Soils with clay increasing at depth occupy considerable areas of the eastern part of southern Africa. Of their three types, Luvisols and Nitisols are most suitable for agriculture since they have generally better chemical properties, relatively high nutrient content, moderate to high water storage capacity and are well drained. Planosols found mainly in South Africa, however, are constrained by several deficiencies such as the low structural stability of the surface horizon, compactness of the subsoils and seasonal waterlogging properties, that make them difficult to improve.

The third dominant type, soils with low nutrient holding capacity, is mainly found in northern Zambia and the central plateau of Tanzania and in some parts of southern Tanzania and northern Mozambique. The soils are strongly weathered, dominated by Kaolinite clays and a certain residual accumulation of iron and aluminium oxide and hydroxide. They are poor soils chemically, with a low ion exchange capacity, and nutrient reserves that are easily disrupted by agricultural practices, while inactivation of phosphorus is a major problem. The content of available aluminium may reach toxic levels, as may manganese. On the other hand, the physical characteristics of these soils are quite favourable; because of their great depth, high permeability and stable microstructure they are less prone to erosion. Acrisols, which are part of these soils, however, are highly erodible which limits their agricultural potential.

Shallow stony soils are characteristic of high and middle mountain areas with unstable rocky slopes and outcrops of bedrock. The soils occupy much of Lesotho and are found in some parts of the Muchinga Mountains in eastern Zambia and in northwest Namibia as well. Constant soil erosion by wind and water and unfavourable climatic conditions limit their formation and usually layers of less than 300 mm of these soils are found above hard rocks. The limited soil volume makes them subject to drought, waterlogging and rapid run-off and consequently most of Lesotho rivers experience long periods of very low flows or no flows after the rainy season (Sene *et al.*, 1998). Hence, the soils are less suitable for agricultural activities.

Cambisols (moderately developed loamy to clayey soils) are found mainly in the southern highlands of Tanzania and in the eastern lake Victoria are but also in limited areas of lower Zambezi and Limpopo (Fig.3.5). They are characterized by slight or moderate weathering of the parent material and by an absence of appreciable quantities of accumulated clay, organic matter, aluminium or iron compounds. Cambisols develop on medium and fine textured materials derived from a wide range of rocks. The soils have widely varying properties but they generally have good structural stability, high porosity, good water holding capacity, good internal drainage, moderate to high natural fertility and an active soil fauna making them suitable for agricultural activities.

3.4 Vegetation

The natural vegetation of a region is determined primarily by the climate and type of soils. Soil characteristics (Fig.3.5) and the varying climate in southern Africa (Fig.3.2) result in 6 major types of vegetation in the region (Chenje and Johnson, 1996). Except in South Africa, the rest of the region is dominated by Savanna and Desert scrub vegetation with mountainous vegetation found in western and a limited part of central Tanzania. In South Africa, the Mediterranean type, the desert scrubs and the mid-latitude broadleaf vegetation cover the majority of the country.

Dense tropical rainforests are situated west of Tanzania, in central and part of West African Gulf of Guinea countries. The forests are composed principally of closely growing, broadleaved tall and straight trees, typically exceeding 30 m height though a few shorter trees (about 7.5-15 m) are still found in these forests (Butler, unpublished manuscript). They are shallow rooted trees reflecting the abundance of water in the forest areas.

Savanna is an area of tropical wooded grassland characteristic of the drier regions of tropical wet and dry climates. The widely scattered short, flat-topped trees are mixed with tall grasses to make Savanna a transition between forests and open grasslands. On the other hand, tropical deciduous trees and scrub are found in the wet regions of the tropical wet and dry climate. Trees are tall (~ 26 m) and usually do not grow close together. In areas where rainfall is not that abundant, scrubs, which adapt to dry climates, replace the deciduous forests. Spacing of trees allows light penetration onto the floor encouraging bushes to grow. Short plants that grow sufficiently far apart characterize desert scrub vegetation, typically observed in the desert climates in western part of southern Africa.

3.5 Wetlands of southern Africa

3.5.1 Wetland systems

Wetlands are broadly defined as areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support a prevalence of vegetation typically adapted for life in saturated soil conditions[2]. Or in simple terms, wetlands are areas containing much soil water due to the presence of water at or near the soil surface. The natural

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[2] Definition of wetlands as used by the U.S. Army Corps of Engineers (Corps) and the U.S. Environmental Protection Agency (EPA).

Resources Conservation Services (NRCS) of the United States Department of Agriculture (USDA) defines wetlands as areas inundated for 7 days or saturated for 14 days during the growing season at least once every 2 years. Inundated and saturated mean respectively standing water on the surface and a wet surface sustained by capillary action in the soils.

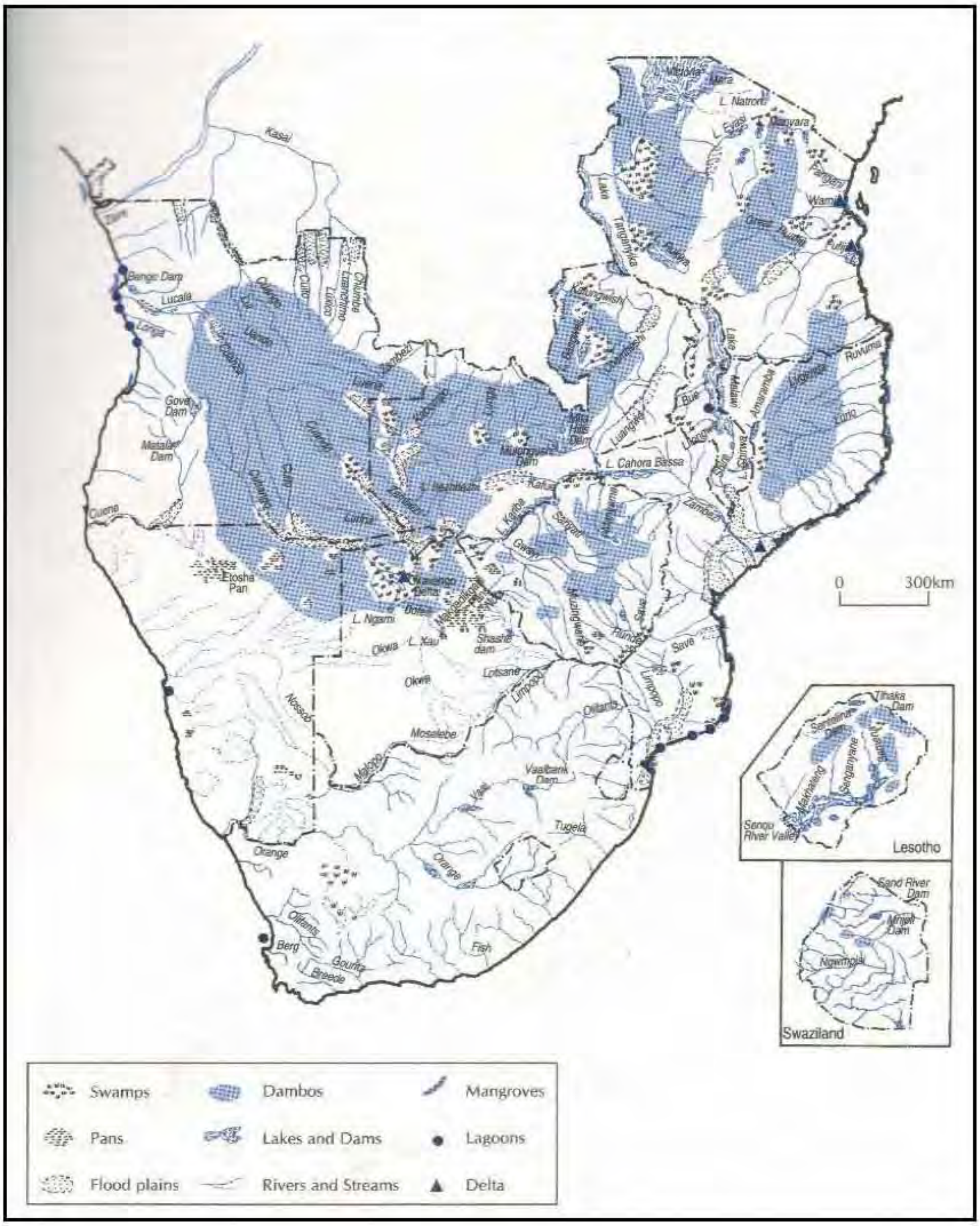

Fig.3.6: Wetlands and main rivers in southern Africa (Source: Chenje and Johnson, 1996).

Wetlands are often characterized by hydric soils and hydrophytes. Hydric soils have characteristics that are unsuitable for the growth of most plants except hydrophytes such as marsh grasses. It should be noted however that the presence of water by flooding, ponding or soil saturation does not necessarily constitute a wetland. Further, wetlands fluctuate seasonally due to their determining variables such as rainfall, groundwater, etc.

From the definition of wetlands and their characteristics, 5 different wetland systems are distinguished in southern Africa (Chenje and Johnson, 1996). These are palustrine, riverine, lacustrine, estuarine and marine systems.

Palustrine include generally all vegetated wetlands from marshes to springs. Other forms of vegetated wetlands are lagoons, ponds, pans, swamps and dambos. A dambo is a spongy-like land area that stores substantial amounts of water during wet seasons and releases it gradually during the dry season. Dambos occupy large parts of Angola, western Zambia, western Tanzania, the eastern mountains of Tanzania and northern Mozambique (Fig.3.6).

Estuarine wetlands are found near river mouths and are characterized by mixed-origin volumes of water. This type of wetland system is found along the coastline of southern Africa. The Rufiji (Tanzania) and Zambezi (Mozambique) are estuarine wetlands, found at the mouths of the Rufiji and Zambezi rivers along the Indian Ocean, and the Orange (western South Africa) and Cuanza (Angola) estuarine wetlands along the Atlantic Ocean are the major estuarine systems in southern Africa.

Lacustrine wetlands are lakes found in depressions or dammed river channels. They are either natural (e.g. Lakes Victoria, Tanganyika, Malawi, Rukwa, Liambezi, Mweru, etc) or manmade lakes (e.g. Kariba, Cabora Bassa, Nyumba ya Mungu). Most of these lakes are perennial although lakes like Liambezi and Ngami (Botswana) are seasonal.

Riverine systems are the largest wetland systems in southern Africa occupying about 110 000 km^2 (Chenje and Johnson, 1996). They comprise mainly rivers, floodplains and riverine swamps. Large rivers are often perennial while small rivers may either be perennial or ephemeral depending on their sources. Flood plains exist in areas surrounding lakes and areas alongside rivers while riverine swamps develop in still water around the lakes.

3.5.2 Rivers and the river networks

Most of the rivers in southern Africa forming the riverine system originate from the mountains and highlands and either drain directly into the oceans or into inland depressions. Most of southern African rivers join into large networks within the large river basins before discharging their waters. There are 20 major river networks (basins) in southern Africa and their main channels drain either into the Indian Ocean, Atlantic Ocean or inland depressions such as the Etosha pan (Namibia) and the Okavango delta (Botswana). Among these 20 river basins, 15 are shared by two or more southern African states (Table 3.1, Fig.3.7). A number of rivers in Angola, Namibia, South Africa and Mozambique drain directly into the Atlantic or Indian oceans.

The Congo River basin is the largest in southern Africa. Its largest portion (62%) falls within the Democratic Republic of Congo (DRC) and other southern Africa states share 17% of the total basin area. The basin has been recently included into southern Africa and is not considered in the present study as sufficient data are not available for DRC.

Apart from the largest Nile River, which has only 5% of its total area within southern Africa, the Zambezi River with its headwaters in northwest Angola and Zambia is the longest in southern Africa draining 8 countries (Table 3.1) before discharging its water into the Indian Ocean in Mozambique.

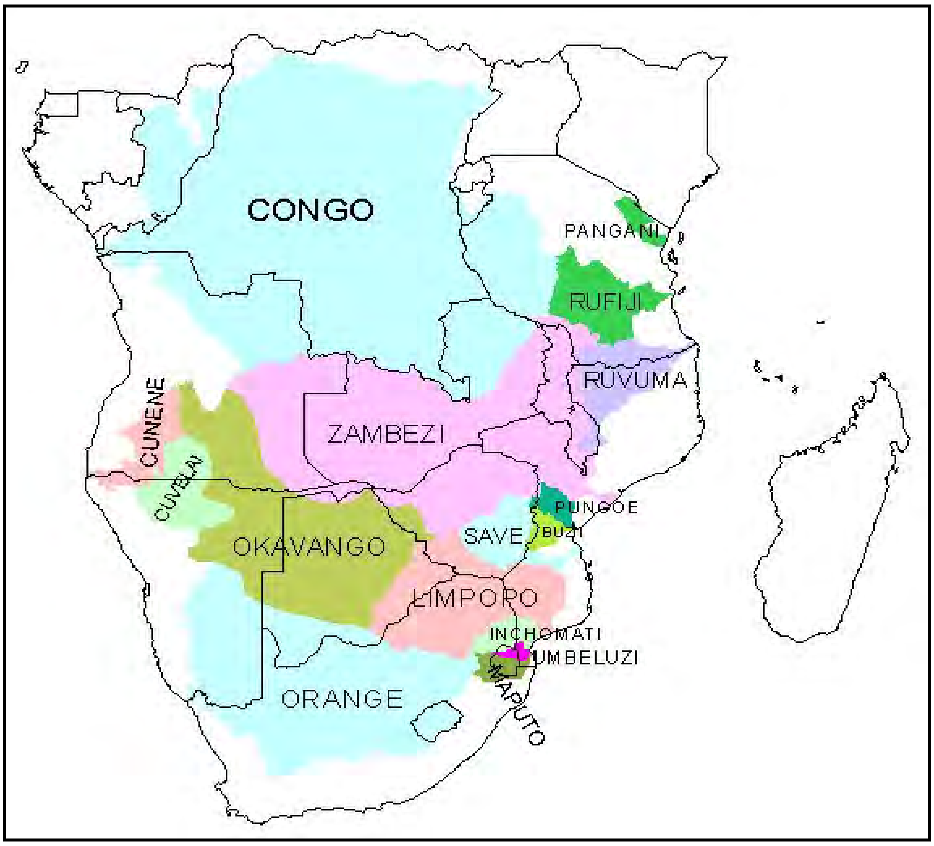

Fig.3.7: Shared (international) river basins in southern Africa. The Pangani and Rufiji non-shared basins are included due to their importance in Tanzania.

Table 3.1: Country areas within the shared (international) river basins in southern Africa (Source: Environmental Sustainability in Water Resources Management, 2000).

Shared river basin	Basin area in SADC (Sq. km)	River length (km)	SADC state	Basin area within the country (Sq. km)
Congo	2,942,700 of 3,699,100 total basin areas		Democratic Rep. of Congo	2 307 800
		4700	Angola	291 500
			Zambia	176 600
			Tanzania	166 800
Zambezi	1,388,200	2,650	Zambia	577 900
			Angola	256 500
			Zimbabwe	215 800
			Mozambique	163 800
			Malawi	110 700
			Tanzania	27 300
			Botswana	19 100
			Namibia	17 100
Orange	947,700	2,300	South Africa	565 600
			Namibia	240 600
			Botswana	121 600
			Lesotho	19 900
Okavango/Cubango	708,600	1,100	Botswana	359 000
			Namibia	176 800
			Angola	150 100
			Zimbabwe	22 700
Limpopo	415,500	1,750	South Africa	184 100
			Mozambique	87 300
			Botswana	81 500
			Zimbabwe	62 600
Etosha-Cuvelai	167,600	430	Namibia	114 370
			Angola	53 230
Ruvuma	152,200	800	Mozambique	99 530
			Tanzania	52 200
			Malawi	470
Nile	142,000 of 3,038,100 total basin area	6,700	Tanzania	120 300
			Democratic Rep. of Congo	21 700
Sabi/Save	116,100	740	Zimbabwe	85 780
			Mozambique	30 320
Cunene	110,300	1,050	Angola	95 500
			Namibia	14 800
Inchomati	46,200	480	South Africa	29 200
			Mozambique	14 300
			Swaziland	2 700
Pungoe	32,500	300	Mozambique	31 050
			Zimbabwe	1 450
Maputo	31,300	380	South Africa	18 600
			Swaziland	11 000
			Mozambique	1 700
Buzi	27,900	250	Mozambique	24 780
			Zimbabwe	3 120
Umbeluzi	5,400	200	Swaziland	3 100
			Mozambique	2 300

The Orange River basin is the third largest in the region draining the four countries of South Africa, Lesotho, Namibia and Botswana. Its headwaters are in the Drakensburg Mountain chain and it drains into the Atlantic Ocean along the Namibia/South Africa border. The Okavango/Cubango basin ranks fourth with an inland drainage into the Okavango delta (Fig.3.7). The Limpopo river basin is the 5th largest and drains water from the upstream states of South Africa, Botswana and Zimbabwe and Mozambique downstream before discharging into the Indian Ocean. Other rivers and river basins are small compared to these 5 basins.

3.6 Factors affecting spatio-temporal variations of rainfall and streamflows

3.6.1 Factors affecting rainfall variations

3.6.1.1 SST distribution and the role of the ocean currents

The Atlantic and Indian oceans, being the major sources of moisture in southern Africa, play a major role in determining the spatio-temporal variations of rainfall in the region. The other source of moisture is the Congo basin. Conditions in the Pacific Ocean have also been linked to climatic fluctuations in southern African.

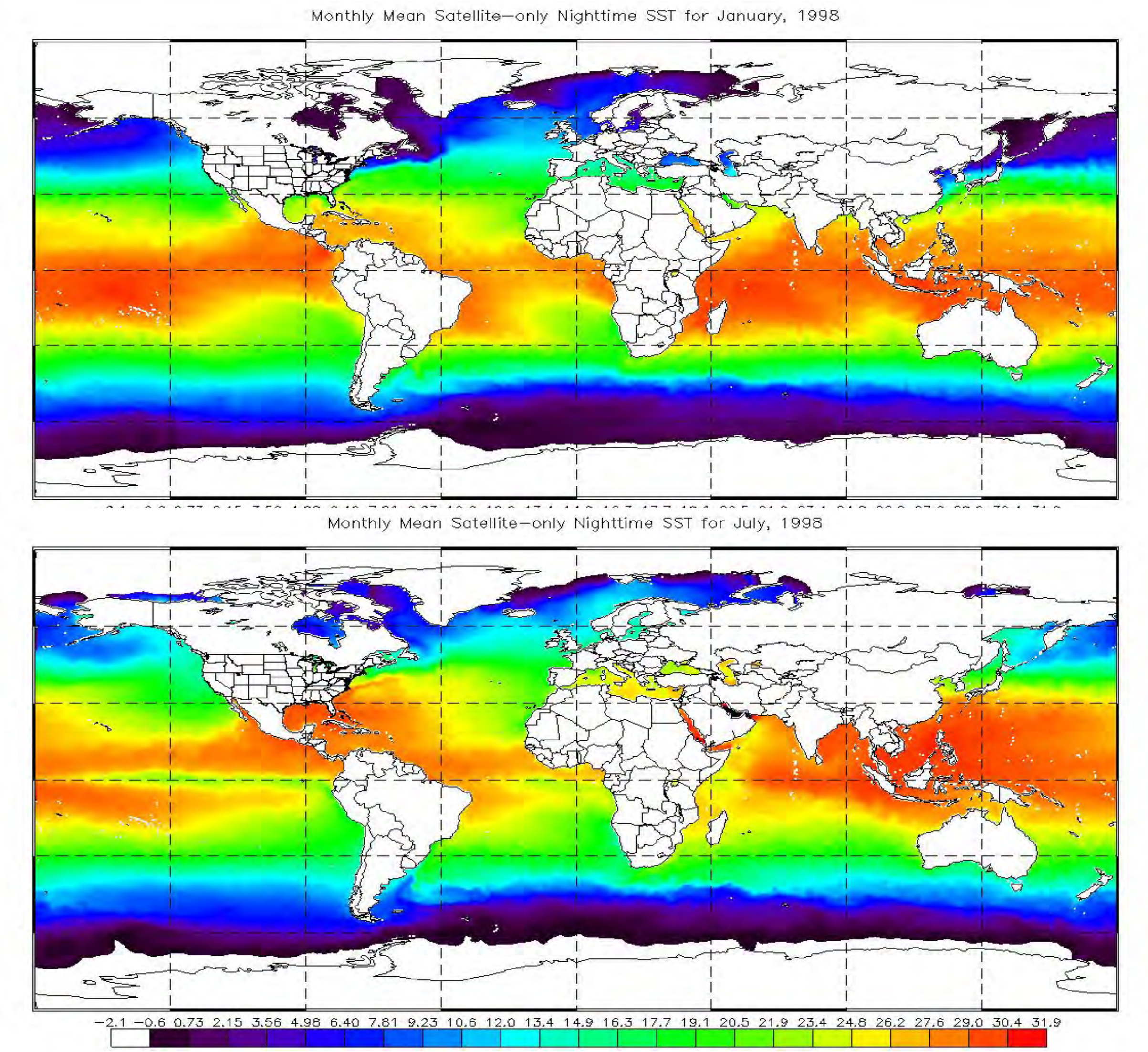

Fig.3.8: January and July 1998 global SST[3].

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[3] Source: NOAA Satellites and Information, National Environmental Satellite, Data and Information Service, Office of Satellite Data Processing and Distribution. Available online in August 2004 at http://www.osdpd.noaa.gov/PSB/EPS/SST/al_climo_mon.html

Southern Africa and the surrounding oceanic basins are characterized by equator-extratropical temperature gradients due to differential solar heating between the equator and the midlatitudes. The highest solar energy is received along the equator throughout the year. Periodic movement of the sun between the equator and the tropics means each of the tropics experiences a period of highest temperatures only once each year.

Constantly high SST in the equatorial Atlantic and tropical Indian Oceans (Fig.3.8) are an important factor for evaporation of seawater, the process that adds moisture into the atmosphere. The SST gradients between the tropical and midlatitude ocean basins drive the ocean currents, which then act to distribute heat energies within and between the different oceans. The ocean currents are either wind-driven surface currents or density-driven deep currents (thermohaline/thermocline currents, Fig.3.9b).

Thermocline currents are made of near-surface warm currents and deeper cold currents. A thermocline’s near-surface seawater begins its descent into the ocean in the North Atlantic. High levels of evaporation, which cools and increases the salinity of the seawater, cause the downwelling. This seawater then moves south along the coast of North and South America until it reaches Antarctica. At Antarctica, the cold and dense seawater then travels eastward. During this part of its voyage the flow splits off into two currents that move northward. In the North Pacific (off the coast of Asia) and in the Indian Ocean (off the coast of Africa), these two currents move from the ocean floor to its surface creating upwelling. The flow then becomes near-surface moving back to the starting point in the North Atlantic. These currents are equivalently referred to as thermohaline currents and their one complete circuit is estimated to take about 1 000 years.

The pattern of surface ocean currents (Fig.3.9a) is a reflection of a combination of surface wind patterns and Ekman transport[4]. Usually wind-driven motion ceases at ocean layers below 100 m. The major surface ocean currents systems influencing southern Africa climate are the cold Benguela/warm Angola system in the South Atlantic Ocean along the western coast and the Agulhas system in the Indian Ocean along the eastern coast.

The Warm Angola Current forms the eastern section of a large, cyclonic gyre. It flows southward along the Angolan coast until it joins the northward flowing cold Benguela Current. In the upper layer (0-100 m), it is formed mainly by the southeast branch of the South Equatorial Countercurrent (SEC) and the southward-turning waters from the north branch of the Benguela Current; the influx of waters originating north of the Equator is only

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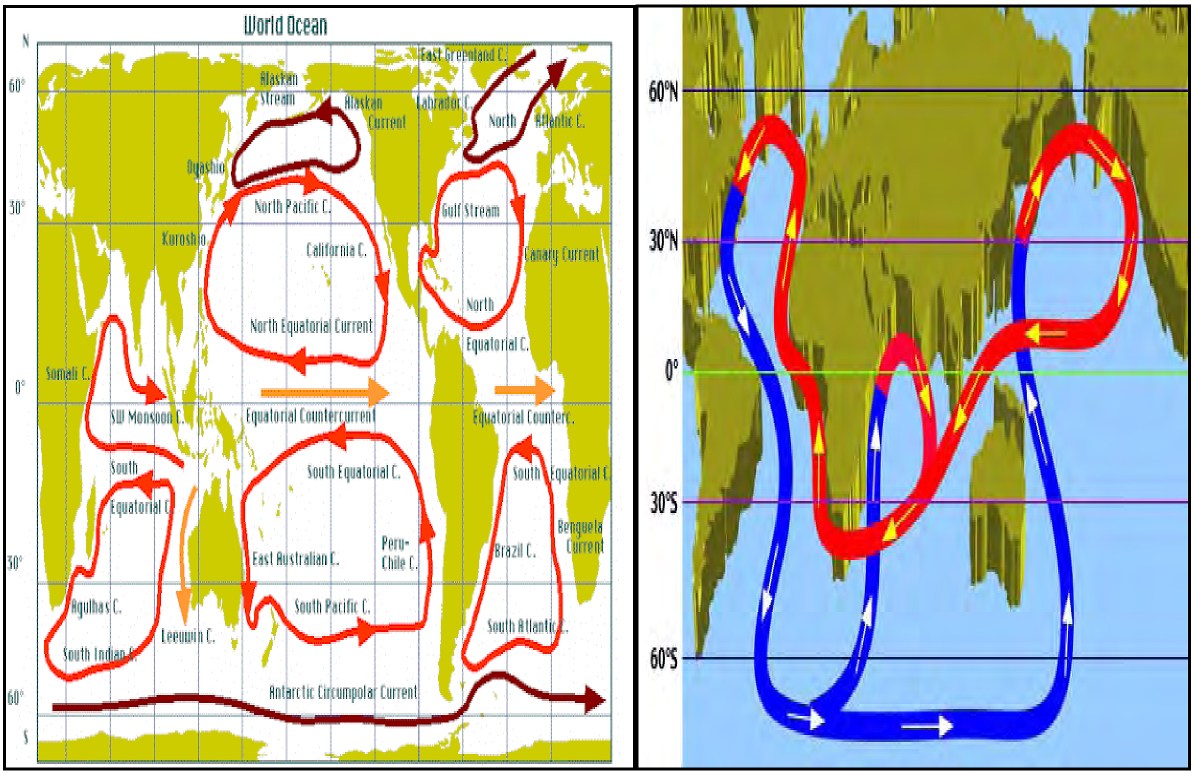
[4] Ekman transport is the net transport of ocean water in all layers of the water column due to winds and is theoretically 90° to the right (left) of the wind direction in the northern (southern) hemisphere.

moderate. However, in deeper layers (> 100 m), northern waters become more important in feeding the Angola Current (Moroshkin *et al.* 1970). The surface water of the current usually has a temperature greater than 24°C with the highest temperatures (27-30°C) observed during the austral summer and in which the surface temperature decreases as it flows southwards.



(a) (b)

Fig.3.9: Major a) surface[5] and b) subsurface (thermocline) ocean currents of the world[6]. Red and blue arrows indicate respectively warm and cold Ocean currents. In b) warm thermocline currents are near-surface currents while cold currents are deep currents.

The Benguela Current is the eastern boundary current of the South Atlantic subtropical gyre (Peterson and Stramma, 1991; Wedepohl *et al.*, 2000). It begins as a northward flow off the Cape of Good Hope, where it skirts the western coast of Africa equatorward until around 24°S-30°S. Here most of it separates from the coast as it bends toward the northwest. However, two branches of the current do continue along the coast, and one of them joins the Angola Current at the Angola-Benguela Front near 14-16°S (Meeuwis and Lutjeharms, 1990; Wedepohl *et al.*, 2000). The location of this northwest-southeast oriented Front has been

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[5] Source: Matthias Tomczak

[6] Source: Michael J. Pidwirny, Department of Geography, Okanagan University College, 2001. Available online in September 2003 at http://www.geog.ouc.bc.ca/physgeog/contents/8q.html

associated with rainfall variations in parts of Angola and Namibia. Its southward displacement corresponds to periodic intrusion of warm tropical surface waters into the northern Benguela enhancing rainfall in Angola and Namibia.

The southwestern part of the Indian Ocean on the eastern coast of southern Africa is dominated largely by the warm Agulhas system. This is the western boundary current of the South Indian Ocean. It flows down the east coast of Africa from 27°S to 40°S (Gordon, 1985). The source water at its northern end is derived from the Mozambique and East Madagascar Currents, but the greatest source of water is recirculation in the southwest Indian Ocean sub-gyre (Gordon, 1985; Stramma and Lutjeharms, 1997). The current extends throughout the water column in March and is only limited to the upper 2300 m in June (Donohue *et al.*, 2000). At the southern tip of Africa, the Agulhas Current flows toward the southwest and it retroflects on reaching the Southern Ocean and flows eastward as the Agulhas Return Current (Quartly and Srokosz, 1993). The Agulhas retroflection region situated around 15°E (the turning point southwest of South Africa in Fig.3.9a) has an average loop diameter of 340 km.

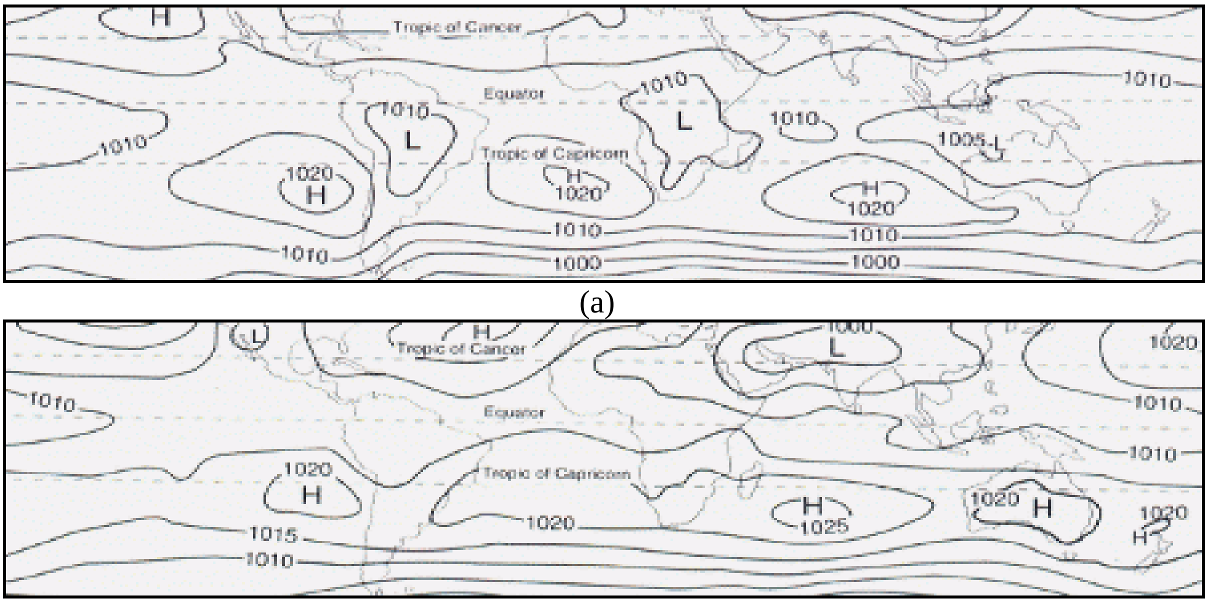
The important features of the ocean currents in relation to climatic variations are i) the large ocean currents gyres in south Atlantic and Indian oceans, ii) the inter-linkage between the surface and thermocline currents and iii) the inter-connection between the South Atlantic and South Indian Ocean basins.

The ocean currents gyres in the South Atlantic and Indian Oceans indicate that, if any part of the South Atlantic or Indian Ocean influences climatic conditions, then the remaining part may or may not have similar influences. Moreover, they provide links between variations in different regions such as between South America and Africa, for example, apart from the influences of factors local to the continents.

The importance of the Agulhas retroflection region is that it is in this region where inter-ocean exchange between the Indian and Atlantic Oceans and the inter-linkage between the surface and thermocline currents take place. An average of 5-6 energetic and saline anticyclonic rings (~ 320 km in diameter), which enclose pools of Indian Ocean water whose temperature is more than 5°C warmer than the temperature of the South Atlantic sea surface at similar latitudes (Gordon, 1985), escape from the unstable Agulhas Current into the South Atlantic Ocean. These rings keep their distinctive thermal characteristics as far west as 5°E and as far south as 46°S. The volume transport into the South Atlantic Ocean per ring is estimated at 0.5-1.5Sv (1Sv is 106 m^3/s) constituting about 7Sv of the 15-25Sv equatorward flow of the main Benguela Current. The properties of the rings (such as their salt content), therefore, mix into the surroundings of the Benguela Current system and they feed into the global upper warm thermohaline (Gordon, 1985) and into the broad SEC thermohaline (Lazar *et al.*, 2001) that provides the largest part of the shallow water of the tropical and equatorial regions (Stramma and England, 1999).

The Inter-ocean exchange of heat and salt, taking place at the Agulhas Retroflection, is thought to be a key link in the maintenance of the global overturning circulation of the ocean. Modeling studies suggest that this Indian-Atlantic inter-ocean exchange is related to wind field structure in the South Indian Ocean basins. The in-phase co-variability of SST between the southwest parts of the Indian and Atlantic Oceans (Fauchereau *et al.*, 2003a) is suggestive of such interconnections between the South Atlantic and South Indian cyclonic ocean currents gyres.

Therefore, while SST and surface ocean currents can significantly influence seasonal to interannual climate variability, SST and climate variability at decadal to centennial time scales is coupled to variations in the ocean's circulation at the global scale, associated thermohaline transport and interactions between surface and subsurface ocean currents.



(a)

(b)

Fig.3.10: Global mean sea level pressures during southern a) summer and b) winter[7].

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[7] Source: John Brandon 2000: Aviation meteorology guide. Available online in September 2003 at http://www.auf.asn.au/meteorology/section4.html

3.6.1.2 SLP distribution and the role of atmospheric circulations

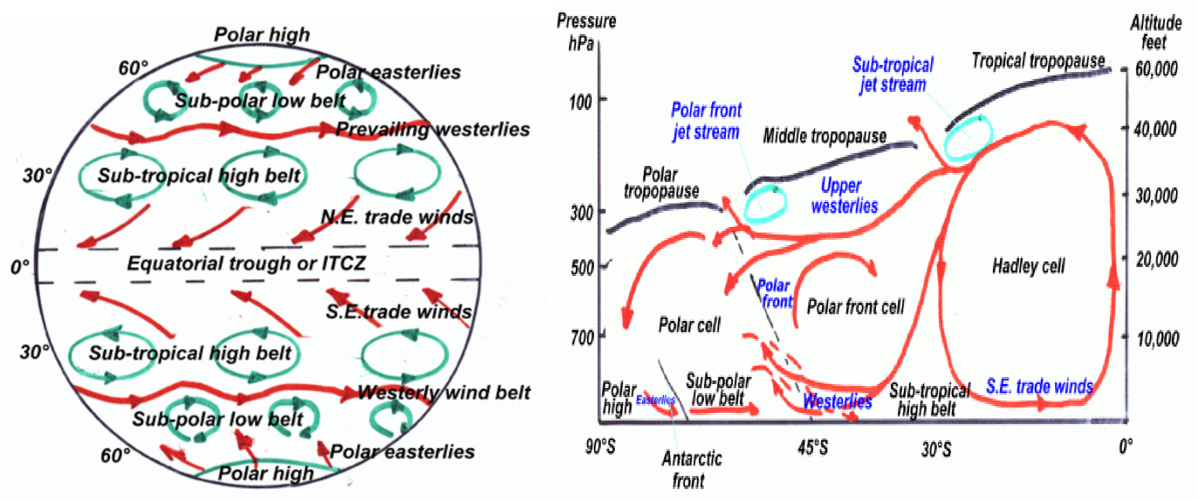
Intense solar heating along the equator means sea surface temperatures (SST) are highest along the equator and decrease poleward (Fig.3.8). High SST along the Equator are an important factor for pressure gradient build-up. Heated air along the equator rises, due to its reduced density and increased water vapour content, leaving space for incoming cool dense air. An increase in volume and temperature causes a reduction in pressure and hence low sea level pressures (SLP) characterize the equatorial region (Fig.3.10). Another region of low pressure is centred approximately on latitudes 60°S and 60°N while zones of high pressure are centred on latitude 30° in each hemisphere.

Periodic movement of the sun between the Equator and the tropics is accompanied by a similar seasonal poleward displacement of the zone of highest SST, seasonal changes in the SLP distribution (Fig.3.10) and consequently seasonal movement of the low-pressure trough, the inter-tropical convergence zone (ITCZ) between 15°N (17°N) and 15°S. Southward displacement of the ITCZ brings rainfall into southern Africa (Nicholson, 1986a; Janowiak, 1988). Rainfall lags the movement of the ITCZ by a month (Mutua, 1999; Nicholson, 2000).

The pattern of SLP distribution influences the general atmospheric wind circulations, which are responsible for moisture distribution and enhancement of further evaporation. The atmospheric circulation between the equator and 60° of latitude of each hemisphere are simply represented by Hadley and Ferrel (Polar front) cells (Fig.3.11b). Hadley cells exist between the equator and 30° while Ferrel cells exist between 30° and 60° in each hemisphere. One Hadley cell (Fig.3.11b) explains the expansion and convergence of air along the equator, its poleward displacement accompanied by cooling which on reaching 30° becomes denser and sinks. This cold surface trade wind moves equatorward to fill the space left by ascending warm air (Fig.3.11a). A Ferrel cell is similar to a Hadley cell with convergence at 60° and divergence at 30°. Surface winds (westerlies) are therefore moving towards latitude 60° while upper air moves towards latitude 30° (Fig.3.11b). Polar winds (between 60° and the poles) are essentially easterlies and move towards the equator.

Most of southern Africa is influenced by the southern hemisphere Hadley cell (Fig.3.11b) and lies within boundaries of the monsoon region defined by Ramage (1971) and Hastenrath (1985). Southern South Africa falls into the southern Ferrel cell. Southeasterly trades blowing from the Indian Ocean during the southern summer bring rainfall to tropical southern Africa. Due to intense solar heating, the land is warmer than the adjacent Indian Ocean creating low pressure and convergence over continental southern Africa and high pressure and divergence over the oceans. Consequently, warm moist air moves from the

Southwest Indian Ocean into southern Africa. The opposite occurs during the southern winter. The Indian Ocean, being warmer than the land, experiences lower pressure and hence warm air convergence in the ocean and cold air sinks in continental southern Africa creating dry conditions. Two exceptions are noted with respect to this general atmospheric circulation-rainfall relationship over southern Africa. The case of southern South Africa and the northern Mozambique/Tanzania region.



(a) (b)

Fig.3.11: Genaralised representation of a) planetary scale tropospheric systems and b) cross-section of tropospheric circulation[8].

The ITCZ is located about 12°-15°S in the December-January period implying that areas north of it are under the influence of cold dry cross-equatorial northeasterlies (harmattan). These winds become northwesterlies on crossing the equator. Hence, rainfall in Tanzania during the southern summer is mainly due to convergence brought about by colliding warm moist southeasterlies and cold dry cross-equatorial northeasterlies. One significant feature is the flow pattern in the Mozambique Channel. The southeasterly trades in this region are met by cross-equatorial northerlies creating a convergence zone in the channel. Tropical cyclones (TCs) often form within the Mozambique Channel during December, January and February. In fact, all oceanic regions with SST above 26°C or air temperatures above 27.5°C (Palmen, 1948) are regions of tropical cyclone generation. These regions are

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[8] Source: John Brandon 2000: Aviation meteorology guide. Available online in September 2003 at http://www.auf.asn.au/meteorology/section4.html

normally located between 5°S and 20°S and the cyclones occur during the November-April period.

Winter rainfall in southern and southwestern South Africa is influenced by weather disturbances associated with the belt of westerly winds in the southern ocean, particularly the cold fronts and sometimes by cut-off lows and by disturbances in the easterlies over the tropical regions lying to the northwest (Reason *et al.*, 2002). Cold fronts are northward propagating cold air of an extra-tropical cyclone (equivalently known as a low, a storm depression or a cold-core cyclone). Primary depressions are isolated from westerly wind belts when moving northward into high-pressure belts, thus forming cut-off lows. Cut-off lows tend to be large, deep and slow moving and they may bring heavy rainfall for several days. Lows usually tend to travel in families of 3 or 4. In doing so they create large eddies in the westerly wind belt. Secondary lows normally trail the primary lows and are intense, rapidly developing and short-lived storms.

3.6.1.3 Topography

Mountainous topography in southern Africa influences regional climates positively through orography and negatively by blocking inland penetration of humid southeasterlies from the Indian Ocean. Orography usually affects rainfall amounts, rates, frequency and distribution around the mountains and their surroundings (Schulze, 1997). Elevated areas usually receive higher rainfall than surrounding areas. Rainfall is highest on the windward side of the mountain while leeward side receives little rainfall. Rainfall increases with altitude up to the base of trade wind inversion. Thereafter significant reduction of rainfall with altitude occurs (Riehl, 1979). The highest precipitation usually occurs between 1000 m and 1400 m altitude. This situation prevails in most tropical high mountains like Kilimanjaro (Tanzania). For slightly elevated mountains with heights less than the height of the base of inversion, normally precipitation increases with altitude. Schulze (1997) indicated increased thunderstorm activities and high lightning incidences for high altitudes which were associated with a steep altitude gradients.

Mountain barriers may affect a wider region in the lee of the mountains, the effect depending mainly on the height and lateral length of the mountain/mountain chain and on the characteristics (direction, tropospheric level) of rain-influencing winds. Moisture from the Indian Ocean is mainly responsible for rainfall in southern Africa (Chenje and Johnson, 1996), particularly along the eastern part of the subcontinent. Accordingly, the eastern mountains extending from southern South Africa to Kenya act in a way to prevent penetration of humid southeasterlies into interior southern Africa. As a result, dry conditions with little rainfall prevail in the western part of the region and humid conditions in the eastern part, particularly south of about 15°S.

3.6.1.4 Proximity to tropical (equatorial) rainy forests

Tropical rainforests (described under vegetation below) are mostly found around the equator where intense solar heating takes place. Mean annual rainfall usually exceeds 2 000 mm and can reach up to 11 000 mm in certain parts within the rainforests region (Butler, unpublished manuscript). Such high annual amounts of rainfall are contributed by all months of the year.

The canopy layer of rainforests is important with respect to the forests life and climate variations. The canopy of rainforests is formed by billions of leaves (Butler, unpublished manuscript), which act as a solar panel providing energy for the forest through photosynthesis. Through evapo-transpiration, about 75% of rainwater returns to the surrounding atmosphere in the form of water vapour. Dense rain clouds and high humidity are thus year round features of the tropical rainforests. It is estimated that each canopy tree transpires about 760 litres of water each year and hence an acre of rainforest (approximately about 100 trees) adds about 76,000 litres of water to the atmosphere each year (Butler, unpublished manuscript).

The ever-present dense clouds over the Congo rainforests periodically affect the southern African countries of Zambia, Angola and Tanzania, parts of which are situated near these equatorial rainforests. Moisture-rich westerlies from the Congo basin are associated with rainfall in most of western, southwestern and southern Tanzania (Nyenzi *et al.,* 1999). However, the spatial extent of the influence depends on the atmospheric circulations and proximity to the forests. Atmospheric conditions that favour eastward displacement of these cloud bands bring rains to most of western Tanzania and northeast Zambia.

Through time, human activities, such as cultivation, have caused considerable changes to the vegetation cover that existed naturally. Human activities have caused a worldwide disappearance of about half of the forest that existed during the post-Pleistocene times (Fig.3.12). The rate of disappearance, however, varies in various parts of the world. Southern Africa has observed a significant disappearance of its forests. The forests that had initially covered most of the region are now present as scattered forests.

3.6.2 Factors affecting streamflow variations

Between their sources and discharge points, some of southern African rivers traverse lands with different climatic and physiographic characteristics as well as socio-economic activities. They therefore undergo changing flow patterns along their lengths. Rainfall, soil and aquifer characteristics, vegetation, population densities and growth and human socio-economic activities in a given region are among the most important factors that influence river flows regimes. Rainfall, soil and aquifer characteristics are the primary (major) factors which are essentially the driving force for other factors (secondary) such as population distribution and growth, changing socio-economic activities and distribution of the vegetation.

The favourable soil and aquifer characteristics (Sections 3.3) are associated with soil fertility, nutrient availability to plants, water holding capacity and high groundwater storage capacity, which ensures river flow throughout the year. These characteristics together with high and well-distributed rainfall are favourable for agricultural activities and water availability in the humid eastern and northern parts of southern Africa. Population densities and growth rates are, therefore, highest in these eastern and northern parts compared to the western and southwestern parts of southern Africa where soil properties and low rainfall are unfavourable for agriculture.

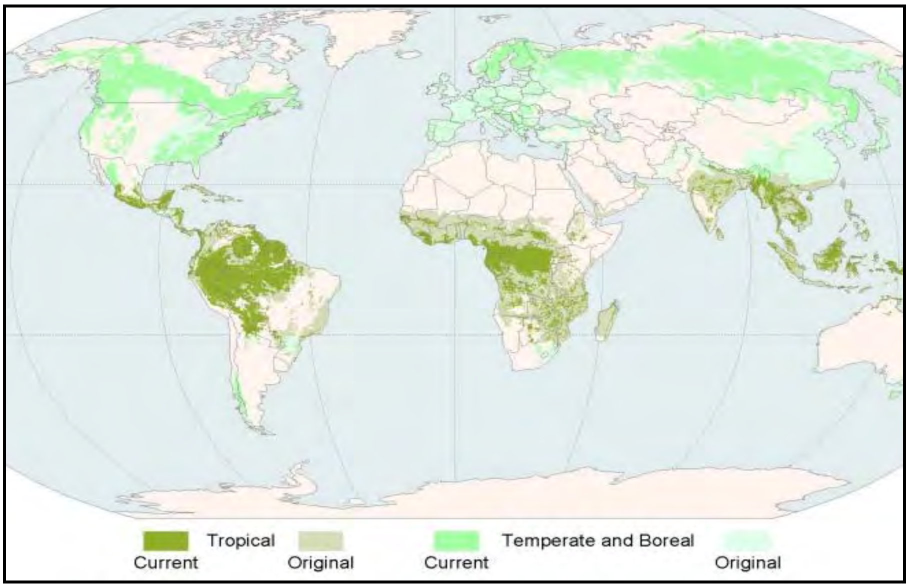

Fig.3.12: Global distribution of original and remaining forests[9].

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[9] Source: United Nations Environmental Programme's World Conservation Monitoring Center (2000). Available online in September, 2003 at http://www.unep-wcmc.org/index.html?http://www.unep-wcmc.org/forest/original.htm~main

The ever-growing population is exerting high pressure on limited land and water resources. In order to cope with such population pressures, there have been constant changes in landuse and water use patterns in the southern African region, particularly in recent decades. Changing landuse patterns involve modifications of natural vegetal cover as well as soil conditions that usually lead to modified runoff production and consequently to changing flow regimes. Increased agricultural activities in the region, which include opening of large plantations, are related to decreasing natural vegetation, which are being replaced by crops. Irrigation canals, constructed along river channels, extract water for irrigation schemes and modify flow patterns along the river length. Steadily increasing demands for food imply similar increasing water abstractions to sustain expanding agricultural activities and therefore suggest constantly changing river flow regimes. Urbanisation, apart from removing vegetal cover, involves the creation of impervious surfaces. The landuse changes and increased demand for water further lead to changes in the water use pattern. Constantly increasing water demands of the growing populations particularly during the dry season has led to the necessity of conserving flows generated during the wet season for use during the dry season. The region has therefore witnessed construction and commission of dams since the 1960s in which the single busiest decade in terms of dam commissioning was 1985-1995. The largest number of these dams is in South Africa (550 dams) and Zimbabwe (213) and most of them are single purpose dams mainly built for irrigation and water supply purposes. Apart from being associated with flow regulation, dams enhance water loss through increased evaporation from open water.

The rainfall distribution within the large southern African river basins is not uniform nor are the rates of modification of natural land surface and vegetal cover. Consequently flow regime changes are likewise not uniform across the basins. The Orange River basin (Fig.3.7) illustrates this. The Orange River has its headwaters in the Drakensburg where mean annual rainfall is around 2000 mm. Its longest path lies within a region where mean annual rainfall is below 600 mm in central South Africa, while mean annual rainfall is less than 200 mm at its mouth. Much of its water, therefore, comes from the eastern upper catchments and socio-economic activities in the low-rainfall middle and lower catchments are dependent on the amount of water that is reaching the areas from the upper catchments. The river basin has been extensively developed through the construction of dams since the 1970s.

CHAPTER 4

LITERATURE REVIEW AND THEORETICAL BACKGROUND

4.1 Introduction

The main aim of this chapter is to review the past studies of hydrological variability in the southern African region with a focus on rainfall and streamflows. The past studies of the interannual variability of these hydrological variables in southern Africa as well as in other parts of the world are reviewed. Oceanic and atmospheric conditions and features that significantly affect spatio-temporal rainfall variations in the region are described. The theoretical background of the study is given in which different statistical methods relevant for the study are briefly described. They include methods of interannual variability analysis such as change-point and linear trend analyses as well as methods of relational analysis such as correlation analysis and multivariate analyses.

4.2 Interannual variations of rainfall and streamflows

Alternating years of above and below average seasonal and annual rainfall amounts have been observed in southern Africa (Nicholson, 1986a; Jury, 1995; Nicholson, 2000; Richard *et al.*, 2001). The occurrence of the two hydrological extremes, floods and droughts, in the region (Harsch, 1992; Chenje and Johnson, 1996; Dyson and van Heerden, 2001; Jury and Mwafulirwa, 2002) as well as changes in the mean streamflows have been often observed in years in which above and below average rainfalls were recorded.

Dam levels have been reported to be in decline since the mid-1970s in Namibia (Jury and Engert, 1999), in South Africa since early 1980s as a reflection of a prolonged rainfall deficit in the 1980s and early 1990s (Mason, 1996). Berhanu (1999), Berhanu *et al.* (2001) and Alemaw and Chaoka (2002) found decreases in mean annual runoff in southern African catchments since 1975 which were particularly marked in Zambia, Angola, Mozambique and the South African highveld. Magadza (1995) found a change in the flow regime of the Gwaai River in which the river has been progressively transformed from perennial to seasonal with a lengthening period of no flow. The observed changes in the flow regime have been linked to, among many factors, changes in rainfall, landuse and water use patterns.

The study of Hulme (1992) concluded that there is an absence of significant trends in southern African regional time series of rainfall amounts. However, significant changes in different indices of rainfall have been identified in different parts of the region. Most parts of northeast Tanzania were characterized by decreasing annual rainfall amounts (Mkhandi and Ngana, 1999). The results of Mkhandi and Ngana (1999) were consistent with those of Mutua (1999) who also identified decreasing October-November-December (OND) and March-April-May (MAM) seasonal rainfall amounts in most of Tanzania, with exceptions in the Kipengule-Udzungwa mountains of southeast Tanzania and along the northwestern shore of Lake Victoria. Annual rainfall amounts in western and southern Zambia were reported to decrease since 1975 (Sichingabula, 1998). A similar decrease was identified in the late 1970s in the South African lowveld in summer rainfall amounts (Mason, 1996) and the extreme rainfall events (Mason *et al.*, 1999). Richard *et al.* (2002) identified shifts in the number of rainy days and in rain rates in the former Transkei and northern Transvaal while Smakhtina (1998) reported a progressive decrease of the number of rainy days, an increase in the rain rate and frequency of high rainfall intensities in the Eastern Cape.

Some studies have linked these changes in rainfall amounts to quasi-oscillations in the time series of rainfall amounts which hypothesize alternating periods of above and below average rainfall. The quasi-oscillatory periodicities mainly in the bands of 2-5, 7-9, 11-13, 17-19 year have been identified in southern Africa rainfall patterns (Tyson, 1986; Nyenzi *et al.*, 1999). However, Mason (1996) observed that some of the cycles in rainfall amounts are not robust features of the climate of southern Africa.

4.3 The influences of the atmosphere and SST on southern African rainfall

4.3.1 The influences of the atmosphere

Surface or near-surface circulation patterns usually provide important links between rainfall and SST. The major synoptic-scale features of the surface or near-surface circulations over the southern African subcontinent are the three wind systems which meet and converge over the region during the southern summer (Tyson, 1986) to produce the inter-tropical convergence zone – ITCZ (Nicholson, 1996; Okoola and Ambenje, 2003) which is the major rainfall-bearing system in southern Africa. Consequently, the peak summer rainfall is associated with the ITCZ and occurs over central southern Africa and the Indian ocean (Todd and Washington, 1999a). The other system is the tropical-temperate troughs (TTTs, Todd and Washington, 1999ab), which are associated with northwest-southeast bands of clouds extending from tropical southern Africa to the southwest Indian ocean and which have been linked to the occurrence of intense rainfall intensities in December through February in southern Africa.

Within southern Africa, the ITCZ has two branches, the meridional branch and zonal branches. The meridional branch of ITCZ located over the Congo basin and adjacent southern African countries during the austral summer, is the zone of convergence of the westerlies and easterlies (Jury and Gwezantini, 2002). The northeasterlies and/or southeasterlies in the Indian Ocean become easterlies on reaching southern Africa while the inland Angolan heat low is associated with the re-curving southeast Atlantic’s southeasterlies into the moist unstable westerlies (Nicholson, 1996). This meridional branch remains within the Congo basin between September and April (Okoola and Ambenje, 2003). The zonal branch of ITCZ is essentially the convergence zone between the cold dry cross-equatorial northwesterlies and warm moist southeasterlies. The northwesterlies are the northeasterlies which become northwesterlies on crossing the equator. This branch fluctuates between 10°S and 15°S during the austral summer and is located about 12-15°S between December and February.

The passage of the ITCZ influences rainfall farther north in Tanzania. Thus, northeast monsoon flow, southeast trade winds and topography act to promote early summer (short) rains in northern Tanzania (Nyenzi, 1992; Mutai and Ward, 2000; Philippon *et al.*, 2002). The abundance or deficiency of short rains depends on the northeast monsoon in which positive rainfall anomalies during the short rains are linked to weak monsoon wind stress (Phillipon *et al.*, 2002). Moreover, these positive rainfall anomalies during the short rains were associated with the lower level dynamics associated with anomalous ascent in the western Indian Ocean and the upper level dynamics associated with anomalous subsidence in the eastern Indian Ocean in September (Phillipon *et al.*, 2002) and October (Hastenrath, 2000). The dynamics represent a Walker cell in the tropical Indian Ocean. Mutai and Ward (2000) further related the low-level dynamics in equatorial Atlantic, Indian and Pacific Oceans and upper-level cyclonic flow over Arabia to the occurrence of a rainfall event in East Africa during the short rains.

Apart from the ITCZ, there are localised cyclonic flows within the Mozambican Channel which are mainly observed between December and February. A cyclonic flow within the channel enhances the southeasterlies on its southern part and the flow itself is more evident in the mean low level circulation in January and February, the period when intense daily events and floods have been observed in Mozambique. The Angolan heat low is associated with cyclonic flow within the Angola/Congo basin boundaries which brings moisture from the tropical Atlantic Ocean and the Congo basin into parts of Angola, northern Botswana (van Regenmortel, 1995), eastern and northern Namibia (Jury and Engert, 1999), Malawi, (Jury and Mwafulirwa, 2002), southwest Tanzania, Zambia and Zimbabwe.

There are other occasional localised circulation features that are affecting rainfall in southern Africa. Short-lived tropical cyclones in eastern Madagascar are related to enhanced or reduced rainfall in eastern and southern Africa (Obasi, 1977; Ogallo, 1988; Jury and Mwafulirwa, 2002) to as far north as Ethiopia (Camberlin and Shanko, 1998). They are observed usually between November and April and have been linked to weakened easterlies/southeasterlies, a southward displacement of ITCZ which becomes less defined and with a restrained convection over east Africa (Macodras *et al.*, 1989; Camberlin and Shanko, 1998). Depending on their strength and location, these tropical cyclones may be associated with significant enhancement of the westerly/northwesterly flow from the Congo basin in the southwestern Indian Ocean (Camberlin and Shanko, 1998) enhancing moisture influx from the equatorial Atlantic Ocean and the Congo basin into western and southern Tanzania, Malawi, Zambia, Zimbabwe and Mozambique.

Anticyclonic circulation anomalies over warmer SST in the Angola/Benguela Front region, usually observed during the Benguela Niños, favour the mean westward inflow of moisture from the Indian Ocean while weakening the mean southeasterly moisture flow out of southern Africa. These conditions have often resulted in above average summer rainfall along the adjacent coast and sometimes in the interior of southern Africa (Hirst and Hastenrath, 1983; Nicholson and Entekhabi, 1987; Rouault *et al.*, 2003).

After March-April, there is a progressive weakening of most of the features of atmospheric circulations associated with rainfall in southern Africa. This weakening corresponds to rainfall withdrawal from the region. The Angolan low is absent in April while the near-surface cyclonic flow within the Mozambique Channel is significantly reduced in March and is absent in April. However, strong southerlies/southeasterlies penetrate from the western/southwestern Indian Ocean into northern Mozambique and Tanzania in April which is the climatological peak of the principal rainy season in Tanzania, the long rains.

Interannual rainfall variations in southern Africa are associated with changes in the characteristics of these features that influence seasonal rainfall variations. A latitudinal shift associated with a failure of the ITCZ to move further south into southern Africa or its weakening, for example, have been linked to dry summers in southern Africa (Shinoda, 1990; Rocha and Simmonds, 1997b). Upper tropospheric westerlies over much of southern Africa which are observed during warm ENSO (Arkin, 1982) were similarly linked to below average rainfall in southern Africa (Lindesay, 1988; Rocha and Simmonds, 1997b; Tyson *et al.*, 1997), while low-level easterlies over Angola/Namibia are unfavourable for the formation of a strong heat low there (Reason, 1998) and consequently an increased likelihood of below average rainfall.

4.3.2 The influences of the SST

A number of past studies have related rainfall variations in southern Africa to SST variations in the different oceanic basins in the Indian, Atlantic and Pacific Oceans. In general, SST in the equatorial, tropical and South Atlantic Ocean basins, in the tropical and Southwest Indian Ocean basins and in the Niño regions (Niño1 through Niño4) in the Pacific Ocean have been identified as influencing rainfall variations in southern Africa.

4.3.2.1 SST in the Atlantic Ocean

The most important influences of the SST in the southeast Atlantic basin is related to the Benguela Niño, a condition when there are anomalous warm waters within the Angola/Benguela Front. The anomalous warm waters, apart from being attributed to an intrusion of warm equatorial waters, also correspond to outcropping subsurface temperature anomalies originating from the central equatorial Atlantic (Florenchie *et al.*, 2003). These conditions have been linked to increased rainfall along the adjacent coast (Rouault *et al.*, 2003).

In general, SST in different basins in the south Atlantic have been linked to rainfall variations in southern Africa. Richard *et al.* (2000) found significant correlations between late summer southern African rainfall and SST in the equatorial Atlantic in which pre-1970 cold SST in the equatorial and southwest Atlantic were associated with below average rainfall in southern Africa (Richard *et al.*, 2001). Jury (1996) found significant correlations between summer rainfall in Zimbabwe, Namibia and South Africa and SST in different basins in tropical and south Atlantic in which significant correlations were observed as early as November in the central equatorial Atlantic basin and January across the eastern equatorial and tropical south Atlantic basins. Mutai *et al.* (1998) and Phillipon *et al.* (2002) found positive influences of SST in the tropical and southeast Atlantic on rainfall in the northern part of southern Africa (northern Tanzania as part of east Africa).

4.3.2.2 SST in the Indian Ocean

The Indian Ocean is considered to be the principal source of moisture for southern Africa. Consequently, a number of studies had found significant relationships between rainfall variations in southern Africa and SST variations in different basins of the Indian Ocean, particularly those in the Southwest Indian Ocean and the whole of the tropical basin north of about 15°S and the tropical central Indian Ocean basin. There are also local influences of the Agulhas Current System on the adjacent southern coast of South Africa (Reason, 1998, 2001). More generally, summer rainfall in much of southern Africa is negatively influenced by SST in the tropical western Indian Ocean basin (Jury, 1995, 1996; Rocha and Simmonds, 1997a; Richard *et al.*, 2000) and positively by SST in the Southwest Indian Ocean basins comprising the Mozambique Channel and the Agulhas System (Walker, 1990; Jury, 1995; Reason and Mulenga, 1999; Richard *et al.*, 2000).

Decadal rainfall variations in eastern and central South Africa show dipole associations with SST in the southern Indian ocean basins in which the SST influence of the southwest basin is positive and that of the southeast negative (Reason and Mulenga, 1999) indicating that cooling to the west of Australia and warming to the south of Madagascar correspond to enhanced rainfall in southern Africa. The dipole association reflects the existing SST dipole in the southern hemisphere Indian Ocean basins (Behera and Yamagata, 2001; Fauchereau *et al.*, 2003a). Reason (2002) further demonstrated the high sensitivity of southern African rainfall to the presence of the two parts of the dipole. Walker (1989) and Mason (1992) noted, however, that the influence of SST in the southwest Indian Ocean on southern African rainfall is enhanced during weak ENSO.

Rainfall in equatorial east Africa, of which northern Tanzania is part, is positively influenced by SST in the equatorial, tropical and southwest Indian Ocean (Ogallo *et al.*, 1988; Mutai *et al.*, 1998; Mutai and Ward, 2000). The associations between the Indian Ocean SST and East Africa rainfall are stronger mainly for rainfall in the October-February period than during the long rains, suggesting that warmer SST in these Indian Ocean basins enhances October-February rainfall in equatorial East Africa.

An increase in SST causes a non-linear increase in the amount of water precipitated from an oceanic vertical column of air (Stephens, 1990; Zhang, 1993) and therefore the warming of the Indian Ocean might have enhanced convection and consequently rainfall becomes more convective leading to reduced frequency of light rainfall events while enhancing the frequency of intense events. Mason *et al.* (1999) identified an increase in the intensity of high rainfall events in much of South Africa while Mason and Joubert (1997) noted similar increases over much of southern Africa under a doubled CO_2 concentration. Severe floods have been reported in the recent years such as that in February 2000 which hit Mozambique, Zimbabwe and northeast South Africa and the November-December 1997 event in East Africa.

4.3.2.3 SST in the Pacific Ocean

The main interannual modes of SST and atmospheric variability in the Pacific Ocean are associated with the El-Niño/Southern Oscillation (ENSO) which corresponds to both SST conditions and the southern oscillation. Teleconnection patterns associated with ENSO have been linked to the modulation of climate in various parts of the world including southern Africa.

ENSO-rainfall associations in southern Africa region are both spatially and temporarily variable but generally the association with warm (cold) ENSO-rainfall is positive (negative) in northern Tanzania and negative (positive) in the rest of the region (Ropelewski and Halpert, 1987; Janowiak, 1988; Nicholson and Kim, 1997; Rocha and Simmonds, 1997ab; Mutai *et al*., 1998; Landman and Mason, 1999; Latif *et al*., 1999; Indeje *et al*., 2000; Mutai and Ward, 2000; Richard *et al*, 2000, 2001). These ENSO-rainfall associations, therefore, indicate that below average rainfall is experienced during warm ENSO (El Niño) events in the southern part while northern Tanzania experiences above average rainfall and vice versa during cold ENSO (La Niña) events, although this is not always the case.

It has been observed that the ENSO signal in southern African rainfall is strongest when it is communicated in rainfall in southern Africa through the Atlantic and Indian Oceans waters (Nicholson and Kim, 1997). According to Wang and Ropelewski (1995), the warming of the tropical (Trenberth, 1990; Kerr, 1992; Wang, 1995; Trenberth and Hoar, 1996) and Southwest (Trzaska *et al*., 1996) Indian Ocean in the 1970s provided a warmer low-frequency climatic base state which is favourable for frequent and amplified ENSO-scale variability which has consequently lead to more warm (El Niño) events than cold (La Niña) events. This suggests that the southern African region will experience more frequent and severe droughts than before. Consequently, drought characteristics in southern Africa have been reported to change with post-1970 droughts being more intense and widespread (Richard *et al*., 2001). However, the ENSO signals in SST in the Indian Ocean have weakened since the late-1970s (Landman and Mason, 1999). As a consequence, the influences of the Indo-Pacific ENSO signal on rainfall in southern Africa have weakened and in certain areas changed and positive associations between SST in the tropical Indian Ocean and rainfall in various parts of the region have been reported (Landman and Mason, 1999).

4.4 Theoretical background

4.4.1 Methods of interannual variability analysis

4.4.1.1 General

The basis of interannual variability analysis is time series analysis. Time series analysis involves the identification or detection and consequently description of the basic components of a time series (Salas *et al.*, 1980). According to Kendall and Stuart (1968), a typical time series consists of a) a trend, b) an oscillation, c) a seasonal effect and d) a random component. Further, changes in the statistical properties of a time series are either evolutive or sudden which need to be detected and justified.

The identification and description of a change in a hydrologic time series involves testing for randomness (homogeneity and consistency) and whenever inconsistencies exist, identification of their cause through a) detection of shifts, b) identification of a trend and when the first two are non-existent then c) identification of oscillations. Testing for randomness commonly uses distribution-free tests such as the Mann-Kendall's rank correlation test and serial correlation test (Kendall and Stuart, 1968). The details of these tests are not included here. Once a time series has been identified to be non-random, the study proceeds with the identification of the cause of such inconsistencies, whether it is due to a) a sudden change (shift) or b) an evolutive change (trend). Oscillations are not considered in the present study.

4.4.1.2 Subjective segmentation and comparison

The main objective of this procedure of interannual variability analysis has been comparison of statistical moments (mean, standard deviation, skewness, etc), correlations, etc of different sub-series (segments) of a time series to check whether significant differences in the statistical characteristics of different segments exist.

A time series is divided into overlapping or non-overlapping segments and statistical characteristics are determined for each segment. The characteristics of one segment are compared to those of the other segments using either statistical tests such as the Student's t-test or simply using differences or fractions with respect to statistical characteristics of a reference segment.

The procedure that uses non-overlapping segments of time series of hydrological variables requires *a priori* knowledge of the change-points which are usually linked to known hydroclimatological events. This procedure has been used in studying interannual rainfall variations in different parts of the world (e.g. Brunetti *et al.*, 2002). To facilitate the choice of the cut-points, standardised rainfall indices have been used. They are computed as the standardised departures from the long-term average in which standardisation is either by the standard deviation or by the long-term average. Visual observations of standardised time series can help in the identification of the change-points as in the case of Sahel rainfall. The standardised elements $x_{i,j}$ of a time series are computed as

$$x_{i,j} = \frac{\sum_{j=1}^{ndata} X_{i,j} - \overline{X}_i}{\sigma_i} \tag{4.1a}$$

or

$$x_{i,j} = \frac{\sum_{j=1}^{ndata} X_{i,j} - \overline{X}_i}{\overline{X}_i} \tag{4.1b}$$

where $X_{i,j}$ are the original time series elements at station or grid point i, $\overline{X}_i$ and σ_i are respectively the long-term average and the standard deviation at that particular station or grid point and *ndata* is the sample size.

The procedure that uses overlapping segments, on the other hand, does not require such *a priori* knowledge of change-points as the points can be indicated by the evolutive or abrupt changing statistical properties. However, this procedure is dependent on the selected segment length (window size) and the overlap interval. To capture the probable change-points, medium-sized windows and short overlap intervals like serial overlap (in which the first element of the segment is left out whenever the next element after the segment is picked up) are more appropriate than long windows and overlap intervals. Small window sizes are less appropriate for computations of statistical characteristics. However, this procedure is time consuming as it involves a number of segments and consequently requires the determination of statistical characteristics for each segment and comparison between different segments.

In most cases, the *a priori* knowledge is missing and there is always a need for exhaustive computations. Therefore, statistical objective methods of change-point and trend analyses are preferred to the subjective segmentation methods. They are described below.

4.4.1.3 Shifts

According to Laraque *et al.* (2001), a discontinuity at a given time represents a change in the probability law of a time series. Under normal circumstances, a time series free of trends and shifts in the first two moments (mean and standard deviation) is free of such changes in other higher moments (Salas *et al.*, 1980).

There exist numerous parametric and non-parametric methods for detection of differences in sub-series average. No parametric probability distribution fits exactly between-the-years monthly flow variations. Consequently, parametric change-point methods such as the Bayesian method of Lee and Heghinian (1977) and the Buishand U test (Buishand, 1982, 1984) were avoided in the analysis. The mathematical details and robustness of these and other tests for hydroclimatic applications can be found, for example, in Lubès-Niel *et al.* (1998).

The non-parametric test of Pettitt (1979) and the autosegmentation procedure of Hubert (Hubert and Carbonnel, 1987; Hubert *et al.*, 1989) were used. The former test is referred to here as the non-parametric data referring method and the latter as the non-parametric data dependent method. The difference is that Pettitt's test assigns values (-1, 0 and 1) for differences between the time series elements involved, whereas Hubert's procedure uses exact values of the difference in the analysis. Hence, Hubert's procedure is affected by the presence of outliers.

Using Pettitt's test, repeated series segmentation was performed until no further segmentation was possible (Assani, 1999). This procedure provides multiple segments, whenever they exist, and reduces the Pettitt's test weakness of providing a single change point (jump) even if more than one exists. The results of this improved procedure, together with those of Hubert's autosegmentation procedure were used in determining series segmentation.

Owing to the weakness of Hubert's procedure, segments which were at least 5 years long were accepted, while segments of less than 5 years were treated as grouped outliers and segments comprising single years as isolated outliers.

4.4.1.4 Trends

A tth element y_t of a time series known to possess a trend can be approximated by an nth order polynomial in t (Kendall and Stuart, 1968; Salas *et al.*, 1980) as

$$y_t = a_0 + a_1 t^1 + a_2 t^2 + a_3 t^3 + ... + a_{n-1} t^{n-1} + a_n t^n{}_t \tag{4.2}$$

in which a_0 is a constant or zero and any of the a_i, i = 1,2,3,…,n are statistically significantly different from zero.

This is a general trend model. When two or more a_i, i = 1,2,3,…,n are non zero, the model is a non-linear trend model and when they are all equal to zero except a_1, the model becomes a linear trend model. The time series can be reasonably well approximated by model (4.2) when higher orders are used. However being based on higher-order moments, higher order coefficients of (4.2) are unstable (Kendall and Stuart, 1968). For such reasons, the linear trend model is widely used. It uses the first two terms of the model (4.2) and a random variable (Wigley and Jones, 1981) and is given as

$$y_t = a + bt + \xi_t \tag{4.3}$$

where y_t is an element of a time series y at time t; a and b are linear trend parameters (intercept and slope respectively) and ξ_t is the random part with zero mean and unit standard deviation.

The trend model of eq.(4.3) has a consequence of overestimating effective sample size (Trenberth, 1984) and hence the significance of a trend is likewise overestimated (von Storch, 1995). This model is not very appropriate for modeling hydroclimatic variables, which normally show temporal dependence between their elements (e.g. Berhanu, 1999). The performance of model (4.3) has been observed to improve when autoregressive terms are included (e.g. Hirsch *et al.*, 1993; Zhang *et al.*, 2000). Despite this weakness, no attempts were made to incorporate autoregressive terms into the trend model (4.3) due to a lack of detailed studies on the applicability of autoregressive models in modeling rainfall in southern Africa. Thus, model (4.3) was retained and used in this study.

The slope (*b*) of a linear trend linear model (4.3) is commonly estimated by a least square method. However, least square estimates are affected by the presence of abnormally low or high elements of a time series (Hirsch *et al.*, 1993). The use of Mann-Kendall's procedure (Kendall and Stuart, 1968) in estimating the trend slope b reduces the effects of unusual low or high values. In this method, the trend slope b is indirectly estimated by the standard normal variate, Z (Hirsch *et al.*, 1993; Yu and Zuo, 1993) as

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{var}(S)}} & if \quad S > 0 \\ 0 \quad if \quad S = 0 & \\ \dfrac{S+1}{\sqrt{\mathrm{var}(S)}} & if \quad S < 0 \end{cases} \tag{4.4}$$

where S is calculated as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(y_j - y_i) \tag{4.5}$$

in which y_i to y_n are elements of a time series and the sign function $sgn(y_j - y_i)$ is

- 1 when $y_j - y_i > 0$
- 0 when $y_j - y_i = 0$
- -1 when $y_j - y_i < 0$

The mean and variance of S are given by

$$E(S) = 0$$

and

$$\mathrm{var}(S) = \frac{\left[n(n-1)(2n+5) - \sum_k k(k-1)(2k+5) \right]}{18} \tag{4.6}$$

where n is the length of record used and k is the length of any given tie. A tie is a subset of the ordered data that comprises a sequence of the same value. *Var(S)* as given in eq.(4.6) includes an overall correction for tied data (Hirsch *et al.*, 1993). In this study, no correction for tied data was applied (i.e. $k = 0$). The value of Z refers indirectly to the magnitude of a trend (slope b in eq.(4.3)) while its sign indicates the direction of the trend.

4.4.2 Classification of daily rainfalls and streamflows

The review in the preceding sections and chapters show that rainfall in southern Africa is highly variable both in time and space. There are parts in which intense daily rainfall intensities are more frequent than in others while the amounts and intensities received at the start and end of the rainy seasons are less than those received during the core of the rainy seasons. In order to better understand the characteristics of the spatial variation of rainfall in the region, it is important to characterise the rainfall in southern Africa by the characteristic daily intensities, that is, the daily rainfall intensities that are commonly observed in different parts in the region.

In order to account for the observed spatial variation of rainfall in southern Africa, a station-dependent approach (see e.g. Stone *et al.*, 2000) is used in establishing the class limits at each rainfall station in the region. The approach involves assigning class extremities according to what prevails at each station. An exceedence index P*f* is defined as the value (of a daily rainfall intensity or an average daily river flow) that has been equalled or exceeded for *f* percent of the available record.

The *f* are essentially the probabilities of having a certain P magnitude being equaled or exceeded and can be associated to a return period (T) used in statistical probability distributions. Therefore, the exceedence indices P*f* have been variously determined for the time series of hydrological variables using probability theory. Some studies used the probability distributions in which the most suitable probability distribution is fitted to the data and the P*f* determined for different values of *f* (Mason and Joubert, 1997; Egozcue and Ramis, 2001). However, none of the probability distributions fits exactly the statistical distribution of the data and in order to reduce this stochastic uncertainty inherent in the probabilistic models, the plotting position formulae for an unspecified probability distribution are used. The plotting position formula method involves re-arranging the time series elements in the ascending or descending order of magnitude and assigning ranks to the new series and the required plotting positions f , the exceedence probabilities for the descending ordered series, are determined.

The exceedence frequency f is, therefore, determined from the plotting position formula for unspecified probability distribution (Mutreja, 1995) as

$$f = \frac{i - 0.5}{N} \qquad (4.7)$$

where i denotes rank in the descending series and N the total number of elements of the sample, while the index P*f* corresponds to the i^{th} value of the descending sequence that gives the required *f*.

The description of the procedure can be found in, for example, Mutreja (1995). This method has been commonly used in studies of low flows (Quimpo *et al.*, 1983; Mimikou and Kaemaki, 1985; Pearson, 1995; Smakhtin *et al.*, 1995) and the overall procedure of the determination of the flows (P*f*) that have been equaled or exceeded for the specified percentages of time (*f*) constitute the flow duration curves (FDCs). The method has also been used in studying other hydroclimatic variables such as rainfall and air temperature (e.g. Salinger and Griffiths, 2001).

The non-zero daily rainfall intensities are used and the P*f* values are interpreted as daily rainfall intensities that have been equaled or exceeded for f% of the time when it rains. A similar interpretation is adopted for flows. The values of P*f* are also computed for the cases that include zero flows aiming at distinguishing seasonal and perennial rivers and they are interpreted as flows that have been equaled or exceeded for *f*% of the time. Since the P*f* are computed for the period of the available record, whether it is 10 or 50 years, the approach, therefore, provides period(or length)-of-the-record exceedence intensities or flows, which are therefore sensitive to record lengths (Smakhtin *et al.*, 1995).

4.4.3 Coherent rainfall regions and regional indices

4.4.3.1 Regionalisation of rainfall indices

Rainfall data from various stations are frequently correlated with each other. One implication of these correlations is that there will be some redundancy in the information provided by station data. For two perfectly correlated data sets, one of them is redundant since knowledge of one data set removes the degree of freedom of the other data set. Multivariate methods such as Principal Components Analysis (PCA) exploits the redundancy in such multivariate data enabling a) identification of patterns (relationships) in the variables and b) reducing the dimensionality of the data set without a significant loss of information.

PCA attempts to explain the variance-covariance structure of high dimensional random vector through a few linear combinations of the original correlated component variables.

The first principal component can be expressed as follows

$$Y_1 = a_{11}X_1 + a_{21}X_2 + ... + a_{p1}X_p \qquad (4.8a)$$

or in matrix form

$$Y_1 = \mathbf{a'x} \tag{4.8b}$$

The a_{j1} are scaled such that $\boldsymbol{a_1'a_1} = 1$. Y_1 accounts for the maximum variability of the p variables of any linear combination. The variance of Y_1 is λ_1. The next, principal component Y_2 is formed such that its variance, λ_2 is the maximum amount of the remaining variance and that it is orthogonal to the first principal component. That is, $\boldsymbol{a_1'a_2} = 0$. One continues to extract components until some termination criterion is encountered or until p components are formed. Practically, the number of components or a required explained variance are used as termination criteria.

Principal components (PCs) are usually computed from either the covariance matrix (without division by standard deviation) or the correlation matrix (through division by standard deviation) of the p variables.

The weights used to create the principal components are the eigenvectors of the characteristic equation,

$$(\mathbf{S} - \lambda_i\mathbf{I})\mathbf{a} = \mathbf{0} \tag{4.9a}$$

or

$$(\mathbf{R} - \lambda_i\mathbf{I})\mathbf{a} = \mathbf{0} \tag{4.9b}$$

where $\boldsymbol{S}$ is the covariance matrix, $\boldsymbol{R}$ is the correlation matrix and the λ_i are the eigenvalues (the variances of the components) which are obtained by solving

$$|\mathbf{S} - \lambda_i\mathbf{I}| = 0 \text{ for } \lambda_i. \tag{4.10}$$

PCA therefore represents the originally correlated variables by a set of a few uncorrelated empirical orthogonal functions (EOFs) that explains the largest part of the variance inherent in the original correlated variables. When performed on hydrological variables in the spatial (S-) mode, the EOFs represent homogeneous regions while their time series (the PCs) represent common temporal modes of variability for time series within the regions. The analysis in the temporal (T-) mode correlates a series of temporal elements in which a group of spatially referenced observed values characterise each element.

There are several criteria which assess the significance of the extracted PCs. The include the North *et al*. (1982) sampling errors of the PCs, the Kraiser (1959, as referred to in Indeje *et al*., 2000) criterion of eigenvalue greater than 1 and the Scree test (Cattell, 1966) for the break of the slope of the Scree plot. Adherence to these tests may result in a large number of significant PCs being retained and the final selection of the PCs to be retained depends on the main purpose of the study. This may be the case with rainfall in southern Africa which is affected by the diverse influences of local-scale (topography, lakes), regional-scale (surrounding Atlantic and Indian Oceans) and global-scale (ENSO phenomenon) variables, all of which vary spatially and seasonally. Such heterogeneity may necessitate a number of EOFs to explain a substantial part of variance in regional rainfall.

Sometimes, the retained significant unrotated PCs are difficult to interpret and in such cases, their rotation may remove the ambiguities by distributing the variance within the eigenvectors while conserving the total variance. The orthogonal (Varimax) rotation is the common. However, this orthogonal rotation, as noted by Richman (1991, and referred to in Peñarrocha *et al*., 2002), sometimes produces spatial patterns that do not reflect the reality and in such cases an oblique (Oblimin) rotation served to resolve the difficulties.

4.4.3.2 Regional indices

Area average indices are calculated simply as spatial average of indices from each station or grid that falls within the given region. The general equation is given as

$$x_j = \frac{\sum_{i=1}^{N} x_{i,j}}{N} \quad , \quad j = ndata1, ndata2 \qquad (4.11)$$

where x_j is an area average for the j^{th} element of the time series, $x_{i,j}$ are j^{th} elements of time series at each station or grid point i. N is the number of stations or grids within the given region while *ndata1* and *ndata2* are respectively initial and end elements of the selected section of the time series.

It is, however, necessary to eliminate the influences of local environments of different stations or grids before using their $x_{i,j}$ indices in equation (4.11). This is done by standardization of the series through division of the departures from the long-term average by the standard deviation as given in eqns.4.1.

The elements $x_{i,j}$ in (4.11) are in fact the standardized elements. Areal average regional indices are not always appropriate unless they are derived for homogeneous regions, that is, for regions in which patterns of interannual variability are similar irrespective of what is observed at a site. Therefore, areal average rainfall indices in this study are derived for coherent rainfall regions.

4.4.4 Correlation analysis

The correlation coefficient expresses the degree of the association between two variables. There are several types of correlation coefficient to choose from, the choice being based on the nature of the variables being correlated.

For example, if two variables are to be correlated in which one is measured on a continuous scale while the other is measured on a dichotomous scale, then the Point-Biserial correlation will be appropriate. Since most hydrological data are measured on a continuous scale, the Pearson's product moment is appropriate and has been commonly used. The other types are either poor estimators of the population correlation coefficients (e.g. tetrachoric correlation coefficient) or not a significant improvement on the Pearson's correlation coefficient except for extremely non-normality in data when Kendall Tau holds up better.

The Pearson's correlation coefficient is estimated, for two samples X and Y with N elements in the common period, as

$$r_{X,Y} = \frac{\sum_{i=1}^{N} X_i Y_i - \frac{\left(\sum_{i=1}^{N} X_i \sum_{i=1}^{N} Y_i\right)}{N-1}}{\sqrt{\left(\sum_{i=1}^{N} X_i^2 - \frac{\left(\sum_{i=1}^{N} X_i\right)^2}{N-1}\right)\left(\sum_{i=1}^{N} Y_i^2 - \frac{\left(\sum_{i=1}^{N} Y_i\right)^2}{N-1}\right)}} \qquad (4.12)$$

and ranges between ±1. This correlation coefficient is used in this study.

CHAPTER 5

THE DATA SETS

5.1 Introduction

The bibliographic analysis indicated the importance of studying the variability of hydrological variables (rainfall and streamflows) using the short-duration records such as daily and monthly records in order to account for hydrological phenomena like droughts and floods which have significant impacts on the management of water resources. Therefore this section describes the data sets that were considered necessary for the present study and were eventually acquired from various sources worldwide. They include

- Time series of daily and monthly rainfall.
- Time series of mean daily and monthly river flows.
- Sea surface temperature and its derived indices.
- Sea level pressure and its derived indices.
- Atmospheric fields (wind speeds, geopotential heights, relative humidity, air temperatures).

The selection and reconstruction procedures are described for rainfall and streamflow data.

5.2 Rainfall data

5.2.1 Description of data sets

Time series of daily and monthly rainfall for 8 countries were acquired from the southern African FRIEND database at the Department of Water Resources Engineering (WRE) of the University of Dar Es Salaam. The data sets were originally supplied by the meteorological departments or the departments of water affairs of individual southern African countries. No rainfall data were available for Angola. This database comprised daily rainfall data from the countries of Botswana, Lesotho, Malawi, Mozambique, Swaziland, Tanzania, Zambia and Zimbabwe. Monthly data were available for Tanzania (1691 stations) and Malawi (23 stations) (Fig.5.1b).

Daily data for Namibia and for the Republic of South Africa (RSA) were kindly provided by the Department of Water Affairs (Namibia) and the Computing Centre for Water Research (CCWR, RSA). Daily rainfall data for Tanzania were only available in the three basins of Lake Victoria (north), Pangani (northeast) and Rufiji (southwest). Updates of daily rainfall data for 25 stations in northeast Tanzania were provided by the Tanzania Meteorological Agency (TMA) and cover the 1990s decade.

Record lengths of the acquired data vary from 1 year to 140 years in which the longest daily records are mostly found in Namibia, RSA and Swaziland. Moreover, Botswana, Namibian, RSA and Tanzanian daily data span the mid- to late-1990s and some stations have data for the year 2000. The Zambian and Zimbabwean records of daily rainfall are about 28-43 years long (Table 5.1) and span the early-1950s to early-1990s (not later than 1993). Daily data sets for Malawi are only 8-12 years spanning mainly the period 1979 to 1989.

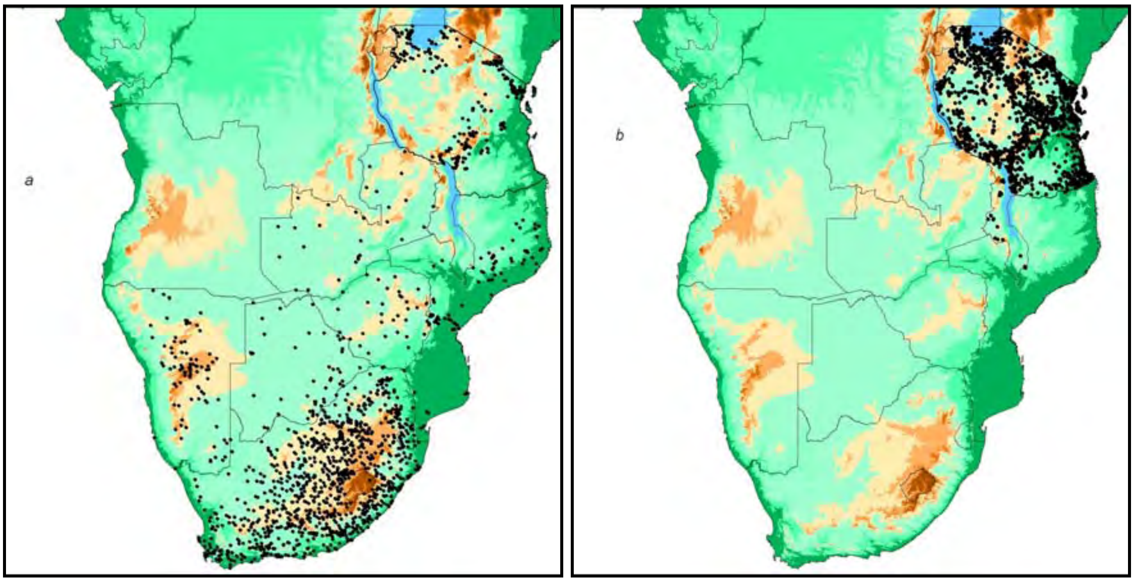

Fig.5.1: Spatial distribution of rainfall stations in southern Africa whose a) daily and b) monthly data were available for the study.

Most of available daily records for Mozambique are more than 20 years (Table 5.1) but terminate in the late-1970s or early-1980s (not later than 1984) and are characterised by frequent missing observations in the 1970s and 1980s. The distribution of rainfall stations is denser in South Africa (daily data, Fig.5.1a) and Tanzania (Monthly data, Fig.5.1b). Except in Botswana and Mozambique, most of the acquired data are from stations located in hilly terrain.

5.2.2 Data selection and time series reconstruction

5.2.2.1 Data selection

The acquired data from different sources were of variable quality and record length. The selection criteria were therefore necessarily different and more stringent criteria were used in the areas such as Tanzania (monthly data) and South Africa (daily data) where the largest number of good or reasonable quality records were available.

The main objectives of the selection process are therefore a) to obtain a spatially representative data set for the southern African region for the determination of climatological rainfall indices and b) to have the longest and most continuous time series of rainfall indices for interannual variability analysis. The selection criteria were formulated to achieve the two objectives and were based mainly on a) record length, b) continuity of the records and c) spatial evenness of the distribution of rainfall stations.

- Selection for climatological indices

The study is interested in interannual variability of rainfall during the 20th century and perhaps the period before. However, the study is restricted by the length of the available records in which most of them span the period 1950-1990 and are less than 45 years, except for the Namibia and South African records (Table 5.1). Therefore, all stations which had more than 30 years of most continuous records in the 1960-1990 period were initially retained. The continuity of the record was defined by the presence of 15% or less missing monthly, seasonal or annual values. The requirement of at least 30 years was relaxed to 20 years of data in Mozambique due to the poor data situation in the post-1970 period. The retained stations at this stage (Fig.5.2a) were used in the determination of climatological indices of rainfall. The aim of retaining as many stations as possible particularly in the mountainous areas was to facilitate in the spatial interpolation of the climatological rainfall indices as altitude affects significantly rainfall variations in the region. However, there are a number of areas where no daily data were available (Fig.5.1a, Fig.5.2a) and these areas were not considering during the interpolation.

Table 5.1: Summary of available daily rainfall data in southern Africa by record length.

Country	Number of rainfall stations with record length (nyrs):					
	nyrs <20	20 ≤ nyrs < 30	30 ≤ nyrs < 45	45 ≤ nyrs < 60	nyrs ≥ 60	*Total*
Angola						*0*
Botswana	1	2	24	2	13	*42*
Lesotho		3	2	1		*6*
Malawi	41					*41*
Mozambique		56	32	8	1	*97*
Namibia			4	21	63	*88*
South Africa*					515	*515*
Swaziland	5	3	12	3	12	*35*
Tanzania	23	67	72	43	31	*236*
Zambia	9	3	19	4	3	*38*
Zimbabwe	5	19	14	1		*39*
Total	84	153	179	83	638	*1137*

* Only for selected stations as described in the text.

- Selection for interannual variability

Interannual rainfall variations are affected by variations in the background climatic variables in which the influences are usually coherent over a number of stations. The distribution in Fig.5.2a may not be necessarily advantageous over that of selected representative stations which retain the spatial even distribution. Therefore, additional criteria of most continuous daily records exceeding 45 years in the 1950-2000 period and the even distribution of stations within the 1°x1° grids were imposed on the South African records in areas where the distribution was dense. Only 149 South African rainfall stations were retained for interannual variability analysis (Fig.5.2b). However, not all stations satisfying the record length and missing data criteria were suitable for interannual variability analysis. An additional criterion of less than 4 consecutive missing values was imposed. This was important in avoiding erroneous results. For example, an 80-year record of annual rainfall amounts with 9 consecutive missing annual values satisfies the first two criteria but not the third. The distribution of missing monthly, seasonal and annual values within the time series with less than 15% missing was investigated. Those stations with 4 or more consecutive values missing were further investigated. If the reduction of the record length caused the removal of missing period(s) resulted in a record length of less than 30 years or the record not including the 1961-1990 period, the station was then rejected. The spatial distribution of the retained stations for interannual variability analysis is shown in Fig.5.2b.

- Monthly, seasonal and annual indices

Monthly rainfall indices for the retained stations were computed from daily observations only for complete months. Wherever daily observations were unavailable for calculation of monthly rainfall amounts, acquired monthly rainfall amounts (Fig.5.1b) were used. Seasonal rainfall indices were determined only for seasons in which all contributing months were non-missing. An annual index value was determined in the following ways. For stations with only monthly indices, annual index values were calculated for years with non-missing monthly indices. For stations where daily observations were available, annual index values were computed for years with less than 6 missing daily observations. Missing data during the dry season were not ignored. Further, a 6-day missing period would not result in missing a significant number of daily rainfall events.

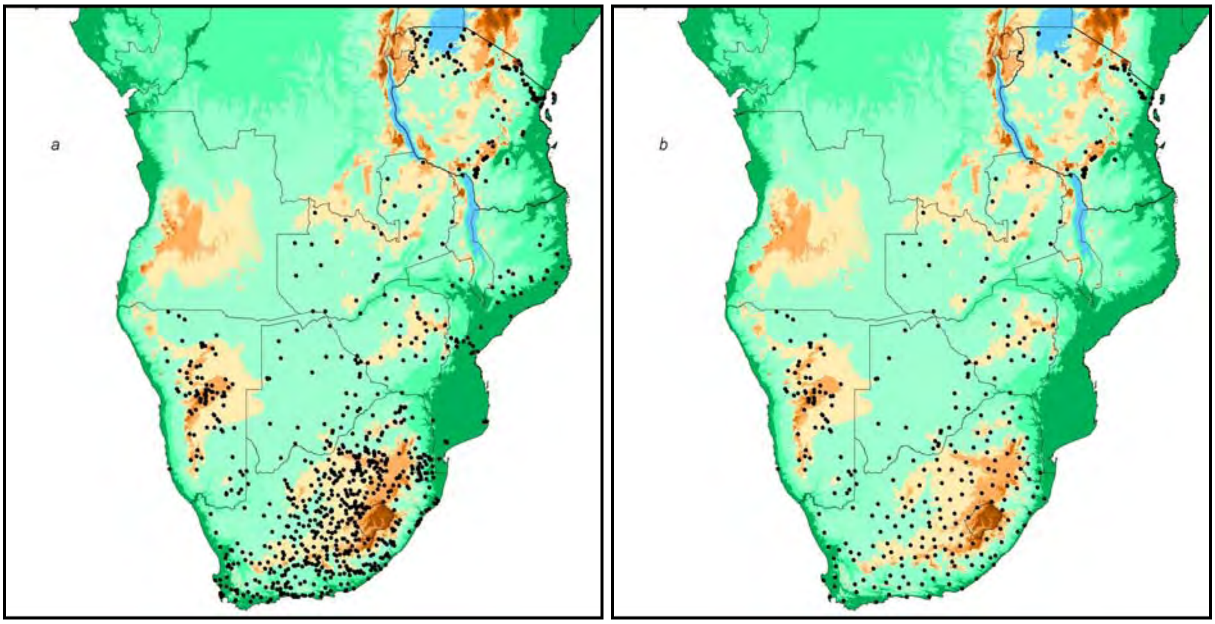

Fig.5.2: Spatial distribution of rainfall stations a) with at least 30 complete years of daily data and b) selected for trend and change-point analyses in southern Africa.

5.2.2.2 Time series reconstruction

The reconstruction of missing monthly, seasonal and annual values was done through their replacement by long-term averages. This way of series reconstruction may introduce an artificial drop (rise) in such periods of high (low) index values. The effect is considered low due to short length of consecutive missing values allowed in the present study and whenever the replacement by the long-term average was considered inappropriate, the missing value was replaced by a moving average value which approximately represented the trend pattern. Rainfall in the region is spatially highly variable in which two close stations have been found to exhibit different interannual variability patterns as indicated by their existence into different homogeneous regions. Therefore, the methods that use cross-stations correlations or regional averages in replacing the missing values at a station requires the use of stations within the coherent regions and so they were not used.

5.3 River flow data

5.3.1 Description of data sets

Average daily flow data in rivers in the 11 southern African countries have been acquired from the southern African FRIEND HYDATA database at the Department of Water Resources Engineering (WRE) of the University of Dar Es Salaam. The database was compiled by the Centre for Ecology and Hydrology (formerly the Institute of Hydrology, Wallingford) for the Southern African FRIEND. It comprises time series of average daily river flows for 676 gauging stations (Fig.5.3a) which have been used in previously studies (Berhanu, 1999; Berhanu *et al.*, 2001; Alemaw and Chaoka, 2002). Additional 23 records of average daily flows and updates of the 79 records in the FRIEND database for gauging stations in the Pangani and Rufiji basins in Tanzania were originally obtained from the Hydrology Section of the Department of Water Resources in the Ministry of Water and Livestock Development (Tanzania) and processed at the Department of Water Resources Engineering (WRE) of the University of Dar Es Salaam. Their quality is described in the Water Resources Engineering Programme report (WREP, 1999). Mean monthly discharges for the Shire River at Chiromo were obtained from a UNESCO (1995) report on selected rivers of Africa.

The spatial distribution of the river flow gauging stations is dense in the eastern, northeastern and southern South Africa, in the eastern and southwestern Zimbabwe, in central-western Namibia and in the two Pangani (northeast) and Rufiji (southwest) basins in Tanzania (Fig.5.3a). Table 5.2 indicates that the three countries South Africa, Tanzania and Zimbabwe together accounts for 68.7% of the available data and separately account for 39.9%, 17.0% and 11.8% of the available river flow data respectively. The flow data in Namibia, Malawi and Swaziland account separately for 5.0-6.6% of the available data while data in the remaining 5 countries account individually for 2.3-3.6%.

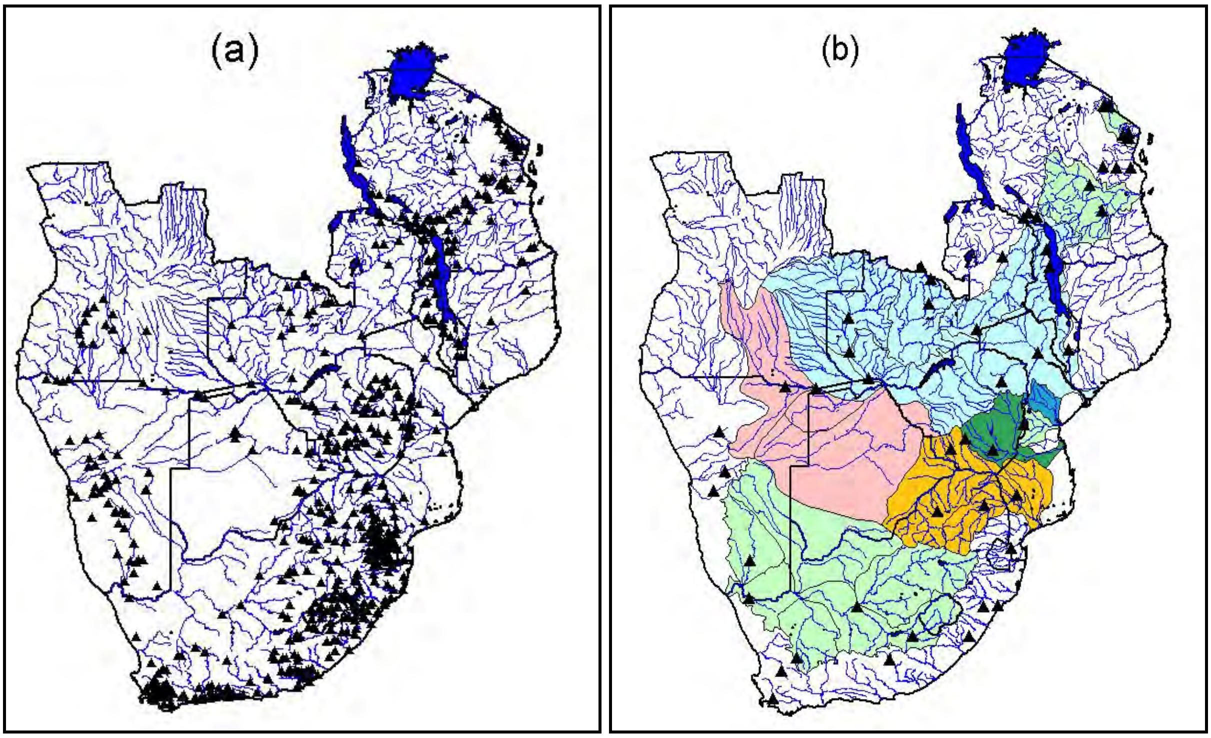

Fig.5.3: Spatial distribution of a) all stations with average daily flow data and b) selected flow gauging stations used in the interannual variability analysis in southern Africa. The coloured background indicates some of the shared river basins in the region (Fig.3.7 in section 3.5.2).

The available records were of variable quality, lengths as well as the periods of data. The available records varies from 1 year to over 50 years and span mainly the period 1940-1995. The longest records of 52 years are found in 3 South African gauging stations while 62.9% of the available records 20 years or more longer, about half of which (representing 31.6% of the available data) are at least 30 years. The flow records in Angola and Lesotho are less than 20 years in which only two Angolan flow records are 10 years long while the rest are less than 10 years and span mainly the 1963-1974 period. 32.1%, 19.3% and 11.5% of the available records in the database start respectively before 1961, 1956 and 1951 while 78.0% and 66.2% extend after 1985 and into the 1990s respectively. However, only 15.4% and 21.6% of the available records spanning the 1955-1985 and 1960-1990 periods respectively, most of which are found in South Africa.

5.3.2 Data selection and time series reconstruction

The preceding discussion indicates that the southern African region is characterised by short stream flow records indicating that they are not very appropriate for interannual variability analysis. This study is focused on a) interannual flow variations with respect to changing rainfall and landuse patterns and b) investigating whether or not changes in flow regimes are uniform across river basins.

Table 5.2: Summary of available mean daily river flow data in southern Africa by record length.

Country	Number of river flow gauging stations with record length (nyrs):						
	<5	5 ≤ nyrs < 10	10 ≤ nyrs < 20	20 ≤ nyrs < 30	nyrs ≥ 30	*Total by country*	*% of overall total*
Angola	3	14	2			*19*	*2.6*
Botswana	1	5	6	12		*24*	*3.3*
Lesotho		6	17			*23*	*3.2*
Malawi	1	7	9	5	15	*37*	*5.1*
Mozambique		1	4	8	3	*16*	*2.2*
Namibia		3	29	8	6	*46*	*6.4*
South Africa		2	52	113	120	*287*	*39.9*
Swaziland	2	3	16	6	8	*35*	*4.9*
Tanzania	8	15	27	29	43	*122*	*17.0*
Zambia			7	13	5	*25*	*3.5*
Zimbabwe		3	24	31	27	*85*	*11.8*
Total by record length	*15*	*59*	*193*	*225*	*227*	*719*	*100*
Percentage of overall total	*2.1*	*8.2*	*26.8*	*31.3*	*31.6*	*100*	

5.3.2.1 Data selection

The selection criteria of record length, missing data and period of interest as used in the selection of rainfall stations for interannual variability analysis were similarly applied to the flow records in addition to some other criteria. In order to study interannual flow variations with respect to interannual variations in rainfall, basins were selected according to the results of interannual rainfall variability analysis (Chapter 7). Analyses of rainfall indices show that areas such as the southern highlands of Tanzania, northern half of Mozambique and the South Africa lowveld where high rainfalls are observed are characterized by intense daily rainfall events and are prone to flooding. The western part of southern Africa is dry and rivers here experience frequent and prolonged dry conditions. Basins whose rivers drain these areas are of particular interest in studying relationships between rainfall and flow variations.

The selection process further excluded all gauging stations that were known to be located downstream of any artificial regulation point which regulates the flow measured at those particular stations. Gauging stations within the selected basins were further selected in such a way to avoid closely located gauges while retaining as many gauges as possible along the river lengths. This aimed at investigating the spatial variations of the changes of the river flows regimes, if any present, within the basins. The overall requirements of analysing long continuous records from unregulated catchments within the selected basins, therefore, retained 38 river flow record as shown in Fig.5.3b.

5.3.2.2 Time series reconstruction

Mean monthly flows were computed at each of the retained gauging station and only for months in which 90% of average daily flows were available. Using cross-correlations between different months, missing monthly flows were replaced by values computed from (Haan, 1977)

$$X_j = \frac{S_j}{S_{j\pm k}} \times r_{XjXj\pm k} \times X_{j\pm k} \tag{5.1}$$

only for months with a cross-correlation of at least 0.7. X_j and $X_{j\pm k}$ are monthly flows in month j and $j\pm k$. k is the time lead/lag between the two months that are highly correlated. $r_{xj,xj\pm k}$ is the coefficient of cross-correlation between X_j and $X_{j\pm k}$, Sx_j and $Sx_{j\pm k}$ are their respective standard deviations. The cross-correlations were computed for months at the same site and whenever low correlations prevailed, the correlations were computed between the gauging station under consideration and the nearby gauging stations either upstream, downstream or in the nearby river which is considered to be under almost the similar climatic, landuse and water use conditions. If filling was not possible, the monthly flow was considered missing.

The filling of missing monthly frequencies of excess (high) and deficit (low) flows was made first through investigation of the behaviour of the time series of average daily flows. The behaviour of the time series (increasing, decreasing or fluctuating flows) was investigated and flow magnitudes before and after the missing observations were compared to the threshold values. For the short gaps of less than 4 days a month, the missing daily observations were considered to be relatively not very different from those before and after the gap if the flows were significant higher (lower) than the threshold defining the high (low) flows before and after the gap and number of missing flows observations was added to the frequencies. Whenever the filling by this procedure was not possible particularly for the cases of fluctuating series or when the flows before and after the gap are on the opposite sides of the threshold such as, for example, flows before the gap are above (below) the threshold flow and those after the gap are below (above) the threshold. In such cases, the cross-correlation procedure described for monthly flows was used. The filling of monthly flow volumes was done in a similar way as for monthly flows.

Mean seasonal and annual flow indices were calculated for years with non-missing monthly indices and the missing values replaced by values computed from filled monthly indices.

5.4 Climatic data

5.4.1 Sea surface temperatures (SST) and indices of El Niño

Time series of 5° × 5° gridded monthly mean SST were obtained from the United Kingdom Meteorological Office (UKMO) Global Sea-Ice and SST (GISST 2.3b) data set (Rayner *et al.*, 1996). The data span the period January 1856 to December 1999. Indices of El Niño were acquired from the Climate Analysis Section (CAS) of the National Center for Atmospheric Research (NCAR) and include area average SST in the 4 Niño regions (Niño1 - Niño4; Niño1.2 and Niño3.4. regions) and the Trans-Niño Index (TNI). The TNI and Niño3.4 data span the period January 1871 to September 2000 while Niño1.2, niño3 and niño4 data span the period January 1950 to November 2001.

The quality of pre-1950 SST analyses is not as good as in the recent years and data are frequently missing in the Atlantic and Indian ocean basins. Data are very often sparse and their quality is restricted by the method of spatial analysis used (Trenberth, 2001). Therefore, only the period 1950 to present is used in the analyses in this study.

5.4.2 Sea level pressure (SLP) and southern oscillation index (SOI)

Time series of monthly SLP were obtained from various sources. Monthly mean SLP data at both Darwin and Tahiti have been acquired from the Climate Research Unit (CRU)[10] of the University of East Anglia (UEA), Norwich, UK. These data span the period January 1866 (Darwin)/June 1855 to June 1998. Similar time series of monthly SLP at Darwin and Tahiti were obtained from CAS[11] of NCAR. They span the period January 1951 to December 2000. Time series of monthly SOI values were obtained from CSIRO[12] division of Atmospheric Research of the CSIRO Environment and Natural Resources Alliance (Australia), CRU (UK) and CAS (USA). The CAS data set spans the period January 1882 to December 2000, that of CSIRO January 1886 to October 2000 while that of CRU January

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[10] http://www.cru.uea.ac.uk/cru
[11] www.cgd.ucar.edu/cas/indices
[12] http://www.dar.csiro.au/

1866 to December 2002. The CSIRO data set has been computed relative to the 1933-1992 base period used by the National Climate Centre of the Australian Bureau of Meteorology.

5.4.3 Atmospheric data

Atmospheric National Center for Environmental Predictions(NCEP)/NCAR monthly re-analyses (Kalnay *et al.*, 1996) were acquired from NCEP/NCAR and include the atmospheric wind speeds, geopotential height and air temperature. The reanalyses span the preiod January 1948 to December 2001. Despite being extending back into the late-1940s, the upper air reanalyses prior to 1968 are not fully reliable for the African continent (Camberlin *et al.*, 2001) and therefore only the period after 1968 is used in this study.

CHAPTER 6

DAILY RAINFALL CHARACTERISTICS AND SPATIAL VARIATIONS OF RAINFALL AMOUNTS AND NUMBER OF EVENTS

6.1 Introduction

The spatio-temporal variability of accumulated (overall) rainfall amounts at monthly, seasonal and annual timescales have been investigated in a number of studies. Some studies have investigated the spatio-temporal variability of the number of rainfall events while others have included variability of intensity maxima. However, monthly, seasonal and annual rainfall amounts and number of rainfall events are a result of accumulation of different types of daily rainfall events. It is therefore necessary to go beyond the analysis of spatio-temporal variability of these overall rainfall amounts and number of rainfall events by investigating spatio-temporal characteristics of daily rainfall. The daily timescale is the shortest duration in which data were available for this study.

This chapter explores spatial variations of indices established from daily rainfall intensities at monthly and annual timescales in southern Africa. They include monthly and annual rainfall amounts, number of rainfall events and maximum daily intensities. A peak-over-threshold (POT) method is used to establish daily rainfall intensities that correspond to different relative frequencies (probabilities), the exceedence intensities, which are then used in grouping daily intensities in southern Africa into different classes. Rainfall amounts and number of rainfall events are computed for each class of daily intensities and for each month, season and year and their spatial variations are investigated.

It should be noted that spatial interpolation technique of Kriging was used to derive contours in this study. This method was found to provide better spatial patterns in northeast Tanzania (Abass, 1999). However, this method cannot provide better estimate through the southern Africa region as found by Lynch and Schulze (1995) and Lynch (1998) compared to several other methods like the Schafer method, inverse square distance method (Lynch, 1998), multiple regression methods (Dent *et al*., 1989), etc. Moreover, the spatial interpolation in complex physiography requires a dense and representative distribution of raingauges to provide more accurate estimates. Despite efforts made, this could not be ensured due to data problems and therefore the contours in the figures might have been affected by this fact.

To simplify the presentation and discussion, the following terms are used in this chapter and hold for the rest of the document, unless stated otherwise:

- A rain day is any day of a year in which an amount of rainfall has been measured and recorded as non-zero intensity. This definition is not applicable in chapter 8 on rainy seasons.
- Overall monthly or annual rainfall amounts refer to the amounts of rainfall accumulated over a given month or single year for all types of daily rainfall events. For simplicity, monthly and annual amounts refer to these quantities.
- Overall monthly or annual number of daily rainfall events are simply referred to as monthly or annual rainfall events and indicate the total number of all types of daily rainfall events within the given month or year.
- Monthly or annual class X rainfall amounts refer to the amounts of rainfall accumulated over a given month or year for all daily rainfall events which belong to the class X of daily rainfall intensities. For simplicity, monthly or annual class X amounts refer to these quantities.
- Monthly or annual number of daily rainfall events which belong to the class X of daily rainfall intensities are simply referred to as monthly or annual class X rainfall events.
- A monthly or an annual daily intensity maximum is the highest daily intensity that have been recorded in that particular month or year.

6.2 Average daily intensities

Rainy seasons are characterised by varying amounts of rainfall received each day, between which sequences of completely dry days are typical. It is useful to represent the time-varying daily rainfall intensities by a few statistics that appropriately describe the inherent temporal variations. Average daily rainfall intensities (ADI) and the standard deviation of intensities are often used. However, these two statistics can be derived using all available records (all-record statistics) or derived for a particular month or season (monthly or seasonal statistics).

All-record average daily rainfall intensity (AADI) is defined as the average daily intensity computed from all daily rainfall intensities. This quantity refers, roughly, to the expected daily amount of rainfall at a particular place within the rainy season. However, it does not indicate the seasonality of rainfall within the year. Monthly and seasonal ADI are determined likewise using daily rainfall in particular months or seasons. Rainfall seasonality is addressed through comparison of monthly ADI and the AADI.

Southern Africa is characterised by an west-east/north-south increase of AADI (Fig.6.1) in which the lowest AADI are found in the Namib desert along the southern coast of Namibia and northwest South Africa while the highest characterise central Mozambique and the southwest highlands of Tanzania

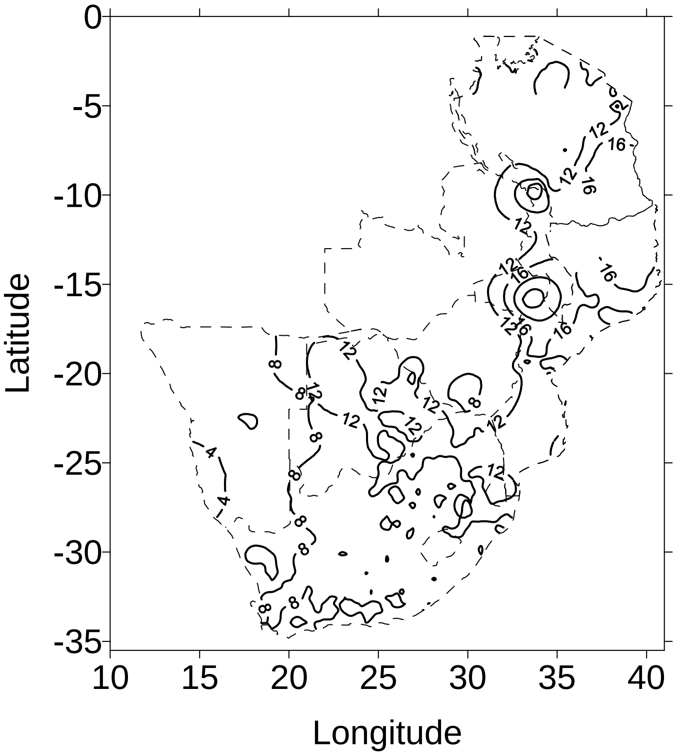


Fig.6.1: Spatial variation of AADI (in mm) in southern Africa.

Standardised percentage deviations of mean monthly ADI (computed as percentage departures from their respective AADI) (Fig.6.2) show a substantial change between October and November across much of southern Africa marking the start of the wet season. The high negative percentage deviations in October are significantly reduced and changed to positive percentage deviations in November, except in the southwestern part of the region (western Namibia and western South Africa). The November ADI equals or exceeds AADI in the northern and eastern parts of southern Africa including eastern South Africa, southern Mozambique, Zimbabwe and Tanzania. Monthly ADI values for December through February persist above AADI as indicated by positive percentage departures, the period when the highest monthly ADI are observed in central Mozambique. After March, there is a progressive decrease of monthly ADI, which remain above AADI only in Tanzania in April and in northeast Tanzania in May.

Despite a gradual increase in monthly ADI in Namibia after October, only January ADI values exceed AADI in northern Namibia and persist above AADI until March with a peak in February. In southwest South Africa, monthly ADI values decrease progressively between September and February and thereafter increase and exceed AADI in the May to September period with a peak in June-July.

AADI and ADI are derived only from amounts and number of days with measurable rainfall. Repetitive occurrences of one or two isolated intense rainfall events during the dry months cause non-zero monthly ADI even during the known June-September dry period in southern Africa. The study of ADI has simply highlighted spatial variation of expected daily intensities across southern Africa. Subsequent sections are devoted to analysing spatial variations of rainfall amounts and number of rainfall events, the two quantities which were used to derive ADI's.

6.3 Overall rainfall amounts (totals)

Mean annual rainfall (MAP) varies from as high as 2708.4 mm to below 100 mm with a general decrease from the north/east coast to south/southwest and its spatial pattern of variation distinguishes the dry southwestern part from the "humid" eastern and northern parts (Fig.6.3a). Low MAP and high interannual variations of annual rainfall characterise the dry areas of central Tanzania, Botswana, Namibia and most of the western half of South Africa (Fig.6.3a, 6.3d). The relatively dry part of Tanzania, extending from central areas to the northeast in the lee of the mountains, receives between 500 mm and 750 mm of rainfall annually (Fig.6.3a). The eastern Zimbabwe Manicaland mountains and the Drakensberg chain prevent moist air from the Indian Ocean from reaching the interior and western part of southern Africa and consequently, areas in the lee of these mountains are mostly dry receiving less than 500 mm of rainfall annually, mainly from less than 100 mm in the Namib desert along the Namibian coast to about 400-500 mm in Botswana.

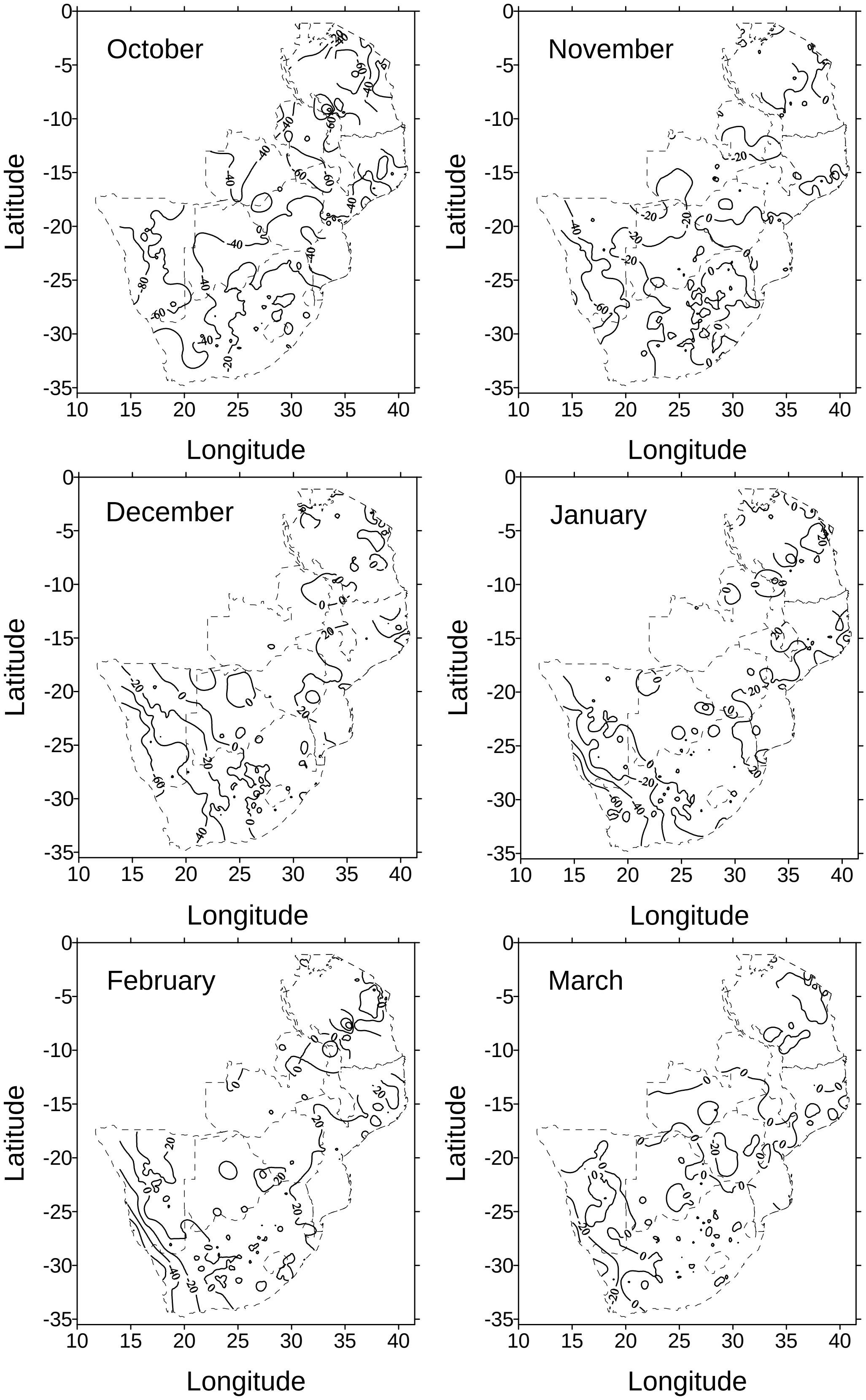


Fig.6.2: Monthly ADI (% departures from AADI) in southern Africa.

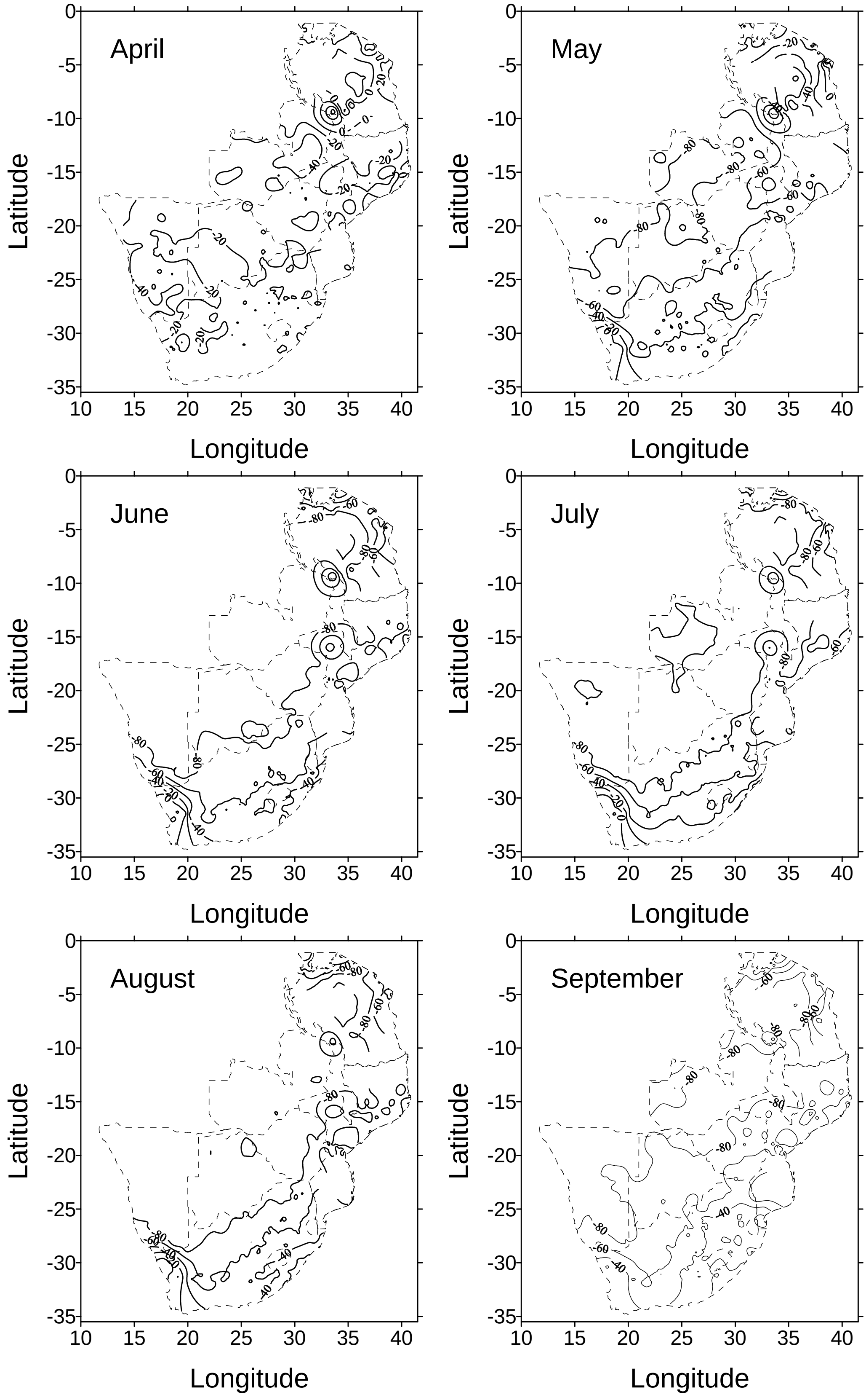


Fig.6.2: Monthly ADI (% departures from AADI) in southern Africa (*Continued*).

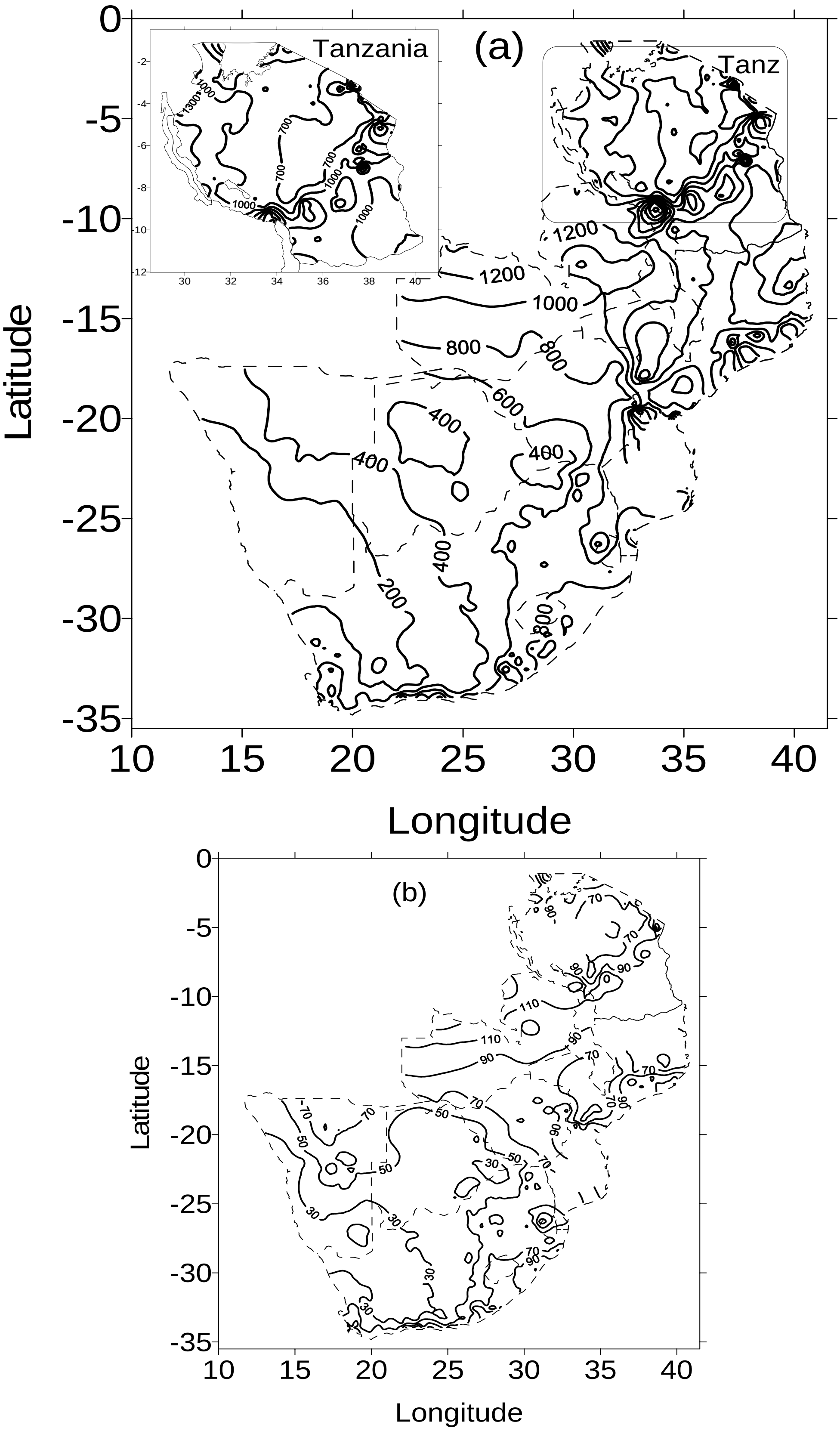


Fig.6.3: Spatial variations of mean a) annual totals, b) annual number of rainfall events, c) mean annual maximum intensity (mm) and corresponding spatial variations of cv of d) annual totals, e) annual frequencies and f) annual intensity maxima in southern Africa.

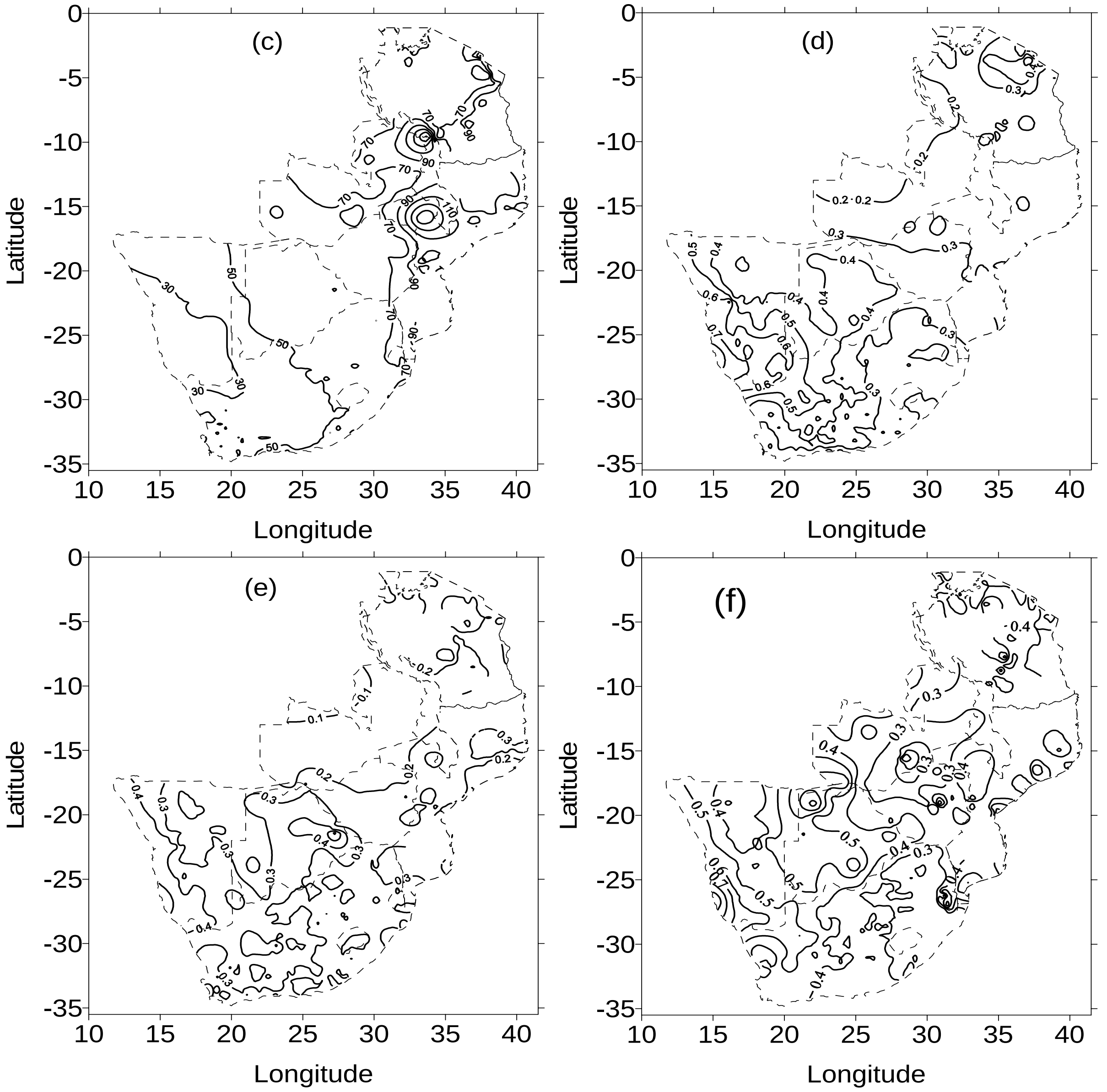


Fig.6.3: Spatial variations of mean a) annual totals, b) annual number of rainfall events, c) mean annual maximum intensity (mm) and corresponding spatial variations of cv of d) annual totals, e) annual frequencies and f) annual intensity maxima in southern Africa (*Continued*).

The rest of southern Africa is characterised by MAP exceeding 600 mm, typically between 700 mm and 1200 mm and low interannual variations of annual rainfall. MAP is generally high in Mozambique and along the northern coast, in the mountains and in the northwestern Lake Victoria in Tanzania and typically exceeds 1000 mm. Lake circulations and orography have been considered to be the cause of high rainfalls in the Lake Victoria region, in the mountains of northeast and southwest Tanzania (Nyenzi *et al.*, 1999). Cyclonic flows within the Mozambique channel and the TTTs have been linked to high rainfall in the adjacent low-lying areas of the central Mozambique.

Spatially, MAP variations reflect the orientation of the ITCZ and in general the low-level circulation features associated with moisture distribution in the region (see Nicholson, 1996; Okoola and Ambenje, 2003). The main features of the spatial pattern of monthly rainfall are briefly discussed below.

Mean monthly amounts indicate a i) relatively dry period of June through September (JJAS) in most of southern Africa except in the coastal and mountainous northeast Tanzania and in the Western Cape and b) a wet period of October-May (Fig.6.4).

- The beginning of the wet season is characterised by significant increases in rainfall amounts between October and November which are linked to the southward displacement of the ITCZ into southern Africa. The early summer months of October and November are characterised by the meridional rainfall distribution.
- The ITCZ is well developed and remains in the 12°S-15°S latitudes between December and February, the highest monthly amounts, exceeding 200 mm, occur in the December-March period and characterise the northwest-southwest (zonally) oriented region extending from western Zambia/western Tanzania through Malawi and northern Zimbabwe to northern and central Mozambique. Spatially, the variation is more or less zonally in the equatorial and tropical southern Africa and meridionally in the southwestern part.
- The end of the wet season in the southern part of the region is marked by a progressive decrease of rainfall amounts and northward/ eastward displacement of the zones of high rainfall. The southwest-northeast-oriented contours in Tanzania (see April, Fig.6.4) and meridionally-orientated contours in Mozambique and the east coast of South Africa correspond to the southeasterlies and easterlies which bring moisture from the southwest and tropical Indian ocean into these parts.
- The period June through September is relatively dry except in the Western Cape which receives most of its annual amount during this period, mean monthly amounts vary between 25 mm and 190 mm while in northeast Tanzania, they exceed 60 mm.

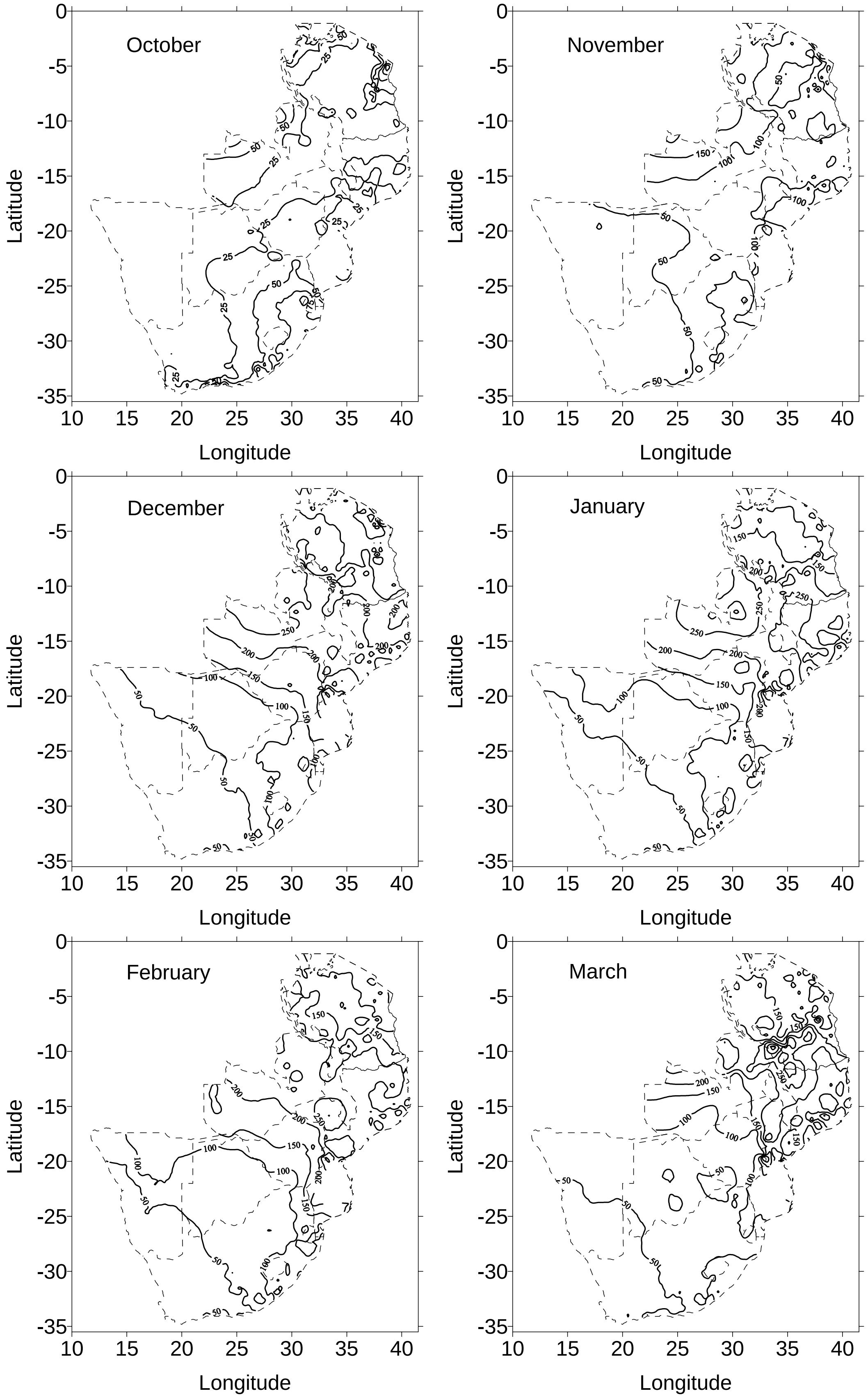


Fig.6.4: Spatial variation of mean monthly rainfall in southern Africa.

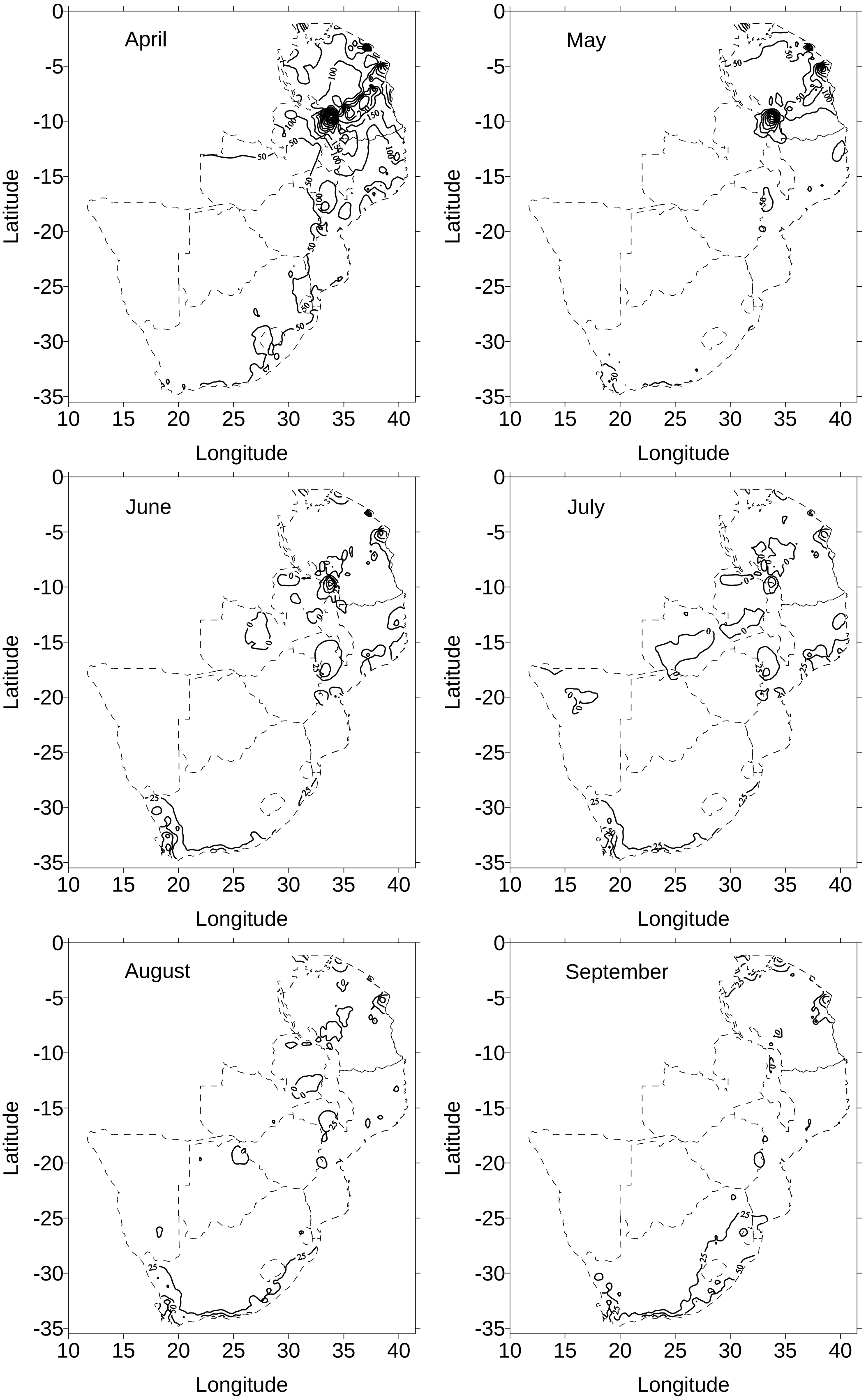


Fig.6.4: Spatial variation of mean monthly rainfall in southern Africa (*Continued*).

- Despite the highest mean amounts being observed in the northern Lake Malawi region of the southern highlands (Tanzania), stations in the northwest record about twice the rainfall compared to those in the northeast. MAP in the northwest varies between 2040 mm and 2708 mm with the highest MAP observed at the lake, while it is between 1030 mm and 1150 mm in the northeast. Except for the spatial locations, the other station details like altitude are similar suggesting the possible role of lake-land thermal contrast. However, no detailed studies have yet quantified the influence of Lake Malawi on rainfall in the surrounding areas.

6.4 Overall number of rainfall events

The spatial patterns of variation of annual and monthly number of rainfall events are shown in Fig.6.3b and Fig.6.5, respectively and are very similar to those of rainfall amounts and therefore are not discussed in detail. Only those features that differ from the rainfall amounts or which were not very apparent, are discussed.

- Despite having lower MAP than the neighbouring southern highlands and central Mozambique, much of Zambia receives the highest number of daily rainfall events in southern Africa, significantly exceeding those in the two high rainfall areas.
- Central Mozambique receives a lower number of rainfall events than the southern highlands of Tanzania. Despite experiencing the highest MAP, low AADI in areas in the southern highlands of Tanzania compared to AADI in central Mozambique are caused by a significant difference in the number of daily rainfall events which contribute to MAP.
- The interannual variations of annual number of rainfall events is low to moderate even in the dry southwestern part of southern Africa (Fig.6.3e) which are characterised by high interannual variations in annual amounts (Fig.6.3d).
- The zonally-oriented contours along the southern part of South Africa correspond to moisture advection from the Agulhas Current.
- The areas in coastal northeast Tanzania and southern South Africa which experience rainfall throughout the year are characterised by 2-7 daily rainfall events a month. Moreover, the eastern coast of the region receives rainfall, on average, at least 2 days throughout the year.

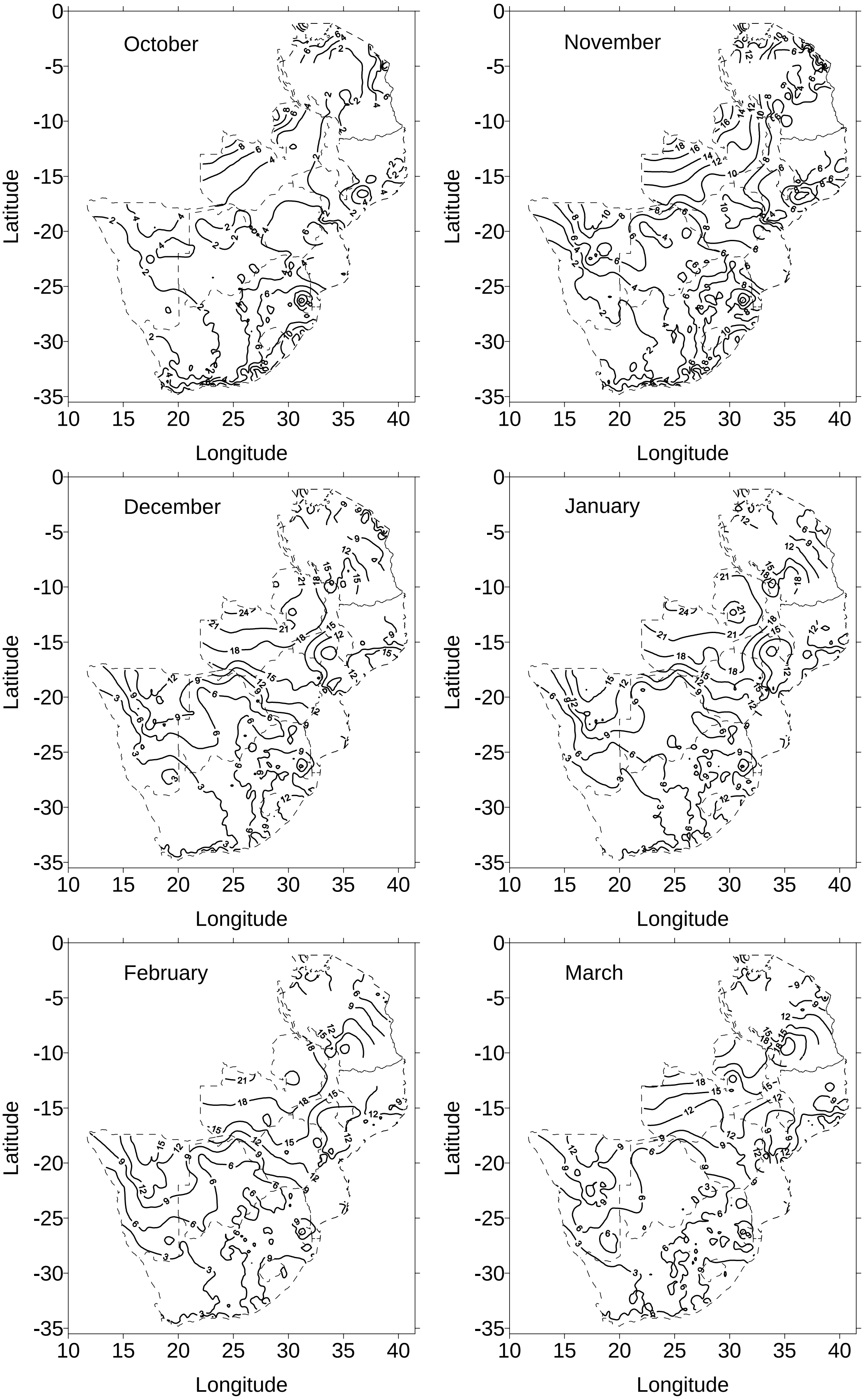


Fig.6.5: Spatial variations of mean monthly number of rainfall events in southern Africa.

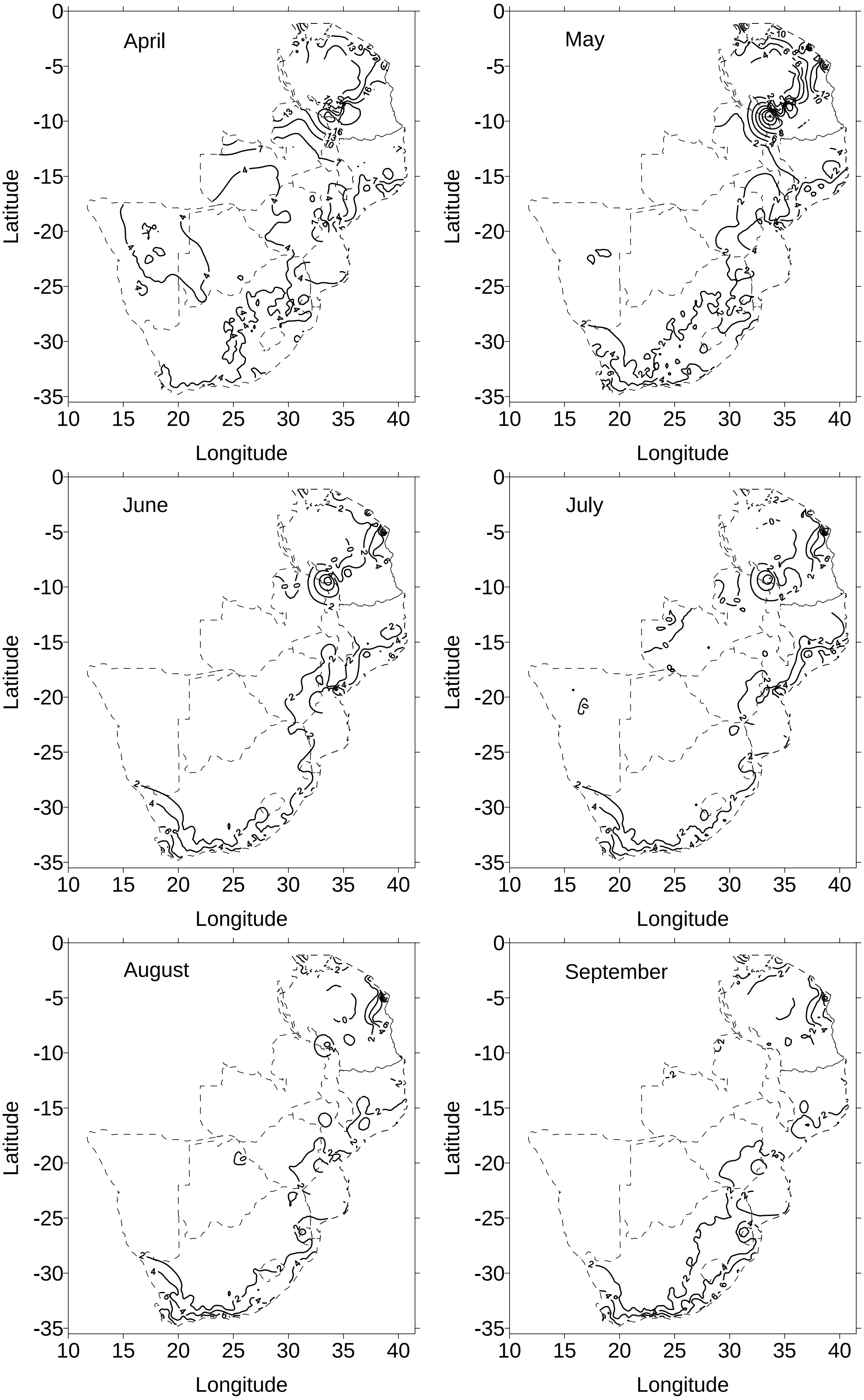


Fig.6.5: Spatial variations of mean monthly number of rainfall events in southern Africa (*Continued*).

6.5 Annual daily intensity maxima

6.5.1 Spatial variation of average intensity maxima

Maximum daily intensities are variable both in time and in space. The average annual daily intensity maxima (Fig.6.3c) are computed as averages of annual daily intensity maxima. Spatially, the highest daily intensity maxima characterise the high rainfall areas of southwest Tanzania (the southern highlands) and central Mozambique while the lowest are found in the dry southern and southwestern parts of southern Africa. The interannual variation of annual intensity maxima (Fig.6.3f) is identical to that of annual amounts as indicated by a similar spatial pattern of variation and almost the same magnitudes of coefficients of variations (compare Fig.6.3d and 6.3f).

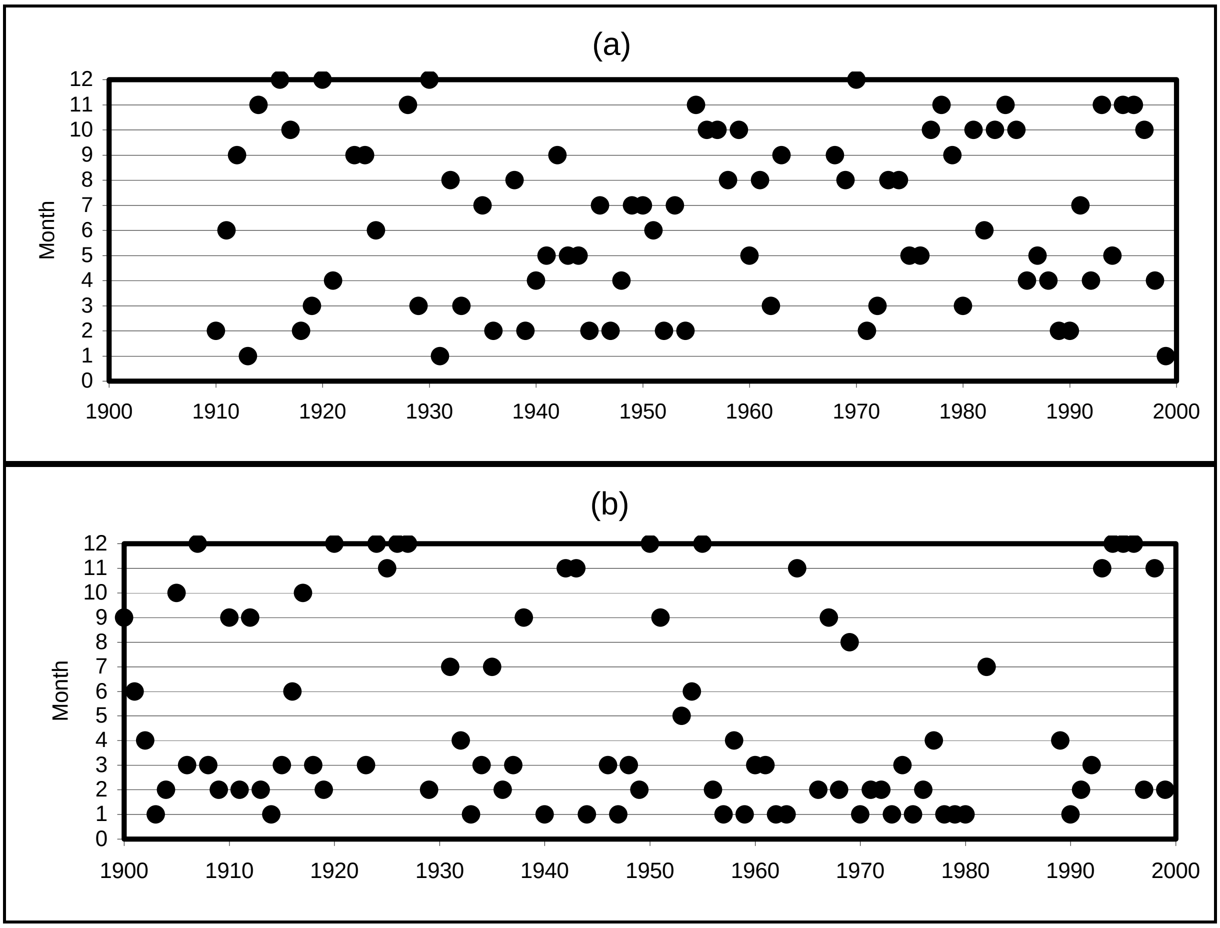


Fig.6.6: Variation of the month of annual daily intensity maxima at a) Goudveld (BOS) and b) Keilands in the southern part of South Africa.

6.5.2 Months of annual intensity maxima

Investigations of time series of daily rainfall and of monthly daily maxima further indicated temporal variations associated with the month in which the annual daily intensity maxima are observed. Along the southern coast of South Africa, for example, annual daily rainfall maximum can occur in any month of the year (Fig.6.6a) while in the Eastern Cape, it mainly occurs during the December-March period (Fig.6.6b), although it can occur in other months as well.

Where the annual intensity maxima are relatively high (Fig.6.3c), a precise knowledge of the period (months) in which they are most likely to be experienced is of utmost important in relation to the reduction of their impacts. The following procedure was used to establish these months in the region. At each station, one standard deviation of the annual daily intensity maxima was added to the average annual daily intensity maxima and the resulting intensities (mean + 1 standard deviation) was subtracted from the average monthly daily intensity maxima. The months showing positive departures were considered as the months of high rainfall intensities and which are most likely to experience the annual daily intensity maxima and are shown in Fig.6.7.

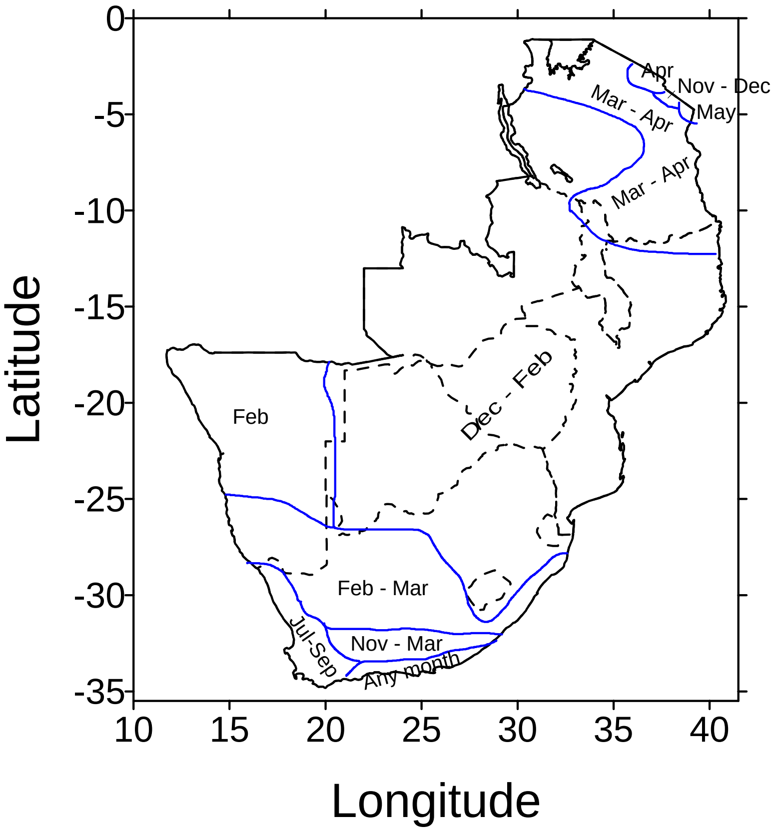


Fig.6.7: Spatial variation of months of annual intensity maxima in southern Africa.

It is observed that most of Tanzania experiences its highest daily rainfall in the March-April period while northeast Tanzania has two other periods of maximum intensities. Areas between the northern mountains (Kilimanjaro and Meru) and southern Usambara Mountains have their highest daily rainfall amounts during the short rains, in November or December. Areas lying north of the Usambara and Pare Mountains experience their highest daily rainfall in May. Most of Namibia experiences intense daily events in February while they are experienced in the western coast of South Africa in July-September and mainly in September. In the southern coast of South Africa, annual daily intensity maxima can be experienced in any month of the year. This is exemplified by the daily intensity maxima at Goudveld (BOS) (Fig.6.6a). Intense midlatitude cut-off lows (described in section 3.6.1.2) have been linked to heavy rainfall events in the Western Cape (Reason *et al.*, 2002) and southern coast of South Africa (Tyson, 1986; Jury *et al.*, 1993) in which the warm Agulhas current acts as the main source of moisture for these systems. The areas between 32°S and the northern boundary of the southern coastal region experience annual daily intensity maxima between November and March (e.g. Fig.6.6b). Elsewhere in southern Africa, intensity maxima are experienced in December, January or February.

Records of daily rainfall in southern Africa show further that wet years are characterised by multiple intense daily events that are well above average annual daily intensity maxima. In relatively dry years, low daily intensities are a characteristic. An all-record average annual daily intensity maximum of 150.3 mm at Kwiro Mission in the southern highlands in Tanzania, for example, was exceeded 3 times in 1978/79 (260.0 mm in November 1978, 226.1 mm in March 1979 and 165.0 mm in April 1979) while the period October 1966 to December 1971 recorded only 2 daily events whose rainfall amounts exceeded 100 mm (123.7 mm in November 1969 and 120.0 mm in February 1970). The extraction of a single maximum intensity for each year, therefore, would fail to account for the multiplicity of intense daily events. The Peak-over-threshold method, which selects all intensities exceeding a predefined intensity limit (threshold), would better address the impacts of multiple extreme events during dry and wet years. This method is used in grouping daily intensities into different classes. Threshold (exceedence) intensities, P*f*, are objectively established and used in defining classes of daily intensities in southern Africa.

6.6 Classifying daily rainfall intensities

6.6.1 Exceedence daily rainfall intensities

Results show that the lowest P*f* occur in the drier southwestern part of southern Africa while the highest P*f* values characterise the humid northern and eastern parts, east of about 30°E and north of about 30°S (see e.g. Fig.6.8). The non-zero intensities that have been equalled or exceeded for 40-95% of the time when it rains (P40-P95), spatially, have a small range of values in southern Africa. This is illustrated in Fig.6.8 in which P90 are mainly below 2 mm across the region and all stations in Namibia, Zambia and Zimbabwe having values below 1.5 mm. It was further observed that the intensities which have been equalled or exceeded for 30-40% of the time when it rains (P30-P40) approximately equalled the AADI indicating that 60-70% of the daily rainfall events at most locations in southern Africa are less than the expected daily rainfall intensities.

The daily intensities which have been equalled or exceeded for 5-25% of the time when it rains (P5-P25) represent, on average, between 124.4% and 391.2% of the AADI and are spatially highly variable across southern Africa (P5 and P10 in Fig. 6.8). The highest P5, for example, exceeds 55 mm in southwest Tanzania and central Mozambique, while it is below 26 mm in Namibia. The spatial differences, however, reduce from P5 towards P25.

6.6.2 Classes of daily rainfall intensities

About 60-70% of the daily rainfall events in southern Africa are less than the all-record average daily rainfall intensities (AADI) which vary typically in the range 8-12mm (Fig.6.1). Therefore, a daily intensity of approximately 10 mm can be used to separate the most frequent daily events in the region from other events. However, daily intensities below 1 mm, which approximately represent the P90-P95, are highly susceptible to errors (Mekis and Hogg, 1999) and hence are separated from the rest of the most frequent (below 10 mm) daily intensities. The first two classes (I and II), therefore, comprise the intensity ranges 0.1-0.9 mm and 1.0-9.9 mm. Daily intensities exceeding 10 mm, approximately represented by high P*f* (P25-P5), exhibit high spatial variations and despite the low P*f* in the southwestern part of southern Africa, daily events with intensities equalling or exceeding 40 mm have been recorded. Equal intervals were then used to group daily intensities exceeding 10 mm into broad classes which include the class III, class IV, class V and class VI representing respectively 10-19.9 mm, 20-29.9 mm, 30-39.9 mm and intensities equalling or exceeding 40 mm.

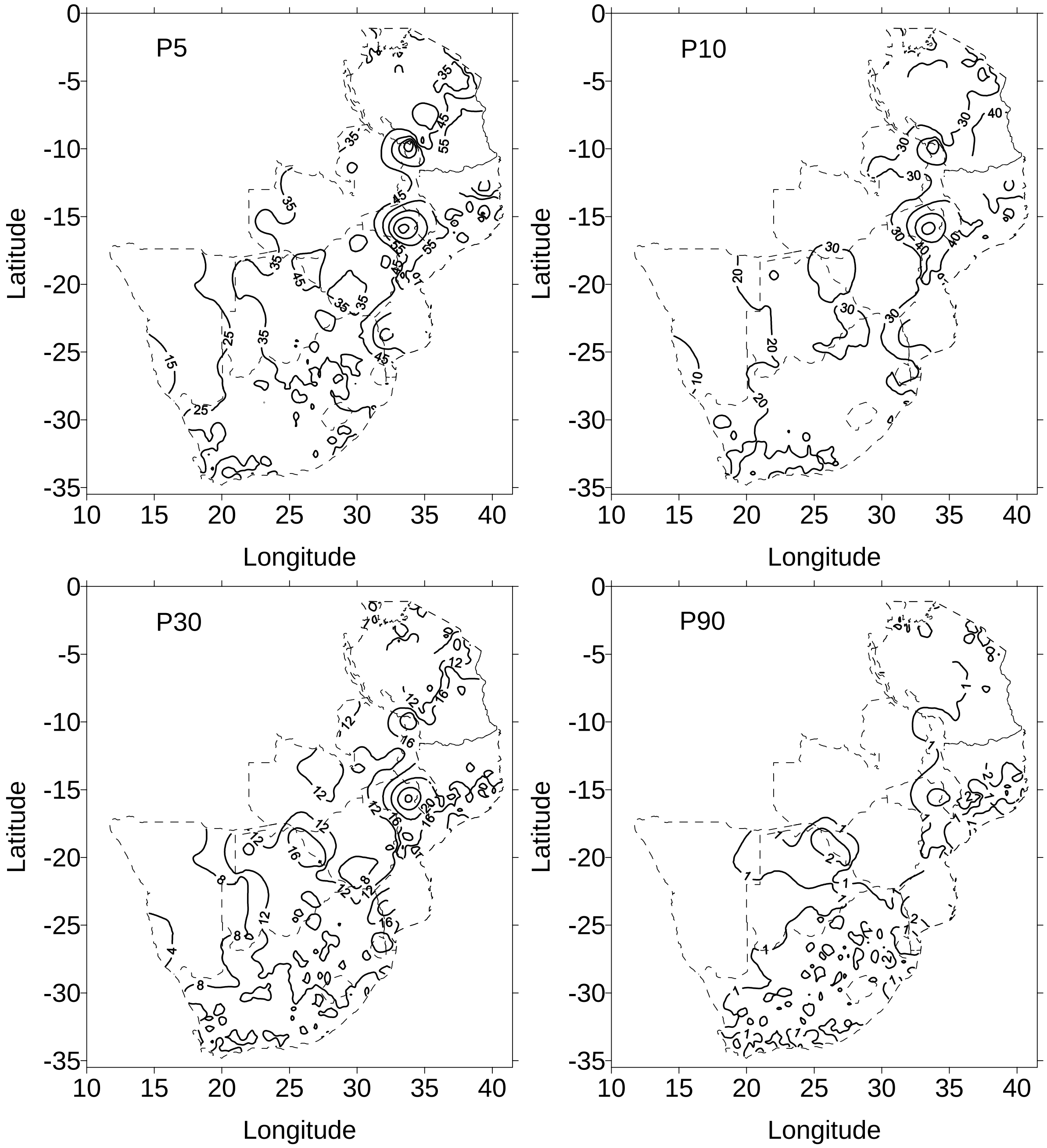


Fig.6.8: Spatial variations of some threshold intensities in southern Africa.

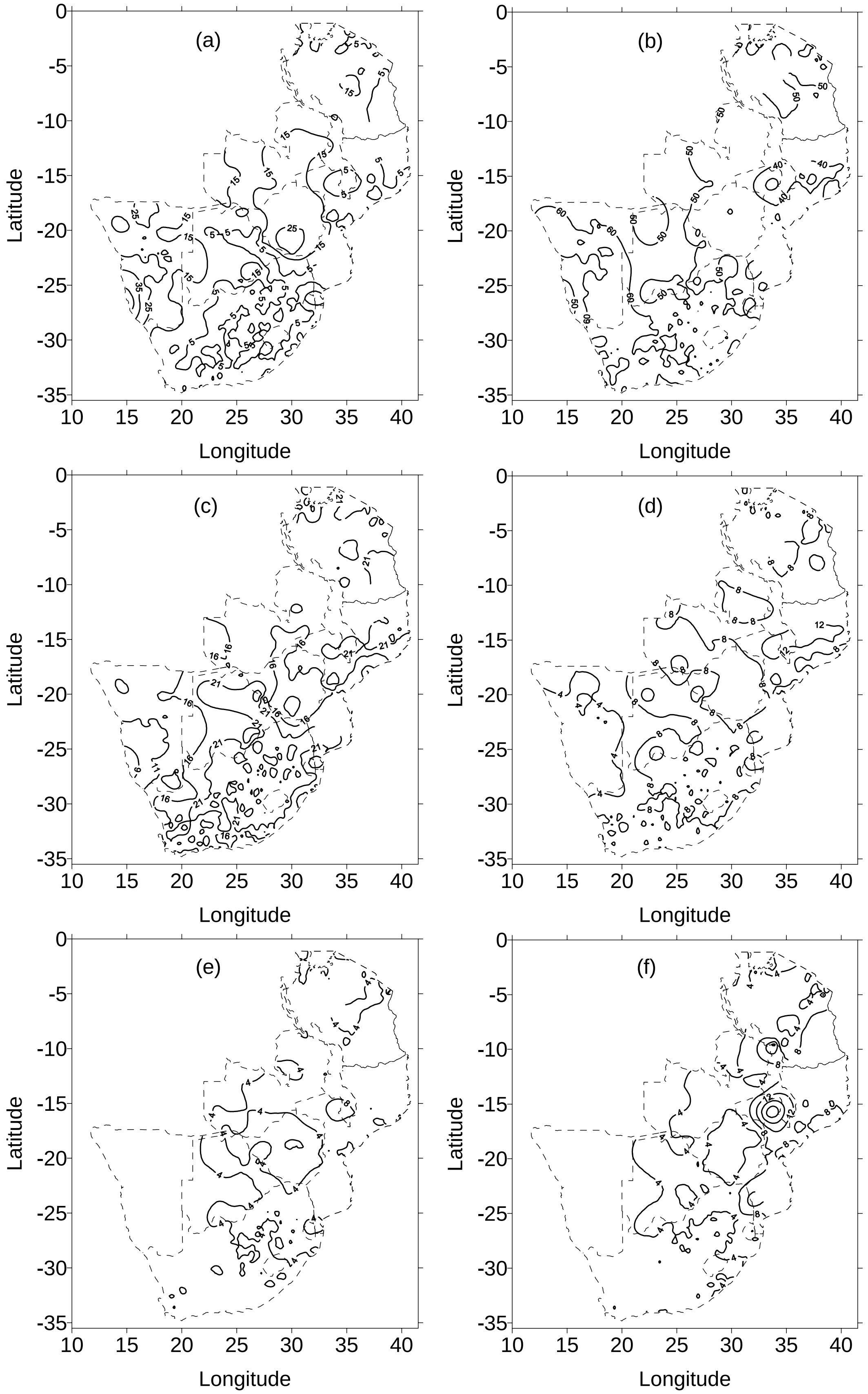


Fig.6.9: Spatial variation of annual number of a) class I, b) class II, c) class III, d) class IV, e) class V and f) class VI daily rainfall events in southern Africa, expressed as percentages of annual daily rainfall events.

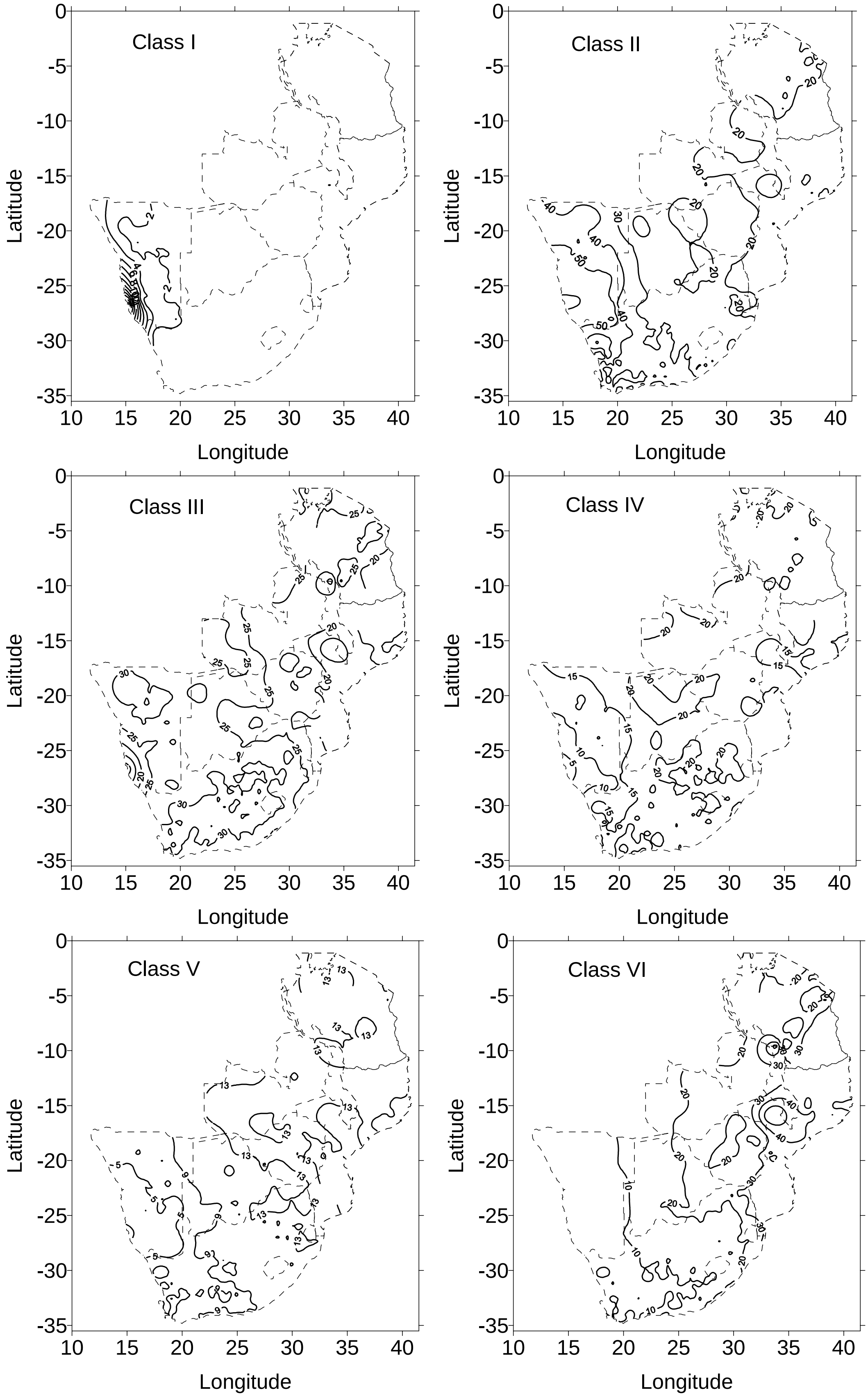


Fig.6.10: Spatial variation of mean annual rainfall amounts in each intensity class expressed as percentage of annual total rainfall.

The spatial patterns of variation are shown in Fig.6.9 for annual rainfall events, in Fig.6.10 for annual amounts and in Fig.6.11 only for monthly rainfall events in the classes II and IV. They indicate mainly increasing percentages for the four lower classes (Class I to class IV) and decreasing for the higher two classes (Class V and VI) from the eastern coast and northern areas of the region towards the west and southwest (Figs.6.9 and 6.10). That is, the low intensity daily events are the most frequent rainfall events in the western/southwestern part of the region. The patterns are more meridional than zonal, particularly for the class II, III and VI and are more evident in rainfall amounts (Fig.6.10) than in the number of rainfall events (Fig.6.9).

- The decreasing contribution of high rainfall from the east to the west suggests the importance of the moisture from the Indian Ocean and its redistribution in southern African by atmospheric winds and the combined influences of the dry air from the south Atlantic and eastern mountain chains (Drakensberg chain in eastern South Africa and the Manicaland Mountains in eastern Zimbabwe) on rainfall in the interior and southwestern areas of the region. These areas are found in the lee of these eastern mountain chains which block the penetration of the moist southwest Indian Ocean winds into the western parts while the southwesterly flow from the coastal zone brings dry air into the adjacent interior (Jury and Engert, 1999). Therefore, Namibia, being located farthest from the moist Indian or Congo sources and closest to the dry south Atlantic source, has its highest percentages of annual rainfall events (59-86%) and amounts (67-85%) contributed by daily intensities less than 20 mm. The lowest percentages of low intensity daily events in Namibia, however, characterise the northeastern part, in which, part of its rainfall is caused by the moisture advected from the Congo basin and the equatorial and tropical Atlantic (van Regenmortel, 1995; Jury and Engert, 1999).
- The lowest contributions of the lower two classes (classes I and II) and highest percentages of the higher two classes (class V and VI) to annual amounts are found in central Mozambique. A multiplicity of factors favourable for their occurrence in the two areas of Mozambique are observed during the wet season. The zonal branch of the ITCZ is located over parts of central Mozambique during the December-February period which is also the main season of the tropical cyclones in the western tropical Indian Ocean (Camberlin and Shanko, 1998 and references therein) and the period when the TTTs are most likely to occur (Todd and Washington, 1999ab). The

result is enormous convergence of moist air from the Congo basin, south Madagascar and tropical and equatorial Indian Ocean over central Mozambique favouring the occurrence of heavy rainfall events over light events. Floods have been mostly observed during the same period in Mozambique, such as that which occurred in February-March 2000.

- Similarly, these intense daily rainfall events are also observed in the northern Lake Malawi region in the southern highlands of Tanzania in April. Unlike the Mozambique case, the influences of the cyclonic activities over the Mozambique Channel and eastern Madagascar and those of the TTTs are low or absent and it is the northward displaced ITCZ into the country that brings the zone of convergence into the areas favouring the occurrence of heavy events in the southern highlands of Tanzania. Flooding almost every year during the March-April period of the Kiwila River, with headwaters in the southwestern part of the southern highlands and draining into northern Lake Malawi, (Kachroo *et al.*, 1999) can be related to these intense events which usually occur late in the season when soils are wet due to early season rainfall.
- Results further show that these intense daily events can be observed in November and March in the southern part of Southern Africa, except in southwest Namibia and the Western Cape.
- The dry June-September rainfall in northeast Tanzania, the northern Lake Victoria and in the areas along the coast of South Africa mainly experience class II daily events (Fig.6.11a) and occasionally class I and class III daily rainfall events (not shown). It is unlikely that other types of daily rainfall events will occur during this period.

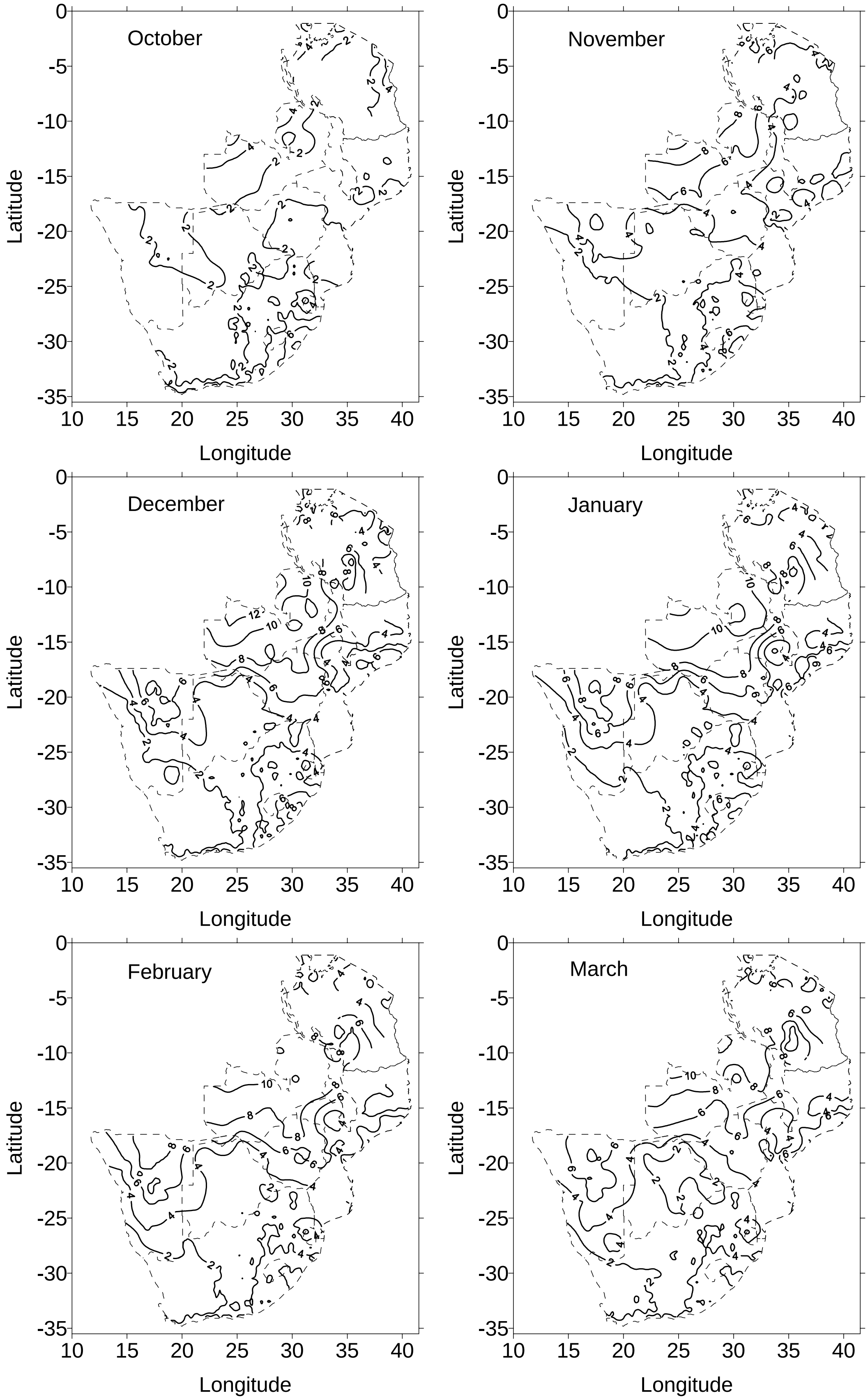


Fig.6.11(a): Spatial variation of mean monthly number of class II events in southern Africa.

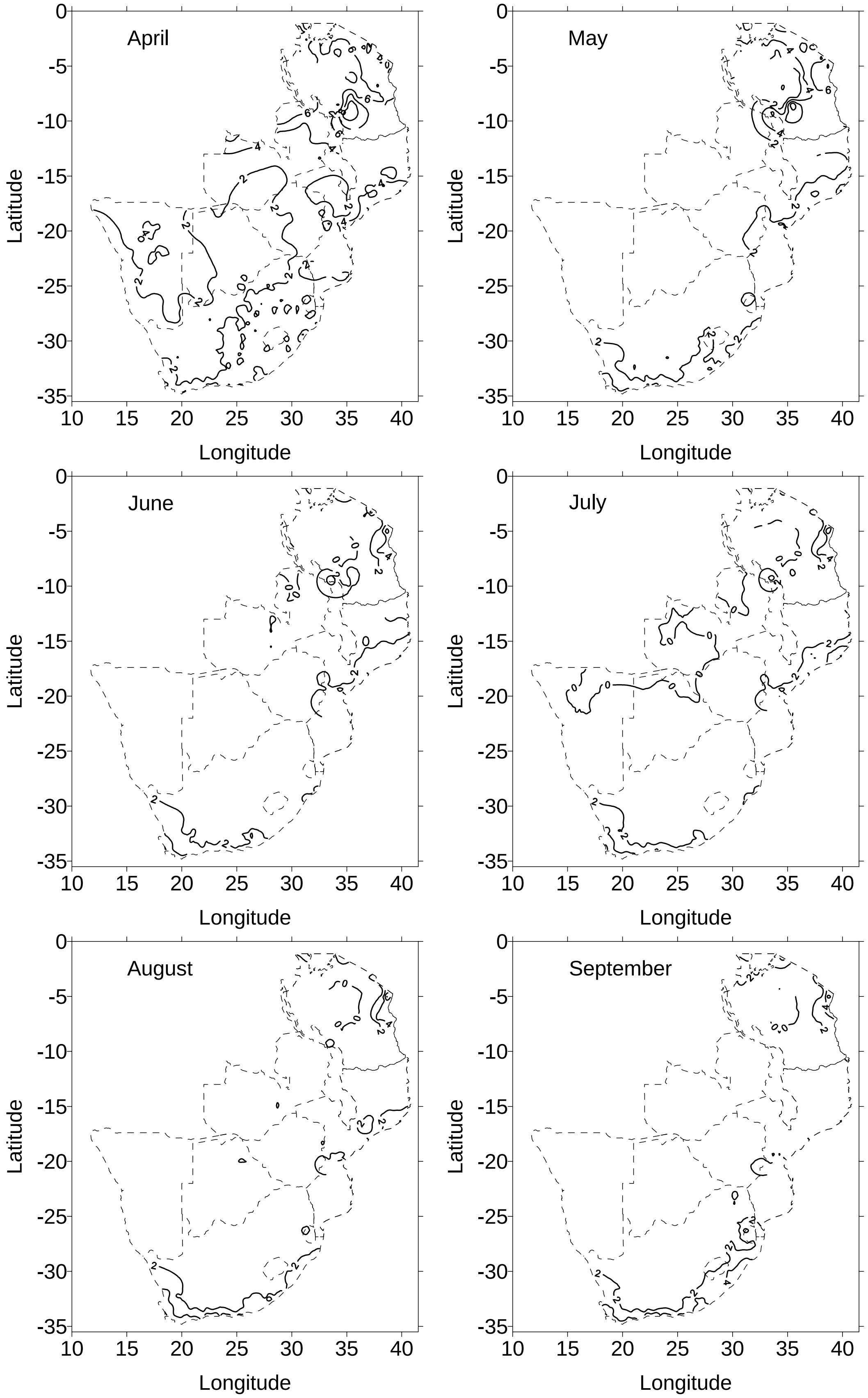


Fig.6.11(a): Spatial variation of mean monthly number of class II events in southern Africa (*Continued*).

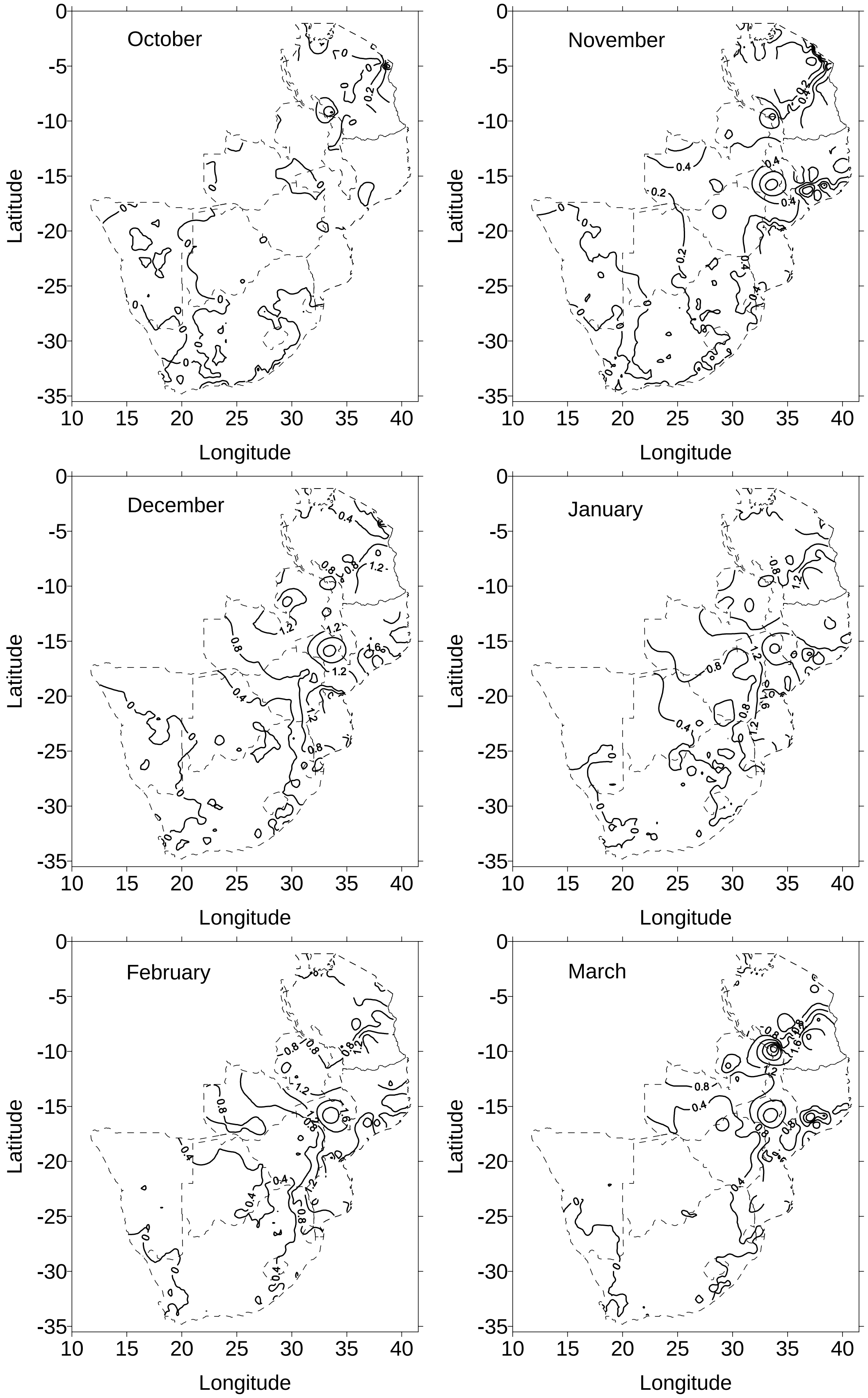


Fig.6.11(b): Spatial variation of mean monthly class VI frequencies in southern Africa.

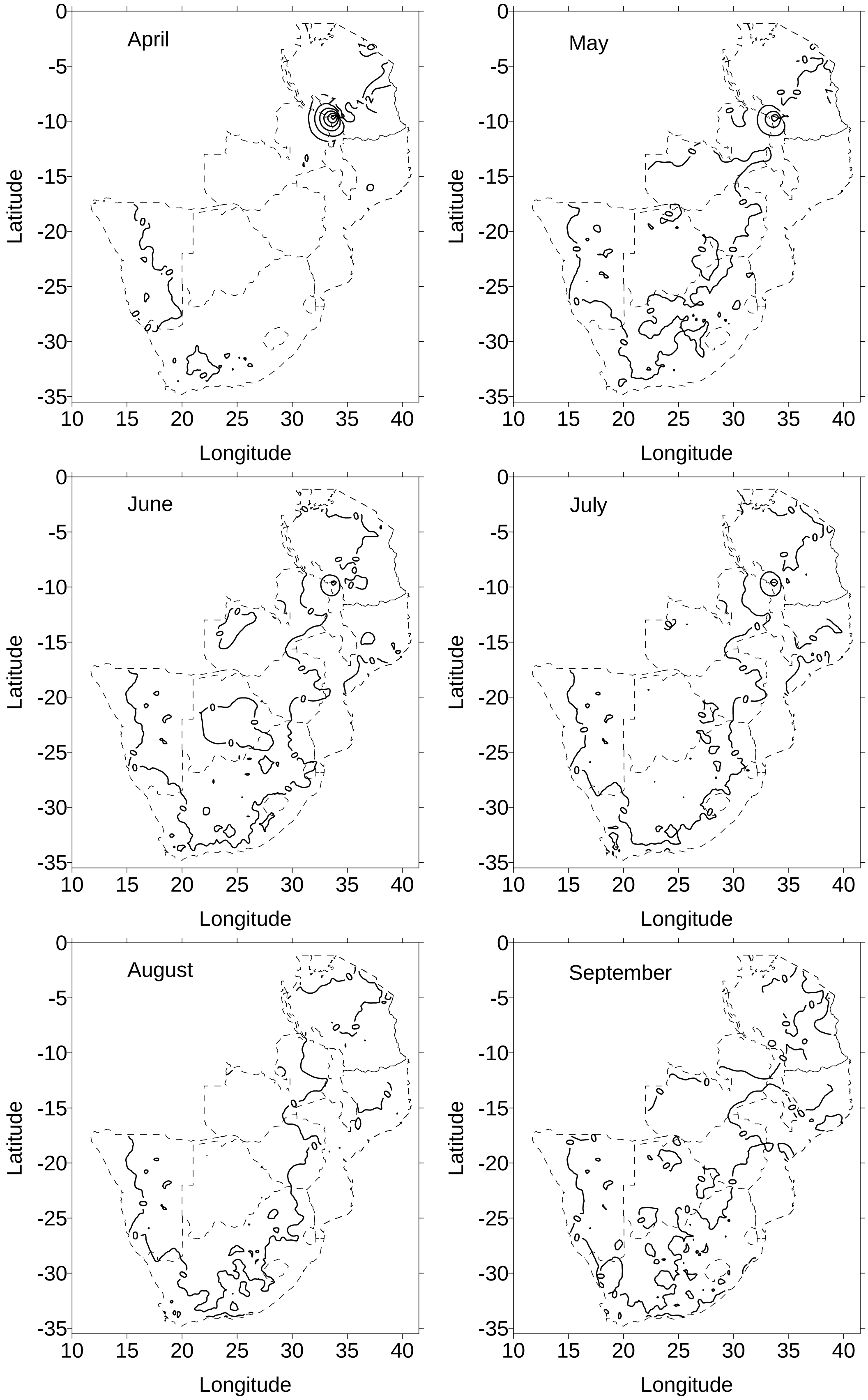


Fig.6.11(b): Spatial variation of mean monthly class VI frequencies in southern Africa (*Continued*).

6.7 Seasonality of rainfall in southern Africa

All indices of rainfall amounts and frequencies (Figs.6.4, 6.5, 6.11) indicate seasonality of rainfall in southern Africa and spatially distinguish between the dry and humid zones. Most of the region receives rainfall between October and May except in the Western Cape in southwest South Africa that experiences rainfall during the austral winter. The wet season October-May/June is mainly a continuous single season, between May and September (Western Cape) and between November and April (the rest of the region), except in Tanzania (northern Tanzania in particular) where it is characterised by a break in January-February which separates the short rains (October-November-December) from the long rains (March-April-May). In general, a high number and intensity of daily rainfall events characterise the December-February (DJF) period in unimodal southern Africa and this period is regarded as the core of the wet season. The period June through September (JJAS) is relatively dry in southern Africa and August is generally the driest month.

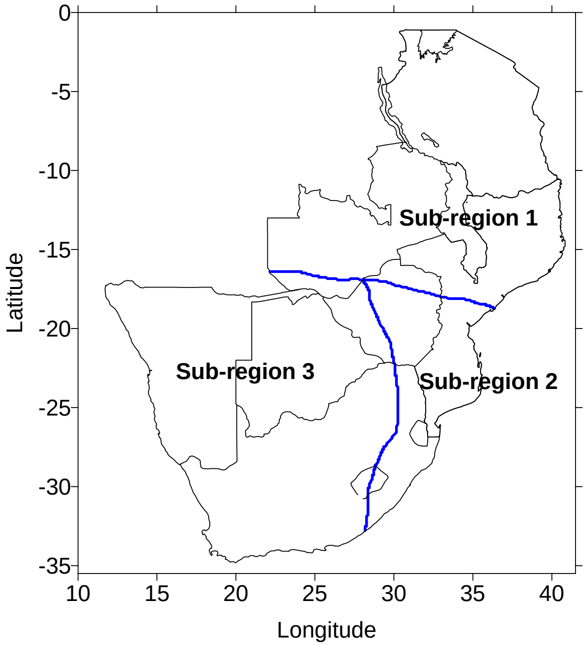


Fig.6.12: Sub-regions in southern Africa as distinguished by spatial rainfall characteristics.

6.8 Major rainfall sub-regions according to average rainfall indices

The results have been used to divide southern Africa into three major sub-regions with regard to rainfall amounts and number of rainfall events: the sub-region north of about 17°S comprising Tanzania, Zambia, Malawi, the northern Zimbabwe and the northern half of

Mozambique (sub-region 1), the sub-region south of 17°S and east of about 27°E comprising eastern Zimbabwe, the southern half of Mozambique and eastern South Africa (sub-region 2) and the sub-region south of 17°S and west of 27°E comprising Namibia, Botswana, western Zimbabwe and western South Africa (sub-region 3) (Fig.6.12).

Using probabilities of exceedence, as computed from distribution-free plotting position formula, daily intensities were classified into 6 groups: class I (0.1-0.9 mm), class II (1-9.9 mm), class III (10-19.9 mm), class IV (20-29.9 mm), class V (30-39.9 mm) and class VI (≥ 40 mm). Class I intensities represent about 5.5-22.5% of the annual number of rainfall events but only about 0.4-2.3% of annual rainfall amounts rendering them less important in water resources. They are, therefore, not included in the summary of the main spatial characteristics of rainfall in the three sub-regions given below.

6.8.1 Sub-region 1

This sub-region borders the Congo rainforests on the west and it is within the Mozambique Channel where summer tropical cyclones are frequently observed. The northern part (0-5°S) lies within the equatorial region.

- Most of the region receives more than 800 mm of rainfall annually except the central plateau of Tanzania were MAP ranges between 500 mm and 800 mm. MAP exceeds 1500 mm in central Mozambique, in northwest lake Victoria, the Indian Ocean islands of Zanzibar (Unguja and Pemba) and Mafia, in areas around Kilimanjaro, the Meru and Usambara Mountains in northeast Tanzania and in the southern highlands of Tanzania.. Annual rainfall amounts show low interannual variations as indicated by low interannual coefficients of variation (cv) which are lowest in Zambia.
- Mean annual number of daily rainfall events varies between 70 and 130, typically between 70 and 90 in which the highest annual number of events (90-135) characterize the mountains of northeast and southwest Tanzania and western and northern Zambia. The annual number of rainfall events show low interannual variations in this region.
- Mean annual maximum daily rainfall intensities in this region vary typically between 70 mm and 150 mm and the highest daily intensity maxima in southern Africa are found in the Usambaras and in the southern highlands of Tanzania near northern lake Malawi and in central Mozambique. Daily intensities exceeding 350 mm have been

observed in certain years in this region, mainly in December-February (Mozambique) and March-May (Tanzania).

- Long-term average daily rainfall intensity ranges between 12 mm and 24 mm. Daily intensities that are equaled or exceeded 5% of the time range between 40 mm and 80 mm, while those equaled or exceeded 10% of the time range between 30 mm and 50 mm. Daily intensities equaled or exceeded 90% of the time are less than 1.5mm while intensities equaled or exceeded 95% of the time are typically less than 1mm.
- Light (Class II) daily events represent about 30-64% of annual events contributing 10-34% of annual rainfall amounts in which their lowest contribution is found in central Mozambique and the highest contributions in western Zambia and in Tanzania. Class III intensities represent between 9 and 28% of annual events and about 7-35% of annual amounts. Class IV intensities are about 5-15% of annual events but contribute between 10 and 24% of annual amounts with spatial patterns resembling that shown by class II amounts. Class V and class VI intensities are the most infrequent representing about 2-11% (class V) and 2-20% (class VI) of annual event. Despite their infrequency, they contribute typically about 11-13% (class V) and 20-35% (class VI) of annual rainfall amounts.

6.8.2 Sub-region 2

This sub-region is influenced by the warm Agulhas current system, which includes the Mozambique current, east Madagascar current and the Agulhas current itself.

- MAP ranges typically between 600 mm and 800 mm, though areas in the Drakensberg and the east coast of South Africa receive more than 1000 mm (sometimes up to 2000 mm) a year. MAP decreases from the east towards the interior and the central parts of South Africa are characterized by MAP around 600-800 mm. Interannual variations of annual amounts in this region are identical to those in region 1.
- Mean annual number of rainfall events varies between 50 and 110 with the highest (about 90 or more) found in Mozambique and along the east coast of South Africa, decreasing westward.
- Mean annual maximum daily rainfall intensities range typically between 50 mm and 90 mm a day. The highest annual daily intensity maxima are found in Mozambique

and they decrease from east to west and their interannual variations resemble those of annual intensity maxima in region 1.

- Average daily intensities vary from 8 mm in southern Zimbabwe to 12 mm in the rest of the region. Daily intensities equaled or exceeded 5% of the time range between 40 mm and 60 mm, while those equaled or exceeded 10% of the time range between 30 mm and 40 mm. Intensities equaled or exceeded 90% of the time are less than 1.5 mm except in eastern South Africa where they are high. Intensities equaled or exceeded 95% of the time are typically less than 1 mm.
- Class II intensities represent about 40-60% of annual events in this region and contribute about 15-30% of annual rainfall amounts in which their lowest percentages are found in Mozambique. Class III intensities represent between 24 and 36% of annual events and about 16-35% of annual amounts. Class IV represent about 6-15% of annual events but contribute between 16 and 24% of annual amounts with a spatial pattern resembling that shown by class II amounts. Class V and class VI intensities are the most infrequent representing about 4-10% (class V) and 4-16% (class VI) of annual events. They contribute typically about 9-13% (class V) and 10-35% (class VI) of annual amounts. Their highest contributions to annual amounts and number of daily rainfall events are observed in eastern South Africa.

6.8.3 Sub-region 3

Its unfavourable geographical location corresponds to its arid condition. It is located in the lee of the eastern mountains (Drakensberg chain in the eastern South Africa and the Manicaland Mountains in the eastern Zimbabwe) which block the penetration of near-surface moisture-rich winds from southwest Indian Ocean. Moreover, cold dry winds associated with the cold Benguela Current along the western coast of the region further reduce rainfall. The two deserts of Kalahari and Namib are found in this region.

- The region generally receives less than 600 mm of rainfall annually, typically below 500 mm and generally increases from the western coast to the interior. MAP decreases toward the west coast in which it is less than 100 mm in the Namib desert along the Atlantic coast of Namibia. The highest MAP (about 400 mm) characterizes most of Botswana and northeast Namibia while it is less than 300 mm in southern Namibia and western South Africa. Annual rainfall amounts show the highest interannual variations in southern Africa, particularly Namibia. Exception to this pattern are the areas along the winter rainfall region along the southern coast of

South Africa where MAP of up to 900-1300 mm is observed which exceeds 2000mm in certain years at certain locations. This abundant rainfall is brought by the interactions between the cold fronts and the Agulhas which acts as the source of moisture that is advected to the adjacent coastal areas of southern South Africa.

- Mean annual number of rainfall events varies between 30 and 70, but is typically less than 50. The lowest annual number of rainfall events (30 or less) characterize the Namibian Atlantic coast and western South Africa, except at the Cape’s tip and along the southern coast where mean annual number of rainfall events of about 50-90 are observed.
- Mean annual maximum daily rainfall intensities in the region are the lowest, ranging typically between 30 mm and 60 mm, and highly variable between years. The lowest intensity maxima are found in the southern and coastal Namibia.
- Average daily intensities in this region are the lowest in southern Africa and vary between 4 mm and 12 mm with Namibia and the western South Africa observing less than 8 mm while Botswana observes an average daily intensity of about 12 mm. Daily intensities that are equaled or exceeded for 5% of the time range between 6 mm and 47 mm, while those equaled or exceeded for 10% of the time range between 4 mm and 40 mm. Intensities equaled or exceeded for 90% of the time are less than 1.5 mm while intensities equaled or exceeded for 95% of the time are less than 1mm.
- Class II intensities represent 35-70% of annual events and contribute 12-64% of annual amounts. Their highest contributions are found in the southern and coastal areas of Namibia where they contribute between 50 and 70% of annual amounts. Class III intensities represent about 2-18% (Namibia) and 12-30% (Botswana and western South Africa) of annual events and about 21-34% of annual rainfall amounts. Class II and class III intensities together contribute between 67% and 85% (Namibia) and 36% and 62% (Botswana) of annual rainfall amounts. Daily events whose intensities are below 20mm are, therefore, the most important particularly in Namibia, and their variations have significant impacts on the surface water resources in these countries. Daily intensities exceeding 20mm are infrequent in Namibia and represent the remaining 15-33% of annual amounts. Class IV represent, on average, 0.1-5.2% of annual events in Namibia while class V and class VI intensities respectively represent 0-2.5% and 0-1% of annual events in Namibia.

6.9 Conclusions

The results of the spatial analysis of different indices of rainfall have identified three sub-regions in southern Africa. The rainfall characteristics in each of these sub-regions were summarized in the preceding section. They reflect a combination of various factors which influence rainfall variations in the region such as the location with respect to the sources of moisture (equatorial and tropical Atlantic and Indian ocean basins, southwest Indian ocean and the Congo basin), the general atmospheric circulations and synoptic-scale circulation features such as tropical cyclones and the mountains and lakes. The interannual variations of rainfall indices whose spatial distributions have been discussed in this chapter are investigated in the next chapter to complete the spatio-temporal variability analysis of rainfall in southern Africa.

CHAPTER 7

INTERANNUAL VARIATIONS OF RAINFALL AMOUNTS AND NUMBER OF DAILY RAINFALL EVENTS

7.1 Introduction

This chapter investigates interannual variability of seasonal and annual rainfall amounts and number of daily rainfall events in southern Africa. Different months have been pooled to form different 2-month to 5-month seasons in the region (Nicholson, 1986b; Latif *et al.*, 1999; Indeje *et al.*, 2000; Mutai and Ward, 2000; Richard *et al.*, 2000; Reason *et al.*, 2002) depending on different factors such as atmospheric circulation (D'abreton and Lindesay, 1993). However, Richard *et al.* (2002) indicated that rainfall in November through May in South Africa show similar patterns of interannual variability and seasons can be formed from pooling of any of these months. The year was, therefore, divided into three (3) 4-month seasons, October-November-December-January (ONDJ or early summer), February-March-April-May (FMAM or late summer) and June-July-august-September (JJAS or austral winter). The first two seasons form the dry season in the Western Cape and the wet season in the rest of the region and vice versa.

The interannual variability analysis involves i) an investigation of temporal patterns displayed by anomaly indices and ii) identification of discontinuities and trends. Anomaly indices are used to provide rapid characterisation of patterns of interannual variability and are defined as departures from the 1950-1989 averages standardised by 1950-1989 standard deviations. The period 1950-1989 consists of the most continuous records which provides the best spatial distribution of rainfall stations in the region. Eight 5-year segment averages were computed for the period 1950-1989. The 5-year window was selected based on the presence of quasi-periodicities within the 2-7 year band in southern African rainfall (Tyson, 1986; Nyenzi *et al.*, 1999; Nicholson, 2000) reflecting the ENSO signals. Therefore, time windows of 10 years or more may incorporate more than one alternating wetter and drier period and consequently, averaging over the wet and dry periods will lead to anomalies close to zero. The anomalies at each station were spatially interpolated to obtain region patterns.

Time series of seasonal and annual rainfall indices were tested for randomness and change-point and linear trend analyses were then performed on non-random time series. The whole time series were used in the change-point analyses while the linear trend analysis used the periods 1960-1990 and 1940-1990 respectively for the whole of southern Africa and for some long stations in Tanzania, Namibia, Botswana and South Africa to assess the influence of the record length and period on the nature (direction and magnitude) of a trend.

Results of change-point analysis allow the identification of the dates when changes had occurred and are presented, while those of trend analysis are included in the discussion. Owing to the resemblance of patterns of variability between different indices studied and in order to avoid repetition, only the main representative recurrent features are presented and discussed.

In order to simplify the discussion, the following terms have been used:

- Rainfall events refer to the number of daily rainfall events e.g. annual events implies annual number of daily rainfall events.
- Annual or seasonal amounts refer to the annual or seasonal amounts of rainfall due to all rainfall events.
- Annual or seasonal events refer to the annual or seasonal number of all daily rainfall events.
- Annual or seasonal class X amounts refer to the annual or seasonal amounts that are contributed only by daily rainfall intensities within that particular class X.
- Annual or seasonal class X events refer to the annual or seasonal number of daily rainfall events due to daily rainfall intensities within that particular class X.
- Season identifications such as ONDJ, FMAM, JJAS, late summer, early summer are sometimes used in place of the word seasonal.
- Class E20mm groups all daily rainfall intensities exceeding 20 mm.

7.2 Results

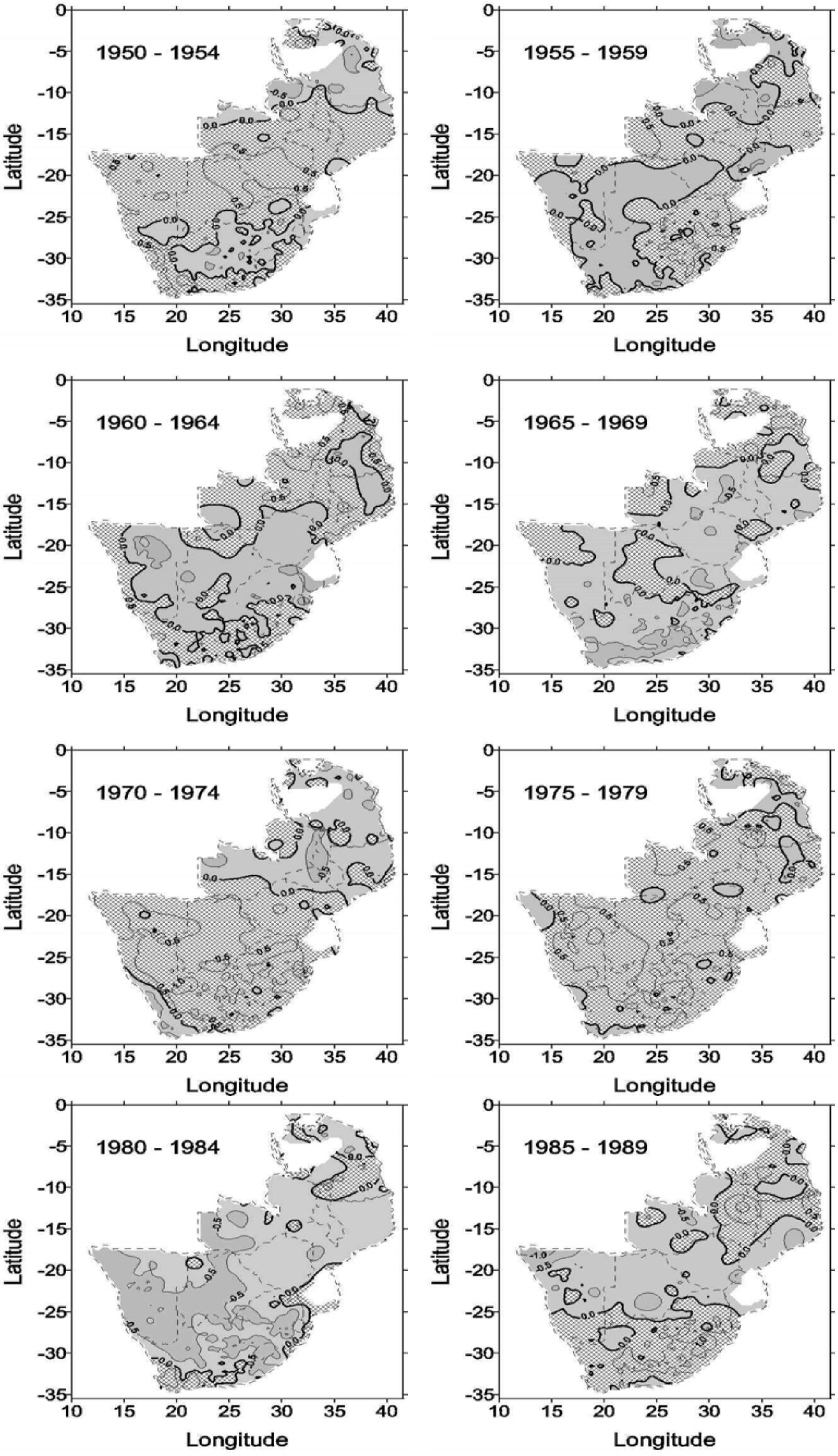
7.2.1 Patterns of anomalies

Fig.7.1 and Fig.7.2 show the most recurrent patterns of anomalies of rainfall amounts and events which indicate the wet 1975-1979 and dry 1980-1984 periods in southern Africa. They further show:

- A dipole between the northern and southern part with a node in the 10°S-15°S latitudes. The dipole pattern, which is apparent in the 1970-1974 period and to a lesser extent in the 1950-1954 and 1965-1969 periods, is analogous to the type 4 pattern in Nicholson and Kim (1997) and is more evident in the annual amount

(Fig.7.1a) than in either the annual events (Fig.7.1b) or seasonal amounts (Fig.7.2). It reflects a response of the southern Africa rainfall to an ENSO signal (Nicholson and Kim, 1997).

- A tendency for the occurrence of anomalies of the same sign across the whole of southern Africa. This is evident in the wet 1975-1979 and dry 1980-1984 periods in annual amounts and events (Fig.7.1) and late summer amounts (Fig.7.2b) but not in early summer amounts (Fig.7.2a).
- The persistency of negative anomalies over a decade or more. This have been observed in the anomalies of annual events (Fig.7.1b) and annual class II events (not shown) in Botswana.
- Influences of the dominant classes on the patterns of interannual variability of total indices. The patterns of anomalies of annual events resemble those of the most frequent class II events while the patterns of anomalies of annual amounts were rather a combination of anomaly patterns of daily intensities exceeding 10 mm (Class III-class VI) which contribute about 75% of annual amounts in southern Africa, except Namibia.
- Changes in the spatial patterns of anomalies of rainfall in certain classes between the different 5-year periods. While the anomalies of class VI annual amounts (not shown) display opposing patterns of interannual variability between eastern (including the Lake Victoria region) and western Tanzania, except in the 1960-1964 and 1980-1984 periods when positive anomalies of class VI annual amounts were found only in the Lake Victoria region. Anomalies of class III annual amounts (not shown) show a change in their spatial pattern of interannual variability across Tanzania since the 1970-1974 period in which the 1950-1969 period was characterised by anomalies of the same sign across the country while the period 1970-1989 experienced opposite anomaly signs between eastern Tanzania and the rest of the country.
- Different patterns of anomalies of rainfall in the early (ONDJ, Fig.7.2a) and late (FMAM, Fig.7.2b) summers during the same 5-year period. The differences, for example, are apparent in the 1960-1964, 1965-1969 and 1980-1984 periods.


1950 - 1954

1955 - 1959

1960 - 1964

1965 - 1969

1970 - 1974

1975 - 1979

1980 - 1984

1985 - 1989

Fig.7.1a: Variation of 5-year average standardized anomalies of annual rainfall amounts in southern Africa for the period 1950-1989. Positive anomalies are cross hatched.

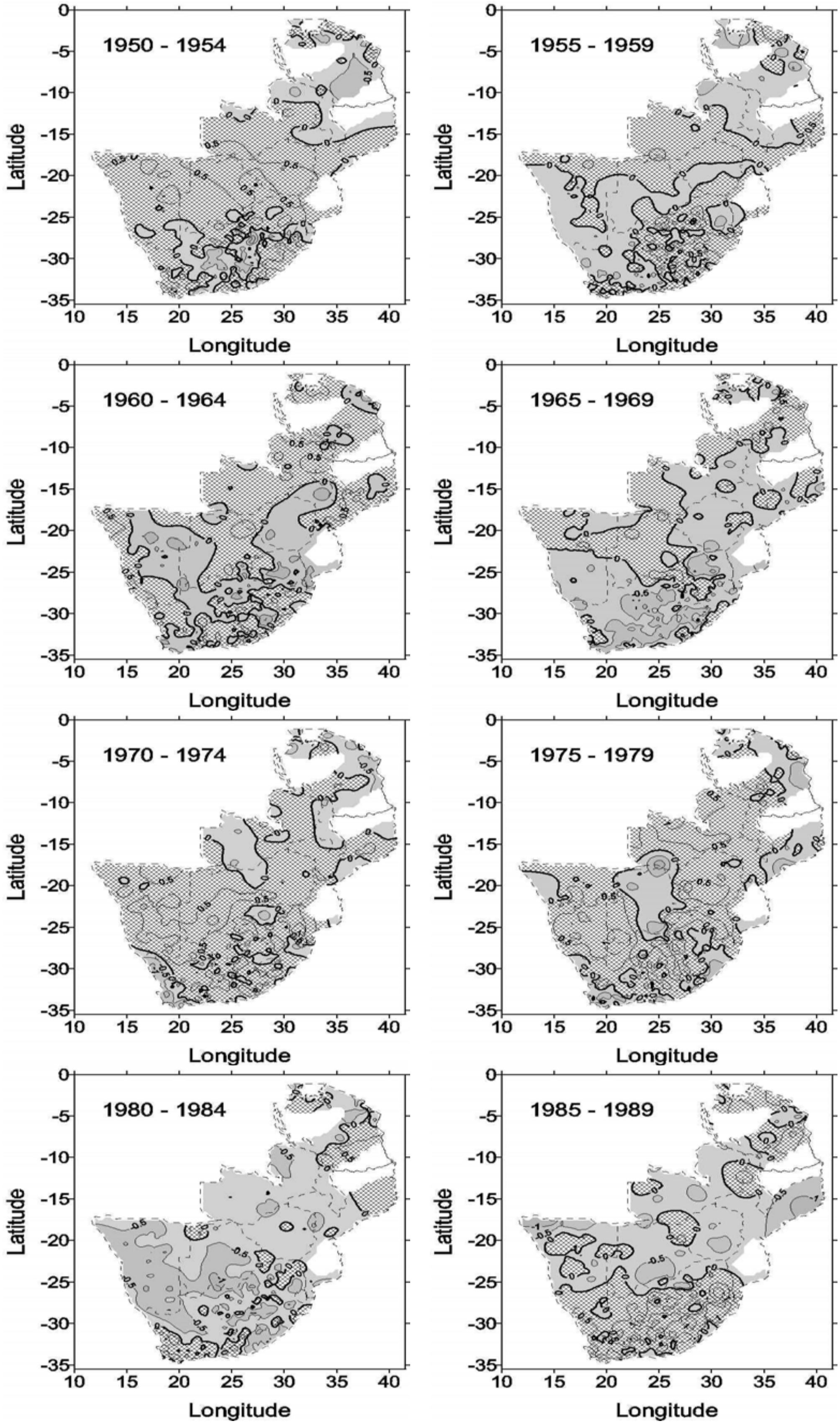


Fig.7.1b: Variation of 5-year average standardized anomalies of annual rainfall events in southern Africa for the period 1950-1989. Positive anomalies are cross hatched.

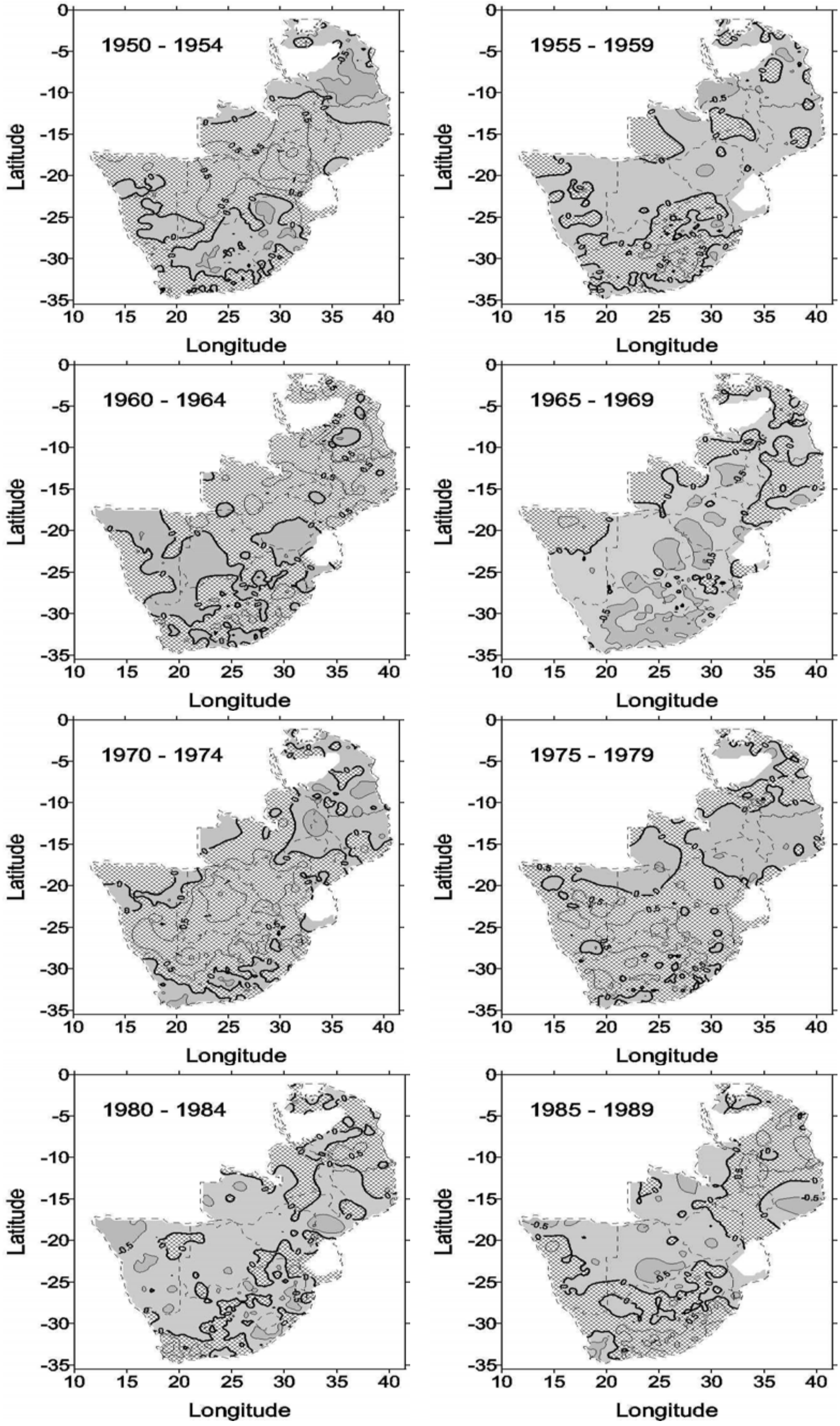


Fig.7.2a: Variation of 5-year average standardized anomalies of early summer (ONDJ) rainfall amounts in southern Africa for the period 1950-1989. Positive anomalies are cross hatched.

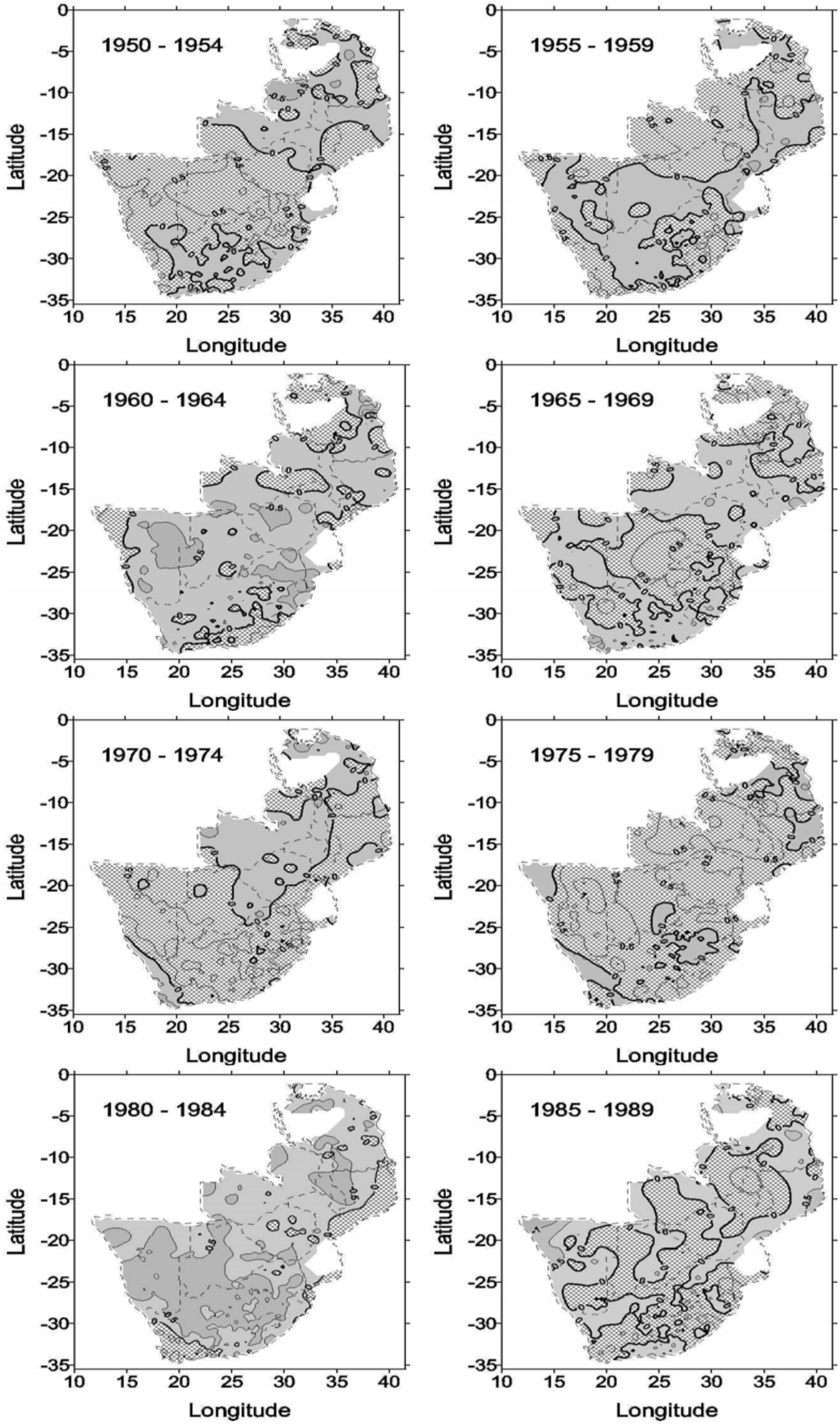


Fig.7.2b: Variation of 5-year average standardized anomalies of late summer (FMAM) rainfall amounts in southern Africa for the period 1950-1989. Positive anomalies are cross hatched.

7.2.2 Abrupt changes

The final results of the change-point analysis after comparison of those provided by the Hubert's autosegmentation (Hubert and Carbonel, 1987; Hubert et al., 1989) and Pettitt's test (Pettitt, 1979) are summarised in Table 7.1 through Table 7.3 and in Fig.7.3 and Fig.7.4. They confirm some features present in the patterns of rainfall anomalies and further indicate the following:

- Discontinuities characterise annual events (Table 7.1b) more than annual amounts (Table 7.1a) indicated in these tables by "total". This is illustrated, for example, by high percentages of stations with shifted annual events (61.5%) and low percentages for annual amounts (15.3%) and suggests a lack of any real evidence of trends in annual rainfall amounts in the region as a whole and a strong evidence of spatially localised trends in annual amounts like in Namibia.
- Changes characterise mainly the light daily rainfall events. This is indicated by the highest percentages of stations in which discontinuities in class II events were identified compared to percentages in the other classes (Table 7.1b).
- The domination of downward over upward changes in southern Africa (Table 7.1) and mainly characterise the light and moderate daily rainfalls (< 20 mm).
- Influences of the dominant classes on the patterns of interannual variability of total indices. The dominance of class II events on annual events in southern Africa (Chapter 6) is reflected by almost the same number of stations with discontinuities (Table 7.1b) while their low contributions to annual amounts in the region (except Namibia) correspond to unequal numbers (Table 7.1a).
- Opposing patterns of interannual variability of rainfall in the early and late summers. This is shown by predominantly abrupt increases in early summer amounts against predominantly abrupt decreases in late summer amounts (Table 7.1a, Figs.7.4a, 7.4b). The magnitude of increases and decreases were similar, ranging from 34 mm to 228 mm in early summer amounts and from 37 mm to 228 mm in late summer amounts, in which the highest amount changes (> 90 mm) were found in the late summer. The effects of this tendency of opposing changes were related to a lack of abrupt changes in annual amounts in the eastern part of Tanzania (Fig.7.3a).
- The influences of the changes at the seasonal timescale on the changes at the annual timescale. The predominant decreases in late summer amounts in Namibia, for example, caused decreases in annual amounts in this country (Table 7.1a) since the

decreases occurred at almost similar times (compare Fig.7.3a and Fig.7.4b) while shifts were almost absent in early summer amounts (Table 7.1a, Fig.7.4a).

Table 7.1: Summary of number of stations in southern Africa in which discontinuities in rainfall indices were identified.

a) Rainfall amounts

Direction of shift	Country	Annual					Seasonal			Number of stations
		Total	Class II	Class III	E20mm	E40mm	ONDJ	FMAM	JJAS	
Downward	Botswana	3	12	1	2	0	0	1	0	25
	Namibia	15	10	9	8	6	3	17	1	65
	South Africa	12	41	6	8	6	4	21	5	142
	Tanzania	5	25	2	3	3	0	16	2	59[a]
	Zambia	2	7	0	3	0	0	1	2	22
	Zimbabwe	0	2	0	0	0	1	0	0	21
	No. of stations	37	97	18	24	15	8	53	10	
Upward	Botswana	1	1	1	1	1	1	0	2	25
	Namibia	0	0	0	0	0	0	0	0	65
	South Africa	5	24	5	13	4	18	3	1	142
	Tanzania	13	10	3	3	7	11	3	3	59*
	Zambia	1	0	0	1	2	1	0	0	22
	Zimbabwe	0	1	0	1	0	0	1	0	21
	No. of stations	20	36	9	19	14	31	7	6	
No. of stations observed shifts[c]		57	116	30	45	28	39	60	16	
No. as % of all stations analysed		15.3	34.6	9.0	13.4	8.4	10.5	16.1	4.3	335[b]

b) Rainfall events

Direction of shift	Country	Annual					Number of stations
		Total	Class II	Class III	E20mm	E40mm	
Downward	Botswana	14	13	1	0	0	25
	Namibia	32	13	10	7	4	65
	South Africa	68	66	3	3	8	142
	Tanzania	29	32	2	3	3	59
	Zambia	6	3	1	2	1	22
	Zimbabwe	0	2	0	0	1	21
	No. of stations	149	129	17	15	17	
Upward	Botswana	5	2	2	0	0	25
	Namibia	6	2	2	0	0	65
	South Africa	59	46	15	19	6	142
	Tanzania	15	14	3	2	7	59
	Zambia	0	0	1	0	2	22
	Zimbabwe	1	0	0	0	1	21
	No. of stations	86	64	23	21	16	
No. of stations observed shifts[c]		206	177	39	36	32	
No. as % of all stations analysed		61.5	52.8	11.6	11.0	9.6	335

a: 96 stations were used for annual total amounts.
b: 372 stations were used for annual total amounts.
c: Stations with both upward and downward shifts are counted once.

- The temporal heterogeneity of the changes. This is indicated by a range of dates in which discontinuities were identified (Table 7.2). Both the longest and moderately long records indicate that most of the abrupt decreases in rainfall amounts and events had occurred between the late-1960s and early-1980s, particularly in the 1970-1981 period while abrupt increases were identified throughout the period late-1940s to late-1970s. The changes in the 1940s were identified in the longest records some of which extend back to the late-1890s and early-1900s.

- The spatial heterogeneity of the changes. This is indicated by the differences in dates in which shifts were identified across the region although some sort of spatial clustering, which is defined by the similar direction and almost similar dates of a change, is also apparent (Fig.7.3, Fig.7.4, Table 7.3). The stations in Namibia, for example, experienced abrupt decreases in annual amounts (Fig.7.3a), annual events (not shown) and annual class II amounts (Fig.7.3c) and events (not shown) in mainly the 1974-1980 period; stations in Zambia experienced abrupt decreases in annual class II amounts (Table 7.1a) and events (Table 7.1b) in the 1973-1983 period (Fig.7.3c); stations in southeast Botswana in the 1968-1977 period; stations in areas along the southern half of Tanzania abruptly increased in early summer amounts in the 1976-1980 period while those in the northern Tanzania underwent such abrupt increases in early summer rainfall amounts in 1960/61 (Fig.7.4a). Furthermore, abrupt increases in early summer amounts were concentrated along the eastern part of southern Africa (Fig.7.4a).

Table 7.2: Percentages of stations in which shifts in rainfall amounts were identified in different periods in southern Africa.

Period	Index of annual amounts									
	Total		Class II		Class III		Class E20mm		Class VI	
	Down*	Up*	Down	Up	Down	Up	Down	Up	Down	Up
Before 1941	0.0	0.0	0.0	2.8	0.0	0.0	0.0	5.3	0.0	7.1
1941-1945	11.1	0.0	2.1	2.8	0.0	0.0	4.3	0.0	0.0	0.0
1946-1950	2.8	10.0	0.0	16.7	0.0	22.2	8.7	5.3	6.7	0.0
1951-1955	2.8	5.0	6.3	2.8	0.0	11.1	0.0	15.8	0.0	7.1
1956-1960	5.6	5.0	7.4	13.9	11.1	0.0	13.0	5.3	13.3	7.1
1961-1965	13.9	30.0	12.6	8.3	11.1	33.3	17.4	0.0	13.3	35.7
1966-1970	0.0	5.0	10.5	16.7	0.0	11.1	8.7	5.3	6.7	0.0
1971-1975	8.3	30.0	14.7	5.6	11.1	0.0	4.3	52.6	20.0	14.3
1976-1980	44.4	10.0	26.3	30.6	55.6	11.1	34.8	10.5	40.0	28.6
1981-1985	11.1	5.0	15.8	0.0	5.6	11.1	8.7	0.0	0.0	0.0
After 1985	0.0	0.0	4.2	0.0	5.6	0.0	0.0	0.0	0.0	0.0

* Down and up imply respectively downward and upward shifts.

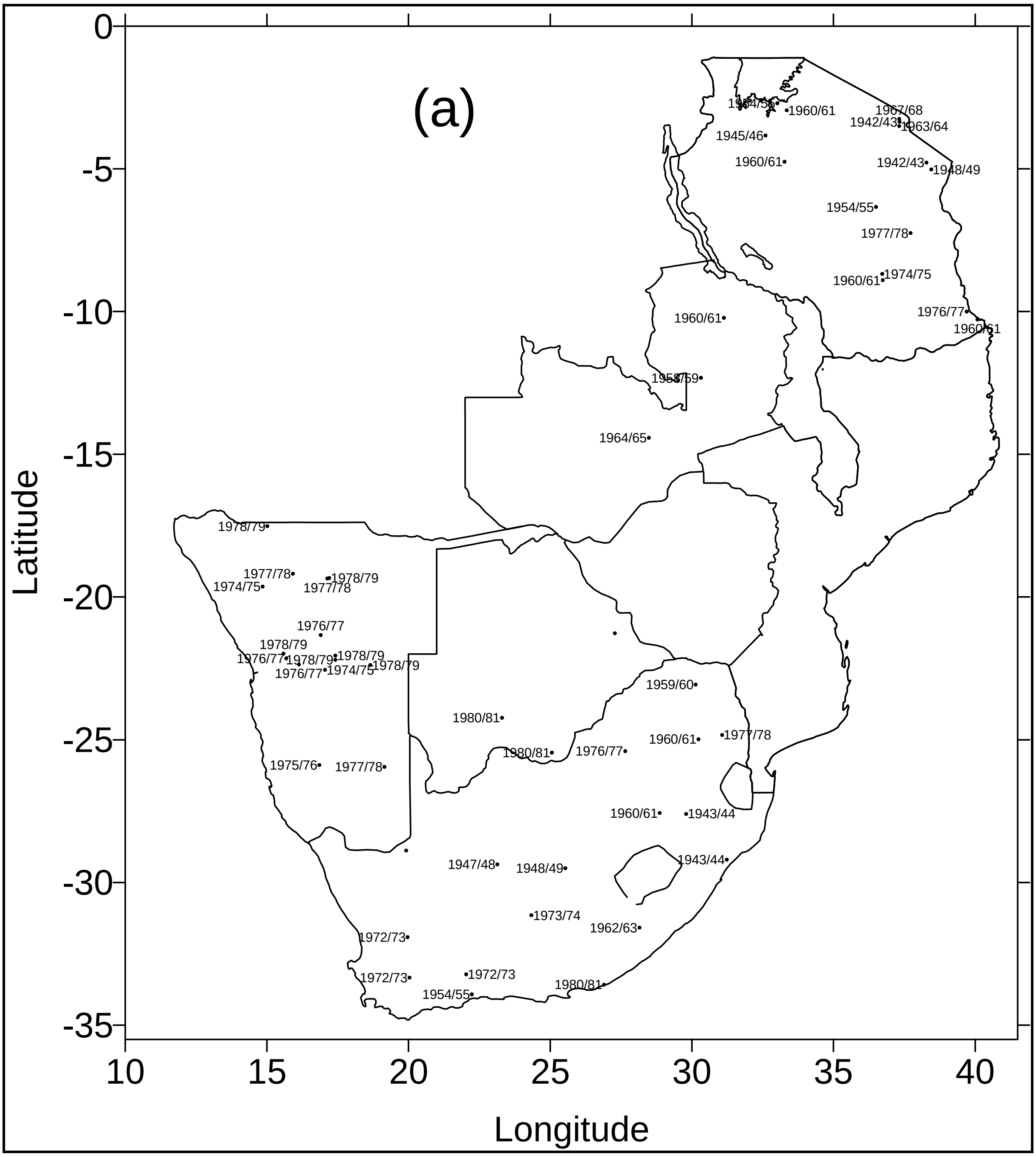


Fig.7.3a: Dates of identified unidirectional shifts in annual amounts in southern Africa.

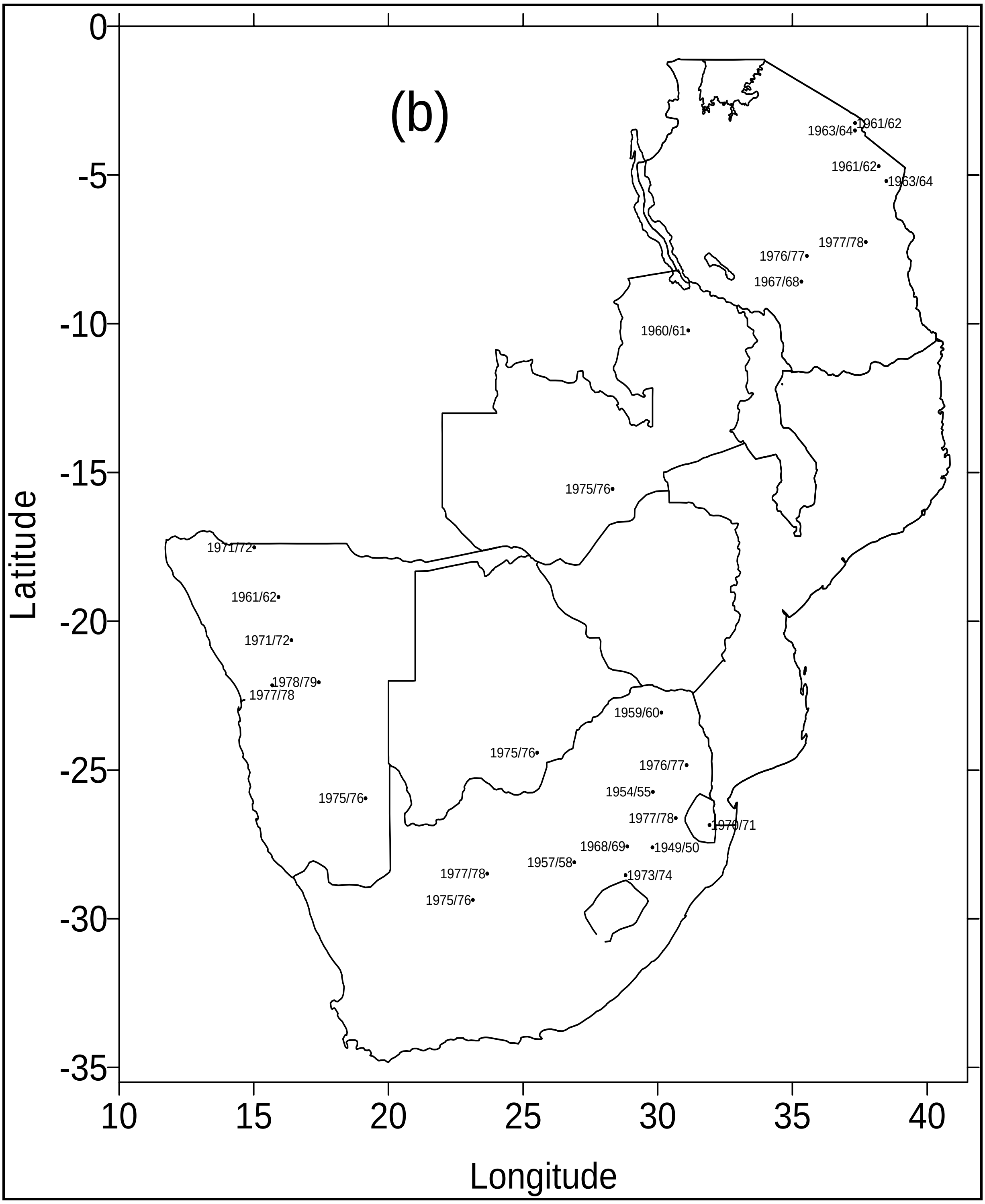


Fig.7.3b: Dates of identified unidirectional shifts in annual class VI amounts in southern Africa.

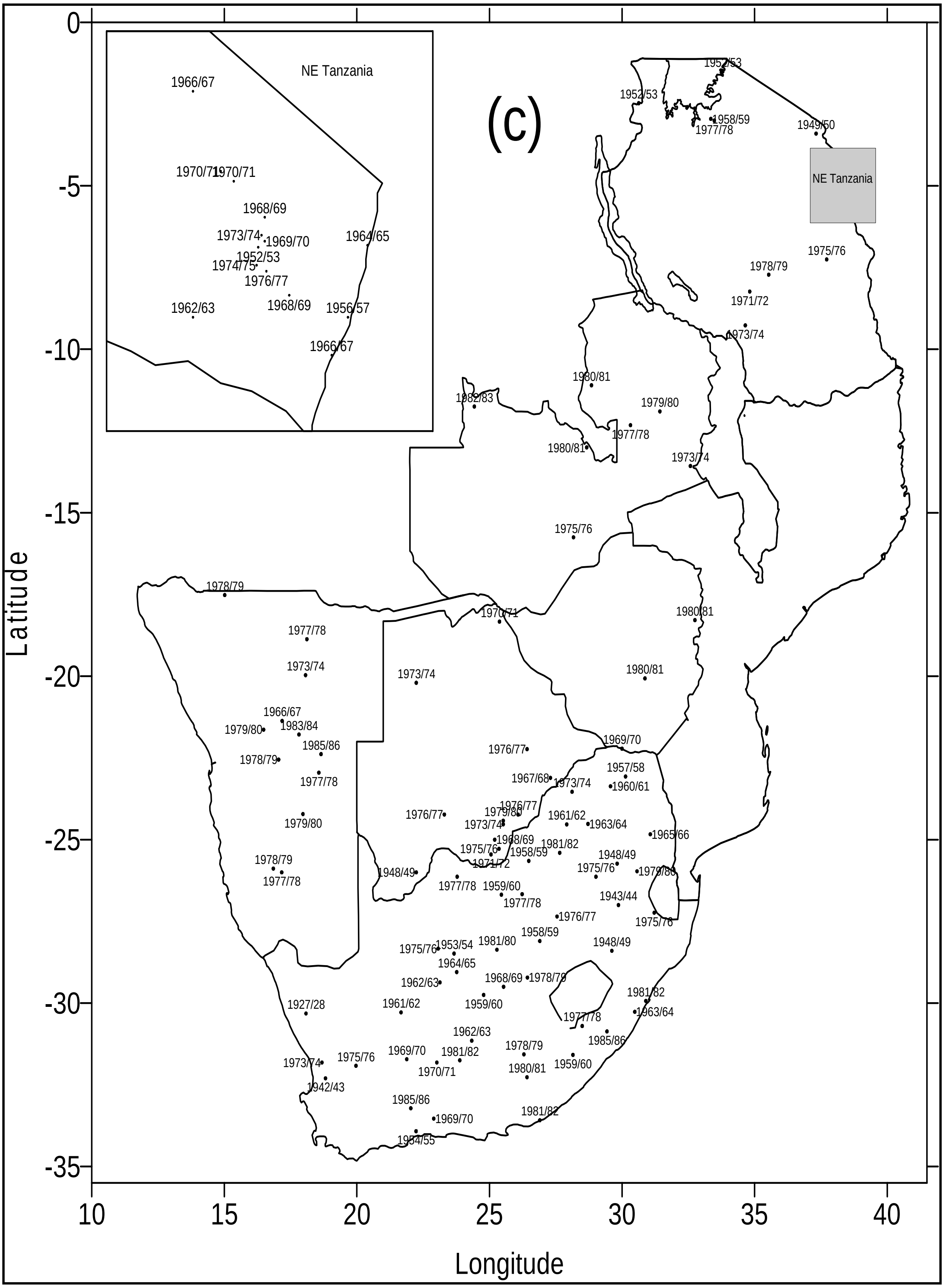


Fig.7.3c: Dates of identified unidirectional shifts in annual class II amounts in southern Africa.

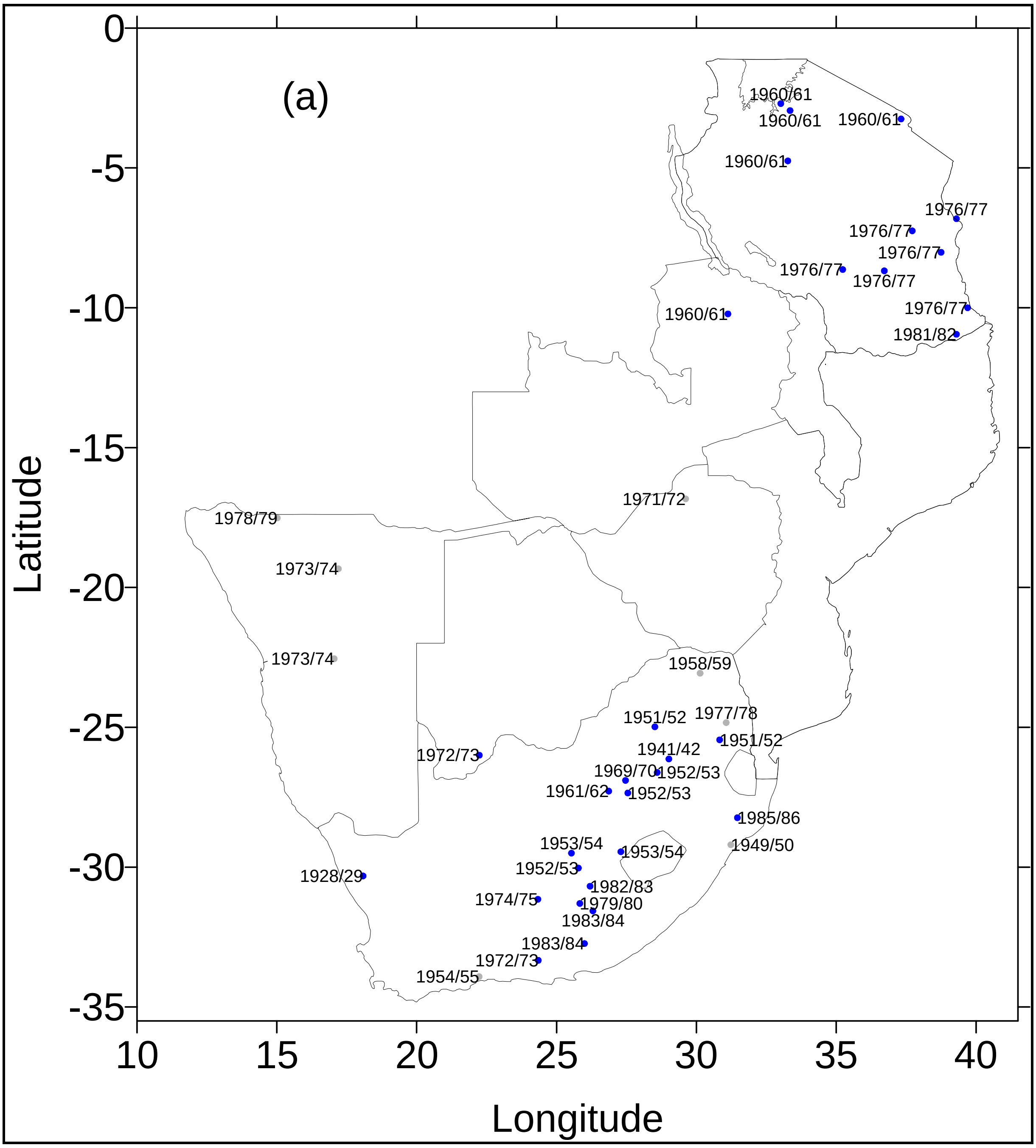


Fig.7.4a: Dates of shifts in early summer (ONDJ) seasonal amounts in southern Africa. Blue dots indicate an increase while light black dots correspond to a decrease.

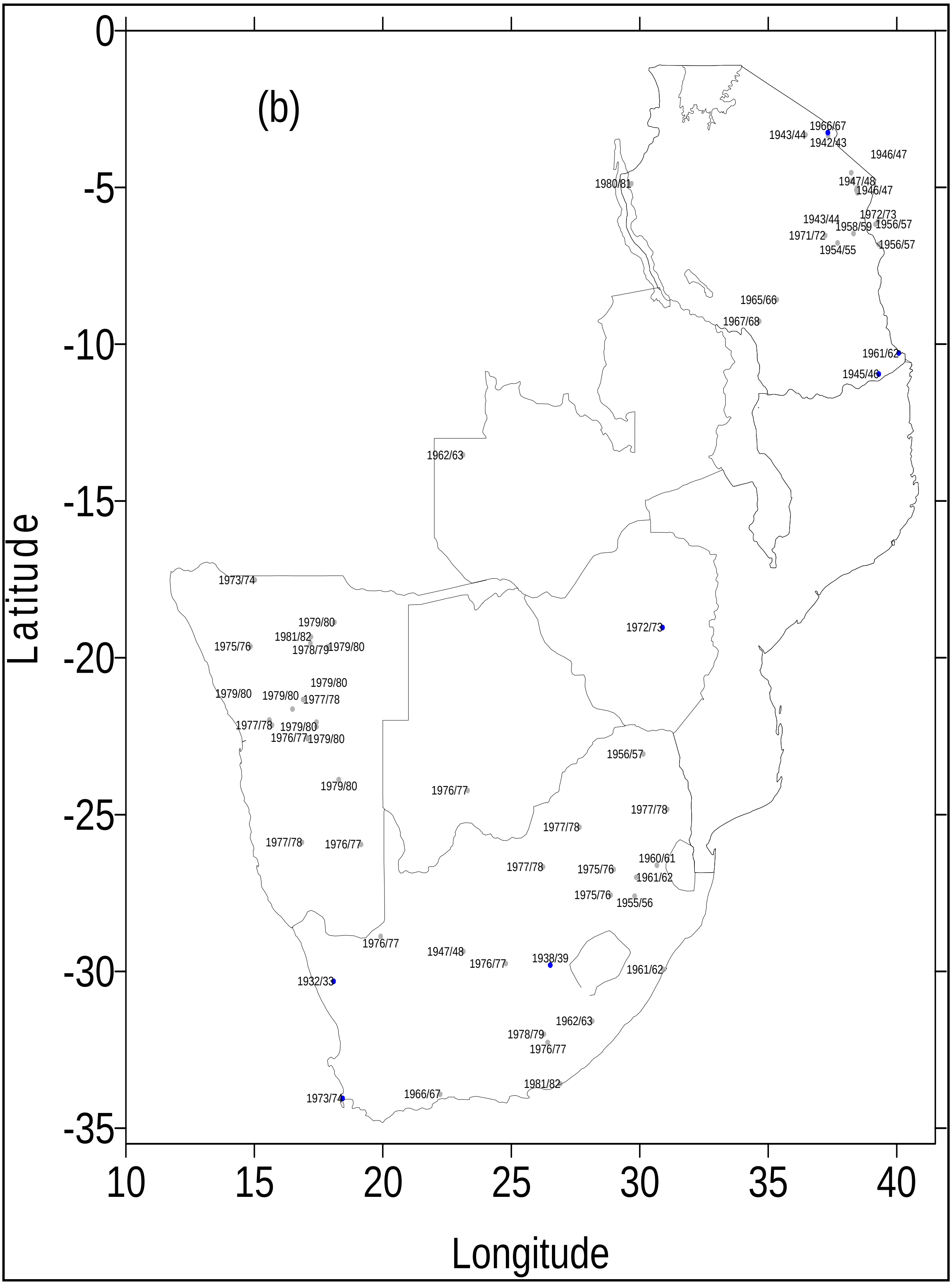


Fig.7.4b: Dates of shifts in late summer (FMAM) seasonal amounts in southern Africa. Blue dots indicate an increase while light black dots correspond to a decrease.

- The varying degree of the severity of the changes (Table 7.3). The changes in the frequency of intense (> 40 mm) daily events in Namibia, for example, are of the order of fractions of a day but represent a decrease of more than 66%. The changes have caused these events to become even rare in some stations in which only 1 or 2 events have been observed in the 19-25 years after the change while in other they have disappeared (Table 7.3). The largest change of 6 events at Kyela Boma (ID 09933010, Table 7.3), on the other hand, represent only 26% of the average before the change. In stations which observed shifts in both annual amounts and annual class II amounts, the changes in the frequency of intense events in the dry parts contributed about 21-35% of the changes in annual amounts. The light daily events represented a significant portion (up to 75%) of changes in annual amounts in dry parts compared to humid parts (Table 7.3a).

7.3 Discussion

7.3.1 Patterns of anomalies

The wet early-1950s and late-1970s in most of the southern part of southern Africa (Chenje and Johnson, 1996; Mason, 1996), as well as the drought conditions in the mid-1970s in Tanzania and East Africa in general (Nyenzi *et al.*, 1999; Ogallo and Nasib, 1984) and the widespread drought in the early-1980s across much of southern Africa and other parts of Africa (Chenje and Johnson, 1996) are apparent in the patterns of anomalies (Fig.7.1, 7.2). Furthermore, the patterns of anomalies show alternating wet and dry periods at the regional spatial scale consistent with reported absence of any real long term trends in southern Africa rainfall amounts (Hulme, 1992).

However, the anomalies show some features which contradict what has been reported in the past studies. The dry 1967-1973 period in most southern parts of the region (Chenje and Johnson, 1996) is evidenced by negative anomalies in the time series of annual rainfall amounts and events (e.g. Fig.7.5) and anomalies of annual amounts (Fig.7.1a) and events (Fig.7.1b) in the 1965-1969 period but those in the 1970-1974 period indicate the opposite. The strong and extended June 1973-April 1976 La Niña event (Trenberth, 1997) was responsible for the heavy 1974 rainfall in the southern part of southern Africa in which anomalies of up to 4 standard deviations were observed in certain areas. Similarly, Nyenzi *et al.* (1999) linked the 1973-1976 rainfall deficits and drought conditions in Tanzania to this La Niña event. Therefore, the high rainfalls of 1974 were essentially the cause of positive anomalies in the 1970-1974 period given the slightly below or above average rainfalls in the preceding years. Similarly, the influence of the 1973-1976 La Niña, a weak 1976/77 El Niño signal in southern African rainfall (Nicholson and Kim, 1997) and above average rainfall in the other non-ENSO years were responsible for the positive anomalies in the 1975-1979 period.

Table 7.3: Summary of shifts in annual class VI events in southern Africa as identified by the Pettitt's test and Hubert autosegmentation procedure.

Country	Station	Alt (m)	Shift date	Before	After	Change (days)	% change
Namibia	0781/309	1500	1975/76	0.3	0.0	-0.3	-100.0
	1003/608	1200	1974/75	0.5	0.0	-0.5	-100.0
	1008/302	1450	1962/63	1.2	0.4	-0.8	-66.7
	1009/639	1550	1979/80	1.0	0.2	-0.8	-80.0
	1199/001	1000	1971/72	0.9	0.2	-0.7	-77.8
RSA	0146588	1500	1979/80	0.4	1.1	0.7	175.0
	0177178	1780	1956/57	0.4	1.1	0.7	175.0
	0201482	1423	1946/47	0.6	1.4	0.8	133.3
	0240716	115	1958/59	4.2	2.9	-1.3	-31.0
	0255202	960	1975/76	0.6	0.1	-0.5	-83.3
	0322329	1419	1974/75	1.2	0.4	-0.8	-66.7
	0328726	1326	1957/58	1.9	0.9	-1.0	-52.6
	0337795	777	1982/83	2.7	6.7	4.0	148.1
	0339352	76	1955/56	2.8	4.4	1.6	57.1
	0370486	1515	1949/50	3.5	2.1	-1.4	-40.0
	0446741	100	1964/65	1.8	3.2	1.4	77.8
	0590028	1052	1924/25	3.0	1.5	-1.5	-50.0
	0595110	880	1976/77	5.8	3.6	-2.2	-37.9
	0723155	853	1959/60	4.8	2.8	-2.0	-41.7
Tanzania	09337006	1433	1960/61	8.5	11.9	3.4	40.0
	09337028	701	1962/63	1.6	3.1	1.5	93.8
	09438012	1889	1960/61	1.3	2.6	1.3	100.0
	09538020	305	1964/65	3.1	5.5	2.4	77.4
	09735017	1386	1976/77	1.2	4.3	3.1	258.3
	09737005	457	1976/77	7.0	12.2	5.2	74.3
	09835009	1859	1967/68	5.9	3.7	-2.2	-37.3
	09933010	549	1967/68	23.2	17.2	-6.0	-25.9
Zambia	Kasama	1384	1960/61	3.8	5.9	2.1	55.3
	Mongu	1053	1965/66	4.9	2.7	-2.2	-44.9
	Mt Makulu	1213	1975/76	2.1	4.9	2.8	133.3

The positive anomalies in the 1975-1979 period in some areas of Tanzania, on the other hand, were attributed to high rainfall in the 1977-1979 period which were partly influenced by an extended August 1976-January 1978 warm ENSO despite the preceding strong 1974-1976 La Niña-related rainfall deficits. Most of the stations in northeast Tanzania, for example, recorded above average rainfall during the two seasons (Fig.7.2a, 7.2b) while time series at some stations indicate that the short and long rains were almost merged in 1978/79, being separated only by about 20-30 days of light rainfall.

The other important pattern that is displayed by the anomalies is the seasonality. The anomalies of ONDJ amounts in the 1980-1984 reported dry period in southern Africa are positive over much of Tanzania consistent with the expected positive response of early summer rainfall to a strong warm 1982/83 ENSO. The drought conditions at the annual timescale are, however, reflected from similar deficit rainfalls during the FMAM. Consequently, the FMAM rainfall deficits correspond to the longest 4-year drought during the long rains which lasted between 1982 and 1985 in northeast Tanzania (Nyenzi *et al.*, 1999). In general, the rainfall deficit in the early-1980s were linked to ENSO (Chenje and Johnson, 1996) or ENSO-SST mode and its changed relationship since the 1970s (Folland *et al.*,1986; Janicot *et al.*, 1996; Richard *et al.*, 2000; Janicot *et al.*, 2001).

The reported dry 1967-1973 period in the southern part of southern Africa are apparent in the anomalies of annual indices (Fig.7.1) and late summer (ONDJ, Fig.7.2a) amounts in the 1965-1969 period but not in the anomalies of late summer amounts (FMAM, Fig.7.2b). Moreover, the 1973-1976 drought in Tanzania tends to characterize rainfall amounts at both seasonal and annual timescales. However, the drought was severe in the equatorial northern Tanzania and during the short rains (October-December) (Nyenzi *et al.*, 1999), the part and season that are significantly influenced by ENSO (Ropelewski and Halpert, 1987; Latif *et al.*, 1999; Indeje *et al.*, 2000; Mutai and Ward, 2000). The drought was influenced mainly by the strong and extended 1973-1976 La Niña (Nyenzi *et al.*, 1999) and is indicated by the dates and duration of the drought which coincide with those of the La Niña event.

7.3.2 Abrupt changes

It is important to assess the reality of the identified abrupt changes as they may have resulted from inhomogeneities introduced by changes in the station location or units of measurement, for example, which may have a significant impact on the intensities of daily rainfall. The spatial patterns and dates of abrupt changes, however, indicate that it is unlikely that the changes can be attributed to such inhomogeneities although the probability of such influences are not ruled out completely.

The small number of stations in which discontinuities were identified in annual amounts of rainfall support the claim that there is no real evidence of any trends in rainfall amounts in most parts of southern Africa (Hulme, 1992; Smakhtina, 1998) except in certain areas such as the South African Lowveld (Mason, 1996), Botswana and Zimbabwe (Hulme, 1992), southern Zambia (Sichingabula, 1998), etc. However, results indicate strong evidence of decreasing annual amounts in Namibia since the mid-1970s, in some northeast South Africa stations since the early-1960s and in others since the late-1970s. Mason (1996) and Mason *et al.* (1999) reported decreases in annual amounts in the Lowveld in northeast South Africa since the late-1970s while Jury and Engert (1999) reported decreases in dam levels in Namibia since the mid-1970s.

The changes in early and late summer amounts reflect mainly the influences of ENSO and SST in the surrounding Indian Ocean basins. The ENSO influences on rainfall in the region is communicated mainly through the Indian and Atlantic Ocean waters (Nicholson and Kim, 1997). Its influences on rainfall in Tanzania peak in the October-December period (Latif *et al.*, 1999; Mutai and Ward, 2000; Trenberth and Caron, 2000). Abrupt increases in early summer amounts in eastern and southern Tanzania occurred mainly in 1976/77, consistent with the period when warming in the tropical Indian and Pacific Oceans occurred (Trenberth, 1990; Kerr, 1992; Wang, 1995; Trenberth and Hoar, 1996). The increase in the northern Tanzania, on the other hand, occurred earlier in 1960/61, the changes which could be probably reflecting a reoccurrence of an active phase of ENSO in the late-1950 to early-1960s (Wang and Wang, 1996; Kestin *et al.*, 1998; Torrence and Compo, 1998) and in which ENSO signals were probably communicated through the atmosphere.

The abrupt increases in early summer amounts in South Africa occurred mainly in the early-1950s in the northern part of the central interior and early-1970s in the southern part of the central interior. The influences of the great Agulhas Current system on the rainfall in central southern South Africa (Reason, 1998; Reason and Mulenga, 1999; Reason, 2001), the warming of the southwest Indian Ocean since the early-1970s (Trzaska *et al.*, 1996) and an enhanced influence of the Agulhas during weak ENSO (Walker, 1989; Mason, 1992) and a low ENSO signal in rainfall during the months of early-summer are possibly responsible for the increase in the early-1970s in the central southern Africa. The negative influences of the Indo-Pacific ENSO signal on rainfall in the southern part of southern Africa (Jury, 1995; Landman and Mason, 1999; Richard *et al.*, 2000) peaks after December and therefore significantly affects the late summer rainfall. Consequently, the warming in the tropical Indian and Pacific Oceans since the mid-1970s is consistent with late summer rainfall decreases since the late-1970s in Namibia and in some areas of southeast and northeast South Africa.

There is also strong evidence of decreases of light (< 10 mm) daily rainfall events in the region. The results indicated that daily rainfall events whose intensities are below 10 mm have significantly decreased in the most parts of the region and consistently since the second half of the 1970s possibly related to warming in the tropical Indian and Pacific Oceans. The decrease is indicated by a significant reduction of the number as well as the amounts contributed by these light daily events. Owing to their low contribution to annual amounts in the region, the decreases in the light daily events could not affect significantly annual amounts except in areas such as Namibia where their contributions are high. The decreases in the number of these most frequent light daily rainfall with relatively unchanged or increasing frequency of occurrences of intense events are reflected by the decreasing annual events (not shown) as well as rain rates in the Eastern Cape (Smakhtina, 1998) and in the former Transkei and the northern Transvaal (Richard *et al.*, 2002).

On the other hand, abrupt decreases in number of class II events along the northeast coast of Tanzania have occurred in the late-1960s and early-1970s, while increases in the areas around Mount Kilimanjaro occurred in the early-1960s. The changes in Mount Kilimanjaro could be linked to signals embedded in the atmosphere as discussed above, while decreases around 1970 could be due to warming in the southwest Indian Ocean since rainfall in equatorial East Africa, in which the coast northeast is part, correlates significantly with SST (Latif *et al.*, 1999) and atmospheric winds (Mutai and Ward, 2000) in the southwest Indian Ocean.

Simulation experiments of an enhanced greenhouse state indicated increases of convective activity (Mitchell and Ingram, 1992; Whetton *et al.*, 1993) due to enhanced greenhouse effects leading to increasing frequency of high rainfall events and a decrease in the number of rain-days. Consequently, Smakhtina (1998) found an increase in the frequency of high rainfall in the Eastern Cape while Mason and Joubert (1997) simulated an increase of the frequency and intensity of these high rainfalls in much of southern Africa. Similarly, abrupt increases in both the frequency (Table 7.3) and amount (Fig.7.3b) of intense (> 40 mm) daily events have occurred in northeast Tanzania during 1961-1964. However, these intense daily events in Namibia have become very rare or disappeared since the mid-1970s while they have generally decreased in northern central (since mid-1970) and northeast South Africa (between early-1960s and late-1970s), the result for northeast South Africa being consistent with the decreases identified in Mason *et al.* (1999).

The changes in the characteristics of daily rainfall intensities identified in the 1970s in the southern African region seem to have occurred in other parts of the world which have different climatic regimes to those in southern Africa. Brunetti *et al.* (2001) found increasing trends in the number and intensity of high rainfall events and decreasing trends in the lightest events in Italy since the 1970s leading to decreases in the number of rainfall events. Salinger and Griffiths (2001) found an abrupt increase in the frequency of high rainfall in 1977 in the southwest of the South Island of New Zealand and around mid-1950s in the north of the North Island. They further found significant increases in the minimum temperatures around 1970 in the northern and central areas of the North Island. Several other studies have found a mixture of increases and decreases in extremes of rainfall and other climatic variables in different parts of the world (Karl *et al.*, 1995).

It was also tempting to associate the abrupt decreases and increases with the 11-19 years decadal/multidecadal cycles in southern African rainfall (Tyson, 1986; Nicholson and Entekhabi, 1987; Nyenzi *et al.*, 1999; Nicholson, 2000). Interannual variability of Namibian rainfall is, however, dominated by 2-5 year cycles (Nicholson and Entekhabi, 1987; Nicholson, 2000) suggesting that there is little possibility that an abrupt decrease could be attributed to the decadal/multidecadal cycles of 11-19 years. The presence of the 11-19 year cycles in rainfall in northeast South Africa and Tanzania indicates that for decreases occurring in the 1970s, a return to normal rainfall condition was expected around the early- to mid-1990s while for the decreases that occurred in the early-1960s, the cycle is irrelevant. Therefore, the changes since the 1970s could be part of the long periodicity oscillations but the records since the early-1990s are too short to draw firm conclusions. Nonetheless, Mason (1996) cautioned of the robustness of the 18-year cycle particularly when recent records are used.

7.4 Conclusions

Changes have been identified in southern Africa rainfall which significantly affect the number and amounts of the light (< 10mm) daily rainfall events and consequently the annual number of daily rainfall events. The changes were predominantly decreasing and have occurred mainly in the 1970s characterising mostly rainfall in the late (FMAM) season. Changes that have been identified in rainfall in the early (ONDJ) summer season, on the other hand, were predominantly towards increasing rainfall. These changes were not attributable to the decadal/multidecadal cycles in rainfall but rather to the changes in the background oceanic and atmospheric conditions which have been identified in the 1940s through late-1970s, although the influence of the long periodicity cycles were not ruled out.

It was further observed that the patterns of anomalies averaged over 5-year periods were significantly affected by the extreme years. Therefore, since the dominant modes of interannual rainfall variability in the region are related to ENSO which has a preferred range of 3-8 years periodicity and whose influences are seasonally varying, averaging over time windows sometimes results in unrealistic patterns while combining the opposing early and late summer rainfalls may dampen the annual pattern.

Shorter and few records in Zambia and Zimbabwe hindered an appropriate characterisation of time series behaviour in that part of southern Africa. Shifts were identified as early as in the late-1940s, in the 1950s and in early-1960s but most of the records used for the two countries cover only the early-1950s and early 1990s. It was not possible to characterise pre-1950s rainfall behaviour and it was difficult to distinguish between shifts and grouped outliers pre-1965, as only a few years of records are available. Similarly, unavailability of daily data in most of western and southern Tanzania hindered the verification of patterns of variability displayed by annual amounts. The unavailability of data in northeast and southern Mozambique and excessive missing observations in the 1970s and 1980s prevented a satisfactory regional characterisation of rainfall variability in southern Africa.

Changing frequencies of rainfall in the region indicate modification of rainfall occurrence in the region and consequently modifications in rainy season patterns are anticipated. The modifications may involve lengthening dry episodes during the rainy seasons or shortening of the seasons. Moreover, changes in rainy season behaviour may cause regime changes in river flows. Therefore, interannual variations of rainy season characteristics and streamflow regimes in southern Africa are investigated respectively in chapter 8 and chapter 9.

CHAPTER 8

THE RAINY SEASONS IN SOUTHERN AFRICA

8.1 Introduction

Amounts of rainfall during the rainy season to some extent depend on its onset and/or cessation (Camberlin *et al.*, 2002). It is obvious that the short rainy season is normally dry, but the interrelationship between dryness of a season and duration of the season in southern Africa is little understood. What may be causing shortened (prolonged) rains, whether it is their early (late) end, late (early) onset or both is not well understood. The knowledge of the onset of the rainy season as well as of its cessation is therefore of utmost importance especially to rain-fed agriculture, which is widely practised in southern Africa. Perfect timing of the start of the rainy season has substantial economical benefits to southern African farmers. A false start of a rainy season (indicated by a few isolated pre-season rainy events), for example, always has negative impacts on agricultural activities. In most cases, it leads to resowing of crops. A combination of a late start and early termination of the rainy season usually corresponds to insufficient soil moisture for crops like rice, which results into either crop failure or low agricultural productivity.

Therefore, the main objective of this chapter is to investigate any relationships between interannual variations of the rainy season characteristics (onset, end and duration) and interannual variations of rainfall amounts and number of daily events in southern Africa. The rainy season characteristics are defined and their spatial variations across southern Africa are studied. The interannual variability of the rainy season characteristics is mainly discussed in relation to the interannual variations of rainfall amounts and number of events presented in the preceding chapter.

8.2 The review of the definitions of the rainy seasons

Previous studies of rainy seasons attempted, in one way or the other, to produce definitions of a rainy season that are capable of capturing spatio-temporal variations of daily rainfall intensities and sequences of dry days. A variety of methods that define rainy season characteristics (onset and cessation) exists. The methods are generally grouped (Camberlin *et* *al.*, 2002) into 1) agroclimatic-based methods, 2) methods based on climatic variables such as winds, convections and 3) purely precipitation-based methods.

The first group comprises methods whose definitions of onset and cessation of rainy seasons are based both on rainfall characteristics (such as daily rainfall intensities) and on availability of sufficient soil moisture for crop sowing. The methods in this group have been used in studies of rainy seasons in West Africa (Diop, 1996; Houndenou and Hernandez, 1998).

Methods in the second group relate changes in climatic variables to onset and cessation of rainy seasons. They have been used in the studies of Holland (1986), Omotosho (1990, 1992) and Omotosho *et al.* (2000). Omotosho (1992) related sudden changes in 400 hPa wind direction, from westerly to easterly, to the onset of a rainy season in the West African Sahel. Kousky (1988) defined the onset and end of rainy seasons in the Amazoni basin based on out-going longwave radiation (OLR). Others used a combination of OLR and rainfall in defining rainy season's onset and end. Hendon and Liebmann (1990) combined wind and rainfall in their definition of a rainy season.

Methods in the third group use only rainfall characteristics in determining the onset and cessation of a rainy season. They were used as early as in the 1970s and early-1980s (Ilesanmi, 1972; Nicholls *et al.*, 1982) and in the more recent studies of Liebmann and Marengo (2001), Marengo *et al.* (2001), Camberlin and Diop (2002), Camberlin *et al.* (2002), and Valimba *et al.* (2004d). The methods in this group usually use data either from individual stations or grids (Liebmann and Marengo, 2001; Valimba *et al.*, 2004d) or regional indices (Camberlin and Diop, 2002; Camberlin *et al.*, 2002) derived as regional averages (Marengo *et al.*, 2001) or as empirical orthogonal function (EOF) principal components (PC) (Camberlin *et al.*, 2002). Depending on the method, different timescales have been used, from daily observations to pentad or decadal averages.

The first two methods were considered inappropriate for the study since

- The methods in the first group are dependent on the agronomic requirements which are, in turn, dependent on several other non-climatic variables.
- The methods in the second group, despite being robust, suffer from the inadequate availability of climatic data over Africa (Camberlin *et al.*, 2002) or where available, the network is sparse (Omotosho *et al.*, 2000). Consequently, studies of rainy seasons at finer spatial scales become difficult to conduct and hence these methods are not very suitable for southern Africa.

- The use of all-record averages hampers studies of the temporal evolution of rainy season characteristics since only a single climatological onset and a single cessation date are determined.
- The use of spatial averages hinders the studies of spatial variation of the rainy season characteristics since only single onset and end dates of the rainy seasons are computed for an area and given the varying degree of the influences of the topography and other climatic variables in southern Africa, the dates may not be spatially representative in the region.

The present study is interested in spatio-temporal variations of rainy seasons characteristics. Hence methods that allow for spatial as well as temporal investigation of rainy seasons characteristics such as those of Marengo *et al.* (2001), Camberlin *et al.* (2002) and Valimba *et al.* (2004d) are considered appropriate. However, there is a need to consider the diverse climatic conditions in the region in which accounting for a sequence of dry days in the dry parts of southern Africa is considered important in order to avoid the false onset and end (Benoit, 1977) of the rainy seasons.

In this chapter, a method that defines rainy season onset and cessation on the basis of daily rainfall intensities and length of sequences of dry days is proposed. Plots of daily rainfall intensities for different years at various locations in southern Africa and daily rainfall characteristics in Chapter 6 are used in establishing the definitions.

8.3 Defining the rainy seasons

8.3.1 Plots of daily rainfall intensities and the sequences of dry days

Plots of daily rainfall for different years (e.g. Fig.8.1), at various locations in the region and the sequences of the dry days before, during and after the rainy seasons show various characteristics of daily rainfall in relation to the start and end of the rainy seasons in the region. In the plots, the year was defined as a hydrological (water) year between 1st October and 30th September and they confirm a dominance of unimodal rainfall regimes in southern Africa. The main features that were considered useful in relation to the definitions of the rainy season characteristics are presented below.

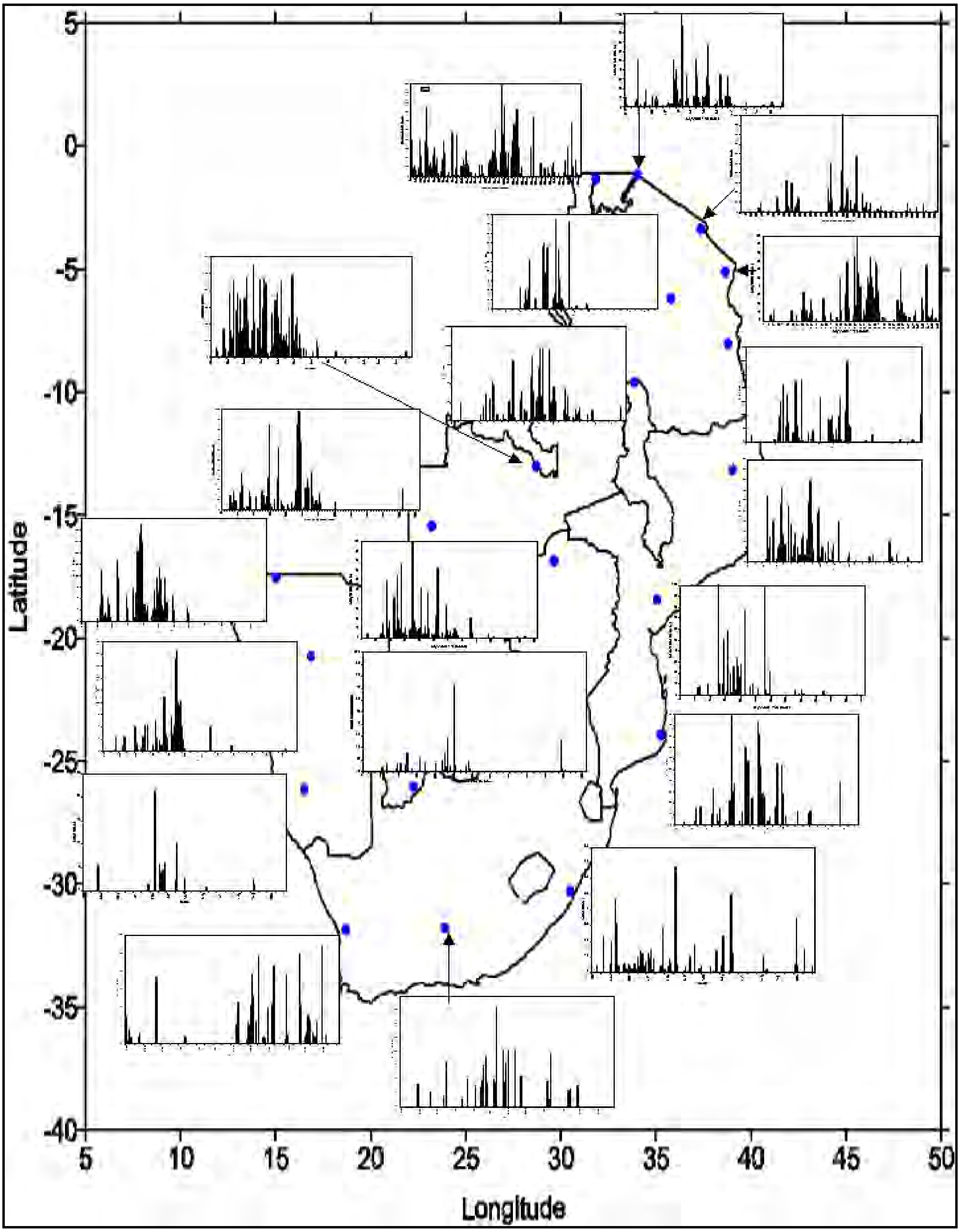


Fig.8.1: Typical plot of daily rainfall in various parts of southern Africa to highlight different rainfall regimes. Plots are for a year defined from 1st October to 30th September, the dates being represented respectively by leftmost and rightmost sides of the plots.

a) The rainfall regimes

- The unimodal and bimodal regimes

  Most of southern Africa is characterised by a unimodal rainfall regime, except in northern Tanzania where a bimodal regime exists. Rainfall seasons start in unimodal southern Africa between the first two weeks of October (in southeast South Africa and in north-northwest Zambia) and the first two weeks of January (in Namibia). The end of the rainy season is observed between mid March in the deserts in southeast Namibia and southern Botswana and mid April in northern Zambia and Mozambique. In the Western Cape, the rainy season extends, on average, from late April to early September.

- Distinguishing the short and long rains in the northern Tanzania

  In northern Tanzania, the bimodality of the rainy season is more evident in the Arusha and Kilimanjaro regions around mounts Kilimanjaro and Meru in northeast Tanzania. A relatively dry January-February period separates the short rains from the long rains in the lowlands in the lee of the mountains and amid the northern (Kilimanjaro and Meru) and southern (the Usambaras) mountains (Fig.8.1). In the mountainous and coastal areas of the northeast as well as in northern Lake Victoria, the two seasons are still distinct but are separated by a January-February period of reduced rainfall intensities. The bimodality is not well marked in areas between the Usambaras and the Indian Ocean coast in northeast Tanzania where the long rains appear to be a continuation of the short rains (Fig.8.1).

  Further, three types of years are distinguished with respect to rainfall bimodality. There are years (e.g. 1978/79) when the two seasons are almost combined into a single continuous season between October and May. In such years, the two seasons are typically separated by less than 30 dry days. Daily intensities during the January-February period remain above 5mm and frequently exceed 10mm. Other years correspond to separated short and long rains whereby short rains are either well developed (e.g. in 1982/83, Fig.8.3) or practically absent (e.g. 1975/76, Fig.8.2b).

  The plots of daily rainfall further show that the short rains, commonly regarded to occur between October and December, are actually observed between early October and early February. The peak of the short rains shifts between the three months of November, December and January (Fig.8.3). Moreover, daily rainfall events during the short rains are usually less intense compared to those during the long rains

(Fig.8.2 and 8.3). However, in strong warm ENSO years such as 1982/83 (Fig.8.3b), intense daily events are observed during the short rains.

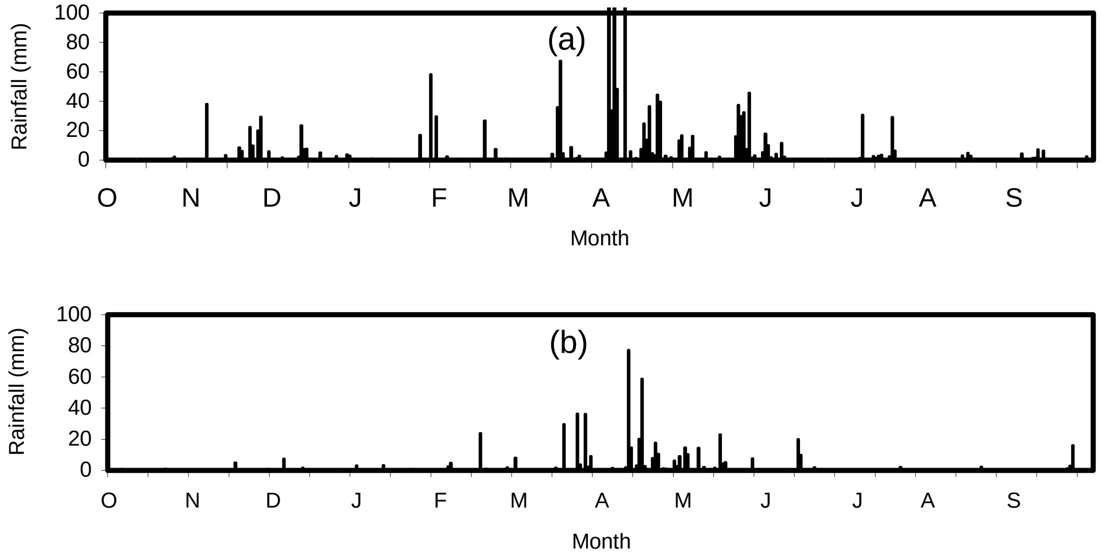


Fig.8.2: Time series of daily rainfall at Moshi airport (ID 09337004) in northeast Tanzania for the year a) 1978/79 and b) 1975/76.

b) The importance of the definition of a dry day and the length of dry sequences

- Further investigation shows that pre-season and post-season rains are characterised by 1-3 daily events with intensities around 5-20 mm separated by long (> 15 days) sequences of days with intensities below 1 mm. Thus, in order to avoid false onset or cessation, a dry day was redefined as a day whose intensity is below 1 mm (1.1 mm in the Western Cape).

- The occurrence of daily rainfall during the pre-season/early season and late season/post-season periods October-November and April-May (unimodal areas) and October-November, December-January, February-March and May-June (bimodal areas) shows that i) during the month (30 days) preceding the onset of the rainy season, the sequence of dry days is usually longer than 10-15 days and reduces to below 10-15 days in the month following the onset, ii) in bimodal areas in northeast Tanzania, the use of a 30-day period following the onset does not completely eliminate the likelihood of a false onset of short rains as well as long rains in certain years while the use of a 45-day period does, iii) coastal areas and the Usambara Mountains in northeast Tanzania and areas in northwest Lake Victoria in Kagera region (Tanzania) receive rainfall throughout the year (Fig.8.1) and a length of 20 dry days was appropriate to discriminate the long rains from dry season rains while shorter lengths (e.g. 15 days) and longer lengths (e.g. 30 days) would result into early and sometimes false cessation.

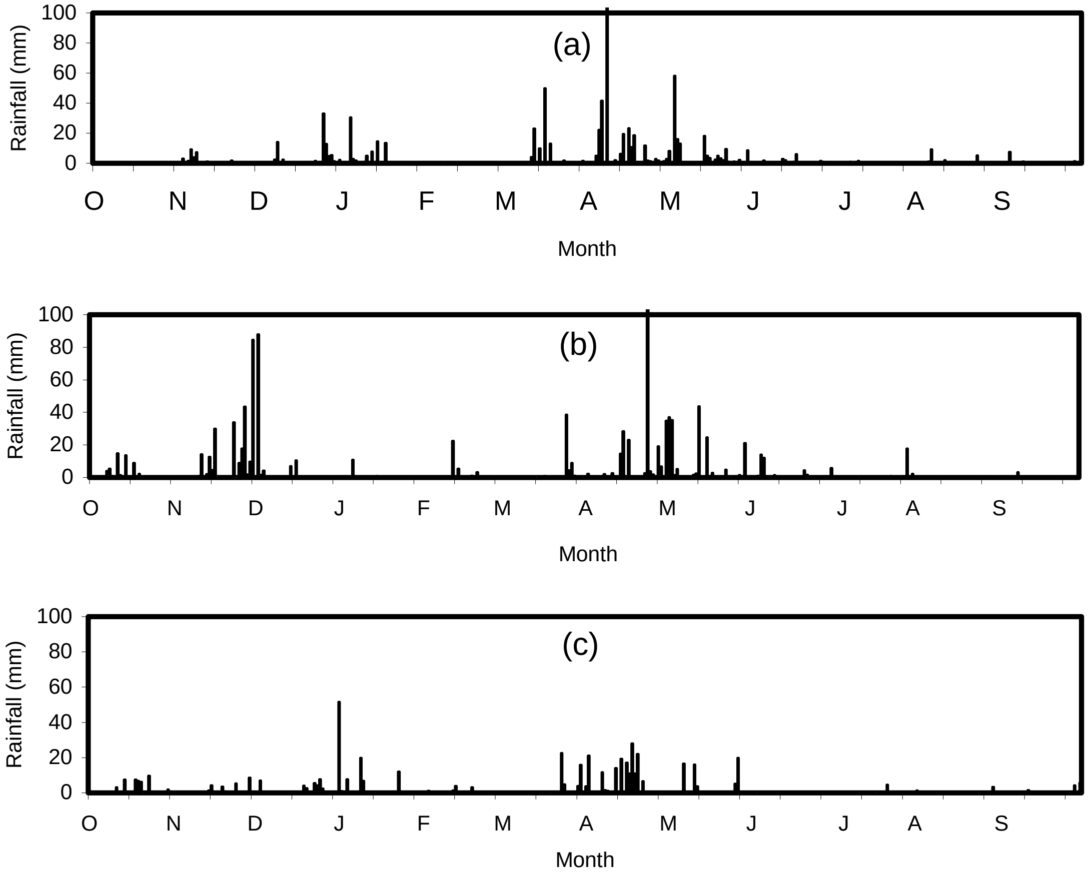


Fig.8.3: Examples of temporal variations of the short rains in northeast Tanzania:a) 1988/89, b) 1982/83 and c) 1964/65 at Moshi Airport.

8.3.2 The definition of the onset and end of the rainy seasons

From the preceding observations and the comparison of the daily intensities during the rainy seasons and the all-record average daily rainfall intensities (AADI), the onset of the rainy seasons in southern Africa was, therefore, defined as the second day when the average rainfall intensity of two consecutive days exceeds AADI and after which, during the next 45 days there is no sequence of days with intensities less than 1 mm that exceeds 15 (10 in bimodal areas) days. The end of the rainy season was likewise defined as the last day after which the daily intensity falls below AADI and is followed by a sequence of at least 28 (18 in the bimodal areas) out of 30 (20 in bimodal areas) days whose intensities are below to 1 mm. The length of the rainy season was defined as the difference between the end and onset dates. These definitions were used to provide results discussed in the subsequent sections of this chapter.

The applications of the definitions involved a spatial delineation of the southern African region according to the prevailing rainfall regimes: the bimodal northern Tanzania, the unimodal summer and winter regions. The following procedure was used to separate the bimodal northern Tanzania and unimodal Western Cape from the unimodal summer areas in the region:

- Three time periods were analysed in Tanzania, a whole year (1st October to 30th September), the period 1st September - 28th February for short rains and 1st February - 31st July for long rains and two in the southern and western South Africa, 1st March – 28th/29th February and 1st October – 30th September. In Tanzania, September and February are included so as not to exclude the possibility of early onsets of the short and long rains respectively, while January-February and June-July are included in order not to exclude late cessations of the two seasons. It should be noted that February is used in both sub-periods. February was purposely included in the two sub-periods so as to enable appropriate identification of unimodal and bimodal areas.
- Using the definitions of the onset and end of the rainy season, the onset and end were calculated at each station in the corresponding regions and are shown in Fig.8.4 for Tanzania.
- A presumption of a period of at least one and a half to two months separating the two seasons indicates that the bimodal region of Tanzania extends from western Lake Victoria region sweeping across northern and northeast Tanzania to the northeast coast along the Indian Ocean, north of about 7.5°S (Fig.8.4). Nevertheless, the whole region above the 40-days contour show bimodal characters and is considered as the bimodal region in this study. The region immediately south of the bimodal region experiences characteristics of both bimodal and unimodal rainfall regimes. It is referred to as transition region between the unimodal and bimodal regions (Nyenzi *et al.*, 1999). The Western Cape was similarly separated from the rest of South Africa.

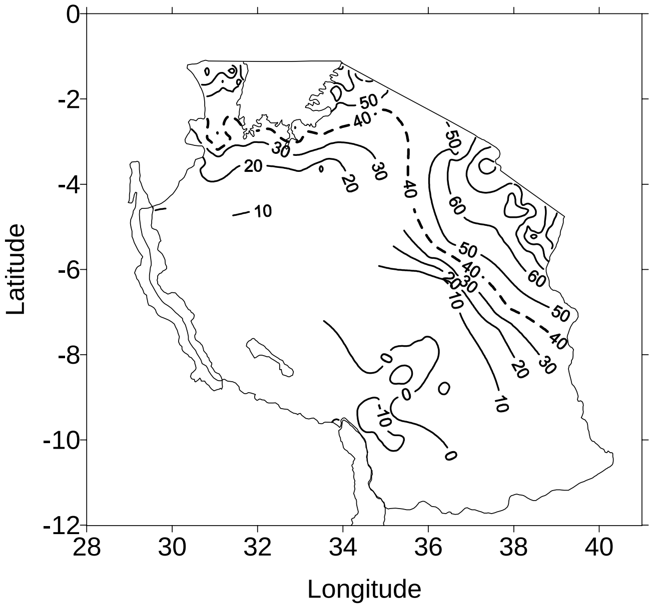


Fig.8.4: Differences (in days) between onset of long rains and end of short rains in Tanzania when the sub-periods for short and long rains were used. The region north of the bold dashed line roughly represents the bimodal areas of northern Tanzania.

8.4 Sensitivity of parameters defining the rainy seasons

Sensitivity tests were performed on intensities and lengths of dry day sequences which define the onset and cessation of rainy seasons. Sensitivity of onset dates was performed i) by comparing onset dates given by AADI as a limiting intensity to those resulting from the use of 5 mm and 10 mm fixed daily intensities for a 15-day long dry day sequence and ii) by comparing onset dates given by a 15-day long sequence of dry days to those resulting from the use of 7-day and 10-day long sequences with AADI as a limiting intensity.

Likewise, sensitivity of cessation dates was assessed i) by comparing cessation dates given by AADI as a limiting intensity to those resulting from the use of 0.5AADI and 1 mm fixed daily intensities for a 30-day long dry day sequence and ii) by comparing cessation dates given by 30-day long sequence of dry day to those resulting from the use of 20-day and 40-day long sequences with AADI as a limiting intensity.

Results show generally that onset and cessation of rainy seasons determined by the proposed method are more sensitive to varying length of sequence of dry days than to variation of the limiting intensities. Moreover, onset of the rainy season is more sensitive to changing limiting intensities than the end. The main features are

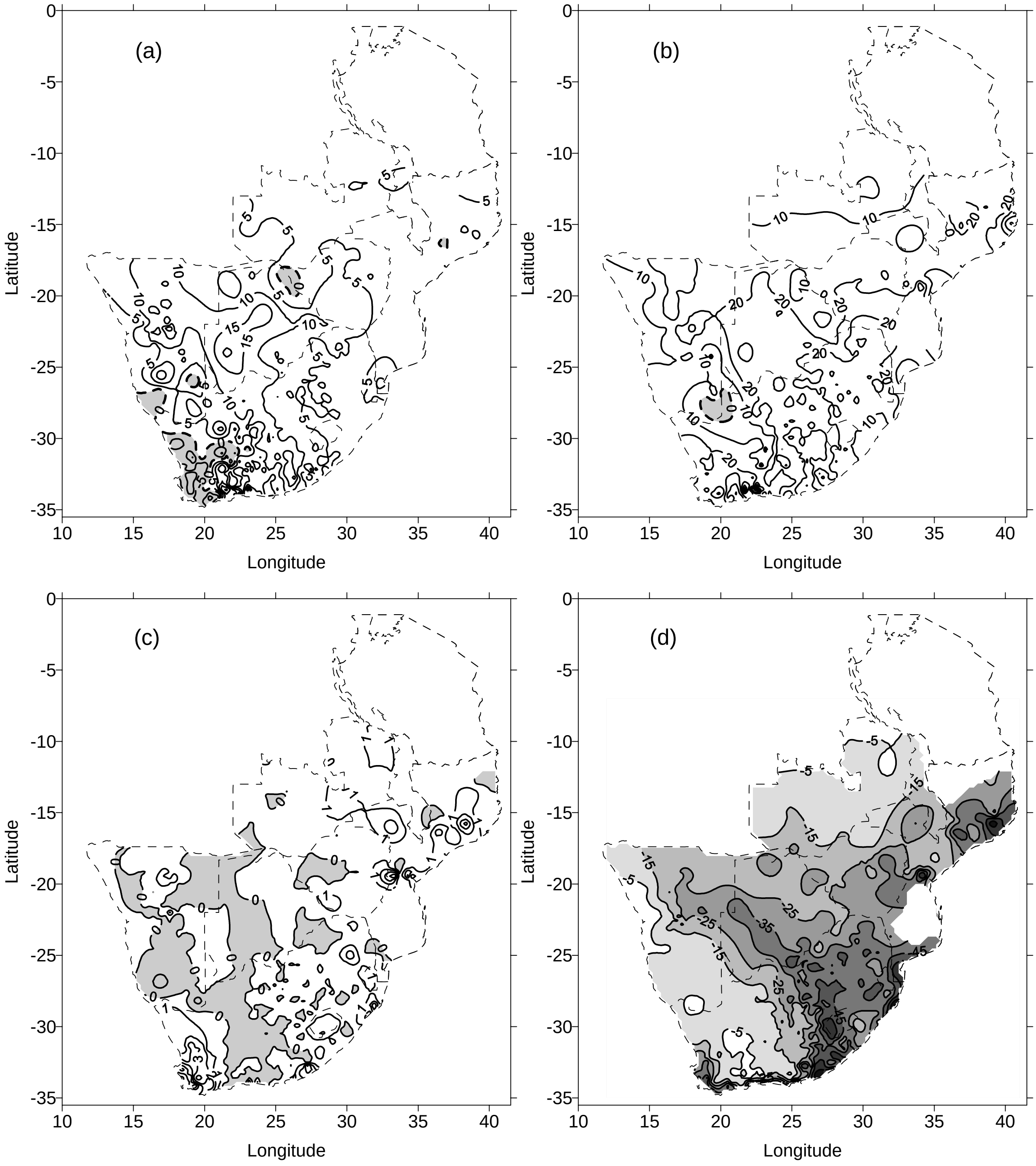


Fig.8.5: Differences between onset dates given by a) 5mm against AADI intensities, b) 15 days long and 10 days long dry day sequences and between cessation given by c) 1mm against AADI intensities and d) 20 days long against 30 days long dry day sequences in the unimodal rainfall southern Africa. Negative differences are shaded.

- Changes of onset-defining intensities from AADI to 5 mm or 10 mm fixed intensities lead to an early onset in the Western Cape and a delayed onset in the rest of unimodal southern Africa (Fig.8.5a). The significant delays of up to a month are found in Botswana while in the remaining part the changes are moderate. The decrease of the length of the sequence of dry days from 15 to 10 days result in a delayed onset across the whole of unimodal southern Africa (Fig.8.5b) which is longer in the southern and eastern parts than in the northern (Zambia) and western (western Namibia) parts.

- At a constant month (30 days) long sequence of dry day, there are practically no changes in the dates of the end of the rainy season across southern Africa whether AADI, its half or 1 mm intensities are used as limiting intensities (Fig.8.5c). However, a change from 30-day long sequence of dry days to 20-day long sequence for a fixed limiting intensity (AADI, 0.5AADI or 1 mm) results in an early end of the season across the whole of the unimodal southern Africa, affecting significantly the eastern part of the region particularly in southern Mozambique, eastern South Africa and southwest Botswana (Fig.8.5d). The isolated nature of daily rainfall events in the dry southwestern part of southern Africa and high frequencies of rainfall events in Zambia make the end of the season less sensitive to changes in the length of the sequence of dry days as indicated by the lowest changes in these parts. The earliest ends around early January in Botswana or around late January in central South Africa, for example, were not consistent with what is shown by time series suggesting the inappropriateness of this length.

8.5 Spatial variation of averages of the rainy seasons

8.5.1 Onset, end and duration in the bimodal northern Tanzania

The results of the average onset and end dates of the short and long rains in the bimodal northern Tanzania are summarised in Fig.8.6. They show generally characteristics which are related to the start, advances and retreat of the two seasons in the bimodal northern Tanzania:

- The average dates and durations

  The short rains in bimodal Tanzania last, on average, about 55-60 days between 1st week of October and 2nd week of January (around 13th January) (Fig.8.6a, 8.6b) while the long rains start in late-February (around 27th February) in southern Lake Victoria and between 12th and 22nd March in northeast and they retreat from the bimodal region between 12th and 27th May and have average durations not significantly different from that of the short rains (Fig.8.6c, 8.6d).

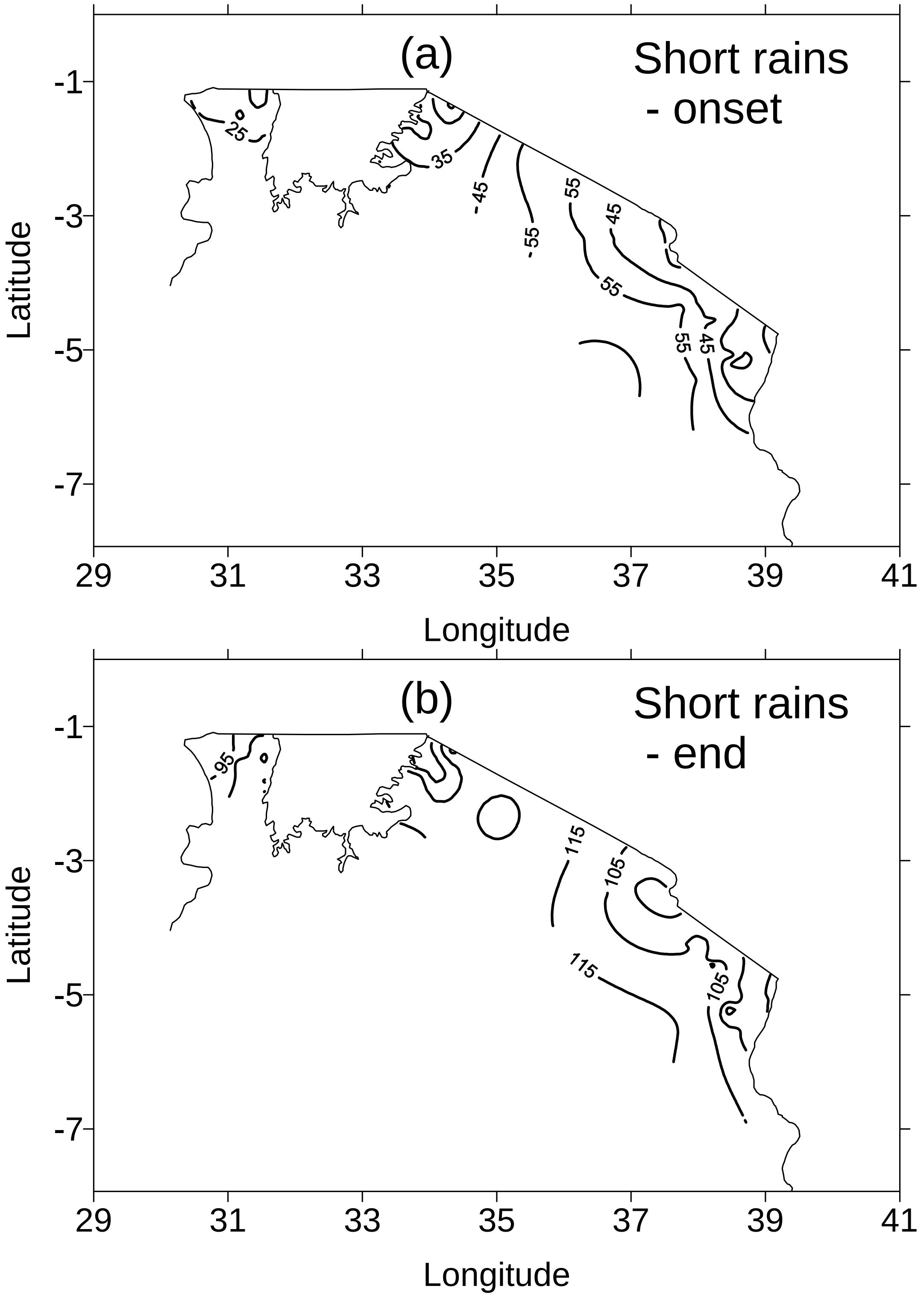


Fig.8.6: Average a) onset and b) end of the short rains in the bimodal northern Tanzania. The number indicate days since 1st October.

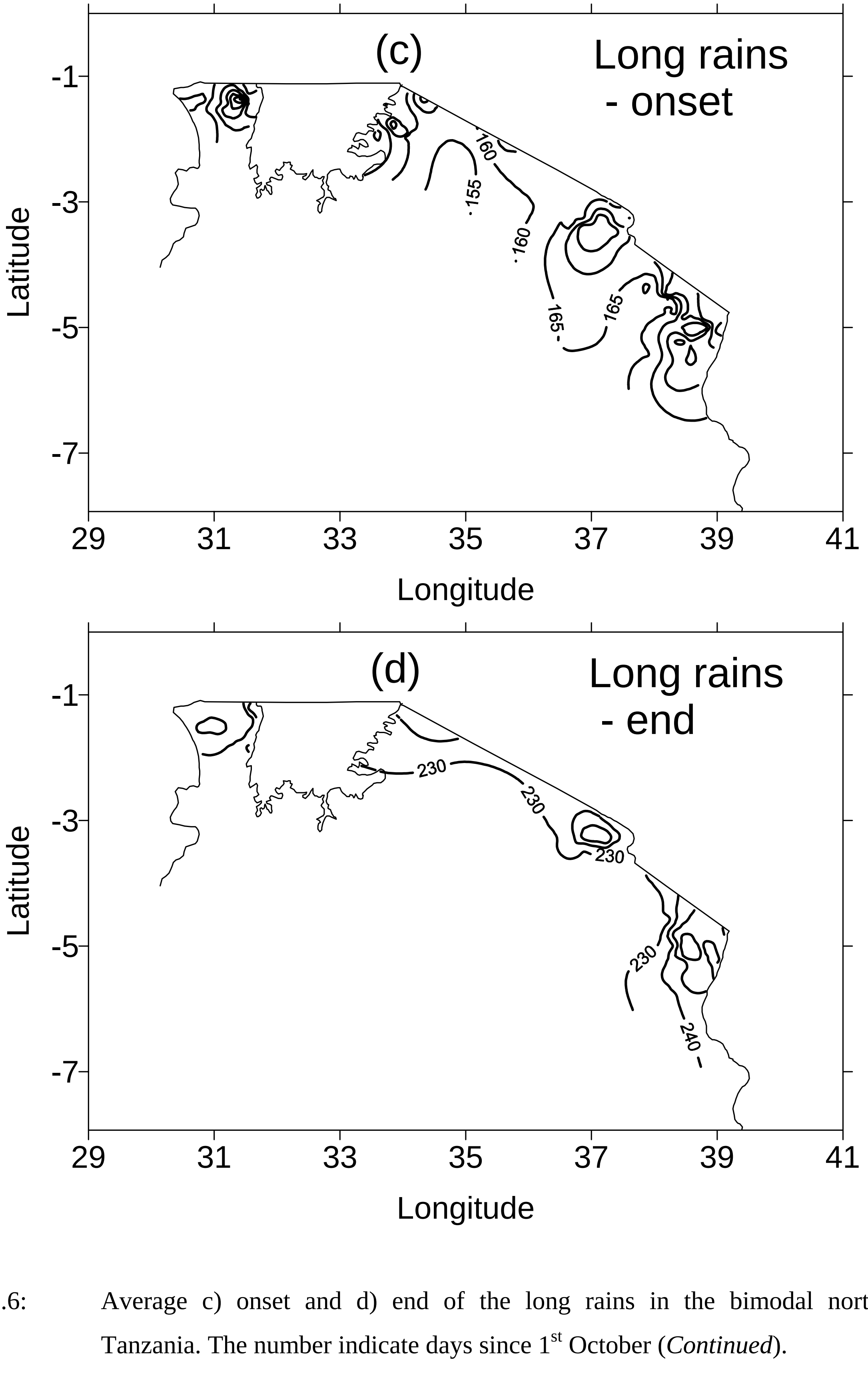


Fig.8.6: Average c) onset and d) end of the long rains in the bimodal northern Tanzania. The number indicate days since 1st October (*Continued*).

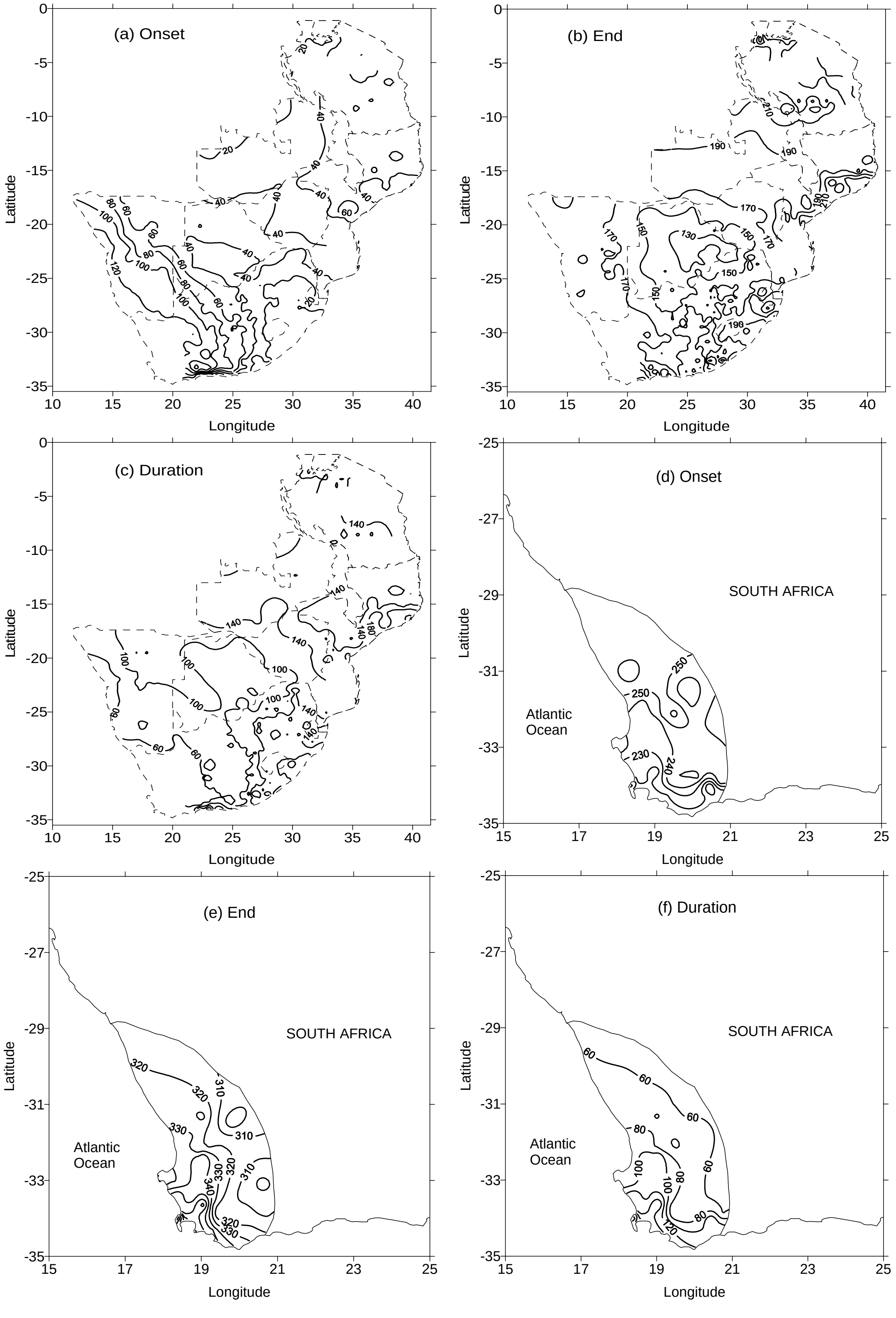


Fig.8.7: Average onset, end and duration of the rainy season in unimodal areas of southern Africa: a)-c) summer rainfall areas and d)-f) Western Cape. Onset and cessation dates are days since 1st October.

- The spatial patterns of advances and retreat

  The short rains spread into northern Tanzania from i) northwest Lake Victoria and ii) the northernmost coast of Tanzania (Fig.8.6a) while their pattern of retreat follows that of its start (Fig.8.6b). The spatial pattern of long rains onset is almost the reverse of that of the short rains in which the long rains start in southern Lake Victoria and the southwest part of northeast Tanzania (Fig.8.6c) while they cease earliest in the southern part of the bimodal areas and latest in the coastal areas of the northeast (Fig.8.6d).

- The evidence of the differences between the short and long rains

  Seasonal amounts and number of daily rainfall events indicate that these two quantities are lower during the short rains than during the long rains. The long rains receive about 4-27 extra daily rainfall events compared to the short rains. The Lake Victoria region experiences comparable seasons with typical differences of below 10 days. However, the greatest differences (typically between 10-20 days) are observed in the mountainous areas in northeast Tanzania. Moreover, amounts of rain falling during the long rains are about 1.1-1.5 of those during the short rains. These results suggest that the names (short and long rains) are derived from the expected number of daily rainfall events and rainfall amounts rather than their lengths.

8.5.2 Onset, end and duration in the unimodal southern Africa

The spatial variation of the average dates of onset and end and the average durations of the rainy seasons in the unimodal summer and winter (Western Cape) areas of southern Africa are shown in Fig.8.7. The main features are summarised as follow:

- The average dates and durations

  The rainy season in the summer areas of the unimodal southern Africa is observed between the 1st week of October and 4th week of April (8.7a, 8.7b) while in the Western Cape it extends between 4th week of April and mid-October (8.7d,8.7e).

- The spatial patterns of advances and retreat

  The rainy season in the summer unimodal areas spreads from the southeastern coast of South Africa (1st two weeks of October) in the south and from northern and western Zambia (20th-30th October) in the north into the interior part of southern Africa (1st three weeks of November) and occurs latest in western and southern Namibia (between the 4th week of November and 3rd week of January; Fig.8.7a). The cessation begins in Botswana (around mid- to late-February) and progresses radially into other parts of the region (Fig.8.7b) in which the latest cessation in April is experienced in areas approximately north of 17°S.

In the Western Cape, the rains begin first in the southwestern tip of South Africa between the 4th week of April and 2nd week of May and progress northwestward (Fig.8.7d). The retreat is almost the reverse of the pattern of advance in which it starts in the 1st week of August from the inland areas towards the coast where the latest cessation is observed at the Cape's tip in mid-October. The zones of retreat approximately parallel the coastline (Fig.8.7e).

8.5.3 Rainfall amounts during the rainy seasons

Southern Africa receives about 80% of its annual rainfall amounts during the rainy seasons proper (Fig.8.8a), although the percentage amounts vary across the region. Most of Zambia, for example, receives over 90% of its annual amounts during the rainy season whereas much of South Africa receives 70% or less. The fraction of annual amounts falling within the established rainy seasons show high interannual variation in two regions (Fig.8.8b) i) the region comprising southwest Zimbabwe and the eastern and central Botswana and ii) the region comprising much of Namibia (except northeast Namibia) and the western half of South Africa which is hereafter referred to as the southwest region.

In general, fractions of annual amounts received during the rainy seasons decreases from the west to the east coast and from north to south. Two main factors attribute to this general pattern:

- Pre- and post-season rainfall

  According to the definitions of the onset and end of the rainy season used and the nature of the occurrence of daily rainfall events in the region, a few rainfall events are observed at the beginning and end of the season and which are either less intense or significantly isolated in such a way that they could not satisfy the criteria. In the dry areas, a few moderate or heavy daily events, which contribute significantly to seasonal amounts, were often separated by a long sequence of dry days and consequently fell out of the onset or end dates.

- Dry season rainfall

  Rainfall events are observed along the eastern coast of southern Africa during the dry season which correspond to significant rainfall amounts in the coastal northeast Tanzania, northern Lake Victoria region and central southern South Africa.

8.6 Interannual variations

Since the main aim of this section was to investigate the impacts of the changes identified in rainfall amounts and number of events on the rainy season characteristics, the main features of interannual variability of the rainy season characteristics are presented. They are discussed under a) interannual variability and b) inter-relationships between the rainy season characteristics.

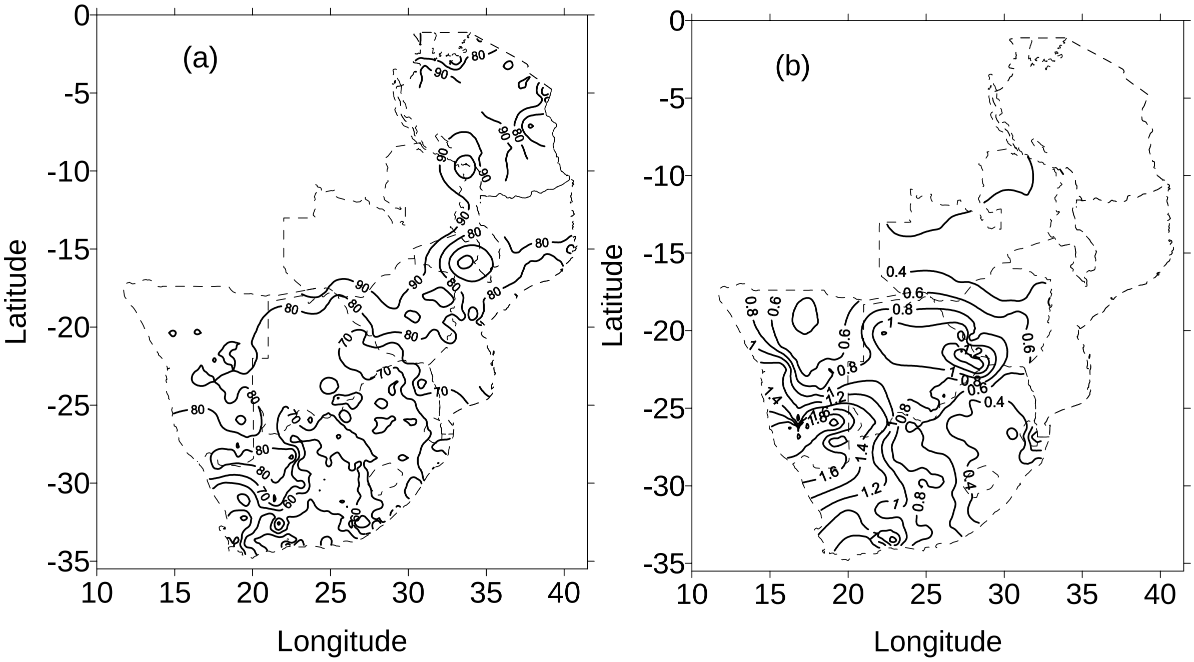


Fig.8.8: Spatial variation of a) average and b) coefficients of variations of rainfall amounts during the rainy seasons in southern Africa. Averages in a) are expressed as percentage of annual rainfall amounts. Amounts in northern Tanzania are accumulations of the two seasons.

8.6.1 Interannual variability

Change-point and linear trend analyses were not performed and results of interanual coefficient of variation (Fig.8.9) and maps of the rainy season characteristics for the wet and dry periods are used to highlight the possible interrelationships between interannual variations of rainfall amounts and number of daily events on one hand and interannual variations of the onset, end and duration of the rainy seasons in southern Africa. The interannual coefficients of variation (CVs) show that:

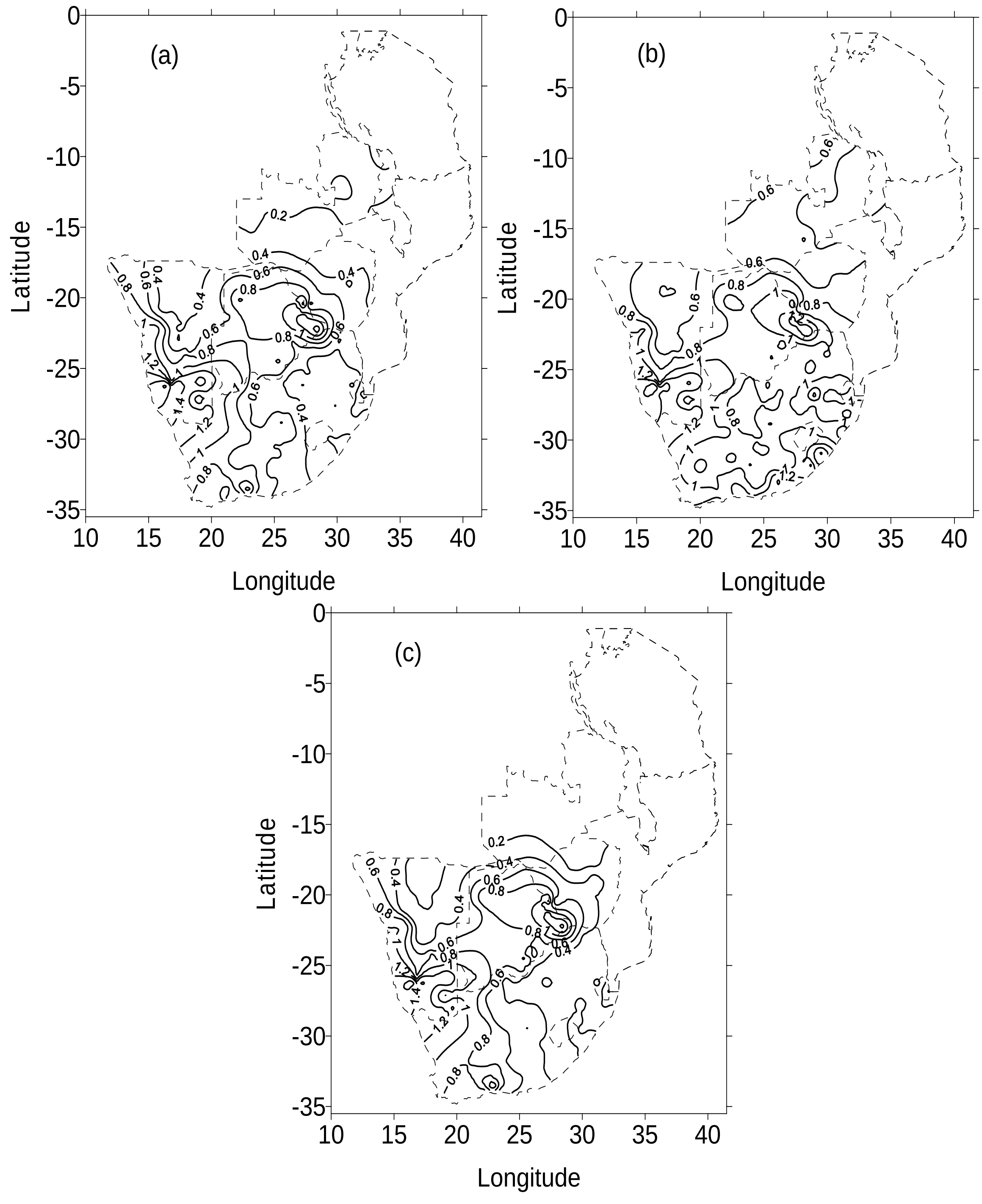


Fig.8.9: Coefficients of variation for the rainy season characteristics in the unimodal southern Africa. Mozambique is excluded.

- The spatial patterns of CVs of the duration and end of the rainy season are very similar and they differ from the pattern of CVs of the onset. The duration and end of the rainy season in summer areas of the unimodal southern Africa are less variable between the years in the eastern and northern parts of the region (sub-region2 in Fig.6.12) as indicated by the lowest CVs in the northern and western Zambia. The highest interannual variations characterise areas in the dry western coast and southwest Namibia, northwest South Africa, southwest Zimbabwe and southeast Botswana. The onset of the rainy season show high interannual variations in these similar areas as well as along the coast of South Africa where low interannual variations in the duration and end of the rainy season are a characteristic.

- The high interannual variations of the onset of the rainy season were often associated with years of early start and years of late start which were often accompanied by the absence of the season in the dry part of southern Africa. This was apparent, for example, in the period 1979/80 – 1985/86 which comprised years of significant deficit rainfall. During this period, a significant number of stations experienced a complete failure of the rainy season (Fig.8.10) in Botswana, Namibia and western South Africa while most of the stations in the eastern central South Africa were characterised by a shorter season (Fig.8.11). The failures were mainly attributed to longer sequences of dry spells. The wet 1972/73-1976/77 period was characterised by long and prolonged rainy seasons (Fig.8.11) as well as the least number of failed stations (Fig.8.10).

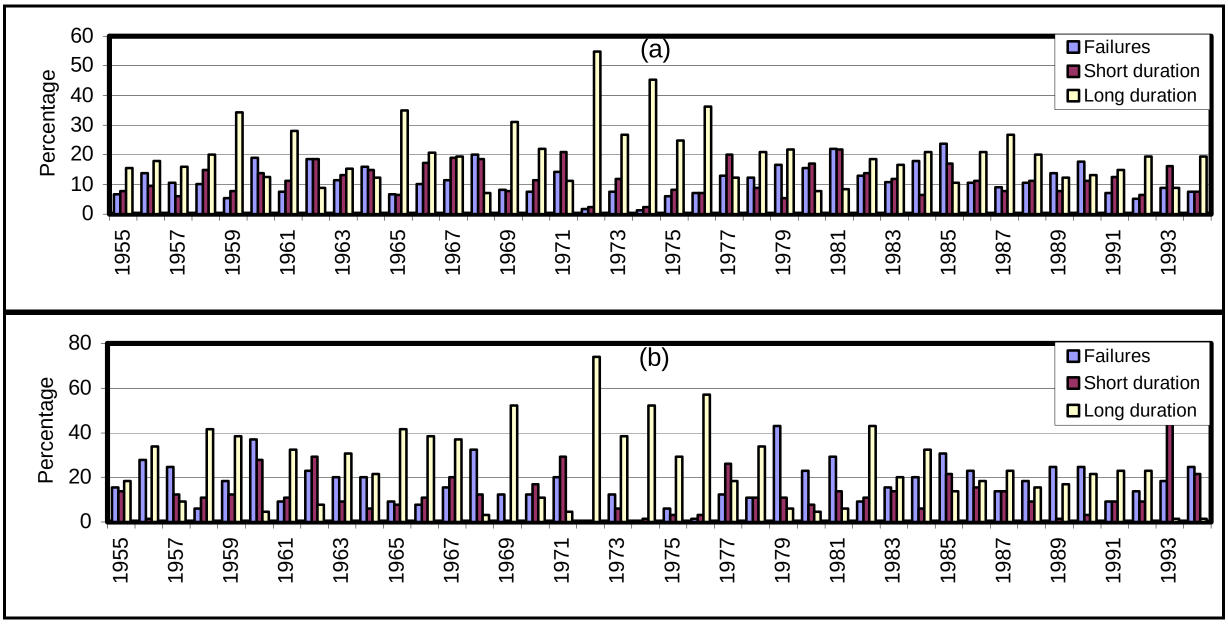


Fig.8.10: Temporal evolution of the number of stations with a completely failed rainy season and number of stations with longer and shorter than average duration of the rainy season in the 1955-1994 period: a) Whole of unimodal southern Africa and b) Namibia. The percentages for the durations involve stations in which the duration was 30% or more longer or shorter than the long-term average.

8.6.2 Interrelationships between the rainy season characteristics

The relationships between the duration of the rainy season and the onset and end of the rainy season on one hand and between the duration and the amounts and number of daily rainfall events during the rainy season on the other were investigated using correlation analysis. The results are presented in Fig.8.12 and Fig.8.13 and the main observations are summarised below.

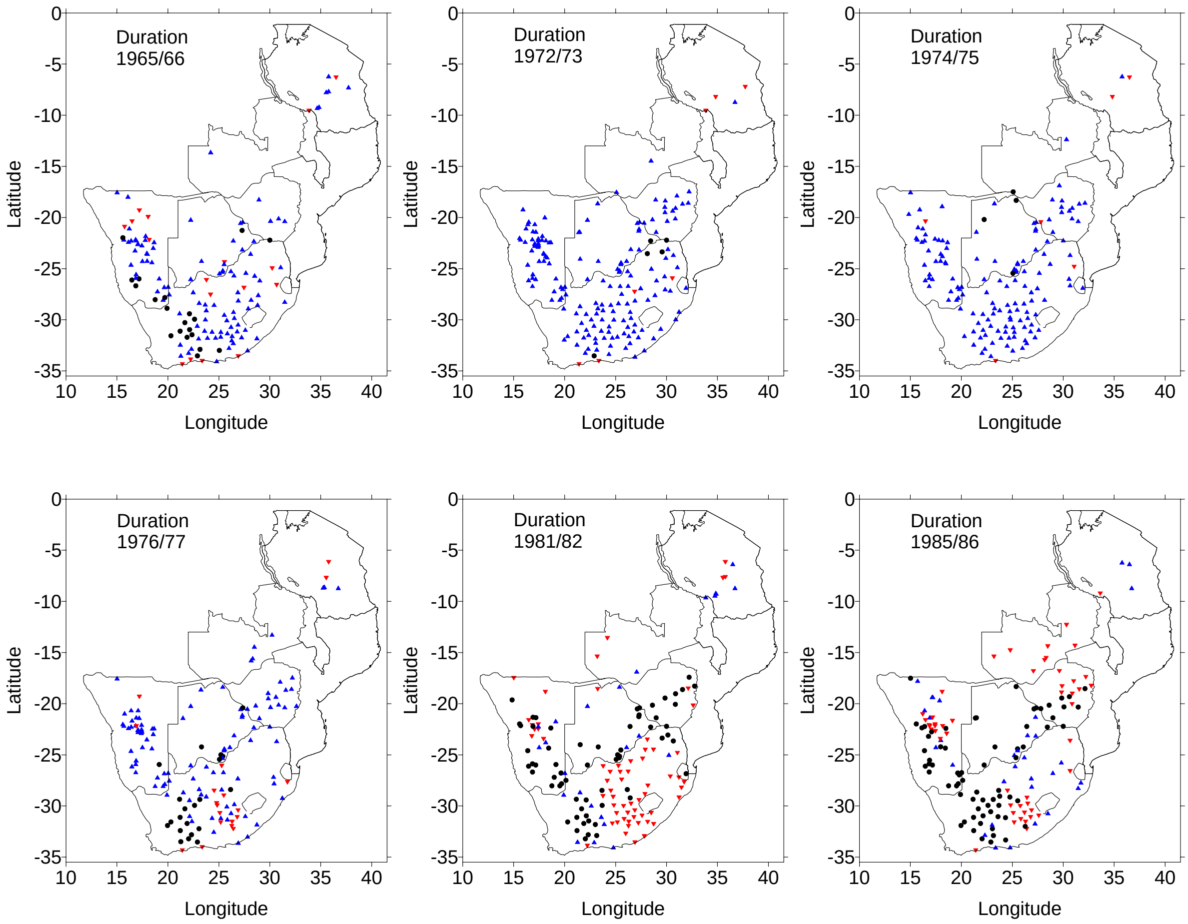


Fig.8.11: Duration of the rainy season for different years in unimodal southern Africa. Blue (red) triangles indicate >30% longer (shorter) duration with respect to long-term average. Black dots indicate stations which experienced a complete failure of the rainy season.

a) Time shift of the rainy seasons

This is indicated by significant positive relationships between the onset and end dates and characterise the lowlands of bimodal northeast Tanzania during both the short and long rains and the southwest region defined above. Accordingly, early onsets of the rainy season correspond to early ends and vice versa. This was observed, for example, in 1972/73 and 1974/75 in Namibia and western South Africa in which both the onset and end were late. Neither onset nor end of the rainy season show any significant relationships with the duration of the rainy season in these areas.

b) The relationships between the duration of the season and the onset and end

- Both the onset and end influence the duration of the rainy season in the tropical region of southern Africa comprising the southwestern highlands of Tanzania, Zambia, northern Zimbabwe and central Mozambique (Fig.8.13). However, relationships between the onset and end of the rainy season are almost non-existent in these areas suggesting that longer seasons may result from either an early onset or a late end but not simultaneously from both.
- The onset significantly affects the duration of both the short and long rains in the bimodal northern Tanzania as indicated by high negative correlations (long rains, Fig.8.12) suggesting that earlier than normal onsets correspond to long seasons and vice versa. This was exemplified by the early and prolonged 1978 and the late and short 1984 long rains (Camberlin *et al.*, 2002; Valimba *et al.*, 2004d). The end of the season significantly affect the duration of the long rains in northern Lake Victoria but not in northeast Tanzania (Fig.8.12) while it does show low correlations in early summer.
- In the remaining part of southern Africa, the duration of the rainy season is positively and significantly affected by the end of the season as indicated by high positive correlations (Fig.8.13) while no significant relationships exist between the duration and onset. This fact suggests that longer seasons correspond to late ends rather than to early starts as was observed in the long rainy seasons in 1972/73 and 1974/75 (Fig.8.11) which corresponded to late ends of the season rather than early onsets.

c) The relationships between the duration of the season and the amounts and number of daily rainfall events

The duration of the rainy season is significantly related to both rainfall amounts and the number of daily rainfall events received during the rainy season. This is shown by i) high cross-correlations between the three (see e.g. Fig.8.12) and ii) their similar spatial patterns of variations and magnitude of the interannual coefficients of variation (compare Fig.8.8b and Fig.8.9a). Hence, longer seasons are usually characterised by abundant and more frequent rains in most parts of the region.

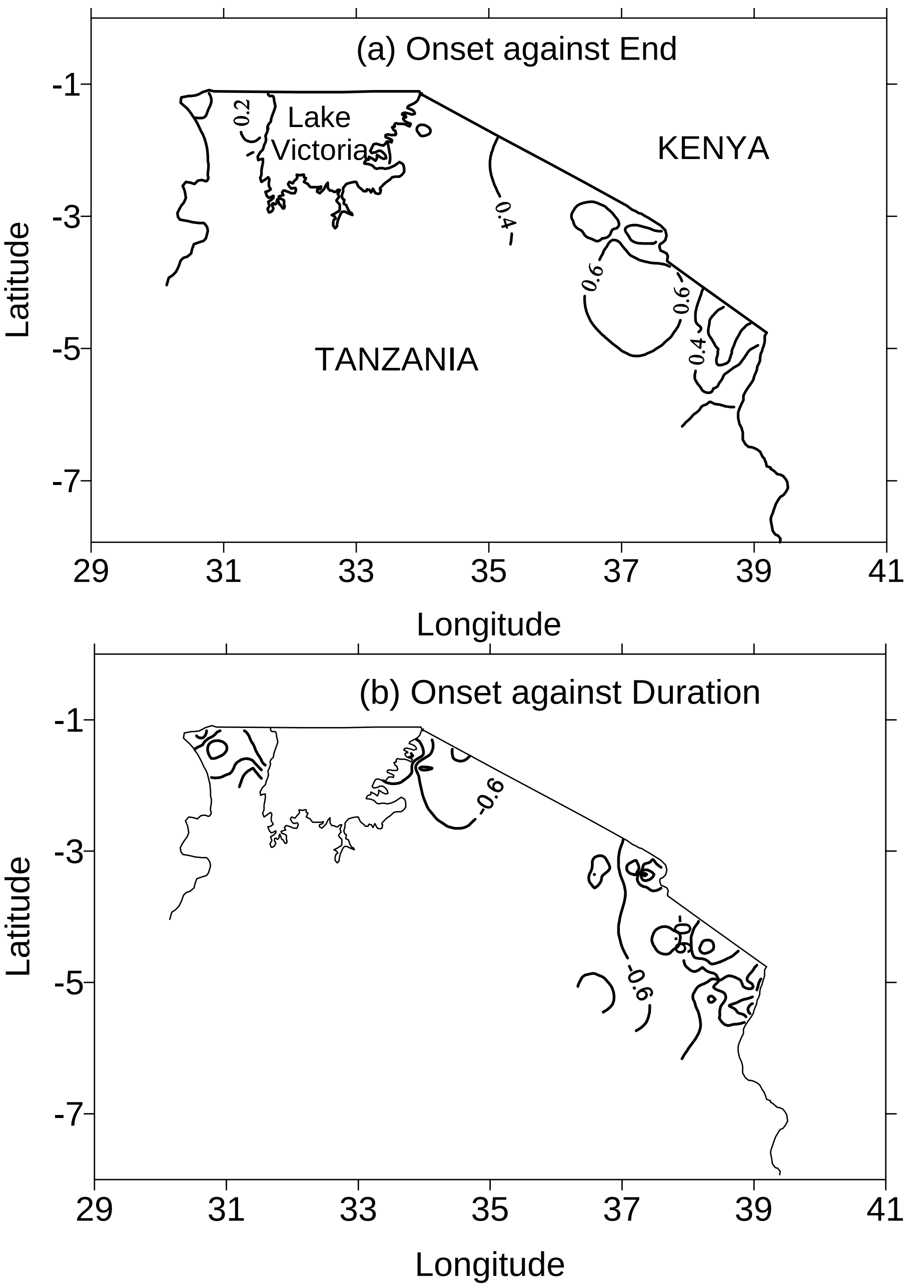


Fig.8.12: Correlations between rainy season characteristics in the bimodal northern Tanzania for the long rains.

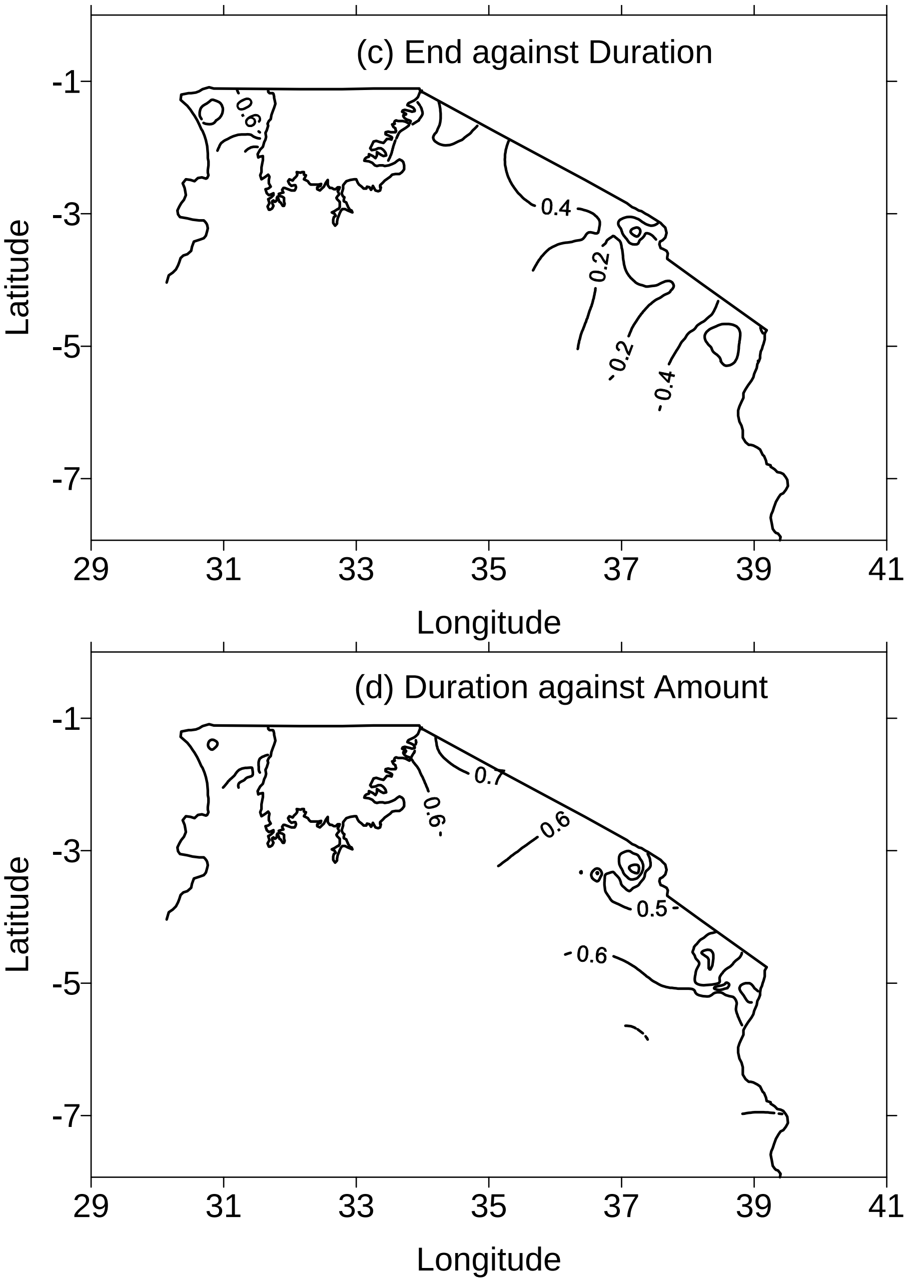


Fig.8.12: Correlations between rainy season characteristics in the bimodal northern Tanzania for the long rains (*Continued*).

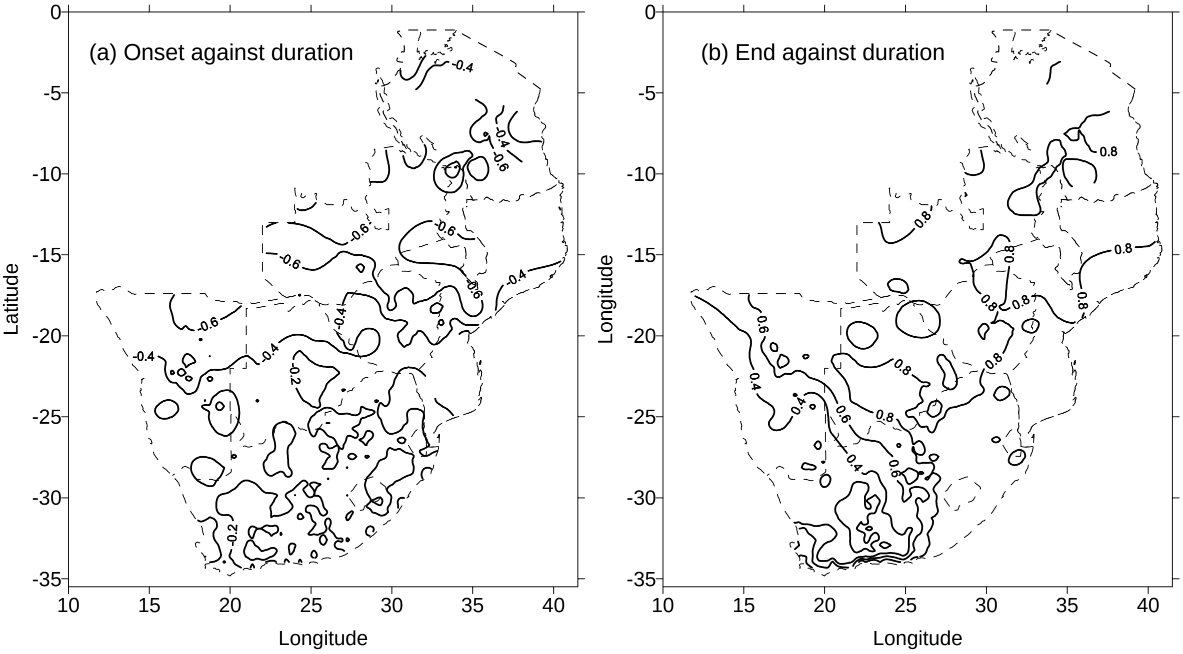


Fig.8.13: Correlations between duration of the rainy season and the onset and end in the unimodal southern Africa.

8.7 Discussion

8.7.1 Spatial variation of average rainy season characteristics

The two rainfall regimes (unimodal and bimodal) and the spatial pattern of the beginning of the rainy seasons, their advances and retreat from the southern Africa correspond to the seasonal displacement of the inter-tropical converge zone (ITCZ) into and from the region and the winds associated with it. The low-level climatological wind patterns in September and October (Fig.8.14) indicate prevailing westerlies extending from the Congo basin into the western Lake Victoria bringing moisture from the Congo source into the northwestern Victoria region while recurved westerlies around the Angolan heat low bring this into the western and northern Zambia. Easterlies from the tropical Indian Ocean bring moisture into northeast Tanzania while the cyclonic flow southeast of Madagascar advects moisture into the eastern part of South Africa. Subsequent changes in the low-level circulation winds between October and December which include, for example, southward displacement of the ITCZ and replacement of southeasterlies by northeasterlies, are associated with the advances of the season into the interior southern Africa. The northernward displacement of the ITCZ in late summer marks the retreat of the rainy season in the southern part and the start of the long rains in the northern Tanzania. Therefore, the bimodality in the northern Tanzania is caused by bi-passage of the ITCZ when it goes into and out of the southern African region.

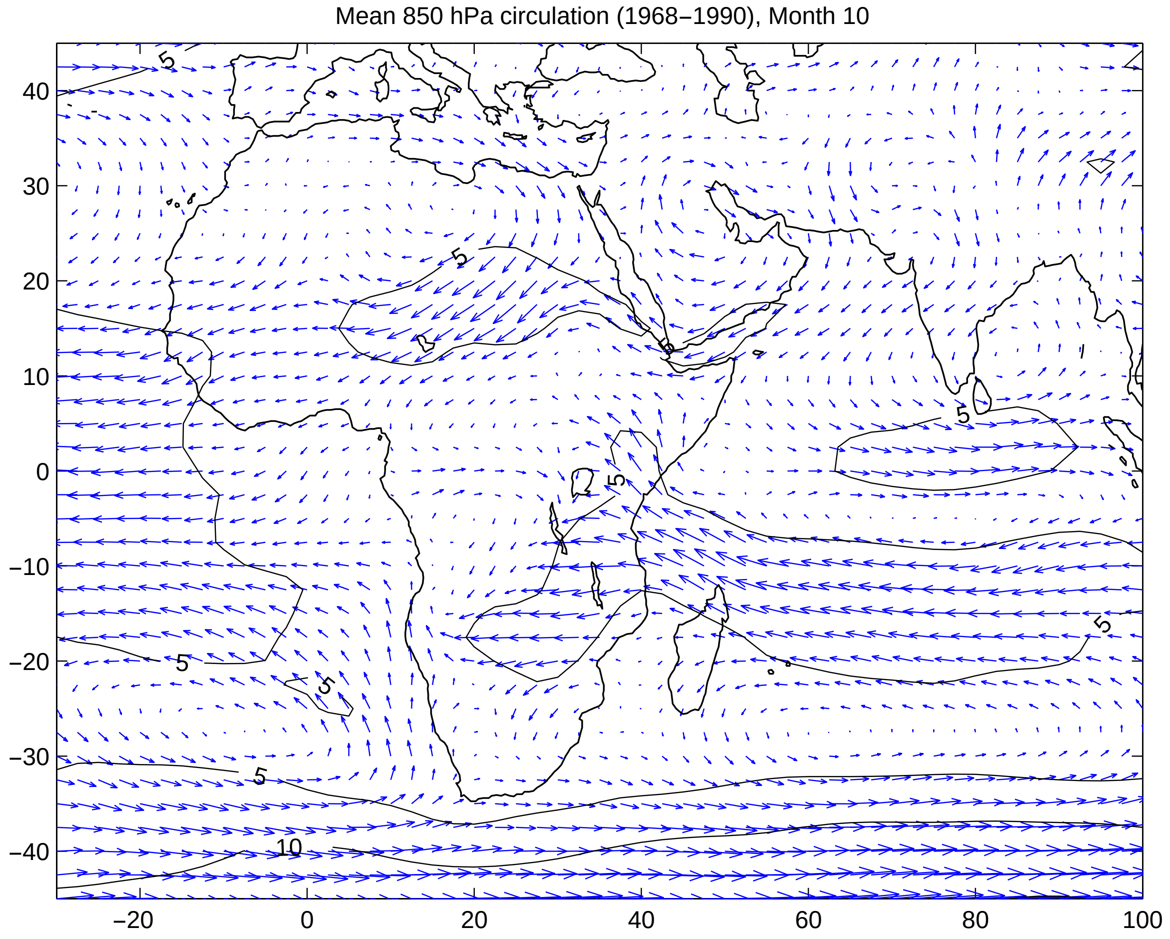


Fig.8.14: Near-surface wind climatologies in October over southern Africa.

Despite a limited number of studies which were devoted to rainy season characteristics in the region, the dates of onset and ends of the long rains, for example, were consistent with those found in the literature. Camberlin *et al.* (2002) found that the longs rains start in northeast Tanzania, on average, around 25th March, Asnani (1993) around 22nd – 26th March, Alusa and Mushi (1974) placed the average onset around 12-17th March in Kenya bordering northeast Tanzania while this study found the earliest and latest starts to be around 12th and 22nd March respectively. Further, the average end of the long rains on 21st May (Camberlin *et al.*, 2002) lies within the earliest and latest ends around 12th and 27th May, respectively, found in this study. The range of dates found in this study corresponds to the spatial nature of variations in which the southern part of the northeast experiences both the earliest onset and end of the long rains while the mountainous and coastal areas experience the latest end.

8.7.2 Interannual variations

As expected, interannual variations of the rainy season characteristics are observed to follow those in the amount and number of daily events since the two quantities are used in the definitions of the onset and end of the rainy season. The wet years (e.g. 1972/73, 1974/75) in the unimodal summer areas of southern Africa correspond to longer than average seasons while the dry years (e.g. 1981/82) were characterised by shorter than average seasons.

There is evidence of shortening of the rainy seasons, delayed onset and increased interannual variability since the late-1960s to the 1970s while no significant changes were associated with the end of the rainy season . The long rains in northeast Tanzania, for example, were often later than average in the 1970s except in 1978 and 1979, while since the early-1980s, they show high interannual variability and are delayed. These results are consistent with those of Valimba *et al.* (2004d). There is little evidence that these results could be attributed to the definition of the rainy season characteristics used in this study and that of Valimba *et al.* (2004d) which were based on the daily intensities and the length of the sequences of dry spells. Camberlin *et al.* (2002), who used a different approach to the one used in the present study, found a trend towards late onsets influenced significantly by late onsets since the early-1970s (see their Fig.4).

The fact that the number of stations experiencing failure of the rainy season and that of stations observing shorter than average durations in Namibia has not significantly changed, while there is a significant reduction in the number of stations in which longer than average durations of the rainy season were identified in Namibia since around 1978/79 suggests a shortening of the rainy season in the stations which were initially characterised by long rainy seasons. The durations were more often below their long-term averages since around 1978/79, the period consistent with that in which abrupt decreases in the amounts and number events were identified in Namibia.

8.8 Conclusions

A method that defines the rainy season in terms of daily rainfall intensities and length of dry spells has been established. The general definitions of onset and end of rainy seasons established in this chapter are more sensitive to the length of sequences of dry days than to intensities defining them. Sequences of dry days have not been widely used but high sensitivity of the onset and end dates of the rainy season to the length of these sequences indicates that they are an important parameter of the rainy season.

The onset, advances and retreat of the rainy season in southern Africa have been related to the seasonal movement of the ITCZ and the associated atmospheric wind patterns. The early starts were observed in the northwestern part (northwest and northern Zambia), southeastern part (southeast South Africa) and northeastern part (northeast Tanzania) of the region while the retreat starts in the central part (Botswana) and progresses radially. On the other hand, interannual variability of the rainy seasons were observed to resemble those in rainfall amounts and number of events suggesting factors that influence interannual variations of the amounts and number of daily events are likewise affecting the rainy season characteristics since more than 70-90% of the amounts and events are observed during the established seasons.

The method proposed in this chapter was able to identify probable dates of the onset and end of rainy seasons in southern Africa including seasons in the dry southwestern part of southern Africa and the highly variable short rains in northern Tanzania. Changing frequency of occurrence of daily events was observed to cause failure to identify the rainy season, particularly in the dry southern Africa. However, frequent absence of the season may be attributed to a failure of the proposed scheme to account appropriately for daily rainfall characteristics in these dry areas. Further studies of daily rainfall variations in dry southwest southern Africa are therefore recommended.

CHAPTER 9

SEASONAL AND INTERANNUAL VARIATIONS OF RIVER FLOWS IN SOUTHERN AFRICA

9.1 Introduction

It is hypothesized that identified changes in southern African rainfall are similarly reflected in streamflows as observed in West Africa (Olivry and Mahé, 1991; Olivry, 1993; Olivry *et al.*, 1993; Servat *et al.*, 1997a) and their severity is increased by anthropogenic human influences. Dam levels have been reported to decline since the mid-1970s in Namibia (Jury and Engert, 1999), in South Africa since the early 1980s as a reflection of a prolonged rainfall deficit in the 1980s and early 1990s (Mason, 1996). Berhanu (1999) and Berhanu *et al.* (2001) found a recent decrease in mean annual runoff in southern African catchments to have occurred since 1975, particularly marked in Zambia, Angola, Mozambique and the South African Highveld. The changes in annual runoff in southern African catchments are occurring at shorter timescales such as monthly and seasonal. Moreover, identified increasing frequencies and/or intensity of high rainfall, in some parts of the region, may cause an increase of frequencies and/or volumes of high flow and a decline of dry season flows due to poor infiltration and consequently insufficient groundwater recharge.

The intention of this chapter is, therefore, to investigate changes in mean flows and extreme streamflow characteristics (flood and drought flows) at monthly and seasonal timescales and their relationships with changes in rainfall. Change-point and linear trend analyses are used to check the existence of any discontinuities in the average values of flow time series indices. It should be noted, however, that the interest is related to the hypothesis that high and low flows are more frequent and severe in recent decades than in the past and therefore the peak-over-threshold method (POT) is used and annual maxima and minima are not investigated.

9.2 Streamflow seasonality

Flow seasonality is studied using mean monthly and mean annual flows to define months of high and low flows in southern African catchments. Behaviour of average daily flows is studied using flow duration curves (FDCs) and these are used to distinguish catchments with different response characteristics. A catchment is considered flashy when its groundwater storage capacity is low and consequently most of the falling rain is immediately transformed into runoff and flow ceases soon after the end of the rains. Rivers in flashy catchments are usually seasonal, flowing only during the rainy season, or ephemeral, flowing intermittently.

9.2.1 River flow regimes

The FDCs calculated with zero flows included (e.g. Fig.9.1) distinguished i) seasonal rivers from perennial rivers and ii) highly seasonal (or ephemeral) rivers from moderately seasonal rivers. in the southern Africa region.

- Highly seasonal or ephemeral rivers, flow when there is rainfall and cease almost immediately afterwards. There are frequent periods of no flow within a wet period. This type of river characterises rivers in Botswana, Namibia, western Zimbabwe and South Africa (Mngodo, 2002). All three Namibian rivers, for example, flow for less than 10%-30% of the time (Fig.9.1) regardless of catchment size. Time series of average daily (not shown) and monthly (e.g. in the Swakop River at Westfalenhof in Fig.9.2) flows indicate that flows in these rivers are observed between January and April for rivers in western Namibia which drain directly into the Atlantic and between December and May for the Fish River which joins the Orange River.
- Moderately seasonal rivers, flow continuously during the rainy season and cease sometime after the end of the rains and dry up completely during the dry period. These are the characteristics of small catchments in the Limpopo and in the Western Cape in South Africa. In these catchments, rivers flow continuously mainly between May and December for catchments in the Western Cape and between November and April-July for catchments in the other parts of unimodal southern African, the exact end month of the flow between April and July being dependent on catchment characteristics.
- Perennial rivers flow throughout the year and are a characteristic of most rivers in southern Africa, particularly the main rivers in the large river basins or their main tributaries in the large river sub-basins. These rivers are characterised by non-zero FDCs (e.g. Upper Zambezi in Fig.9.1) indicating residual flows during the dry period, which are dependent on catchment characteristics. Further, these rivers are characterised by periods of high and low flow as opposed to seasonal rivers, which experience periods of flow and no flow.

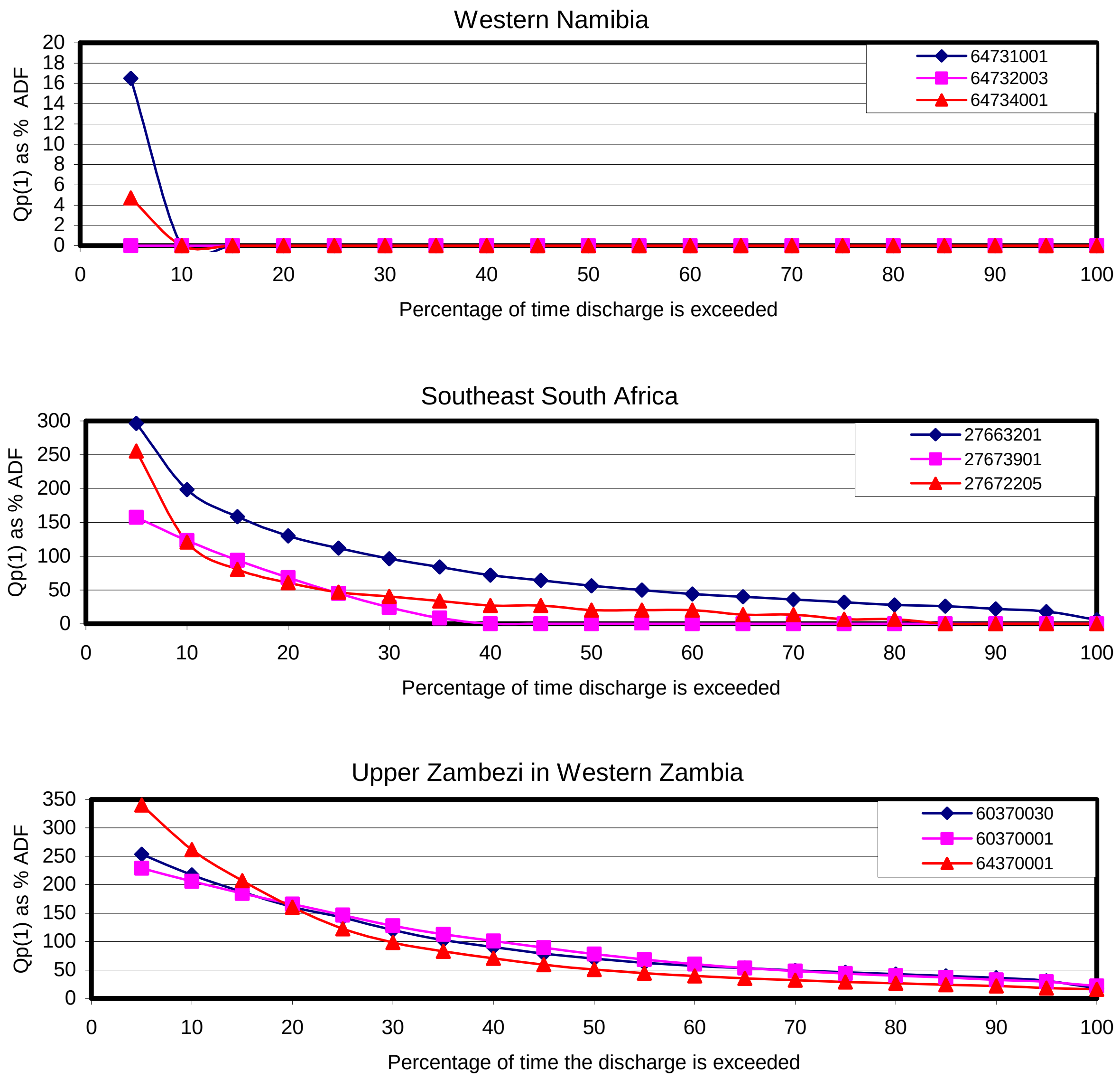


Fig.9.1: FDCs for selected rivers in southern Africa. Exceedence flows were determined including the zero flows to highlight seasonality of river flow regimes.

9.2.2 Flow seasonality

Seasonal flow variations in the perennial rivers in southern African are characterised by double flow peaks in northern Tanzania, as well as parts of the southern and Eastern Cape and a single flow peak in the rest of the southern African subcontinent (Fig.9.2). The peaks correspond to seasonal rainfall variations in the region, double peaks in northern Tanzania corresponding to the bimodal rainfall regime reflecting the short (October-December) and the long (March-May) rains while in the southern and Eastern Cape, the flow peaks are observed in April and December corresponding to early and late summer rainfalls. A single peak in the remaining area corresponds to the unimodal rainfall regime. It was further noted that the peak in the bimodal northern Tanzania is well defined and more apparent during the long rains than during the short rains (e.g. Pangani at Hale in Fig.9.2).

To define months of high and low flows, mean monthly flows (μ_{mon}) were compared to mean annual flows (μ_{an}). However, high flows during the long rains in northeast Tanzania caused mean annual flows above mean monthly flows during the short rains (Pangani in Fig.9.2) and consequently a peak during the short rains could not be established. Subtraction of half a standard deviation of annual flow ($\frac{1}{2}\sigma_{an}$) from the mean annual flow, however, was able to isolate the weak peak during the short rains. Results show that:

- Months of high and low monthly flows vary between catchments. Generally, the periods June-September and January/February-April/May are characterised as high flow periods in the Western Cape and in the rest of the unimodal southern Africa respectively (Fig.9.2) and April-June in northern Tanzania. Rivers that drain the catchments in southeast Angola and western Zambia have their high flow period extending into May. The highest monthly flows are observed in January-February in most parts of unimodal southern Africa, in August in the Western Cape, in March-April in Zambia and Malawi and in May-June in northeast Tanzania (Fig.9.2). Similarly, low flows are observed during the dry periods, between July and November in most parts of unimodal southern Africa, between December and March in the Western Cape and in both August-October and February-March in bimodal northeast Tanzania.
- Despite similar seasonal flow patterns, mean monthly flows vary greatly between southern African catchments depending, among other factors, on the catchment size, catchment slope, rainfall amounts and soil and aquifer properties related to water holding capacity and groundwater storage. Mean monthly flows are high along the length of the main rivers in the large basins or their main tributaries (e.g. the Zambezi basin or its Luangwa sub-basin; the Okavango basin, etc, Fig.9.1) which drain the humid part of southern Africa.

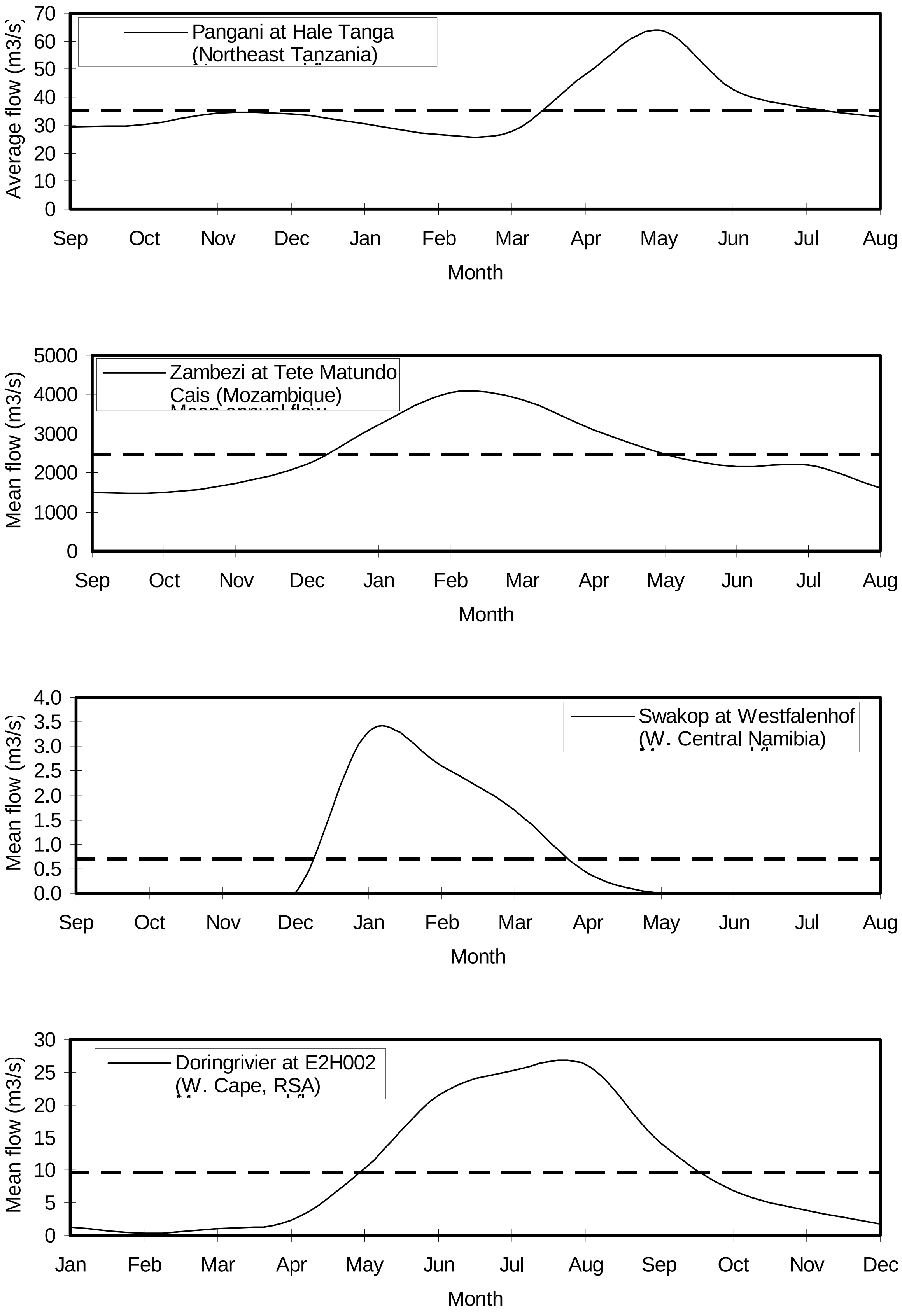


Fig.9.2: Typical seasonal flow variations in different southern African rivers. The dashed line represents the mean flow.

9.3 Flow persistency

Coefficients of correlation of monthly flows are shown in Table 9.1 for some southern African rivers. These were computed for time series of monthly flows constructed as single time series comprising of the all months during the period studied (e.g. for a 30 years record, the series comprises of 12 × 30 = 360 monthly data points). The residual flow characteristic of the perennial rivers is an important factor of the within-the-year and between-years flow persistency. Time series of mean monthly flows show high Lag 1 serial correlations in all the selected gauges except those in the Orange basin and western Namibia (Table 9.1). The highest lag 1 serial correlations were found for rivers in the Upper Zambezi sub-basin, the Shire sub-basin and the Okavango basin. The correlations for other intra-annual lags, particularly for lags 3 to 10, were low and sometimes negative.

Table 9.1: Correlation coefficients for time series of mean monthly flows in selected rivers in southern Africa constructed for the 1960-1989 period.

Gauge Details				**Series correlations at lag (months):**							
Sub-basin	Gauge	Area (Sq. km)	MAF (m^3/s)	1	2	3	12	24	36	60	120
Upper Zambezi	60370030	212450	239.6	0.81	0.40	-0.03	0.89	0.80	0.75	0.78	0.80
	60370001	290572	296.3	0.84	0.48	0.05	0.91	0.84	0.78	0.80	0.85
	64370001	339521	352.1	0.77	0.35	-0.03	0.80	0.70	0.63	0.62	0.79
Kafue	60334005	433	0.8	0.61	0.19	-0.07	0.66	0.48	0.32	0.25	0.58
	60334050	5163	16.0	0.78	0.37	0.00	0.73	0.60	0.50	0.54	0.66
	60334620	1125	2.1	0.64	0.20	0.05	0.43	0.43	0.30	0.12	0.55
	60334280	23218	53.1	0.80	0.40	0.01	0.76	0.69	0.61	0.58	0.70
Luangwa	60773275	1008	6.5	0.80	0.49	0.20	0.02	0.01	-0.01	0.07	0.26
	60332040	142760	169.8	0.68	0.24	-0.10	0.75	0.68	0.69	0.69	0.66
Western Namibian	64731001	6567	0.3	0.12	0.02	-0.03	0.10	0.27	0.22	0.17	0.05
	64732003	8986	0.3	0.18	0.16	0.02	0.01	0.14	0.14	0.05	0.00
	64734001	7729	0.1	0.17	-0.03	-0.02	0.05	0.25	0.26	0.15	0.00
Western Cape	27712202	6895	4.0	0.59	0.33	0.02	0.25	0.20	0.32	0.14	0.25
	27711403	46	0.4	0.62	0.38	0.06	0.45	0.44	0.49	0.34	0.43

At the interannual timescale, most rivers show low flow persistency except those rivers which drain the large catchments or sub-basins in the Zambezi and Okavango. Except for rivers in the Shire sub-basin, rivers in the other Zambezi sub-basins and the Okavango basin are found within the central African/Sahara Sedimentary aquifer system (Fig.3.5 in Chapter 3) in which the sedimentary layers form important groundwater reservoirs. The soils in these basins are predominantly sandy soils (Fig.3.4) with low water holding capacity within the root zone, a factor favourable for infiltration that eventually leads to aquifer recharge. Therefore, as suggested by Jury and Gwazantini (2002), this high persistence can be attributed partly to the large sizes of the catchments and partly to the Atlantic decadal variability through rainfall variability.

Correlations were also computed for annual series of each month. The series for each month (e.g. January) comprises monthly mean flows for that particular month over the record period (e.g. for a 30-year period, a series for January comprises 30 mean January monthly flows, etc). They show that:

- Flows in perennial rivers are more variable during the high flow period than during the low flow period. The lowest interannual variations characterise rivers in the upper Zambezi sub-basin and the Okavango basin. Flows during the high flow period are contributed to by both groundwater storage and rainfall in which the latter displays considerable interannual variations in southern Africa (cf Chapter 7) compared to the former. The low interannual variations during the low flow period are not unexpected as flows during the dry period are contributed mainly by groundwater storage.
- Flows in seasonal rivers and in the perennial rivers which drain the small catchments in the humid parts show high interannual variations during the dry period and low interannual variability during the high flow period. This is attributed mainly to low mean flows and high interannual variance during the low flow months since flows are either very low in perennial rivers or observed only in certain years in seasonal rivers while the rivers usually flow during the wet flow period.

The interannual flow persistency in some of these southern African rivers, therefore, may lead to delayed responses of streamflows to the long-term changes in rainfall while damping the impacts of the short-term rainfall changes depending on the magnitude of the change and on the groundwater contribution to streamflows.

9.4 Indices of high and low flows

The selection of high and low flow thresholds involves reaching a compromise between having a significant number of daily flows above or below a threshold appropriate for interannual variability analysis and the flow magnitudes that are representative of the two flow extremes. This necessitates taking care of the frequent zero-drought/flooding years which are apparent when high thresholds are used (Tallaksen and Hisdal, 1998). Fixed-magnitude FDC flows are used to define the appropriate thresholds in favour of the seasonally varying indices defined using average and standard deviation flows or annual maximum or minimum flows (see e.g. Valimba *et al.*, 2004c). Often, the choice of a low flow threshold is linked to the flows that define hydrological droughts and is usually dependent on the overall water requirements of the society including demands from hydropower plants, recreational uses, maintenance of the ecosystems, irrigation, industries, etc. The low flow thresholds are usually associated with flows in perennial rivers in which fractions of the all-record average daily flows (ADF), particularly the 50% ADF, have been frequently used.

9.4.1 Low flow thresholds

The low flow thresholds have been mostly defined in relation to hydrological drought. Previously used thresholds have been different but mainly percentiles of the annual flow duration curve (Tallaksen *et al.*, 1997; Demuth and Heinrich, 1998; Tallaksen and Hisdal, 1998; Hisdal *et al.*, 2001). Owing to the use of different percentiles in different studies and a lack of identifiable thresholds over the whole of southern Africa it was necessary to define new thresholds for this specific region.

The FDCs show that daily flows in perennial rivers in southern Africa exceed ADF for only 25-35% of the time, suggesting that flow is below the ADF most of the time. Q70, the flow that has been equalled or exceeded for 70% of the time, and Q50 correspond respectively to 40-60% ADF and 51-82% ADF in perennial flow regimes in the Upper Zambezi sub-basin and Okavango basin. In the other perennial rivers, Q50 corresponds to 33-70% ADF while Q70 represents 14-51% ADF (typically 20-40% ADF). Q70 was finally adopted as the threshold defining drought conditions in perennial rivers. A similar index has been used as a low flow threshold in the studies of Tallaksen *et al.* (1997), Tallaksen and Hisdal (1998) and Hisdal *et al.* (2001).

In seasonal (including ephemeral) rivers, however, there are usually prolonged periods of no flows after the end of the rainy seasons and hydrological droughts in seasonal rivers can be studied with respect to the number of days with no flow in which the severity of droughts can be related to lengthened periods of no flows. Therefore, $Q = 0.0\ m^3/s$ is considered as the threshold defining the drought conditions in seasonal rivers and the number of days with no flows are analysed.

9.4.2 High flow thresholds

Despite prolonged periods of no flows in seasonal rivers, flows during the rainy season can sometimes be very high. The FDC computed with zero flows included gave very low exceedence flows particularly for ephemeral rivers in which, for example, the Q5 flow in the Kuiseb River at Schlesien Weir was 1.0 m^3/s, the discharge that was exceeded by 55% of the non-zero flows in the record. Therefore, to avoid such low exceedence flows, the indices of high flows were defined from FDCs calculated using non-zero flows.

Q10 and above (Q5, Q3, Q1) exceeded twice ADF. Time series of daily flows show that the Q5 and above were mainly exceeded in wet years and the time series of seasonal excess flow volumes and frequencies consisted of frequent spells of values. Therefore, the series were considered unsuitable for interannual variability analysis. The use of Q10 reduced significantly the problem of frequent zeros in the time series of seasonal excess volumes and frequencies while the Q10 exceeded ADF significantly. Therefore, Q10 was retained as the threshold defining high flows in southern Africa rivers.

9.4.3 Time series of deficit and excess flow volumes and frequencies

Persistence of low (high) flows was defined as the number of days in which flows are below (above) a predetermined flow threshold and is referred to hereafter as deficit (excess) flow frequency. Deficit and excess volumes are respectively the cumulative flows below or above the correspond thresholds.

Monthly excess and deficit flow volumes and frequencies were computed only for complete months. Otherwise a monthly value was considered missing. The reconstruction of the missing monthly values was done as described in section 5.3.2.2 in Chapter 5. Seasonal values were computed from non-missing monthly values (after reconstruction of monthly series), otherwise the seasonal values were considered missing.

The seasons used for the river flow indices were essentially those used in the analyses of rainfall with slight changes to account for the observed flow regimes. The month of October was omitted from the early summer season (ONDJ), used in the rainfall analyses, in order to separate the low flow October from the other months. The season April-May-June (AMJ), June-July-August (JJA) and FMA were used for high flow indices in rivers in northeast Tanzania, the Western Cape and in the rest of southern Africa respectively. The JJA season was considered in the low flows against the August-September-October (ASO) season as most of the time flows during the latter season are usually below Q70 and the resulting time series are not very useful for interannual variability analysis. It should be noted that time series of JJA seasonal indices for seasonal rivers consist of zeros and were therefore not useful for analysis.

9.5 Interannual variability of seasonal streamflow indices

9.5.1 Summary of identified shifts in streamflow indices

Results of change-point analysis performed on different seasonal flow indices in the selected rivers in southern Africa are summarised in Table 9.2. Excess and deficit flow volumes and frequencies show almost similar patterns of interannual variability but more often shifts characterised the frequency indices than the volume indices and therefore only excess and deficit flow frequencies are presented

Shifts were mostly identified in mean seasonal flows than in the frequencies of high and low flows. A comparison of shifts in the different seasons indicates that the highest number of shifts in seasonal flow indices were identified in the FMA season for the seasonal mean flows and excess flow frequencies and in the JJA for the deficit flow frequencies. The identified shifts in NDJ and FMA seasonal flow indices were mostly unidirectional and towards a decrease. The cumulative flow volumes during the November-April period account for 56.7-99.2% of annual flow volume and the two seasons, NDJ and FMA, account separately for 9.7-59.0% and 34.0-79.9% of annual flow volumes. The annual flow volumes are entirely observed during the November-April season in the seasonal rivers in unimodal southern Africa and the highest percentages correspond to these rivers. The dominant unidirectional abrupt decreases in the two seasons, therefore, indicate declining water resources in the region. The number of unidirectional shifts in the JJA deficit flow frequencies is not significantly different from that of alternating shifts.

Table 9.2: Summary of shifts in seasonal flow indices for the analysed southern Africa rivers.

	Seasonal Flow Index							
	Mean flow			Excess Flow Freq.		Deficit Flow Freq.		
	NDJ	FMA	JJA	NDJ	FMA	NDJ	FMA	JJA
Total number of analysed stations	41	43	43	43	43	42	44	44
Total number of stations with shifted flows	13	22	14	7	19	12	13	19
Total number of unidirectional shifts in	12	20	13	7	16	9	8	11
Total number of upward unidirectional shifts in	4	6	5	1	3	2	3	4
Total number of downward unidirectional shifts in	8	14	8	6	13	7	5	7

9.5.2 Spatial patterns of identified shifts

To evaluate whether regional changes have occurred in southern Africa, spatial patterns of shifts in the seasonal flow indices were investigated and are shown in Fig.9.3. Some sort of spatial clustering, as defined by a similar direction and almost similar dates (temporal homogeneity) of change, is apparent in this figure, particularly for the frequency indices. These clusters are observed in northeast Tanzania, in the southern Zimbabwe/northeast South Africa, in Namibia and in the western/northern Zambia (Fig.9.3). The changes in the seasonal river flow characteristics were mainly identified in the 1970s and early-1980s although changes were identified as early as in the late-1950s and early-1960s.

The identified changes in the river flows corresponded to increasing flows in the rivers in northeast Tanzania which corresponded mainly to increasing mean flows and decreasing deficit flow volumes and frequencies (Fig.9.3; Valimba *et al.*, 2004c), except in rivers which drain the eastern Kilimanjaro areas where decreases were identified. The abrupt increases in low flow characteristics in rivers in northeast Tanzania resulted into dry seasonal flows remaining above the low flow threshold in the post-change period.

Changes in river flow characteristics in other parts of southern Africa were associated with decreasing river flows particularly during the FMA season. The decreases which were related to changes of up to 50% or higher, characterised the mean flows, high flows as well as low flows. This is illustrated by complete declines in the Namibian rivers and abrupt decreases in FMA and JJA mean seasonal flows and deficit flow frequencies in the upper Zambezi in western Zambia (Fig.9.3). The start of the declining flow indices in Namibia is consistent with the start of declining dam levels in Namibia around the mid-1970s (Jury and Engert, 1999). Berhanu (1999), Berhanu *et al.* (2001) and Alemaw and Chaoka (2002), reported declining annual runoff in parts of Zambia and Angola. Furthermore, frequent and lengthening periods of no flows were observed in some of the perennial rivers since the early-1980s indicating that these rivers are being progressively transformed into seasonal rivers, results which were similarly observed in Zimbabwe (Magadza, 1995).

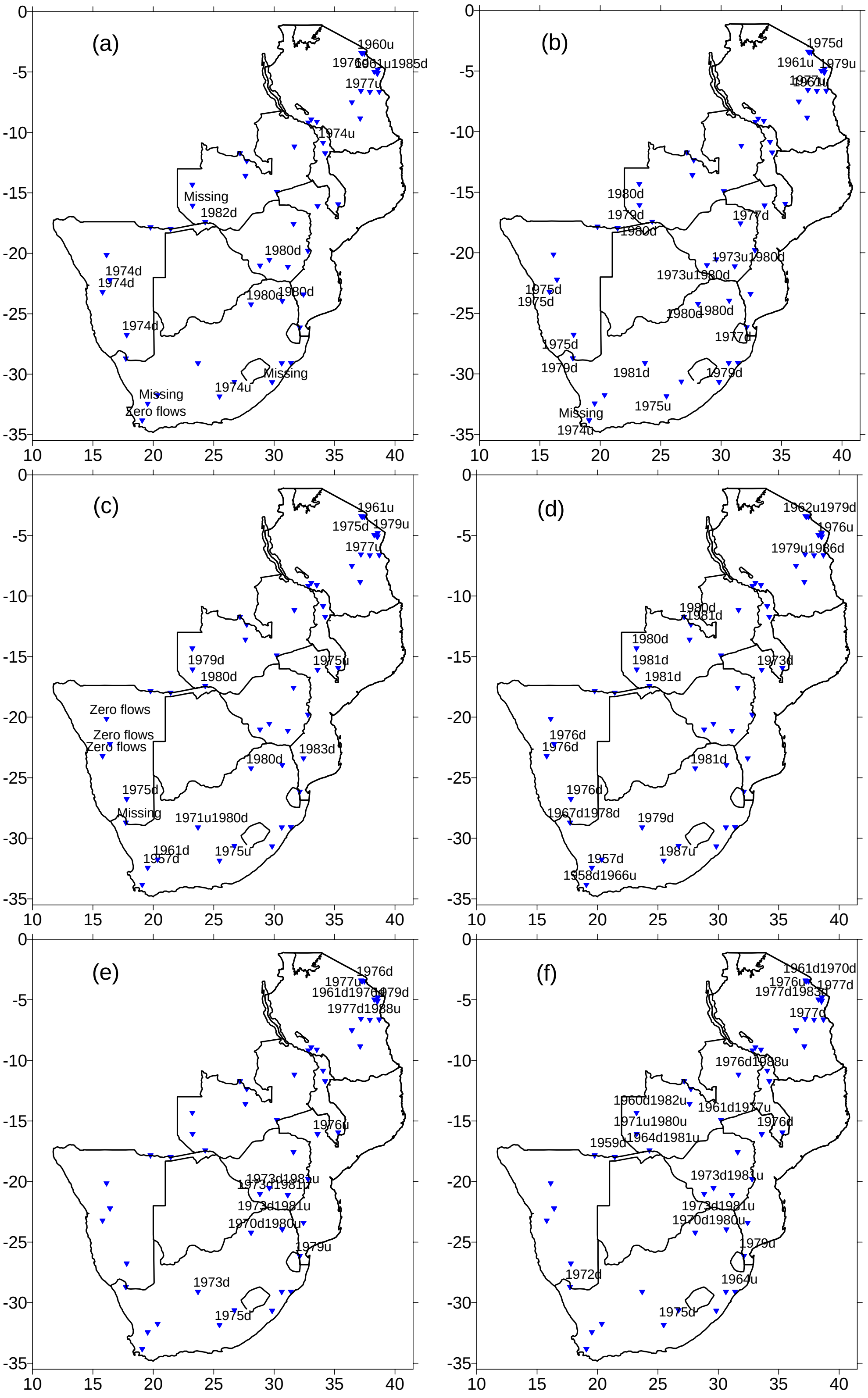


Fig.9.3: Dates of shifts in a) NDJ, b) FMA and c) JJA mean seasonal river flows; in the frequencies of d) excess flows (see text for the high flow seasons), e) FMA deficit and f) JJA deficit flows in the southern African rivers. The year indicates the date of shift while the letters indicate the direction of shifts, u for the upward and d for the downward shift.

9.6 Discussion

9.6.1 Mean flows

Changes in river flow regimes may result from a variety of factors such as changes in the climatic parameters (precipitation, temperature) and artificial influences in the catchment, including changing landuse and water use patterns (Hisdal *et al.*, 2001). The selection procedure of the gauging stations for use in this interannual analysis (see section 5.3.3.2 in Chapter 5) tried to minimise the influences of flow regulation but not of other artificial influences such as flow abstraction points and changing landuse patterns. However, it was not possible to obtain details about the changing landuse and water use patterns and a comparison of the interannual patterns of variability of flows and rainfall may help in the identification of artificial influences on the flow regimes. This is illustrated for the Groot-Vis (Fish) River in South Africa which has experienced a regime transformation since the mid-1970s from seasonal to perennial.

The following discussion will be limited mainly to the influences of rainfall variations on the identified changes in river flow regimes. The influences of rainfall on streamflow changes may be plausible with regard to consistent dates of shifts in certain indices of river flows. It should, however, be remembered that most of the changes related to artificial influences in the catchments such as dam construction and commissioning, accelerated landuse changes, etc have occurred since the 1960s and they are discussed whenever differences exist between patterns of variations of rainfall and flow. Similarly, changes in the extreme flow characteristics (flood and low flows) are influenced partly by changing rainfall characteristics and partly by the changing vegetation cover and soil properties (e.g. permeability). In such cases of extreme flows, therefore, it might be difficult to obtain strong links between the changes in streamflows and rainfall. The following discussion focuses mainly on the spatial clustering and interannual patterns of flow variability that differ appreciably from those of rainfall indices.

In general, NDJ mean flows in southern African rivers have remained unsegmented or showed abrupt increase, except for the rivers in Namibia, northeast South Africa and southern Zimbabwe (Fig.9.3a). This pattern during the early summer is identical to changes in early summer seasonal rainfall amounts, which had either remained unsegmented or abruptly increased in the region except in Namibia and northeast South Africa (Fig.7.6a in Chapter 7). Similarly, predominantly decreasing FMA mean flows in unimodal southern Africa correspond to declining overall rainfall amounts in late summer (Fig.7.6b). The abrupt decreases in late summer overall amounts in Namibia were identified mainly in the 1977-1980 period lagging flow decreases. Owing to their seasonal nature, the slight changes in rainfall since the mid-1970s might be a cause of the early decreases in river flows. The flow decreases in northeast South Africa were consistent with decreases in the late summer overall rainfall in that area but lagged the rainfall decreases by about 2-3 years.

The lack of abrupt decreases in seasonal as well as annual amounts in western Zambia (Fig.7.5, 7.6) could be hardly linked to the abrupt decreases in mean seasonal flows in the upper Zambezi (western Zambian) catchments. However, the results of linear trends for the 1961-1991 period (not shown) showed decreasing trends in seasonal amounts in these parts of Zambia. Sichingabula (1998) found decreasing annual rainfall in southern and eastern Zambia since 1975, while Bigot (1997) and Bigot *et al.* (1998) identified declining annual rainfall in the central Africa and the Congo basin since the late-1960s, a decline which was similarly identified by Laraque *et al.* (2001) in the catchments within the Congo basin and which was reflected in the decrease of annual flows in the Congo River basin since the 1970s and which amplified and became widespread since the early-1980s (Laraque *et al.*, 1998, 2001). The changes in the western Zambian catchments could be partly related to the changes in rainfall mostly identified in the Congo basin.

The increasing FMA mean seasonal flows identified in the 1960s and 1970s in rivers draining areas of the Usambara Mountains in northeast Tanzania (Fig.9.3b) contradict the decreases in late summer seasonal amounts which were identified mainly in the late-1940s to late-1950s (Fig.6.6c, 6.6d). In fact, monthly flows in September through March have increased in these rivers while those in April-August have remained unsegmented. This could not be attributed to the length of the flow records but rather to increases in OND and January-February amounts. Linear trends calculated for 3 different periods, 1961-1990, 1941-1990 and 1931-1990 were consistently increasing for OND and January-February (JF) seasonal amounts for the latter two periods (Valimba *et al.*, 2004a). The long records of annual and early summer seasonal amounts for stations in the Usambara Mountains and coastal northeast Tanzania show fluctuating dry and wet periods in which the 1940s and 1950s were characterised mainly by below average rainfall while the decades 1960s and 1970s observed above average rainfall.

Long rainfall records further indicate shifts towards persistent wetter conditions in the areas around Mount Kilimanjaro (Valimba *et al.*, 2004ab). Despite a number of existing flow abstractions upstream, mean flows in all months at the most downstream gauge in the Kikuletwa River, which drains the western part of the Kilimanjaro, have increased since 1960/61 (Valimba *et al.*, 2004c), consistent with the reported increases in rainfall amounts. A number of past studies have identified similar increases in rainfall in the early-1960s in east Africa (including Tanzania) and other hydrological variables such as lake levels (Bergonzini, 1998; Nicholson, 1998, 1999, 2000; Bergonzini *et al.*, 2001, 2002; Nicholson and Yin, 2001). However, the rivers which drain the eastern part of Mount Kilimanjaro were characterised by decreasing flows in all months, contradicting the rainfall increases. A number of studies have linked decreasing river flows from the slopes of Mount Kilimanjaro to the population increase and degrading landuse and water use practices (Mujwahuzi, 1999; Mwamfupe, 1999; Shechambo, 1999; Yanda and Shishira, 1999; Mwamfupe, 2002; Ngana, 2002; Shishira, 2002; Yanda, 2002) This linkage has been discussed in Valimba *et al*. (2004c).

The striking feature was the regime transformation of the Groot-Vis River located in the central southern part of South Africa that did not correspond to the interannual pattern of rainfall variability. The river has become perennial since around 1974/75 while the abrupt increases in early summer overall amounts in a few stations in this part of South Africa were identified mainly in the early-1980s (Fig.7.6a). Time series of NDJ seasonal flows are persistently below average before the mid-1970s even during the period of above average rainfall in the 1950s (Fig.9.4a). The FMA rainfall series is predominantly below average after the mid-1970s while the corresponding flows are mostly above average (Fig.9.4b). The cause of the observed regime change in this river was the inter-basin transfers from the Orange River basin for irrigation water along the Fish and Sundays Rivers (Hughes, personal communication; Department of Water Affairs and Forestry (RSA)[13]) through the Orange Fish Tunnel. Consequently, all the flow in the Fish (Groot-Vis) River is, since 1975, managed releases from the Gariep (formerly Hendrik Verwoerd) Dam (completed in 1972) on the Orange River.

9.6.2 High and low flows

Changing extreme flows (excess and drought flows volumes and frequencies) are partly affected by changes in the amounts of rainfall due to intense daily rainfall events and partly by changes in the catchment characteristics that affect runoff generation mechanisms. The results (Fig.9.3d) show consistent and persistent decreases in the frequency (duration) of excess flows in the rivers in western and northern Zambia (early-1980) and in Namibia (mid-1970s). In other southern African rivers, the changes were heterogeneous and not very persistent since they did not characterise a number of rivers and only segments of high or low

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[13] Available online in January 2004 at http://www.dwaf.gov.za/orange/gariep.htm

frequencies were observed, after which, the time series returned mostly to the pre-change states. This fact is also observed in the frequencies of deficit flows, except in northeast Tanzania where low flows had increased since the mid-1970s.

The pattern of the changes in the frequencies of excess and deficit flows seem to reflect the wet and dry periods in southern Africa (compare Figs.7.7e, 7.7f and Figs.7.2a, 7.3). Abundant rainfall observed in the early-1970s to late-1970s in southern Africa (Chenje and Johnson, 1996) could have caused considerable groundwater recharge which lead to increased flows during both the rainy season and the following dry season and therefore corresponded to decreased frequencies of deficit flow volumes. The rainfall deficits since the early-1980s and low between-the-years flow carry-over in most of the catchments caused a return of the low flows almost to the values before the changes and this corresponds to an increase in the deficit flow frequencies since the early-1980s (Fig.9.3e, 9.3f).

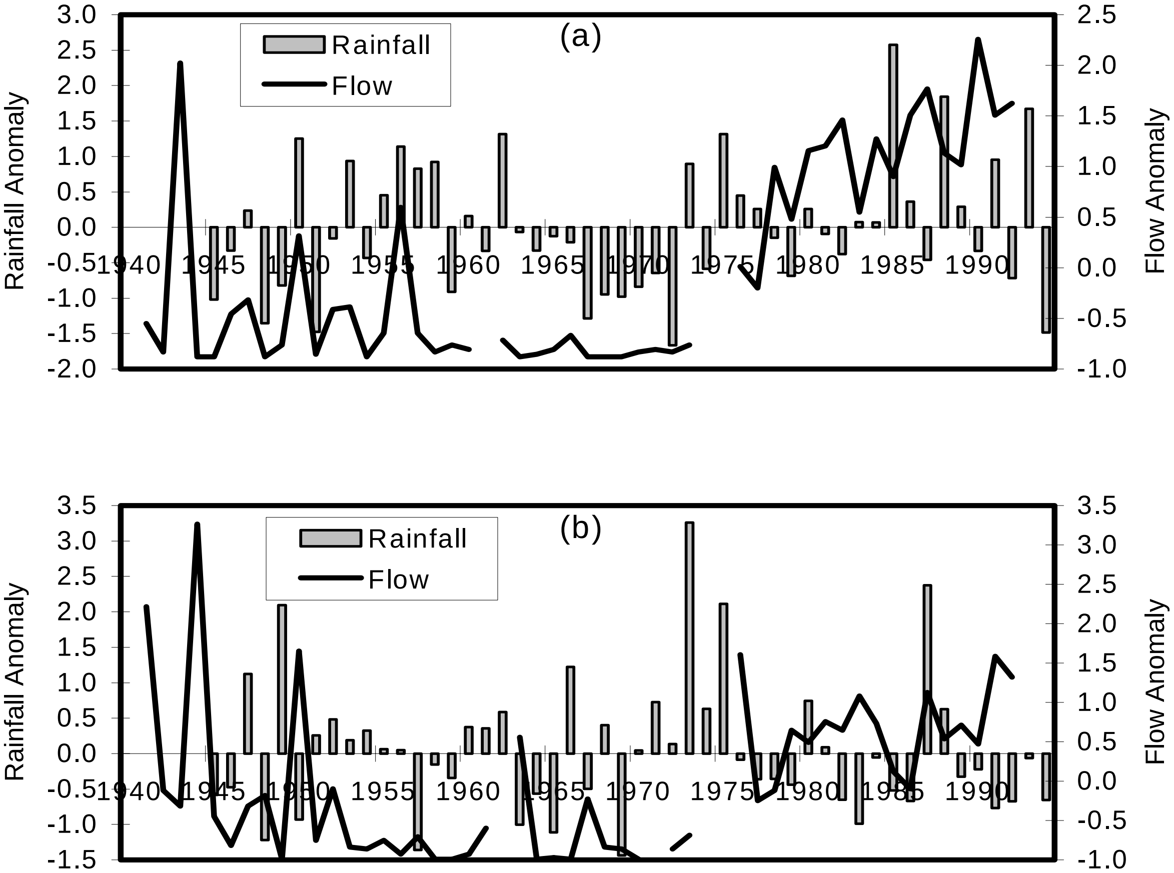

Fig.9.4: Time series of anomaly a) NDJ and b) FMA seasonal flows and catchment overall rainfall amounts for the catchment of the gauge 27673901 in the Groot-Vis (Fish) River.

9.7 Conclusions

Significant changes in the river flows regimes in the southern African rivers were identified in the 1970s through early-1980s. These changes led to decreases in river flows in western Zambia, Namibia and northeast South Africa considerably affecting the flows during the high flow months in which 34-80% of the annual flow volumes are observed. Flows in the Zambezi, upstream of Victoria Falls, have decreased to about a half of the flows before the change, while periods of no flow are observed in recent decades (Magadza, 1995) in some perennial rivers and are extending in seasonal rivers. In the other parts of southern Africa, alternating increases and decreases in river flow indices were observed which corresponded mainly to interannual patterns of rainfall variation. However, in certain rivers such as the Mue River, which drains areas of eastern Mount Kilimanjaro, the influences of degrading landuse practices have led to declining flows despite observed increasing rainfall.

It was not possible, however, to provide strong links between the identified changes in streamflows and those in rainfall due to a) short available flow records, b) lack of the detailed information on the landuse, water use and other socio-economic activities within the catchments and c) unavailability of the stations details such as the rating curves and their quality, gauge history (e.g. on the relocation of the gauging sites).

Therefore, despite a certain degree of consistency of changes in rainfall and flows, detailed studies at the catchment level are necessary in order to verify these broad regional observations and to more fully investigate the links between the identified changes in streamflow and rainfall indices and other factors affecting streamflows. The progressive transformation of perennial rivers into seasonal rivers, for example, can be partly influenced by deficit rainfall but changes at the soil surface relating to soil permeability and removal of vegetation cover can result in insufficient groundwater recharge which eventually may lead to reduced dry season flows or to flow cessation in the perennial rivers. This transformation can also be related to a number of factors such as reservoir construction, increasing water abstractions, etc. Therefore detailed information of developments within the catchments is required.

CHAPTER 10

RESPONSE OF RAINFALL AND STREAM FLOWS TO CLIMATIC VARIATIONS

10.1 Introduction

In this chapter, relationships between southern African rainfall and climatic variables are investigated using seasonal rainfall amounts and number of events in each class of daily intensities as well as overall unclassified seasonal amounts and number of events. The main questions that are investigated are:

- In which classes of daily rainfall intensities do ENSO and SST have stronger influences?
- In which parts of southern Africa and in which seasons do ENSO and SST have stronger influences?
- Is there any possibility of forecasting the impacts of ENSO and SST variations? It is the question of lead-lag relationships and their stability over time.

In order to avoid noisy stations series, regional time series of seasonal rainfall amounts are used. Principal components analysis (PCA) and correlation analysis are used to establish coherent rainfall regions. Moreover, the areal average indices of SST anomalies in the key oceanic basins in the Atlantic and Indian oceans (see next section) are used.

Pearson’s correlation coefficients, computed between regional seasonal rainfall indices and monthly/seasonal SOI and SST anomalies for the 1955-1985 common period, are used to assess the ENSO/SST-rainfall lead-lag relationships. Absolute correlations exceeding 0.39 and 0.49 are significant at the 95% and 99% levels, respectively.

The stability of ENSO/SST-southern African rainfall associations is investigated for the common period 1950-1994 using long Namibian and South African data. Since major changes in oceanic and atmospheric variables had occurred in the late-1970s and only 18 years are available for analysis in the post-1977 period, a 15-year window is used to compute sliding correlations between SOI/SST indices and seasonal rainfall indices. Absolute correlations exceeding 0.5 and 0.43 are significant at the 95% and 90%, levels respectively.

In order to investigate possible changes in atmospheric circulations due to an SST anomaly forcing, correlations are computed between SST anomalies in each of the 5 key basins and gridded NCEP/NCAR reanalysis fields (winds, moisture flux and geopotential heights) in the Atlantic and Indian oceans. This enables the study of interannual variability of SST and associated atmospheric dynamics. However, the pattern associated with the post-1970 warmer SST, which is a decadal signal, is likely to be different as the spatial signature of this decadal signal is different from that associated with interannual variability. The resulting correlation atmospheric patterns are compared to mean fields and are related to circulation features that have been linked to dry and wet conditions in southern Africa.

Correlations are, therefore, computed for the period 1968-1990 between areal average SST anomalies in each key of the 5 key basins and gridded reanalysis fields (winds and geopotential heights). Lower (850 hPa) and upper (200 hPa) tropospheric levels are considered. Results of correlations for the 1968-1985 period are relatively similar to those of the 1968-1990 period while the latter offer longer records than the former.

ONDJ and FMA seasons are used to define early and late summer seasonal rainfall. May is omitted from the original FMAM late summer season (cf chapter 6) as atmospheric circulations responsible for rainfall in northern Tanzania at this time resemble those in early summer and differ from March-April (Mutai and Ward, 2000; Camberlin and Okoola, 2003) while May rainfall in the southwestern and southern part of South Africa is predominantly frontal. ENSO seasons (SON, DJF, MAM and JJA; Trenberth and Caron, 2000) are used to compute seasonal SOI values while seasonal SST anomalies are computed for rainfall seasons (OND, FMA) and for the JJA ENSO season.

10.2 Key oceanic basins in the Atlantic and Indian oceans

Past studies indicate 5 major oceanic basins in the Atlantic and Indian Oceans that are influencing rainfall variations in southern African. The Tropical Indian Ocean (TIO) basin north of about 15°S extends from the western Indian Ocean along the eastern coast of Africa to the eastern Indian Ocean in the maritime continent. Its central basin, which extends between 10°N-10°S and 50°-75°E (Fig.10.1), has the highest influences upon rainfall variability in southern Africa during both ENSO and non-ENSO years (Jury, 1996; Rocha and Simmonds, 1997a; Landman and Mason, 1999; Richard *et al.*, 2000). This region has been equivalently referred to as the Tropical Western Indian Ocean (TWIO) and this terminology is used in this chapter.

The second region is the Southwest Indian Ocean (SWIO) basin, which forms a dipole with southeast Indian Ocean basin (Fauchereau *et al.*, 2003). The SWIO basin is defined by 30°S-40°S latitudes and 55°E-75°E longitudes (Fig.10.1) and is weakly associated with

ENSO (Latif *et al.*, 1999; Mutai and Ward, 2000; Fauchereau *et al.*, 2003). The third region is the Mozambique/Agulhas Currents (MADA) basin region which is located south/southwest of Madagascar within the 25°S-40°S latitudes and 35°E-45°E longitudes (Mason, 1995). This basin has also been referred to as SWIO in some past studies (e.g. Reason and Mulenga, 1999) but the term MADA is used in this study to distinguish it from the southwest Indian Ocean basin defined above.

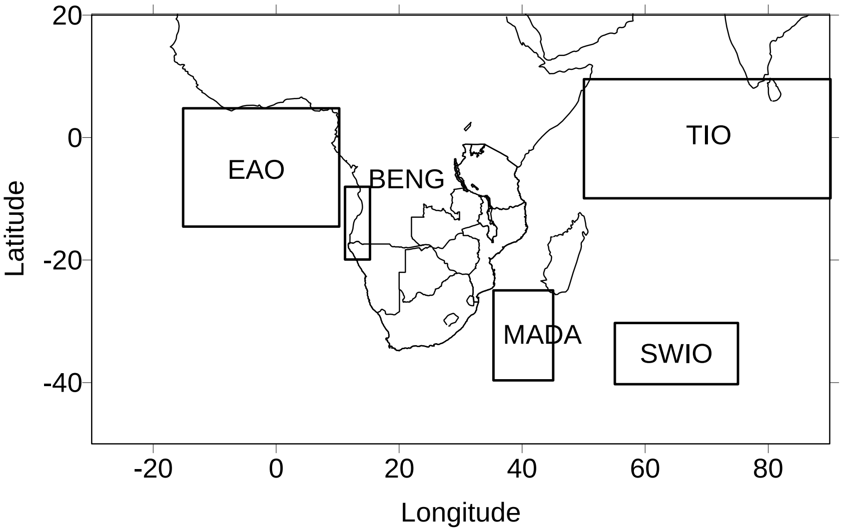

Fig.10.1: Selected key oceanic regions in the Atlantic and Indian Oceans which influences southern African rainfall.

The fourth region is the Atlantic northeast-southwest dipole (Fauchereau *et al.*, 2003), between the Southwest Atlantic Ocean (SWAO) basin centred around 36°E, 25°W and the large northeast Atlantic Ocean's Benguela system (Mason, 1995). The Benguela system includes the Angola/Benguela Front region off the Angola/Namibia coast extending northwestward from the Front region to equatorial Atlantic. Owing to local Benguela Niños within the Angola/Benguela Front region, the large northeast Atlantic basin is sub-divided further into the equatorial Atlantic Ocean (EAO) and the Angola/Benguela Front region (BENG) (Fig.10.1). The EAO is defined by latitudes 5°N-15°S and longitude 15°W to the coastline (Phillipon *et al.*, 2002) while the BENG basin lies within latitudes 8°S-20°S and longitudes 12°E-15°E approximately defining the core of extreme warmer SST anomalies during the Benguela Niños (see e.g. Rouault *et al.*, 2003).

10.3 Spatially coherent rainfall regions

10.3.1 Results of the principal components analysis

Unrotated and orthogonally (Varimax) rotated S-mode PCA performed on the correlation matrix of seasonal rainfall amounts for each of the 5 classes of daily intensities produced large spatial clusters mainly for the three lower classes. The Kaiser criterion of eigenvalues exceeding 1 resulted in 30 significant principal components (PCs). Scree test (Cattell, 1966) plots show sharp drops between the first 5 PCs and thereafter slopes are gentle but the curves do not flatten. The first 20-23 unrotated and rotated PCs have explained variances exceeding 2% in both early and late summers. Scree plots of varimax rotated PCs yielded almost flat curves after the 15th PCs although discontinuities were less marked after the 7-8th PC. However, the first 5-8 PCs explain individually more than 4% while the rest explain less than 4%, typically below 3.5%.

This chapter is interested, apart from relating rainfall variations to climatic variations, in investigating relationships between widespread droughts in southern Africa and SST variations and variations in atmospheric fields. Therefore large spatial clusters are of interest. Considering areas within the 0.4 isopleth of every PC, only 4-5 PCs of class II through class IV showed large spatial regions. This 0.4 isopleth represents a correlation contour that is significant at 95% for the 31-year period used and provides minimal overlapping between spatial clusters. The first 7 and 9 PCs were retained for class V and class VI respectively.

10.3.2 Spatially coherent rainfall regions

Spatial patterns of loadings of the retained first 4-9 PCs in each class of rainfall show some similarities and differences with respect to the regions of significant loadings. For the same season, the spatial patterns of loadings for the three lower classes (class II – IV) defined spatial clusters, which were mostly identical with a few differences corresponding to the sub-division or fusion of the clusters. This can be observed, for example, in Fig.10.2. The significant PC1 loadings during the early summer (ONDJ) season are concentrated mainly in Namibia and northern Botswana for class III (Fig.10.2a) while for class IV, they are insignificant and negative in northern Botswana differing from the significant positive loadings in northwestern Namibia and southwest Botswana (Fig.10.2d). Significant positive PC1 loadings of class II rainfall in early summer are found in the whole of central South Africa while those of class III during the late summer (not shown) divide this central part of South Africa into the western and eastern part around a 25°E longitude.

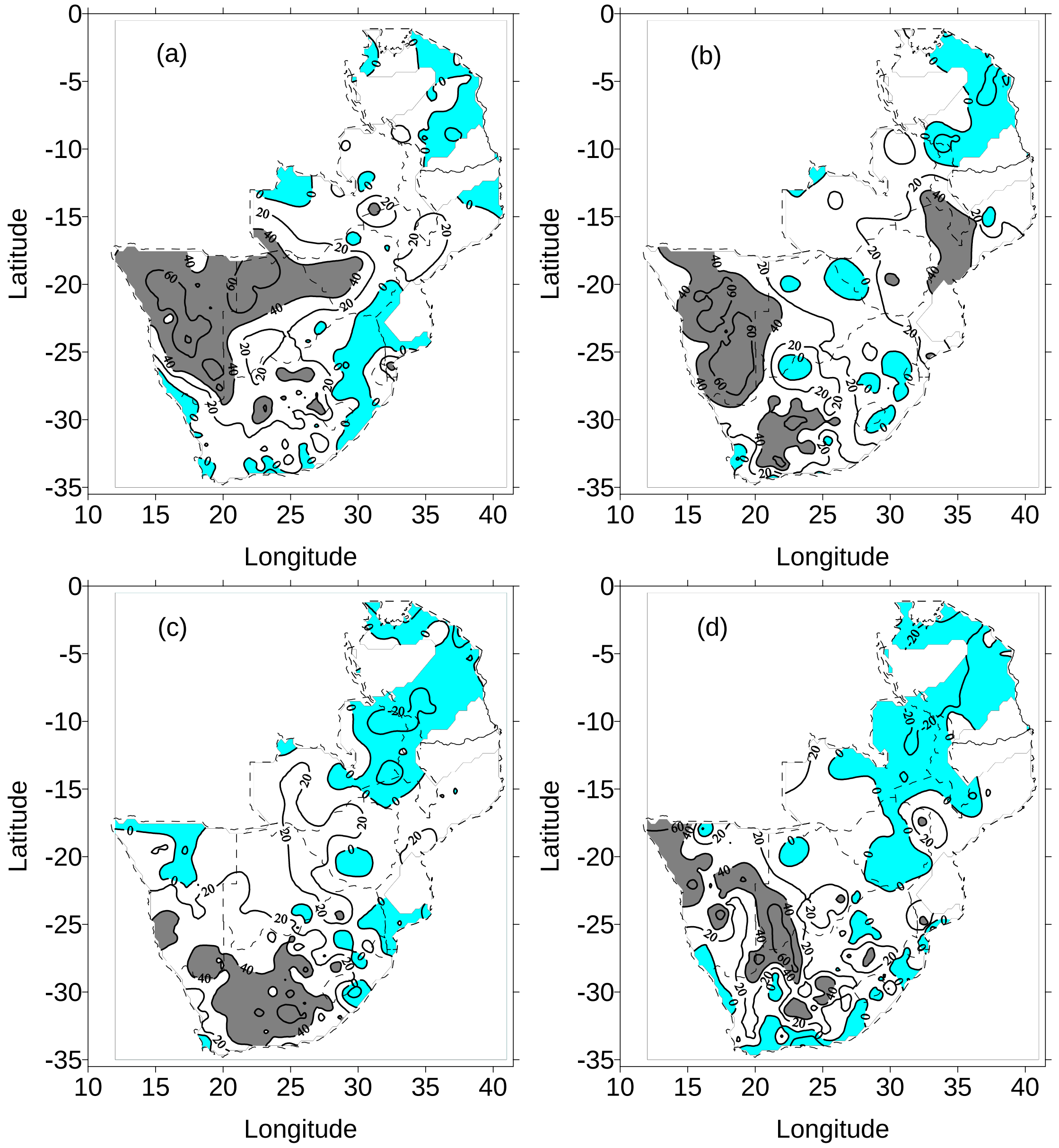

Fig.10.2: a) ONDJ and b) FMA class III , c) ONDJ class II and d) ONDJ class IV rotated PC1 loadings in southern Africa. Negative loadings are shown in cyan shading.

It was further observed that spatial patterns of PC loadings of the same class were often spatially different between early and late summer. This is shown, for example, in Fig.10.2 for class III rainfall. The significant PC1 loadings in northern Botswana in the early summer (Fig.10.2a) have been replaced by insignificant negative loadings while almost the whole western region, extending from northern Namibia to southern part of South Africa (excluding the Cape), experiences significant loadings in late summer (Fig.10.2b).

This procedure established preliminary regions for each class in each season. The verification process of these spatial clusters involved taking correlations between the time series of PCs which define the regions and stations series within the region. Only stations which correlated at 0.5 or higher (significant at 99%) with the PCs were retained in that particular region. This was done for all regions.

In order to facilitate interpretation of the results of the analysis between the different classes of daily rainfall and between seasons, it was necessary to define a few regions which are the most representative for the various classes and seasons. The most recurrent spatial patterns of the PC loadings, therefore, described basically about 10 regions across southern Africa (Fig.10.3). These regions were mostly depicted by the first 3-5 PCs of the three lower classes (class II to class IV). PCs of the higher two classes (class V and VI) tend to divide these large regions into much smaller regions (see e.g. a small insert in Fig.10.3) creating geographical outliers (van Regenmortel, 1995) in which as few as one or two stations tend to form their own regions. The finer regions therefore suggest modulation of the large-scale signal by mesoscale influences such as topography, which mostly impact on heavy rainfall events (upper classes).

The regions are briefly described except for the two regions, S7 and N3 due to the presence of a few, poorly distributed stations.

- Region S1:

  PC loadings that were associated with this region parallel the coastline in the northwest-southeast orientation with the highest loadings in the central and southeast mountains of Namibia. Such orientation corresponds to the mean circulation pattern along the southwest coast of Africa during the austral summer. Near-surface southwesterly flow over the cold Benguela water brings dry air to the immediate interior of Namibia and western South Africa (Jury and Engert, 1999). Orographic influences of the western escarpment enhances rainfall in the mountains. Weak recurving northeasterlies around the Angolan low brings moisture into eastern Namibia.

  Occasional intensification of the surface low over Namibia (Bhalotra, 1984) increases rainfall in northern Namibia, western and northwest Botswana (van Regenmortel, 1995). This is shown, for example, by PC1 for ONDJ class III (Fig.10.3a) in which the highest loadings extend from Namibia to western and northern Botswana. Moreover, anomalously warm waters off the Angola/Namibia coast during the Benguela Niños (Shannon *et al.*, 1986) accompanied by local cyclonic and anticyclonic flows (Rouault *et al.*, 2003) are related to enhanced rainfall along the adjacent coast of Namibia favouring the occurrence of intense daily events rather than increased amounts and frequencies of light to moderate daily events (see chapter 6). Thus sub-regions in Namibia shown in a small insert (Fig.10.3) are identified by higher intensity classes and correspond to these occasional features.

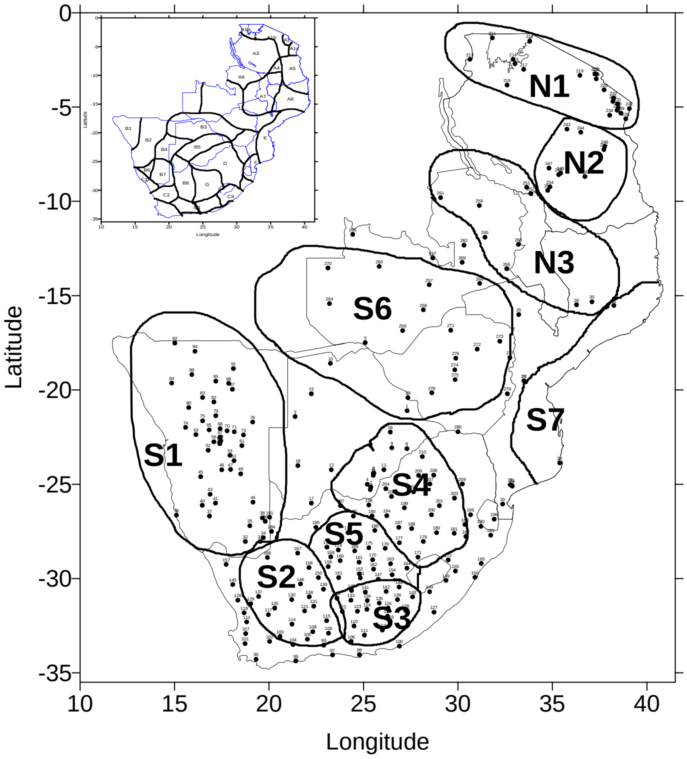

Fig.10.3: General coherent clusters as depicted by PCA and correlation analysis.

- Regions S2, S3 & S5:

These three regions are quasi-independent. This is indicated by PC loadings of different classes (e.g. Fig.10.2c) which tend to combine the central southern South Africa (S3) region and the western interior (S2) or northern central South Africa (S5). Apart from the influences of the near-surface southwesterly flow over the cold Benguela water which affects the western part (S2), the zonally-oriented PC loadings in the southern part of South Africa are reflecting the influences of moisture from the Agulhas Current region off the southern coast of South Africa and wind circulations which advect this moisture into the adjacent areas in S2 and S3 (Reason and Mulenga, 1999; Rouault *et al.*, 2001, 2002).

- Region S4:

  PCA results further distinguished region S4 from other South African regions. This region does not combine with any of the three (S2, S3 and S5) regions for all classes in both early and late summers. Rainfall variations in region S4, comprising northeast South Africa and southeast Botswana, has been linked to tropical-temperate troughs (Todd and Washington, 1999ab), the northwest-southeast cloud bands that are considered to have little influence on rainfall variations in the rest of South Africa.

- Region S6:

  Significant zonally-oriented PC loadings are observed in the broad region of tropical southern Africa, comprising Zimbabwe, northern Botswana and Zambia (excluding its northern edge). The pattern is apparent mainly in late summer and particularly for class II and class III seasonal amounts. The zonally-oriented loadings are similar to van Regenmortel (1995) PC4 loadings representing northern Botswana. They indicate the tropical influences in relation to a zonal branch of the ITCZ in which the Congo air boundary in the north fails to link up with a westerly flow to the south (van Regenmortel, 1995).

- Regions N1 & N2:

  Northern regions (N1 and N2) usually show opposite spatial loadings to the rest of the region especially in early summer. Despite possession of a similar sign, PCA distinguished Tanzania into these two major regions for lower classes (class II-IV), while for higher classes, the regions are further sub-divided (see a small insert in Fig.9.2). Finer sub-regions of N1, for example, distinguish the Usambaras and coastal northeast Tanzania from areas around Mounts Kilimanjaro and Meru. Similarly, different sub-regions of N1 exist in the Lake Victoria region. The broad regions (N1 and N2) resemble the generally coherent regions of Ogallo (1989) while finer sub-divisions indicate the influence of mesoscale features on large-scale climatic signals and those in northern Tanzania resemble those identified by Indeje *et al.* (2000).

The general South Africa regions (S2-S5) resemble those of Landman and Mason (1999). Their western interior region is essentially a combination of the regions S2, S3 and south-southwest Namibia is the region which is distinguished by PC2 of class III late summer amounts (not shown), while their northeastern highveld resembles S4.

Six southern regions (S1-S6) and two northern regions (N1 and N2) were therefore retained and used in studying relationships between classified rainfall amounts and SST and SOI as an index of ENSO. Results in which SOI and SST lead rainfall are presented as they are appropriate for forecasting purposes.

10.4 The ENSO-southern African rainfall associations

10.4.1 ENSO-southern African rainfall relationships

Results show that SOI affects rainfall amounts and number of rainfall events similarly, as indicated by almost similar correlations both in magnitude and sign. Therefore, only correlations shown by seasonal amounts are presented and discussed. This facilitates comparison with findings of past studies, which used seasonal amounts. Furthermore, correlations between seasonal amounts in the *S* regions and ENSO seasons (SON/MAM) are slightly less than those obtained when rainfall seasons (OND/FMA) are used while in the *N* regions the opposite is observed. Only correlations computed between seasonal rainfall amounts and SOI in which ENSO seasons are used for SOI, are presented.

In general, the results of correlation analysis between SOI and seasonal rainfall amounts (Table 10.1) indicate the seasonality of rainfall responses to an ENSO signal and the spatial variation of the responses which can be summarised, spatially, according to the strength of the response (Fig.10.4a) and the nature and seasonality of the relationships (Fig.10.4b).

a) The consistent influences of ENSO on all classes of daily rainfall.

The correlations between SOI and rainfall amounts (Table 10.1) indicate that the responses of rainfall in the different classes to an ENSO signal are generally identical. However, it is worth noting that the highest influences of ENSO are often found in class III and class II and that the ENSO signals in southern African seasonal rainfall reduce with increasing daily intensities.

Table 10.1: Correlations between ONDJ and FMA seasonal amounts in southern Africa and seasonal SOI values. Significant correlations at 95% are in bold italics.

Region	Class	ONDJ seasonal amounts against				FMA seasonal amounts against			
		SOI_MAM	SOI_JJA	SOI_SON	SOI_DJF	SOI_MAM	SOI_JJA	SOI_SON	SOI_DJF
S1	II	0.12	0.22	0.25	0.04	0.38	***0.50***	***0.67***	***0.54***
	III	0.12	0.27	0.33	0.03	0.38	***0.45***	***0.68***	***0.65***
	IV	0.11	0.27	0.39	0.00	0.35	***0.43***	***0.62***	***0.61***
	V	0.16	0.28	***0.40***	-0.02	0.31	0.36	***0.54***	***0.54***
	VI	0.13	0.27	0.35	0.03	0.14	0.29	***0.48***	***0.43***
	Overall	0.13	0.27	0.35	0.02	0.36	***0.45***	***0.66***	***0.61***
S2	II	0.29	0.26	0.31	0.09	0.33	***0.47***	***0.58***	***0.47***
	III	***0.40***	0.30	***0.40***	0.21	0.28	0.34	***0.49***	***0.47***
	IV	0.36	0.23	0.30	0.18	0.09	0.28	0.36	0.31
	V	0.37	0.21	0.27	0.28	0.20	***0.44***	***0.46***	***0.43***
	VI	0.18	0.14	0.32	0.04	0.23	***0.48***	***0.47***	***0.46***
	Overall	0.36	0.25	0.36	0.18	0.25	***0.45***	***0.53***	***0.49***
S3	II	0.32	0.23	0.34	-0.06	***0.43***	***0.40***	***0.58***	***0.66***
	III	0.17	0.16	0.24	-0.11	0.38	***0.42***	***0.47***	***0.51***
	IV	0.24	0.31	0.31	0.14	***0.40***	***0.49***	***0.57***	***0.56***
	V	0.23	0.23	0.29	0.15	0.30	***0.52***	***0.56***	***0.52***
	VI	-0.12	0.01	0.10	-0.05	0.36	0.35	***0.48***	***0.45***
	Overall	0.20	0.21	0.29	0.00	***0.43***	***0.49***	***0.60***	***0.60***
S4	II	0.14	0.39	***0.47***	-0.09	0.30	0.27	0.23	0.35
	III	0.31	***0.44***	***0.55***	-0.02	0.32	0.23	0.25	0.35
	IV	0.30	***0.44***	***0.46***	0.11	0.28	0.29	0.32	0.39
	V	0.30	0.35	0.31	0.17	0.26	0.31	0.27	0.37
	VI	0.19	0.09	0.15	0.25	0.11	0.30	0.38	***0.46***
	Overall	0.30	0.37	***0.43***	0.13	0.26	0.31	0.34	***0.44***
S5	II	0.07	0.31	0.34	-0.08	***0.41***	0.29	***0.54***	***0.57***
	III	0.30	***0.51***	***0.58***	-0.05	***0.50***	0.36	***0.57***	***0.61***
	IV	0.20	***0.42***	***0.47***	-0.06	***0.43***	***0.42***	***0.46***	***0.53***
	V	0.39	0.29	***0.41***	0.14	***0.40***	***0.52***	***0.58***	***0.55***
	VI	0.20	0.22	***0.43***	-0.04	***0.42***	***0.58***	***0.56***	***0.54***
	Overall	0.29	***0.43***	***0.55***	-0.03	***0.49***	***0.50***	***0.60***	***0.63***
S6	II	0.17	0.25	0.29	0.15	0.06	0.28	0.36	***0.41***
	III	0.19	0.31	0.32	0.14	-0.03	0.18	0.21	0.26
	IV	0.11	0.20	0.31	0.18	0.12	0.24	0.34	0.31
	V	0.24	0.25	0.32	0.24	0.14	0.18	0.26	0.29
	VI	0.26	0.22	0.24	0.12	-0.20	0.04	0.05	0.13
	Overall	0.23	0.27	0.31	0.18	-0.01	0.18	0.22	0.27
N1	II	-0.18	***-0.40***	***-0.41***	0.11	0.09	-0.07	-0.12	0.08
	III	-0.33	***-0.48***	***-0.53***	0.12	0.18	-0.15	-0.14	-0.08
	IV	-0.34	-0.33	-0.38	-0.09	0.17	-0.17	-0.13	-0.10
	V	-0.27	-0.37	***-0.46***	0.07	0.02	-0.29	-0.19	-0.15
	VI	-0.32	***-0.42***	***-0.52***	0.07	-0.06	-0.38	-0.31	-0.25
	Overall	-0.32	***-0.42***	***-0.49***	0.06	0.06	-0.31	-0.24	-0.16
N2	II	-0.26	-0.34	-0.36	-0.14	***0.44***	0.29	0.34	0.32
	III	-0.33	-0.38	***-0.41***	-0.01	***0.56***	0.16	0.19	0.24
	IV	-0.08	-0.20	-0.27	0.15	0.39	0.08	0.26	0.32
	V	-0.04	-0.30	-0.26	0.10	0.00	-0.03	-0.01	-0.10
	VI	-0.20	-0.34	-0.36	0.09	0.00	0.01	-0.01	0.03
	Overall	-0.21	-0.35	-0.37	0.06	0.26	0.10	0.15	0.17

The two higher classes (class V and VI) in S4 and S6 show generally poor correlations with SOI in early summer. The two regions are located within the influence of tropical-temperate troughs (TTTs, Todd and Washington, 1999ab) which are observed mainly during November-March period and which have been associated with infrequent but intense rainfall events. These TTTs may partly be responsible for the low correlations between rainfall and SOI in S6 although links between TTTs and ENSO are not yet known.

b) The spatial variation of rainfall responses to an ENSO signal.

The magnitude and significance of the correlations (Table 10.1) indicate that the strongest ENSO signals in southern African rainfall are found in the western parts of southern Africa (Fig.10.4a) while moderate to weak signals are found in the northern and eastern parts of the region. These results are consistent with those in the past studies (Ropelewski and Halpert, 1987; Janowiak, 1988; Nicholson and Kim, 1997; Rocha and Simmonds, 1997a; Landman and Mason, 1999; Latif *et al.*, 1999; Indeje *et al.*, 2000; Trenberth and Caron, 2000).

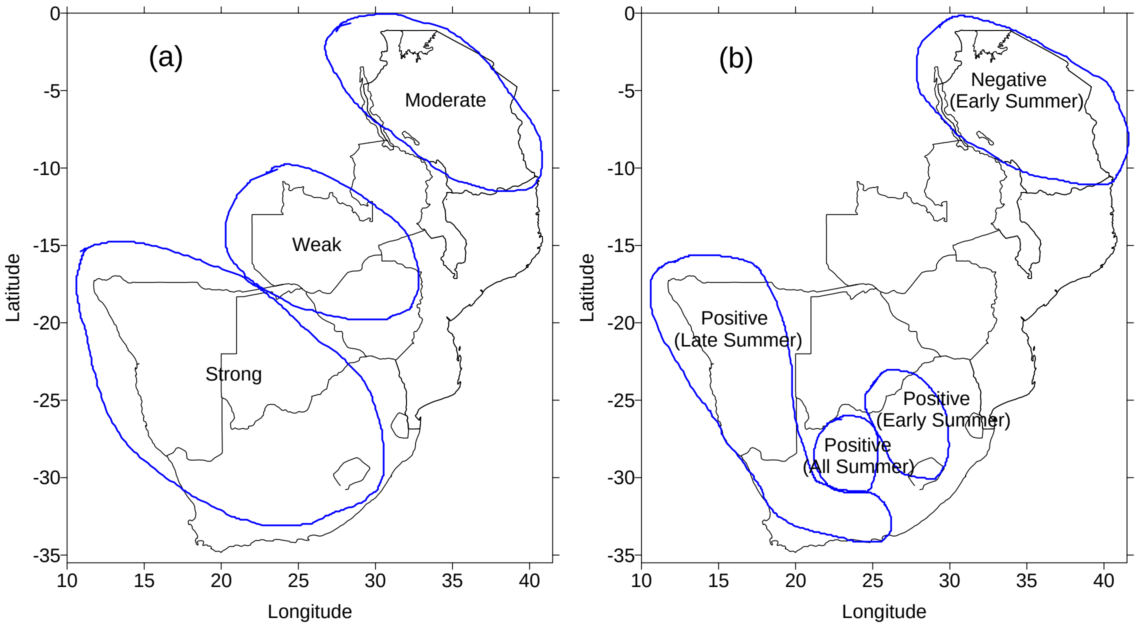

Fig.10.4: Generalisation of the ENSO-southern African rainfall relationships according to a) strength and b) seasonality and sign of the association with SOI.

c) The seasonality of the influences of ENSO.

ENSO signals in early summer rainfall are strong in the eastern regions (northeast South Africa/southeast Botswana or S4 and northern Tanzania or N1), while the strongest signals in late summer are observed in the western and southern regions - Namibia (S1), western interior South Africa (S2) and central southern South Africa

(S3). An exception is the central interior of South Africa (S5) where the influences of ENSO on rainfall in both early and late summer is significant.

Generally, correlations between SOI and late summer seasonal amounts are low in the northern (*N*) regions. Moreover, the weak response of late summer rainfall in the northern (N1) region is consistently negative while it is positive in the southwest (N2) (Table 10.1). These correlations suggest that post-ENSO long rains are not always below average in northern Tanzania, results which are consistent with the findings of Indeje *et al.* (2000), but which differ from those of Nicholson (1996).

The correlations are consistently positive in the southern (*S*) regions in both early and late summers and consistently negative in early summer in the northern (*N*) regions.

d) The lead-lag influences of ENSO

As noted by Jury (1996), it is observed that the southern spring (September-December) SOI values show the highest influences on southern African rainfall in both early and late summer. Correlations are progressively increasing with reducing SOI lead and usually peak in SON (Table 10.1) and decay thereafter. Correlations with monthly SOI indicate a steadily increasing correlation from June to peak in October (for early summer rainfall), November (late summer class IV-VI), January (late summer, *S* regions) or April (late summer, N2) for the lower classes. Monthly SOI values during the April-May ENSO transition period (Trenberth and Caron, 2000) gave generally poor correlations with both early and late summer rainfall. Therefore, significant correlations obtained with FMA or MAM seasonal SOI were mainly attributed to February and March SOI.

10.4.2 SST-southern African rainfall relationships

Results of correlation analysis between classed seasonal amounts and SST in the Atlantic and Indian Ocean basins are given in Table 10.3 and indicate mainly the dominant influence of SST in the tropical western Indian Ocean (TWIO) and also the influence of SST in the south Madagascar (MADA) basin on heavy rainfall events. The influence of TWIO SST are positive in the northern *N* regions and negative in the southern *S* regions while that of MADA is generally the opposite. SST in other oceanic basins show low correlations with southern African rainfall.

Table 10.2: Correlation coefficients between seasonal rainfall amounts in southern Africa and seasonal SST anomalies. Significant correlations at 95% (r > 0.39) are shown in bold italics. MA = MADA, SW = SWIO, TW = TWIO, EA = EAO and BE = BENG.

Region	Class	ONDJ Seasonal amounts against					FMA Seasonal amounts against				
		MA_OND	SW_OND	TW_OND	EA_OND	BE_OND	MA_FMA	SW_FMA	TW_FMA	EA_FMA	BE_FMA
S1	II	0.21	0.10	-0.18	0.01	0.04	0.34	0.11	***-0.59***	0.05	0.18
	III	0.11	0.05	-0.19	0.00	0.06	0.39	0.20	***-0.57***	-0.04	0.11
	IV	0.09	0.08	-0.22	-0.04	0.04	0.36	0.19	***-0.52***	-0.10	0.04
	V	0.04	0.09	-0.20	-0.03	0.00	0.28	0.18	***-0.40***	-0.29	-0.15
	VI	0.04	0.10	-0.23	-0.03	0.05	0.28	0.04	-0.36	***-0.47***	-0.27
S2	II	0.18	0.12	***-0.41***	0.14	0.12	0.30	0.20	***-0.52***	0.20	0.18
	III	0.09	0.24	***-0.59***	-0.07	-0.15	0.21	0.16	***-0.47***	0.27	0.26
	IV	0.09	0.22	-0.27	-0.05	-0.09	0.33	0.31	-0.23	0.29	0.19
	V	0.22	*0.33*	-0.22	0.13	-0.14	0.09	0.19	-0.25	0.06	0.20
	VI	0.06	0.26	-0.18	0.08	-0.13	***0.41***	0.37	-0.26	-0.09	-0.03
S3	II	0.28	0.11	***-0.52***	-0.16	-0.03	0.23	0.10	***-0.45***	0.00	-0.04
	III	*0.37*	0.17	***-0.45***	-0.03	0.08	0.37	0.38	-0.28	0.05	-0.04
	IV	0.22	0.27	***-0.39***	0.17	0.06	***0.43***	0.39	-0.33	0.00	-0.05
	V	0.17	0.21	*-0.35*	-0.01	-0.09	0.35	0.34	-0.37	0.00	0.09
	VI	***0.42***	0.29	-0.06	0.15	0.15	***0.51***	0.33	-0.30	0.09	0.01
S4	II	0.16	-0.01	-0.23	-0.15	0.06	0.06	-0.01	-0.20	-0.09	-0.08
	III	0.14	-0.08	***-0.41***	-0.23	-0.07	0.08	0.05	-0.39	-0.10	-0.10
	IV	0.12	0.12	*-0.35*	-0.24	-0.23	0.13	0.04	-0.36	-0.18	-0.22
	V	0.10	0.23	*-0.31*	-0.08	-0.22	0.15	0.03	-0.38	-0.13	-0.21
	VI	-0.04	-0.06	-0.25	*-0.33*	*-0.30*	0.23	0.12	***-0.43***	-0.28	-0.21
S5	II	0.28	0.04	*-0.36*	-0.02	0.20	0.14	0.13	-0.36	-0.18	-0.06
	III	0.15	0.14	***-0.53***	-0.20	0.12	0.26	0.22	-0.38	-0.02	-0.03
	IV	0.01	0.04	***-0.52***	-0.05	0.11	0.18	0.30	-0.29	0.02	0.00
	V	0.11	0.22	***-0.44***	0.04	-0.05	0.29	0.37	-0.31	-0.24	-0.12
	VI	0.14	0.10	*-0.32*	-0.19	-0.05	0.24	0.19	-0.34	-0.19	-0.08
S6	II	0.13	-0.01	-0.17	-0.01	-0.01	***0.51***	0.28	-0.29	-0.22	-0.17
	III	0.18	0.22	-0.21	0.05	-0.09	0.39	0.16	-0.23	-0.31	-0.22
	IV	0.24	0.22	-0.12	0.15	-0.01	0.39	0.16	-0.33	-0.34	-0.23
	V	***0.41***	*0.35*	-0.14	-0.16	-0.08	0.36	0.30	-0.25	-0.36	-0.33
	VI	0.24	0.16	-0.08	-0.15	-0.09	***0.44***	0.16	-0.11	-0.32	-0.38
N1	II	-0.24	-0.05	*0.35*	0.10	-0.04	-0.27	-0.11	0.23	-0.15	-0.08
	III	-0.09	0.02	***0.57***	0.23	0.05	-0.38	-0.29	0.14	-0.21	-0.02
	IV	-0.03	0.06	***0.47***	0.19	0.11	-0.07	-0.08	0.14	-0.24	-0.18
	V	-0.09	0.04	***0.47***	0.16	0.08	-0.06	-0.12	0.25	-0.35	-0.29
	VI	-0.02	-0.04	***0.60***	0.20	0.10	-0.14	-0.24	0.32	-0.13	-0.14
N2	II	0.15	0.19	***0.49***	*0.37*	0.19	-0.25	0.00	-0.18	0.05	0.25
	III	0.15	0.20	***0.48***	0.20	-0.07	***-0.61***	-0.25	-0.20	-0.19	0.07
	IV	0.09	0.11	*0.30*	0.21	0.09	-0.39	-0.14	-0.27	-0.13	0.04
	V	0.19	0.24	*0.39*	0.16	0.04	-0.15	-0.23	-0.06	-0.39	-0.14
	VI	0.04	0.21	***0.50***	0.19	-0.01	-0.39	-0.24	0.03	-0.01	0.11

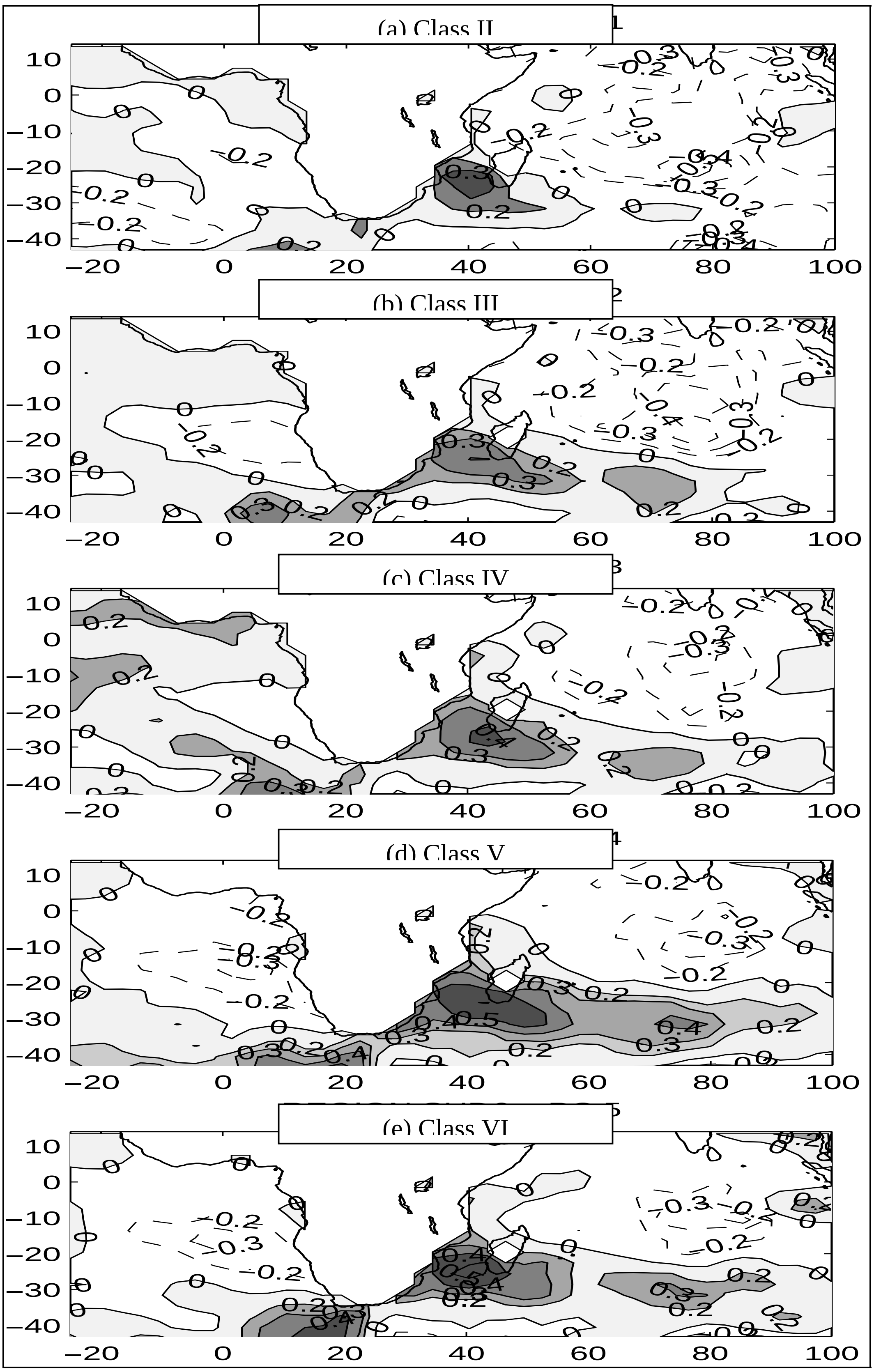

Fig.10.5: Correlations between OND SST and S6 (Zambezi) regional ONDJ seasonal amounts. All correlations exceeding 0.39 are significant at 95%.

In the *N* regions, the influence of SST is almost consistent for all classes but peaks for the higher classes. In the *S* regions, the lower classes of daily intensities are predominantly influenced by the SST in the tropical Indian Ocean (e.g. Table 10.3, Fig.10.5a, 10.5b), which are known to modulate regional scale atmospheric dynamics notably the Walker and Hadley cells. However, the influence generally decreases with increasing intensities suggesting the increasing role of local or regional scale influences on heavy rainfall events. This is indicated, for example, by the SST signals which are confined mainly around southern Africa, particularly in the southern Madagascar (MADA) basin (Fig.10.5c-10.5e). The regional SST can be playing an important role in modulating the moisture of the air which is advected towards the continent. The studies of Reason (1998), Crimp and Mason (1999), Reason and Mulenga (1999), Reason (2001) and Rouault *et al.* (2002) found the influences of the SST and moisture from the southwest Indian Ocean basins on rainfall and extreme rainfall events in different parts of South Africa.

10.5 Stability of the ENSO/SST-southern African rainfall relationships

10.5.1 Stability of the ENSO-southern African rainfall relationships

The stability of the ENSO-southern African rainfall was assessed in the five southern regions (*S1-S5*) which have long records. Due to a large number of rainfall and SOI indices used, the complete results are not presented but only the main results are discussed. Results of sliding correlation analysis indicate significant changes in the relationships in all regions while the changes differ between the different ENSO seasons involved.

a) Dates and direction of changes

Significant changes were observed mainly in the mid-1950s and mid-1970s in which significant correlations between SOI and early and late summer rainfall characterise all the 15-year segments starting between 1956/57 and 1975/76 while weak correlations or correlations of opposite sign were found for segments starting before 1956/57 or after 1975/76 (Fig.10.6b). The two extreme dates correspond to a period of re-occurrence of an active ENSO phase in the late-1950s/early-1960s after its calm phase in the1930s-1950s (Torrence and Compo, 1998; Kestin *et al.*, 1998) and of warming in the tropical Pacific basins in about 1976/77 (Wang, 1995; Trenberth and Hoar, 1996). The earlier changes in the mid-1950s improved the ENSO-rainfall associations while the latest changes in the 1970s deteriorated or even changed the associations.

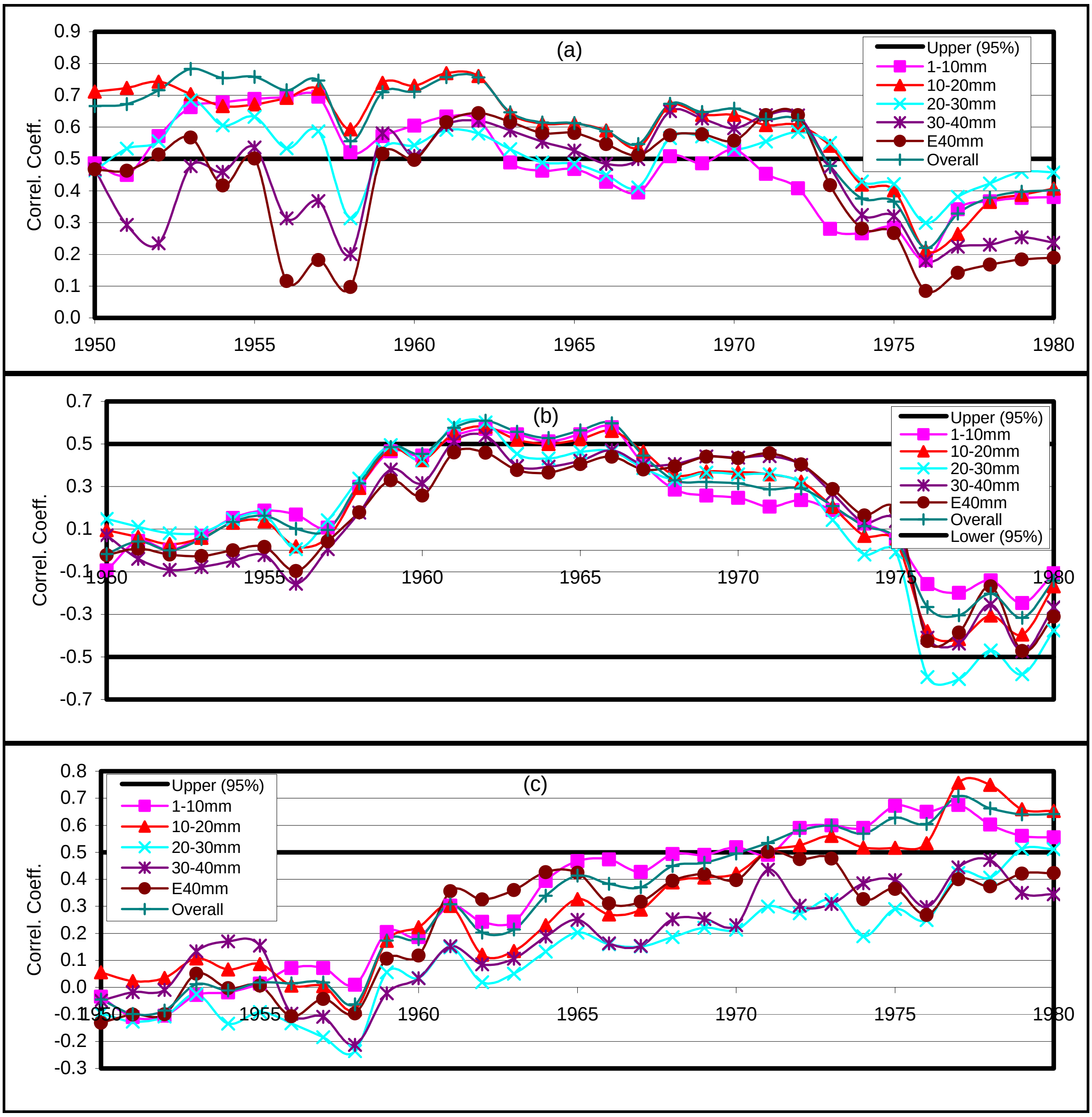

Fig.10.6: Typical temporal evolution of correlations between seasonal rainfall and SOI: a) FMA seasonal number of events and DJF SOI in S5, b) ONDJ seasonal number of events and JJA SOI in S1 and c) FMA seasonal number of events and MAM SOI in S2. Absolute correlations exceeding 0.50 (0.43) are significant at 95% (90%). The year shown correspond to starting year of the 15-year segment such as 1970 implies the 1970-1984 period.

b) The changing influences of ENSO

The typical temporal patterns of evolution of SOI-rainfall correlations are illustrated in Fig 10.6. They indicates a reducing influence of the austral spring (September-December) SOI on early summer rainfall in southern Africa affecting significantly the three higher classes (class IV-VI) (e.g. Fig.10.6a). In fact, most of the relationships during early summer have changed from positive to negative for segments starting after 1975/76, the changes which were more evident in the western (*S1* and *S2*) regions and to some extent in *S4*. The influences of the spring SOI on late summer rainfall have reduced as in *S5* or remained relatively unchanged besides correlation depressions caused by low correlations in the periods 1975-1989, 1976-1990 and 1977-1991.

A steadily increasing influence of the austral winter (JJA) and summer (January-March) SOI values on southern Africa rainfall in late summers was observed (e.g. Fig.10.5c, Table 10.2) while in early summer, the influence remained relatively unchanged despite correlation depressions. The changes affect mainly the southern (*S2*, *S3*) and southeast (*S4*) regions in which correlations has become significant for segments starting in 1971 or later. Richard *et al.* (2000) found similar significant post-1970 association between JFM overall rainfall amounts in southern Africa and JFM SOI.

c) The possible impacts of the changes on the relationships over the 1955-1985 period

Significant reductions or the change in the nature of the SOI-rainfall associations in the southern (*S*) regions generally resulted in weak associations. This is exemplified in Table 10.2. The changes have been observed mostly around 1976 and the 1950-1994 period was therefore divided into the 1950-1976 and 1977-1994 sub-periods (see e.g. Landman and Mason, 1999) and correlations calculated for each sub-period. The correlations are stronger in the first sub-period than in the second. Since 71% of the 1955-1985 period falls within the first period, it is obvious that high correlations in the 1950-1976 period influenced significantly the correlations computed in the 1955-1985 period (Table 10.1).

d) Possible implications of the changes

The results showed the change of the nature of the SOI-early summer rainfall relationships in certain regions since mid-1970s from positive to negative. The relationships in late summer are persistently positive but have significantly reduced for spring SOI and increased for summer SOI. The negative SOI-early summer rainfall association suggest that post-1975/76 decaying SOI (warm ENSO) correspond to enhanced early summer rainfall and reduced late summer rainfall as indicated by persistent positive SOI-late summer rainfall.

Table 10.3: Correlations between seasonal SOI and early and late summer regional seasonal number of events in southern Africa. Significant correlations at 95% are shown in bold italics: |r| > 0.39 for 1950-1976 period and |r| > 0.46 for 1977-1994 period.

Region	Class	1950-1976 ONDJ seasonal frequencies against					1977-1994 ONDJ seasonal frequencies against				
		SOI_MAM	SOI_JJA	SOI_SON	SOI_DJF	SOI_OND	SOI_MAM	SOI_JJA	SOI_SON	SOI_DJF	SOI_FMA
S1	II	-0.08	0.29	0.25	-0.08	0.20	0.08	-0.10	0.08	-0.09	0.11
	III	0.04	0.39	***0.42***	-0.04	***0.41***	0.06	-0.26	0.06	-0.20	0.12
	IV	0.09	***0.45***	***0.53***	-0.06	***0.52***	-0.14	***-0.46***	-0.07	-0.25	0.02
	V	0.17	0.39	***0.50***	-0.04	***0.49***	-0.13	-0.34	0.00	-0.32	0.06
	VI	0.06	0.29	0.39	0.00	0.37	-0.07	-0.34	-0.02	-0.21	0.08
	Overall	-0.02	0.35	0.35	-0.07	0.31	0.06	-0.17	0.07	-0.13	0.11
S2	II	0.27	0.29	0.35	-0.01	0.33	0.21	0.17	0.20	0.13	0.24
	III	0.38	0.37	***0.51***	0.01	***0.54***	0.34	0.17	0.16	0.31	0.22
	IV	0.38	***0.43***	***0.54***	0.11	***0.52***	0.27	-0.14	-0.21	0.25	-0.19
	V	***0.58***	***0.64***	***0.61***	0.28	***0.63***	0.05	-0.31	-0.30	0.21	-0.23
	VI	0.25	***0.42***	***0.57***	-0.09	***0.61***	0.11	-0.27	-0.27	0.35	-0.26
	Overall	0.36	***0.40***	***0.50***	0.02	***0.49***	0.26	0.11	0.12	0.22	0.17

Region	Class	1950-1976 FMA seasonal frequencies against					1977-1994 FMA seasonal frequencies against				
		SOI_MAM	SOI_JJA	SOI_SON	SOI_DJF	SOI_OND	SOI_MAM	SOI_JJA	SOI_SON	SOI_DJF	SOI_FMA
S1	II	0.24	-0.19	***0.67***	***0.49***	***0.42***	0.14	-0.12	0.21	0.03	0.05
	III	0.18	-0.15	***0.55***	***0.52***	0.37	0.28	0.03	0.36	0.31	0.30
	IV	0.26	0.00	***0.48***	***0.50***	***0.43***	0.33	0.17	***0.48***	***0.44***	***0.44***
	V	0.24	-0.11	***0.43***	***0.43***	0.39	***0.41***	0.27	0.29	0.37	***0.42***
	VI	0.10	-0.15	***0.40***	0.38	0.27	0.10	0.19	0.15	0.19	0.12
	Overall	0.24	-0.16	***0.64***	***0.54***	***0.44***	0.22	-0.04	0.29	0.16	0.17
S2	II	0.21	-0.10	0.38	0.27	0.30	***0.44***	-0.05	0.33	0.39	***0.50***
	III	0.18	0.01	0.27	0.22	0.27	***0.57***	0.08	***0.60***	***0.45***	***0.53***
	IV	0.06	-0.14	0.25	0.20	0.15	***0.40***	0.03	0.26	0.06	0.23
	V	0.08	-0.11	0.17	0.12	0.12	0.26	-0.19	***0.60***	***0.45***	0.30
	VI	0.18	-0.08	0.38	0.33	0.27	0.35	0.24	***0.40***	0.33	0.24
	Overall	0.19	-0.09	0.36	0.27	0.29	***0.51***	-0.02	***0.45***	***0.41***	***0.52***

10.5.2 Stability of SST-southern African rainfall relationships

Results of sliding correlation analysis are almost identical to those obtained with SOI which indicate changes in the SST-rainfall associations in the 1956-1966 and 1970-1978 periods. A few representative examples are shown in Fig.10.7.

a) In general, the changes which involve SST in the three Indian Ocean basins had occurred mainly in the 1970s. The changes in the early-1970s were evident in the correlations involving JJA SST in the TWIO basin and OND SST in the MADA basin.
b) In early summer, correlations for segments starting after 1970-1975 were predominantly positive with the highest (and sometimes significant) correlations characterising the three higher classes.

c) In late summer, the changes involving TWIO SST led to positive associations after mid-1970s (Fig.10.7a) while those involving SST in the two southwest Indian Ocean basins (MADA and SWIO) led generally to negative associations for FMA SST (Fig.10.7b). The influence of SST in the two Atlantic Ocean basins (BENG and EAO) has remained generally insignificant and relatively unaltered.

d) Increasing influences of the austral winter (JAS) SST and decreasing influences of the austral spring (OND) SST in these three Indian Ocean basins on summer rainfall in southern Africa were observed. This is suggesting a probable shift of the influence from the austral spring to austral winter, increasing the SST lead favourable for forecasting purposes.

10.6 SST-atmospheric circulations associations and interannual variability of southern African rainfall

Both observational and experimental studies have shown responses of the atmosphere and southern African rainfall to changes in SST in the Atlantic and Indian Oceans south of the Equator. The main influences of SST changes on southern African rainfall are through changes in atmospheric circulation patterns due to SST forcing. These atmospheric changes involve generally strengthening or weakening of Walker and Hadley circulations as well as weakening/strengthening of the inland Angolan/Namibia heat low and/or its eastward displacement into Mozambique or the Mozambique Channel (Reason, 1998). Tropical-temperate troughs (TTTs, Todd and Washington, 1999ab) are usually linked to an inland heat low and the eastward shift of this heat low offshore into eastern Madagascar and is associated with a similar eastward shift of TTTs (Reason, 1998).

Correlations between TWIO SST and lower (850 hPa) and upper (200 hPa) zonal and meridional winds show i) wind patterns that are less consistent at 850 hPa than patterns at 200 hPa (Figs.10.8, 10.9) particularly over the southern African subcontinent, ii) less consistent correlation with wind patterns in early summer than those in late summer and iii) some similarities for the two southwest Indian Ocean basins (MADA and SWIO) and also for the two Atlantic Ocean basins (EAO and BENG). Patterns involving the Atlantic basins are not discussed since no significant correlations between SST in the Atlantic and southern Africa rainfall were found while patterns for the two southwest Indian Ocean basins are discussed together.

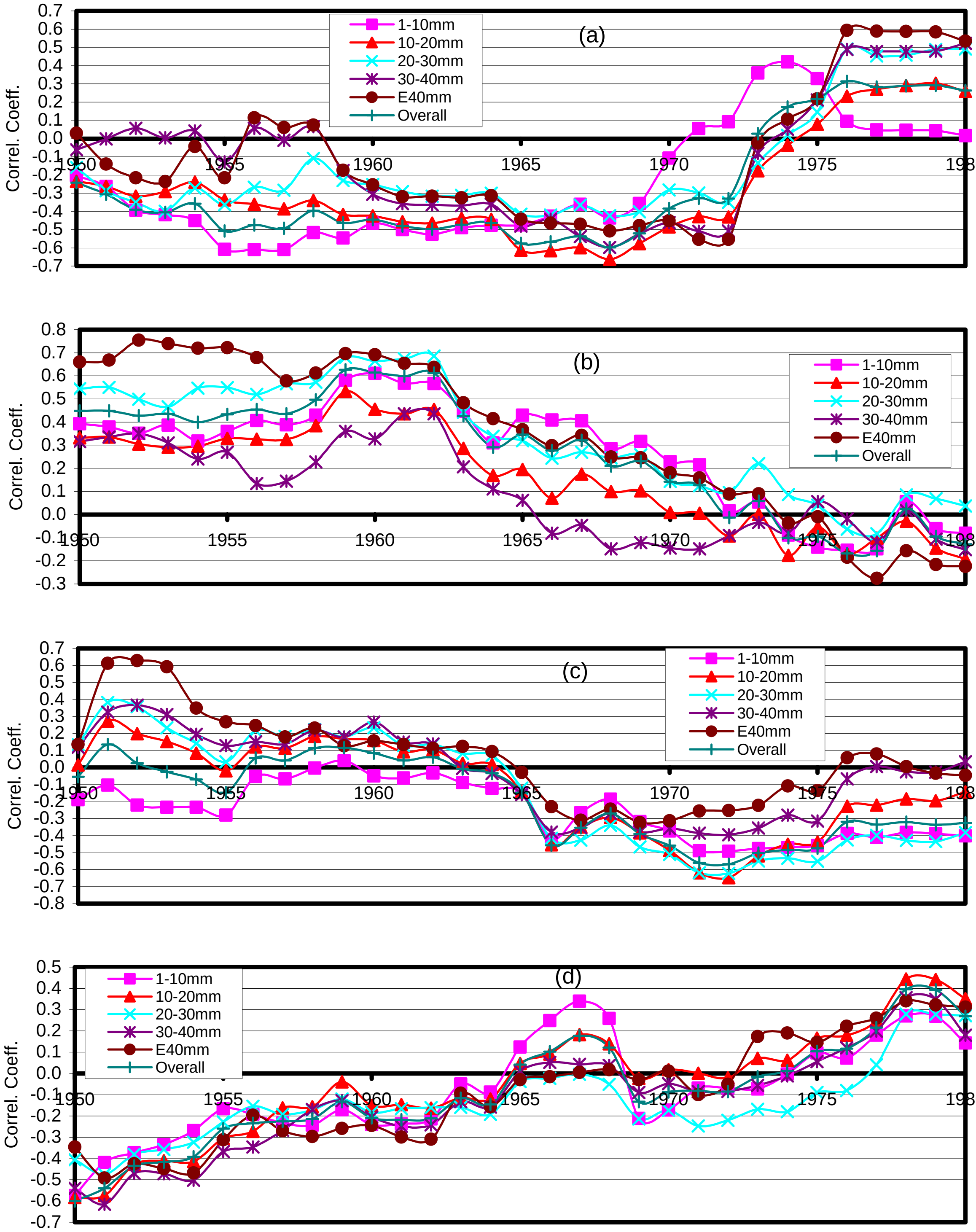

Fig.10.7: Temporal evolution of correlations between FMA seasonal number of events a) in S5 and FMA TWIO SST, b) in S2 and FMA MADA SST, c) in S3 and OND MADA SST and d) in S4 and FMA BENG SST. Absolute correlations exceeding 0.50 (0.43) are significant at 95% (90%). The year shown correspond to starting year of the 15-year segment such as 1970 implies the 1970-1984 period.

10.6.1 Atmospheric circulations related to TWIO SST

The TWIO SST correlation map shows an indication of three weak low-level cyclonic/anti-cyclonic correlation gyres at approximately 30° centres south of Africa in early summer (Fig.10.8a). Two cyclonic flows, one in the southeast Atlantic centred around 40°S, 5°E and the other in the southwest Indian Ocean centred at 40°S, 70°E. Anti-cyclonic anomalous flow is found over the Agulhas between the two cyclonic flows. Cyclonic flow southeast of Madagascar introduces a northerly component into the southeast trades and divert moisture into the central Indian Ocean (Rocha and Simmonds, 1997b). Some of these trades penetrate into Mozambique and reach as far north as Tanzania bringing moisture into the eastern coast (Mozambique) and the northern (Tanzania) part of southern Africa. They meet northwesterlies in northern Tanzania and converge, enhancing early summer rainfall there. An anti-cyclonic anomalous flow southeast of South Africa advects dry air from the midlatitudes into the eastern and southern parts of South Africa reducing the likelihood of abundant rainfall. This effect is indicated by negative correlations between TWIO SST and rainfall in the South African *S* regions (Table 10.2).

Low-level correlation circulations features that prevail in early summer are not similarly observed in late summer. Correlations between FMA TWIO SST and FMA 850 hPa winds show recurving southwesterlies from the southeast Atlantic over cold Benguela waters into western southern Africa (Namibia, western South Africa; Fig.10.9a). These recurved southwesterlies then combine with recurving northeasterlies around the Angola heat low forming northwesterlies which overly *S4* and extend into the Agulhas, preventing moisture influx from southwest Madagascar. Northerly flow in the Mozambique Channel further takes moisture away from southern Africa into Tanzania. This may result in an enhancement of late summer rainfall in northern Tanzania and reduction in the rest of southern Africa, consistent with the correlation results in Table 10.4 (TWIO SST) and Table 10.1 (SOI) indicating probably the response to ENSO forcing.

At 200 hPa, two features that are associated with wet short rains (early summer) are present in Fig.10.8d. Mutai and Ward (2000) observed the presence of twin anti-cyclonic flows centred around 20° on both sides of the equator, 30-50°E during the wettest short rains. An anti-cyclone centred around 20°S, 35°E-60°E is observed in correlation map of TWIO SST (Fig.10.8d). Upper tropospheric easterlies which are linked to enhanced convection over East Africa and the western Indian Ocean (Mutai and Ward, 2000) leading to positive rainfall anomalies are also present in Fig.10.8d. These two features further suggest that SST anomalies in the tropical Indian Ocean lead to upper level circulation changes in favour of short rains.

Fig.10.9d further shows upper level anomalous westerly flow extending from the Atlantic crossing over much of the subcontinent of southern Africa into eastern Madagascar where it acquires a northerly component. These upper-level westerlies correspond to weakened Walker-type circulation over the tropical Atlantic and subcontinental southern Africa. They have been previously observed during dry years in southern Africa (Lindesay, 1988; Rocha and Simmonds, 1997b; Tyson *et al.*, 1997) and linked to ENSO (Arkin, 1982) in which convection is inhibited by weakening vertical wind shear (Harrison, 1986) and corresponds to the eastward shift of the inland heat low and associated TTTs (Reason, 1998).

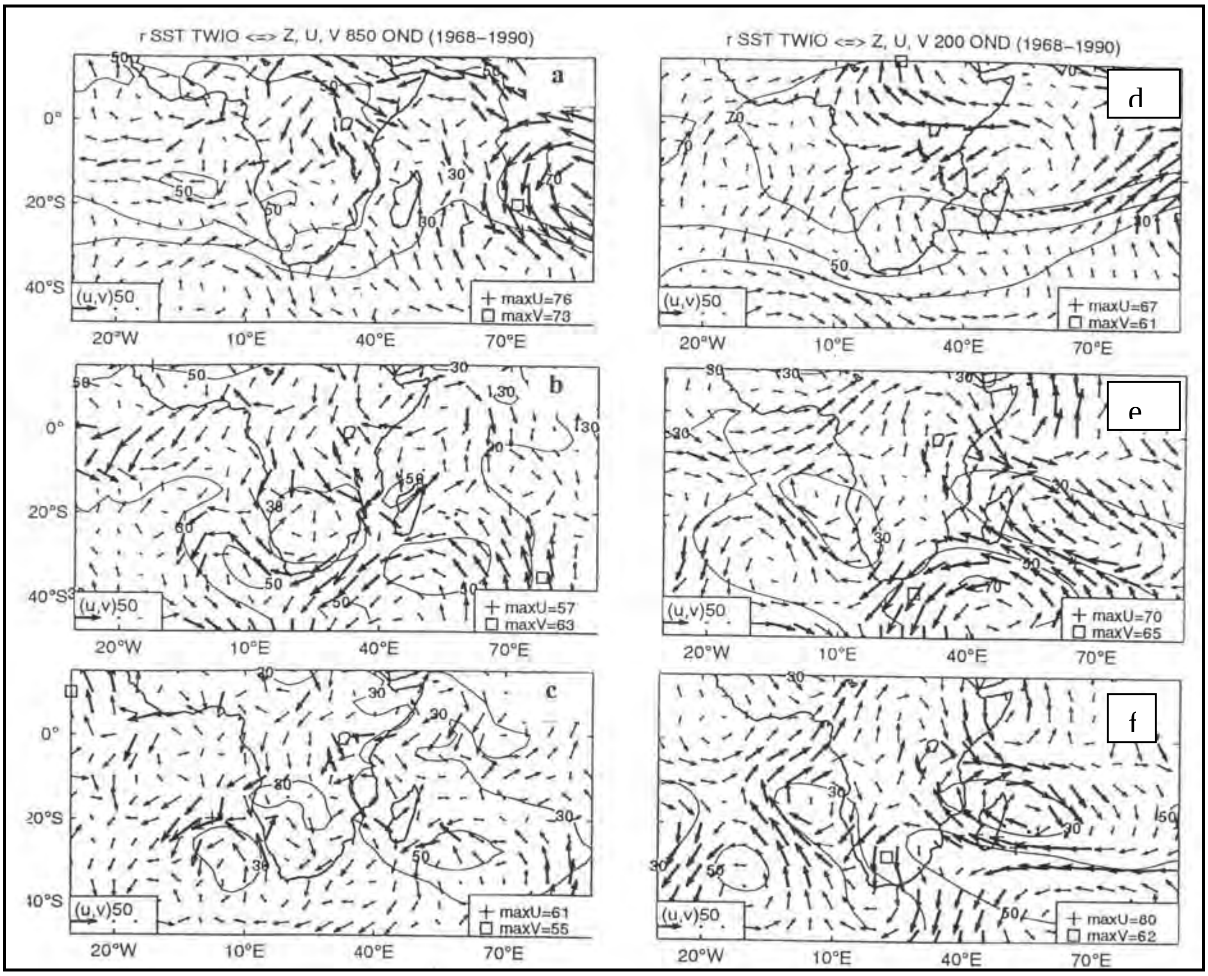

Fig.10.8: Correlations between NCEP/NCAR re-analysis OND winds (arrows) and geopotential height (contours) (1968-1990, correlations × 100) and OND SST anomalies in a) and d) TWIO; b) and e) MADA and c) and f) SWIO. Contours display correlations of –70, -50, -30, 30, 50 and 70 with correlations exceeding absolute 52 are significant at 95%. Thick arrows are significant at 95%. Left panels are for 850 hPa and right panels for 200 hPa.

10.6.2 Atmospheric circulations related to MADA and SWIO SST

An anomalous low-level cyclonic flow is observed over much of southern Africa in the correlation map for OND MADA SST (Fig.10.8b) in which northerlies/northwesterlies on its equatorward side bring moisture from the Congo basin into southern Tanzania, Zambia, eastern Zimbabwe, Botswana and central/southern Mozambique. These northerlies extend into the eastern and southern parts of South Africa and might be advecting moisture into these parts of South Africa. A weak anti-cyclonic correlation gyre is found off the Tanzania coast with its northerlies paralleling the northern coast and penetrate the southern coast. These winds may correspond to negative and positive correlations between OND MADA SST and early summer rainfall in *N1* and *N2* respectively (Table 10.2). Apart from an anti-cyclonic correlation gyre within the Mozambique Channel and southwest directed vectors over southeast/south-central South Africa, there are no other specific features in the correlation map of SWIO SST (Fig.10.8c) which are associated with enhanced or reduced influx of moisture into southern Africa.

Anti-cyclonic anomalous flows in the central south Atlantic, to the southeast of Africa and in the Mozambique Channel are observed in a map of correlations between FMA MADA SST and FMA low-level winds (Fig.10.9b). Weak northerlies/northeasterlies and southerlies/westerlies meet and converge over Zambia. Furthermore, northerly flow over the Mozambique Channel recurves and penetrates into southeast South Africa bringing moist air into *S3*. These low-level circulation features favour an increase in late summer rainfall in Zambia, Malawi, central and southern Mozambique and southeast South Africa and this is indicated by positive correlations between FMA MADA SST and late summer rainfall in the *S3* and *S6* regions (Table 10.2). Northerlies/northwesterlies along the Tanzanian coast hinder Indian Ocean moisture influx into the country leading to a negative association between late summer rainfall in Tanzania and FMA SST in southwest Madagascar (Table 10.2).

At 200 hPa, an anomalous easterly flow is observed over much of southern part of southern Africa in late summer in the maps of both MADA SST (Fig.10.9e) and SWIO SST (Fig.10.9f). The anomalous easterly flow may suggest wet conditions in the southern part as they oppose the westerly flow which is related to dry conditions in the region.

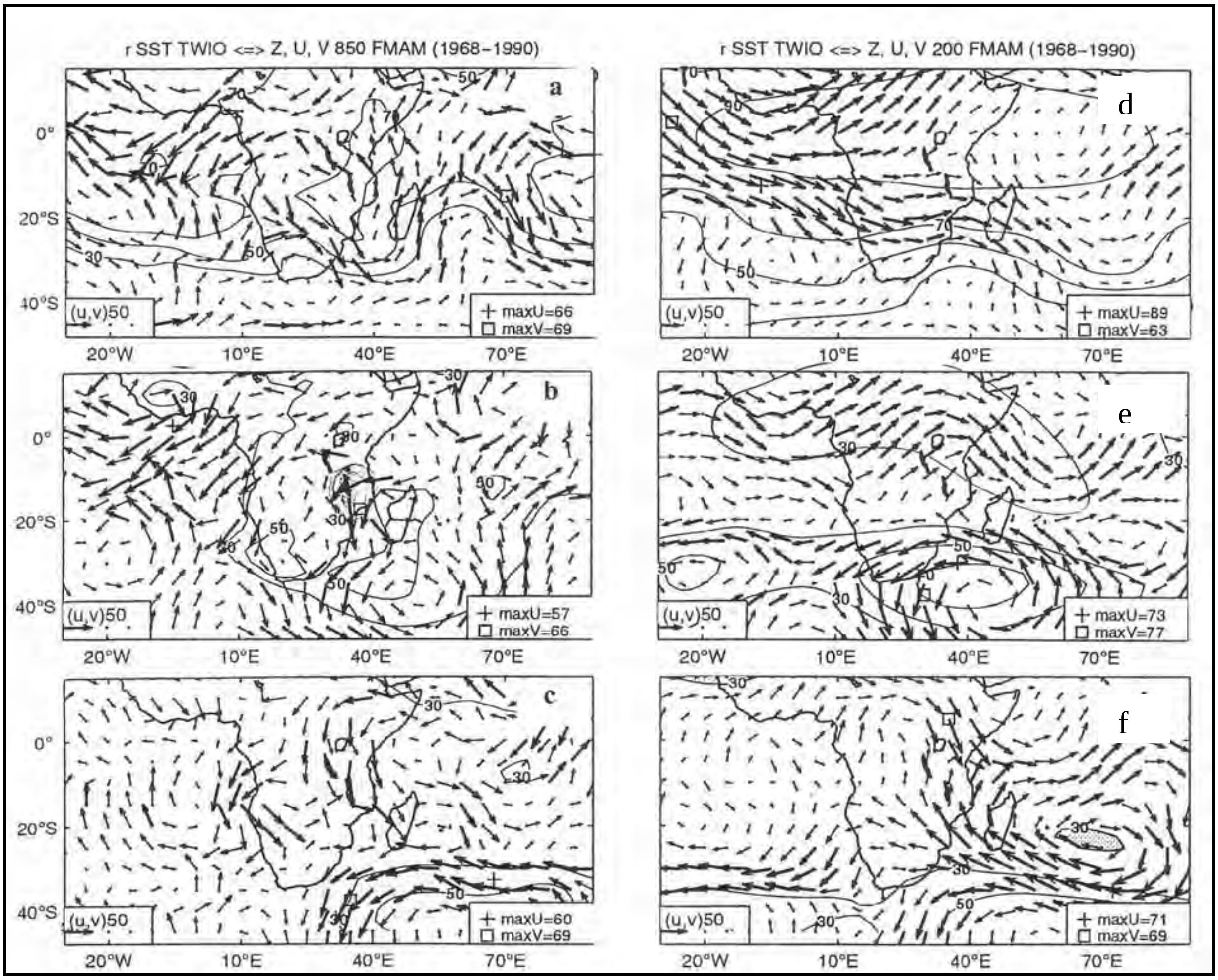

Fig.10.9: Correlations between NCEP/NCAR re-analysis FMA winds (arrows) and geopotential height (contours) (1968-1990, correlations × 100) and FMA SST anomalies in a) and d) TWIO, b) and e) MADA and c) and f) SWIO. Contours display correlations of –70, -50, -30, 30, 50 and 70 with correlations exceeding absolute 52 are significant at 95%. Thick arrows are significant at 95%. Left panels are for 850 hPa and right panels for 200 hPa.

10.7 Discussion

The results presented above show the dominance of influences of ENSO and SST in the tropical Indian Ocean on interannual variability of southern Africa rainfall. Also SST variations in south/southwest Madagascar were observed to influence interannual rainfall variations in the Zambezi basin (*S6*) and central southern South Africa.

The TWIO basin is influenced by ENSO and simultaneous associations between southern African early and late summer rainfall and SOI (Table 10.1) and TWIO SST (Table 10.2) suggest modulation of regional rainfall by ENSO. The Indo-Pacific influences vary between regions and slightly among classes of daily rainfall. While early summer rainfall in the *N* regions is predominantly responding to the Indo-Pacific ENSO signal, the responses in the *S* regions are different. Significant (at 90% and 95%) correlations between early summer amounts in all classes in southwest Tanzania (N2) and SOI and TWIO SST and MADA SST indicate mixed influences of the remote ENSO/TWIO SST signal and regional SST in south/southwest Madagascar.

ENSO became active again in the late-1950s-early-1960s (Kestin *et al.*, 1998; Torrence and Compo, 1998). Negative SOI-early summer rainfall association in the *N* regions suggests enhanced early summer rainfall (short rains) in a low phase of SOI. Identified shifts in early summer seasonal amounts (Fig.7.4, Chapter 7) as well as class VI amounts (Fig.7.3b) in the southern Lake Victoria region and northeast Tanzania were likely to be caused by these ENSO changes. The mechanisms that lead to such changes in some parts of northern Tanzania and not all over the northern part are not yet well understood.

Responses of early summer rainfall in *S4* and *S5* and late summer rainfall in *S5* to the Indo-Pacific ENSO signal resemble those in the *N* regions although the relationships are inverted, towards reduced rainfall during El Niño years. Early summer rainfall increases and late summer rainfall decreases in late the 1970s in these regions (Fig.6.6) could have been induced by warming in the tropical Pacific and Indian Oceans in the late 1970s (Trenberth, 1990; Kerr, 1992; Wang, 1995; Trenberth and Hoar, 1996) which drove changes in atmospheric circulations. Using AGCM forced with positive SST anomalies typical of ENSO anomalies, Rocha and Simmonds (1997b) observed an upper-level westerly flow over much of southern Africa that is associated with reduced DJF rainfall in the region.

Early summer rainfall increases in eastern South Africa (Fig.6.6) could not be linked to warming in the tropical Indian Ocean or Pacific Ocean, whose SST are negatively correlated with rainfall in this region (Table 10.2). However, positive association between rainfall in this part of South Africa and MADA SST and positive associations with TWIO since 1972 (Not shown) could be responsible for such rainfall increases. A warm SST anomaly in MADA produces a low-level cyclonic anomaly over the warmer southwest Indian waters (Fig.10.8b) and its southeasterly vectors advect moisture into southeast South Africa leading to enhanced early and late summer rainfall. Furthermore, low-level anomalous northwesterlies extend from the Congo basin to the eastern coast of southern Africa bringing moisture into the region from the Congo basin. It is noted that dates of upward shifts (Fig.7.4) are spatially variable with only shifts in early summer overall seasonal amounts in S3 identified in the late-1970s-early-1980s. Abrupt increases in *S5* were identified in the early-1950s (1952/53), in S4 they occurred between 1951/52 and 1969/70, while decreases in the seasonal number of rainfall events were identified in the early-1950s and early-1970s in northeast Tanzania (Valimba *et al.*, 2003b). Earlier changes in rainfall in South Africa have been identified in a number of previous studies (Tyson, 1986; Smakhtina, 1998).

Shifts in southern African rainfall that were identified before the late-1960s do not correspond to changes in SST in the Indian and tropical Pacific Ocean basins in the 1970s. They may be linked to changes that involve the atmosphere or land-atmosphere interactions and in general to global warming. Warming in both southern and northern hemispheric annual mean surface air temperatures after 1960 has been reported (IPCC, 2001). Global surface air temperature trends, show abrupt rises in the early 1940s and early 1960s. According to Flohn and Kapala (1989), warming of the tropical troposphere has a consequence of accelerating a delayed oceanic warming in low latitudes. Hence oceanic warming in the 1970s could be an oceanic response to tropospheric warming in the 1960s which in turn feedbacks into the atmosphere modifying further atmospheric circulations. It is then possible that atmospheric-related changes in southern African rainfall were the cause of observed changes in SST-southern African rainfall associations before the 1970s.

An increase in SST causes a non-linear increase in the amount of water precipitated from an oceanic vertical column of air (Stephens, 1990; Zhang, 1993). Warming of the southwest Indian (including MADA and SWIO) and tropical Indian and Pacific Ocean waters in the 1970s may have enhanced convection in these oceans and consequently rainfall becomes more convective leading to reduced frequency of light rainfall events. Decreases in class II amounts and number of events were identified mainly in the 1970s in coastal northeast Tanzania, Namibia and the southeast coast of South Africa (e.g. Fig.7.3c). Positive and significant correlations between class VI (≥ 40 mm) in *S3* and MADA SST in both early and late summer and insignificant correlations with both TWIO SST (Table 10.2) and SOI (Table 10.1) may be indicating a contribution of enhanced convection over local warmer southwest Madagascar waters to the increase of higher rainfall in the southeast South Africa (Smakhtina, 1998). Mason *et al.* (1999) found a decreasing intensity of high rainfall in northeast South Africa (*S4*) since the late 1970s, decreases which have been similarly identified in annual amounts (Fig.7.3a) and number of events (Table 7.3) of class VI rainfall. However, the decreases were identified in the present study between early 1960s and late 1970s. In contrast, these intense daily events had increased in eastern and northeast Tanzania in the early-1960s.

Tables 10.1 and Table 10.2 link changes in southern African rainfall mainly to SOI and TWIO SST changes and their induced atmospheric circulation changes discussed above. Correlations between class VI rainfall in *S4* and SOI (TWIO SST) are significant and persistently positive (negative) for late summer rainfall while in early summer, they are insignificant and have shifted to negative for SOI in post-1975/76. In an almost similar period, correlations between early summer class VI rainfall events in *S4* and SST in TWIO, MADA and SWIO have shifted from negative to positive. These correlations suggest that a decaying phase of SOI (warm ENSO) and/or warming of TWIO, SWIO and MADA waters correspond, therefore, to reduced intense daily events in late summer in northeast South Africa and their increase in early summer in the post-1975/76 period. Low-level easterlies, northeasterlies or southeasterlies over the Congo basin and Angola/northern Namibia (Fig.10.7a, 10.8a) due to warmer TWIO SST are unfavourable for the development of an inland heat low (Reason, 1998; Reason and Mulenga, 1999) indicating reduced likelihood for TTTs formation which in turn implies reduced frequency and/or intensity of heavy rainfall in northeast South Africa.

Further, SST in the Atlantic Ocean basins (BENG and EAO) are significantly and persistently negatively correlated with early summer rainfall in *S4* since 1968-1970 at both lag-0 and lag-1 season but correlations reduced to insignificant negative after 1978. These negative correlations suggest that warming in these Atlantic Ocean basins, as is observed during Benguela Niños, corresponds to reduced intense rainfall in *S4*. The mechanism may involve weakening of the temperature gradient between the tropical/subtropical Atlantic and southwest Indian Ocean, conditions unfavourable for strengthening of strong southeasterlies, which advect moisture into eastern South Africa including S4.

10.8 Conclusions

Results show that interannual variability of rainfall in southern Africa is mostly influenced by ENSO and SST in the tropical Indian Ocean and south/southwest Madagascar basins. SST in southwest Indian Ocean and in the Benguela Current system, including the Angola/Benguela Front region and the equatorial Atlantic, have selective influences upon southern African rainfall. The study has mainly found the following

- Influences of ENSO:
  - ENSO influences are consistent in all classes and highest in the light (< 20 mm) daily events.
  - There is a dipole-like response of rainfall in the northern and southern part of southern Africa to an ENSO signal in which the ENSO influence is strong and positive in early summer in the north and strong and negative in late summer in the south.

- There has been a significant change in the ENSO-southern African rainfall relationship since the mid-1970s, which led to an increasing influence of austral winter SOI and decreased or changed associations for austral spring SOI.

o Influences of SST in the Indian and Atlantic Oceans

- SST in the tropical Indian ocean have a dominant influence on the interannual variability of rainfall in the region.
- The interannual variability of the light/moderate (< 20 mm) daily events is being modulated by large-scale influences of the Indo-Pacific signals while regional SST in the south/southwest Madagascar were found to have a considerable influence on heavy daily events.
- SST in the tropical Indian ocean show an inverse relationship with rainfall in the southern part and a direct relationship with rainfall in the north, while SST in the south Madagascar basin show the opposite influence to that of the tropical Indian ocean.

It was not possible, however, to reach firm conclusions based on the observed results as it was not possible to link pre-1950s rainfall changes to climatic changes since pre-1950s SST in the southern Atlantic and Indian Oceans and pre-1968 upper air data over Africa are doubtful and frequently missing.

Changes were identified in the mid-1970s but the records were too short to provide any strong conclusions in the post-1975 period. Moreover, it was not possible to study similar temporal evolutions of SOI/SST-rainfall associations in other parts of southern Africa due to short available records.

Nevertheless, evolving long lead SOI/SST-summer rainfall associations in Namibia and South Africa offer the possibility of using SOI and SST as predictors of summer rainfall in these countries. But one should also be cautious when constructing summer seasons as it was observed that the two parts (early and late summers) of the single rainy season in the summer region of southern Africa displayed opposing interannual patterns of variability.

CHAPTER 11

GENERAL SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

11.1 Summary and conclusions

The main objective of the study was to investigate hydrological variability in southern Africa at a regional spatial scale and its relationship to climatic variations. Additional interest was in studying hydrological variability in relation to hydrological extremes, floods and droughts, which have been reported to be more frequent, severe and widespread in recent decades than in the past. This necessitated the use of indices of rainfall and streamflow that define the hydrological extremes, which in turn required data of short-duration such as daily data. The fact that these hydrological extremes do not characterise the whole of southern Africa at the same time and that floods and droughts of different levels of severity and duration have been reported in different areas of the region at the same time, indicates the spatial non-uniformity of the variations. The main findings of this study are summarised below.

11.1.1 Spatial-temporal variations of rainfall

11.1.1.1 Spatial variations

Climatologies of daily rainfall indicated that about 60-70% of the time when it rains, daily rainfall intensities are below the long-term average daily rainfall intensities (AADI) and light (< 10 mm) daily intensities are generally the most frequent in the region (Section 6.6.2).

The dry western/southwestern part of southern Africa is dominated by light (< 10mm) daily rainfall intensities, has low annual amounts and number of daily events and the highest interannual variability while the “humid” eastern and northern part has generally high annual amounts and number of daily events, almost similar contributions of different types of daily events to annual amounts and low interannual variability.

The high daily rainfalls exceeding 30 mm were experienced mainly during the core of the principal wet seasons: March-April in most of Tanzania, June-August in the Western Cape and December-February in the rest of southern Africa (Fig 6.11). Further, the areas in central Mozambique and the southern highlands of Tanzania receive the highest number of these intense daily events and are therefore the most prone to flooding.

11.1.1.2 Temporal variations

Change-point and linear trend analyses of seasonal and annual rainfall amounts and number of daily rainfall events resulted in a number of conclusions. It should be noted that linear trends were investigated for the common periods 1941-1990 and 1961-1990 to provide comparison of trending behaviour (strictly increasing/decreasing or alternating) in the two sub-periods.

- There is an opposing pattern of interannual variability of rainfall in the early and late summer which leads to a tendency towards decreasing late summer rainfall in various parts of southern Africa since the 1970s and increasing early summer rainfall in the eastern part since early-1960s (Table 7.1a, Figs 7.4a, 7.4b). The recent decreases in late summer rainfall affected significantly rainfall in Namibia.
- There is a lack of any real evidence of trends in annual rainfall amounts in the region as a whole and there is strong evidence of spatially localised trends in annual amounts like in Namibia (Table 7.1a).
- There is strong evidence of trends towards declining annual number of daily rainfall events as well as the number of light (< 10 mm) daily rainfall events in the region (Table 7.1b).
- The opposing patterns of interannual variability of rainfall in the early and late summer affect the patterns of overall rainfall indices at the annual timescale. Abrupt decreases in annual rainfall in some southern parts of southern Africa were similarly identified in late summer rainfall but were lacking in early summer rainfall. In eastern Tanzania, increases in early summer rainfall were countered by similar decreases in late summer rainfall resulting in the lack of abrupt changes in annual rainfall (Fig 7.3a).

11.1.2 Spatial-temporal variations of the rainy seasons

The rainy seasons characteristics (onset, end and duration) were objectively defined (Section 8.3) and their spatio-temporal variations in the southern African were investigated (Sections 8.5 & 8.6). Spatially, the start and end of the rainy seasons in the region (Figs 8.6, 8.7) were related to the pattern of low-level atmospheric circulation features including the ITCZ, the southeast trades and the inland Angola heat low. Temporally, interannual variability of the rainy season characteristics were similar to interannual variability of rainfall amounts and number of daily events. Wet years, for example, corresponded to prolonged rainy seasons (Fig 8.11) which recorded significant amounts and number of events while in dry years the opposite was observed.

11.1.3 Seasonal and interannual streamflow variations

Seasonal and interannual variations of streamflows (Sections 9.2 & 9.5) were almost similar to seasonal and interannual variations of rainfall. Seasonally, flow peaks correspond to rainfall peaks and occur mainly during the core of the rainy seasons. Interannually, significant unidirectional abrupt changes in mean flows have occurred mainly in the mid-1970s to early-1980 which

- significantly affected streamflows during the late summer rather than during the early summer (Table 9.2);
- led to significant reduction of streamflows in the upper Zambezi basin, Namibia and northeast South Africa (Fig 9.3);
- were observed in other areas like the upper Zambezi in which evolutive rather than abrupt changes of rainfall were identified, suggesting that slight changes in rainfall could translate into significant changes in streamflows;
- indicated little evidence of changes in the flow extremes (high and low flows) except in the upper Zambezi and Namibia (Figs 9.3d, 9.3e, 9.3f).

11.1.4 Relationships between rainfall variations and ENSO/SST

Relationships were investigated between the different types of daily rainfall events and ENSO and SST in the Atlantic and Indian Oceans. The results concluded that

- Interannual variability of southern Africa rainfall is mainly influenced by ENSO, SST in the tropical Indian Ocean and in southern Madagascar with weaker influences of other oceanic basins in the Indian and Atlantic oceans.
- ENSO influences are relatively consistent for all types of daily rainfall events; highest for light intensities, highest in early summer in the northern part of southern Africa (Tanzania) and in late summer in the western part (Table 10.1). Furthermore, the responses of southern Africa rainfall to an ENSO signal show a dipole-like effect between the northern and southern parts (Fig10.4).

- Interannual variability of light and moderate (< 20 mm) daily rainfall events is modulated by SST in the tropical Indian Ocean, while regional SST were found to show significant influences on heavy rainfall events (Table 10.2, Fig 10.5).
- The ENSO/SST-southern African rainfall associations are dynamic and underwent significant changes in the mid-1950s and in the 1970s (Figs 10.6, 10.7). The latter changes led to weaker or reversed associations, while the former generally led to strengthened associations. The reversed associations characterised mainly the early summer rainfall. Consistent positive associations between SOI and late summer rainfall in the southern part of southern Africa and decreases in SOI around the mid-1970s due to warming in the Pacific could be linked to predominantly decreasing late summer rainfall in various parts of the region.
- There is an increasing influence of the austral winter (JJA) ENSO and SST on summer rainfall in southern Africa

11.2 General conclusions

The findings on rainfall variations lead to the following general conclusions with respect to the widespread droughts and devastating floods in southern Africa and their changing characteristics:

- Daily rainfall intensities below 20 mm are dominant in the region, dominating annual amounts in the western and southern parts comprising of Namibia, Botswana, southwestern Zimbabwe and western South Africa. Warmer than average SST in the tropical Indian Ocean basin since the mid-1970s, frequent warm ENSO events since the mid-1970s and strong inverse relationships between amounts/frequencies of daily rainfall intensities below 20 mm and ENSO and SST in the tropical Indian Ocean basin point towards decreasing these type of daily rainfall events in the region. Since they account for a significant portion of annual rainfall amounts in the large part of the west and south southern Africa, they are partly responsible for the widespread droughts in these areas.
- Positive and sometimes significant relationships between daily rainfalls and SST in the surrounding oceanic basins, particularly between high rainfalls and SST in the south Madagascar basin, suggested that the unexpected observed above average

rainfall amounts in certain warm ENSO years could be attributed to the influence of SST in the surrounding basins.

- The high positive association between the high daily rainfalls and SST in the surrounding oceanic basins particularly the south Madagascar basin and the low associations between these daily rainfalls and SST in the tropical Indian Ocean suggest an important role of SST in the surrounding oceans in relation to floods. As identified in some recent studies, these basins are other sources of moisture into the region and the regional SST can be playing an important role in modulating the moisture of the air, which is advected towards the continent.

11.3 Recommendations

11.3.1 Revision of operational and forecasting hydroclimatological models

The results in this study showed significant changes in the rainfall, streamflows and rainfall-ENSO/SST relationships particularly in the 1970s. It has been a common practice to calibrate and verify parameters of the hydroclimatological models using long records. However, in southern Africa, most of the rainfall and streamflow records span the period 1950s-1990s. Therefore, the significant changes that have been identified in the 1960s through the 1970s suggest

- a revision of the operational and forecasting hydrological models that use rainfall and streamflows. Models that have been calibrated using data spanning the period of significant changes (e.g. 1960s, 1970s) should be revised by considering the pre- and post-change periods separately. The suitability of the model can be assessed by considering, for example, the pre-change period for calibration and the post-change period for verification and vice versa.
- a revision of the regional general circulation models (GCMs) that are used for operational and forecasting purposes in southern Africa. The revision may consider, for example, the separate influences of the SST in the tropical central Indian Ocean and those in the south Madagascar basin. The stability of model parameters should be investigated separately with consideration of the pre- and post-1970s periods.
- that climatological models should also take advantage of the temporal shifting of the influences of ENSO and SST.

11.3.2 Detailed hydrological studies at finer spatial scales

Results have highlighted consistent changes in both rainfall and streamflows in certain catchments like those in Namibia and western Zambia while in others it was not possible or very difficult to associate changes in streamflows with identified changes in rainfall. An example was given for Groot-Vis (Fish) River where the flow supplement from the Orange River modified this seasonal river into a perennial river. However, to accurately quantify the magnitude of the influence of rainfall changes on changes of streamflows, studies at finer spatial scales like catchment scales are recommended. The use of water balance models can assist in quantifying the influence of climate and rainfall changes on streamflows once other model components have been quantified and accounted for.

11.3.3 Studies of characteristics of short-duration rainfall events

The study has indicated the spatially and temporally varying compositions of different types of daily events in southern Africa. Light daily rainfall events dominate annual rainfall amounts in the western and southern parts while moderate and heavy daily events dominate the eastern and northern parts. This spatial variation has been linked to droughts and floods in the region. The frequent heavy daily events in central Mozambique, Malawi and northern Shire basin in the southwest highlands of Tanzania marked the respective areas as flood prone while the dominant light daily events in the western part like in Namibia indicate that the western part is the most drought prone in the region.

However, details of how the different types of daily events are related to observed hydrological droughts and floods were not investigated in detail in this study while they are necessary. Studies which will investigate different indices of flood-producing rainfall events (e.g. persistent daily events of more than 30 mm, isolated intense daily events, etc) and their relationships to different flood magnitudes, for example, are therefore encouraged.

11.3.4 Studies of the relationships between climatic factors and types of rainfall

Apart from the known influences of ENSO and SST in the tropical Indian Ocean, SST in the other oceanic basins such as the equatorial Atlantic Ocean (EAO) and the south Madagascar (MADA) basins were influencing rainfall variations in different parts of southern Africa. SST in the surrounding oceanic basins were influencing mainly the high rainfalls, the fact which needs further investigation.

11.3.5 Data availability and reliability

However, caution should be exercised in applying the results of this study. The results were hindered by the data unavailability and quality:

- The spatially uneven distribution of rainfall and flow gauging stations caused mainly by unavailability of records and excessive missing observations. No rainfall data were available for Angola, available data in most of the countries studied ended between mid-1980s and early-1990s while Mozambican data were characterised by long periods of missing observations.
- The short records used in some regions in which alternating periods of high and low rainfall or streamflows could be interpreted in relation to abrupt unidirectional changes.
- The quality of the records is not always known, as detailed information concerning the rainfall and flow gauging stations were mostly missing or only partially available.

Therefore efforts are required to improve the spatial distribution of rainfall and streamflow stations and availability of quality data. For streamflows, the emphasis will be on gauging all rivers at different points and at the most downstream points before they discharge into the oceans, lakes or wetlands. The efforts may involve i) improving collection and processing of historical data with emphasis on their quality, ii) installation of new rainfall and streamflow gauges across the region with priority given to accounting for factors like topography and iii) documenting detailed inventory of the gauges (e.g. as gauge relocation, changing techniques of measurements and for streamflows) and details of changes involving any factors that add or abstract water upstream of the gauges.

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