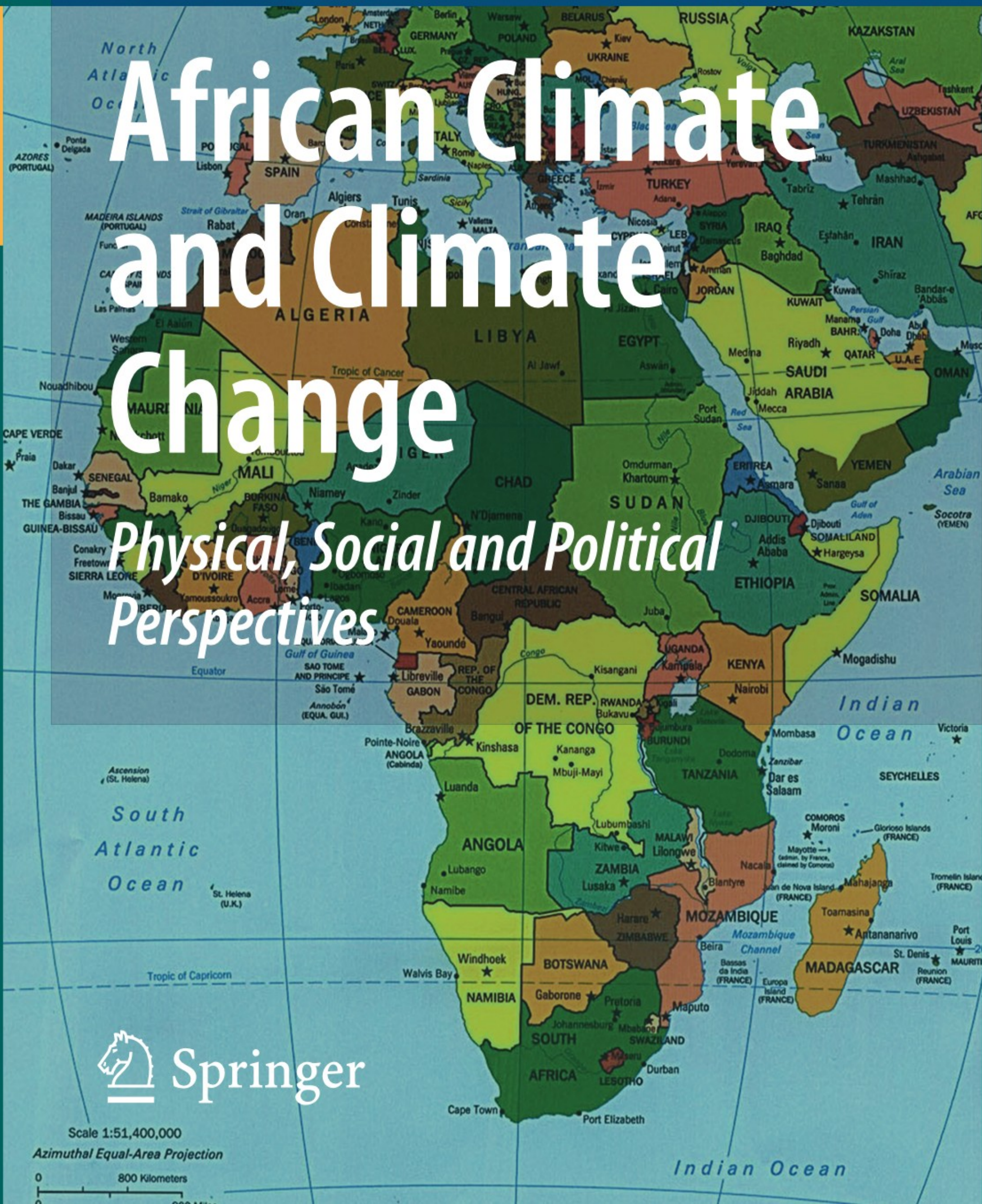
Charles J. R. Williams
Dominic R. Kniveton
*Editors*

ADVANCES IN GLOBAL CHANGE RESEARCH 43

# African Climate and Climate Change

## *Physical, Social and Political Perspectives*

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African Climate and Climate Change

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Editors

# African Climate and Climate Change

## Physical, Social and Political Perspectives

Springer

*Editors*
Dr. Charles J.R. Williams
2U18 Department of Meteorology
University of Reading
RG6 6BB Reading
United Kingdom
c.j.r.williams@reading.ac.uk

Dr. Dominic R. Kniveton
University of Sussex
Dept. Geography
Chichester 1-143
BN1 9QJ Brighton
Falmer
United Kingdom
d.r.kniveton@sussex.ac.uk

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# Contributors

**C. Ambrosino** Department of Geography, Oganization University College London (UCL), UK, c.ambrosino@ucl.ac.uk

**L. Andersson** Swedish Meterological and Hydrological Institute, Norrköping, Sweden, lotta.andersson@smhi.se

**R. Black** Sussex Centre for Migration Research, University of Sussex, Brighton, UK, R.Black@sussex.ac.uk

**E. Black** NCAS-Climate, Walker Institute for Climate System Research, University of Reading, Reading, UK, emily@met.reading.ac.uk

**Gulilat Tefera Diro** Earth System Physics Section, The Abdus Salam ICTP, Trieste, Italy; Department of Meteorology, University of Reading, Reading, UK, gtefera@ictp.it

**A. Farnsworth** NCAS-Climate, Walker Institute for Climate System Research, University of Reading, Reading, UK, a.j.farnsworth@reading.ac.uk

**D.I.F. Grimes** Department of Meteorology, University of Reading, Reading, UK, d.i.f.grimes@reading.ac.uk

**Bruce Hewitson** Department of Environmental and Geographical Science, University of Cape Town, Cape Town, South Africa, climate@csag.cict.ac.za

**D. Hughes** Institute for Water Research, Rhodes University, Grahamstown, South Africa, d.hughes@ru.ac.za

**Dominic R. Kniveton** Department of Geography, School of Global Studies, University of Sussex, Brighton, UK, d.r.kniveton@sussex.ac.uk

**R. Layberry** Environmental Change Institute, University of Oxford, Oxford, UK, russell.layberry@geog.ox.ac.uk

**L. Mileham** Department of Geography, Organization University College London (UCL), UK, l.mileham@ucl.ac.uk

**M. Murray-Hudson** HOORC, University of Botswana, Botswana, mmurray-hudson@orc.ub.bw

**Henny Osbahr** Oxford University Centre for the Environment, Oxford, UK, h.osbahr@reading.ac.uk

**S. Raghavan** University of Maryland, College Park, USA, raghavan@umd.edu

**Len Shaffrey** NCAS-Climate, University of Reading, Reading, UK, l.c.shaffrey@reading.ac.uk

**C. Smith** School of Global Studies, University of Sussex, Brighton, UK, C.D.Smith@sussex.ac.uk

**R. Taylor** Department of Geography, Organization University College London (UCL), UK, r.taylor@ucl.ac.uk

**David S.G. Thomas** Oxford University Centre for the Environment, School of Geography, Oxford OX1 3QY, UK, david.thomas@ouce.ox.ac.uk

**M.C. Todd** Department of Geography, University College London (UCL), London WC1E 6BT, UK, m.todd@geog.ucl.ac.uk

**Thomas Toniazzo** NCAS-Climate, University of Reading, Reading, UK, t.toniazzo@reading.ac.uk

**Chasca Twyman** Department of Geography, University of Sheffield, Sheffield, UK, C.Twyman@sheffield.ac.uk

**E. White** Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, OK, USA, esther.white@ou.edu

**Charles J.R. Williams** Department of Meteorology, NCAS-Climate, Walker Institute for Climate System Research, University of Reading, Reading, UK, c.j.r.williams@reading.ac.uk

**P. Wolski** HOORC, University of Botswana, Gaborone, Botswana, pwolski@orc.ub.bw

**S. Wood** School of Informatics, University of Sussex, Brighton, UK, S.Wood@sussex.ac.uk

# Introduction

**Charles J.R. Williams and Dominic R. Kniveton**

**Keywords** Introduction · Background · Climate change · Mitigation · Adaptation · Impacts · Uncertainty · Vulnerability · Options · Resilience

## 1 General Background

It is widely accepted that the trend in rising global temperatures during the twentieth-century can be attributed to anthropogenic greenhouse gas emissions, stated with 90% certainty by the most recent report of the Intergovernmental Panel on Climate Change (IPCC 2007). Even with immediate and complete mitigation of emissions, an unlikely eventuality under the current political consensus, global impacts of such increasing temperatures are unavoidable; far less certain are the regional impacts. It is generally agreed, however, that economically developing and vulnerable countries will be hardest hit, being less able to adapt to future changes in climate.

Of all developing regions, Africa (and in particular sub-Saharan Africa) is likely to be the worst affected by any present-day climate variability and future climate change. The region is the only in the world to have become poorer in the last generation (Ravallion and Chen 2004), and although it comprises only 12% of the world's population (Population Reference Bureau 2009) it accounted for 28% of the world's poverty in 2005 (World Bank 2005, Washington et al. 2006). It has been estimated that 30% of the population of sub-Saharan Africa suffers from food insecurity and extreme poverty (Balasubramanian et al. 2007). As a whole, Africa's population has recently passed the one billion mark and is expected to double by 2050 (Population Reference Bureau 2009). This population explosion, underdevelopment and poverty can be attributed to many socio-economic, political and environmental factors, one of the most important ones being an inability to adapt to extremes of climate (such as flooding and drought) which are prevalent across the continent (Washington et al.

C.J.R. Williams (✉)
Department of Meteorology, NCAS-Climate, Walker Institute for Climate System Research, University of Reading, Reading, UK
e-mail: c.j.r.williams@reading.ac.uk

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2006). Tropical Cyclones Gafilo and Eline in 2004 and 2000, respectively, highlight the sudden impacts of climate variability and extreme events on society, whereas more chronic climate extremes such as the East African and Sahelian droughts demonstrate the longer term impacts. Therefore, even under the current highly variable climate conditions, the majority of sub-Saharan Africa is unable to cope with extremes in climate (e.g. IPCC 2001, Cook et al. 2004, Segele and Lamb 2005, Washington et al. 2006). With projections of future climate change suggesting that the continent will become drier (e.g. Desanker and Magadza 2001, Hulme et al. 2001, Thomas et al. 2005) and extremes more frequent (e.g. IPCC 2007), it is clear that the situation will worsen.

Africa is considered particularly vulnerable to the effects of climate change and climate variability, relative to many other regions of the world. African society possesses a low resilience and limited adaptative capacity to climate-related shocks and stresses, because of widespread poverty, an extensive disease burden and pockets of political instability across the continent. An improved understanding of African climate change and its likely impacts cannot be gained by studying one aspect alone, thus research on the subject of African climate change requires an interdisciplinary approach linking studies of environmental, political and socio-economic spheres. However this interdisciplinary approach has, for the most part, been lacking, with scientists conducting excellent research within their own spheres but often failing to communicate and discuss their findings (and implications) to other disciplines.

This book aims to help rectify this problem. It is the outcome of a 2-day meeting held in April 2007, which was highly successful in bringing together the physical science of African climate with the social, economic and political issues surrounding climate change over Africa. Examples of the physical side of climate research included present-day climate variability and change, past climatic changes and future predictions under various scenarios of climate change, whereas examples of the socio-economic side included adaptation, food security and possible migration outcomes. In this introductory chapter, a general background to the problems facing Africa (within the context of climate variability and change) is provided. Some of the largest uncertainties over climate change, both globally and specific to Africa, are introduced in Section 2. The reasons for Africa's particularly high level of vulnerability to climate shocks and stresses are outlined in Section 3, before a discussion of the main impacts of present-day climate variability and future climate change on Africa in Section 4. An introduction to some possible options for reducing vulnerability is given in Section 5, before concluding with an outline of the rest of the book.

## 2 Uncertainty over Climate Change

Despite the IPCC's confidence in the causes of twentieth-century climate change, there remains considerable uncertainty as to how this climate change will be manifested and what will be the likely impacts on a regional scale. For African society, it is generally agreed that the availability of water is going to be critical for any future social and economic development, yet at the same time this high level of dependence on water availability (itself dependent on rainfall variability and its efficient management) is coming from a continent subject to highly variable rainfall, both spatially and temporally (Washington et al. 2006).

Furthermore, even at a global scale, of all the possible impacts of increasing global temperatures, changes in mean rainfall, rainfall variability and associated hydrological processes are the most uncertain. Although the models do agree on twentieth-century drying over Africa, there is no robust agreement in their predictions of twenty-first-century rainfall (Giannini et al. 2008). The uncertainty is demonstrated by Fig. 1, adapted from the latest IPCC Assessment Report and showing global changes in precipitation under the expected scenario of future climate change. Both increases and decreases in rainfall are projected across Africa, however the most important point of the figure is the lack of agreement between model predictions. Africa shows the least agreement between models of all the continents and, apart from relatively small regions, for the majority of Africa the models do not agree on even the sign of change, let alone its magnitude (Fig. 1).

At smaller spatial scales, such as the regional, uncertainty over climate change (and its impacts) increases further. For example, Giannini (2010) describes two mechanisms of climate change over the Sahel, both of which show surface warming but with an increase in rainfall in one and a decrease in the other. In the first scenario, increased rainfall occurs because of the increase in net terrestrial surface radiation, amplified by an increase in near-surface humidity and associated water vapour feedback (Giannini 2010). Thus surface warming is resulting in a direct rainfall change. Conversely, in the second scenario it would appear that the reverse is occurring, with rainfall and evaporation decreases occurring due to remote forcings, which therefore contributes to local land surface warming (Giannini 2010). Uncertainty over the Sahel region also varies according to what rainfall metric is used, with the models showing some agreement over changes in the length of the wet season but

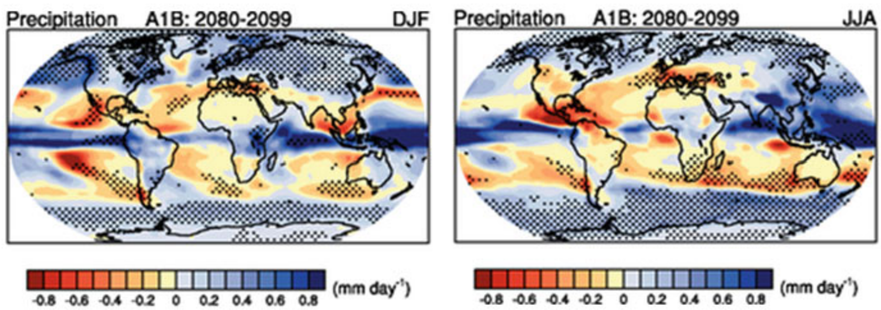


**Fig. 1** Multi-model mean changes in precipitation in mm day$^{-1}$, for DJF (*left*) and JJA (*right*). Changes are given for the SRES A1B scenario, for the period 2080–2099 relative to 1980–1999. Stippling denotes areas where the magnitude of the multi-model ensemble mean exceeds the inter-model standard deviation. Adapted from Fig. 10.9 of the IPCC Fourth Assessment Report (Meehl et al. 2007)

much less agreement in changes to total rainfall (Biasutti and Sobel 2009). There is therefore high uncertainty over future rainfall changes and thus water availability.

## 3 Reasons for Particularly High Vulnerability of Africa

As explained in Section 1, our understanding of climate variability and change and its impacts over Africa is hampered by numerous problems. These include environmental constraints, such as Africa being a region of relatively low and highly variable rainfall yet at the same time having a high dependence on rainfed agriculture (Williams et al. 2007). Of equal importance are the socio-economic factors, including technological and scientific underdevelopment exacerbated by civil war, political instability, population pressures, extensive poverty, widespread disease and the HIV/AIDS crisis (Desanker and Magadza 2001, Hudson and Jones 2002, Williams et al. 2008).

Yet, despite this high vulnerability, there remain large knowledge gaps on African climate, manifestations of future climate change and variability for the region and the associated negative impacts of climate change. There are several reasons, specific to Africa, for these knowledge gaps, the two most important being a lack of reliable data and a lack of African scientific expertise. For the former, although it is clearly agreed that understanding the climate system requires accurate, reliable, long-term and spatially distributed climate data, Africa has the worst climate-observing system of any continent and this is gradually deteriorating (Washington et al. 2004, 2006). The World Metrological Organisation (WMO) estimates that the network of World Weather Watch (WWW) stations has an average station density that is 8 times lower than their recommended level, at one station per 26,000 km$^2$ across Africa (Washington et al. 2006). The few stations that do exist are unevenly distributed, and suffer maintenance and transmission problems meaning that much of the continent is constantly unmonitored (Washington et al. 2006). The uneven distribution of observations is particularly poor for rain gauge stations, such as those of the Global Telecommunications System (GTS) network. As Fig. 2 shows, with the exception of certain countries such as South Africa and small regions of West Africa, most of the continent has either very few stations or none at all. One direct result of this is that, of the little work on climate coming out of Africa, the majority of past studies on daily rainfall variability have been mainly restricted to the relatively data-rich South Africa (Fauchereau et al. 2003, Williams et al. 2007). However, even here, institutional support and funding for climate science has been poor over the last few years compared to more developed countries (Reason et al. 2006).

The second main reason for our knowledge gaps is a lack of expertise in African climate science. Although there are several centres of excellence across Africa focusing on a number of crucial climate issues, internationally there is a relative scarcity of climate scientists from Africa and the continent has one of the lowest number of peer-reviewed publications in the world (Washington et al. 2006). This is partly due to the perception of climate science in many parts of Africa, where

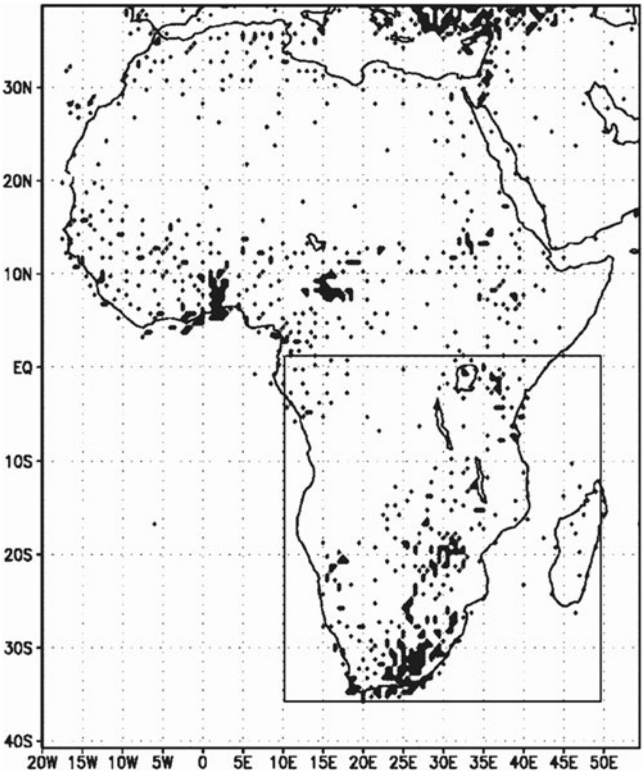


**Fig. 2** Spatial coverage of the Global Telecommunications System (GTS) rain gauge dataset from 1990 to 2000, showing cells that contain one or more rain gauges at 0.5° spatial resolution (Layberry et al. 2006)

the imperative to fund climate scientists is at times so low that scientists' salaries are well below administrators (Washington et al. 2006). Many African governments concentrate funding on other issues such as food security, education and health, and although there is clearly a pressing need for this it has often been to the detriment of scientific development. Where there is interest in climate science, it has often been focused on interannual variability and seasonal forecasting only, as data on these timescales (such as wet season start dates or dry spell length) have direct relevance for agricultural production and therefore food security (Washington et al. 2006). Whilst this is of utmost importance, it has nevertheless meant that the longer timescale at which climate change operates is seen as less immediate and therefore less important.

## 4 Expected Impacts of Climate Change on Africa

Despite the above uncertainties, and in light of Africa's high vulnerability and low adaptive capacity to climate change, there are a number of detrimental impacts on the continent which can be expected as global temperatures rise. In the following, only those impacts directly related to changing rainfall variability are discussed. Whilst other impacts are considered extremely worrying for Africa, including increasing heat stress, sea-level rise (and resultant flooding) and changes in the spatial distribution of diseases (such as malaria, dengue fever and cholera) (Boko et al. 2007), it can be argued that water stress resulting from changing rainfall patterns is of primary concern. Returning to the global scale and Fig. 1, some models suggest that during December–February (DJF) equatorial regions of Africa are expected to become wetter, with drying over the tropics and subtropics. During June–August (JJA), rainfall changes are projected to be smaller, with slightly wetter conditions over equatorial regions. These projections are made, however, within the above caveat of the lack of agreement between models, which only show consensus over eastern (southern) Africa during DJF (JJA). Socio-economic factors such as land-use changes driven by population growth, shifting cultivation and overgrazing will also worsen the large-scale impacts of climate change, with one study suggesting increased temperatures, increased heat stress and drier conditions across Africa as a result of the combined impact of increasing global temperatures and local land-use change (Bronnimann et al. 2008).

At smaller spatial scales, projections of the impacts of climate change have also been made for certain African regions, despite the uncertainty as discussed above. Southern Africa, for example, is expected to experience a decrease in total rainfall and an increase in dry spells during the wet season, both of which will negatively impact crop and livestock production and thus economic development (Twomlow et al. 2008). Projections have also been made at even smaller spatial scales, such as the country or local level. For example, experiments on the effect of increasing temperature on annual mean rainfall over the Highveld region in South Africa suggest a reduction in rainfall over this already dry and thus vulnerable region, with average agricultural yield decreasing by up to 30% as a direct consequence (Walker and Schultz 2008). In Namibia, it has been suggested that the effect of climate change on natural resources alone may cause a reduction in the economy by 5% of GDP over the next 20 years (Reid et al. 2008). Therefore, projections of how climate change may impact Africa do exist, despite the large uncertainty. What is more certain is that whatever spatial scale is used, Africa is likely to be impacted in a number of direct and indirect ways by changing rainfall patterns. For example, climate change will directly impact African society through its impact on crop yields, while indirectly it will influence migration and conflict patterns.

For many countries that already experience semi-arid conditions, changes in rainfall are expected to constrain agricultural production and therefore detrimentally impact food security. An example of this is might be a reduction in the growing season length or bringing increasing uncertainty into wet season start dates. Agricultural yield in some countries is projected to fall by 50% by 2020 and overall crop revenue might decrease by 90% by 2100 (Boko et al. 2007). Because of their low adaptive capacity, small-scale farmers are likely to be the worst affected by these decreases in revenue (Boko et al. 2007). Water stress will also significantly worsen for countries that are already stressed (and will become a risk for the others), with several countries projected to exceed the limits of their usable water resources before 2025 even under current conditions (Boko et al. 2007). Currently, approximately 25% of Africa's population experiences pressure from water availability and accessibility, and this water stress is projected to increase to between 40 and 75% of the population by the 2050s (Boko et al. 2007). This, as has been demonstrated in the past, will undoubtedly worsen both national and international conflict, as countries and societies compete for access to diminishing water supplies. In addition to the large human cost, Africa's ecosystems (such as forest, grassland and marine) will also be detrimentally impacted by this increased water stress, with changes already being detected in certain areas (Boko et al. 2007).

Not all regions are expected to become drier with increasing global temperatures, with expectations that parts of eastern Africa will experience an increase in rainfall (IPCC 2007). However these regions are expected to experience different but equally challenging problems such as flooding, a shift in wet season length and duration, and the destruction of crops because of unpredictable and increasingly erratic rain. Water stress, resulting from either increasing or decreasing rainfall changes, is therefore likely to become a key issue for both human and environmental systems. There are, however, several options for adapting and reducing vulnerability to climate variability, and although it is recognised that these adaptations may not be sufficient to cope with future changes, they are still nevertheless being developed to address current concerns (Boko et al. 2007).

## 5 Options for Reducing Vulnerability

In order to reduce vulnerability to future climate change, it is evident that adaptation to current climate variability (to reduce vulnerability to present-day climate extremes) is important. Thornton et al. (2006) go further, stating that adaptation is not an option but a necessity for many African countries. It is clear that, in terms of adaptation strategies, there is a distinction between the timescales of climate variability and climate change, with the former receiving the most priority in many African weather and climate centres. There is clearly a need to focus on the climate variability timescale, not least because it is likely that climate change will be partly manifested by a change in the frequency of extreme events currently experienced within present day climate variability (Washington et al. 2006). Lessons can be learnt on how the most vulnerable (usually the rural poor) currently adapt to this variability, and these lessons can then be used to assist in further adaptation to future climate change (Twomlow et al. 2008). Although climate variability and climate change are often seen as separate issues, it is recognised that the two can be bridged, with adaptation to the immediate impacts of climate variability being vital in preparing for the longer term impacts of climate change (Washington et al. 2006). In this way, successful management of shorter term climate variability provides a win–win outcome, by reducing vulnerability both now and in the future. At the same time, however, it is acknowledged that it would be shortsighted to only focus on short-term adaptive capacity, such as immediate responses to climate shocks and uncoordinated or isolated adaptation projects (Sachs 2005).

Adaptation often occurs spontaneously within a society rather than being imposed and managed by governmental policy or another institution (Washington et al. 2006). For example, adaptation to drought often takes the form of evasion, whereby farmers move their livestock on a seasonal basis to exploit the best resources at the appropriate time of year (O'Farrell et al. 2009). However, the extra adaptation needed to cope with future climate change needs to be managed and planned. If properly managed and embedded within civil and political rights, adaptation has been shown to be both successful and sustainable (Brooks et al. 2005). Thus adaptation measures and strategies have already been adopted by many African nations, summarised below. In the following, adapted from Table 9.2 from the IPCC's Fourth Assessment Report (Boko et al. 2007 – see original table for full list of authors), adaptation practices have been divided into those providing social and economic resilience.

1. Social resilience

- *Social networks*
  - Networks of community groups created, depending on the perception of risk, which itself determines the type of adaptation
  - Local saving schemes created, where possible, and subsequently used during times of climate stress
- *Institutions*
  - Institutional support recognised as vital in informing policy to improve resilience, however if not properly managed has danger of constraining adaptive capacity

2. Economic resilience

- *Equity*
  - Needs to be viewed on several scales such as locally (e.g. between communities) and globally/regionally (e.g. Clean Development Mechanisms). Again, if not properly managed, interventions to enhance community resilience can cause reductions in equity
- *Diversification of livelihoods*
  - For example – agricultural diversification and intensification, based on increased livestock, using natural fertilisers, soil conservation techniques, etc
- *Technology*
  - For example – technological improvements to current farming systems, via adaptation measures such as water-harvesting systems, dam building, water

conservation, drip irrigation, development and use of other crop types such as drought-resistant varieties, etc
    - Development, production and most importantly successful dissemination and use of improved seasonal forecasting

- *Infrastructure*

    - For example – improvements in physical infrastructure (such as road, rail and communication networks) to allow better exchange of information

In terms of providing climate information, one of the more important examples above is the improvement of early warning systems of extreme weather events, at short timescales such as seasonal, monthly, daily and even hourly. However successful early warning systems require a good understanding of the processes that control climate variability, which requires reliable and well-distributed observational data which, as discussed above, are seriously lacking across Africa. A further constraint for many, if not all, of the above adaptation strategies is the cost, both to initially set up the scheme and then sustainably maintain it (Boko et al. 2007). These costs need to be balanced against the potential costs resulting from climate change impacts with *no* adaptation, despite the challenges in doing so (Yohe and Schlesinger 2002). Therefore, whilst adaptation measures are clearly needed to reduce vulnerability to both current climate variability and future climate change, their implementation is not straightforward and further interdisciplinary work is required.

## 6 Structure of Book

Despite the relative lack of attention previously given to African climate science, this is starting to be addressed and this book provides a number of examples showing how we can improve our knowledge of current African climate, future African climate change and its potential impacts. In this book we use several case studies of climate variability and change in Africa, to illustrate different approaches to the study of African climate from across the spectrum of physical, social and political sciences. In doing so we attempt to highlight a toolbox of methodologies, along with their limitations and advantages, that may be used to further the understanding of the impacts of climate change in Africa. In turn, this will help form the basis for strategies to reduce the negative impacts of climate change. Despite focusing on Africa, the methodologies illustrated in this book can be extended to other countries and regions, and provide a basis for a framework for understanding climate change globally and its impacts on society in general.

As discussed above, our knowledge of African climate and associated processes relies on a selection of in situ and remotely sensed climate data, reanalysis data and climate models. One of the first steps is to understand the processes occurring over regions of Africa, and ascertain the uncertainty or knowledge base on climate in the region. Using Ethiopia as a case study, Chapters 2 and 3 give an example of this, using observational/reanalysis and climate model-generated data respectively.

The next stage in the process is to try and identify potential controls on climate, as shown by Chapters 4 and 5 which focus on southern and central Africa respectively. An examination of the expected impacts of climate variability and change on hydrology across Africa is then given in Chapter 6, before focusing on the sensitivity of social-ecosystems to changes in climate and possible adaptation strategies in Chapter 7. Finally, the impact of climate change (and also resultant adaptation measures) on African society is addressed, by focusing on the effect of climate change on migration in Chapter 8. In examining the impacts of climate change, two different methodologies are shown: (i) one of scenario modeling, where scenarios of climate change are fed through a series of hydrological and ecological models to assess the potential impacts (Chapter 6); and (ii) one of sensitivity testing, whereby a model of migration decision-making (in the face of climate change) is used to test the sensitivity of migration flows to different climate changes (Chapter 8). The former of these provides useful starting points for discussions over future developments of the affected systems. While less immediately usable by stakeholders, the latter of these approaches attempts to deal with the uncertain and dynamic nature of climate change prediction and promote an adaptation pathway of building resilience. The chapters on impacts also illustrate different methodologies to explore social and physical impacts of climate change, but share the premise of being developed using process-driven theory in order to more accurately represent change which, in the case of climate change, is likely to be outside of that already experienced.

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# Large Scale Features Affecting Ethiopian Rainfall

**Gulilat Tefera Diro, D.I.F. Grimes, and E. Black**

**Abstract** In this chapter we will discuss the large scale atmospheric and oceanic features associated with the long (Kiremt) and the short (Belg) rainy seasons. Considering the spatial variability of rainfall, the analysis was carried out for each homogeneous rainfall zones separately. Composite analyses on selected variables (wind, humidity, geopotential heights and sea surface temperature (SST)) from ERA-40 and HadISST reanalysis dataset were done based on excess/deficit seasonal total rainfall events. The result shows that during the Kiremt rainy season the large scale features associated with anomalous rains are the tropical easterly jet (TEJ), African easterly jet (AEJ), Quasi Biennial Oscillation (QBO), inter tropical convergence zone (ITCZ), East African Low Level Jet (EALLJ), Azores high, humidity anomaly over Red Sea and Gulf of Guinea and low level wind anomalies from Atlantic and Indian ocean to Africa and ENSO. Similarly for the Belg rainy season the large scale features associated with rainfall anomalies are the subtropical westerly jet (STWJ), ITCZ, ENSO, Arabian High, humidity anomaly over eastern Africa and low level wind anomalies from the Indian and Atlantic Ocean.

**Keywords** Ethiopia · Rainfall · Composite analysis · Large-scale features · Atmospheric circulation · Oceanic circulation · Jets · SST · QBO

## 1 Introduction

Ethiopia is situated in the Horn of Africa. It has complex topography, with altitudes ranging from hundreds of metres below sea level in the north east to over 4,000 m above sea-level in the northern highlands as shown in Fig. 1. The Ethiopian highlands are thought to be an important factor for the rainfall pattern over Ethiopia.

G.T. Diro (✉)
Earth System Physics Section, The Abdus Salam ICTP, Trieste, Italy; Department of Meteorology, University of Reading, Reading, UK
e-mail: gtefera@ictp.it

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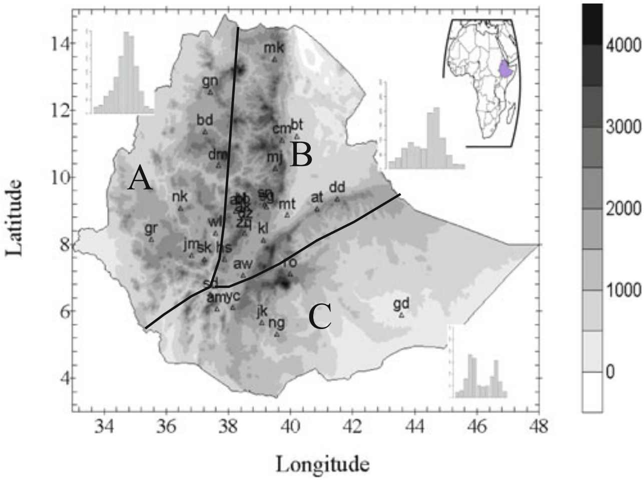


**Fig. 1** Location, topography (in meters) and Rainfall regimes in Ethiopia. The small triangles represent the stations used in this study. The histograms are climatological monthly rainfall (January – December) averaged over the rainfall regimes A, B and C. (after Diro et al. 2009)

For instance the rainfall is generally higher over the highlands than over the lowlands. An idealised study by Slingo et al. (2005) using the atmosphere only GCM (HadAM3) forced with observed SST confirms the influence of the East African highlands on central and eastern Africa rains. They found that the rainfall over central and eastern Africa is systematically enhanced in all seasons by the presence of the East African Highlands.

Understanding the characterstics of Ethiopian rainfall is crucial because of its huge impact over the Ethiopian economy. For instance Fig. 2 shows how the GDP follows the rainfall pattern over Ethiopia, especially during the 1984 and 1990 dry years.

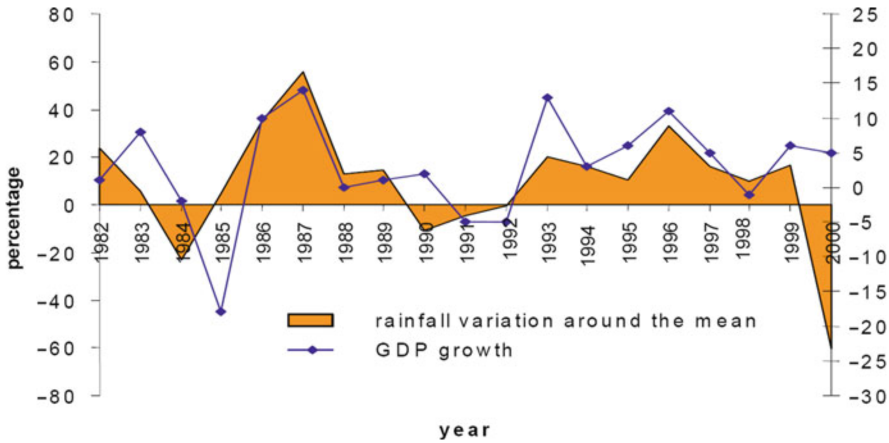


**Fig. 2** Rainfall variability and GDP in Ethiopia (after Grey and Sadoff 2005)

The overall aim of this chapter is to understand the mechanisms behind the atmospheric and oceanic parameters that controls the Ethiopian rainfall anomalies at a seasonal time scale. This of particular relevance because previous studies (for example Gissila et al. 2004, Diro et al. 2008) have shown that seasonal forecasting systems based on oceanic teleconnections have skill.

This chapter starts with the description of the data methodologies used in the analysis. The large scale features associated with Kiremt (June–September) and Belg (February–April) rainfall anomalies will be discussed in Sections 3 and 4 respectively. Section 5 will discuss about the spatial variability and non-linearity in the process. Finally a summary and conclusions will be given in Section 6.

## 2 Data and Methods

### *2.1 Data*

The type of data used in this study are rain gauge data over Ethiopia, global atmospheric reanalysis fields (except for precipitation) from ERA-40, and Sea Surface temperature (HadISST) from UK Met Office Hadley Centre.

#### 2.1.1 Rain Gauge Data

The rain gauge data used in this study are the same as in Diro et al. (2008). i.e. 45 stations covering a period of 35 years (1969–2003). The data have been rigorously quality controlled for missing data and outliers (see Diro et al. 2008).

Clustering the Gauge Data into Homogeneous Rainfall Zones

As the rainfall over Ethiopia exhibits high spatial variation, it is necessary to divide the country into homogeneous rainfall zones. There are different ways of doing this. Many studies (e.g. Dyer 1975, Ehrendorfer 1987) have used principal component analysis for the reduction of the dimensionality and for grouping of station into homogeneous clusters. When the spatial variation of rainfall is complex and the first few principal components account for only a small percent of the variance then the reduction in dimensionality by this method does not work well for delineation of zones (Gadgil et al., 1993). Therefore an alternative method has been developed for Ethiopia involving comparison of the annual cycles and the interannual variability. The methodology is explained in detain in Gissila et al. (2004) and Diro et al. (2008) and described here briefly. The first criterion to identify homogeneous rainfall zones is to group gauges which show similar annual cycles. Based on this criterion six zones were identified.

The second criterion is based on the interstation correlation both within and across the different zones. In this method, zone boundaries were adjusted to ensure that the mean interstation correlation within each zone was higher than the mean

**Table 1** Kiremt mean inter-station correlation within and across zones

| Kiremt | ZoneI | ZoneIIa | ZoneIIb | ZoneIII | ZoneIV | ZoneV |
|---|---|---|---|---|---|---|
| ZoneI | **0.26** | 0.16 | 0.02 | 0.16 | 0.16 | −0.06 |
| ZoneIIa | 0.16 | **0.24** | 0.15 | 0.15 | 0.14 | 0.05 |
| ZoneIIb | 0.02 | 0.15 | **0.33** | 0.16 | 0.13 | 0.08 |
| ZoneIII | 0.16 | 0.15 | 0.16 | **0.25** | 0.17 | −0.08 |
| ZoneIV | 0.16 | 0.14 | 0.13 | 0.17 | **0.31** | −0.06 |
| ZoneV | 0.06 | 0.05 | 0.08 | −0.08 | −0.06 | **0.14** |

Note: bold values indicates statistical significance

**Table 2** Belg mean inter-station correlation

| Belg | ZoneI | ZoneII | ZoneIII | ZoneIV | ZoneV |
|---|---|---|---|---|---|
| ZoneI | **0.50** | 0.30 | 0.10 | 0.21 | 0.09 |
| ZoneII | 0.30 | **0.36** | 0.19 | 0.21 | 0.11 |
| ZoneIII | 0.10 | 0.19 | **0.51** | 0.44 | 0.27 |
| ZoneIV | 0.21 | 0.21 | 0.44 | **0.50** | 0.26 |
| ZoneV | 0.09 | 0.11 | 0.27 | 0.26 | **0.40** |

Note: bold values indicates statistical significance

interstation correlation with any other zone. The interstation correlations are shown shown in Table 1 and 2.

The final homogeneous rainfall zones (as defined by these criteria) for the Kiremt and Belg rainy season are shown in Fig. 3. Six homogeneous rainfall zones for Kiremt and five zones for Belg are identified. Time series for each zone are obtained by taking the average of stations within Zone. If the number of missing stations within a zone for a given year is greater than 50% then it is regarded as a missing year.

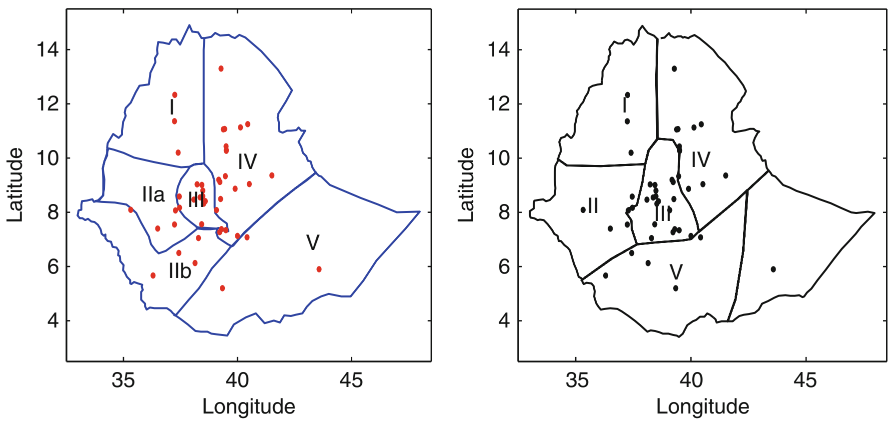


**Fig. 3** Homogeneous rainfall zones for Kiremt (*left*) and Belg (*right*) seasons

#### 2.1.2 Other Data

ERA-40 re-analyses covering 1969–2001 were used for this study. The reanalysis fields include wind (horizontal and vertical), humidity and geopotential height. More information on ERA-40 can be found in Uppala et al. (2005). **Had**ley Centre Global Sea **I**ce and **S**ea **S**urface **T**emperature (HadISST) version 1.1 (Rayner et al. 2003) covering a period 1968–2003 were used. This product is monthly means with a resolution of $1^{\circ} \times 1^{\circ}$.

### *2.2 Methods*

The purpose of this chapter is to investigate the mechanisms that give rise to rainfall in Ethiopia. The main method used focuses on the composite mean anomalies computed on selected variables from ERA-40 data based on samples of extreme rains over 1969–2001 (the common years for the gauge and ERA-40 data). Composites can be viewed as climatology based on specified conditions (Achtor and Horn 1986). Composite analysis was used to summarize the large scale atmospheric features for the two extreme cases (excess and deficit rainfall years). Composite analysis has advantages over individual case studies because compositing emphasises commonly occurring features while smoothing more random fluctuations. Composite analysis is also better than correlation because it allows the study of non linearity. However it has disadvantages if the atmospheric fields considered vary substantially between events. A set of extreme (excess/deficit) seasonal total rainfall events have been selected for each homogeneous rainfall zones. Excess years are the five wettest years and deficit years are the five driest years. The Student's t-test was used to compare the means of the different composites on each grid points. A 0.1 significance level was used to reject the null hypothesis that the difference in the means is equal to zero. The significance test is used here only as a guidance because of the small dataset. The composite analyses have been done for Kiremt and Belg rainy seasons and the large scale features affecting the rainfall during these two seasons are discussed in the following sections. The anomalous dry and wet-rainfall years for the period (1969–2001) are shown in Tables 3 and 4 for Kiremt and Belg season respectively.

## 3 Large Scale Features Associated with Kiremt Rainfall Anomalies

According to the published literature Kassahun (1987), Grist and Nicholson (2001), Nicholson and Grist (2003), Asnani (2005), Camberlin (1995, 1997), Segele and Lamb (2005), the phenomena most likely to control the rainfall during Kiremt season are Tropical Easterly Jet (TEJ), Inter Tropical Convergence Zone (ITCZ), East African Low Level Jet (EALLJ), westerly wind from Atlantic, Azores High and humidity anomaly over Red Sea. Below is a discussion of how the large scale features affect the homogeneous rainfall zones.

**Table 3** Excess and deficit Kiremt rainfall years selected for composite analysis for each zone

| Zone | Deficit years | Excess years |
|---|---|---|
| I | 1982 | 2001 |
| | 1987 | 1975 |
| | 1997 | 1974 |
| | 1992 | 1990 |
| | 1983 | 1973 |
| IIa | 1997 | 1988 |
| | 1982 | 1998 |
| | 1980 | 1973 |
| | 1969 | 2001 |
| | 1995 | 1970 |
| IIb | 1993 | 1970 |
| | 1985 | 1973 |
| | 1999 | 1981 |
| | 1990 | 1996 |
| | 1991 | 1974 |
| III | 1987 | 1996 |
| | 1982 | 1978 |
| | 1986 | 1993 |
| | 1983 | 1970 |
| | 1976 | 1992 |
| IV | 1987 | 1999 |
| | 1984 | 1994 |
| | 1982 | 1988 |
| | 1972 | 1998 |
| | 1991 | 1986 |
| V | 1993 | 1976 |
| | 1969 | 1981 |
| | 1990 | 1983 |
| | 1995 | 1975 |
| | 1973 | 1984 |

### *3.1 Upper Level Tropospheric Wind and Tropical Easterly Jet (TEJ)*

The TEJ is a band of strong easterlies with a core around 150 mb extending from south East Asia across the Indian ocean and Africa as shown in Fig. 4. The development of the TEJ is related to the thermal wind pattern during the northern hemisphere summer (Hastenrath 1990). Related to the jet stream is the rainfall distribution, which is indicative of the vertical motion pattern in the lower troposphere. Air is accelerated into the jet and decelerated as it leaves the jet. This induces ageostrophic motion at the jet entrance and exit because of the imbalance between pressure gradient and Coriolis forces as shown in Fig. 5. At the jet entrance air is being depleted from the right hand side of the jet and is accumulated on the left hand side, leading to divergence and convergence in the right and left side of the jet respectively. From the Dines compensation model (Petterson 1969) it can be shown that at lower levels the air should be ascending and pressure decreasing to the right

**Table 4** Excess and deficit Belg rainfall years selected for composite analysis

| Zone | Deficit years | Excess years |
|---|---|---|
| II | 1988 | 1983 |
| | 1977 | 1992 |
| | 1999 | 1993 |
| | 1984 | 1969 |
| | 1973 | 1996 |
| III | 1999 | 1981 |
| | 1973 | 1983 |
| | 1994 | 1986 |
| | 1984 | 1969 |
| | 2000 | 1987 |
| IV | 1973 | 1995 |
| | 1999 | 1989 |
| | 1992 | 1990 |
| | 2000 | 1993 |
| | 1997 | 1987 |
| V | 1997 | 1970 |
| | 2000 | 1979 |
| | 1999 | 1982 |
| | 1973 | 1980 |
| | 1984 | 1981 |

(north) of the jet stream entrance and left (south) of the jet stream exit at low level. This ascending air is likely to induce rainfall.

In Fig. 6, except for zone IIb (southwest), it can clearly be seen that there is a strong easterly wind anomaly at 200 mb in excess rainfall years composites and a westerly anomaly in deficit rainfall composites around a latitudinal band of 7° N–20° N starting from south Asia to Africa. This suggests that a stronger TEJ is

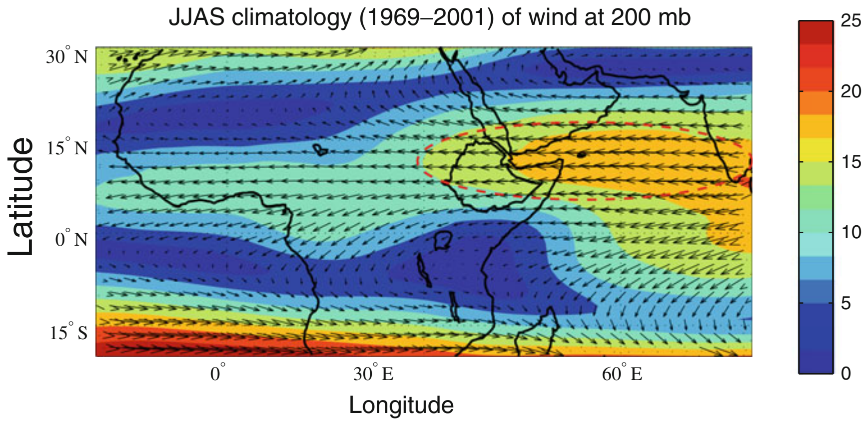


**Fig. 4** Kiremt (JJAS) climatological wind at 200 mb. The filled contour represents the magnitude of the wind speed (m/s) and the vectors indicate the direction. The broken lines indicates the location of maximum wind speed region of TEJ

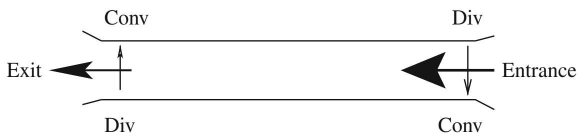


**Fig. 5** Schematic diagram of jet stream and the associated area of cyclonic and anticyclonic regions

associated with excess rainfall and a weaker TEJ with deficit rainfall. The physical link between the TEJ and rainfall may be the upper level divergence associated with the jet stream, which could enhance the rainfall by promoting ascent at lower level beneath the jet core (Grist and Nicholson 2001). For zone IIb (the southwest), deficit rainfall is associated with a strong TEJ but it is not clear why this is so. The result for other zones agrees with the study of Segele and Lamb (2005), where they found strong (weak) jet is associated with short (long) dry spells in the Kiremt season over central Ethiopia. This may be due to a frequent appearance of stronger TEJ events during the Kiremt season. In addition to the zonal wind anomaly, there is a meridional wind anomaly at 200 mb associated with excess/deficit rainfall. Northerly (north-easterly wind) is associated with excess rainfall and southerly (south-westerly wind or south-easterly wind for zoneIIb) is associated with deficit rainfall (Fig. 6). This makes sense if we associate it with the Hadley circulation (the moist low level southerly and upper level northerly will enhance the Hadley circulation and induce more rainfall over Ethiopia).

## *3.2 Stratospheric Influence - Quasi Biennial Oscillation (QBO)*

Reed et al. (1961), Veryard and Ebdon (1961) showed that the lower stratospheric wind above the equator changes on average every 26 months between easterly and westerly. These westerly and easterly regimes propagate vertically down ward as time progresses. This oscillation of wind from easterly to westerly is known as the Quasi Biennial Oscillation (QBO). The QBO is characterised by an alternating pattern of eastward and westward wind regimes in the lower equatorial stratosphere that repeat at an interval varying from 22 to 34 months with an average period of 28 months (Takahashi and Holton 1991). Holton and Tan (1980) suggested that successive regimes of westerlies and easterlies propagate downward at an average rate of about 1 km/month but with the westerly shear zone descending more rapidly and more regularly than the easterly shear zone. The oscillation is observed to have an approximate Gaussian distribution in latitude, with the maximum amplitude at the equator.

The Equatorial QBO is a non-linear Oscillation produced by vertical transfer of momentum by Kelvin and Rossby-gravity waves (Lindzen and Holton 1968, Holton and Lindzen 1972, Plumb 1977). The equatorially trapped Kelvin waves provide the westerly momentum and the Rossby-gravity waves are important for easterly momentum (Takahashi and Holton 1991).

Although these phases of the QBO are associated with excess and deficit rainfalls over Ethiopia, they are significant only for the west and south west parts of the

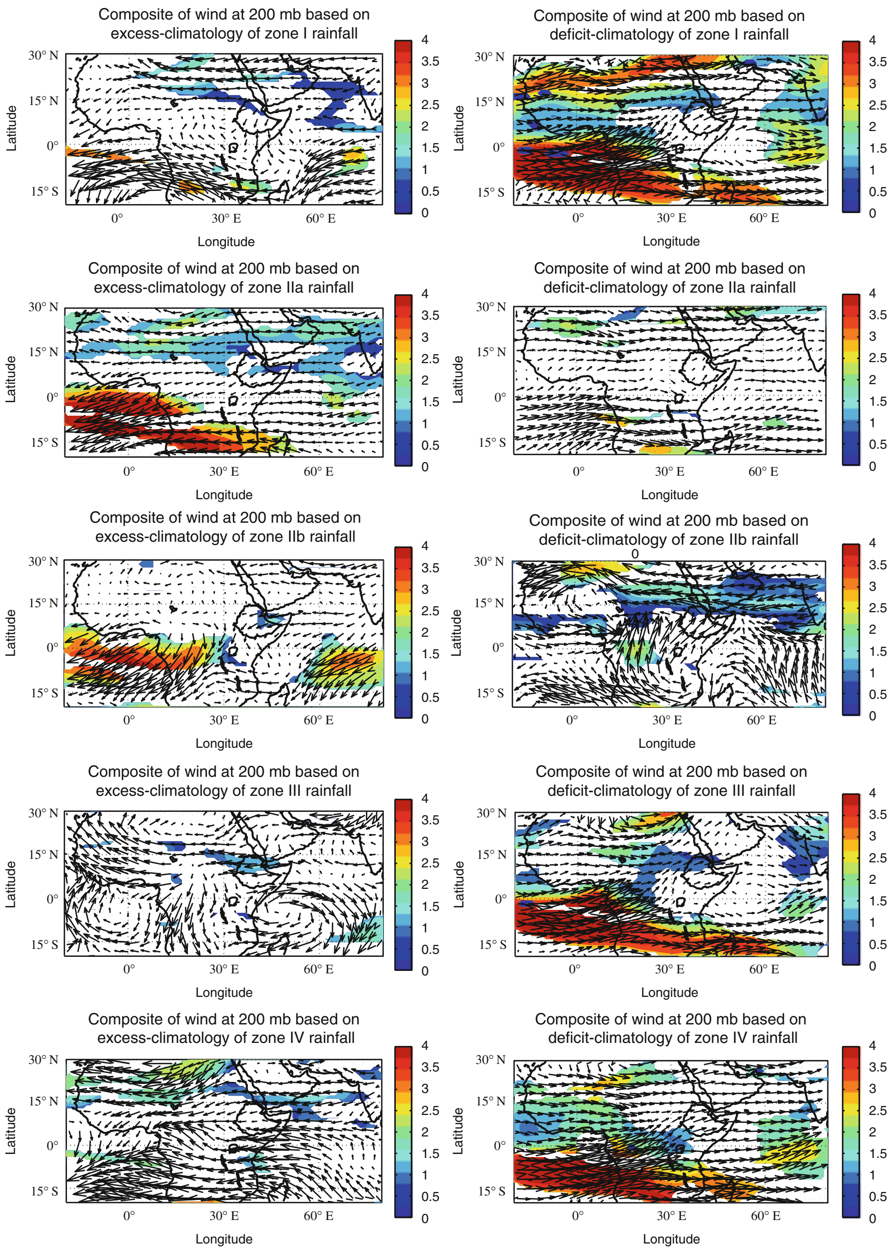


**Fig. 6** Kiremt (JJAS) wind at 200 mb for excess-climatology (*left*) and deficit-climatology (*right*). The arrows indicate the direction of the wind anomaly and the filled contours represent the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

country (zones IIa and IIb). Strong positive zonal wind anomalies in the stratosphere (westerly phase of QBO) are associated with deficit rainfall years as shown in Fig. 7. The easterly phase of the QBO is associated with excess rainfall, however, this is not as strong as the deficit year composites. For these regions (zones IIa and IIb) the low level flow is predominantly westerly. During the easterly phase of the QBO the zonal circulation (which is westerly at low level and easterly aloft) becomes strong and this enhances the westerly influx of moisture from Atlantic and hence gives rise to above normal rainfall. During the westerly phase of the QBO, the zonal circulation becomes suppressed (because the low level westerly is not accompanied by an upper level easterly) leading to a weaker westerly influx of moisture from the Atlantic at low level (see Fig. 13 of Zone IIb), and in turn to a deficit in rainfall. For equatorial Africa, the association between rainfall and the QBO is documented for the long rains (MAM) by Indeje and Semazzi (2000). They found that in the absence of a strong El Niño, the westerly phase is associated with excess rainfall and the easterly phase with below normal rainfall. This implies that the westerly phase of the QBO is associated with deficit rainfall in summer and excess rainfall in spring season. This is due to the fact that for northeast Africa the structure of the mean low level wind is easterly in spring and westerly in summer.

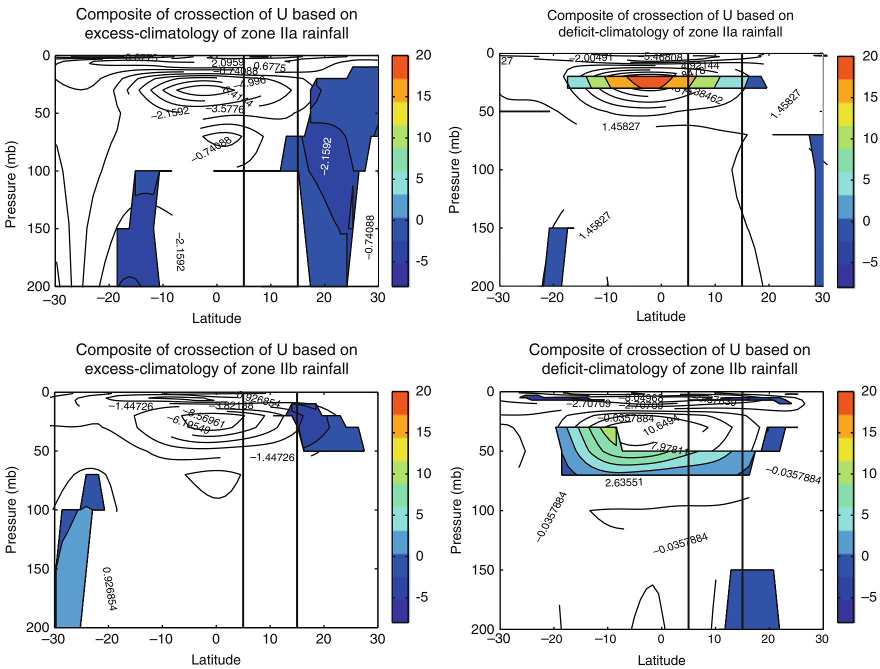


**Fig. 7** excess-climatology (*left*) and deficit-climatology (*right*) composites of cross sections of zonal wind speed (m/s) during Kiremt season. The filled contour represents significant at 0.1 level

## 3.3 African Easterly Jet (AEJ)

The African Easterly Jet is a mid-tropospheric jet (at around 600 mb in ERA-40 data) located over tropical north Africa during northern hemisphere summer (Fig. 8). Cook (1999) suggested that the AEJ over west Africa during the northern hemisphere summer is formed as a result of the strong meridional soil moisture gradients, whereas Thorncroft and Blackburn (1999) suggested that AEJ is maintained by two diabatically forced meridional circulation patterns: The circulation associated with the dry convection in the Saharan heat low regions; and the one associated with deep moist convections in the ITCZ. Burpee (1972) showed that the AEJ is both barotropically and baroclinically unstable resulting in easterly waves which grow at the expense of the jet. This implies that the observed AEJ results from the combination of the diabatically forced meridional circulation that maintains it, and the easterly waves that weaken it (Thorncroft and Blackburn 1999). The vertical shear associated with the jet are crucial in organizing moist convection and the generation of squall lines, whereas the vertical and horizontal shears together are important for the growth of easterly waves (Thorncroft and Blackburn 1999).

For most parts of Ethiopia, rainfall anomalies are associated with a north-south displacement of the AEJ. A southward displacement occurs in deficit rainfall years and northward displacement in excess years, as can be seen by the dipole structure north and south of 15° N over northeast Africa (Fig. 9). Generally, positive zonal wind anomalies over Ethiopia (less easterly) at 600 mb are associated with excess rainfall and negative anomalies with deficit rainfall. This association of a north-south shift in the jet with excess and deficit rainfalls is also witnessed over west Africa and documented by Grist and Nicholson (2001), Yeshanew and Jury (2007). The mechanism by which the African Easterly Jet affects rainfall is by creating divergence of moisture below the level of condensation (Cook 1999), and hence a decrease in the rainfall. The latitudinal cross section of vertical wind speed ($\omega$)

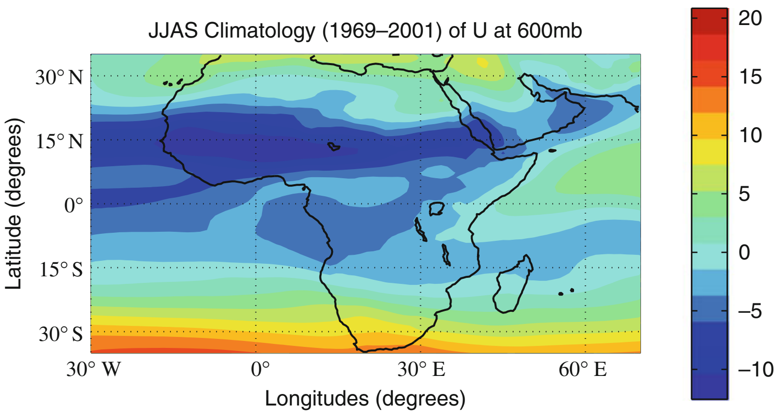


**Fig. 8** Kiremt (JJAS) climatological zonal wind speed (m/s) at 600 mb. Negative values indicate easterly winds

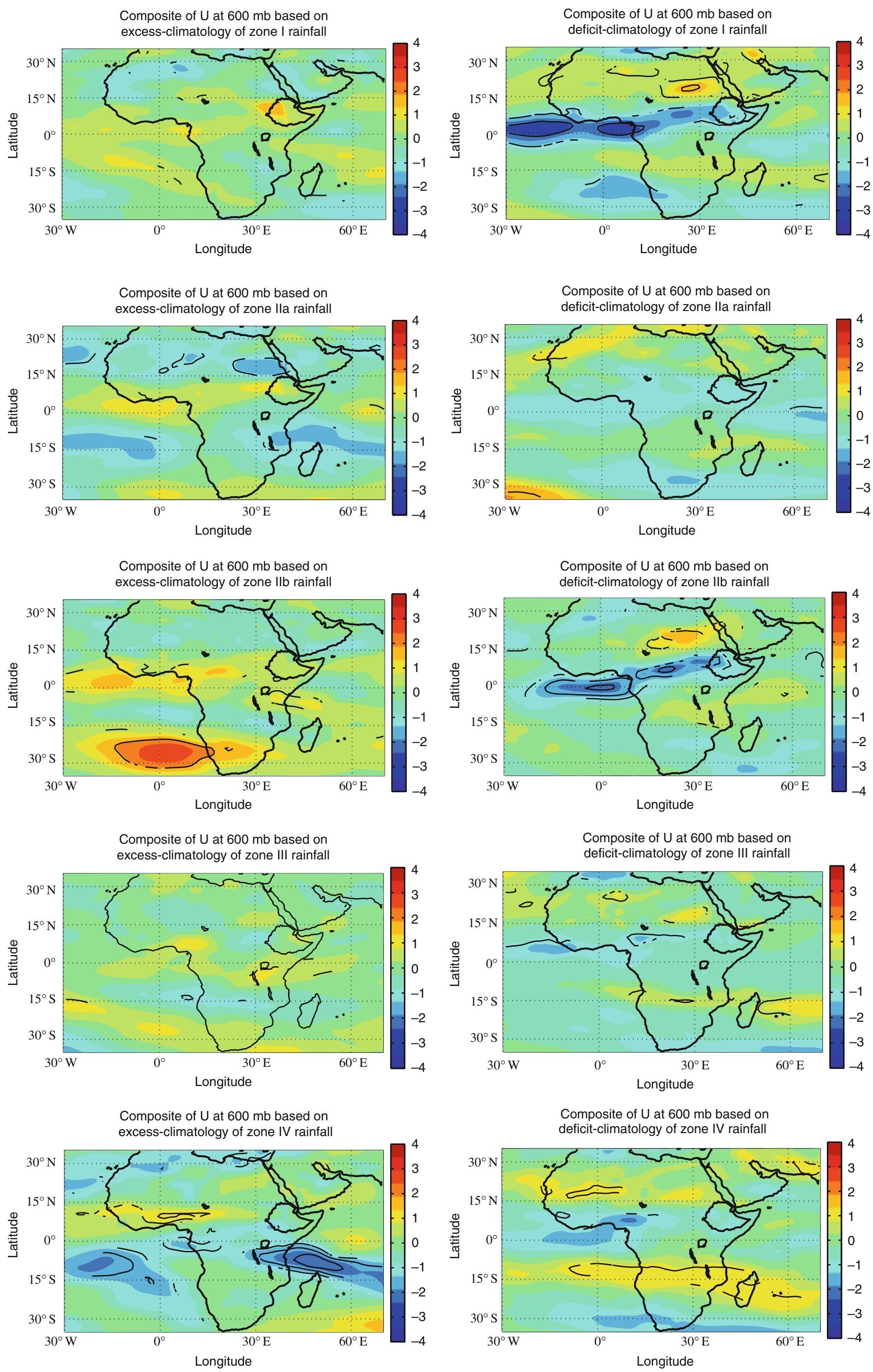


**Fig. 9** Composite plot of zonal wind speed (U) in m/s at 600 mb for excess-climatology (*left*) and deficit-climatology (*right*). The contour lines represent significance at 0.1 level

also shows a shift in the region of divergence, creating a dipole structure below the 600 mb level (Fig. 11). This suggests that the shift in the location of the AEJ is associated with a shift of the region of moisture convergence (ITCZ) at lower levels.

## *3.4 Inter-Tropical Convergence Zone (ITCZ)*

In Africa, the ITCZ oscillates annually between an extreme northward location of 15° N in July and an extreme southward location of 15° S in January (Asnani 2005). The passage of the ITCZ give rise to a bimodal rainfall pattern in southern Ethiopia (MAM (Belg) and OND), and a monomodal pattern in the northern Ethiopia (JJAS). Additionally in East Africa, there is a meridional arm of the ITCZ due to the difference in heat capacity of the land surface and the Indian Ocean. This produces rainfall over the south west of Ethiopia (zone IIb) in February/March even though the main ITCZ is still in the southern hemisphere (Kassahun 1987).

The ITCZ shows an interannual variation in location and strength. For the northeastern part of Ethiopia excess/deficit rainfall years are associated with northward/southward displacement of the ITCZ.

For the western part of Ethiopia, deficit rainfalls are associated with an east-west dipole in the mid-tropospheric ITCZ anomaly over Africa (Fig. 10 top). An active ITCZ over East Africa and the Red Sea is associated with excess rainfall; conversely a weak ITCZ is associated with a deficit rainfalls. For the eastern part of Ethiopia (zone IV), the mid tropospheric ITCZ shows a N-S dipole as can be seen from the vertical wind anomaly structure at 500mb in Fig. 10 (bottom), with deficit rainfall associated with southward displacement of the ITCZ. The latitudinal cross section

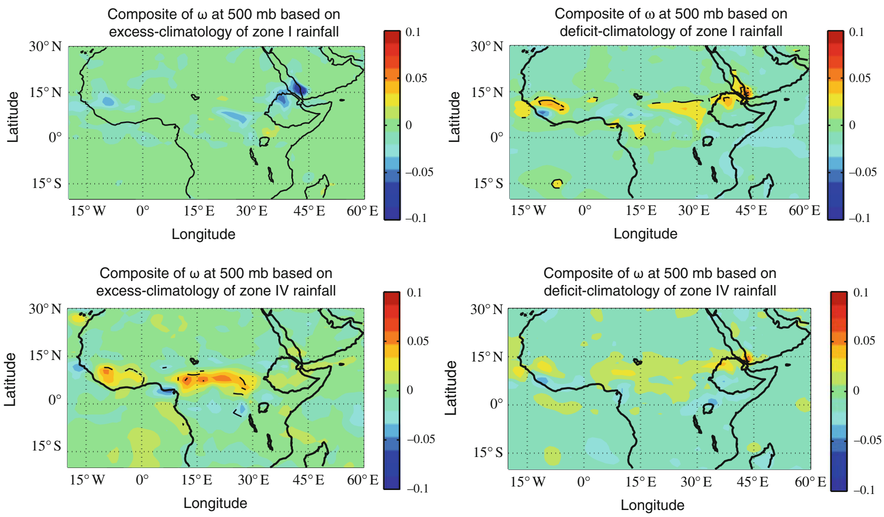


**Fig. 10** Composite plot of vertical wind speed ($\omega$) in Pa/sec at 500 mb for excess-Climatology (*left*) and deficit-climatology (*right*). The contour lines represent significance at 0.1 level. Negative value means upward motion

of vertical wind $\omega$ shows that, for most of the country, a north-south dipole occurs below 600 mb (as shown in Fig. 11) which may be associated with the north-south displacement of the AEJ. For the eastern part of Ethiopia (Zone IV) both below and above 600 mb, it shows north-south displacement.

### 3.5 Low Level Humidity

The composites of humidity based on excess/deficit rainfall identify two important locations: the Red Sea and the southeast Atlantic. For the western half of Ethiopia, a positive humidity anomaly over the Red Sea is associated with excess rainfall as shown in Fig. 12. The low level westerly wind from the Atlantic may be responsible for the humidity anomaly over southeast Atlantic. This is because a strong westerly inflow from the south Atlantic will advect moisture from the ocean into land and cause the humidity anomalies over the sea to be negative. For those regions (like Zone IIb) where excess rainfall years are associated with strong westerlies from Atlantic, excess/deficit rainfall is also associated with negative/positive humidity anomalies over the southeast Atlantic. Analogously for those regions whose excess rainfalls are associated with reduced westerlies (like zone IV), excess rainfall is associated with positive humidity anomaly over southeast Atlantic (since the moisture advected from the ocean is less).

The low level humidity also shows a low level shift from its climatological location for zone I (deficit composite), zone IIa (excess composite), zone III (deficit composite), and zone IV (excess and deficit composites). This north-south shift in the humidity can be related to the low level shift in the ITCZ (discussed in the previous section). This implies excess/deficit rains are characterised by a northward/southward shift in the low level moisture convergence associated with the ITCZ.

### 3.6 Low Level wind

The low level wind features affecting the rainfall are the westerly winds coming from the Atlantic, and the southerly winds from the south Indian Ocean which are associated with the East African Low Level Jet (EALLJ). For all regions except for the northwest (zone I) southwest (zone IIb), a strong EALLJ is associated with excess rainfall whereas a weaker jet is associated with deficit rainfall. For Zones IIa and III excess rains are associated with southerly anomalies from southwest Indian ocean associated with a stronger EALLJ. This is because southerly anomalies from the southwest Indian ocean mean a stronger influx of moisture from the Indian Ocean, which is a favourable condition for increased rainfall. For the south west (Zone IIb), in contrast, a strong/weak EALLJ is associated with a deficit/excess rainfall (Fig. 13). However excess/deficit rainfall years are associated with a stronger westerly/easterly anomaly from Atlantic suggesting the moisture source from Atlantic is important for the south west part of the country. Generally a stronger westerly anomaly from Atlantic is associated with excess rainfall except

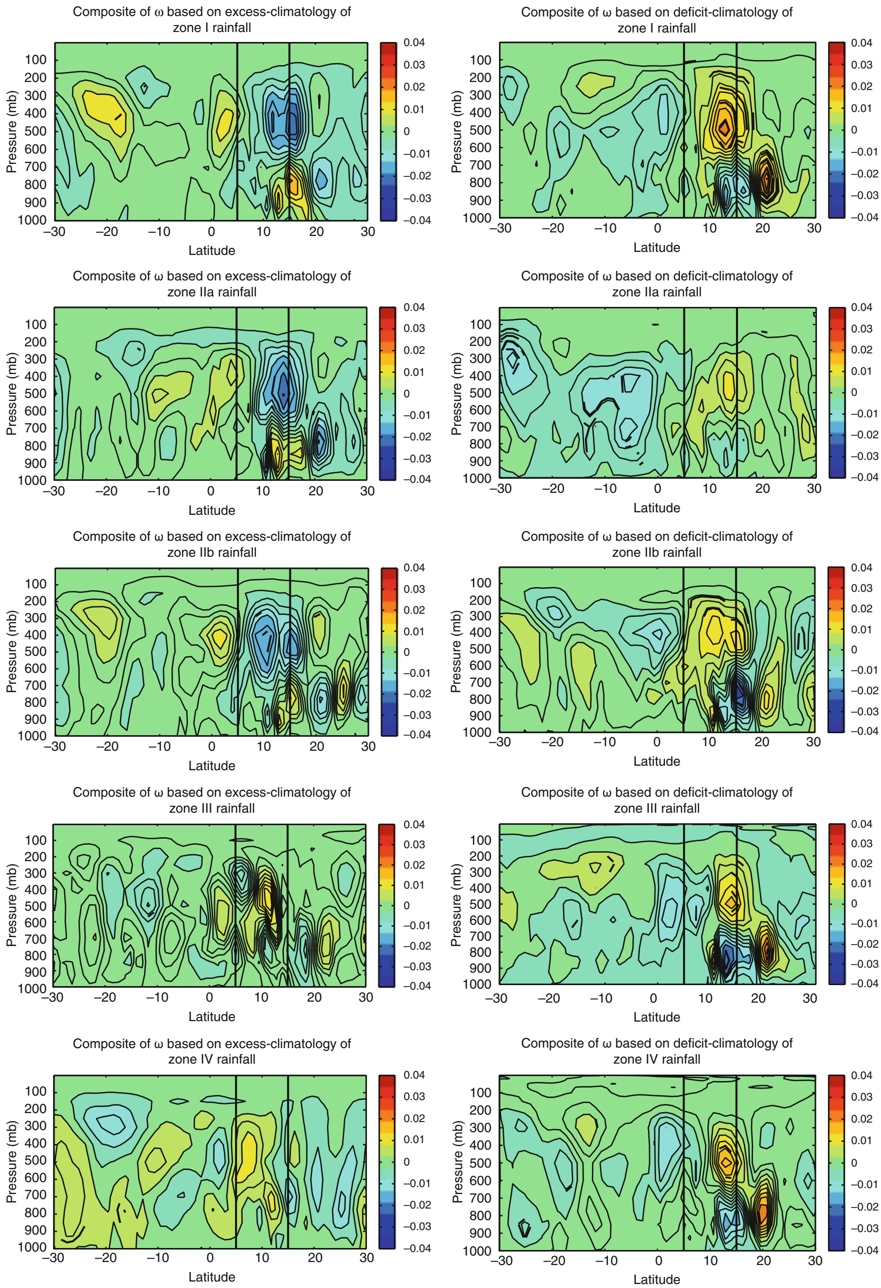


**Fig. 11** excess-climatology (*left*) and deficit-climatology (*right*) composites of cross sections of vertical wind speed (in Pa/sec) during Kiremt season. The contour lines represent significance at 0.1 level. The vertical black lines represent the location of Ethiopia in terms of latitudes

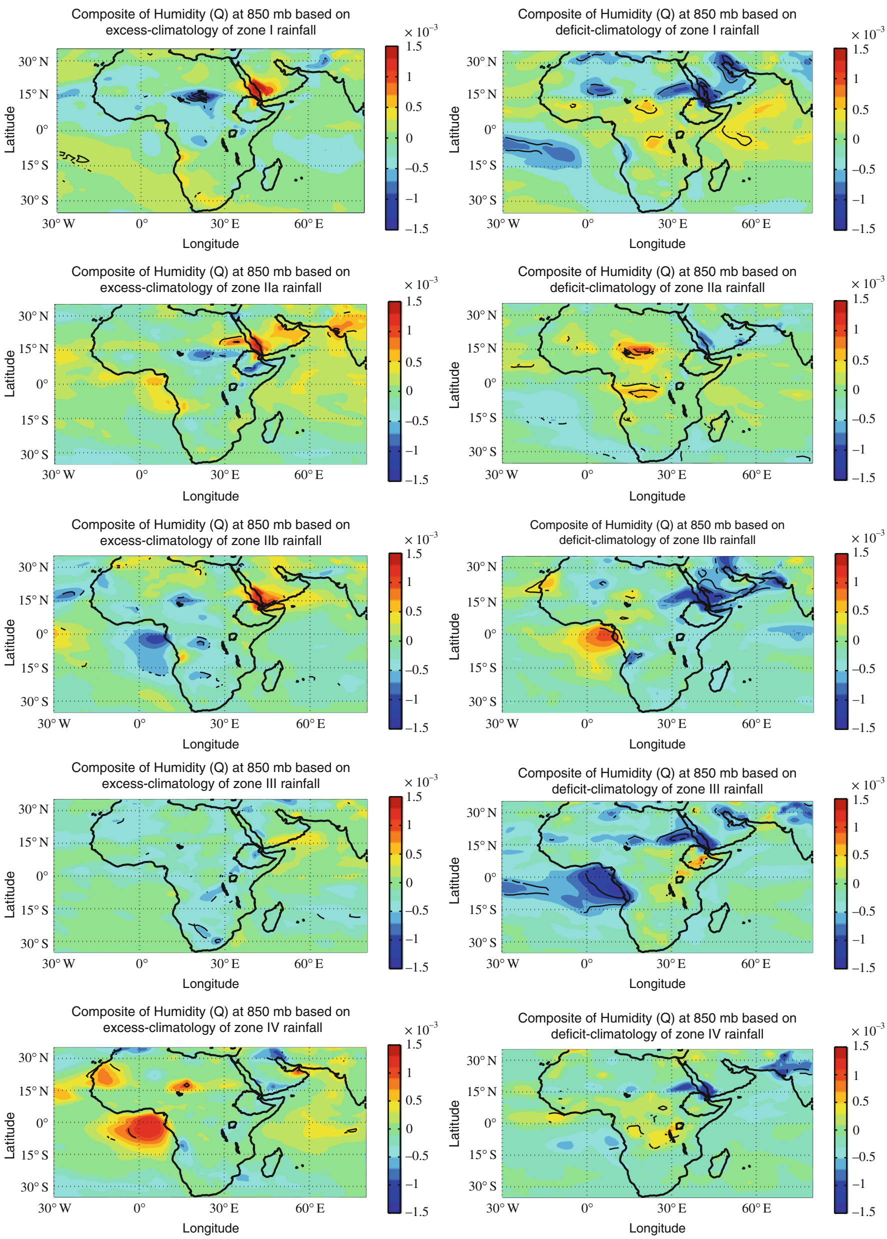


**Fig. 12** Excess-climatology (*left*) and deficit-climatology (*right*) composite plot of Q (kg/kg) at 850 mb. The contour lines represent significance at 0.1 level

for the eastern part (zone IV). For the eastern part (zone IV) excess rainfalls are associated with weaker westerlies from south Atlantic but stronger westerlies from north Atlantic around 15° *N* latitude. In Fig. 13 the excess composites of Zone IV shows that the westerlies from north Atlantic during excess rains are penetrating to northeast Africa and the north part of the Red Sea (well north of the climatological location of ITCZ) and this agrees with the northward shift of the vertical wind speed which also suggest the northward shift of ITCZ during excess rainfall years.

## *3.7 Low Level Pressure*

The low level moisture sources during the Kiremt rainy season (JJAS) are the Atlantic and the Indian Ocean. The flux of moisture depends on the intensity and position of the St Helena and Mascarene highs (Kassahun 1987). For instance, the orientation of the Mascarene ridge axis is normally centered about 27° S and 50° E but if the ridge axis lies over the coast of East Africa the moisture flux decreases, leading to a decrease in rainfall (Kassahun 1986). The confluence between Atlantic/Congo air and Indian Ocean air defines a boundary zone, which extends northwards along western part of Ethiopia (Kassahun 1987). When the St. Helena high is weak or the boundary is displaced westwards of the western part of the country, a marked decrease in rainfall is observed (Kassahun 1987).

For the western part of Ethiopia (Zone I, IIa and IIb), excess/deficit rainfalls are associated with negative/positive height anomalies over Indian Ocean. Whereas for the eastern part (zone IV), both excess and deficit rainfalls are associated with positive geopotential height anomalies over all of the Indian Ocean except the northwest Indian Ocean and Arabian Sea. Low/high pressure anomalies over the northwest Indian Ocean and Arabian Sea are associated with excess/deficit rainfall years. Regarding the Highs over Atlantic ocean, for northwest, west and central regions (Zones I, IIa, III), a strong/weak Azores high (or a positive/negative NAO) is associated with excess/deficit rainfall as shown in Fig. 14. The link between a positive/negative NAO with excess/deficit rains can be explained by the tropospheric temperature (TT) over the Asia. Goswami et al. (2006) have shown that strong negative NAO events lead to a negative tropospheric temperature anomaly over the southern Eurasia via their influence on the storm tracks. These negative tropospheric temperature anomalies over Eurasia lead in turn to a weaker Tibetan high at upper levels. A weaker Tibetan high means the easterlies (i.e. the TEJ) associated with this anticyclone are also weaken. In section 3.1 it is shown that that a weaker TEJ is associated with deficit rains.

## *3.8 ENSO*

Gissila et al. (2004), Korecha and Barnston (2007), Segele and Lamb (2005) have shown that SST over the Eastern Pacific is related to the Kiremt rainfall. In fact there is a significant relationship between Kiremt seasonal rainfall total and SST in several parts of the globe. The contemporaneous correlation between SST and

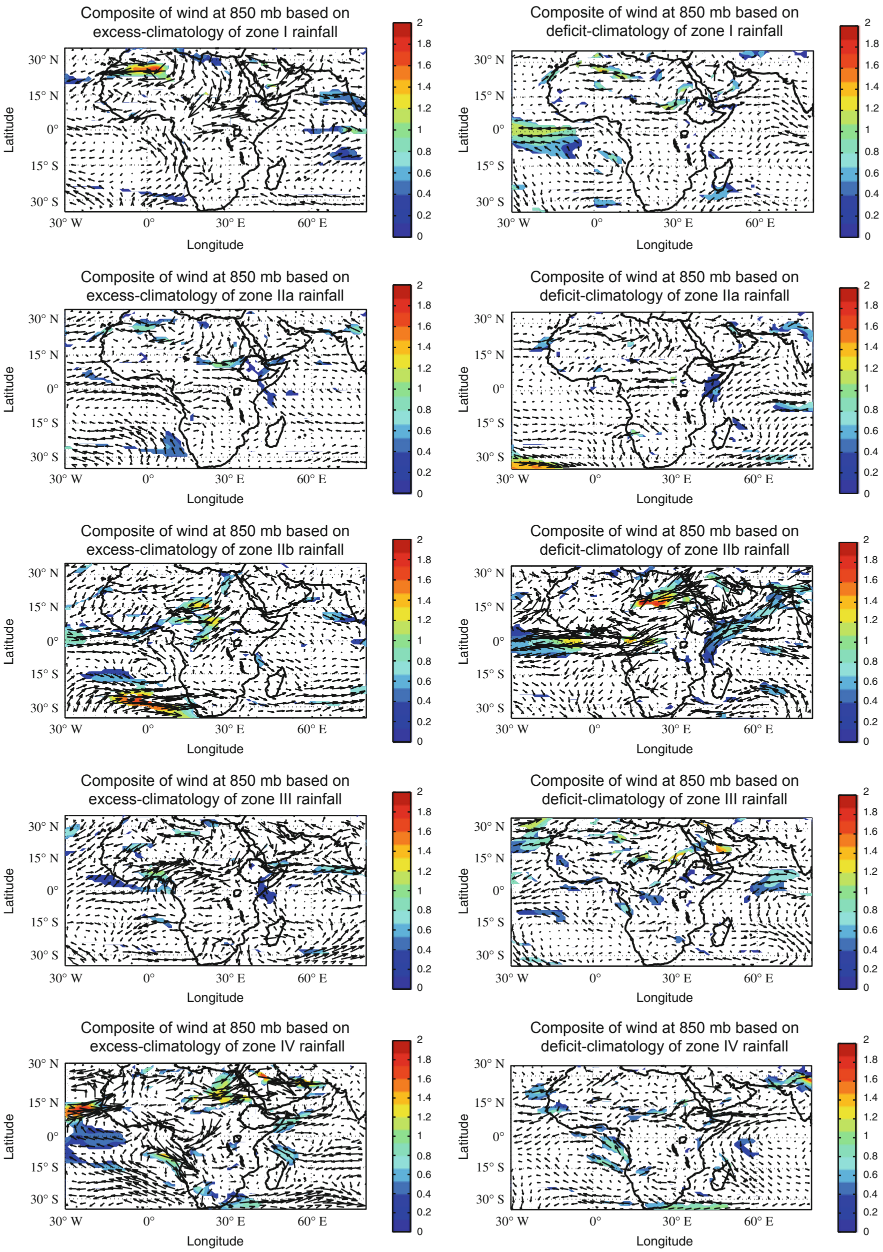


**Fig. 13** Excess-climatology (*left*) and deficit - climatology (*right*) composite of wind at 850 mb. The arrows represent the direction of the wind anomalies and the filled contours represent the magnitude of the wind anomalies (m/s) that are significant at 0.1 level

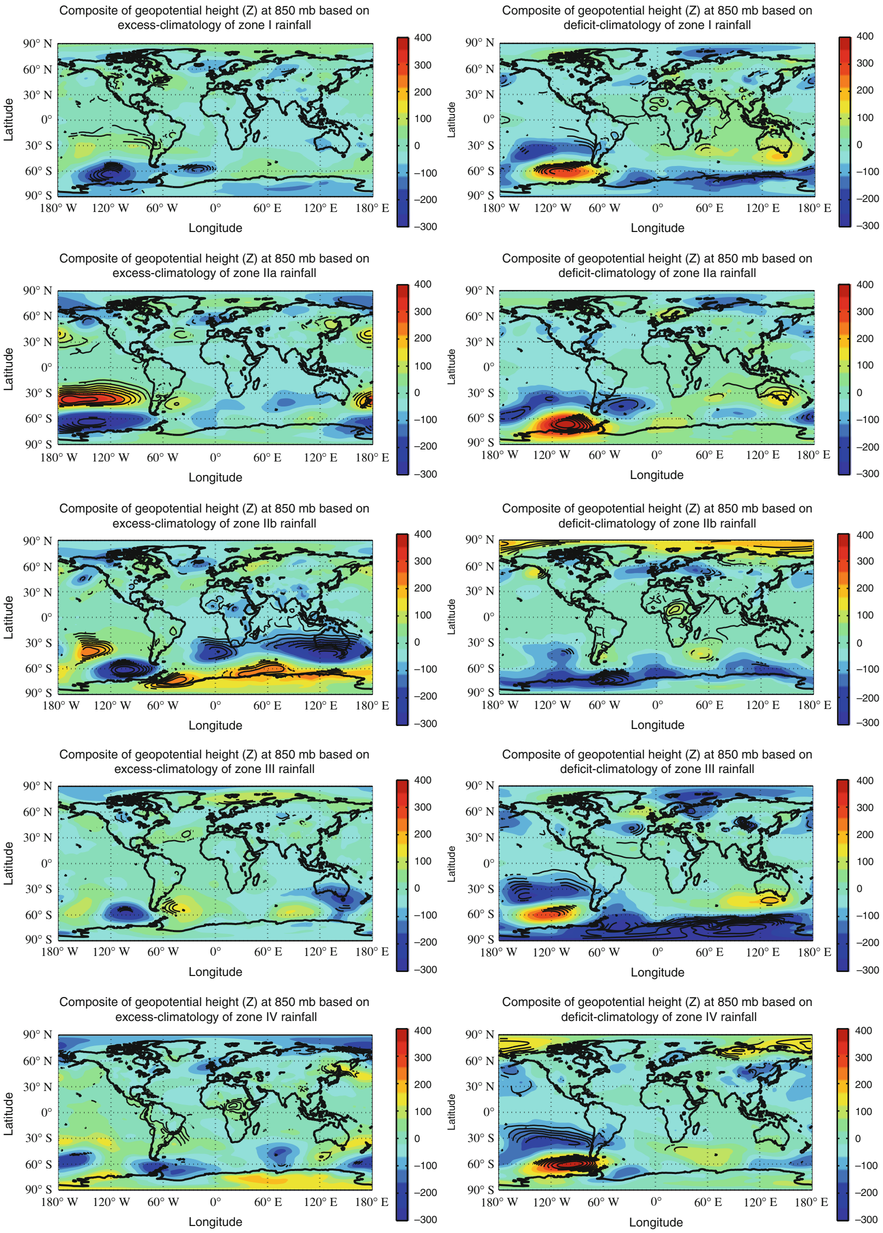


**Fig. 14** Excess- Climatology (*left*) and deficit-climatology (*right*) composite plot of geopotential heights ($m^2s^{-2}$ )at 850 mb. Contour lines represent significant at 0.1 level

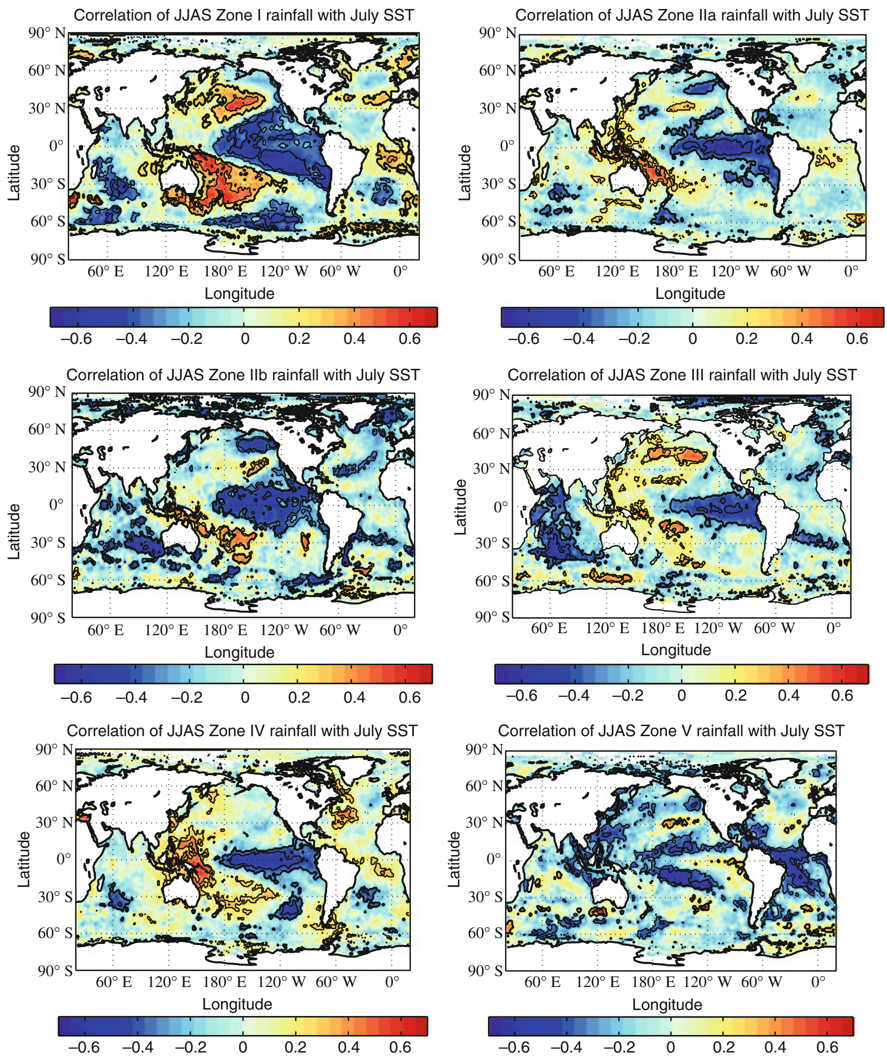


**Fig. 15** Correlation of Kiremt rainfall in different zones with global SST in July. Contour lines represent significant at 0.1 level

rainfall (Fig. 15) shows that for all regions except for zone V (which is dry for this time of the year) the correlation values are highest over tropical Pacific, suggesting a strong link with ENSO. The strength of the link however varies between zones. The mechanisms by which the warming of equatorial Pacific is leading to a deficit rainfall has been discussed in (Diro et al. 2010).

The effect of a warm equatorial eastern Pacific (El-Niño) depends on the season of occurrence and the region of Ethiopia. Specifically, El-Niño in the previous winter is associated with excess Kiremt rainfall whereas El-Niño in the contemporaneous

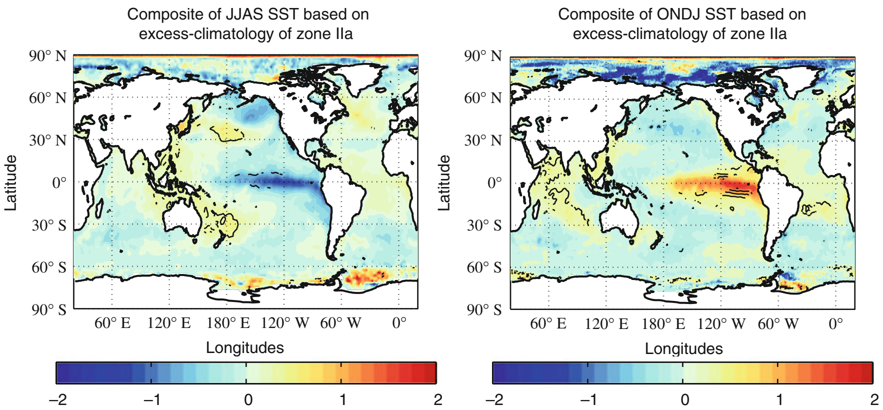


**Fig. 16** Excess-climatology composites of SST (K) in Kiremt season (*left*) and in Bega season (*right*) based on Kiremt Zone IIa rainfall years

summer is associated with deficit Kiremt rainfall as shown in Fig. 16 for all zones except Zone I (northwest). For the northwest, El-Ni*ñ*o is always associated with deficit Kiremt rainfalls irrespective of season of occurrence.

## 3.9 Discussion on Kiremt Large Scale Features

From the previous studies, the large scale features we expect to affect the Kiremt rainfall are the ITCZ, TEJ, Highs over Mascarene and St Helena, winds from Atlantic and Indian Ocean and ENSO. From this chapter we have seen the large scale features associated with Kiremt rainfall anomalies are ITCZ, TEJ, AEJ, QBO, the Azores High (NAO), ENSO, winds from Atlantic, and Indian Ocean, EALLJ, humidity anomalies over the Red Sea and over the Southeast Atlantic Ocean. We have also seen the response of these large scale features for the different homogeneous rainfall zones are not entirely the same. Here are some examples:

- Low level circulation: Deficit rains over the southwestern part of Ethiopia (Zone IIb) are associated with weaker westerlies from the Atlantic even if the EALLJ is stronger suggesting the moisture source from the Atlantic is most important (Fig. 17 left), whereas for the eastern part (Zone IV), excess rains are associated with stronger EALLJ and this suggests that the moisture from the Indian Ocean and the Atlantic Ocean also play a role (Fig. 17 right).
- Upper level circulation: a westerly anomaly at 200 mb indicative of a weaker TEJ is linked to deficit rainfall in all areas except Zone IIb (Fig. 18), probably via reduced upper level divergence associated with the weaker jet. For Zone IIb, it is likely that the effect of the jet is less important than other factors such as the effect of the QBO on the westerly moisture flux as described in Section 3.2.

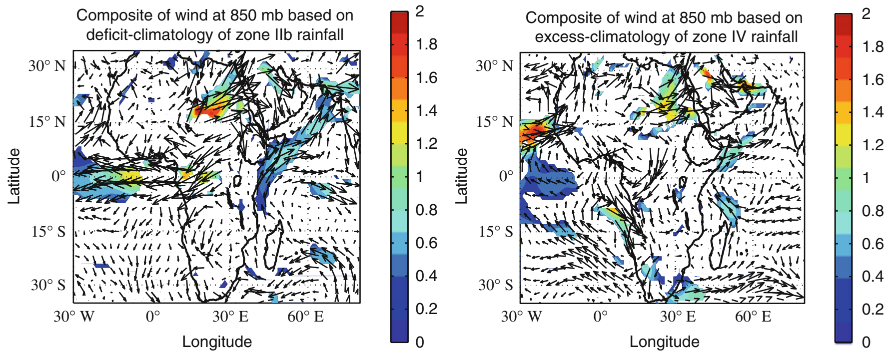


**Fig. 17** Composites of wind at 850 mb for deficit-climatology of Zone IIb in (*left*) and excess-climatology of Zone IV (*right*). The arrows indicate the direction of the wind anomaly and the filled contours represent the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

- ENSO: for the contemporaneous season deficit rains in all zones (except Zone V) are associated with El-Niño. However, the influence of a previous winter El-Niño in the following Kiremt is opposite between Zone I and the rest of the regions as shown in Fig. 16.
- There is an opposite pattern between Zone IIb and Zone IV in terms of geopotential height (Fig. 19). A positive geopotential height anomaly over central Africa is associated with deficit rains of Zone IIb and excess rains of Zone IV. For Zone IIb this positive geopotential height anomaly relates to a weaker westerly anomaly. For Zone IV this positive height anomaly over central Africa is associated with westerly inflow from the north Atlantic (around $15^0$N) and a northward shift of the ITCZ, which in turn leads to high rainfall.

The schematic of the large scale features associated with rainfall anomalies in Kiremt season is shown in Fig. 20.

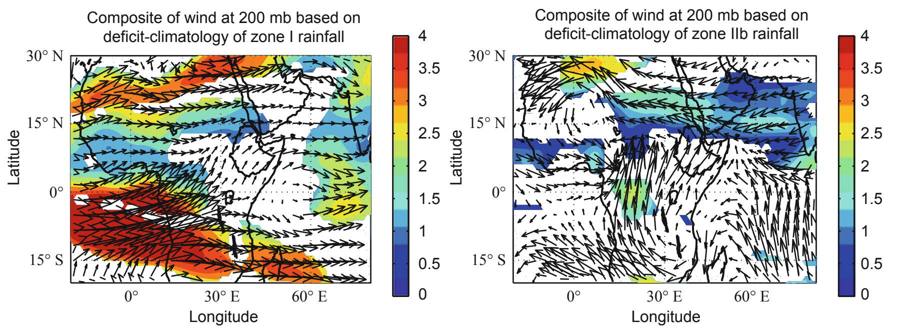


**Fig. 18** Deficit-climatology composites of wind at 200 mb for Zone I in (*left*) and Zone IIb (*right*). The arrows indicate the direction of the wind anomaly and the filled contours represent the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

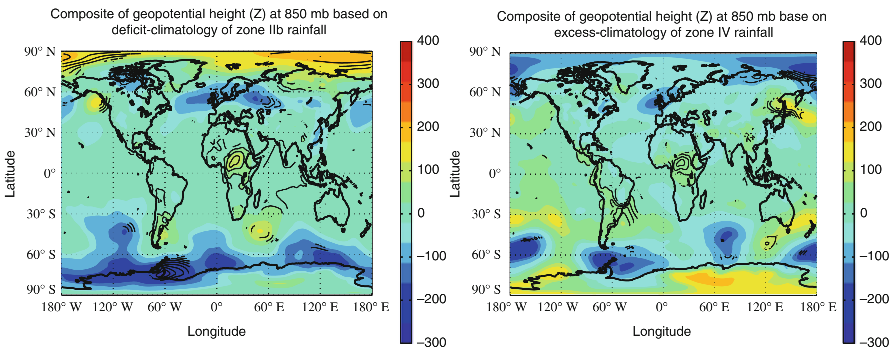


**Fig. 19** Composites of geopotential height ($m^2s^{-2}$) at 850 mb for deficit-climatology of Zone IIb in (*left*) and excess-climatology of Zone IV (*right*). Contour lines represent significant at 0.1 level

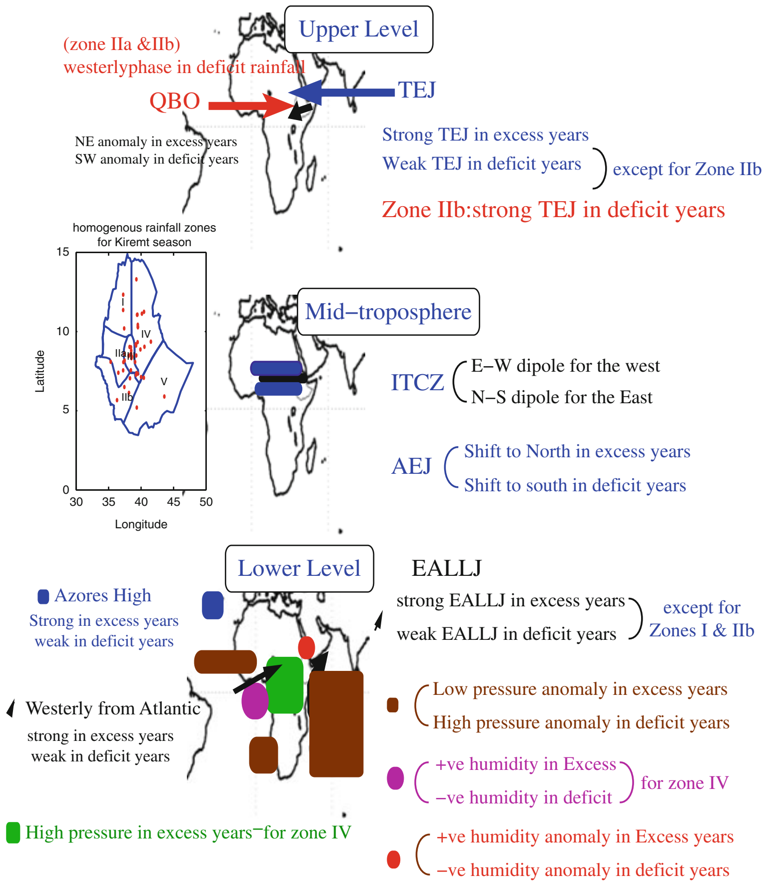


**Fig. 20** Summary of large scale feature associated with rainfall anomaly in kiremt season

# 4 Large Scale Features Associated with Belg Rainfall Anomalies

Belg (FMAM) is the main rainy season for the southern part of Ethiopia (Zone V) and is the short rainy season for the rest of the country except for the northwest (Zone I). Zone I is dry for this time of the year. The large scale features associated with excess and deficit rainfalls during the Belg season will be discussed in the following section. From previous studies, the large scale features which affect Belg rains are the ITCZ, Subtropical westerly jet streams, Arabian High, NAO and the frequency of tropical cyclones over the southwest Indian Ocean. Now we will look at the wind, geopotential height, humidity at 850mb, 200mb and the height-latitude cross section to examine some of these features and also check how they vary over the different homogeneous rainfall zones.

## *4.1 Sub-Tropical Westerly Jet (STWJ)*

During the short rainy season, Camberlin and Philippon (2002) have shown the existence of a trough over the Red Sea at about 200 mb. This trough pattern corresponds to an anomalous southerly extension of subtropical westerly jet streams (STWJ) over Northeast Africa. The STWJ is relatively narrow and shallow streams of fast flowing air in the upper troposphere with maximum speed at about 200 mb level as shown in Fig. 21. The STWJ is formed as a result of conservation of angular momentum as the air moves from the lower latitudes to the higher latitudes (Mcilveen 1998). The Jet speed is largest in the ridge and weakest in troughs (Hastenrath 1990). This means that the west of the trough can be treated as the exit of the jet, and hence the ageostrophic component points to the high pressure. The east of the trough can be taken as the entrance of the jet, meaning that the ageostrophic component points to the low pressure. Therefore the area of divergence will be ahead of the trough as shown in Fig. 22. This divergence ahead of the trough is likely to induce

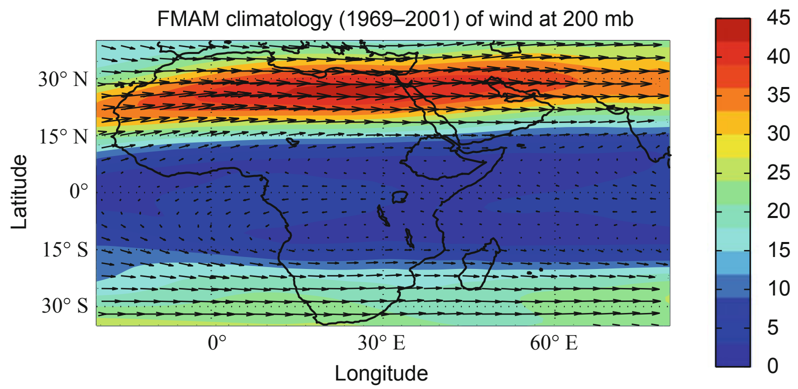


**Fig. 21** Wind climatology at 200 mb during the Belg (FMAM) season. The colours represent the magnitude of the wind (m/s) and the arrows indicate the direction of the wind

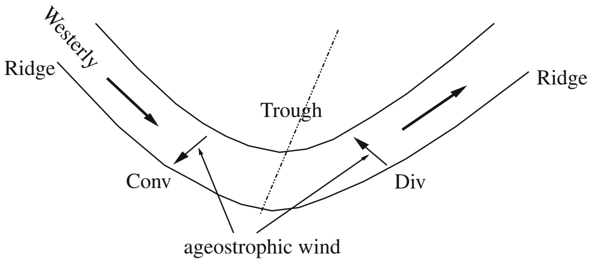


**Fig. 22** Schematic diagram of the path of the downward bend of the subtropical westerly jet stream and associated area of divergence

upward motion (Hastenrath 1990) and hence be conducive to the generation of precipitation.

The most prominent features at upper levels (200 mb) are the wind anomalies associated with excess and deficit rainfall years (Fig. 23). During deficit rainfall years, the STWJ shows a dipole pattern, with easterly anomalies over NE Africa ~15°$N$ and westerly anomaly ~30°$N$. This suggests that the STWJ is shifted to the north from its climatological location during deficit rainfall years. Excess rain in all zones is associated with upper level trough over Africa (Fig. 23) which could be linked to the south ward tilt of the STWJ. For Zone IV, the location of the trough (cyclonic anomaly) is placed further west over the Sahara compared to the trough for other zones in excess composites, which is located around northeast Africa. For Zone IV, there is an anticyclonic anomaly over the Horn of Africa during excess rains. This upper level anticyclonic flow anomaly ahead (east) of the trough could be the one that enhances ascent flow and trigger convection. For deficit years the wind anomaly forms an anticyclonic pattern over Arabian peninsula. This wind anomaly pattern for excess and deficit rainfalls is in agreement with the Camberlin and Philippon (2002) study over north Ethiopia and Eritrea.

## *4.2 Low Level Humidity*

For all zones, deficit rainfall years are associated with significant negative humidity anomalies over NW Indian Ocean, the Arabian peninsula and East Africa, and positive humidity anomalies over the eastern Indian Ocean and the southeast Atlantic (Fig. 24). Looking at the wind anomaly at 850 mb during deficit rainfall years (Fig. 25), which shows an westerly anomaly over Indian ocean, the westerly anomalies in the Indian ocean will advect humidity to the eastern Indian ocean and at least explaining the observed positive anomalies over eastern Indian ocean and negative anomalies over western Indian Ocean and over the Horn of Africa. The easterly anomaly over west Africa and the Atlantic also means less moisture is advected to the African continent from south Atlantic, which means positive humidity anomalies over Atlantic Ocean.

For all zones except Zone V, excess rains are associated with positive anomalies of humidity over the western Indian Ocean, the Arabian peninsula, the Red Sea and Eastern Africa and negative anomalies over the eastern Indian Ocean. Again except

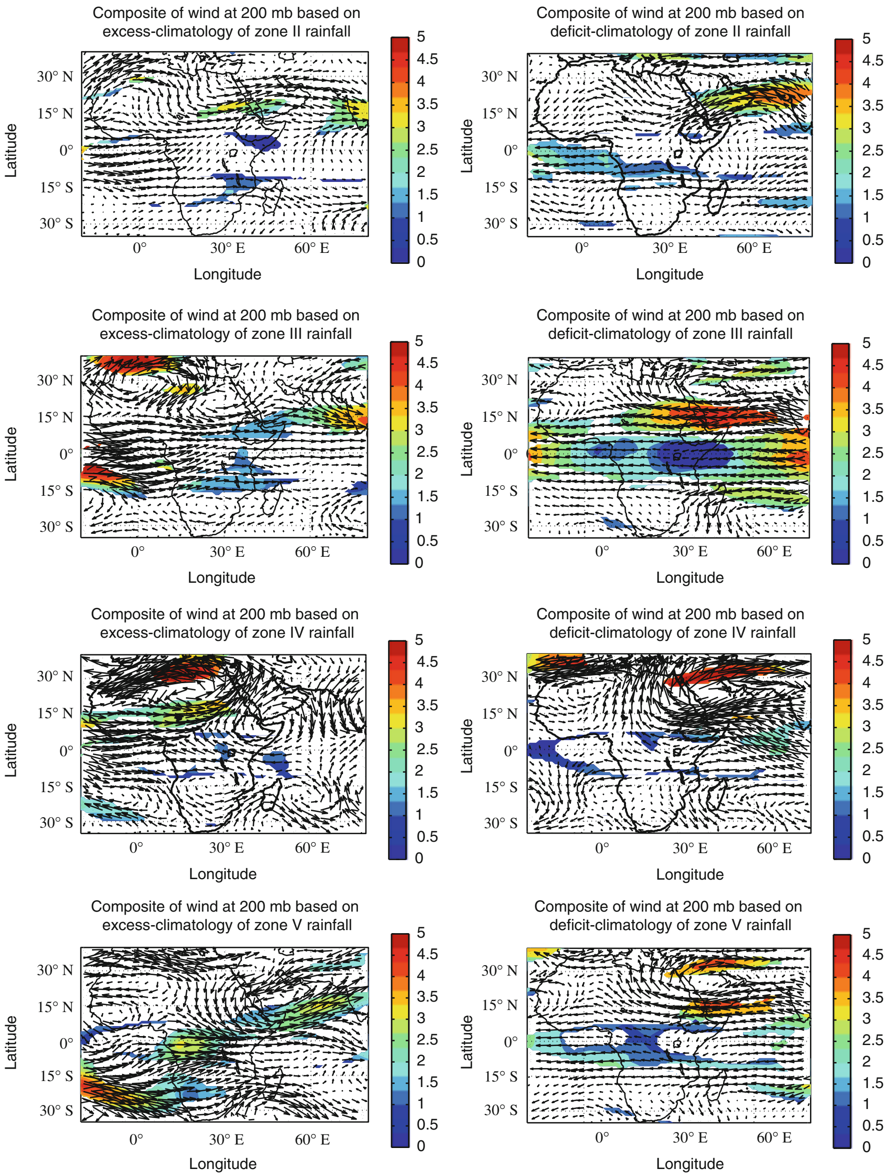


**Fig. 23** Belg (FMAM) wind at 200 mb for excess-climatology (*left*) and deficit-climatology (*right*). The arrows indicate the direction of the wind anomaly and the contour shading represents the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

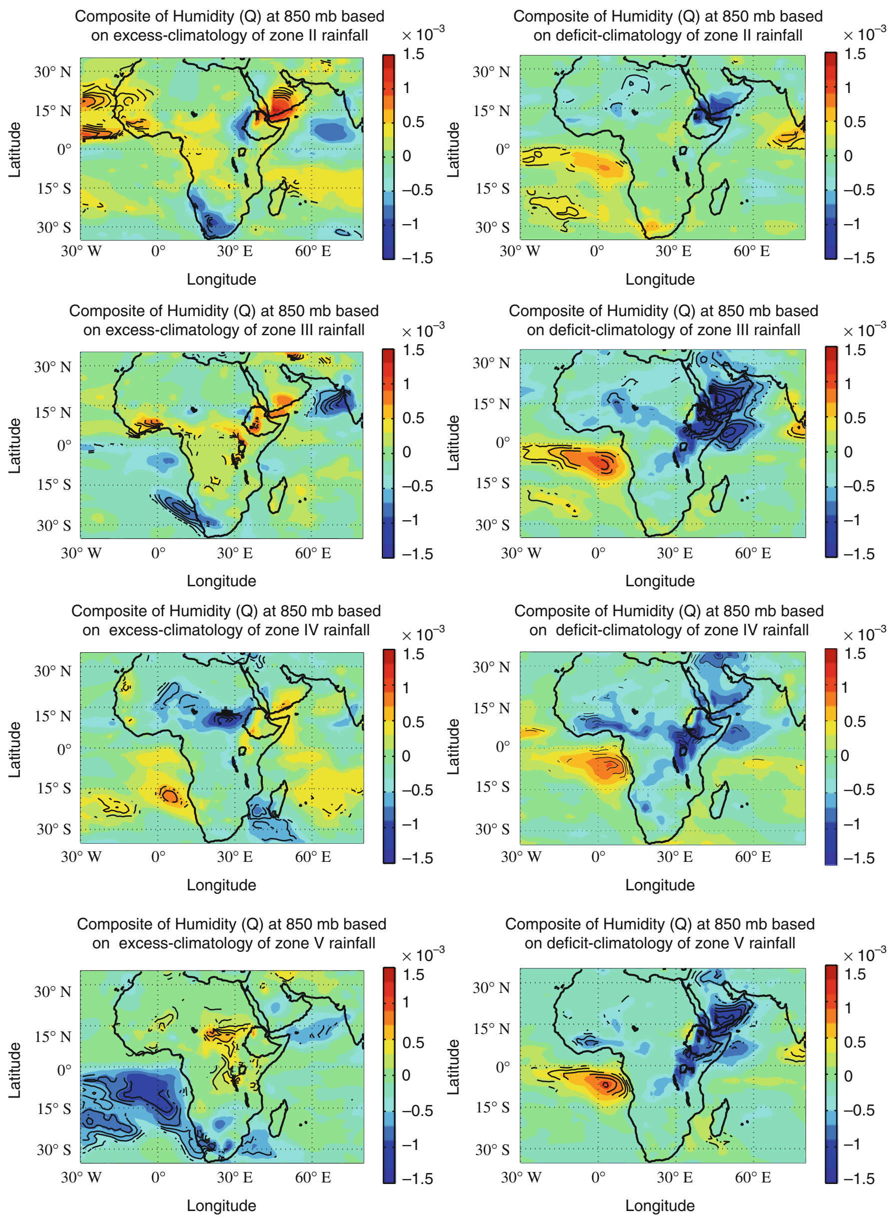


**Fig. 24** Belg (FMAM) specific humidity (kg/kg) at 850 mb for excess-climatology (*left*) and deficit-climatology (*right*). Contour lines represent significant at 0.1 level

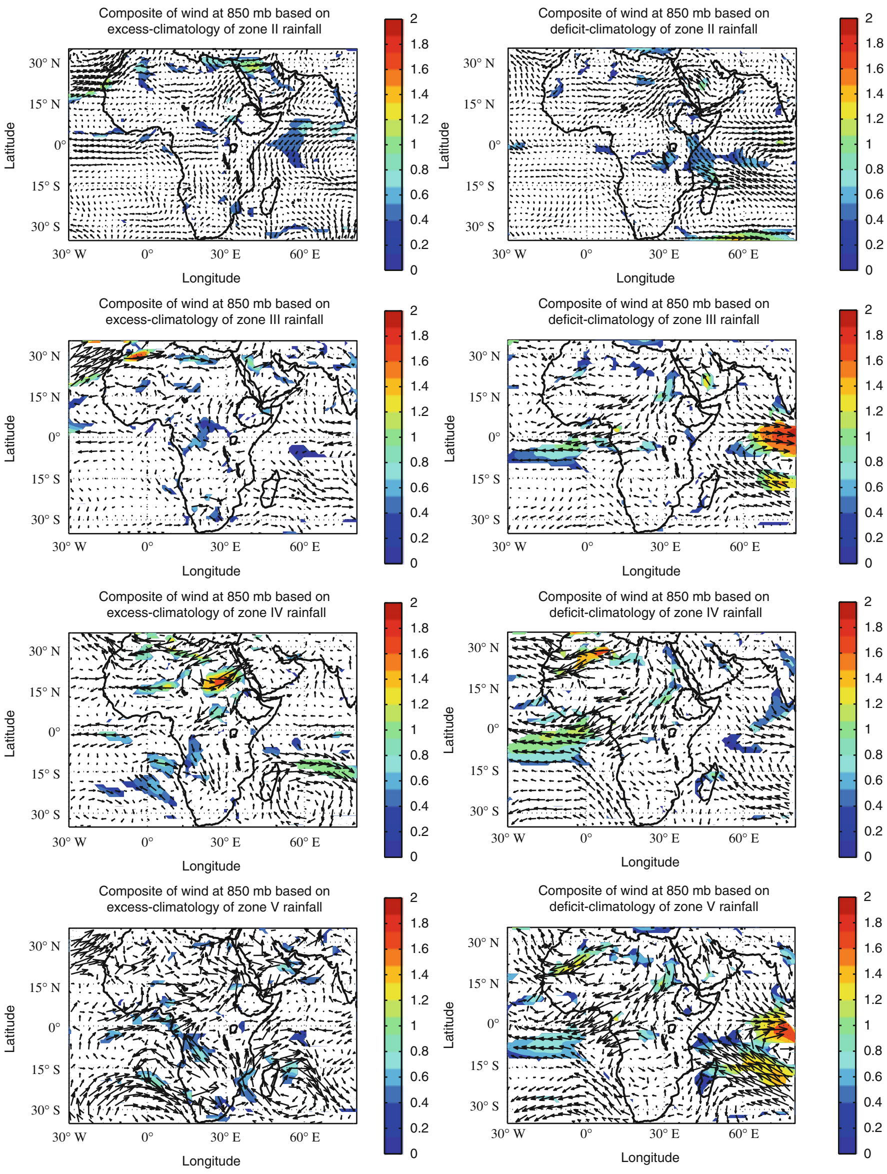


**Fig. 25** Belg (FMAM) wind at 850 mb for excess-climatology (*left*) and deficit-climatology (*right*). The arrows indicate the direction of the wind anomaly and the contour shading represents the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

for Zone V the humidity anomalies over Africa during excess rainfall years show a dipole over Ethiopia and Sudan with positive values over Ethiopia and negative values over Sudan. The alignment of the dipole of humidity anomalies suggests that the meridional arm of the ITCZ may be shifted to the east (to Ethiopia) during excess rainfall years.

### *4.3 Low Level Wind*

During deficit rainfall years there is a consistent wind anomaly at 850 mb for all zones (Fig. 25) namely westerly anomalies over the Equatorial Indian Ocean and easterly anomalies over the Atlantic. If we consider the zonal (Walker) circulation, the westerly anomalies to the east of the Horn of Africa and easterly anomalies to the west of the Horn of Africa make the region an area of divergence (and hence deficit rainfalls). For excess rainfall years (except for zone V), there is an easterly anomaly over the Indian Ocean, which advects moisture and makes a favourable environment for excess rainfall. For zone V, there are cyclonic anomalies over the western Indian Ocean that hinder the easterlies delivering moisture to the continent from the Indian Ocean. However there are strong westerly anomalies over the Atlantic and over Africa, suggesting that the moisture influx for the southern part of Ethiopia comes from the Atlantic during excess rainfall years. These observations for Zone V i.e. the association of moist south Atlantic westerly flow with the excess rains is in agreement with studies made for the equatorial east Africa regions eg. McHugh (2006), which suggest that these westerlies from Atlantic are linked to ENSO with stronger/weaker westerlies associated with El Niño/La Niña periods.

In summary, for the northern part of Ethiopia the easterlies associated with the Arabian Anticyclone are important in bringing moisture from Indian ocean, whereas for the southern part it is the westerlies from Atlantic that are more favourable for excess rain.

### *4.4 Low Level High Pressures*

During the Belg (FMAM) season, easterly to north easterly outflow on the southern periphery of the Arabian anticyclone, which lies over the Arabian sea for this time of the year, carries moisture into East Africa (Camberlin and Philippon 2002). In the previous section i.e. Section 4.3, it is shown that the easterlies from the Indian Ocean are the main source of moisture and cause rain over most of the northern and central part of Ethiopia.

Figure 26 shows the composites of geopotential height at 850 mb based on excess and deficit rains and it suggests that a stronger signal is observed over extra tropical Atlantic and Pacific Oceans. Again from Fig. 26, it can be seen that in most cases negative North Atlantic Oscillation (NAO) i.e. negative anomaly around Azores and positive anomaly over Iceland is associated with excess rains and positive NAO with deficit rains. The link between the high over the north Atlantic and Belg rainfall over

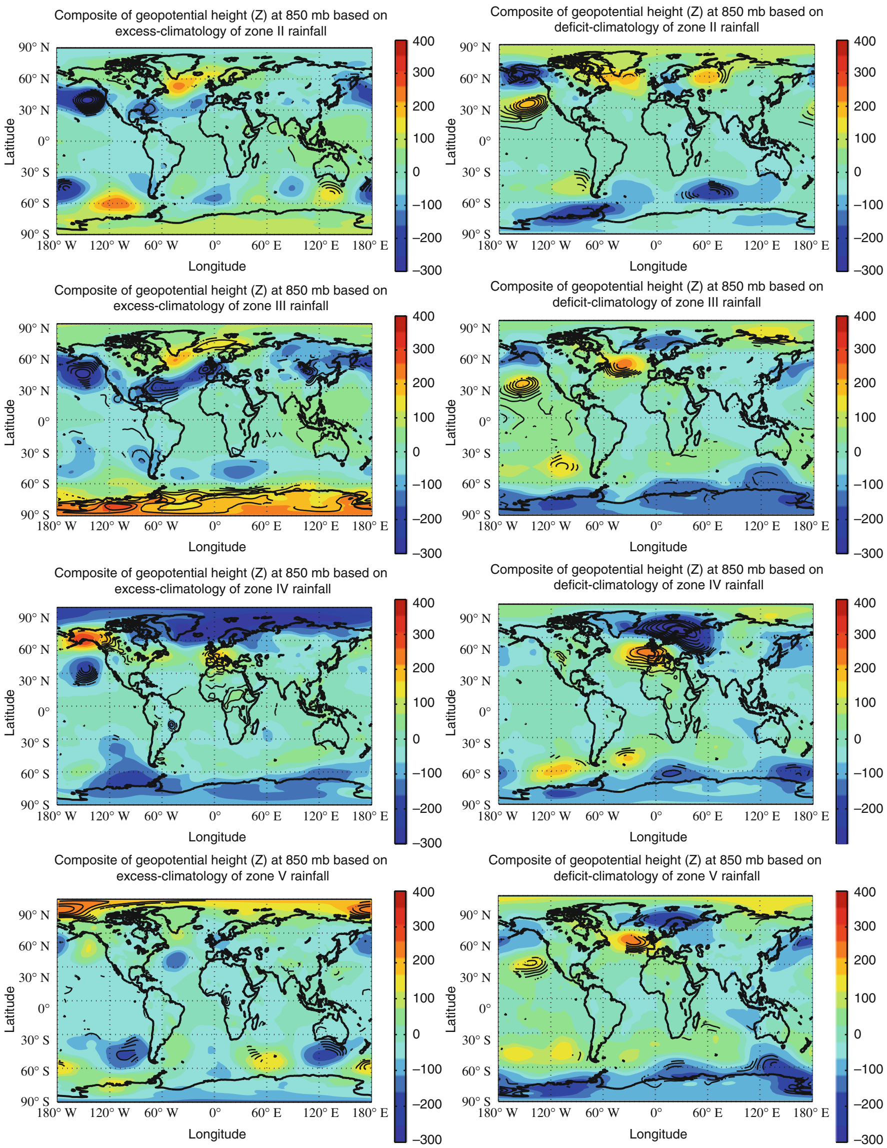


**Fig. 26** Belg (FMAM) geopotential height ($m^2s^{-2}$) at 850 mb for excess-climatology (*left*) and deficit-climatology (*right*). Contour lines represent significant at 0.1 level

Ethiopia could be via the easterlies in the Indian Ocean which advects moisture to East Africa. A weaker Azores High (or a negative NAO) implies the storm tracks are deflected to the south (i.e. penetrate to the Mediterranean and to the middle east) and this will displace the Arabian High to the south over the Arabian Sea which means

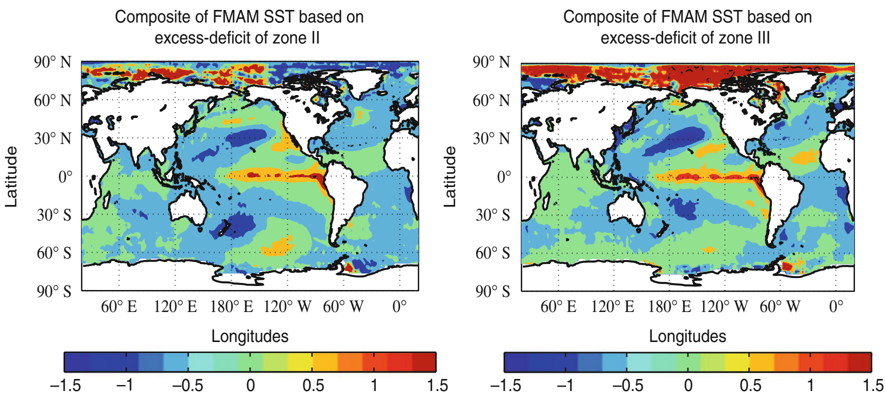


**Fig. 27** Excess-Deficit composite of SST (in K) Belg season for Zone II (*left*) and Zone III (*right*)

that more moisture is advected to the horn of Africa from the western Indian ocean by the easterlies south of this anticyclone. Although the signal is weak, the excess composites in Fig. 26 also shows a positive height anomaly over the Arabian Sea especially for the north and central (Zones II and III) which agree with the above possible extra tropical-tropical interaction.

## *4.5 ENSO*

Unlike the Kiremt season where rainfall is correlated negatively with the tropical Pacific (i.e. El Niño is associated with deficit rains), for the Belg (FMAM) season, rainfall is correlated positively with the tropical Pacific (though the strength is lower than the Kiremt-SST correlation). The strongest signal of ENSO is shown over western and central part of Ethiopia, where warm/cold equatorial eastern Pacific is associated with excess/deficit Belg rainfalls as shown in Fig. 27.

The one season lag in the SST-rainfall relationship (i.e. ONDJ SST correlates with FMAM rainfall) is similar to the contemporaneous rainfall-SST relationship but weaker in strength. In other words both contemporaneous (Belg) and the previous Bega (winter) warming/cooling of Equatorial Pacific are associated with excess/deficit rainfall although the contemporaneous relation is stronger.

For the two season lag SST-rainfall relationship (the previous JJAS SST correlating with FMAM rainfall), warming of Eastern Pacific (coast of S. America) during the previous Kiremt (which is accompanied by warming of the Indian Ocean) is associated with deficit Belg rainfall. In other words, the occurrence of El Niño (accompanied by warming of Indian ocean) in the previous summer is associated with deficit Belg rains, but the occurrence of El Niño / La Niña in the previous Bega or contemporaneous Belg is associated with excess/deficit Belg rains as shown in Fig. 28.

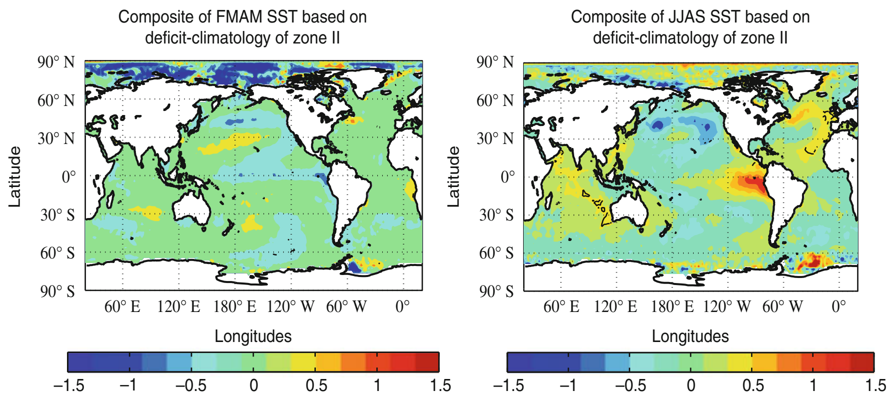


**Fig. 28** Deficit-Climatology composite of (*left*) SST (in K) in Belg season (*right*) SST in previous Kiremt season for Zone II

Generally for Zone V, The ENSO teleconnection is weak and located over the central Pacific, whereas in other zones the strongest correlation is associated with the equatorial eastern Pacific.

## *4.6 Indian Ocean Related Teleconnections*

For the central part of Ethiopia, consistent with the ENSO teleconnection, correlation of Zone III rainfall with the Indian Ocean shows is positive in the contemporaneous season and negative in the previous summer. In other words, warming of the Indian Ocean in the contemporaneous season is associated with excess Belg rainfall but warming of the Indian ocean in the previous summer is associated with deficit Belg rainfall as shown in Fig. 29.

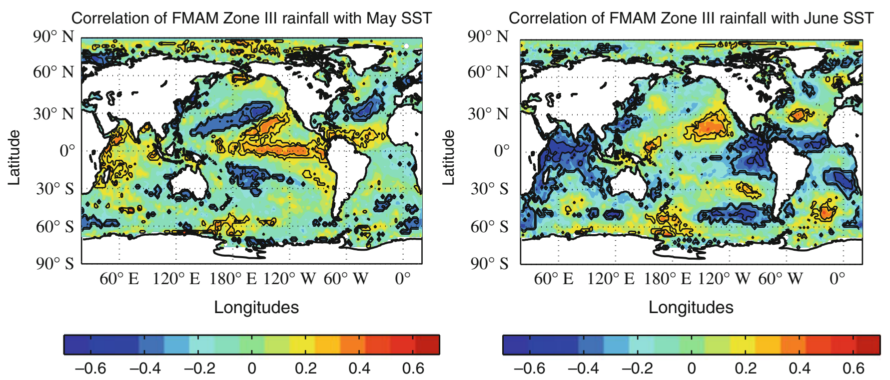


**Fig. 29** Correlation of Belg rainfall with SST in (*left*) May (*right*) previous June

Shanko and Camberlin (1998) have examined the relationship between the tropical cyclones over the southwest Indian Ocean and rainfall for the short rainy season (FMAM) and found that low/high frequency of Tropical cyclone is associated with heavy/deficit rainfall in the Belg season.

## *4.7 Discussion on Belg Season Large Scale Features*

From the literature it is known that Belg rainfall is affected by upper level troughs associated with the subtropical westerly jet, the ITCZ for the southern part of Ethiopia, the easterly anomaly from the Indian Ocean, and the frequency of tropical cyclones over the southwest Indian Ocean. The composite analysis not only confirmed the association of the above features (except the effect of tropical cyclones) with the Belg rains but also reveals additional features. The following are some of the additional features:

- Low level circulation: although for deficit rains there is a consistent westerly anomaly over the Indian ocean for all zones, the excess composites suggests that there are regional differences on the impact from the Atlantic. For instance excess rains are associated with easterly anomaly for the eastern and western part of Ethiopia but associated with westerly anomaly for the southern Ethiopia as shown in Fig. 30. This suggest that the easterly anomaly associated with the anticyclonic flow over the Arabian Sea is crucial for wet conditions over the western and eastern Ethiopia (Fig. 30 left) whereas the moist southwesterly anomaly from the Atlantic is responsible for wet conditions over southern Ethiopia (Fig. 30 right).
- The upper level features affecting the Belg season are the trough related to the southward shift of the subtropical westerly jet in excess years and the weaker or northward shift of subtropical westerly jets in deficit rainfall years. There is, however, a slight variation over the location of the trough for different regions For example the location of the trough or cyclonic anomaly is located further west during excess years of zone IV rainfall compared to say Zone V as shown in Fig. 31.

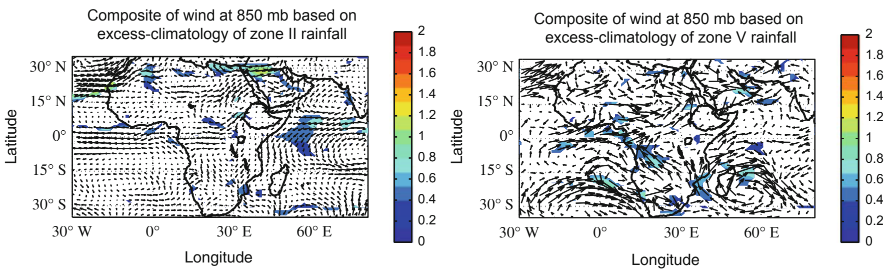


**Fig. 30** Excess-climatology composite of wind at 850 mb for Zone II (*left*) and Zone V (*right*) of Belg season. The arrows indicate the direction of the wind anomaly and the contour shading represents the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

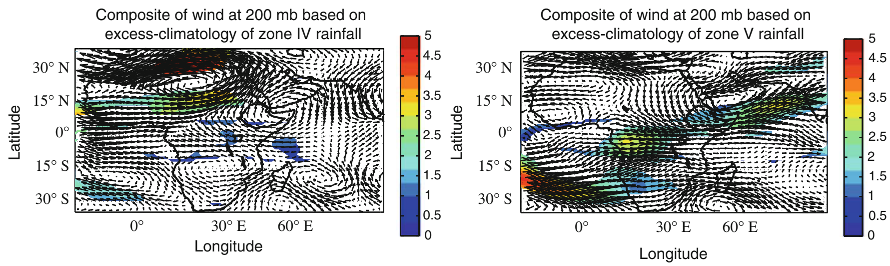


**Fig. 31** Excess-climatology composite of wind at 200 mb for Zone II (*left*) and Zone V (*right*) of Belg season. The arrows indicate the direction of the wind anomaly and the contour shading represents the magnitude of the wind anomaly (m/s) that are significant at 0.1 level

- It is interesting that the impact of ENSO on Belg rainfall is the opposite to the impact of ENSO on the Kiremt rainfall. In Section 3.8, it is shown that in Kiremt, El-Niño is related to deficit rains, however in the Belg season, El-Niño is related to excess rains.

  Another interesting feature is that the lag relationship between ENSO and Belg rains. At zero lag (contemporaneous season) the occurrence of El-Niño is associated with excess Belg rains, However, the occurrence of El-Niño at two season lag (the previous summer) is associated deficit Belg rains.
- There are also opposite patterns between Zone V and the rest of the zones in terms of the geopotential height (Fig. 32). Negative geopotential height over Africa and positive geopotential height over Atlantic Ocean are associated with excess rains of Zone V. For the rest of the zones excess rains are associated with a positive height anomaly over Africa and Atlantic ocean. This might explain the westerly inflow from Atlantic during excess rains over the southern Ethiopia. For Zone V (the southern part of Ethiopia), the zonal pressure gradient between the Atlantic ocean and African continent might be responsible for the the westerly influx from the Atlantic during excess rains.

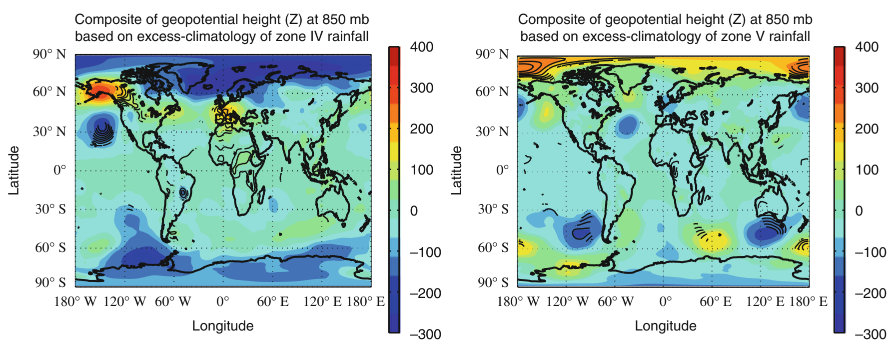


**Fig. 32** Composites of geopotential height (in $m^2s^{-2}$) at 850 mb for excess-climatology of Zone IV in (*left*) and Zone V (*right*) of the Belg season

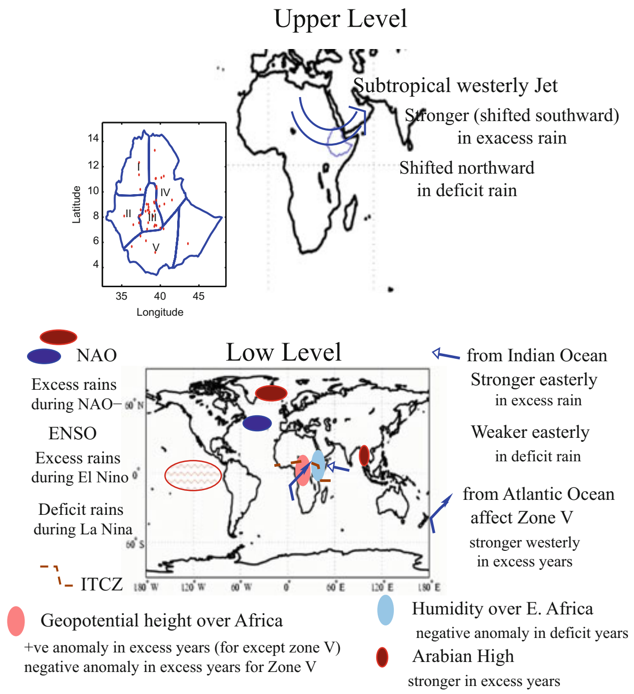


**Fig. 33** Summary of large scale feature associated with rainfall anomaly in Belg season

The schematic of the large scale features associated with rainfall anomalies in the Belg season is shown in Fig. 33.

## 5 Summary and Conclusions

In this chapter the large scale atmospheric and oceanic controls on Kiremt and Belg rainfall have been studied and the main points are summarised below.

For Kiremt, in most cases excess (deficit) rainfalls are associated with:

- a stronger (weaker) Tropical Easterly Jet (TEJ). A stronger (weaker) jet implies a strong (weak) divergence associated with the jet and hence more (less) convective activity over Ethiopia.
- a northward (southward) shift in African Easterly Jet (AEJ). The climatological location of the jet is around 15° N and the geostrophic component of the Jet transports the moisture from east Africa to west Africa and ultimately to the Atlantic (since the flow is easterly). This implies that the weaker (stronger) jet or the northward (southward) shift of the jet means less (more) moisture is taken away from east Africa and hence to more (less) rainfall.
- a stronger (weaker) East African Low Level Jet (EALLJ). A stronger (weaker) EALLJ means more (less) moisture from southern Indian Ocean penetrating into

east Africa and hence giving rise to more (less) favourable conditions for for high rainfall.
- stronger (weaker) westerly moisuture influx from the Atlantic.
- a cold (warm) summer SST over the equatorial Pacific, which alters the circulation over Africa (see Diro et al. 2010) in such a way that there is more (less) rainfall over Ethiopia.
- a positive (negative) phase of North Atlantic Oscillation (NAO). The positive NAO is associated with warmer upper tropospheric temperature (TT) anomalies over north Africa and Asia (Goswami et al. 2006). This warm TT anomaly over Asia leads to a stronger Tibetan High (at upper level) and hence a stronger easterlies south of this High – in other words a stronger TEJ. Positive NAO conditions may also lead to a stronger EALLJ by strengthening the meridional TT gradient between Asia and the Indian Ocean.
- an easterly (westerly) phase of the Quasi Biennial Oscillation (QBO). Since the mean low level flow is westerly and if the upper level flow is easterly (easterly phase of QBO) then the zonal circulation gets stronger and hence more moisture is injected from Atlantic. This implies that during a westerly phase of the QBO, the zonal (east-west) circulation is reduced meaning less westerly influx from Atlantic, which in turn may mean less moisture and less rainfall.

There are, however, exceptions. For instance, the southwestern part of Ethiopia (Zone IIb), deficit rains are associated with stronger EALLJ but weaker westerly influx from Atlantic this may suggest it is the moisture influx from the Atlantic which is important for this region. Again for this region (Zone IIb) unlike the other parts of Ethiopia deficit rains are associated with stronger TEJ and westerly phase of QBO. This also suggest the upper level feature important for this region is the QBO rather than the TEJ.

Another interesting point is the relationship between Kiremt rainfall and ENSO in the previous winter. For Zone I (northwest) El Niño in the previous winter is associated with deficit rainfalls but for zone IIa (west), El Niño in the previous winter is associated with excess rain.

For the Belg season, excess (deficit) rains are associated with:
- a stronger (weaker) and southward shift in the subtropical westerly Jet (STWJ). A trough is associated with the southward shift of subtropical westerly jet. Convection is likely to occur to the east of this upper level trough.
- a warm (cold) equatorial Pacific (El Niño). Warm SSTs over central equatorial Pacific excites stationary Rossby waves, which propagate eastward and northward, entering the subtropical westerly jet in the Atlantic and reaching north Africa (Shaman and Tziperman 2005). This means convective anomalies generated from the eastern Pacific reach north east Africa via subtropical westerly jets linked to Rossby waves. We have already seen that a stronger or southward shift in the subtropical westerly jet is associated with excess rainfall.
- a negative (positive) phase of the North Atlantic Oscillation (NAO). Negative phase of NAO (weaker Azores High) mean the mid latitude depressions can propagate via the Mediterranean sea and displace the Arabian High to the south (to the Arabian Sea). When the Arabian High is displaced south the easterlies (associated

with the anticyclone) bring moisture to the Horn of Africa and contribute to the excess rains.

- a stronger (weaker) easterly anomaly from Indian Ocean. The easterlies in the Indian Ocean are associated with the Arabian High, the Arabian High in turn may be associated with the Azores High (or the NAO). Excess rains are associated with negative phase of NAO (weaker Azores High), stronger Arabian High, and stronger easterly anomalies from the Indian Ocean.
- less (more) frequent tropical cyclones over southwest Indian ocean. The effect of the tropical cyclone is through the diversion of moisture to the cyclone region (Shanko and Camberlin 1998).

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# Ethiopian Rainfall in Climate Models

**Gulilat Tefera Diro, Thomas Toniazzo, and Len Shaffrey**

**Abstract** In this chapter we present an analysis of the simulated rainfall over Ethiopia in climate simulations from the current generation HadAM3 climate model and from the new high-resolution HiGAM climate model. Comparisons are made with observations of rainfall from Ethiopian rain gauge data, merged gauge-satellite datasets and the ECMWF reanalysis datasets (ERA-40 and ERA-Interim). An intercomparison between observational datasets shows that the ECMWF reanalyses have significant biases in rainfall, for example severely overestimating rainfall during the season of Kerimt over the Ethiopian Highlands. When evaluated against the rain gauge data, the climate models, particularly the high-resolution HiGAM model, are able to provide a good representation of the regional rainfall over Ethiopia. Errors in the simulation of the interannual variability of rainfall in the HiGAM model are associated with biases in the large-scale circulation over the tropical Indian Ocean.

**Keywords** Ethiopia · Climate modelling · High resolution · Satellite data · Reanalysis · Model evaluation

## 1 Introduction

Understanding and predicting how the climate of Africa will change over the next century is an issue of increasing importance. African society and its economy are strongly dependent on its agriculture (Challinor et al. 2007). One measure of this economic dependence is that agriculture is estimated to account for 30% of African GDP (IPCC 2007b). In rural Africa, over 70% of the population derive the bulk of their income from agriculture (Jayne et al. 2003). A substantial proportion of this agriculture is not irrigated; for example, nearly 90% of cereals in sub-Saharan Africa are rain-fed (Cooper 2004). Sustained crop growth thus depends on the occurrence

G.T. Diro (✉)
Earth System Physics Section, The Abdus Salam ICTP, Trieste, Italy; Department of Meteorology, University of Reading, Reading, UK
e-mail: gtefera@ictp.it

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of sufficient rainfall throughout the growing season. The implication is that relatively small changes in rainfall may have large socioeconomic impacts. Changes in the seasonal cycle, the geographical distribution, or the year-to-year variability of rainfall may drastically change rainfed crop yields (Challinor et al. 2004, 2005).

Disease transmission is also sensitive to shifting spatial or temporal patterns of rainfall. An example is the incidence of malaria in the epidemic regions of Africa (Morse et al. 2005). It has been suggested that by the end of the century the Highlands of Ethiopia, Kenya, Rwanda and Burundi, which are currently malaria free, may become suitable environments for malaria mosquitoes (IPCC 2007b). Understanding the human-scale impacts of climate change in Africa requires detailed predictions of how rainfall may change in the future, particularly over the next few decades. Currently, the understanding of how climate will change over the next century is largely informed by the projections of the global coupled climate models used in the Fourth IPCC assessment report on climate change (IPCC 2007a).

The degree to which confidence can be placed in climate model projections is to some extent determined by their ability to adequately represent the present day climate. On global scales, climate models can make credible simulations of the temperature record of the twentieth century (IPCC 2007a) and of the response of global temperatures to major climatic events, such as the eruption of Mount Pinatubo or the El Niño-Southern oscillation (ENSO) in the Tropical Pacific. In general, however, the current generation of climate models simulate climate on much larger spatial scales than those relevant for climate impacts. For example, crop models are often based on processes that occur at the scale of individual fields (Hansen and Jones 2000) or homogeneous geographical regions (Challinor et al. 2004). Down-scaling predictions of rainfall using regional climate and statistical models are common methodologies for providing information at smaller spatial scales, but their use can be problematic (Jenkins and Lowe 2003).

The requirement that climate models need to be capable of making detailed predictions has provided the impetus for the development of a new range of climate models (K1-Developers 2004, Shaffrey et al. 2009). These global climate models have *higher resolutions* than those used in the current generation of climate models. Climate models represent quantities such as temperatures, winds, and clouds at specified locations on the globe. This set of locations is often given in the form of a grid, and each point of the grid represents the area surrounding it (the "grid box"). A higher resolution climate model with smaller grid-boxes can represent processes on smaller spatial scales than a coarser resolution climate model. Climate models with higher resolution should be more capable of resolving local circulations, and of capturing important processes such as the impact of mountain ranges and variations of the land surface on the geographical distribution of rainfall. High-resolution climate models are therefore better suited, in principle, for providing input for impact-related studies.

Assessing the suitability of climate models for forcing impacts models, however, requires an evaluation of climate model performance on the relevant regional scales. Such an evaluation can be hindered by low availability of in-situ observational data. A lack of observations also limits our ability to understand what processes are most in need of improved representation in climate models. Over much of Africa, in particular, the observations network is sparse and there are few observational records with long time periods (for example, Conway et al. 2004). Nevertheless, in some regions enough observations exist to make a meaningful comparison between climate models and observations. In particular, over Ethiopia a climatology of rain gauge measurements has recently been produced (Diro et al. 2009), which for the first time allows a detailed assessment of the simulated rainfall on a regional scale over the Ethiopian region.

The geography of Ethiopia presents a difficult test for climate models. The central part of Ethiopia is dominated by the East African Highlands (the Semain and Bale mountains) which split the country climatically (Fig. 1). In the south and east of the country, prevailing conditions are semi-arid, with the rains falling in two short spells before and after the dry season of Kiremt (June to September). In the north and west the vegetation is denser, and Kiremt is the major rainy season (Diro et al. 2009). The spatially inhomogeneous distribution of rainfall, with differing seasonal cycles in different regions of Ethiopia imply stringent requirements for resolution and accuracy in climate models. Furthermore, the year-to-year (interannual) variability of Ethiopian rainfall, and the circulations which control it (such as the Inter-Tropical Convergence Zone, ENSO, the Indian Monsoon, and the African Easterly Jet (AEJ)), also need to be correctly represented in climate models. Disentangling these remote influences on the climate of Ethiopia, and correctly simulating them in a climate model is challenging. More details of these remote

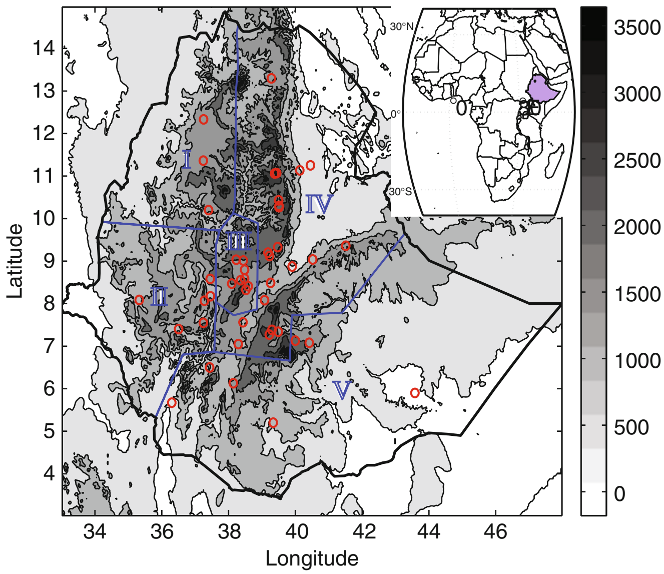


**Fig. 1** The topology of Ethiopia. *Circles* indicate the locations of the rain gauges in the Kriged rainfall dataset. Delineates the geographical rainfall zones used in this study

influences are described in the chapter, *Large scale features affecting Ethiopian rainfall*.

In this chapter we assess the ability of two IPCC-class global atmospheric climate models to simulate the observed rainfall and circulation patterns over Ethiopia. The first is a current generation model, HadAM3 (Gordon et al. 2000), and the second a higher resolution climate model, HiGAM (Shaffrey et al. 2009). We focus on the impacts of higher resolution, and in particular we address the following questions:

- How well can climate models represent the geographical distribution, the seasonal cycle and the interannual variability of rainfall over Ethiopia?
- What improvements in the representation of regional climate can be expected from using higher resolution climate models?
- Where the climate model simulations are poor, can we understand the causes?

In the next section the details of the observational datasets and the climate models used in this study are given. In Section 3 the ability of climate models to simulate the geographical distribution and seasonal cycle of Ethiopian rainfall is described. Section 4 focuses on the interannual variability of rainfall over Ethiopia. Conclusions are discussed in Section 5.

## 2 Models, Observations and Methodologies

The primary focus of this study is to investigate the ability of climate models to simulate rainfall over Ethiopia. This is done by integrating an atmospheric climate model with prescribed sea-surface temperatures (SSTs) as the lower boundary condition. This allows the climate model's simulation of the atmosphere to be studied without the added complication of SST errors that are typically introduced in the fully coupled ocean-atmosphere simulations. Spatially and temporally resolved SST data-sets for this use are made available from continuous observations taken by a variety of methods (ship observations, buoy measurements, and satellite radiances) over the historical period, starting from the late nineteenth century (e.g. Rayner et al. 2003).

The two atmospheric climate models analysed in the present chapter are HadAM3 and HiGAM. HadAM3 was developed by the Met Office Hadley Centre (Gordon et al. 2000, Pope et al. 2000) and has a horizontal resolution of 3.75° longitude by 2.5° latitude with 19 levels in the vertical. HadAM3 was used with an ocean model in a coupled ocean-atmosphere configuration, known as HadCM3, in the third IPCC assessment report on climate changes (IPCC 2001). In this study HadAM3 has been forced using the 1969–2001 HadISST SST dataset (Rayner et al. 2003).

HiGAM is the atmosphere-only version of a high-resolution coupled climate model known as HiGEM. HiGEM is based on the latest coupled climate configuration of the Met Office Unified Model, HadGEM1 (Johns et al. 2006, Martin et al.

2006, Ringer et al. 2006). HadGEM1 contributed to the fourth IPCC assessment report (IPCC 2007a). In HiGAM, the horizontal resolution of the atmosphere is increased to 1.25° longitude by 0.83° latitude and there are 38 levels in the vertical. For the integration discussed in the present study, HiGAM was driven with 1983–2002 SSTs from the AMIP2 dataset (Fiorino 2000).

As mentioned in the introduction, evaluating climate models is difficult over Africa due to the sparse nature of the observational network. This study takes advantage of a recently analysed Ethiopian rainfall dataset, based on a network of rain gauges which provides relatively dense coverage over regions of Ethiopia (Diro et al. 2009). The rain gauge dataset consists of 45 Ethiopian stations covering a period of 33 years (1969–2001). The data is quality-controlled for missing values and outliers (Diro et al. 2009). In order to compare the gauge values and the model outputs at the same spatial scales, gauge data (point values) are converted to area averages. Block Kriging was used to to convert the gauge measurements to ERA-40 grid squares. The process of calculating grid square estimates from gauge data using block Kriging is described in detail in Diro et al. (2009). The Kriging interpolation method not only provides best estimates but also the associated uncertainties. To avoid problems associated with sparseness of gauge network, only grid boxes containing at least one gauge were used in the analysis.

An alternative methodology for providing continuous spatial coverage of rainfall estimates with only a sparse network of rain gauges, is to merge and calibrate satellite estimates of precipitation rates with rain gauge data. In this study, use is also made of such a merged rain gauge and satellite rainfall dataset, known as CMAP (Climate Prediction Center's Merged Analysis of Precipitation, Xie and Arkin 1997). CMAP covers the period 1979–2001 and is produced on a 2.5° × 2.5° grid.

The dynamical fields in the climate models, such as winds and upper tropospheric streamfunction, will be evaluated against a reanalysis dataset. Reanalyses assimilate a wide range of observations (for example, surface station data, satellite radiances and tropospheric soundings) into a high-resolution numerical model, such as those used by operational weather-prediction centres. For the dynamical fields the observations can provide strong dynamical constraints on the model and so the reanalysis will have good spatially homogeneous estimates. In this study the dynamical fields from the climate models will be evaluated against the ERA-Interim reanalysis (European Centre for Midrange Weather Forecasts Interim Reanalyses, Simmons et al. 2007, Uppala et al. 2008).

ERA-Interim is the successor to the ERA-40 reanalysis dataset (Uppala et al. 2005). ERA-Interim aims to improve on a number of known issues in ERA-40. The issues that are particularly relevant for this study are that ERA-Interim has a higher horizontal resolution (T255, approximately 50 km) than ERA-40 (T159, approximately 90 km). ERA-Interim also includes an improved scheme for assimilating observations of upper tropospheric water vapour. Furthermore, ERA-40 was seen to overestimate Ethiopian rainfall during the season of Kiremt (June to September, JJAS) when compared to Ethiopian rain gauge measurements (Diro et al. 2009).

## 3 Ethiopian Rainfall in HadAM3 and HiGAM

The focus of this section is on the ability of two climate models to simulate the geographical distribution of rainfall during the season of Kiremt (June to September), when most of the rain in Ethiopia falls in the regions to the north and west of the East African Highlands. The ability of the climate models to capture the very different seasonal cycles of rainfall in different regions of Ethiopia is also evaluated.

### *3.1 The Geographical Distribution of Kiremt Rainfall*

The geographical distribution of rainfall in Ethiopia is strongly determined by the regional topography and seasonal evolution of the large-scale circulation. Ethiopia is split into two climatically distinct regions by the East African Highlands, where mountain peaks above 3,500 m are common (see Fig. 1).

The observed Kiremt (JJAS) geographical distribution of rainfall from the Kriged rainfall gauge dataset and the CMAP merged rainfall dataset are shown in Fig. 2. Both observational datasets shows a gradient in the rainfall distribution which runs from south-west to north-east. To the north and west Kiremt rainfall is in excess of 1,000 mm, while in the south-east it is less than 100 mm. The distribution of Kiremt rainfall from ERA-Interim is also shown in Fig. 2. Although the large scale gradient in rainfall is captured in ERA-Interim, the reanalysis greatly overestimates the Kiremt rainfall over the East African Highlands. This error is similar to that found in the ERA-40 reanalysis (Diro et al. 2009).

Figure 2 also shows the Kiremt rainfall from the HiGAM atmospheric climate model. HiGAM is capable of capturing the main features of the rainfall during Kiremt. The model produces a reasonable simulation of the observed south-east to north-west gradient and correctly places the rainfall maximum just to the west of the East African Highlands.

### *3.2 The Seasonal Cycle of Rainfall in Ethiopia*

In addition to capturing the spatial pattern of rainfall, climate models should be able to provide a reasonable simulation of the seasonal cycle of rainfall. Because of the high spatial variation of rainfall over Ethiopia, both in terms of the seasonal cycle and the interannual variability, Ethiopia is aggregated into a number of homogeneous rainfall zones (see Fig. 1). Two criteria were used to identify these homogeneous rainfall zones, namely the similarities of seasonal cycle and the interannual correlations of seasonal rainfall (Gissila et al. 2004, Diro et al. 2009). In this section, the focus will be on evaluating the ability of the climate models to simulate the seasonal cycle of rainfall in Zone I (the north-west) and Zone V (the south-east). Zones I and V are located at the extremities of the south-east to north-west gradient of rainfall across Ethiopia. They were also chosen as they typify the different seasonal cycles of rainfall found in different regions of Ethiopia.

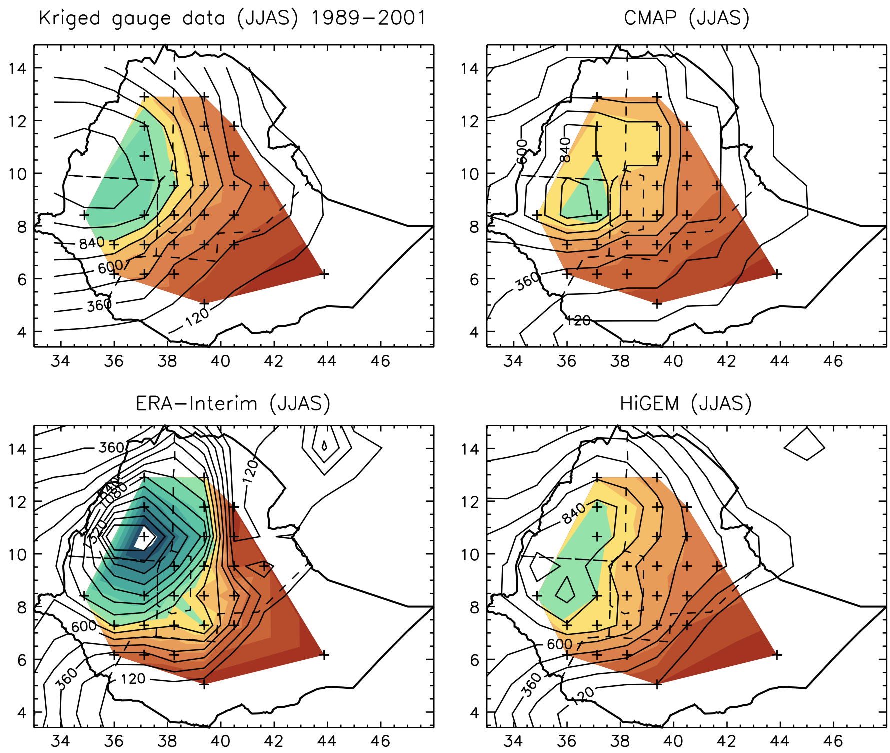


**Fig. 2** Geographical distributions of Kiremt (June, July, August, September) total rainfall (mm) from the Kriged gauge data, the CMAP merged rainfall dataset, the ERA-Interim reanalysis and the HiGAM atmospheric climate model. The Kriged data, ERA-Interim and HiGAM are all interpolated onto a grid of 1.125° × 1.125°. CMAP data remains on its 2.5° × 2.5°. The *black* contours indicate a surface of minimum curvature through the four gridded datasets. The coloured contours are bilinearly interpolated through grid-points that contain at least one rain gauge in the Kriged dataset (indicated by the *black crosses*)

The seasonal cycle of simulated and observed rainfall for Zone I is shown in Fig. 3. In the Kriged gauge dataset the rainfall reaches a seasonal maximum of roughly 300 mm in July and August. Similar to most of North Africa, the seasonal maximum of rainfall in Zone I coincides with the northernmost migration point of the Intertropical Convergence Zone (ITCZ) in summer. During the rainiest months of July and August, CMAP estimates the rainfall in Zone I to be roughly 50 mm month$^{-1}$ less than that seen in the Kriged gauge dataset.

The seasonal cycle in Zone I from the ERA-Interim and ERA-40 reanalyses are also shown in Fig. 3. Diro et al. (2009) found that ERA-40 greatly overestimated the rainfall during Kiremt in the north-west of Ethiopia. During the months of July and August, the ERA-Interim reanalysis similarly overestimates the Zone I rainfall by approximately 100 mm month$^{-1}$ against the Kriged gauge dataset. The seasonal cycles of rainfall from Zone I in the atmospheric climate models, HadAM3 and

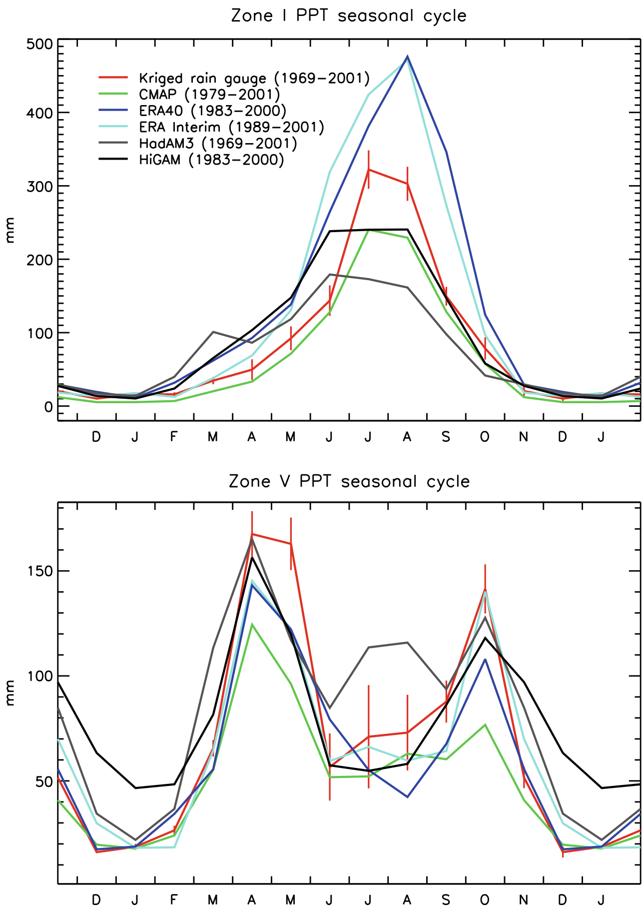


**Fig. 3** Seasonal cycles of total monthly rainfall (mm) from the (*Upper panel*) North Western Zone I and the (*Lower panel*) South Eastern Zone V for the Kriged gauge data, the CMAP merged rainfall dataset, the ERA40 and ERA-Interim reanalyses and the HiGAM and HadCM3 atmospheric climate models. *Vertical lines* on the Kriged gauge dataset are 68% confidence limits

HiGAM, are also shown in Fig. 3. HadAM3 is capable of capturing a seasonal maximum of rainfall, but slightly overestimates the rainfall in March, April and May and tends to underestimate the rainfall by roughly 100 mm month$^{-1}$ during July and August. HiGAM is also capable of capturing the seasonal cycle of rainfall in Zone I. There is a similar tendency to overestimate the rainfall in springtime and underestimate the rainfall in Kiremt, although the underestimation in Kiremt is much less than that seen in HadAM3.

The seasonal cycle of rainfall in Zone V (south-east) from the Kriged gauge and the CMAP merged datasets is also shown in Fig. 3. In the south-east of Ethiopia, the seasonal cycle of rainfall is different from that in the north-west. In Zone V, the rainfall is associated with northward (spring) and southward (autumn) migration of ITCZ, and is similar to that seen in equatorial and south-eastern Africa. Hence the rains fall in two short spells before and after the dry season of Kiremt (June to September). The CMAP merged dataset again produces lower lower rainfall rates than those seen in the Kriged gauge dataset. This is most apparent during the rains that fall in April and October, when the CMAP merged dataset rainfall rates are 50 mm month$^{-1}$ lower than the Kriged gauge dataset. The seasonal cycles of rainfall in both the ERA-40 and ERA-Interim reanalyses are also shown in Fig. 3, and are very similar to those in the CMAP merged and Kriged gauge datasets. The atmospheric climate models, HadAM3 and HiGAM, also provide a reasonable simulation of the seasonal cycle in Zone V, simulating rains in April and October that fall on either side of the drier Kiremt season. HadAM3 has a tendency to rain too much during Kiremt, while HiGAM simulates too much rainfall during winter (DJF).

In summary, both HiGAM and HadAM3 are capable of capturing the general sense of the different seasonal cycles in north-west (Zone I) and south-east (Zone V) of Ethiopia. Both HadAM3 and HiGAM, however, fail to capture the observed seasonal cycles perfectly. Both models produce too much rain during springtime in Zone I. During Kiremt, HadAM3 has a tendency to rain too little in the north-west and too much in the south-east. HiGAM tends too produce too much rain during wintertime in the south-east. The ERA-Interim reanalysis greatly overestimates the rainfall in the north-west (Zone I) of Ethiopia during Kiremt, which is a very similar error to that seen in the ERA-40 reanalysis (Diro et al. 2009).

## 4 Interannual Variability of Ethiopian Rainfall

Kiremt rainfall over Ethiopia is subject to large year-to-year variations. In the north-western region of Zone I, where Kiremt is the main rainy season, the rainfall between the driest year and wettest year vary by almost a factor of two. These variations are related to changes in the atmospheric circulation both at regional and at planetary scales. Capturing such variability in models and understanding it theoretically from the point of view of the atmospheric circulation is one of the most important practical remits of climate science. Both climate models and reanalysis products are suited as tools for such studies in that they maintain an internal consistency over time of the represented associations between circulation and rainfall anomalies. (It should be noted that such is not the case for forecast products.) However, such consistency does not, in general, carry across different models or across different reanalysis products, and the mechanisms that generate rainfall variability in one particular region are not necessarily the same between different models, between models and reanalysis products, or between different reanalysis products. Additionally, it needs to be kept in mind that, due to the procedure of assimilating data into a model, reanalysis products do not guarantee complete physical consistency between their representation of the dynamical state of the atmosphere and the tendencies implied by their representation of the diabatic processes (such as rainfall) forcing that dynamics.

In summary, the association between rainfall anomalies and circulation anomalies can vary from one case to another, and no model or product can (and should) be taken on faith when attempting to assess such associations. Both a comparison between data-sets and a conceptual interpretation of the results are necessary in order to make a scientifically defensible use of model and reanalysis data. It may be appreciated that this is a very challenging task, which requires a dedicated and sustained scientific effort for each area of the world separately. The present short section merely attempts to provide and example discussion of such work for the case of Kiremt rainfall in Zones I and V of Ethiopia.

## *4.1 Kiremt Rainfall Time-Series*

Figure 4 show the Kiremt total accumulated precipitation for each year in the Kriged gauge data-set, in the CMAP product, in the ECMWF reanalysis products, and in the two atmospheric climate models HadAM3 and HiGAM. Two main features should be noted. First, the correlations between the two different observational products are positive but imperfect. For Zone I, in particular, CMAP has a correlation of only 0.4 with the rain-gauges, which is formally not significant. In other words, the two data-sets do not agree as to which years in the past were particularly wet or which were particularly dry in Zone I. In Zone V, however, they agree rather well. Second, the two reanalysis products, albeit issued by the same institution and based on different versions of the same model, disagree even more between themselves over the period of overlapping data. This is expected, in that ERA-Interim has been created explicitly in order to obviate for some of the shortcomings of ERA-40, of which the representation of atmospheric humidity, and convective precipitation, is one. The errors in ERA-40 tend to result in a constant offset towards wet conditions (Diro et al. 2009); but, somewhat surprisingly, here we find that the offset is just as large in ERA-Interim, while the more significant improvement appears to be in the inter-annual variability. Indeed, the agreement between the gauge data and ERA-Interim is much better (correlations of $c \approx 0.7$) than that of ERA-40 ($c \approx 0.3 - 0.4$) Finally, HiGAM shows the best correspondence with the gauge data in Zone I ($c > 0.7$); while in Zone V, it misses the excess rainfall of 1996, even while comparing well with the observations up to 1993. The lower-resolution model considered here, HadAM3, suffers from a poor separation of the two zones in terms of rainfall. Thus, Zone I tends to be too dry, and Zone V too wet. Moreover, the variability in Zone I is much too weak, even if it has a significant correlation with the gauge data-set.

The errors in the precipitation estimates from the Kriged gauge data-set are around 10% for Zone I, and 30–40% for Zone V. For the latter, this implies that much of the apparent variability is not significant, or in other words that small year-to-year variations of the precipitation are very uncertain. Thus, based on these error estimated, statistical correlations between data-sets for Zone V are not meaningful. Nevertheless, wet and dry years are to some extent well separated, with the wettest

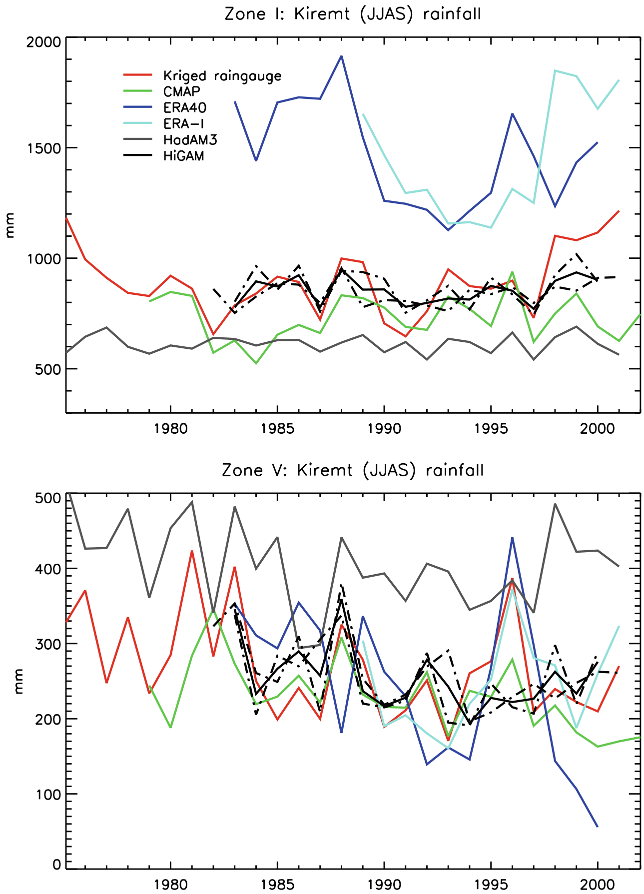


**Fig. 4** Timeseries of Kiremt (JJAS) rainfall from (*Upper panel*) Zone I and (*Lower panel*) Zone V for the Kriged gauge data, the CMAP merged rainfall dataset, and the ERA40 and ERA-Interim reanalyses, the HadAM3 integration and two integrations of the HiGAM atmospheric climate model (*dashed-dotted black lines*) and the mean of the two HiGAM integrations (*solid black lines*)

years in the 1983–2000 period being 1983, 1988 and 1996, with a Kiremt-total average rainfall of 371±45 mm, and the driest years 1985, 1990 and 1993, with a mean of 186±46 mm. For Zone I, the measured year-to-year variations are significant and correlations are meaningful. The three wettest years in the 1983–2000 period are here 1998, 1999 and 2000, with an average of 1,100±50 mm, and the three driest years 1990, 1991 and 1997, which average 694±48 mm.

To simplify the following discussion we shall concentrate on the data-set from in-situ observations, which are intrinsically more reliable than satellite-based estimates, and on the newer reanalysis product, ERA-Interim, and model, HiGAM. This choice can be justified both from a-principio arguments, as the newer products supersede, and improve on, the older ones, and higher-resolution models are expected to simulate the real system, and thus perform, better; and from the fact that the best agreement is indeed found among these three data-sets, giving some confidence that they may be the closest ones to reality.

## *4.2 Kiremt Rainfall and Atmospheric Circulation Anomalies*

In the deep tropics, precipitation is essentially controlled by two factors: the availability of atmospheric moisture and the convergent motions determined by the dynamical forces acting on the circulation. The high surface air temperatures and the intense exchange of radiation imply that atmospheric moisture is generally cycled much more rapidly than in the extratropics, and thus local or regional circulations generally have much greater consequences for the amount precipitation falling in a particular area. At the same time, however, the rapidity and efficiency (or lack of dissipation) with which dynamical anomalies are transmitted around the tropics imply that regional circulation anomalies are often associated with changes in the circulation at the planetary scale.

In general terms, no single mechanism can explain rainfall variations over Ethiopia, because it is controlled by a combination of several processes. These have been variously documented in the literature as the strength of the Tropical Easterly Jet, the strength and position of ITCZ, the moisture influx from the Indian and Atlantic Oceans, the entrance of AEJ over north-eastern Africa, and also the strength of the Quasi-Biennial Oscillation (Kassahun 1987, Camberlin 1995, Segele and Lamb 2005, Segele et al. 2009, Grist and Nicholson 2001, Nicholson and Grist 2003; Diro et al. 2009).

The cumulative impact from these dominant features of the summer-season circulation over tropical Africa on rainfall in Ethiopia varies between the different zones. In this respect Zone I is similar to most parts of north Africa, where rainfall coincides with the north-most point of migration of the ITCZ in northern-hemisphere summer. By contrast, in Zone V, like in much of equatorial and south-eastern Africa, rainfall is associated with both northward (spring) and southward (autumn) seasonal migrations of the ITCZ and hence summer is a dry season.

Here we focus on the circulations associated with precipitation anomalies in Zones I and V of Ethiopia. The case of Zone I is the simplest, as all three data-sets considered here agree in terms of wet and dry years, and the consistency between the HiGAM model and the ERA-Interim reanalysis is good. Figure 5 shows, for each of the two dynamical data-sets, the most important differences in the circulation between years in which Zone I receives excess Kiremt precipitation and years in which it is deficient. The streamfunction anomalies indicate a strengthening of the zonal flow over the tropical Pacific and a weakening, on average, elsewhere, which corresponds to globally cool conditions in the upper troposphere of the deep tropics. Such anomalies are characteristic of La Niña years, when diabatic heating from moisture condensation is more zonally confined to the Eastern Indian and West Pacific sector, and globally weaker. Indeed, the three excess years for Zone I follow

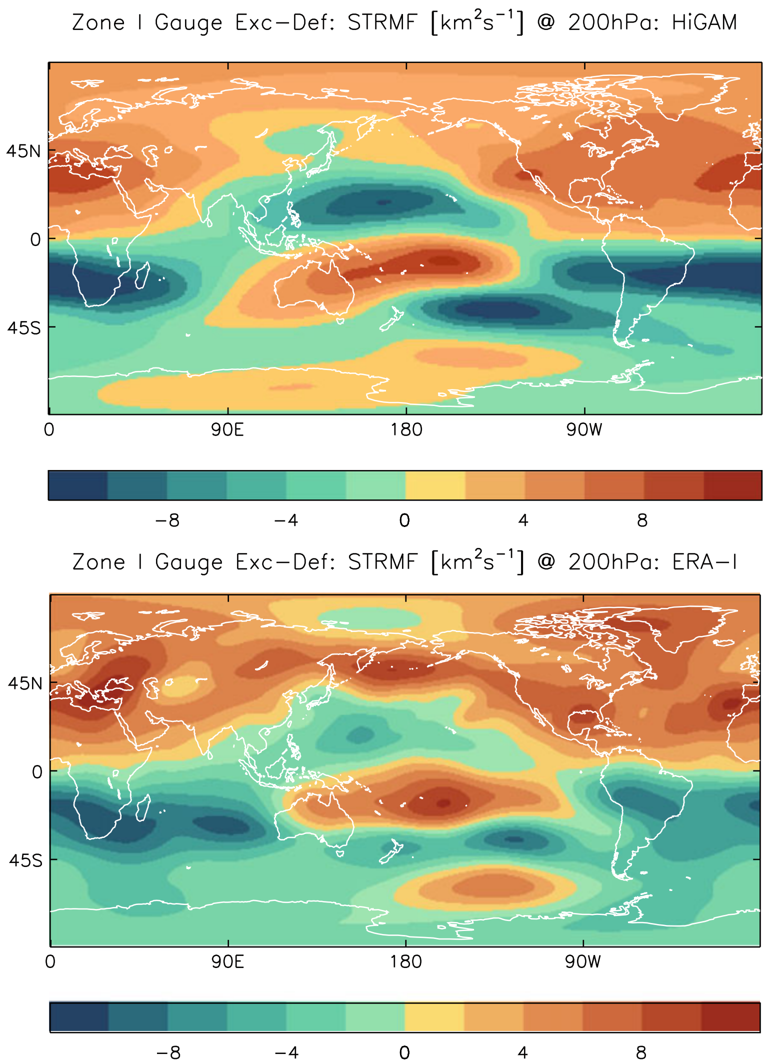


**Fig. 5** Circulation differences for Kiremt (JJAS) excess minus deficit rainfall years in Zone I. *Upper*: 200 hPa streamfunction differences in HiGAM based on excess minus deficit rainfall in the Kriged gauge data. *Lower*: The same as the *upper panel* but for the ERA-Interim reanalysis (Refer online version for color images)

the extreme 1997/1998 El Niño, which was so strong that the Equatorial Pacific was left depleted of heat for several following years (starting with the summer of 1998), causing persistent cool SSTs in the central Pacific. Other wet years that stand out in Fig. 4, such as 1988 and 1993, were also La Niña summers; while the dry years 1991 and 1997 saw El Niño conditions. Over tropical north-eastern Africa, the relative cool conditions in the deep tropics entail a strengthened inverse meridional temperature gradient with the warm Saharan and southern Mediterranean region, and thus an intensification, and an increase in elevation, of the seasonal AEJ. Ethiopian Zone I is located at the jet entrance of the AEJ. The zonal acceleration of the jet is associated with a southward drift, advecting air of high vorticity (corresponding to a higher value of the Coriolis parameter) into the area. Such advection is dynamically compensated by vortex compression, which implies an upward motion of the air underlying the AEJ entrance. A second mechanism which may be also contributing depends on the presence of orography, in the lee of which cyclonic flow is generated, with increased intensity when the easterly flow is stronger. Thus extra Kiremt precipitation in Zone I appears to be associated with exceptionally intense mechanical forcing of ascent due to the intensified AEJ, which in turn is associated with global upper-tropospheric cold conditions typically fond in La Niña years.

The circulation anomalies associated with Zone V are more subtle. They appear to be related more closely with atmospheric moisture availability than with dynamical forcing. They are shown in Fig. 6. For HiGAM, we have to distinguish between years that are wet/dry in the model, and years that are wet/dry in the gauge data-set, since they do not coincide. Considering the differences between "internal" excess and deficit years (as before for Zone I), we notice a weakening in the low-level circulation of the Indian Summer Monsoon in HiGAM. The Indian Summer Monsoon circulation is divergent over the southern and eastern Indian Ocean, where moisture is picked up from the ocean and conveyed toward the Indian subcontinent. A reduction in the divergent flow allows more moisture to accumulate locally. The panel on the upper-right of the figure shows that this excess moisture is advected in the Somali jet towards the relatively drier area of south-eastern Ethiopia. This apparent relationship is partially lost when considering actual (i.e., gauge-data) wet and dry years (see the two panels in the middle row of Fig. 6). Although the large-scale anomalies in winds and moisture are very similar, locally there is no net advection of additional moisture over Zone V, and the selected years are not particularly wet or dry in HiGAM. The association between Zone V rainfall and circulation represented by ERA-Interim (bottom two panels in the figure) is quite different. In this case, the "intrinsic" excess and deficit years coincide with those from the gauge data. Again, moisture availability seems to be the determinant factor, but the causative mechanism is another. Here, the air over south-eastern Indian ocean is anomalously dry, and no additional moisture is carried to Zone V from there. Instead, strengthened westerly winds across the African continent are responsible for bringing additional moisture from the Atlantic. Consistently with such different associations, excess Kiremt rainfall in Zone V corresponds with a wetter-than-normal Horn of Africa in HiGAM, but not in ERA-Interim, where the extra rain mostly falls in the southern and western orographic slopes of southern Ethiopia.

A different source of moisture thus appears to cause the discrepancy between HiGAM and ERA-Interim in Zone V. This is an aspect of a more general error of the circulation as represented in HiGAM, where the Indian Summer Monsoon fails to bring an amount of rain over India comparable to the observed one. Instead, rain falls over the Equator in the eastern Indian Ocean, where the low-level flow is convergent instead of divergent, and conversely for the upper-level flow. This error, relative to the ERA-Interim reanalysis, is shown in Fig. 7. Consistently with the presence of active atmospheric convection over the region, in the eastern Indian

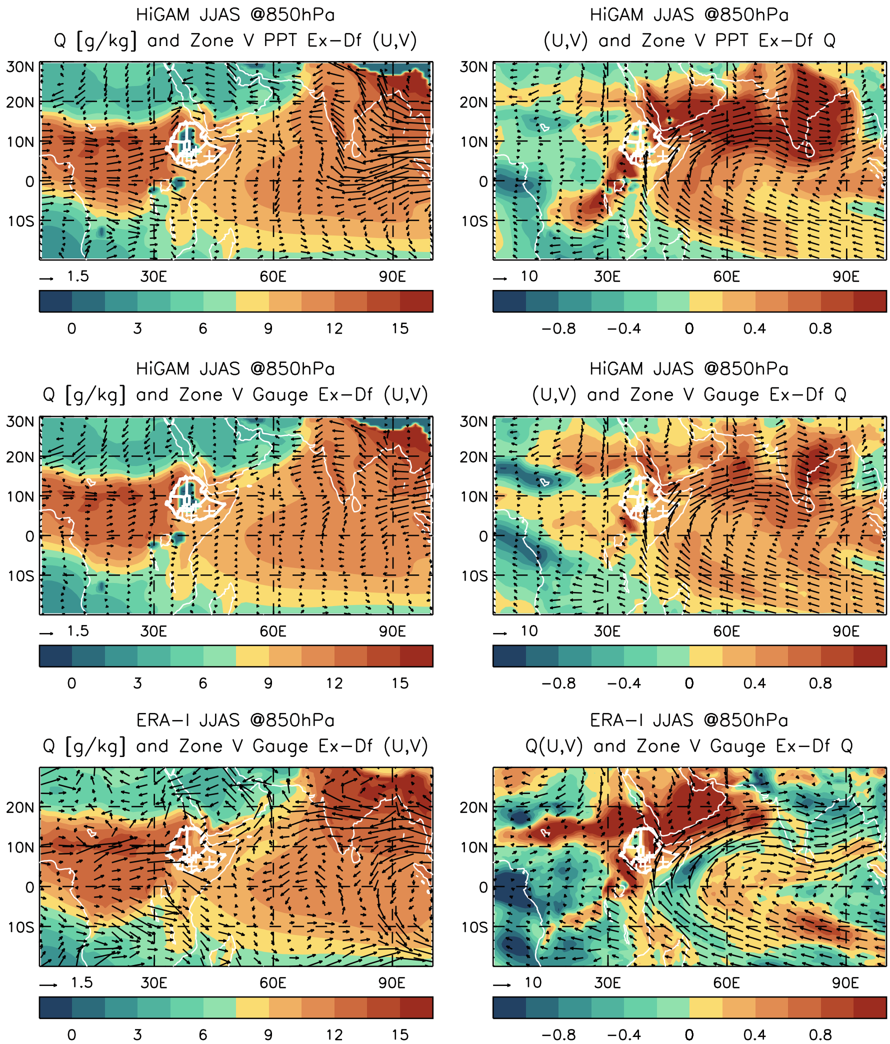


**Fig. 6** Circulation differences for Kiremt (JJAS) excess minus deficit rainfall years in Zone V. *Upper left*: 850 hPa wind vectors differences overlayed on the climatological values of 850 hPa specific humidity in HiGAM based on excess minus deficit JJAS rainfall years in the HiGAM model. *Upper right*: 850 hPa specific humidity differences overlayed on the climatological 850 hPa wind vectors of in HiGAM based on excess minus deficit rainfall in the HiGAM model. *Middle panels*: The same as for the *upper panels* but for HIGAM differences based on the JJAS excess minus deficit rainfall years in the Kriged gauge dataset. *Lower panels*: The same as the *upper panels* but for ERA-Interim differences based on the JJAS excess minus deficit rainfall years in the Kriged gauge dataset

Ocean the upper levels in HiGAM are dry relative to the reanalysis, and the low levels are relatively moist. This allows the Indian Ocean to act as a source of moisture for the precipitation in south-eastern Ethiopia in this model. While we cannot, therefore, have confidence in the HiGAM simulation of the variability of Zone V

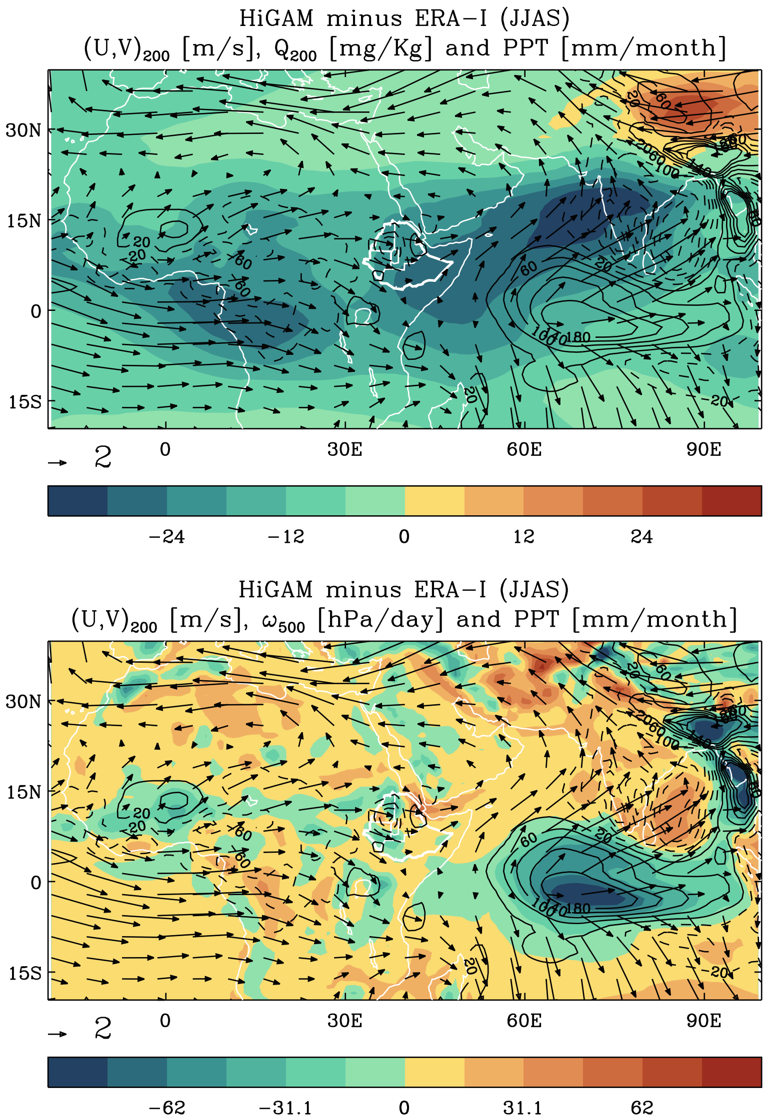


**Fig. 7** Kiremt (JJAS) 1989–2001 climatological differences for HiGAM minus ERA-Interim. *Upper*: Vectors are 200 hPa wind differences ($ms^{-1}$), colours are 200 hPa specific humidity differences (mg $kg^{-1}$) and black contours are precipitation differences (mm $month^{-1}$). *Lower*: Vectors and black contours the same as for the *upper panel*. Colours are 500 hPa vertical pressure velocity (omega) differences (hPa $day^{-1}$) (Refer online version for color images)

Kiremt rainfall, one must nevertheless also exert caution with the use of reanalysis data, because rainfall is not assimilated unto the underlying ECMWF model, but generated by it, and the details of the mechanisms involved still need to be subject to verification.

## 5 Conclusions and Discussion

Assessing the likely impacts of climate change will require climate predictions on regional scales. This is especially true for Africa, where agriculture and disease transmission are particularly sensitive to changes in rainfall. The focus on the ability of climate models to predict changes at regional scales will require greater emphasis on regional-scale evaluations of climate models.

In this study, a regional evaluation of rainfall over Ethiopia in two atmospheric climate models, HadAM3 and HiGAM, has been carried out. Use has been made of a recently developed Kriged dataset of rainfall from 45 rain gauges. Modelling the rainfall over Ethiopia in climate models is challenging. The East African Highlands dominate the central part of Ethiopia, and split the country into two climatically different regions. To the north-west of the Highlands the rains fall during the season of Kiremt (June to September). To the south-east of the Highlands Kiremt is the dry season, and the rains fall before and after Kiremt in April and October.

HadAM3, a current generation climate model, and HiGAM, a new high-resolution climate model, are both able to correctly represent aspects of the complex spatio-temporal patterns of rainfall over Ethiopia. Both models are capable of capturing the different seasonal cycles in different regions of the country. In the north-west of Ethiopia (Zone I) the climate models simulate a seasonal maximum of rainfall in Kiremt (JJAS). In the south-east of the Ethiopia (Zone V) both models can also simulate the rains in the months of April and October. Although HadAM3 is capable of capturing the general sense of the seasonal cycles in Zones I and V, the model has significant biases. This is particularly true in Kiremt, when HadAM3 produces too little rain the north-west and too much in the south-east. In HiGAM the biases in rainfall are less, although HiGAM has a tendency to rain too much in wintertime in the south-east of Ethiopia (Zone V). The high-resolution model, HiGAM, is also capable of capturing the detail that is seen in the observed spatial pattern of rainfall, particularly around the steep slopes of the East African Highlands, which the model is better able to resolve.

The mechanisms of year-to-year variability in rainfall have also been investigated in this study. In both the HiGAM model and the ERA-Interim reanalysis, years of excess rainfall in the north-west of Ethiopia (Zone I) are associated with La Niña. During La Niña years, the easterly winds to the north of Ethiopia are intensified. These easterly winds correspond to the jet exit of the upper-level Tropical Easterly Jet and the jet entrance of the mid-level AEJ. The intensification of this easterly flow leads to dynamical forced ascent and increased rainfall over Zone I. In the south-east of Ethiopia (Zone V), the processes governing year-to-year variability of rainfall are more closely associated with changes in the local circulation that supply moisture to the region. In the ERA-Interim reanalysis, excess years are associated with strengthened low-level westerlies supplying moisture from the Atlantic across the Sahel. In HiGAM, years of excess rainfall in Zone V appear to be more influenced by low-level moisture transport from the Indian Ocean. The failure of HiGAM to correctly capture the behaviour seen in the reanalysis is associated with climatological biases in the atmospheric circulation and rainfall over the western Indian Ocean.

These results indicate that climate models, particularly those with higher resolutions, are able to provide a good representation of the regional rainfall over Ethiopia for present day simulations. Predicting how the climate may change on such regional scales, however, is a much more challenging task. This study also highlights how the poor simulation of the interannual variability in rainfall over Ethiopia in HiGAM is closely associated with the large-scale biases in circulation and rainfall over the west Indian Ocean. Understanding the processes that lead to such biases is crucial to improving climate models, and ultimately providing more trustworthy climate predictions.

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# Extreme Rainfall Events over Southern Africa

**Charles J.R. Williams, Dominic R. Kniveton, and R. Layberry**

**Abstract** It is generally agreed that changing climate variability, and the associated change in climate extremes, may have a greater impact on environmentally vulnerable regions than a changing mean. This research investigates rainfall variability, rainfall extremes and their associations with atmospheric and oceanic circulations over southern Africa, a region that is considered particularly vulnerable to extreme events because of numerous environmental, social and economic pressures. As rainfall variability is a function of scale, high resolution data are needed to identify extreme events. Thus this research uses remotely-sensed rainfall data and climate model experiments at high spatial and temporal resolution, with the overall aim of investigating the ways in which sea surface temperature (SST) anomalies influence rainfall extremes over southern Africa. Extreme rainfall identification is achieved by the high resolution MIRA dataset. This comprises satellite-derived daily rainfall from 1993 to 2002 and covers southern Africa at a spatial resolution of 0.1° longitude/latitude. Extremes are extracted and used with reanalysis data to study possible circulation anomalies associated with extreme rainfall. Anomalously cold sea surface temperatures (SSTs) in the central south Atlantic and warm SSTs off the coast of southwestern Africa seem to be statistically related to rainfall extremes. Further, through a number of idealised climate model experiments, it would appear that both decreasing SSTs in the central south Atlantic and increasing SSTs off the coast of southwestern Africa leads to a demonstrable increase in daily rainfall and rainfall extremes over southern Africa, via local effects such as increased convection and remote effects such as an adjustment of the Walker-type circulation.

**Keywords** Southern Africa · Rainfall · Global/regional climate model · Atmospheric circulation · Oceanic circulation · SST

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C.J.R. Williams (✉)
Department of Meteorology, NCAS-Climate, Walker Institute for Climate System Research, University of Reading, Reading, UK
e-mail: c.j.r.williams@reading.ac.uk

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# 1 Introduction

Many climate modelling studies investigating rainfall and associated processes have highlighted the importance of sea surface temperature (SST, also referred to as surface skin temperature), discussing the relationship between SST and rainfall during the past (e.g. Zhao et al. 2007), the present (e.g. Reason and Jagadheesha 2005a) and the future under possible scenarios of climate change (e.g. Hoerling et al. 2006). Over Africa, general circulation model (GCM, also known global climate model) integrations have been undertaken, forced by observed or idealised SST anomalies, to study rainfall variability over large regions such as Africa as a whole (Paeth and Friederichs 2004), northwest Africa (Li et al. 2003) and southern Africa (Reason and Godfred-Spenning 1998, Reason 1998, Rautenbach and Smith 2001, Reason 2002, Misra 2003). Many of these, as well as other recent studies on southern African rainfall and SST relationships, have focused on three ocean basins; remote effects from the Pacific (e.g. Reason et al. 2005, Okeke et al. 2006), and local and remote effects from the Indian Ocean (e.g. Goddard and Graham 1999, Washington and Preston 2006) and South Atlantic (e.g. Reason and Jagadheesha 2005b, Okeke et al. 2006, Reason and Rouault 2006).

In addition, some recent studies (although fewer relative to the GCM work) have used a regional climate model (RCM) to investigate southern African rainfall. For example, Tadross et al. (2006) used the MM5 regional model with differing convection and boundary layer schemes to study intrannual change of southern African rainfall. Experiments to investigate the sensitivity of southern African rainfall to SST anomalies have also been undertaken using regional models, such as the work of Hansingo and Reason (2006) who used southwest Indian Ocean SST anomalies to force the MM5 regional model.

In contrast to the wealth of studies investigating mean rainfall and SST relationships, far less work has been undertaken on southern African daily rainfall variability and, in particular, daily rainfall extremes. These, however, have been especially devastating for regions of southern Africa in recent years, such as in February 2000 when over a million people were displaced by extreme rainfall events associated with Tropical Cyclone Eline (Layberry et al. 2006). Many recent climate modelling studies into changing rainfall variability and associated processes have been necessarily undertaken using monthly, seasonal and annual rainfall totals (e.g. Landman et al. 2001, Bartman et al. 2003, Landman et al. 2005) or at low spatial resolution. This is partly because of limited data availability over much of the subcontinent outside South Africa (Fauchereau et al. 2003, Hughes 2006, New et al. 2006), and partly because of the relatively coarse temporal and spatial resolutions at which GCMs tend to be used (e.g. Ropelewski and Halpert 1987, Zhao et al. 2005, Anyah and Semazzi 2006, Shongwe et al. 2006). Given that the ability to identify rainfall variability and extremes changes depending on the scale used, many studies have therefore not fully investigated the physical mechanisms associated with rainfall variability and extremes.

A possible solution to the two problems of data unavailability and low spatial scale is to use satellite-derived data to identify rainfall extremes, and then use a climate model in global and regional mode at the daily timescale and at high spatial resolution (for the regional model) to investigate the physical mechanisms associated with these extremes. Thus in this chapter rainfall extremes are identified from a new dataset of satellite-derived rainfall at high spatial and temporal resolution, and the corresponding atmospheric and SST structures are observed. An idealised pattern of these observed SST structures is then used in a number of GCM and RCM experiments, with varying magnitudes of SST in order to investigate how an increasing SST anomaly influences southern African rainfall and daily rainfall extremes. In the following section we describe the satellite-derived dataset and the climate model. Section 3 describes the methodology used to: (i) define and highlight daily rainfall extremes; (ii) identify rainfall and the SST region corresponding to these extremes; and (iii) compare the results from the model experiments. The results from the global and regional model experiments are presented and discussed in Sections 4 and 5, respectively. Finally, Section 6 concludes.

## 2 Data and Model Details

### *2.1 Satellite-Derived and Reanalysis Data*

The satellite-derived rainfall data used in this study, produced from the Microwave Infra-red Rainfall Algorithm (MIRA) (Todd et al. 2001), was generated using a technique which combines passive microwave (PM) estimations of instantaneous rain rates with infra-red (IR) imagery from geostationary satellites. Past work has shown that combining these two methods overcomes many of the limitations from using PM data and IR imagery alone (e.g. Ebert et al. 1996, Adler et al. 2001). As described in Williams et al. (2007, 2009a), the algorithm consists of an IR brightness temperature and rain rate relationship, variable in space and time, that is derived from coincident observations of IR brightness temperature data and SSM/I rain rates (Layberry et al. 2006). Daily rainfall data from MIRA are available for the period from 1993 to 2002 and cover the southern African region (0°–34°S, 10°–50°E) at 0.1° latitude/longitude resolution.

The region covered by MIRA, as well as mean annual rainfall for the whole period, is shown in Fig. 1a, where higher rainfall over tropical and equatorial southern Africa can be seen compared to the drier south and west sides of the subcontinent. This rainfall distribution is in agreement with other datasets of rain-gauge data, as suggested by Fig. 1b which shows the mean annual rainfall from the Global Telecommunications System (GTS) network. This figure is somewhat misleading, however, as it implies that in-situ rainfall data are available for all of Africa. This is not true, especially over western countries such as Angola where rain-gauge measurements are sparse. Satellite-derived rainfall estimates provide a solution to this problem, providing near uniform coverage over southern Africa at high spatial and temporal resolution. Details of the validation of this dataset are discussed in Layberry et al. (2006). Whilst it is acknowledged that MIRA covers a relatively short time-period, data from MIRA are not available beyond 2002. Therefore, a caveat of

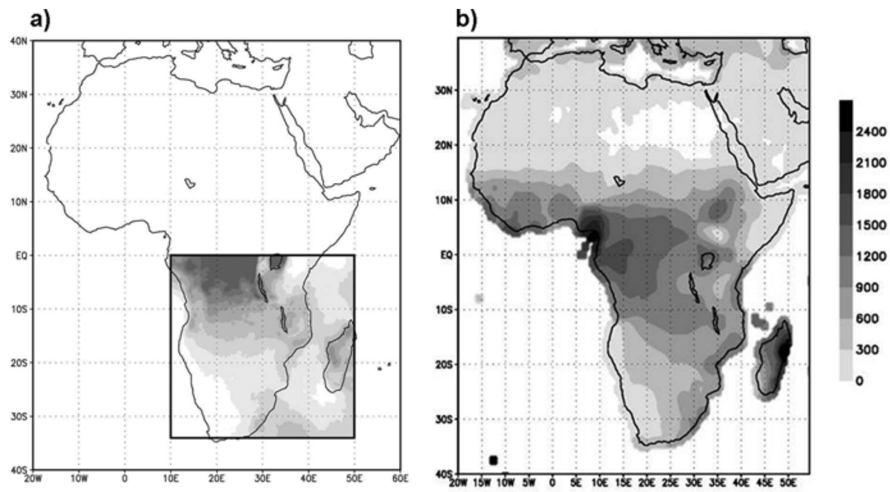


**Fig. 1** Mean annual rainfall from: (**a**) MIRA, covering all of southern Africa at 0.1° spatial resolution for the period 1993–2002; (**b**) the GTS network, covering parts of Africa at 0.5° spatial resolution for the period 1977–2002

this study is that it is limited to using existing data from a satellite-derived dataset which, given the dearth of ground-based rainfall observations throughout Africa, is currently the best available data source.

Reanalysis data were used from the online tools of The NCEP/NCAR 40-year Reanalysis Project at the NOAA-CIRES Climate Diagnostics Center (Kalnay et al. 1996).

Here, we used surface precipitation rate (converted to mm day$^{-1}$), near-surface geopotential heights and SST (converted to °C). It is acknowledged that precipitation rate is a less reliable source than other variables such as precipitable water or OLR, however it was chosen for this study as it provided the clearest comparison with the model simulated data.

## *2.2 Model Details*

For this study we used the Unified Model (UM), which is the collective name for the atmospheric and oceanic numerical modelling software operated by the UK Meteorological Office Hadley Centre. The model includes atmosphere, ocean and coupled components and can be run using either global or regional domains (Van der Wal 1998). Despite the global and regional model used here being described separately, they both stem from the UM and thus are global and regional components of the same model.

In global mode, we used the atmosphere-only component of the UM, HadAM3. This has a spatial resolution of 2.5° by 3.75°, producing a horizontal global grid of 96 points in the East–West direction by 73 points in the North–South direction, and

19 levels in the vertical. The model setup used here meant that surface precipitation rate, near surface (at a level of 850 mb) geopotential heights and near surface winds were available for analysis in this study.

In regional mode, we used PRECIS (Providing REgional Climates for Impacts Studies) which is a standalone version of the regional atmosphere-only component of the UM, HadRM3P. A spatial resolution of 0.5° by 0.5° was used, approximately 50 km at the equator, and the model was run over a limited area of the globe covering Africa south of the equator (including Madagascar) and surrounding waters. This produced a regional grid of 137 points in the East–West direction by 104 points in the North–South direction. A standard UM job was used for both the HadAM3 and PRECIS experiments and thus the parameterisation schemes of the model were not modified in this study. An assessment of how well HadAM3 and PRECIS simulate daily rainfall patterns and rainfall extremes (as shown by the MIRA dataset) is given in Williams et al. (2009a), which suggests that the model reproduces ~72 and ~68% (from HadAM3 and PRECIS, respectively) of the total number of daily rainfall extremes, as well as reproducing the spatial distribution of extreme rainfall with some accuracy.

# 3 Definition and Identification of Extremes, Associated SST Anomalies and Model Experiments

## *3.1 Definition and Identification of Extremes*

In this study we follow the work of Samuel et al. (1999) by defining extreme rainfall events as those rainfall events that were 1.5% of the annual mean. Using this threshold limits the events to the largest 10% of the daily rainfall distribution, which was deemed appropriate for highly variable rainfall regions, such as southern Africa, as it captures a useful number of extreme days. Using a higher threshold would generate less extreme days and would therefore give a poorer signal when used for composite analysis. We adapted the above definition to investigate pixels with extreme rainfall, where an extreme pixel (on a given day) is any pixel where rainfall is greater than 1.5% of the climatological total for that pixel. Covering the southern African region at a spatial resolution of 0.1° (meaning each pixel was ~10 km$^2$), this gave a grid of approximately 136,000 total pixels per day. The number of extreme pixels was then counted for each day, and a day was defined as extreme if the number of extreme pixels exceeded three standard deviations of the total number of extreme pixels.

Figure 2 shows the timeseries of daily extreme pixels for the full MIRA period. The seasonal cycle is evident, with pixel maxima occurring between December and February. Extreme days can be seen as those with pixels exceeding the dashed line in Fig. 2, with extreme days occurring primarily during the long wet season of November–March. Using this threshold, 215 days were defined as extreme during the 10 year period.

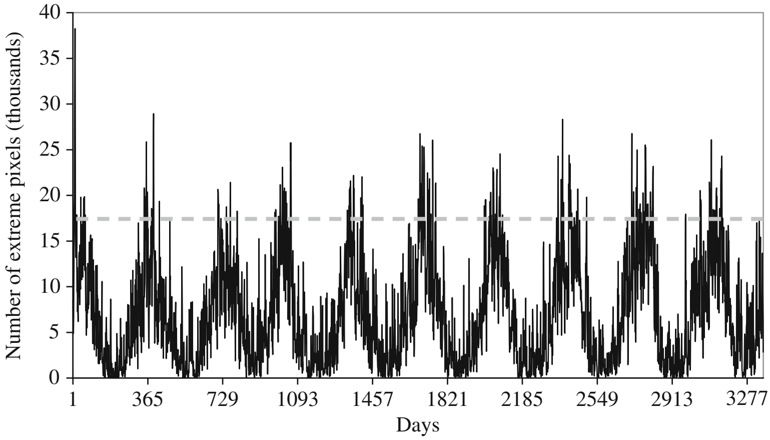


**Fig. 2** Daily extreme pixels from MIRA, 1/1/1993–29/11/2002. *Dashed line* shows threshold used to define an extreme day, corresponding to three standard deviations from the total number of pixels

## *3.2 Rainfall, Pressure and SST Anomalies Associated with Extremes*

The identified extreme days were then used as a basis for composite analysis using data from the NCEP/NCAR 40-year Reanalysis Project (Kalnay et al. 1996), where the composite anomaly from the 1968 to 1996 climatology was used. Figure 3 shows the surface precipitation, near-surface height and SST anomaly for a composite of all identified extreme days. Statistically significant rainfall is widespread throughout southeastern and central southern Africa, with rainfall maxima over the Namibia-Botswana border (Fig. 3a). The near-surface height composite anomaly is shown in Fig. 3b, where a large region of low pressure extends over the majority of subtropical southern Africa and is centred over the region of rainfall maxima. Wind anomalies (not shown) are cyclonic, drawing in moisture from the southeast Atlantic and equatorial southern Africa.

The SST structures associated with the composite of extremes are shown in Fig. 3c. Focusing on the Atlantic, the two most noticeable features throughout the oceans are the large region of statistically significant cold anomalies in the central South Atlantic, and the smaller region of statistically significant warm anomalies (approaching an anomaly of 1°C) close to the Angolan coast. This latter feature

**Fig. 3** (continued) Composite anomaly of rainfall extremes from extreme pixels over southern Africa: (**a**) surface precipitation (mm day$^{-1}$); (**b**) 850 mb geopotential heights (m); (**c**) SST (with land mask) (°C). *Shading* shows regions with >3 mm precipitation anomalies in (**a**) and < –10 m height anomalies in (**b**). *Solid lines* = positive values, *dotted lines* = negative values, *dashed lines* = 90% significance level

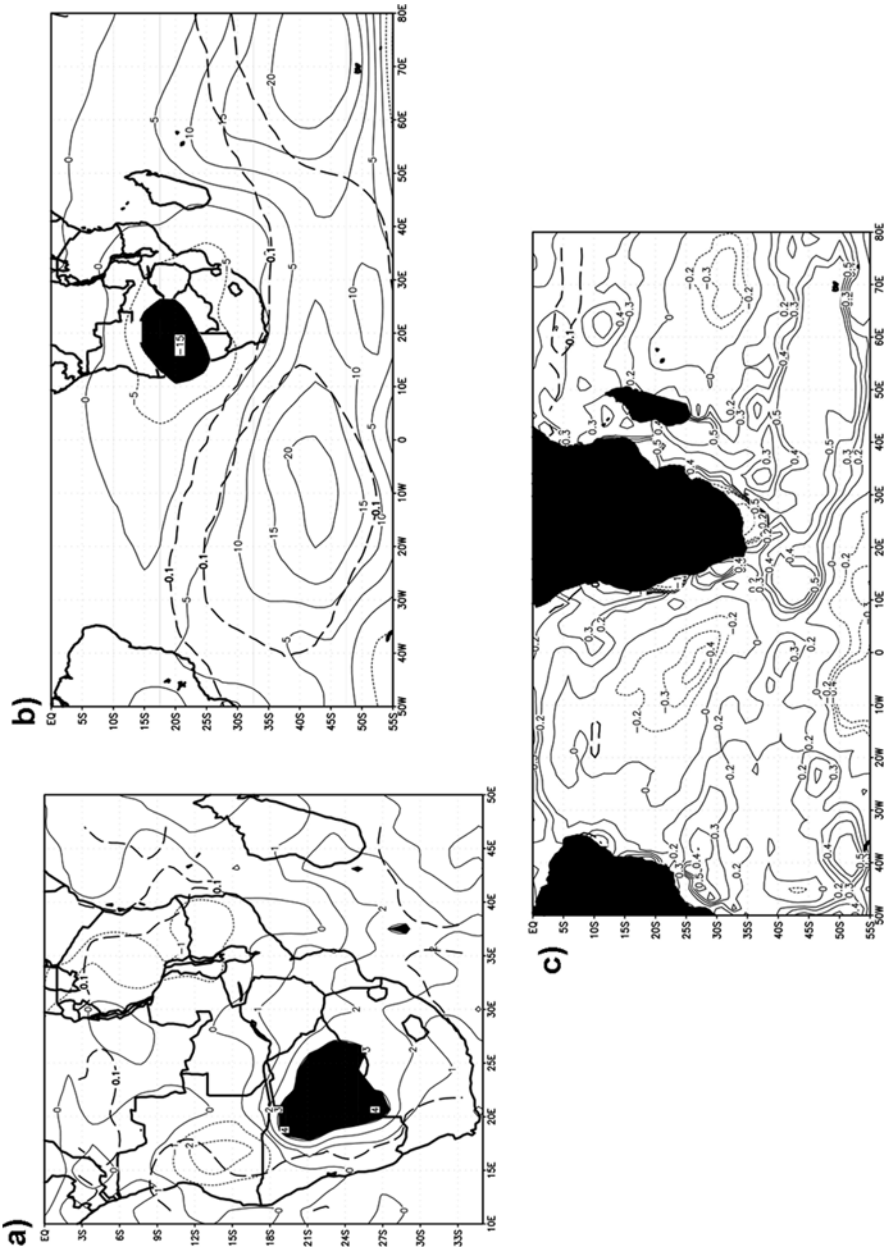


**Fig. 3** (continued)

may be associated with an Atlantic or Benguela El Niño pattern, where an equatorial Kelvin wave (generated by relaxed trade winds in the west) can propagate warm water across the Atlantic similar to a Pacific El Niño, or alternatively an enhancement of the equatorial counter currents may cause an increase in warm water along the coast of Namibia and Angola which then spreads across the Atlantic (Merle 1980, Binet et al. 2001, Florenchie et al. 2004). Being associated with days of extreme rainfall, this pattern of SST suggests a local effect on rainfall, increasing rainfall over southwestern Africa in a similar manner to a Pacific El Niño increasing rainfall over western Peru and Ecuador.

### *3.3 Model Experiments*

Using HadAM3, the large region of central South Atlantic cold anomalies was then used in three model integrations, each forced with varying (in magnitude) SST anomalies from the identified region, as well as a control run with no added anomaly. The first run was forced with an anomaly of –1°C (Had-1), the second with an anomaly of –2.5°C (Had-2.5) and the third with an anomaly of –5°C (Had-5). Using PRECIS, the smaller region of southeastern Atlantic warm anomalies were used in four model integrations, again forced with varying SST magnitudes from the identified region. A control experiment was again run, and then all but one experiment were forced with warm anomalies. The first experiment was run with a cold anomaly of 1°C (PRECIS-1), the second with a warm anomaly of 1°C (PRECIS+1), the third with a warm anomaly of 2.5°C (PRECIS+2.5) and the fourth with a warm anomaly of 5°C (PRECIS+5). Table 1 summarises each model experiment. Previous

**Table 1** Details for each model experiment using HadAM3 and PRECIS

| Experiment | Start date | Run length | SST region | SST magnitude |
|---|---|---|---|---|
| HadAM3 | | | | |
| Control (Con) | 12/1978 | 4 yrs, 1 mo | 8°–31°S, 21°W–9°E | No anomaly i.e. climatology |
| Had-1 | 12/1978 | 4 yrs, 1 mo | 8°–31°S, 21°W–9°E | –1°C |
| Had-2.5 | 12/1978 | 4 yrs, 1 mo | 8°–31°S, 21°W–9°E | –2.5°C |
| Had-5 | 12/1978 | 4 yrs, 1 mo | 8°–31°S, 21°W–9°E | –5°C |
| PRECIS | | | | |
| Control (Con) | 12/1978 | 3 yrs | 5.54°–15.63°S, 1.08°W–10.82°E | No anomaly i.e. climatology |
| PRECIS-1 | 12/1978 | 3 yrs | 5.54°–15.63°S, 1.08°W–10.82°E | –1°C |
| PRECIS+1 | 12/1978 | 3 yrs | 5.54°–15.63°S, 1.08°W–10.82°E | +1°C |
| PRECIS+2.5 | 12/1978 | 3 yrs | 5.54°–15.63°S, 1.08°W–10.82°E | +2.5°C |
| PRECIS+5 | 12/1978 | 3 yrs | 5.54°–15.63°S, 1.08°W–10.82°E | +5°C |

work has suggested that SST has varied by up to ±10°C during the past, throughout various parts of the Atlantic (Marlow et al. 2000, Kandiano et al. 2004) and surrounding waters. It is acknowledged that SST variations during the more recent instrumental period have been smaller, varying from ±3°C. Thus the smaller magnitudes of warm and cold SSTs used in this work are considered realistic, with the larger ±5°C experiments serving the purpose of being an exceptionally large anomaly with which to force (and therefore test the response of) the model.

Indian Ocean anomalies, such as a region of cold anomalies in the western Indian Ocean or warm anomalies in the far southwest Indian Ocean, were not chosen to force the model because the focus of this work was the South Atlantic. Whereas the Indian Ocean has been the focus of much work investigating rainfall variability over eastern and southeastern Africa (e.g. Goddard and Graham 1999, Nicholson and Kim 1997, Rocha and Simmonds 1997, Latif et al. 1999), the South Atlantic has received less attention (in the context of southern African rainfall) and is thought to be more influential for southwestern Africa (e.g. Reason et al. 2002, Reason and Jagadheesha 2005b). The large region of cold anomalies in the central South Atlantic was chosen for the HadAM3 experiments, because it is clearer and larger in spatial extent than other smaller regions of anomalies over the central South Atlantic shown by the composite analysis. The region of warm anomalies off Angola was chosen for the PRECIS experiments because, as described above, the anomalies may relate to a Benguela Niño, where unusually warm water extends along the southwestern Africa coastline because of a stronger easterly transport of water south of the equator (Binet et al. 2001, Florenchie et al. 2004).

The anomalies were introduced during June–November of each year. As discussed above, extreme days (associated with the chosen SST region) occur mainly between November and March. However, an examination of the SST lags suggest that these anomalies are also present during the preceding months, and increase in spatial extent as the dry season ends and the wet season begins (not shown). Given this observation, the anomalies were added into the model during the 6-month period, June–November, preceding the wet season.

Each experiment was run for 4 years and 1 month (December 1978–December 1982) using HadAM3, and 3 years (December 1978–November 1981) using PRECIS, however the first year was ignored to allow for model spin-up thus producing valid model diagnostics of just over 3 and 2 years, respectively (Table 1). The PRECIS experiments were run for a shorter time because of computational restrictions. Although it is acknowledged that a model start date during the 1990s would have been preferable, to be comparable with MIRA, computational restrictions (such as from the boundary data) meant that the default option of December 1978 was chosen as a start date. Spatially, the SST regions are shown schematically in Fig. 4. Although not shown in Fig. 4, the SST regions were smoothed spatially such that there is a ramping from 0°C up to the region of maximum anomalies. Different regions were chosen for the HadAM3 and PRECIS experiments because of (i) the low spatial resolution of HadAM3, meaning anomalies could not be placed near enough to the Angolan coastline; and (ii) the limited area of PRECIS which does not extend far enough into the South Atlantic to include the cold anomalies seen there.

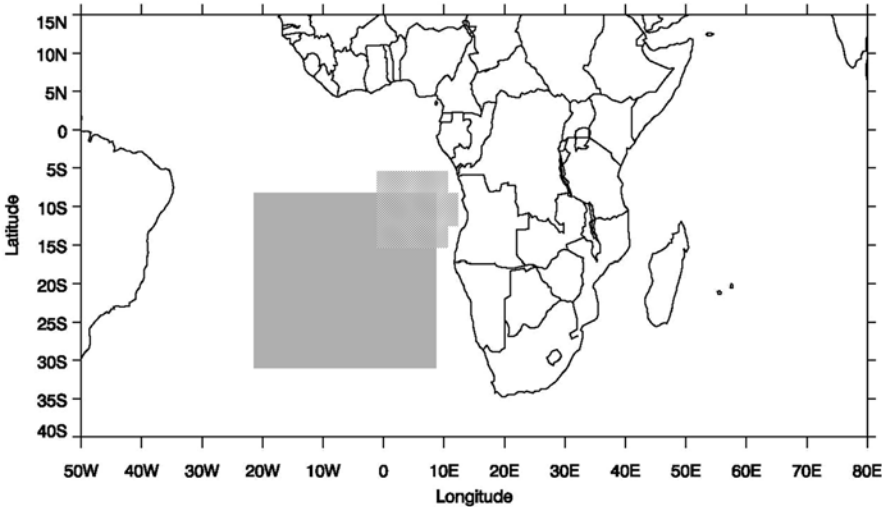


**Fig. 4** Schematic diagram of SST regions used in modelling experiments. *Filled box*: region of cold anomalies used to force HadAM3 (8°–31°S, 21°W–9°E). *Dashed box*: region of warm anomalies used to force PRECIS (5.54°–15.63°S, 1.08°W–10.82°E and then extended to 12.08°E between 8.08° and 12.46°S)

The method for comparing the rainfall variability and extremes from each model experiment is very similar to that used by Williams et al. (2009a). Firstly, rainfall was considered over the subcontinent (as a whole) to give daily areal averages. Secondly the number of extreme pixels from each experiment was compared. Finally, rainfall was compared on a pixel-by-pixel basis to give temporal means. Here, either the control run mean was subtracted from that of the experiment or, to reduce the bias from the spatial patterns of mean rainfall, the standard deviations were subtracted and then normalised by the control mean.

## 4 Model Experiment Results: HadAM3

### *4.1 Rainfall Spatial Averages and Daily Rainfall Extremes*

Figure 5 shows the spatial averages for each model experiment, smoothed with a 10-day running mean for clarity and covering the end of the experiment period. The most difference with the control run can be seen at the beginning of the timeseries, during DJF. The figure also shows that the different SST anomalies are producing different peaks in rainfall maxima, with Had-1 showing the most difference relative to the control.

The main method for assessing the effect of the SST anomaly on southern African rainfall variability was to count the number of rainfall extremes generated by each experiment. Figure 6 shows the total number of extreme pixels for each model run, where a pixel is defined as extreme either if it exceeds 1.5% of that pixel's climatological total (climatological total varying) or if it exceeds 1.5%

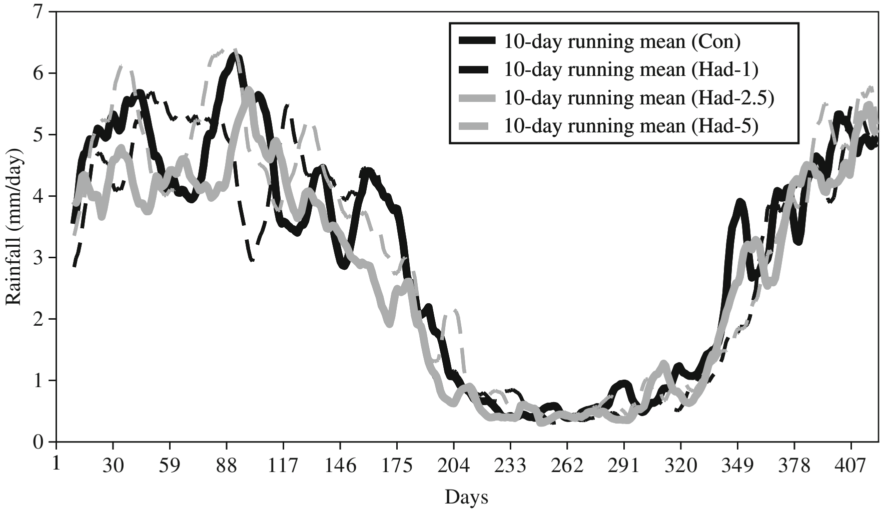


**Fig. 5** Daily rainfall (smoothed with a 10-day running mean) over southern Africa from the three model runs and the control for the end of the experiment using HadAM3, 1/11/1981–31/12/1982. Rainfall in mm $day^{-1}$

of that pixel's climatological total but taken from the control experiment (climatological total fixed). The first definition means that the climatological total varies according to each model experiment, whereas the second definition means that the climatological total is held constant.

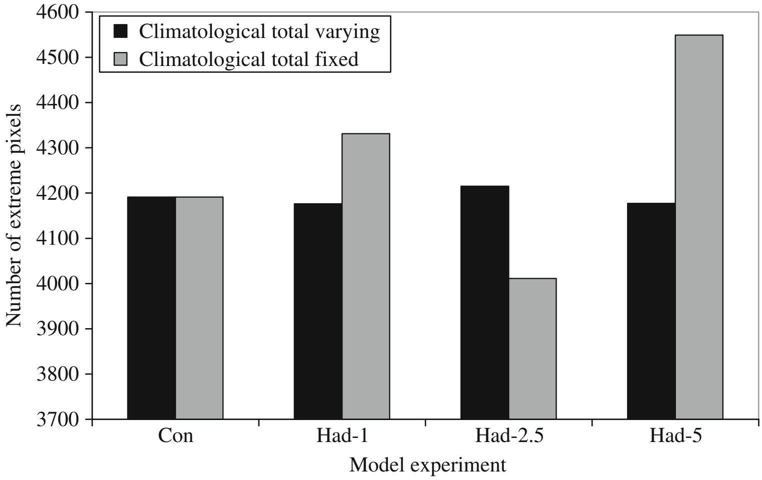


**Fig. 6** Number of extreme pixels over southern Africa for each model experiment using HadAM3. *Black bars*: 1.5% of climatological total from each model experiment (Climatological total varying). *Grey bars*: 1.5% of climatological total from control experiment (Climatological total fixed)

When using the varying climatological total, the figure shows that, as the cold anomaly is decreased to –2.5°C, rainfall extremes increase across southern Africa. However, with a further increase to –5°C, the number of extremes decreases. Compared to the control run, only Had-2.5 shows an increasing number of extremes. Further, significance testing using the Chi-squared Test reveals that these differences are not statistically significant. However, when using the fixed climatological total, the model experiments show very different results. The figure shows that Had-1 is increasing the number of rainfall extremes relative to the control, but suggests a nonlinear response of the model by showing a large decrease in rainfall extremes when the anomaly is increased in Had-2.5. If the anomaly is still further increased in Had-5, the number of rainfall extremes increases to its maximum for all experiments. A Chi-squared Test shows that these differences are statistically significant at the 0.05 level.

## 4.2 Pixel-by-Pixel Temporal Averages

### 4.2.1 Mean Daily Rainfall and Rainfall Variability

Figure 6 suggests that a colder South Atlantic SST anomaly, be it –2.5°C or –5°C, may produce more rainfall extremes, however the figure does not provide any information on how the anomaly affects the spatial patterns of the simulated rainfall.

Figure 7 shows mean rainfall from the control experiment, averaged over the 3 years. Representing the central wet season over southern Africa, the 3 months of DJF are focused upon here. Higher rainfall is shown over eastern southern Africa and in particular Madagascar (relative to the drier western side of the subcontinent), and also over the western Indian Ocean and South America. The differences in DJF

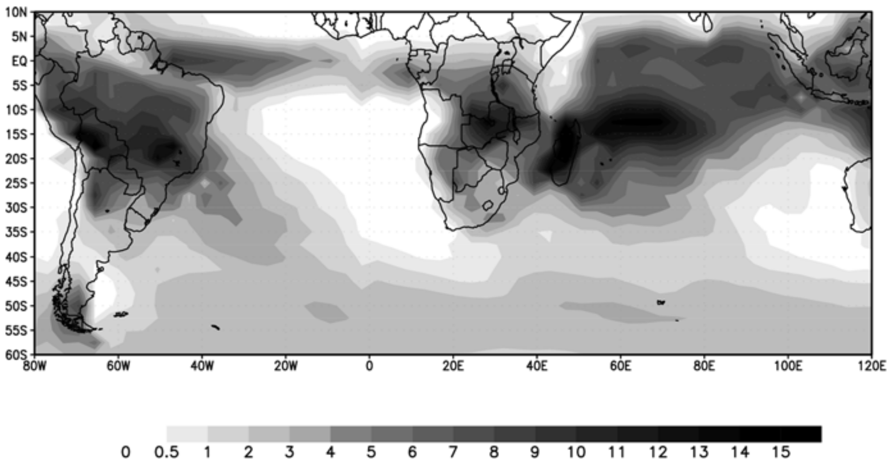


**Fig. 7** Mean rainfall from the control experiment using HadAM3, DJF 1980–1982. Rainfall in mm day$^{-1}$

rainfall over southern Africa between the control and the SST runs, averaged over the 3 years, are shown in Fig. 8. For the period covering the model integration, all three experiments are showing higher rainfall compared to the control over south-eastern Africa, orientated primarily in a diagonal band indicative of a TTT; however, this is shifted to the west relative to its usual location, which is typically further to the east over Madagascar and the Mozambique Channel (Washington and Todd 1999). Further, the results suggest that this feature is increasing in both magnitude and spatial extent as the SST anomaly is increased, with Had-5 displaying the most coherent TTT pattern (Fig. 8c). All three experiments also show a region of slightly lower rainfall relative to the control over southwestern Africa as well as a larger decrease in rainfall over the Mozambique Channel and southern Madagascar, with the largest differences occurring in Had-2.5 (Fig. 8b). Further a field in the Indian Ocean, at approximately 70–80°E and 10–30°S, Fig. 8 shows a region of higher rainfall relative to the control that is increasing in magnitude and spatial extent as the cold SST anomaly in the South Atlantic is increased. This is particularly true in Had-5, where there are two regions of increased rainfall arranged in a wave-like pattern across the Indian Ocean (Fig. 8c). This wave-like pattern is relevant as it also appears in the pressure and winds fields, described below, and so may be indicative of the quasi-stationary standing waves associated with southern African climate.

These results may be biased towards high and low rainfall across southern Africa. To assess this, Fig. 9 shows the normalised standard deviation differences during DJF between the control and the SST runs. Over southern Africa, all three model experiments show higher rainfall variability relative to the control, again orientated in a TTT pattern over southern Africa. Had-5 is displaying the strongest (in magnitude) and largest (in spatial extent) TTT feature, compared to the weaker anomaly experiments (Fig. 9c). The results also show that in Had-5 the subtropical component of this diagonal band, in the southwest Indian Ocean, is displaying the highest rainfall variability.

### 4.2.2 Large-Scale Atmospheric Associations with Daily Rainfall Means

The enhanced rainfall across southern Africa and the Indian Ocean corresponding to an increasing SST anomaly may be associated with larger-scale atmospheric circulation anomalies. The DJF near-surface heights from the control run show low pressure over both western southern Africa and orientated in a diagonal band across eastern southern Africa, the latter of which is suggestive of the usual location of a TTT (not shown). A large region of high pressure is also evident in the South Atlantic.

The differences in DJF heights between the control and experiment runs are shown in Fig. 10. Over southern Africa, the figure suggests that as the SST anomaly is increased, near-surface pressure decreases in each experiment and is orientated in a diagonal band corresponding to the area of rainfall maxima. The region of lowest pressure is centred over Botswana in Had-5 (Fig. 10c). The figure also suggests that the low pressure extending into southern Africa is coming from the south and the higher latitudes. Lower pressure is evident in the subtropics in Had-2.5 (Fig. 10b) and Had-5 (Fig. 10c), relative to Had-1 (Fig. 10a). Further, in Had-5 the low pressure

a
b
c

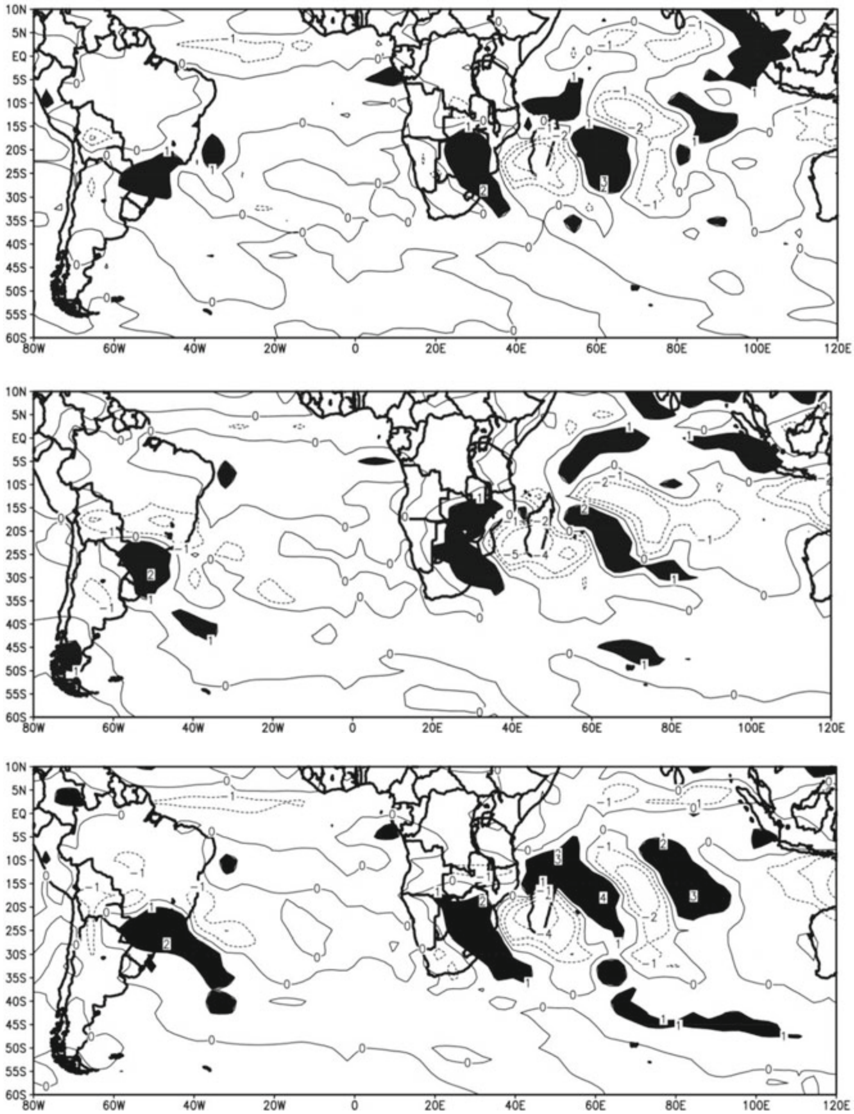


**Fig. 8** Differences in rainfall means from the model experiments using HadAM3, DJF 1980–1982: (**a**) Had-1 minus Con; (**b**) Had-2.5 minus Con; (**c**) Had-5 minus Con. Differences in mm day$^{-1}$. *Shading* shows regions where precipitation differences are positive (i.e. increased mean rainfall in model experiments) by > 1 mm day$^{-1}$

is again indicative of a wave-like structure propagating eastwards across the southern Atlantic, subtropical southern Africa and the southern Indian Ocean (Fig. 10c). In the central South Atlantic, and in particular over the SST anomaly region, the near-surface pressure seems to be getting higher, albeit weak in magnitude, as the anomaly is increased.

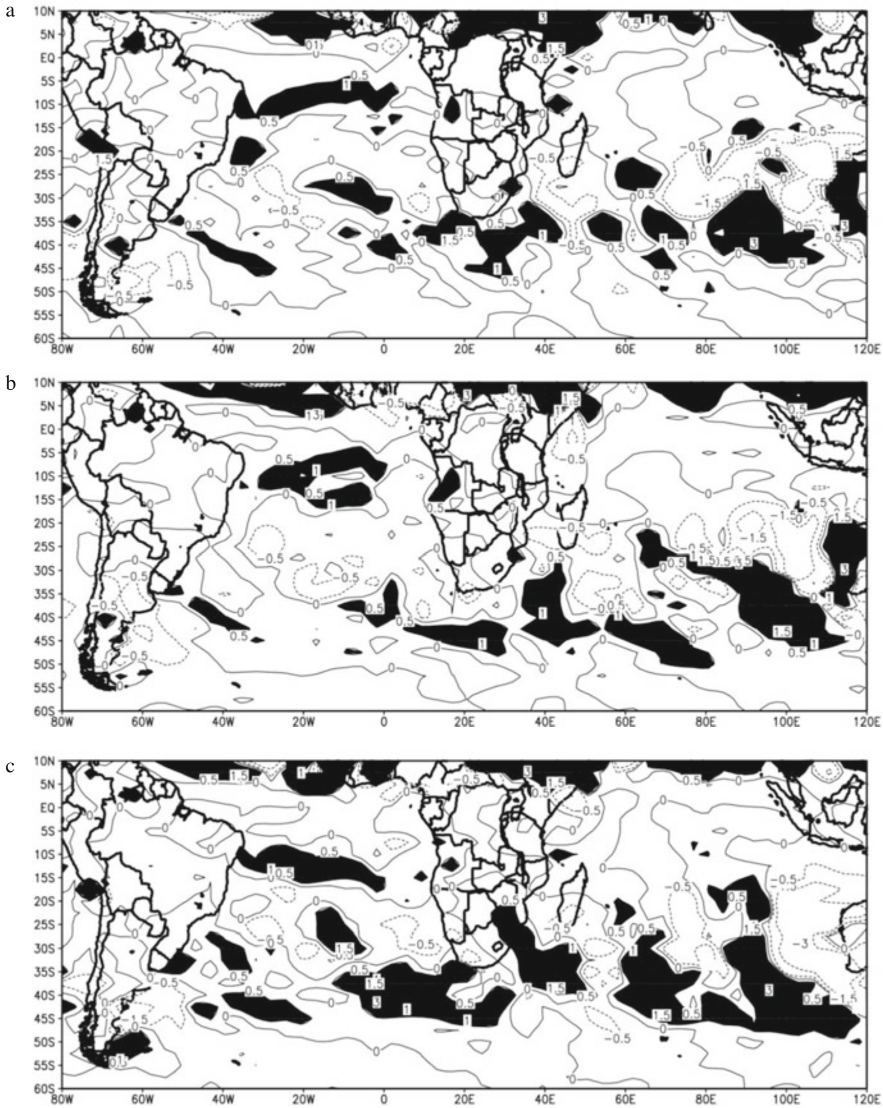


**Fig. 9** Normalised standard deviation differences from the model experiments using HadAM3, DJF 1980–1982: (**a**) Had-1 minus Con; (**b**) Had-2.5 minus Con; (**c**) Had-5 minus Con. *Shading* shows regions where differences are positive (i.e. increased rainfall variability in model experiments) by > 1 standard deviation

Figure 11 shows mean DJF near-surface vector winds over the Atlantic, Africa and the Indian Ocean from the control run, averaged over the 3-year period. Strong westerlies are clear south of 40°S and weak westerlies are shown moving into tropical southern Africa. Strong easterlies are shown throughout the southern Indian Ocean, becoming southeasterlies as they enter southern Africa across the Mozambique Channel. Strong southerlies are evident in the eastern South Atlantic

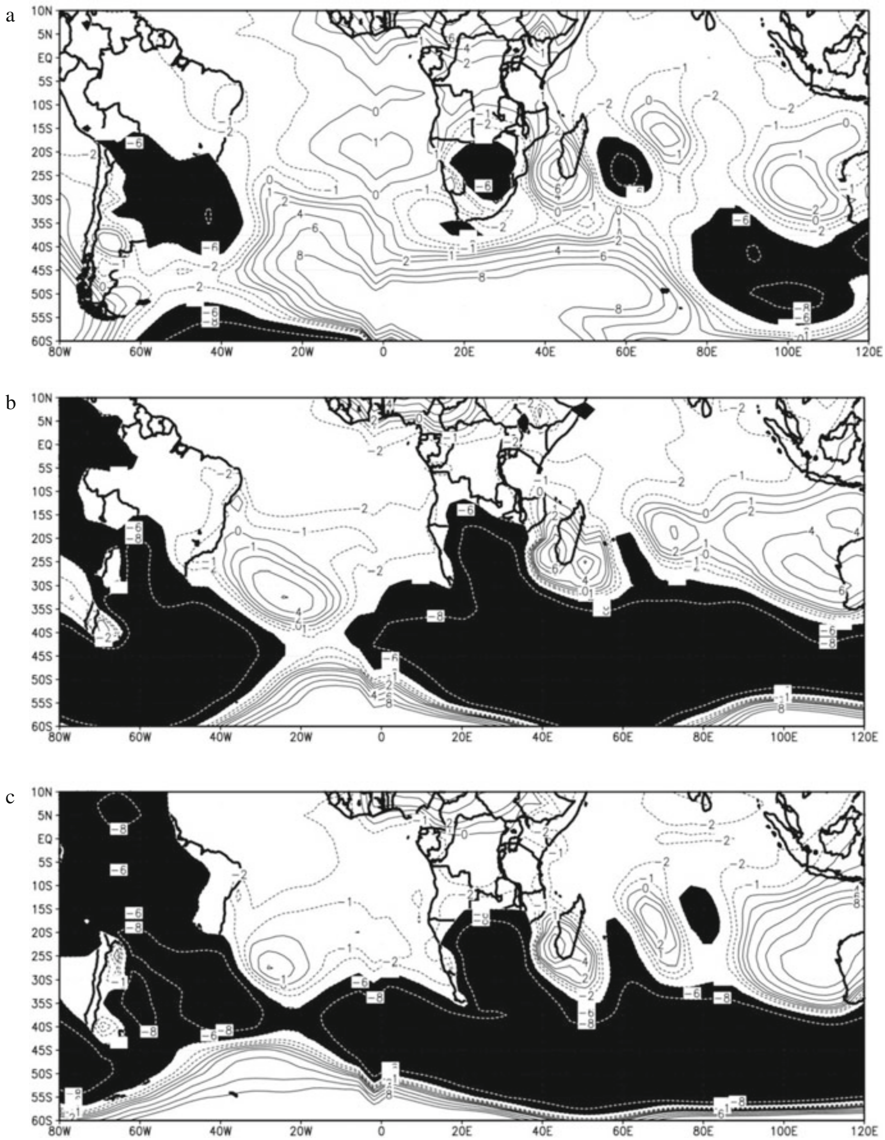


**Fig. 10** Differences in near-surface (1,000 mb) height means from the model experiments using HadAM3, DJF 1980–1982: (**a**) Had-1 minus Con; (**b**) Had-2.5 minus Con; (**c**) Had-5 minus Con. Differences in meters. *Shading* shows regions where differences are negative (i.e. decreased pressure in model experiments) by > 4 m

along the coast of southern Africa which, coupled with northerlies in the western South Atlantic, form an anticyclonic gyre around the region of high pressure mentioned above. An opposite pattern of winds are evident aloft, near the top of the troposphere (not shown).

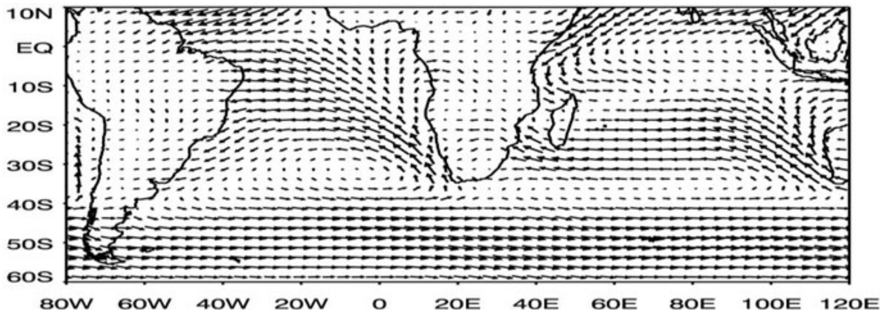


**Fig. 11** Near-surface (0.997 sigma) vector wind means from the control experiment using HadAM3, DJF 1980–1982. Winds in m s$^{-1}$

The differences in DJF vector winds between the control and experiment runs are shown in Fig. 12. Across subtropical southern Africa, there is initially no noticeable increase in near-surface wind anomalies as the SST anomaly increases, with each experiment showing a similar region of westerly and northwesterly flow anomalies over southwestern Africa. An increase is suggested, however, when the strongest SST anomaly is added in Had-5, with stronger westerly anomalies across southwestern Africa (Fig. 12c). Over southeastern Africa, a stronger SST anomaly appears to be increasing the northerly and northeasterly wind anomalies, which are arranged in a clear cyclonic gyre, particularly in Had-2.5 (Fig. 12b) and Had-5 (Fig. 12c). Other systems are shown propagating across the Indian Ocean as the Atlantic SST anomaly is increased. Related to this, the experiment results suggest that the midlatitude westerly anomalies throughout the southern Indian Ocean are increasing with a stronger SST anomaly, particularly in Had-2.5 (Fig. 12b) and Had-5 (Fig. 12c). Over the South Atlantic, the results suggest that as the SST anomalies become stronger, the anticyclonic gyre of winds also strengthens. Further, when the strongest SST anomaly is added in Had-5 (Fig. 12c), the results suggests a new cyclonic system off the coast of South America.

The results from the control run are consistent with previous work describing the location of southern African rainfall and the TTTs (e.g. Washington and Todd 1999, Todd et al. 2001) and atmospheric circulation features over the subcontinent (e.g. Tyson 1986). It has been suggested that the normal situation during DJF is for a Walker-style circulation to operate, with three cells spanning the South Atlantic and southern Africa (Tyson 1986). These cells can be seen schematically in Fig. 13a, and are reproduced by the control run results. These show that under normal conditions, southeastern Africa is wet with rainfall maxima occurring over Madagascar, suggesting that the TTT is located to the east. The semi-permanent low pressure over southwestern Africa seems to be drawing in the northerly winds from the Tropics and southeasterlies from the southwest Indian Ocean, which converge over southeastern Africa and cause increased rainfall here.

As an increasingly cold anomaly is imposed in the South Atlantic, the largest increases in rainfall seem to be arranged in a diagonal band located over

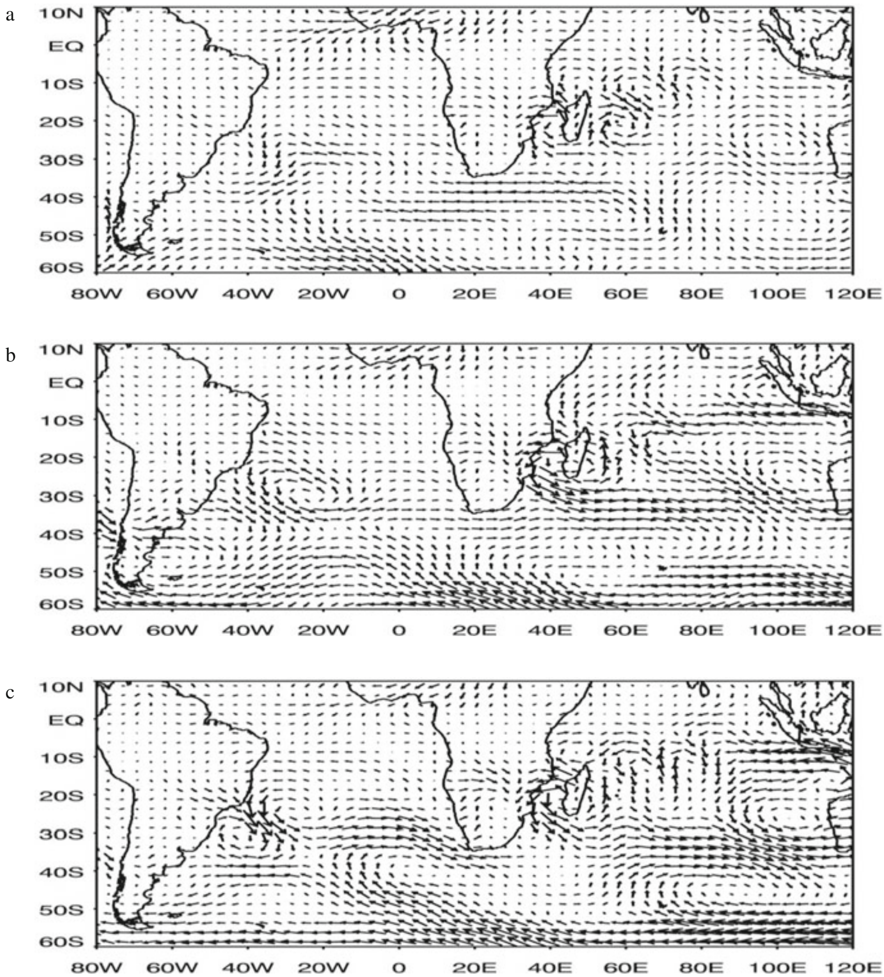


**Fig. 12** Differences in near-surface (0.997 sigma) vector winds from the model experiments using HadAM3, DJF 1980–1982: (**a**) Had-1 minus Con; (**b**) Had-2.5 minus Con; (**c**) Had-5 minus Con. Differences in m s$^{-1}$

southwestern and central southern Africa. The orientation of the rainfall increases over southern Africa is indicative of a TTT feature and therefore suggests that this is being enhanced by stronger SST anomalies, however it is located further west than the usual location of this feature which is to the east over Madagascar and southeastern Africa (Washington and Todd 1999). Thus these results suggest that increasing the cold SST anomaly in the South Atlantic enhances the normal situation of Walker-style circulation, which appears to draw the TTT towards the western side of southern Africa and cause increased rainfall here. As the anomaly is increased, the results suggest that the South Atlantic high is slightly increasing in magnitude.

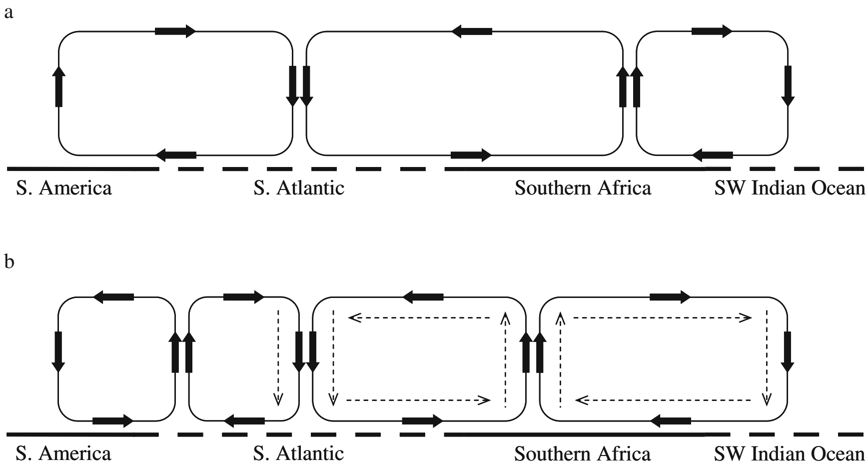


**Fig. 13** Schematic of possible Walker-style circulation changes corresponding to a cold anomaly in the central South Atlantic: (**a**) Cells under normal conditions; (**b**) Enhanced cells with added SST anomaly

This is to be expected, given the increased divergence (resulting from an increasingly cold anomaly) which causes the South Atlantic anticyclone to become more anticyclonic via linear quasigeostrophic theory (Gill 1982). As a consequence, the anticyclonic winds around the high appear to be strengthening. This may have the effect of moving the southern African Walker-style cells towards the west, so that the ascending branch of the two southern African cells is now located over western and central southern Africa, rather than southeastern Africa (shown schematically in Fig. 13b). The westerly and easterly winds over the subcontinent are still present, but the region of convergence appears to be shifted to the west. The descending branch of the southern African/South Atlantic cell still appears to be located over the central South Atlantic, corresponding to the high pressure and SST anomaly region.

The experiment results also raise the possibility that another cell may have been created in the western South Atlantic and over South America (Fig. 13b). Increasingly lower pressure off the South American coast, and strengthening northerly winds in the western South Atlantic and southerly winds off the South American coast suggest a second cyclonic gyre of winds around the low. This may be creating the ascending branch of a Walker-style cell in the western South Atlantic and over the coast of eastern South America, and may also explain the region of enhanced rainfall seen in the South Atlantic Convergence Zone.

There are other possible ways in which the SST anomalies may be increasing rainfall over southwestern Africa. For example, previous work has suggested that tropical Atlantic SST variability impacts the position of the maritime ITCZ, because the SST causes a hydrostatic adjustment of the atmospheric boundary layer which results in changes in surface pressure and low-level convergence (Biasutti et al. 2004). This affects regions remote from the SST anomaly, such as equatorial coastal regions, because circulation anomalies resulting from condensation heating within the maritime ITCZ extend equatorwards and transfer the SST signal inland (Biasutti et al. 2004). Consequently, the increases in low pressure (and associated increased rainfall over southwestern Africa) seen in this study may be due to changes in boundary layer processes, which are being felt inland because of the effect of these changes on rain-producing systems such as the ITCZ and the TTTs.

A shift in the northward track of mid-latitude depressions as well as increased cyclogenesis over southwestern South Africa, and associated increases in rainfall, may also result from SST anomalies in the central South Atlantic and near to the subcontinent (Reason et al. 2002). Cold anomalies in the central South Atlantic may serve to strengthen the transient weather systems over southwestern Africa, by enhancing the near surface meridional temperature gradient in the tropical South Atlantic (Reason et al. 2002). Thus, it is possible that increasing the anomalies in this study is increasing the strength of the weather systems. This is suggested by the HadAM3 experiment results, which show strengthened low-level winds and lower pressure over southwestern Africa, so the increases in rainfall over the TTT region may be because of increased weather systems in this region rather than a larger scale Walker-style circulation change. The results also show an increase in cyclonic flow over southeastern Africa, again suggesting an increase in the weather systems which track into southern Africa from the southeast Indian Ocean.

The results from the HadAM3 experiments also show that some of the largest increases in rainfall, pressure and winds are occurring in a wave-like structure. This is particularly evident from the near-surface pressure results, which show that the low pressure over southern Africa is extending from the higher latitudes and resembles a wave pattern. This may be associated with the quasi-stationary standing waves, particularly wave numbers 1 and 3 which are influential for the southern African climate as they can influence patterns of upper level divergence and surface convergence (Mason and Jury 1997, Tyson and Preston-Whyte 2000, Hudson and Jones 2002).

According to Jury and Mwafulirwa (2002), the standing wave may be expressed by a meandering of the subtropical jet stream which can extend over southern Africa. They state, however, that this leads to vertical motions over the subcontinent which contributes to subsidence and is therefore associated with dry conditions (Jury and Mwafulirwa 2002). The HadAM3 experiments show wetter conditions over southern Africa as the SST anomaly is increased, arguing against this process. Further, if a meandering of the jet stream was the case, this might be shown by the experiment results as an encroachment of the upper westerly winds into the subcontinental interior. However the opposite is suggested by the results, which show the upper level westerlies moving towards the subtropics and away from the subcontinent as the cold SST anomaly is increased. Consequently, it is possible that increasing the cold SST anomaly in the South Atlantic is influencing the standing wave further to the east, causing the subtropical jet stream to move away from southern Africa and resulting in decreased subsidence and wetter conditions.

# 5 Model Experiment Results: PRECIS

## *5.1 Rainfall Spatial Averages and Daily Rainfall Extremes*

Figure 14 shows the areal averages for each model run for the end of the experiment period, again smoothed with a 10-day running mean for clarity. Although there is some agreement between the control and the SST runs, particularly during the dry season, there are differences in rainfall between the experiments. This is particularly evident for PRECIS+5, which is generating higher mean rainfall compared to the control at the beginning (in November) and end (December of the following year) of the timeseries.

The total number of extreme pixels for each model experiment is shown in Fig. 15. As above, a pixel is defined as extreme either if it exceeds 1.5% of that pixel's climatological total, which therefore varies according to experiment, (climatological total varying) or if it exceeds 1.5% of that pixel's climatological total from the control experiment (climatological total fixed). When using the varying climatological total, the results show that a small warm anomaly of 1°C increases the number of rainfall extremes and a cold anomaly of –1°C decreases the number of extremes. Above this warm anomaly, however, the number of extremes decreases in PRECIS+2.5 and PRECIS+5. Conversely, using the fixed climatological total (i.e. where the climatological total is kept constant at the level of the control experiment)

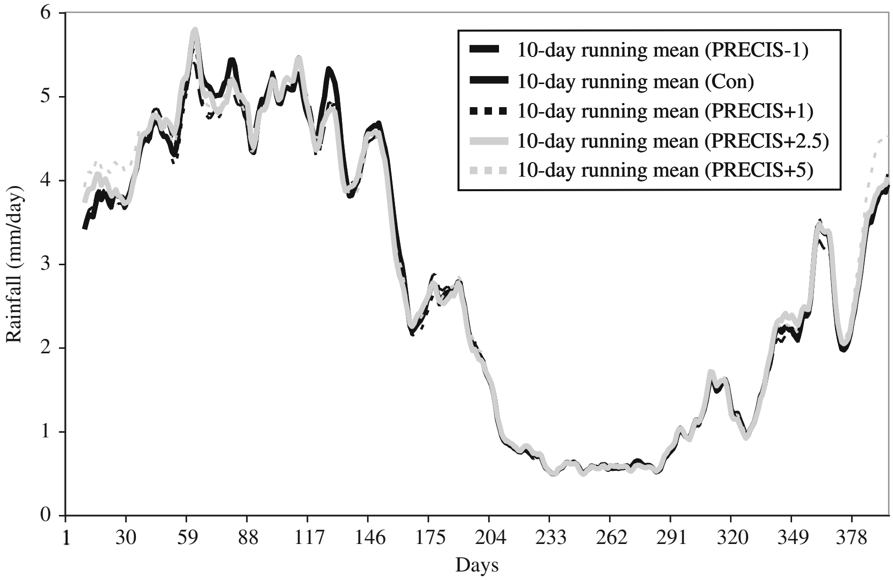


**Fig. 14** Daily rainfall (smoothed with a 10-day running mean) over southern Africa from the four model runs and the control for the end of the experiment using PRECIS, 1/11/1980–30/11/1981. Rainfall in mm day$^{-1}$

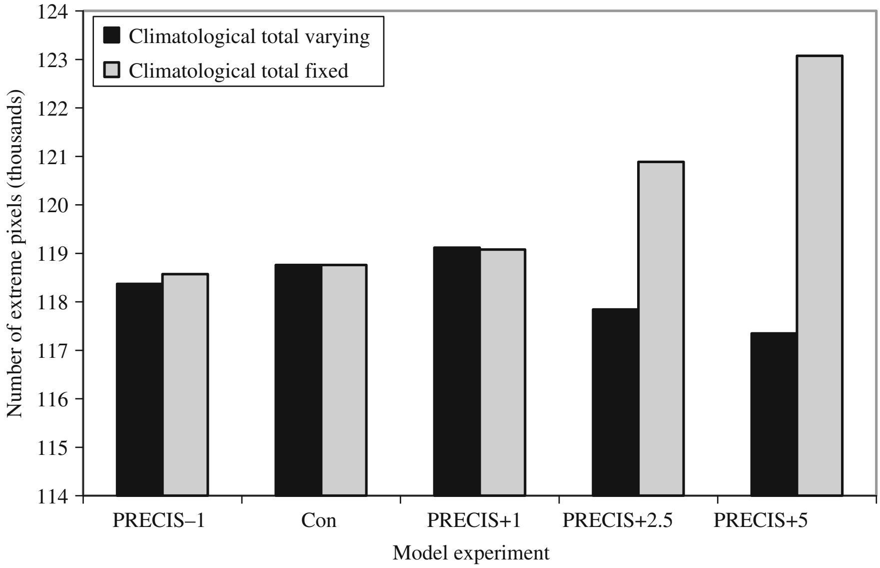


**Fig. 15** Number of extreme pixels over southern Africa for each model experiment using PRECIS. *Black bars*: 1.5% of climatological total from each model experiment (Climatological total varying). *Grey bars*: 1.5% of climatological total from control experiment (Climatological total fixed)

suggests that increasing the magnitude of the warm anomaly results in a steadily increasing number of rainfall extremes. Here, the cold anomaly in PRECIS-1 is generating the lowest number of extremes, which then gradually increase to their maximum in PRECIS+5. Using either definition, a Chi-squared Test shows that these differences are statistically significant at the 0.05 level.

This suggests that an increasing mean is having the effect of decreasing the number of identified rainfall extremes, as a higher mean will produce a higher climatological total. Conversely, if the climatological total is taken from the control run, the identification of rainfall extremes is not being altered by a changing mean but rather may be influenced by a change in variance.

## *5.2 Pixel-by-Pixel Temporal Averages of Daily Rainfall*

Figure 15 suggests that, using the second definition, a warmer SST anomaly off Angola may be producing a larger number of rainfall extremes. The daily rainfall was also considered on a pixel-by-pixel basis, to study the spatial influence of the anomaly across southern Africa.

Figure 16 shows the differences in rainfall for all months over southern Africa between the control and the SST runs, averaged over the 2 years. The figure shows that as the anomaly is increased, rainfall increases to the west of southern Africa

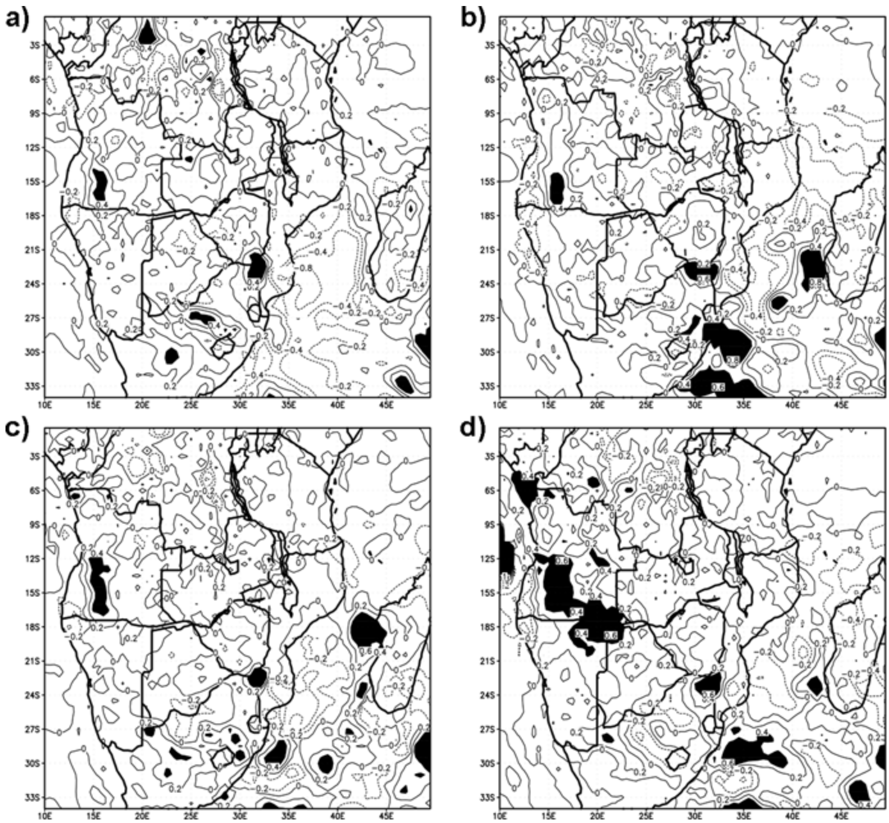

**Fig. 16** Differences in rainfall means from the model experiments using PRECIS, all months 1980–1981: (**a**) PRECIS-1 Con minus; (**b**) PRECIS+1 Con minus; (**c**) PRECIS+2.5 minus Con; (**d**) PRECIS+5 minus Con. Differences in mm day$^{-1}$. *Shading* shows regions where precipitation differences are positive (i.e. increased mean rainfall in model experiments) by > 0.5 mm day$^{-1}$

over Namibia and Angola. This is particularly true in PRECIS+5, where there is a large region of high rainfall near to the coast and over the Angola-Namibia border, as well as a smaller (but showing higher rainfall) region offshore into the southeast Atlantic (Fig. 16d). The experiment using the cold SST anomaly produces the least rainfall over southwestern Africa (Fig. 16a).

If September–November (SON) is examined, a clear increase in rainfall can be seen over southwestern Africa as the warm SST anomaly is increased (Fig. 17). Although the majority of rainfall across southern Africa is normally received after this period, during DJF and later, the results suggests that the largest increases occur during and immediately after the SST anomaly is added. There is little difference between the control and the cold anomaly experiment of PRECIS-1 over southwestern Africa (Fig. 17a), but enhanced rainfall is apparent over Angola in PRECIS+1 (Fig. 17b). This region of rainfall is higher (in magnitude) over Angola in PRECIS+2.5, and reaches its maximum in strength and spatial

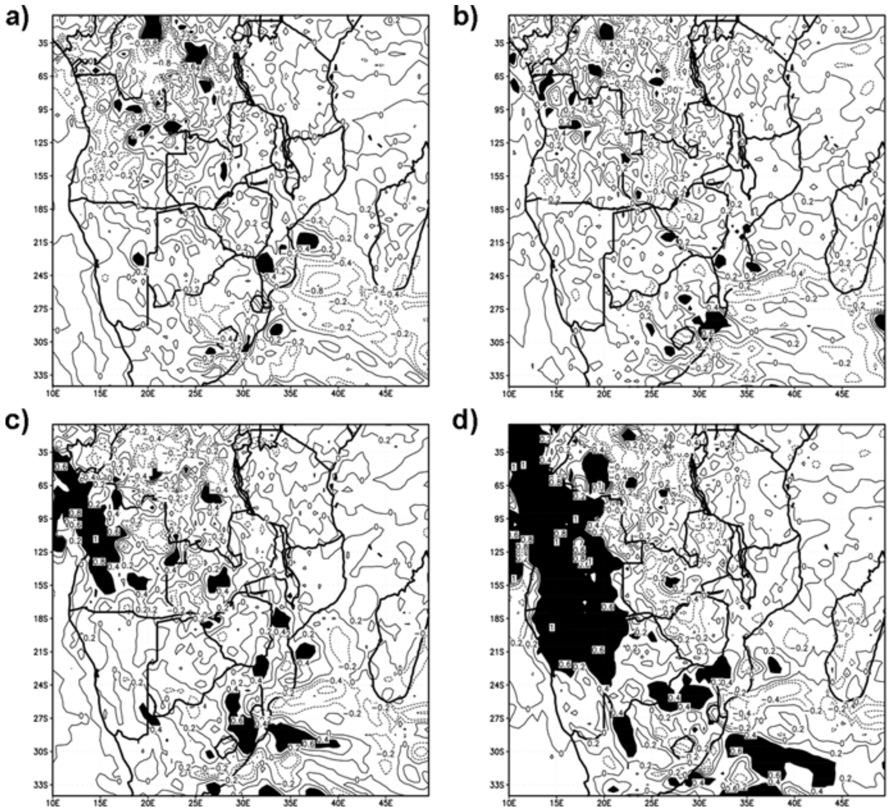

**Fig. 17** Differences in rainfall means from the model experiments using PRECIS, SON 1980–1981: (**a**) PRECIS-1 minus Con; (**b**) PRECIS+1 minus Con; (**c**) PRECIS+2.5 minus Con; (**d**) PRECIS+5 minus Con. Differences in mm day$^{-1}$. *Shading* shows regions where precipitation differences are positive (i.e. increased mean rainfall in model experiments) by > 0.5 mm day$^{-1}$

extent (covering all of Angola and half of Namibia) in PRECIS+5 (Fig. 17c, d, respectively).

To reduce the bias towards the regions of high and low rainfall across southern Africa (which may be influencing the differences in means), the normalised differences between standard deviations are again examined. The results show a similar pattern to the means, i.e. an increase in rainfall variability over southwestern Africa corresponding to an increased SST anomaly, during all months (not shown) and, more noticeably, during SON as shown in Fig. 18. During this season, a small region of higher rainfall variability (relative to the control) is shown off the Angolan coast in PRECIS+1 (Fig. 18b), and this region increases in both magnitude and spatial extent in PRECIS+2.5 and PRECIS+5 (Fig. 18c, d, respectively). Further inland, over Namibia, is also experiencing enhanced rainfall relative to the control in PRECIS+5. The region of increased rainfall is not shown by the cold anomaly experiment, PRECIS-1 (Fig. 18a).

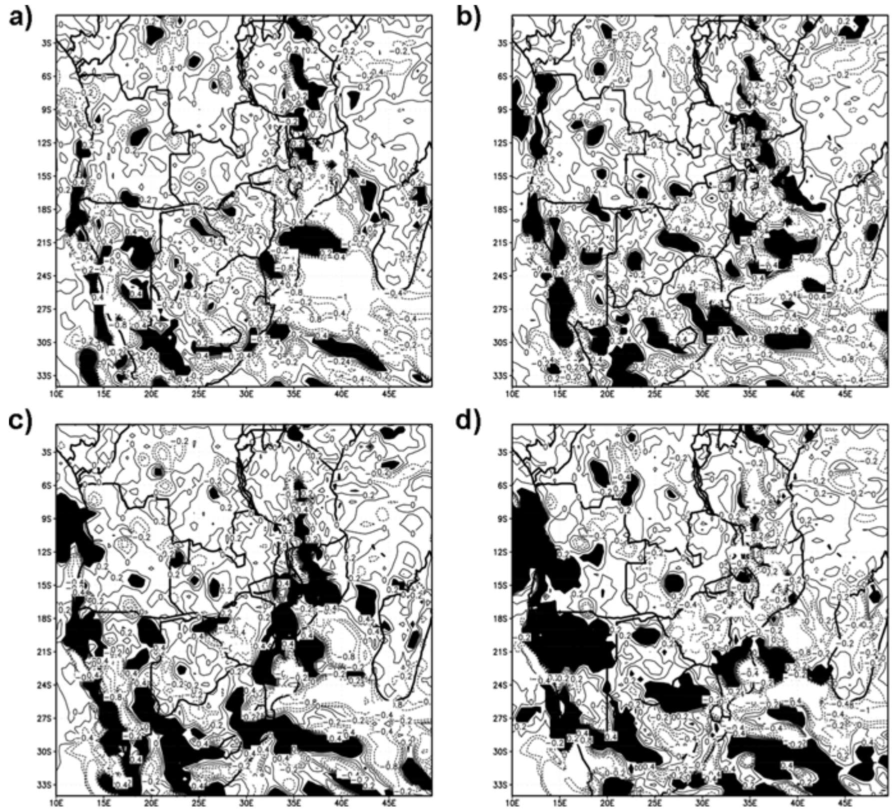


**Fig. 18** Normalised standard deviation differences from the model experiments using PRECIS, SON 1980–1981: (**a**) PRECIS-1 minus Con; (**b**) PRECIS+1 minus Con; (**c**) PRECIS+2.5 minus Con; (**d**) PRECIS+5 minus Con. *Shading* shows regions where differences are positive (i.e. increased rainfall variability in model experiments) by > 0.5 standard deviations

To summarise the results from the PRECIS experiments, the largest differences between the spatially averaged daily rainfall from the model experiments (relative to the control run) are shown before the central wet season, particularly during November. A lag of 3 months at most, between adding the anomaly and observing rainfall increases, is shown. The results also suggest that increasing the warm anomalies off Angola causes an increase in the total number of extreme pixels over southern Africa. Spatially, when a stronger anomaly is added the results suggest that mean rainfall and rainfall variability is increasing over southern Africa, and that the largest increases are occurring over southwestern countries such as Angola and Namibia. Consistent with the spatial averages, these increases are largest before the central wet season of DJF and appear to be most apparent during SON.

Thus the location and timing of maximum rainfall increases suggests that increasing the warm SST anomalies off the Angolan coast causes a local and near-immediate increase in rainfall. It would appear that an increasingly warm region of SSTs is causing increased convection in the local area, which may be advected inland by the typically strong westerlies from the eastern South Atlantic. This would increase the amount of moisture that is carried into southwestern Africa, causing a relatively rapid increase in rainfall in this region, but little change further from the anomaly region. Previous studies have suggested a similar mechanism. For example, according to Reason et al. (2002) a warm anomaly placed directly south of Africa appears to increase local evaporation and strengthens the convergence of low-level moisture flow, which intensifies the local cyclonic systems and causes increased rainfall over southwestern South Africa. A similar process may be occurring here in the PRECIS experiments, whereby a warm anomaly off Angola is increasing evaporation and the amount of local moisture, which serves to increase near-surface convergence and increase rainfall near to the anomaly.

## 6 Conclusions

The main aim of this study was to examine the physical mechanisms associated with how increasing SST anomalies in the South Atlantic may influence southern African rainfall variability and daily rainfall extremes. To achieve this aim, we firstly identified daily rainfall extremes from a new dataset of high resolution satellite-derived rainfall estimates, then secondly observed the associated atmospheric and, most importantly, SST structures. We then used these SST structures to force a climate model in global and regional mode, undertaking a number of model experiments each with varying magnitudes of SST from the idealised identified regions.

As discussed in Williams et al. (2007), SST anomalies may have both a local and remote effect on southern African rainfall variability. The local effect can be via modulations to the latent heat flux and to temperature and pressure gradients, all of which may result in changing regional moisture flows (Hirst and Hastenrath 1983, D'Abreton and Lindesay 1993, Reason 1998). In addition, low-level cyclogenesis may be enhanced by increased surface heat fluxes, resulting from a warm SST anomaly (Singleton and Reason 2007).

Conversely, an SST anomaly can have a remote effect on southern African rainfall via changes to larger scale rain-producing systems such the TTTs. For example, a warm SST anomaly to the south of Africa can have the effect of promoting favorable conditions for the existence of TTTs over the southern Africa, through an intensification of the region's mid-latitude fronts (Walker 1990, Reason 1998). In contrast, a cold anomaly in the southwest Indian Ocean can have the effect of inducing anomalous low-level easterly moisture fluxes, resulting in enhanced convective uplift and increased rainfall over the subcontinent (Washington and Preston 2006).

The results from the PRECIS experiments suggest that a region of warm SST anomalies in the southeast Atlantic is producing a direct effect on southern African rainfall, where the effect is most apparent in a region near to the SST region and occurs at a similar time to the introduction of the anomalies. Conversely, the results of the HadAM3 experiments in this study suggest that a region of cold SST anomalies in the central South Atlantic is producing an indirect effect on southern African rainfall, where the effect is largest in a region that is some distance from the SST region and occurs approximately 6–9 months after the anomalies are first introduced. These results suggest that the normal circulation may be shifted to the west in response to an increasingly cold SST anomaly, drawing the TTT features over southern Africa towards the west and initiating rainfall over southwestern Africa. Reason (1998) describes a reversal of the Walker-style cell in response to the movement of the TTT. The results from this work suggest that the TTT may also move westwards in response to the cells being shifted to the west.

Within this study, several caveats should be noted. Firstly, only one model integration was undertaken for each experiment. It is acknowledged that an ensemble of simulations for each experiment would show a clearer signal of the effect of the SST anomaly, because of the noise component which is often large in single runs. However, the way in which the model was set up meant that ensemble integrations were not possible at this time, and so a single run for each experiment had to be used. Further work has addressed this issue (Williams et al. 2009b).

Secondly, the experiments were run on an atmosphere-only model, meaning the SSTs were prescribed allowing an investigation into their possible influences on rainfall but not vice versa. In these experiments, the modelled atmospheric processes were not able to feedback on the SST anomalies. Future work will address this shortfall by using a coupled ocean-atmosphere model, allowing an assessment of how the regions of idealised SST anomalies may evolve and be influenced by the simulated atmospheric processes.

Thirdly, we were unable to assess the relative importance of each SST region on southern African rainfall, because different SST regions were necessarily used in the GCM and RCM experiments. Further work is currently underway to address this shortfall, running a number of PRECIS experiments which include both the cold central South Atlantic and warm southeast Atlantic anomalies. This future work will, therefore, assess whether one region is more important for southern African rainfall extremes than the other, and will also examine the effect of spatial resolution (of the model) on the SST-rainfall association.

Another caveat was that only rainfall data were analysed from the PRECIS experiments. Unfortunately, due to computational problems, pressure and wind fields could not be analysed with these experiments, so the proposal of an increase in low-level convergence, discussed above, can only be hypothesised. This has been addressed in Williams et al. (2009b).

A final caveat is the relatively short temporal coverage of the MIRA dataset and the model experiments. An important advantage of using satellite-derived rainfall data is the high-resolution and near uniform spatial coverage, which reduces the inadequacies of in-situ measurements which are sparse or non-existent in certain regions such as southwestern Africa. However a disadvantage of using satellite-derived data is the relatively short duration in which the data have been available. Although the MIRA dataset covers a 10-year period only, it was considered the best available product for a study of this nature given its high temporal and spatial resolution. Likewise the model experiments in this study were relatively short, but this was necessary given the computational limitations of running a global and regional climate model. Model runs of 2 or 3 years were considered adequate for this study, as the aim was to examine the processes and physical mechanisms associated with rainfall variability in extremes rather than any long-term changes in mean rainfall.

To conclude, the results suggest that South Atlantic has both remote and local associations with southern African rainfall, with increased rainfall variability and daily rainfall extremes associated with a warming in certain regions and a cooling in others. This has implications for future studies, particularly those examining future impacts on rainfall variability under possible climate change.

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# Understanding the Large Scale Driving Mechanisms of Rainfall Variability over Central Africa

**A. Farnsworth, E. White, Charles J.R. Williams, E. Black, and Dominic R. Kniveton**

**Abstract** Large-scale drivers of rainfall variability over Central Africa (approximately 12°S–7°N and 15°–32°E, roughly comprising the Democratic Republic of Congo basin) are examined using rain gauge data and the NCAR-NCEP reanalysis. Research into Central Africa has been neglected comparatively to other regions of Africa primarily because of a lack of suitable data. This study focuses on how local sea surface temperatures (SSTs), the African jets and mesoscale convective systems modulate precipitation through their influence on the tropical rain belt and the inter-tropical convergence zone (ITCZ). The role of El Nino Southern Oscillation (ENSO) teleconnections on the tropospheric jets and SSTs will also be described. Central Africa has been divided into 6 homogenous regions based on the seasonal cycle in rainfall. Time series analysis from each region identified 5 extremes (wet) and 5 deficits (dry) in rainfall during the primary, and if present, secondary rainy season. These years formed the basis of composites for variables, such as SST and vector wind. The role of the jets, SSTs the ICTZ and ENSO was explored further using cross validation of the rainfall time series. Our results show that Central Africa is a very complex region, with different mechanisms influencing rainfall in each regions and season. It is also shown that the influence of the large scale drivers on rainfall is not necessarily linear, with wet and dry years affected by different factors. The loci and intensity of the tropospheric jets play a determining role in the strength and position of the rainbelt with mesoscale convective activity mostly coupled between their axes. Displacement in the ITCZ (resulting from variability in SST and land-surface gradients) is also indicated as a likely influence on rainfall,. SST and land-surface gradients can also modulate rainfall by directly influencing the strength and loci of the tropospheric jets.

**Keywords** Central Africa · Rainfall · Large-scale mechanisms · Rain gauge data · Composite analysis · Jets · SST

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A. Farnsworth (✉)
NCAS-Climate, Walker Institute for Climate System Research,
University of Reading, Reading, UK
e-mail: a.j.farnsworth@reading.ac.uk

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# 1 Introduction/Rationale

The importance of detailed knowledge of the climate system, and its variability, is undeniable. Previously, work concerning climate and variability on a global scale has been the main focus of investigation, however it is often argued that looking only at large-scale features are not generally applicable to regional studies because climate variables can vary substantially on a regional scale. Therefore it is imperative to investigate on both global and regional scales. A greater understanding of how regional climate behaves is vital, so that researchers are better able to facilitate policy makers to better manage their resources.

Central Africa is one area that has been neglected, with only a handful of studies being conducted (Balas et al. 2007, Todd and Washington 2004, Nicholson and Grist 2003, CLIVAR 2000) on a regional scale. Central African climatology is extremely complex with many different yet related factors (e.g. sea surface temperatures (SSTs) and regional/global circulation patterns) influencing precipitation variability (Balas et al. 2007). Nicholson and Grist (2003) suggest that our present understanding of meteorological processes in the region is weak. With central Africa covering an area roughly 2.6% of the planet and an estimated population of 119,551,000 rising to over 252,057,500 people by 2050 (United Nations 2009), the pressures upon this system can only increase. It is thus essential to understand this region's climate and its variability.

Detailed climate studies of central Africa represent only a small fraction of the available literature on African climate, predominantly due to the lack of data coverage in this region. Previous studies have used proxy data to infer rainfall in the region and its relationship to the large scale circulation (e.g., Hirst and Hastenrath 1984, Todd and Washington 2004). Presently the control of the oceans has been given most attention, with certain regions within central Africa showing both direct and indirect interactions to different Sea Surface Temperature (SST) anomalies throughout the season (Balas et al. 2007). Early work into the effect of the El Nino Southern Oscillation (ENSO) has also been conducted, primarily due to the global impact of this phenomenon upon rainfall characteristics. Understanding of how the jets and other large scale circulation features in the region interact with the Intertropical Convergence Zone (ITCZ) and sources of convection is also not well understood. Likewise the effect of changes into the Hadley and Walker circulation has been given little attention but do have a direct impact upon rainfall interannual variability (Nicholson 1986) and potentially interdecadal variability in the region.

One of the primary reasons for the dearth of studies into central African climate and its large scale drivers is a lack of accurate rainfall data, in part due to a sparse gauge network. Other regions on the African continent have seen greater investment largely due to their greater vulnerability to climatic extremes (particularly in drought prone regions) as well as other social-economic reasons (i.e. nation's level of infrastructure/commitment to research and development).

Therefore the aim of this chapter will be to investigate the importance of regional and global scale processes upon rainfall mechanisms over central Africa during the rainy season(s). The remainder of this chapter is firstly a review the main drivers of central African climate, based on the current literature. The methodology for this study is then presented in Section 4, before a discussion of the results, in Section 5, focusing on rainfall in two regions of central Africa. Section 6 summarises and concludes.

## 2 Review of the Main Drivers of Central African Climatology

### *2.1 Convective Systems*

Presently little is known about the synoptic and mesoscale systems that govern the rainy season in Central Africa on varying time scales due to the aforementioned data constraints. This is further compounded because satellite algorithms used to deduce rainfall amounts over estimate it by a factor of 2–3 (Balas et al. 2007). Mesoscale convective systems (MCS) such as cloud clusters/thunderstorms are a fundamental unit of vertical transport of energy over the central African region. The highest frequency of lightning strikes in the world is also observed here (Nicholson and Grist 2003). MCSs occur wherever there is enough vertical motion to allow deep convection to occur, for instance diabatic heating in the lower layers or injection of moisture into the lower layers (Asnani 2005). Increased strength in the upper-level jets could potentially invigorate convection through creation of and/or influence on African Easterly Waves (AEW). This might allow increased MSCs and squall line activity leading to enhanced precipitation in the vicinity of the jets. Vertical shear is also important to the dynamics of MCSs for the internal transport of moisture, affecting the direction of the MCSs propagation and the life span. However, too much wind shear can result in the system breaking down. Convective instability from easterly waves is also an important feature (Nicholson and Grist 2003, Mathews 2004), inducing adiabatic lifting from the boundary layer to the level of free convection, promoting deep convection of buoyant moist masses. Perturbations to the sources of convection and/or mechanisms that modify deep convection (jets, easterly waves) will impact upon rainfall variability and will be investigated throughout central Africa.

### *2.2 The ITCZ*

The ITCZ is one of the direct drivers of rainfall variability in central Africa through perturbations in its strength and position. The ITCZ forms the ascending branch of the Hadley cell, thus what affects the strength of the trade winds from either hemisphere will also affect the position and strength of the ITCZ.

The North–South seasonal march of the ITCZ can bring two rainy seasons to certain regions in central Africa; however the regions further from the equator will only experience one pronounced dry and wet season. It should be noted that the position and intensity of the ITCZ does not always imply the position of the rainbelt (east–west band of intense localised rainfall), as noted by Nicholson (2009). However the strong moist ascent associated with the ITCZ means its position and intensity will be an important factor in rainfall variability. It is therefore important to investigate what mechanisms could perturb the large-scale circulation patterns in the region.

## 2.3 Sea Surface Temperature

Nicholson and Entekhabi (1987) were one of the first to look at the relationship between large scale SST anomalies and rainfall variability over just equatorial Africa. More recent studies have mainly investigated this relationship only over East and West Africa (Goddard and Graham 1999, Mutai and Ward 2000, Clark et al. 2003, Giannini et al. 2003, Schreck and Semazzi 2004). However, Camberlin et al. (2001) did indicate that such a relationship also existed on a larger scale over the African continent showing that SSTs were a main cause of rainfall variability over inland regions, not just for coastal regions of Africa.

Balas et al. (2007) further investigated this relationship over central Africa, considering regions further from the equator. Their findings show a complex relationship with SSTs having both a direct and indirect influence on rainfall variability. Correlations between SSTs and rainfall were found to be both positive and negative throughout the seasons. This suggests that SSTs and rainfall associations are non-linear, with different ocean basins and external influences upon SSTs being seasonally dependant in the region. For example, warm SSTs over the tropical equatorial eastern Atlantic can bring high rainfall from the ITCZ to regions such as to the west of the Democratic Republic of Congo (DRC). However, warm SST anomalies may also stabilise the passage of the ITCZ, retarding its advance northward over the equator during the boreal summer and causing a negative SST/rainfall relationship (Balas et al. 2007). This brings wet conditions to southern central Africa and drier conditions to northern central Africa. Determining the role of SSTs in rainfall variability is of utmost importance, not only as a moisture source but also its indirect effect on the regional circulation.

Atlantic SST anomalies result from two major spatial modes.

(1) *The Atlantic Nino* is an equatorial warming that creates warm SST anomalies displacing convection south-eastwards. This induces greater rainfall during the boreal summer/autumn creating dry conditions over Cameroon and the Central African Republic and wet conditions over Democratic Republic of Congo (DRC), Congo and Northern Angola. Subsequently the reverse occurs when greater upwelling in the equatorial Atlantic creates cold SST anomalies in these regions (Balas et al. 2007).

(2) *The Inter-hemispheric mode* is where changes to the above dipole will change the SST warm/cold anomalies (Camberlin et al. 2001, Wu et al. 2006, Balas et al. 2007), shifting the predominant source regions of atmospheric moisture of the equatorial Atlantic. This could change the seasonal relationship with Atlantic SST anomalies and teleconnections such as ENSO. Coastal SST anomalies can also have both a positive and negative impact upon rainfall. For

example coastal anomalies may lead to SSTs and rainfall being positively correlated over coastal regions, however further inland into central Africa areas may show a negative relationship with the coastal SST anomaly (Balas et al. 2007).

The role of Indian Ocean SST anomalies is one of potential importance to interannual rainfall variability. During September–November warm SST anomalies in the Indian Ocean are shown to correlate with positive rainfall anomalies over the DRC, whereas cold anomalies correlate with negative rainfall anomalies over Cameroon and the Central African Republic, though these were found to be not statistically significant (Balas et al. 2007). Over Gabon and Congo a positive correlation is shown during June–August and a negative correlation during September–November (Balas et al. 2007). Large scale climatological shifts in SST in the Indian Ocean are a result of other mechanisms (e.g. ENSO) rather than internal variability in SST. Subsequently basins SSTs should not simply be investigated singly but also in relation to what is occurring in other oceanic basins.

## *2.4 Central African Jets*

Atmospheric jets (Fig. 1) in the vicinity of central Africa play an important role on rainfall processes, through impacts upon Africa Easterly Wave (AEW) production and modulation, as well as the impact of vertical shear upon deep convection. Four jets have been identified: (1) the Westerly African Jet (WAJ); (2) the African

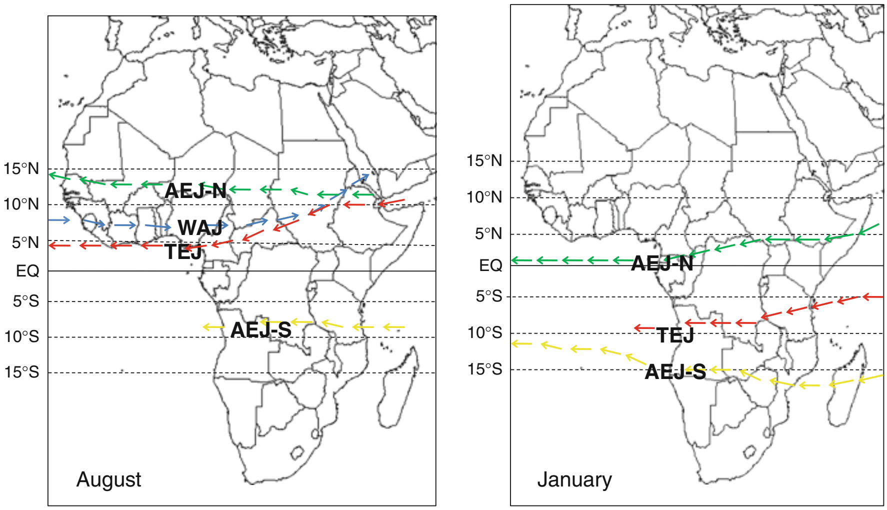


**Fig. 1** Schematic of the position of the Northern African Easterly Jet (AEJ-N), Southern African Easterly jet (AEJ-S), Westerly African Jet (WAJ) and the Tropical Easterly Jet (TEJ) over the African continent during August and January. Positions taken from NCEP-NCAR reanalysis mean climatologies (1961–1990)

Easterly Jet-North (AEJ-N); (3) the African Easterly Jet-South (AEJ-S); and (4) the Tropical Easterly Jet (TEJ). It has been argued that the position of the overlying AEJ and the TEJ in West Africa are of most importance concerning the position of the rainbelt (Nicholson 2009).

Both mid-tropospheric AEJs exist during most months (Nicholson and Grist 2003) and thus potentially influence annual variability. The AEJ-N and AEJ-S are both formed due to the temperature gradient from two diabatically forced meridonal circulations. The AEJ-N is produced from the contrast between the Sahara (hot) and the Guinea coast (humid and warm). Likewise the AEJ-S is formed from the temperature contrast between the semi-arid regions of Southern Africa and the sub-humid vegetated lands of the tropical Central Africa (Nicholson and Grist 2003). The mean position of the AEJ-N migrates throughout the year (Fig. 1). During the boreal winter it is found near 3°–5°N, is moderately weak and is found to even disappear during November. During the boreal summer the AEJ-N over Central Africa strengthens (though weaker than other regions such as Western Sahalian Africa, of only ~10 m $s^{-1}$) with its location between 10°0 and 12°N. The jet core is located at 600 mb in all months except October, where it is dominant at 650 mb (Nicholson and Grist 2003). The AEJ-S is at its most intense during August–November with its position ranging from 5°S (August) to 15°S (November) with core speeds of 6 m $s^{-1}$ in August to 10 m $s^{-1}$ in October. In December–March the jet is not very pronounced and in April–July it is not present at all (Nichoslon and Grist 2003).

The role of the individual AEJs in influencing rainfall is still uncertain. It is thought that the jets can influence the intensity of the rainbelt during August–November, depending on their respective positions and strengths, with the highest rain occurring between August–November for most regions in central Africa when both the AEJ-N and AEJ-S are at their strongest (Nicholson and Grist 2003, Nicholson 2009). Though it is thought that the AEJs might not be responsible for triggering AEWs, it is known that AEWs do propagate along the jet and thus it will be a factor in their development and organisation (Nicholson and Grist 2003, Leroux and Hall 2009). The importance of AEWs is that they can trigger MCSs activity through dynamical instability allowing deep convection for the MCS to form and grow given a constant supply of moisture. Thus intraseasonal variability (and interannual variability) in the intensity and location of the AEJs could influence the AEWs and their ability to allow organised deep convection.

The TEJ is one of the most intense features over equatorial Africa. It is not just restricted to the summer months nor to just the northern hemisphere (Nicholson and Grist 2003) and is one mechanism for the formation of AEWs. Its average location ranges between 5°–10°N in August and 5°–10°S in January. The TEJ is also produced from the thermal contrast but here produced over the Indian sub-continent (deep layer of warm air to the north of the Jet and colder air to the South over the Indian Ocean). Central Africa is in the west exit region of the Asian branch of the TEJ; this exit region will enhance upper-level divergence and lower-level convergence, promoting convective activity. Variability in the TEJ is associated to perturbations in the Tibetan high and so this feature could have a remote impact upon central African rainfall (Nicholson and Grist 2003).

A newly designated Westerly African Jet (WAJ) at 850 mb, with core speeds as high as 10 $ms^{-1}$ and a mean position around 10°N, may also play a significant role in rainfall variability in central Africa (Nicholson 2009). The WAJ development is thought to be controlled by the surface pressure gradient over the tropical Atlantic with a strong cross-equatorial gradient needed to produce inertial instability. A more intense WAJ seemingly leads to increased ascent between the TEJ and the AEJ-N increasing rainfall in the rainbelt (Nicholson 2009). This may be influential over the northern regions of central Africa. Whether a similar relationship between a southern hemisphere WAJ, TEJ and AEJ-S exists has not been determined, however if present it would be an important feature controlling rainfall variability.

## 3 Teleconnections

### *3.1 EL Nino Southern Oscillation (ENSO)*

ENSO events are highly correlated to African rainfall with differing magnitudes, seasonal timings and durations (Nicholson and Kim 1997). Camberlin et al. (2001) indicated that most parts of Africa show correlations between ENSO and rainfall variability, with the strongest correlations occurring during the peak wet season(s). A negative correlation was indicated between central African rainfall and NINO3 SSTs in March–May and August–November; however ENSO's main, but not exclusive, influence is upon the MAM period, the secondary rainy season for most of central Africa (Balas et al. 2007). During an El-Nino event the length of both wet seasons are reduced. The impact of ENSO diminishes towards the West over Africa, and there is also an apparent increase in its impact further from the equator (Nicholson and Kim 1997).

During an El-Nino event rainfall is reduced during the January–March period over the southern Congo basin and Northern Angola. In the dry season Nicholson and Kim (1997) agrees with Camberlin et al. (2001) in seeing a prolonged and drier summer than normal. For the period after the El-Nino event, January–February rainfall is seemingly enhanced but to a small degree. To the southeast of central Africa, Nicholson and Kim (1997) again also show that El-Nino event increases October–December rainfall.

The impact of Atlantic and Indian Ocean SST anomalies is also an important consideration within an ENSO event. Though it is likely that ENSO does modulate central African rainfall to some degree by perturbing Atlantic/Indian Ocean SSTs, which affect the local/regional atmospheric dynamics (Nicholson and Kim 1997), the actual connection is difficult to determine conclusively.

### *3.2 Large-Scale Circulation*

The Hadley circulation has been suggested as the mechanism responsible for widespread continental drought in 1972 in Africa, due primarily to strengthening of the overturning circulation (Nicholson 1986, Long et al. 2000). Despite a continental-wide drought, equatorial regions in contrast experienced more intense rainfall during their wet season(s) but suffered a more prolonged dry season (Nicholson 1986). The Walker circulation shows the opposite sign with a strengthening of the circulation appearing to enhance rainfall in certain regions such as central Africa during 1967 (Nicholson 1986).

However, the above strengthening of the Hadley (Walker) circulation does not always imply a shift to dry (wet) regimes. A shift to a wetter regime in the mid-1970s that lead to higher SSTs in the Atlantic and Indian Oceans was not accompanied by wet conditions everywhere. It has also been suggested that ENSO regulates the large-scale circulation. El-Nino conditions can alter the Walker circulation, enhancing upper-level westerlies along the equator and strengthening the near surface easterly trades, which helps in maintaining upper-level divergence between 10° and 15°N and thus allows equatorial convergence. This relationship suggests that an anomalously strong or weak Walker cell (Ruiz-Barradas et al. 2003) would influence convection over central Africa and thus rainfall variability.

# 4 Methodology

## *4.1 Data Sources*

Currently, the best 'in-situ' dataset for central Africa is African monthly rain gauge data collected by Florida State University (Nicholson 2000). The data set does however contain some limitations, most notably gaps within the data record mainly resulting from conflict within the country. We consider all stations that lie within a pre-defined domain and then eliminate stations according to: (a) The data period must overlap with the NCEP-NCAR reanalysis data set, extending from 1948-present; and (b) The station must exhibit less than 5 missing years of data over this period. It was subsequently found that out of the original 67 stations in Central Africa, approximately 60 remained suitable, with a temporal coverage varying from 1948 to the mid-1990s.

Central African mean rainfall is known to be highly varied spatially. Due to this the rain gauge data were transformed into station rainfall departures (a description of this processes is given in Balas et al. 2007) to reduce the influence of these problems.

NCEP-NCAR reanalysis data are used in conjunction with the gauge dataset as it provides spatially homogenous environmental data not present in the rain gauge data series. The NCEP-NCAR model is described in greater detail in Kalnay et al. (1996). There are known problems with reanalysis rainfall over tropical Africa, e.g. Trenberth et al. (2001), Camberlin et al. (2001), Janowiak et al. (1998). We opt, therefore, to utilise in situ rainfall when possible, despite the recognized limitations of rain gauge data. The principal role of the NCEP-NCAR reanalysis data is determining the spatial pattern of meteorological variables, and assessment of large scale controls on central African rainfall variability through composite analysis. The primary variables of interest include vector and zonal winds noted to be relatively reliable by Nicholson (2009), at 850 mb (Level of the AWJ), 600 mb (level of the AEJ) and the 200 mb (level of the TEJ), Sea Level pressure (SLP), air temperature, Outgoing long-wave Radiation (OLR, a proxy for cloud cover and rainfall), Sea Surface Temperatures (SST) and soil moisture.

### *4.2 Regions*

Following the work of Balas et al (2007) we divided central Africa into 6 regions A, B, C, D, E, F (Fig. 2) based upon the gauge stations' seasonal cycle. These regions were chosen from preliminary analysis of the rain gauge data, where stations that exhibit the same seasonal cycle are assumed to have the same climatic mechanisms. However, for brevity, only regions B and E will be discussed as these are representative of regions south and north of the equator, respectively. Figure 3 shows the seasonal rainfall cycle and rainfall time series produce from the rain gauge data for regions B and E.

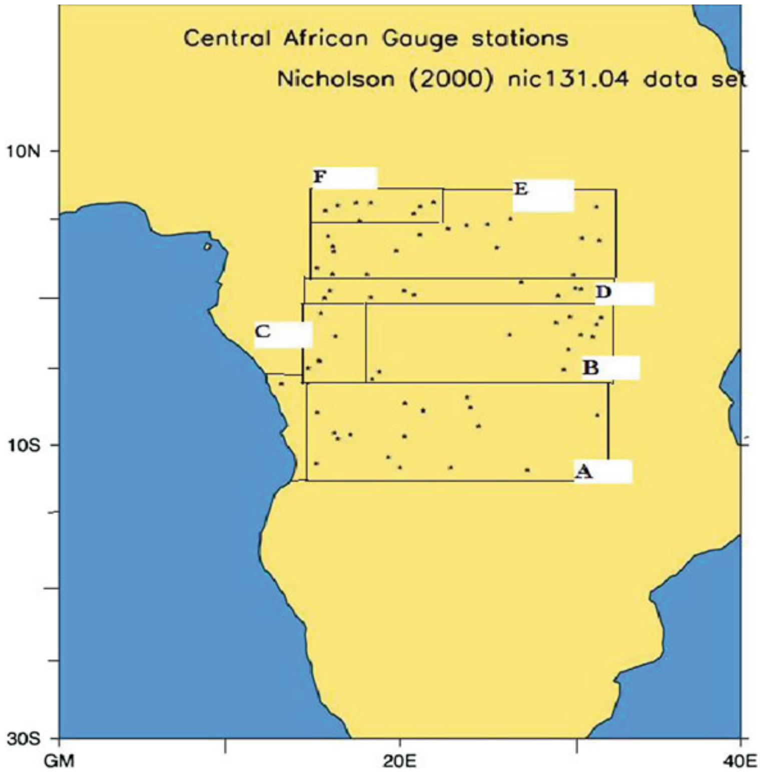


**Fig. 2** Central African rainfall study region

### *4.3 Composite Analysis*

Composite analysis allows us to compare the wettest and driest wet seasons from the observational record against NCEP-NCAR reanalysis data, indicating the large scale

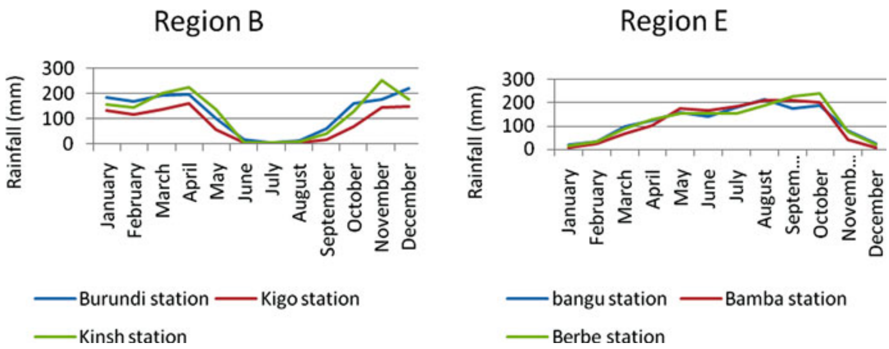


**Fig. 3** Seasonal rainfall distribution for each defined region of central Africa depicting the three 'best' gauge station seasonal data within the region over the time series length

mechanisms that lead to these extremes/deficits in rainfall. Balas et al. (2007) found that inter-regional correlations are relatively low and that station-region correlations suggest that strong local influences on precipitation can drive variability. This means a given station may not be representative of the region surrounding it. It is for this reason that the time series analysis for each region was constructed using the three 'best' stations (this criteria consisted of finding the most complete time series, with regards of missing data). Five clear extreme (wet) and deficit (dry) years of from the time series were chosen to produce wet and dry composites for certain parameters (Table 1). These were compared against 1968–1996 climatology from the NCEP-NCAR reanalysis data to identify what mechanisms were influencing the observed variability.

**Table 1** 5 Wettest and driest years in regions B and E

| Region | Wet years | Dry years |
|---|---|---|
| **B** | 1963 | 1949 |
| | 1975 | 1955 |
| | 1982 | 1958 |
| | 1986 | 1993 |
| | 1995 | 1996 |
| **E** | 1966 | 1960 |
| | 1969 | 1962 |
| | 1976 | 1986 |
| | 1977 | 1989 |
| | 1983 | 1991 |

## 5 Analysis of Rainfall Variability over Central Africa

This section presents the results and analysis of each region within central Africa for any inter-annual or inter-decadal trends.

### 5.1 Region B (0–6S, 18–32E) – Rainfall Seasonal Cycle and Time Series Analysis

Region B's main dry period is during the JJA period; however no stations register zero rainfall over this period. Stations in this region typically have an annual mean rainfall of around 1,000 mm east of approximately 30°E, but totals can be up to 2,000 mm further west. This difference may be indicative of the role of the East African highlands, which enhances rainfall locally to the west of this feature, whilst producing a pronounced 'rain shadow' of lower rainfall to the east. Typical total rainfall over the dry season is less than about 150 mm. The annual average monthly distribution of rainfall shows a bi-modal peak in the transition seasons, with maxima in April and November. The wetter season is MAM, contributing about 35% of the total, with SON contributing 30% on average.

Time series analysis is characterised by low variability in high and low rain years. However the signal shows that the change from a wet year to dry year is more frequent than other regions of central Africa, indicating that this region shows greater inter-annual frequency. Mean rainfall typically lies between 1,000 and 1,400 mm. Annual extremes in rainfall are around 1,700 mm for most stations. Deficit years are generally around 800 mm. The Burundi station exhibited the highest annual total twice in 1975 and 1995; however no other stations exhibit this large increase, this again points towards local characteristics influencing the signal rather than regional characteristics. The region also does not indicate the continental drought of 1972 suggesting that this event did not have a noticeable impact upon rainfall here.

### 5.2 Analysis of Region B's Wet and Dry Year Composites During the Primary Rainy Season (MAM)

OLR during wet years show a large (spatially) negative anomaly (increased cloud clover) over the eastern portion of the region, with dry years indicating the opposite (Fig. 4). However the NCEP-NCAR precipitation composite shows no corresponding anomalies over the region in wet years, emphasising NECP-NCAR reanalysis' inability to accurately simulate central African rainfall. A negative continental-wide SLP anomaly is present in wet years but no anomaly during dry years (not shown), which might indicate that a continental wide mechanism is forcing the increased rainfall.

SST composites show cold anomalies during dry years (Fig. 5). Cold anomalies in both the eastern equatorial Atlantic and western Indian Ocean may have some impact (reduced moisture supply into the west and east of the region), however the anomalies produced are small potentially indicating another influence upon dry years. Wet years show a slight increase in warm SSTs along the Gulf of Guinea and Benguela coast (Fig. 5). A weak La Nina in the tropical Pacific could be forcing this Atlantic anomaly (Balas et al. 2007) though the weakness of this event (–0.5°C) makes this unclear.

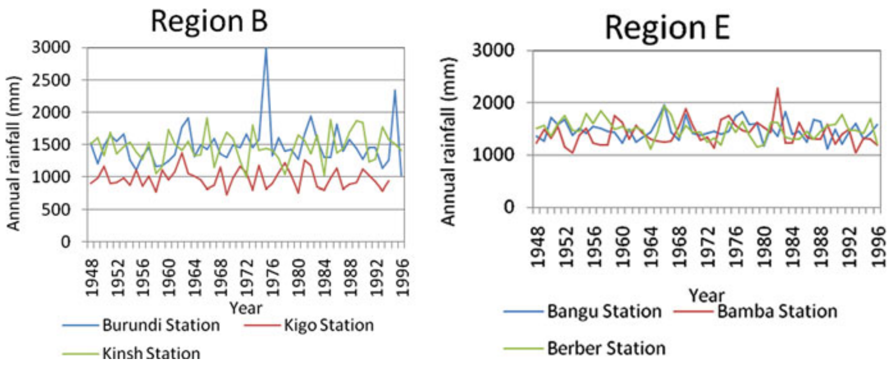


**Fig. 4** Region B OLR (*top*) and SST (*bottom*) anomalous wet and dry composites between MAM

Balas et al. (2007) also agree that wet years in this region are characterised by warm Gulf of Guinea SST anomalies, which was shown by correlating wet years from rain gauge data with regionalised SSTs. A stabilisation of the ITCZ (reduced tropical Atlantic – continental African thermal gradient) during wet years over the western portion of the region could be the primary cause for increased precipitation due to warm SSTs retarding its advance northward over the equator. No westerlies are apparent over the south half of the African continent (easterlies persist here), ruling out westerly sea-breezes causing wet conditions in the western portion of the region. Wet years also show an increase in the TEJ (not shown) encouraging lower level convergence (and increased wave activity), which has also been observed to be stronger during La Nina events. Though weak, the La Nina signal might well be an influence upon wet years in the region with dry years seemingly being forced primarily by cold equatorial Atlantic SSTs. Balas et al. (2007) also highlighted that dry years in this area were coupled to cold equatorial Atlantic SSTs.

### *5.3 Analysis of Region B's Wet and Dry Year Composites During the Secondary Rainy Season (SON)*

Wet year SLP composites indicate no negative anomaly whereas dry years indicate a small negative anomaly on a continental scale. Dry years are marked with small (0.2°C) warm SST anomalies in the equatorial Atlantic and cold SST anomalies in the Indian Ocean that are possibly being forced by a strong widespread La Nina event in the Pacific (Fig. 6). Wet years show the opposite sign to this with El Nino conditions creating opposite sign Atlantic and Indian Ocean SST anomalies. Dry years are also marked by 850 mb easterlies over the region with lower-level divergence and upper-level convergence prominent. A strong TEJ is also present as would be expected (creating strong vertical shear, preventing organisation of deep convection to form MCSs) under La Nina conditions (however this mechanism is secondary to the easterlies over the region).

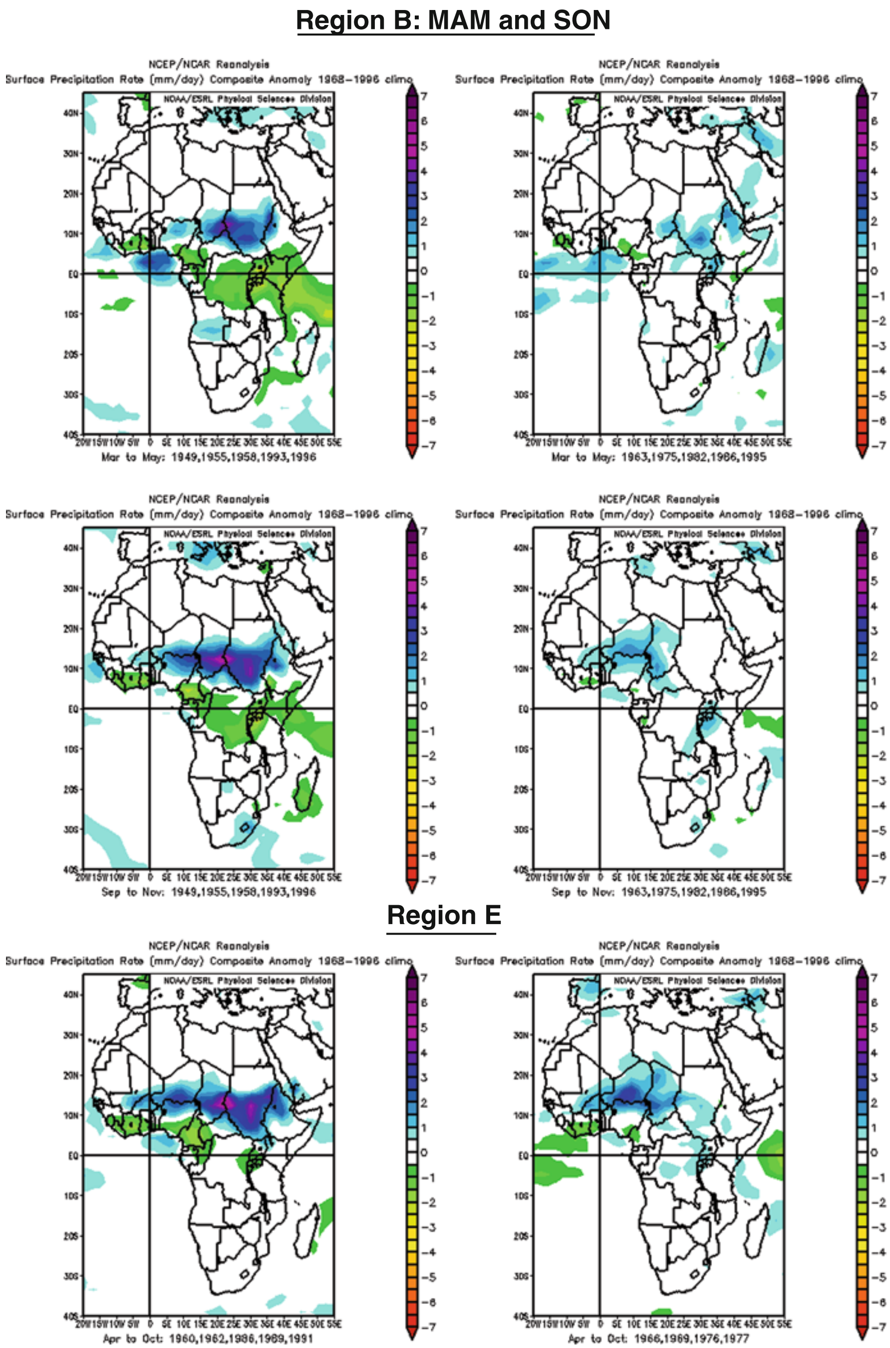


**Fig. 5** Wet and dry precipitation rate anomaly composites for regions B and E during their respective ‘rainy’ seasons

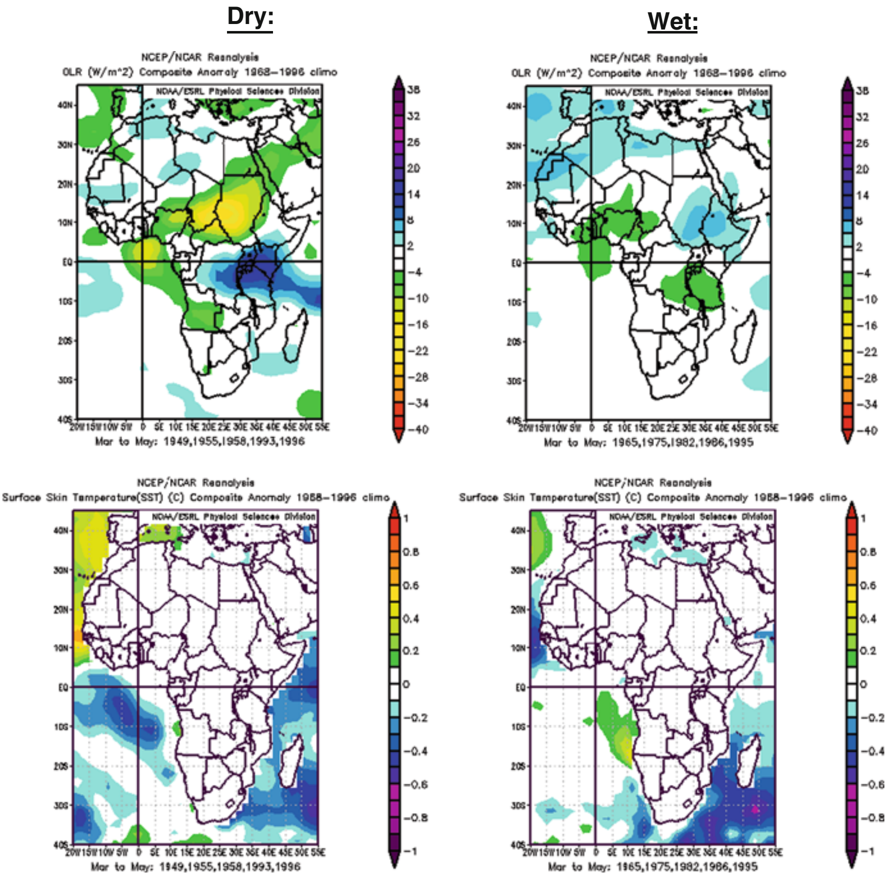


**Fig. 6** Region B Tropical SST anomalies wet and dry composites during SON

Pacific Ocean SST forcing seemingly plays a key role in rainfall variability over the region. The MAM rainy season is marked with La Nina events in wet years but only 2 years show El Nino conditions during dry years (1958 and 1993). However, during SON El Nino events characterise wet years with La Nina conditions present during dry years. Balas et al. (2007) also observed this. Given that the majority of the gauge stations are to the east of the region, any identified mechanisms are likely to be associated with ENSO, because of its stronger influence here relative to further inland.

The WAJ, though known to influence rainfall during the West African monsoon north of the equator, is now thought to be able to influence rainfall south of the equator. Region B (during SON only) in wet year composites shows the WAJ to have a direct influence on rainfall due to this jet having a more southerly position. During dry years the jet is further north of region B than its mean position with omega fields showing the ascent associated with the WAJ away from the regions. For region B during MAM the WAJ has no influence on rainfall.

The WAJ is also potentially having an indirect influence on rainfall south of the equator even when it is in a more northerly position during region B wet years. This is due to a favorable low-level regional southward propagating circulatory pattern influencing the movement of moisture (from the Gulf of Guinea) contained in the WAJ into region B.

## *5.4 Region E (3–5N, 15–22E and 5–7N, 22–32E) – Rainfall Seasonal Cycle and Time Series Analysis*

This region has rainfall characteristics in common with Western and Northern central Africa, which receive much of their annual average rainfall from the West African Monsoon in JJA. The annual distribution is typically uni-modal, with a period of high rainfall between April and October, reaching a maximum in July/August. Annual average totals in this region are typically between 1,500 and 2,000 mm, with JJA monsoonal rainfall contributing approximately 40% of this total. There is no ‘dry’ season, but low rainfall is observed in DJF, where the 3 month total does not tend to exceed 200 mm.

A decreasing trend in annual rainfall is observed from the time series (Fig. 7). This signal is apparent in most of the gauge stations however data loss since the 1970s might be the cause of this. Wet year rainfall can reach in excess of 2,000 mm with dry years reaching 1,100 mm. The near-continental drought year of 1972 shows an increase in annual rainfall in nearly all stations from the previous year, however during 1973 nearly all stations record a drop in annual rainfall.

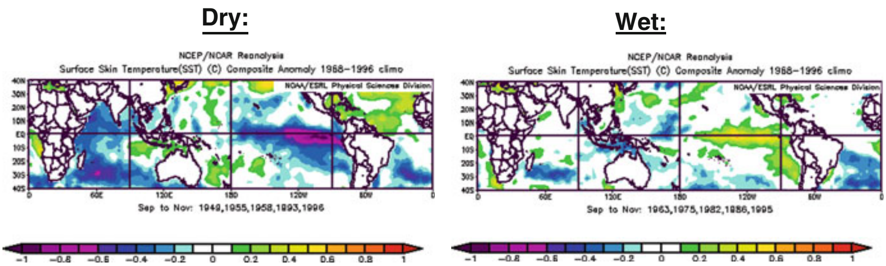


**Fig. 7** Regional time series for regions B and E in central Africa depicting the three ‘best’ rain gauge station data

## *5.5 Cause of Extreme and Deficit Rainfall During the Apr–Oct Rainy Season*

Surface air temperature composites indicate that a stronger positive (Sahara) – negative (equator) gradient is formed during wet years (Fig. 8). This could be causing the ITCZ to be more intense and stationary over the north of the continent thus spending greater time over region. Positive anomalies in run-off and soil moisture fields over the region (not shown) also indicate a more intense ITCZ and/or rainbelt.

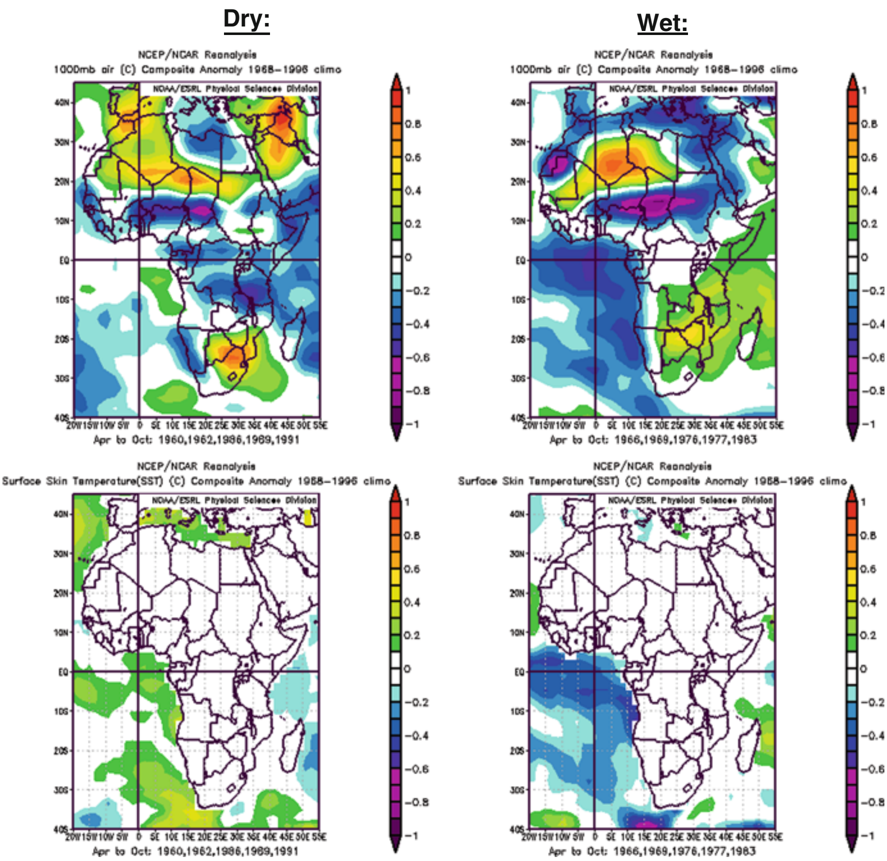


**Fig. 8** Region E Surface air temperature (*top*) and SST (*bottom*) anomalies during wet and dry years during Apr–Oct

During dry years the position of the ITCZ was further north of its mean position. This hypothesis is backed up from run-off, soil moisture fields and surface precipitation rate showing positive anomalies above 10°N with negative anomalies below this (not shown). An enhanced rainbelt could also be forcing wet years with an enhanced AEJ-S (2–3 m/s stronger in wet years than dry years). The AEJ-N mean position during August–October (peak rainy season) indicates the AEJ-N is more northerly than its mean position during dry years. Nicholson (2009) found that a northern excursion of the AEJ-N results in greater Sahel rainfall and reduced Gulf of Guinea rainfall in August, which is shown here for dry years, thus it seems that a reverse of this is also true.

SST composite analysis shows a clear warm (cold) anomaly in the south equatorial and southern Atlantic during dry (wet) years (Fig. 8). However this is contrary to what Camberlin et al. (2001) find, as warm SST should decrease the thermal gradient over the continent suggesting a southern shift in the ITCZ which does not seem apparent here. Thus another mechanism for this ITCZ configuration may be of more influence. Wet years also show El Nino conditions present in the Eastern Pacific which could be driving the cold SSTs seen in the South and equatorial Atlantic during wet years.

## 6 Summary of Findings

Central Africa is a climatologically diverse region shown to vary extensively in both its seasonality as well as its inter-annual/inter-decadal rainfall. It has been identified that rainfall is dictated by three rain-bearing processes (MCS, ITCZ and rainbelt) and modified by mechanisms that have been introduced in this chapter (e.g. SSTs, Jets, Hadley/Walker circulations, ENSO). These, either singularly or combined, can influence the rainfall signal throughout the various regions identified. Figures 9, 10 and 11 are schematics of the mechanisms and influences for wet and dry years over central Africa north and south of the equator.

NCEP-NCAR reanalysis does not represent the finer scale features very well in the composites. As precipitation is derived from model parameters, as well as the dataset having a low spatial resolution, it is likely to suggest that it will miss out smaller scale convective features, however it does generally represent the broad scale patterns shown in the rain gauge data for most regions.

SSTs along the Gulf of Guinea and Benguela current have been identified as an influential mechanism in driving interannual variability, by directly influencing the position and/or intensity of the ITCZ, rainbelt and the jets. Likewise teleconnectons mainly resulting from Pacific ENSO modes can also indirectly influence Atlantic/Indian Ocean SSTs and thus also the main rain forming systems. Specific regions do not necessarily exhibit an opposite pattern during dry and wet years in same rainfall influencing processes. Likewise the rain bearing mechanisms (such as SST/jet stream configurations) will not necessarily create the same wet/dry conditions during the primary rainy season, as well as the secondary rainy season.

ENSO's influence in central Africa, also noted by Balas et al. (2007), diminishes westwards. Where ENSO has been identified to be the main mechanism upon variability, it has been observed to have a more noticeable impact early in the year (MAM) and less so through the summer to winter periods. This suggests that ENSO events may be more influential south of the equator in central Africa as this is their primary rainy season. Conversely the Atlantic Ocean's influence on rainfall has been shown to be seasonally dependant with it being mainly influential during the autumn months (SON). The mechanisms by which the Pacific ENSO signal is able to influence the local SSTs and/or large scale wind patterns over central Africa have not been conclusively established, however its role is likely very important and merits further investigation.

The Indian Ocean is also found to influence variability early in the year, though this also diminishes westwards over central Africa. It has also been noted that where strong SST anomalies in the Atlantic and Indian Ocean where found to be in opposition, an east–west displacement of convection is created, shifting favourable

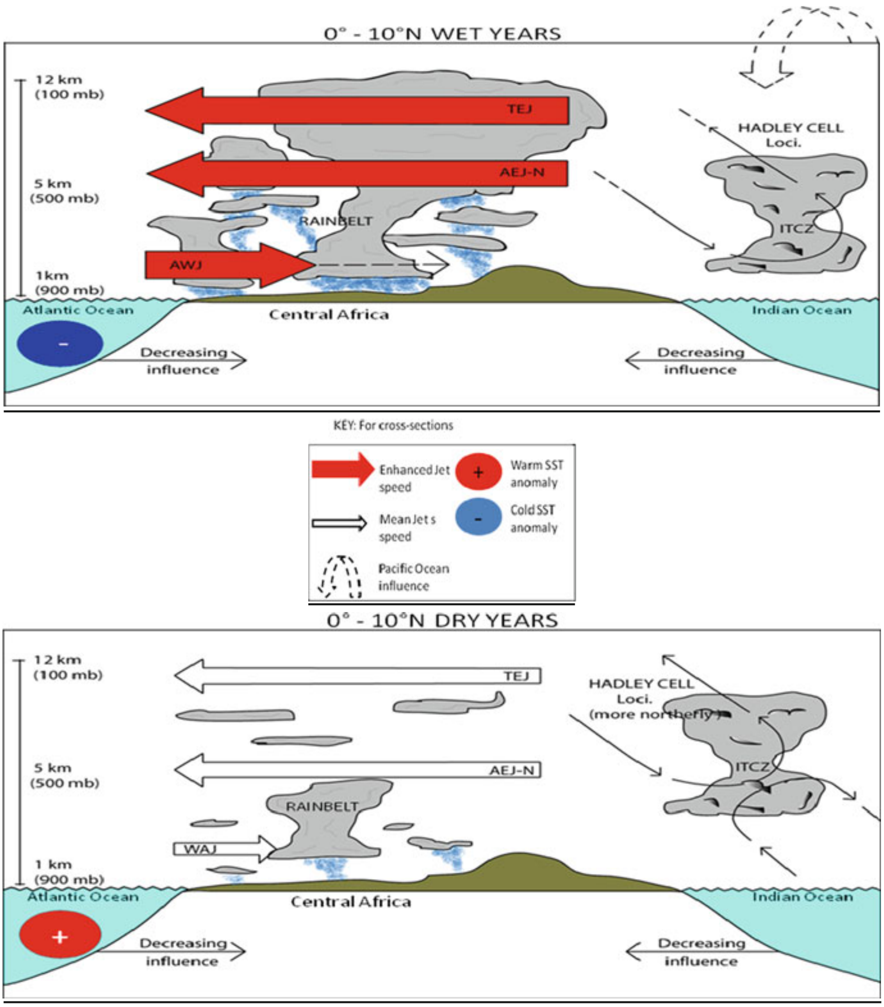


**Fig. 9** Shows a general overview of the influences upon the rain bearing mechanisms (Rainbelt, ITCZ) between wet (*top*) and dry (*bottom*) years in central Africa between 0°–12°N. The schematic indicates the role of the TEJ, AEJ-S, (WAJ), Atlantic/Indian Ocean SST anomalies and the impact of ENSO upon the mechanisms governing wet and dry years

conditions for rainfall over certain regions. The Atlantic and Indian Ocean, though a source of moisture, have been shown to influence rainfall mainly through their modulation of the intensity and/or position of the ITCZ/rainbelt. This can occur by increasing and/or decreasing the temperature gradient between the eastern tropical Atlantic and the African continent, which also affects the intensity and position (Fig. 11) of the AEJs/TEJ and WAJ. This, in turn, can critically influence the loci and magnitude of MCS and squall line activity and thus the position and/or intensity of the rainbelt.

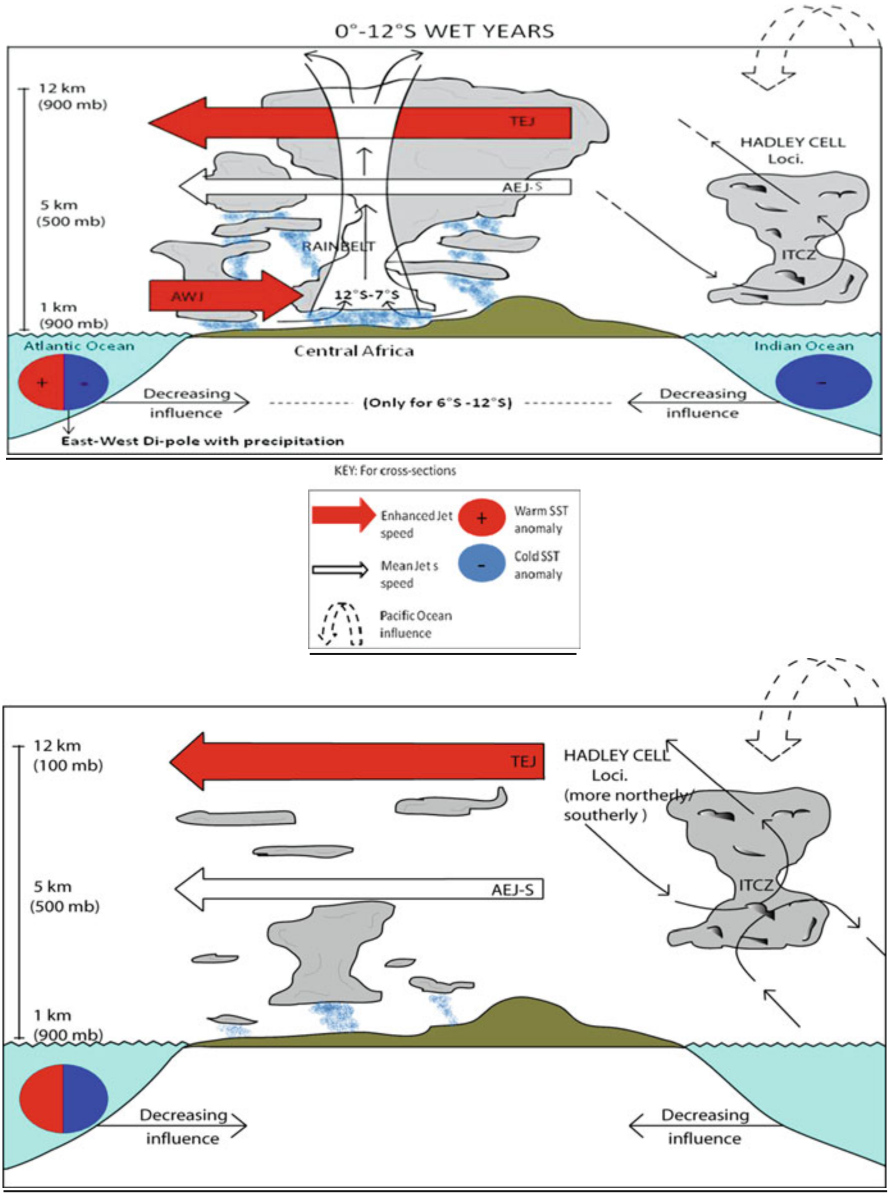


**Fig. 10** Shows a general overview of the influences upon the rain bearing mechanisms (Rainbelt, ITCZ) between wet (*top*) and dry (*bottom*) years in central Africa between 0°–12°S. The schematic indicates the role of the TEJ, AEJ-S, (WAJ), Atlantic/Indian Ocean SST anomalies and the impact of ENSO upon the mechanisms governing wet and dry years

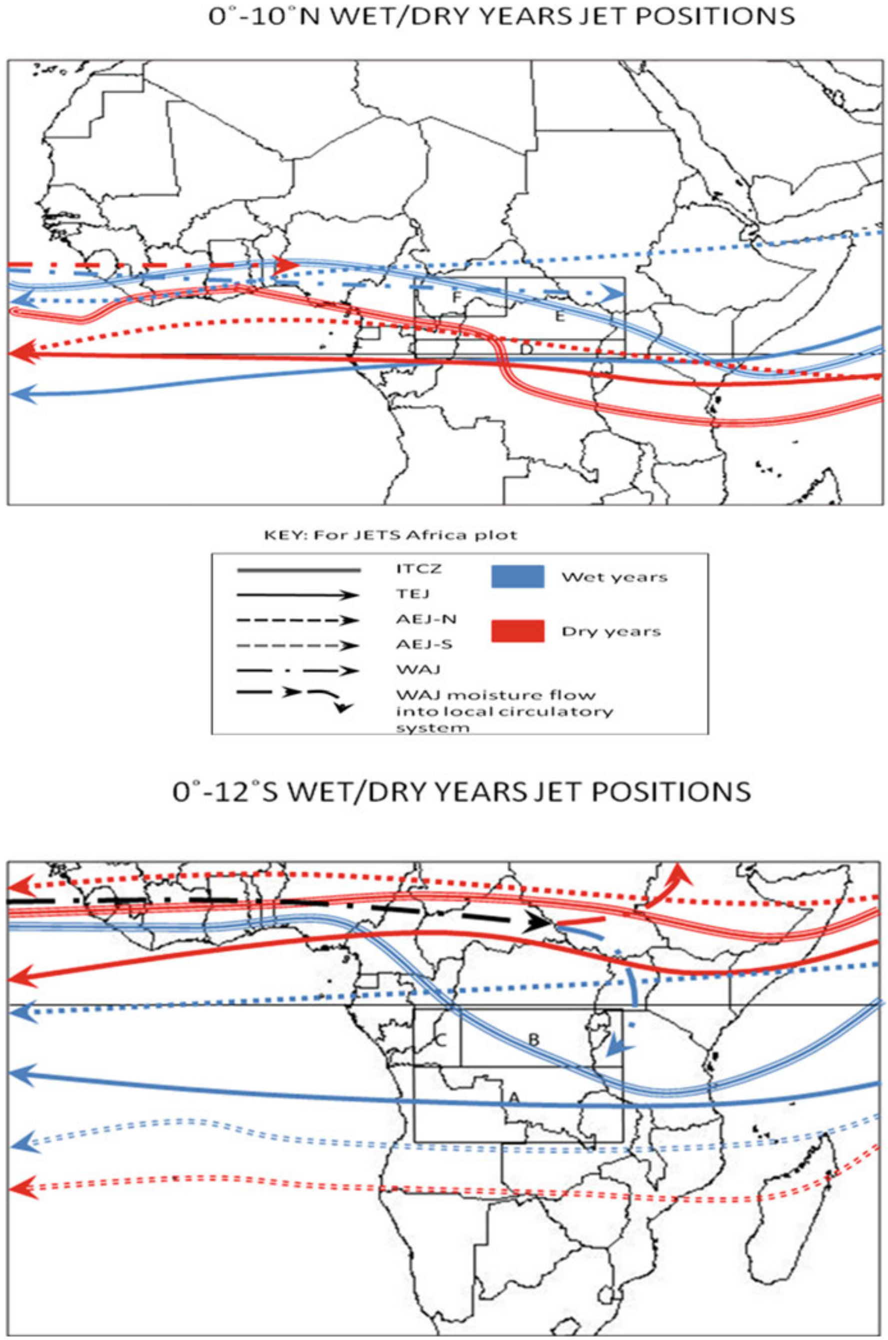


**Fig. 11** Schematic depicts relative latitudinal positions of the ITCZ, TEJ, AEJ-N, AEJ-S and the WAJ during wet and dry years for 0°–10°N (*top*) and 0°–12°S (*bottom*) (Refer online version for color images)

This analysis has also shown that in the southern hemispheric region of central Africa, eastern and western portions of the region do not always display opposite conditions during wet and dry years. In some locations during wet years the western (eastern) portions of the region show positive (negative) rainfall anomalies, but during dry years this pattern is not repeated., however elsewhere this is not the case. This is not only shown in the NCEP-NCAR reanalysis data, but also the rain gauge data.

In this chapter we have aimed to improve the current understanding of the mechanisms that influence rainfall in central Africa. It is hoped that a greater understanding of these mechanisms and their influence on rainfall will enable policymakers to make more informed decisions.

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# Climate Change Impacts on Hydrology in Africa: Case Studies of River Basin Water Resources

**M.C. Todd, L. Andersson, C. Ambrosino, D. Hughes, Dominic R. Kniveton, L. Mileham, M. Murray-Hudson, S. Raghavan, R. Taylor, and P. Wolski**

**Abstract** There is a growing consensus that anthropogenic climate change is a real phenomenon. There is strong evidence that changes to the hydrological cycle have occurred and will continue to do so in the future. Given our dependence on water resources and ecosystem services associated with the river system, this means it is important that appropriate adaptation strategies are developed. Such policies require information on future behaviour of the climate system and impacts on surface hydrology at the river basin scale. This chapter presents two contrasting case studies from river systems in Africa, in which climate change impacts on hydrology are examined. The methodology of climate change impact assessment is described and critically examined with particular respect to quantification of uncertainties. Finally, the implications for water resource management policy are considered.

**Keywords** Southern Africa · Hydrology · River systems · Water resources · Ecosystem services · Impacts · Water resource management policy

## 1 Introduction

There is a growing consensus that human activities, most notably emissions of greenhouse gases (GHG), have resulted in a discernable influence on global climate, and that this has been the primary driver of global warming in recent decades (Solomon et al. 2007). Anthropogenic climate change represents a considerable challenge at many levels of society. Recently there have been efforts to determine the level of GHG emission necessary to avoid dangerous climate change in the future. Nevertheless, on the basis of past GHG emissions and inertia in socio-economic systems we must anticipate that future climate change is unavoidable and that adaptation is necessary. Decision-making bodies, including governments, need to incorporate climate-related risks into decision-making processes. Given that

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M.C. Todd (✉)
Department of Geography, University College London (UCL), London WC1E 6BT, UK
e-mail: m.todd@geog.ucl.ac.uk

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adaptation policy tends to be made at national, regional and local levels there is a need for climate change impact assessment at these scales. This chapter exemplifies this process for climate change impacts on river basin-scale hydrology over selected basins in Africa and the implications for policy.

Freshwater is vital to our life-support systems. Water is a pre-requisite for all forms of life on Earth and is required for almost all human activities. However, for much of the world the availability of adequate water poses a significant challenge to development and environmental sustainability. In recognition of these challenges there have been numerous international initiatives to address the issues associated with freshwater resources. These include the UN's Agenda 21, Millennium Development Goals, Millennium Ecosystem Assessment, World Water Development Report and the World Water Fora.

Climate change is likely to be an important constraint on water availability in the future. There is considerable evidence that the global hydrological cycle has already responded to the observed warming over recent decades (Solomon et al. 2007), through increased atmospheric water vapour content, changing patterns of precipitation including extremes, reduced snow and ice cover and changes to soil moisture and runoff. Climate models suggest further substantial changes to the hydrological cycle in the future under scenarios of GHG emission. Although there is considerable uncertainty in projected patterns of precipitation at the regional scale, the Intergovernmental Panel on Climate Change (IPCC) fourth report (AR4) suggests that precipitation and average annual river runoff are likely to increase in the midlatitudes and some areas of the humid tropics but likely to decline in many semi-arid regions, notably in the tropics (Solomon et al. 2007). The relationship between climate and water resources, however, does not exist in isolation but is strongly influenced by socio-economic and other environmental conditions. Various human activities influence available water resources, most notably agriculture, land use, construction, water pollution, water management and river regulation. At the same time water demand is highly variable, largely determined by population and levels of development.

In this context, African water resources may be particularly vulnerable to future climate change. Africa already suffers disproportionately from water related hazards of flood and drought (World Water Assessment Program 2003). Whilst there is uncertainty about the magnitude of current water issues in Africa, the analysis of Vörösmarty et al. (2005) suggests that about 25% of the African population experiences water stress and 69% live under conditions of water abundance. However, this analysis does not take into account actual water availability and the relative abundance reflects low water consumption resulting from limited water supply infrastructure. Moreover, much of the African continent experiences drought and about one third of the population live in such areas (World Water Forum 2000). Climate extremes are compounded by the relatively low level of economic development in much of Africa. Sub-Saharan Africa is the only region of the world that has become poorer in the last generation (Ravallion and Chen 2004). The continent makes up just 13% of the world's population (Population Reference Bureau 2005) but constitutes 28% of the world's poverty (World Bank 2005) and is home to 32 of the 38 heavily indebted poor countries (World Bank 2005). Its share of world trade more than halved between 1980 and 2002 (UNCTAD 2004). Africa is not currently on target to meet any of the Millennium Development Goals (Commission for Africa 2005). This challenge is made all the more difficult by rapidly growing population. Numerous factors have worked in concert to create this situation of poverty and underdevelopment, and among those is the difficulty of coping with climate variability and change in a continent subject to frequent droughts, floods, high temperatures, land degradation and being substantially dependent upon rain-fed agriculture.

There is a pressing need, therefore, for improved understanding of climate changes related to the hydrological cycle over Africa at scales relevant to decision making. In this chapter we explore this challenge. We begin with a summary of the projected water-related climate changes over Africa, drawing heavily on the findings of the IPCC AR4 (Solomon et al. 2007). This is followed by a more detailed examination of climate change impacts on basin hydrology for two basins located in southern and eastern Africa. These contrasting studies exemplify many of the issues associated with both the science of climate change impacts and associated human dimensions.

## 2 Summary of Changes to the Hydrological Cycle in Africa

### *2.1 Historical Observations*

For many important hydrological variables, including precipitation, our observational record is relatively sparse. This, combined with high space/time variability in these parameters, means that identification of trends likely to be related to the observed warming in recent decades is problematic. More than any other continent (except Antarctica), Africa suffers from a paucity of observations (Washington et al. 2006), such that the challenge of detecting climate change is more acute. Nevertheless, it is clear that those regions with sufficient data indicate that Africa has warmed significantly over the twentieth century (Trenberth et al. 2007). For annual temperature averaged over all grid cells in Africa (from the CRUTEM3 data of Brohan et al. 2006) the trend is 0.07°C decade$^{-1}$ over the period 1900–2007 and 0.3°C decade$^{-1}$ since 1970, which are slightly lower and higher, respectively, than for global land regions. Associated with this, there have been trends of increasing extreme hot days/nights and decreasing extreme cold days/nights over much of subtropical Africa (Alexander et al. 2006). Regarding precipitation, observations show that the Sahelian sector of Africa has witnessed one of the largest hydrological climate changes observed anywhere, with above-average precipitation during the 1950–1960s and persistently low precipitation during the 1970–1990s (Dai et al. 2004a), resulting in devastating droughts. This multi-decadal climate signal is associated with changes in the large-scale circulation and ocean temperatures in the Pacific, Atlantic and Indian oceans (e.g. Giannini et al. 2003). Trends in precipitation elsewhere in Africa are not statistically significant over the twentieth century. However, Alexander et al. (2006) note an increasing contribution of heavy precipitation events to total precipitation over Southern Africa. There is evidence of increasing frequency of drought over both Northern and Southern Africa (Dai et al. 2004b) based on analysis of the Palmer Drought Severity Index (PDSI) which combines both precipitation and temperature data; separating natural and anthropogenic influences is, nevertheless, problematic. Jury (2003) notes some evidence of declining river discharge from a composite of major African rivers.

## 2.2 Future Projections

Projections of future climate for the twenty-first century from Global Climate Models (GCMs) have been coordinated by the IPCC for the AR4 through the 'multi-model ensemble of opportunity'. This allows an analysis of both the multi-model mean climate response and the associated uncertainty, most commonly through analysis of the degree of agreement between model ensemble members. According to the IPCC AR4 report, warming in Africa is very likely to be larger than the global annual mean warming with drier subtropical regions warming more than the moister tropics (Fig. 1, Christensen et al. 2007). The most consistent climate change

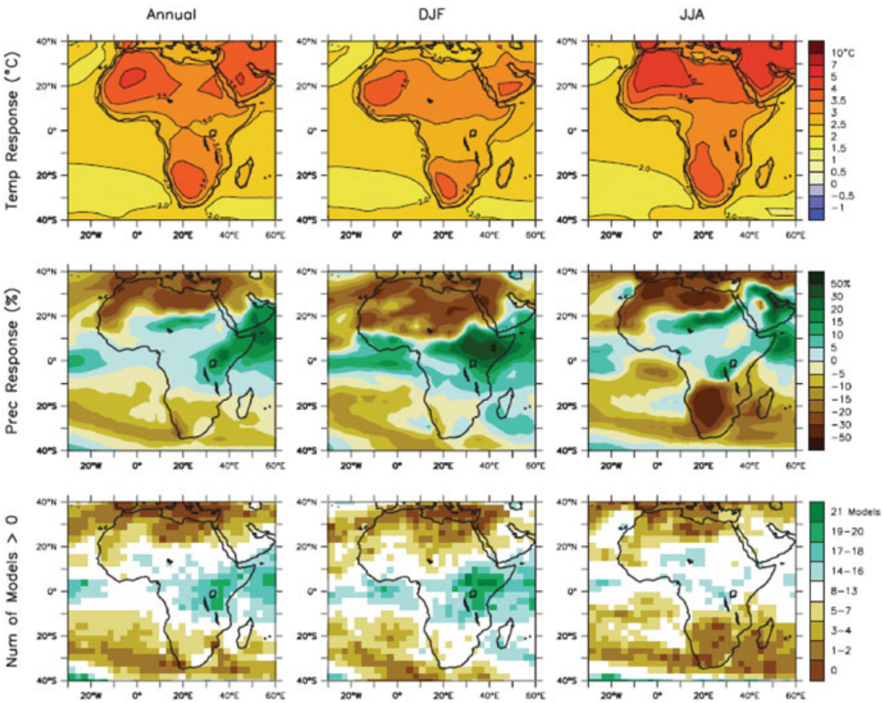



**Fig. 1** Temperature and precipitation changes over Africa from the IPCC Multi Model Dataset under the A1B GHG emission scenario simulations. *Top row*: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. *Middle row*: same as *top*, but for fractional change in precipitation. *Bottom row*: number of models out of 21 that project increases in precipitation (From Christensen et al. 2007)

signals for precipitation across the AR4 GCMs include a likely decrease over much of Mediterranean Africa and northern Sahara, a decrease in winter precipitation over western southern Africa and a likely increase in annual mean precipitation in East Africa. There is less consistency between GCMs in projections of how precipitation over the Sahel, the Guinean Coast and the southern Sahara will evolve. The surface hydrological response in terms of river runoff is a complex function of both precipitation and evapotranspiration changes. Projections of river runoff from multiple GCMs indicate the largest and most consistent signals of reduced annual runoff is over North Africa and much of southern Africa, with increased runoff in East Africa (Milly et al. 2005, Fig. 2). This continental-scale pattern is consistent with the global pattern of GCM response to GHG forcing in which atmospheric moisture convergence increases in the equatorial zone (Kutzbach et al. 2005). Studies using off-line global hydrological models have produced similar results (e.g. Arnell 2004). Moreover, projected increases in population are predicted to result in increased water stress in north, eastern and southern Africa (Arnell 2004). Combined with the projected climate changes it is clear that water stress issues will increase for much of Africa.

Global analyses are useful but suffer from their coarse resolution and the fact that the hydrological models are not well calibrated by local observations. Adaptation to climate change and accelerated development will normally be conducted at the river basin scale. As such these global analyses may be inappropriate to inform decision-making, especially for smaller basins. Hydrological models at the basin scale allow for more explicit representations of available freshwater resources (e.g.

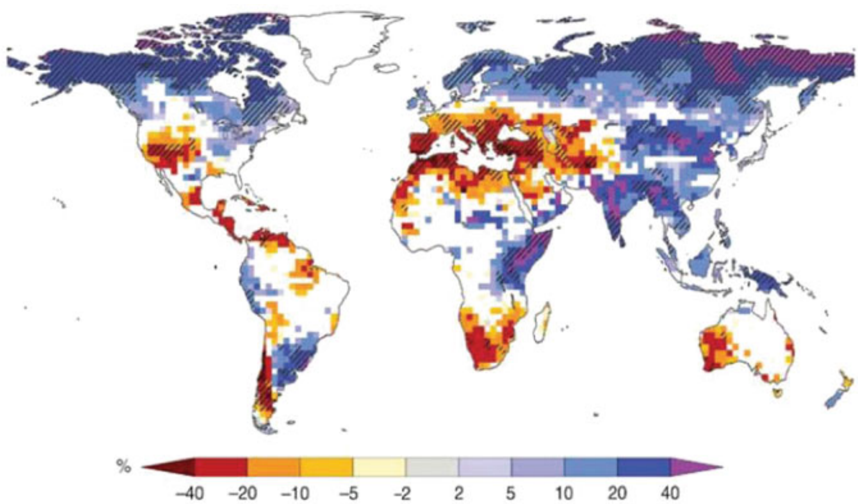



**Fig. 2** Large-scale relative changes in annual runoff for the period 2090–2099, relative to 1980–1999, simulated by selected IPCC AR4 GCMs. *White* areas are where less than 66% of the ensemble of 12 models agree on the sign of change, and hatched areas are where more than 90% of models agree on the sign of change (adapted from Milly et al. 2005 by Bates et al. 2008)

groundwater, the primary source of freshwater for drinking) and water demand, than is permitted by global macro-scale models, and can provide more detailed evaluation of freshwater availability. Basin-scale studies also provide an excellent forum to assess indicator metrics of adaptation, risk and vulnerability defined at the global scale. To date, there are relatively few studies of climate change impacts on basin scale hydrology in Africa (Bates et al. 2008).

In the following sections we present results of river basin-scale climate change impacts studies for two river systems. These two examples were selected to provide contrasting conditions in terms of: (i) the sign of the projected precipitation change from the AR4; (ii) the climatic and physiographical context; (iii) basin size; (iv) population density; and (v) associated water resource issues. In the first example we consider the Okavango river system, a large trans-boundary river system in subtropical southern Africa, where population density and development are relatively low. The emphasis is on river flow and the extent and magnitude of flooding of the Okavango delta wetland in Botswana. As such we consider climate change impacts on environmental flows, the amount of water needed in a watercourse to maintain healthy, natural ecosystems. The second example considers the Mitano river basin in Uganda, equatorial east Africa. This is a relatively small river basin with a high population density and where groundwater resources, rather than surface water, are of primary importance. These studies utilize a common methodology in which a basin hydrological model driven by scenarios of future climate based on output from the IPCC GCMs.

## *2.3 Uncertainty in Projected Climate Change Impacts*

The process of quantifying climate change impacts has been referred to as a 'cascade of uncertainty'. Such uncertainty stems from a number of sources (Stainforth et al. 2007a): (i) forcing uncertainty associated with future GHG emission and other anthropogenic effects like atmospheric aerosol emission and land use change; (ii) initial condition uncertainty is associated with initializing GCMs; (iii) GCM imperfection which includes differences between models, choice of parameterizations and parameter values; and (iv) inadequacies in the impact models such as hydrological models. Considerable effort is being directed at exploring this uncertainty through the use of ensemble experiments which might include multiple GHG emission scenarios (e.g. IPCC SRES scenarios), multiple GCMs (e.g. the IPCC 'ensemble of opportunity'), multiple initial conditions and perturbed physics ensembles (e.g. QUMP). Grand ensemble experiments involve ensembles of ensembles in which one or more ensemble is nested in another, e.g. multiple initial conditions for each perturbed physics ensemble member (e.g. the www.climateprediction.net project). Such experiments are relatively new but have raised important implications for the interpretation of uncertainty.

Clearly, ensembles increase our understanding of the range of possible model behaviour in response to future GHG emission. The size of the experiments involving many hundreds or thousands of model runs has raised the possibility of developing probabilistic climate change assessments (e.g. New et al. (2007) and references therein). This would allow us to move to a risk-based impact and adaptation decision-making framework. However, Stainforth et al. (2007a) argue that it is not possible to produce 'meaningful probability density functions for future climate. . .based on. . .such ensembles'. Rather, results from ensemble experiments can provide rather more qualitative information on climate change such as an estimate of the lower bound of maximum range of uncertainty. Stainforth et al. (2007b) outline an analysis pathway by which such information may be useful to present day decision making. We will return to this issue in Section 5 in relation to our case studies here.

## 3 Case Study I: The Okavango River System

### *3.1 Hydro-Climate and Development Context*

For the people living in the semi-arid climate of southwest Africa water scarcity provides a major stumbling block to increasing societal and individual well-being. One of the major water resources in this region is the Okavango river system, perhaps best known for the Okavango delta in Botswana, an alluvial fan formed where the river terminates. The Okavango river is one of the largest river systems in Africa (the basin area upstream of the delta is ~165,000 km$^2$) and spans three riparian states of Angola, Namibia and Botswana (Fig. 3). Streamflow is mainly generated in the upland regions of central-southern Angola (82% of the basin area lies in Angola) where the Cuito and Cubango tributaries rise. The Okavango delta is maintained by annual flooding of the Okavango River creating the world's second largest inland wetland region; a unique, dynamic mosaic of habitats with exceptionally high beta diversity. The inundated area varies in area from about 5,000 to 6,000–12,000 km$^2$, depending on the size of the annual flood. It is one of the WWF's top 200 ecoregions of global significance and the world's largest Ramsar site. As a whole, the Okavango is perhaps the last near pristine river system in Africa.

The basin lies within a sharp northeast-southwest precipitation gradient across southern Africa. The climate of the basin region is characterized by a pronounced annual cycle with a single wet season of October to March (precipitation ~6 mm day$^{-1}$). The flood in the delta lags the precipitation maximum by about 6 months due to the very low topographic gradients within the delta and highly permeable soils, such that flooding of the delta occurs during the local dry season, a feature that contributes to the importance of the delta as a wildlife resource. The unique ecological status of the Okavango Delta is a function of the regional hydro-climatology and, as such, may be particularly sensitive to future changes in climate (Murray-Hudson et al. 2006). Over the observational period the Okavango system has exhibited pronounced variability in river discharge and flood extent. Most notably, there is a strong multi-annual signal with relatively wet and dry periods during 1974–1985 and 1990–2000, respectively (Wolski et al. 2006).

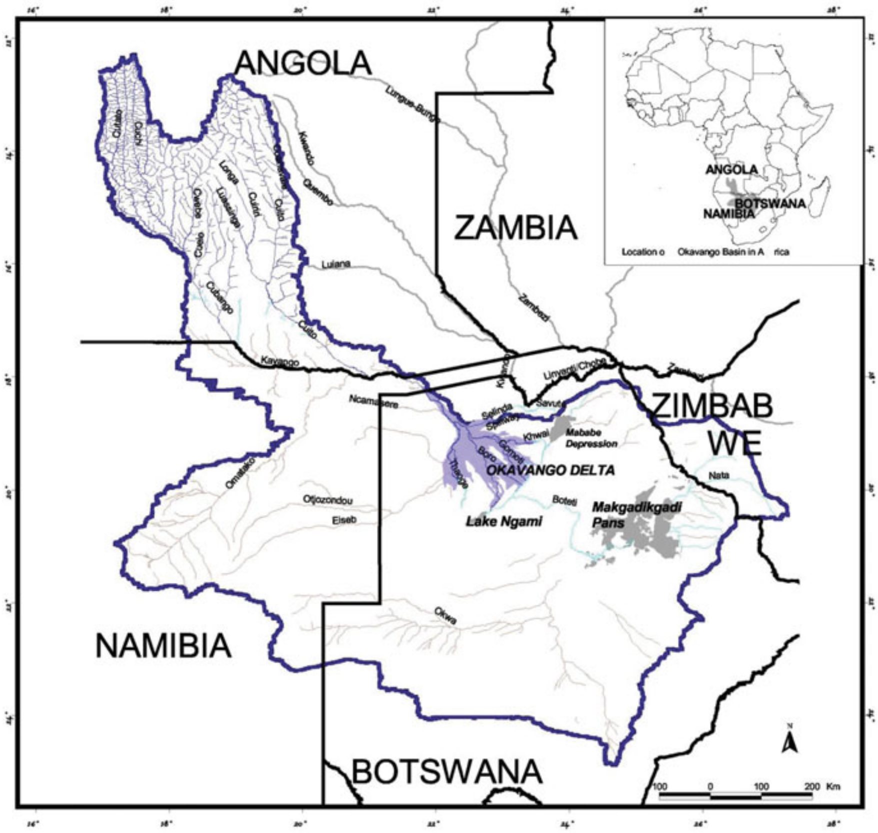



**Fig. 3** The Okavango River basin region

The Okavango River Basin is one of the least developed river basins in Africa. However, socio-economic needs of a growing population threaten to change this situation and the basin has been identified by the World Water Assessment as having the potential for water-related disputes (Wolf et al. 2003). Water resources in Angola are particularly unexploited. This situation is likely to change however following the end of the 27-year civil war in Angola in 2002. Future developments in Angola to fulfill the necessary needs of the basin's inhabitants, including urbanisation, industrialisation and hydropower schemes, have potential consequences for water availability in downstream countries (Pinheiro et al. 2003, Ellery and McCarthy 1994) and negative environmental consequences (Green Cross International 2000, Mbaiwa 2004). Likewise, future development in the semi-arid downstream sections of the basin must be considered. The demand for basin water is further exacerbated by increasing demands from outside the basin includingplans for a pipeline from the Okavango River to Grootfontein, linking the river system with Windhoek (Pinheiro et al. 2003). Any future developments in the basin will occur within the context of climate variability and change. It is important, therefore, that appropriate adaptation strategies are developed.

The development of adaptation strategies first requires integrated assessments of the potential impact of climate change and variability and human interventions on the river system. Possible management interventions must respond to drivers of change as well as to the development needs of stakeholders. The EU-funded project WERRD (Water and Ecosystem Resources in Regional Development – Balancing Societal Needs and Wants and Natural Systems Sustainability in International River Basin Systems) has involved multi-disciplinary research to address these issues (Kgathi et al. 2006). The 3-year multi-disciplinary project ended in 2004 but project partners have continued the work since then. The project had a number of inter-related aims: (i) to develop baseline data on the physical and socio-economic processes in the river basin; (ii) to develop a suite of hydrological models; (iii) to utilise the hydrological models to simulate the response of the hydrological system to these future development and climate change scenarios. The results are available to inform dialogue on future management of the river system at the national and international level.

### *3.2 Hydrological Modeling Tools*

To enable simulation of the hydrological response to climate change and variability (as well as potential development policies) and taking account of the contrasting hydrological characteristics of the basin region and the delta region, two hydrological models were developed. First, for the Okavango river basin upstream of the delta panhandle, a modified version of the Pitman (1973) monthly precipitation-runoff model was developed (see Hughes et al. 2006 for full description). Hereafter this is referred to as the '*basin model'*. This is a conceptual model consisting of storages linked by functions designed to represent the main hydrological processes prevailing at the basin scale. A semi-distributed implementation of the model was undertaken for the Okavango basin above the delta with 24 sub-basins (Fig. 3). The basin model requires estimates of monthly precipitation (P) and potential evaporation ($E_p$) for each sub-basin in the Okavango River Basin. The model was calibrated satisfactorily against river discharge data from the period 1960–1972 and (using satellite precipitation data) for the period 1990–2000. Therefore, the basin model adequately represents the hydrological response of the basin across a range of historical climatic conditions (wet and dry periods), such that it can be used to assess the impact of future development and climate scenarios.

Second, the hydrological model of the Okavango delta (Wolski et al. 2006) integrates 'reservoir' modeling of water volume and GIS-modeling of flood spatial distribution. Hereafter, this is referred to as the '*delta model*'. The Okavango delta is represented as a set of inter-linked linear 'reservoirs' representing major distributaries in the delta (Fig. 4). For each 'reservoir', the volume of surface water (and therefore the total flooded area) is calculated on a monthly basis from the sum of

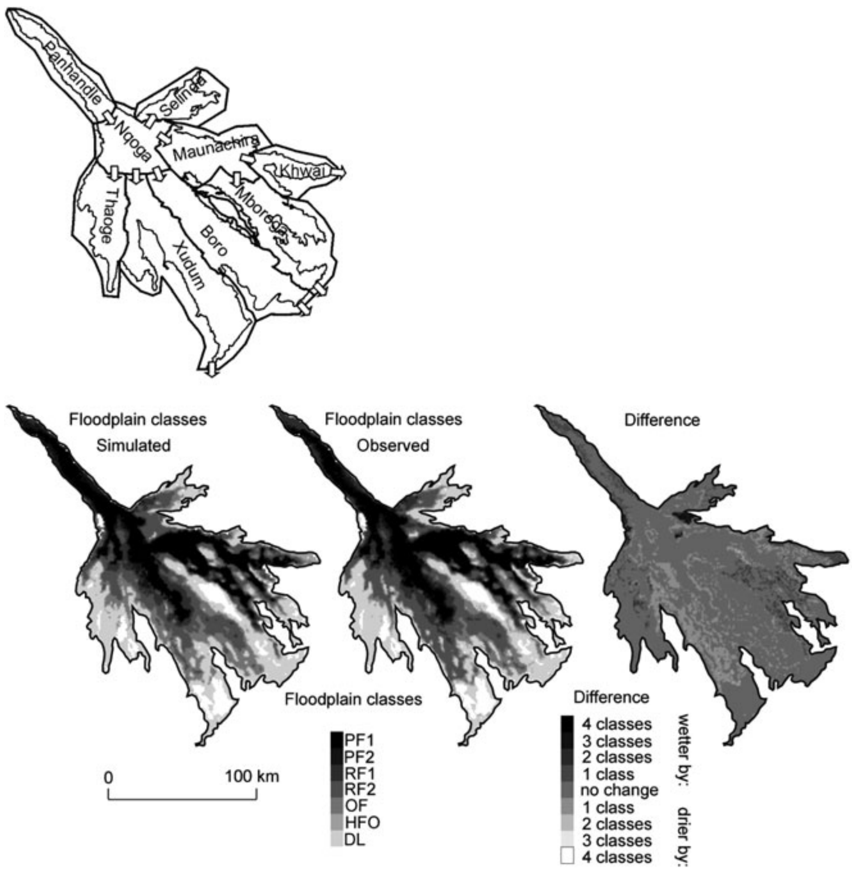



**Fig. 4** **a** surface water reservoir units used in the Okavango Delta hydrological model **b** Okavango delta flood frequency map for the 1990–2000 period (observed, simulated and difference). Floodplain classes are explained in Table 1

upstream inflow, local precipitation and evapotranspiration, groundwater flux and outflow. The delta model requires monthly inflow from the basin model and local P and $E_p$ over the delta region. The lumped value of flood area in each reservoir unit is then used as an input to a GIS model, in which the spatial distribution of that flood is determined based on a 15-year time series of flood maps obtained from classification of NOAA-AVHRR satellite images (McCarthy et al. 2004). Although the spatial resolution of the hydrological model is very coarse (units vary in size from 500–2 000 km$^2$, Fig. 4a), the GIS model provides the distribution of flood at a much finer spatial resolution of 1 km (Fig. 4b). The delta model simulations of flood volume and its spatial distribution were validated against historical data with satisfactory results. Flood frequency in each 1 km grid cell was then translated into the distribution of functional floodplain classes and the associated ecological status using the relationships given in Table 1 (Fig. 4).

**Table 1** Okavango delta hydrological characteristics of functional floodplain classes

| Floodplain class | Sub-class | Class code | Flood frequency | Flood duration (months/year) |
|---|---|---|---|---|
| Permanent floodplain | Proper | PF1 | 1 | 12 |
| | Fringe | PF2 | 1 | 8–12 |
| Regularly flooded seasonal floodplain | | RF1 | 1 | 4–8 |
| | | RF2 | 0.5–1 | |
| Occasionally flooded seasonal | | OF | 0.1–0.5 | 1–4 |
| High floods only | | HFO | <0.1 | <2 |
| Dryland | | DL | 0 | 0 |

## *3.3 Methodology for Climate Impacts Simulation*

The impacts on Okavango river flow and delta flooding of climate change is evaluated through comparison of simulated mean monthly river flow frequencies and delta flood frequencies under various future climate scenarios with the ‘present day’ baseline conditions. The various sources of uncertainty in the climate change impact assessment process are described in Section 2.3, and in this case, some of these were quantified by using numerous simulations of the basin and delta hydrological models, driven by multiple estimates of future climate. To quantify uncertainty associated with GCM inadequacy we: (i) use monthly data from single ensemble runs of four GCMs from the IPCC Third Assessment Report (TAR); and (ii) evaluate the climate change signal of all GCMs included in the IPCC AR4. To account for uncertainty in future GHG/sulphate emissions, data from GCMs forced with two contrasting future GHG emission scenarios are used, namely the IPCC preliminary SRES marker scenarios A2 and B2. (Nakicenovic and Swart 2000). As such, the range of future GHC concentrations in the atmosphere between these two scenarios may encompass much of the uncertainty in the future global cycles of carbon and other gases.

Simulations of the impact of the climate change scenarios on the river flow are made by driving the basin model with perturbed time series of spatially distributed P and $E_p$. The delta model is then forced with the simulated future output from the basin model and perturbed time series of spatially distributed P and $E_p$ over the delta, and the simulated change in future flood extent calculated. This flood extent was then was translated into the change in size and distribution of functional floodplain classes (Table 1) for assessment of the changes in ecological terms.

It is not appropriate to use the GCM data directly due to bias in the GCM estimation of the climate basic state. Instead mean monthly GCM ‘change’ factors are defined ($\Delta$P, $\Delta$T, $\Delta T_{max}$ and $\Delta T_{min}$ where T is near surface temperature) for each GCM and each GHC scenario, for future 30-year epochs, representing the middle (2020–2050), late (2050–2080) and end (2070–2099) of the twenty-first century.

These ‘change’ factors are the GCM-simulated value for a particular quantity relative to the GCM value over the ‘present-day’ period (1960–1990) and therefore represent the relative change in a quantity as simulated by the GCM. For the basin model, the Hargreaves equation is used to calculate $\Delta E_p$ from $\Delta T$, $\Delta T_{max}$ and $\Delta T_{min}$ (Hargreaves and Allen 2003). Perturbed P and $E_p$ records to drive the basin and delta hydrological models are obtained by multiplying the available baseline records (1960–1972, 1991–2002) of sub-basin monthly time series of P and $E_p$ with average monthly $\Delta P$ and $\Delta Ep$ values, respectively. This “GCM change” approach is the most common method of transfering the signal of climate change from climate models to hydrological or other impact models.

## 3.4 Simulated Future Climate Change

The simulated impact of future climate change on Okavango River discharge is highly time and model dependent (Fig. 5, Table 2, see et al. 2006 for full details). For the period 2020–2050, the ‘all-GCM mean’ flow is very close to the baseline conditions for both A2 and B2 GHG scenarios. The results for this period are essentially sensitive to the choice of GCM with certain simulations predicting dramatically increased flow (e.g. those driven by the CCC model) and some dramatically reduced flow (e.g. HadCM3). There is, therefore, very little certainty in the sign or magnitude of future river flow for this period. Differences in future precipitation estimates between models are largely responsible for this. For the period 2050–2080, however,

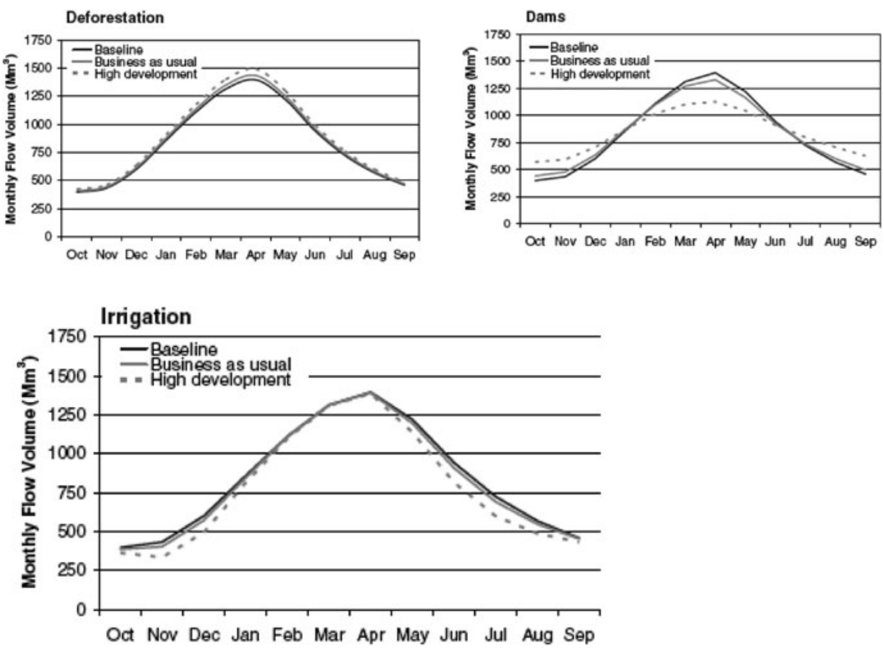



**Fig. 5** (continued)

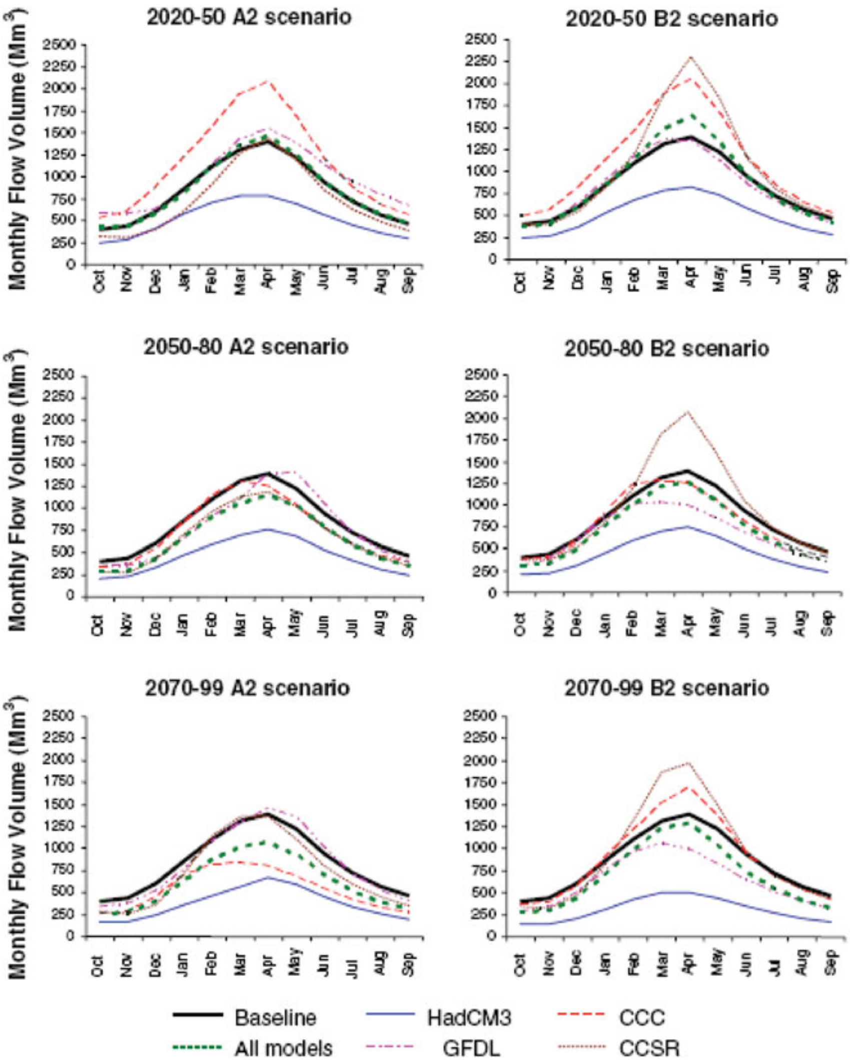



**Fig. 5** Simulated effect of climate change and development on the Okavango river basin discharge upstream of the delta region. Plots mean monthly flow (Mm$^3$) of Okavango river at Mukwe, Namibia (see Fig. 3) simulated by basin hydrological model driven by (a)–(g) changes in precipitation and evaporation derived from various GCMs under the A2 and B2 *greenhouse* gas emission scenarios and (g)–(i) various development scenarios (see text for explanation). Each plot also shows observed historical 'baseline' conditions

there is a clear tendency for the models to simulate reduced flows, with a greater magnitude of change for the A2 than the B2 GHG scenarios. By 2050–2080, the all-GCM mean shows a reduction of 20% (14%) in mean annual flow for the A2 (B2) scenarios. The respective figures for the period 2070–2099 are 26% (17%), when all but one of the GCMs suggest reduced flows under the A2 scenario. It is

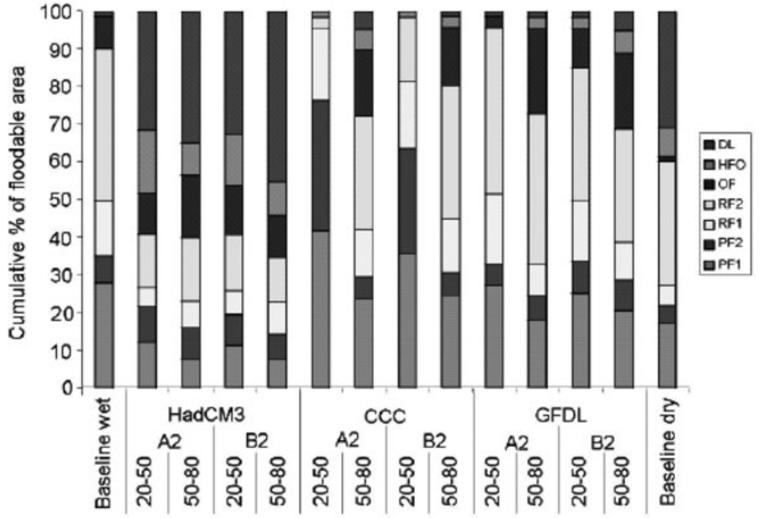
**Table 2** Impact of climatic change on annual mean and minimum monthly flow for the Okavango river at Mukwe, Namibia, upstream of Okavango delta (see Fig. 3)

| Annual mean flow (minimum monthly flow) | | | | |
|---|---|---|---|---|
| | Highest year vs. median (%) | | Lowest year vs. median (%) | |
| Monitored flow 1949–2002 | +70 (+53) | | –38 (–38) | |
| | A2 GHG emission scenario | | B2 GHG emission scenario | |
| | Annual mean flow vs. baseline conditions (%) | Minimum monthly flow vs. baseline conditions (%) | Annual mean flow vs. baseline conditions (%) | Minimum monthly flow vs. baseline conditions (%) |
| | All-GCM mean/highest GCM/lowest GCM output | All-GCM mean/highest GCM/lowest GCM output | All-GCM mean/ highest GCM/ lowest GCM output | All-GCM mean/ highest GCM/ lowest GCM output |
| Modelled flow 2020–2050 | +1 /+38 /–39 | –2 /+29 /–40 | +4 /+32 /–39 | –6 /+18 /–39 |
| Modelled flow 2050–2080 | –20 /–8 /–45 | –27 /–16 /–48 | –14 /+16 /–47 | –20 /–5 /–49 |
| Modelled flow 2070–2099 | –26 /–2 /–55 | –36 /–14 /–59 | –17 /+13 /–67 | –29 /–8 /–64 |

likely that this consistency in response reflects the increasing influence of rising temperatures predicted by all the GCMs. Nevertheless, there remains considerable variability in the magnitude of the simulated response associated with both the different GCMs and GHG emission scenarios, such that uncertainty in our predictions of future mean river discharge is high. The results suggest that future climate change is likely to have a proportionally larger impact on minimum monthly flow compared to mean flow. This may be indicative of a more extreme hydroclimatic regime and will have implications for the maintenance of environmental flows.

It is instructive to view the projected changes in mean flow in the context of historically observed variability (Table 2). Projected changes in the 30-year median annual flow and minimum monthly flow for the selected time slices in the second half of the twenty-first century are similar in magnitude to the absolute observed range during the observed historical period (i.e. the extremes of interannual variability). This implies that under certain scenarios the mean future regime may be similar to the most extreme conditions observed to date. Overall, the results indicate the potential for dramatic changes to Okavango River discharge under future climate conditions, but with considerable uncertainty in the magnitude of any future changes. This uncertainty is largely associated with inter-model differences in projected precipitation changes (Andersson et al. 2006).

The impact on the Okavango delta flood extent (see Murray-Hudson et al. 2006 for full details) is shown in Fig. 6, first as proportions of the floodable area made up



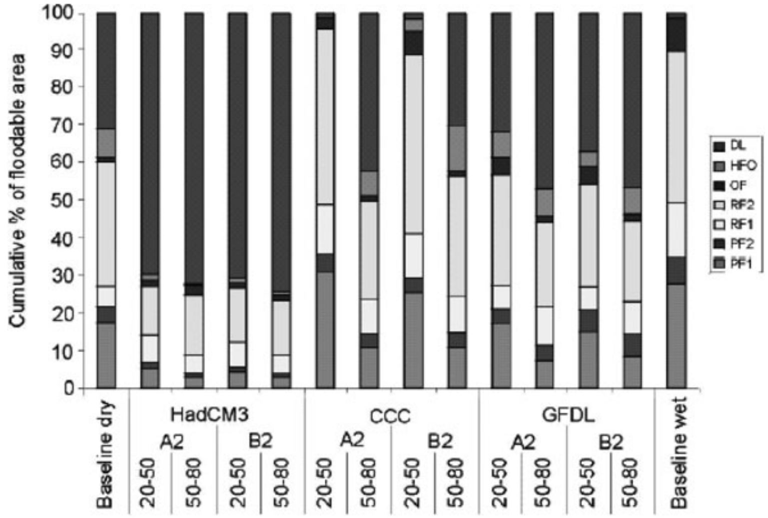




**Fig. 6** Simulated effect of climate change on the Okavango Delta flooding. Plots show proportional floodplain class composition of Okavango Delta floodplains simulated for hydrological conditions obtained from selected climate models (HadCM3, CCC, GFDL) under *greenhouse* scenarios A2 and B2 with respect to **a** historical wet conditions **b** historical dry conditions. Floodplain classes as in Table 1

by the various floodplain classes (Table 1) compared to wet (1974–1985) and dry (1990–2000) baseline conditions. When driven by the HadCM3 model under both the A2 and B2 GHG scenario, the hydrological models suggest substantial drying of the Okavango delta relative to wet and dry baseline conditions. There are large increases in dryland (more than double), and occasionally flooded regions, with similarly large decreases in permanent flood regions. The magnitude of this drying increases over time. In contrast, the results under the CCC GCM suggest an initial expansion of the Okavango delta area for the period 2020–2050 but a reversal to conditions slightly drier than the current baseline conditions by 2050–2080. When driven by the conditions perturbed by the GFDL GCM, hydrological models suggest that the only small changes for 2020–2050 but substantial drying during 2050–2080 with a large increase in seasonally flooded classes and dryland. However this change over time is no greater than the difference between wet baseline and dry baseline conditions. Overall, differences in flooding associated with the two GHG scenarios are not as great as those associated with the different GCMs or the difference between the two future epochs.

These changes are shown spatially in Fig. 7 for GHG scenario A2 and the period 2020–2050 with differences related to the dry baseline. The drier conditions simulated with HadCM3 scenarios are clearly manifest throughout the delta, including the panhandle, with changes of up four classes affecting large areas of the more seasonal (central and western) distributaries in particular. Wetter conditions produced by CCC and to a lesser extent by GFDL outputs are shown affecting peripheral occasionally flooded and dry land areas, with extensive areas showing an increase in flooding of between two and three classes.

The above analysis was based output from the IPCC TAR GCM experiments. The IPCC AR4 includes a more extensive 'ensemble of opportunity' comprising 21 GCMs many of which feature multi-member ensemble runs. These new data provide the potential for a more comprehensive uncertainty analysis. The results described above indicate that the climate change signal in the first half of the twenty-first century is dominated by uncertainty in GCM precipitation. From Fig. 8 it is clear that uncertainty in the precipitation signal is considerable across the range of AR4 models with 13 of the 23 models suggesting an increase in wet season precipitation and 10 showing a (larger magnitude) decrease. As such, the large uncertainties in the simulation of the hydrological impacts of climate change in the WERRD project are relatively robust and not simply a function of the relatively small sample of GCMs used in the analysis above. The wide range of precipitation signals from the IPCC models may result partly from the Okavango basin straddling the boundary between the equatorial zone of increased precipitation and subtropical and decreased precipitation projected by the multi-model mean (Fig. 1, Christensen et al. 2007). It has been well documented that to date most GCMs operate at coarse spatial resolution relative to the scales of basin hydrological processes. Dynamical downscaling of GCM output using regional climate models (RCMs) indicates that the climate change signal varies between the driving GCM and the nested RCM

**Fig. 7** Simulated effect of climate change and development on the spatial structure Okavango Delta flooding. Maps show (a)–(c) simulated floodplain classes for models driven by climate models (HadCM3, CCC and GFDL) under A2 *greenhouse* gases scenario. (d)–(f) change in floodplain classes with respect to baseline dry conditions. (g)–(i) change in floodplain classes for development scenarios (see text for details) with respect to baseline dry conditions. Colour coding as in Fig. 4

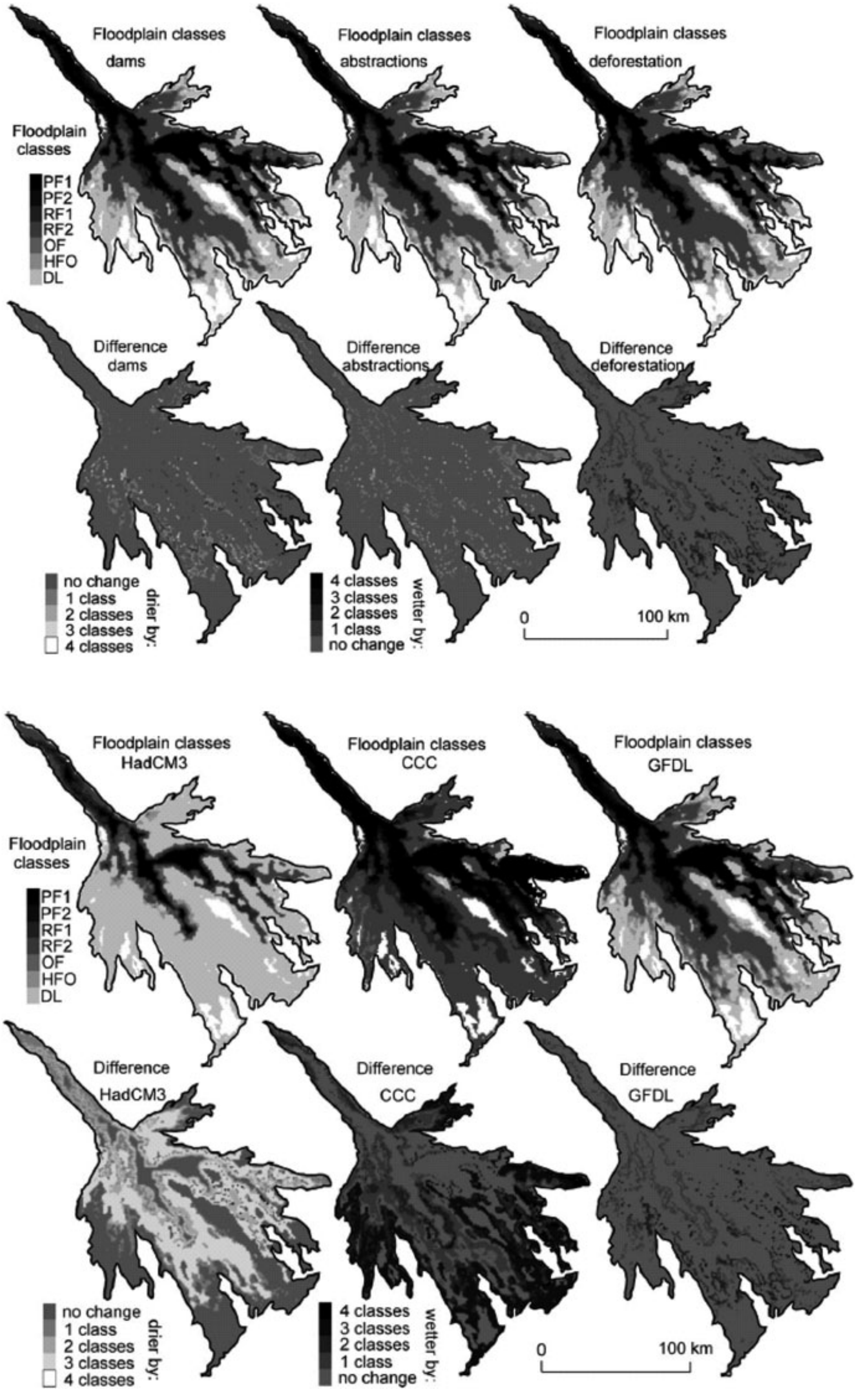



**Fig. 7** (continued)

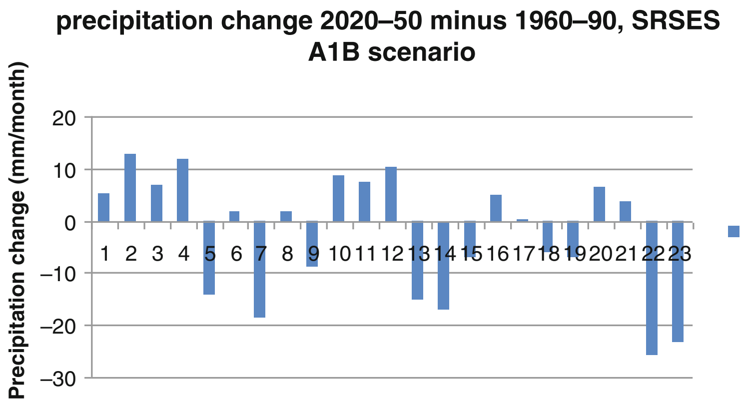



**Fig. 8** Projected change in precipitation (%) over the Okavango River basin region (17º–12ºS, 15º–19ºE) from IPCC Multi Model Dataset under the A1B GHG emission scenario simulations for 2020–2050

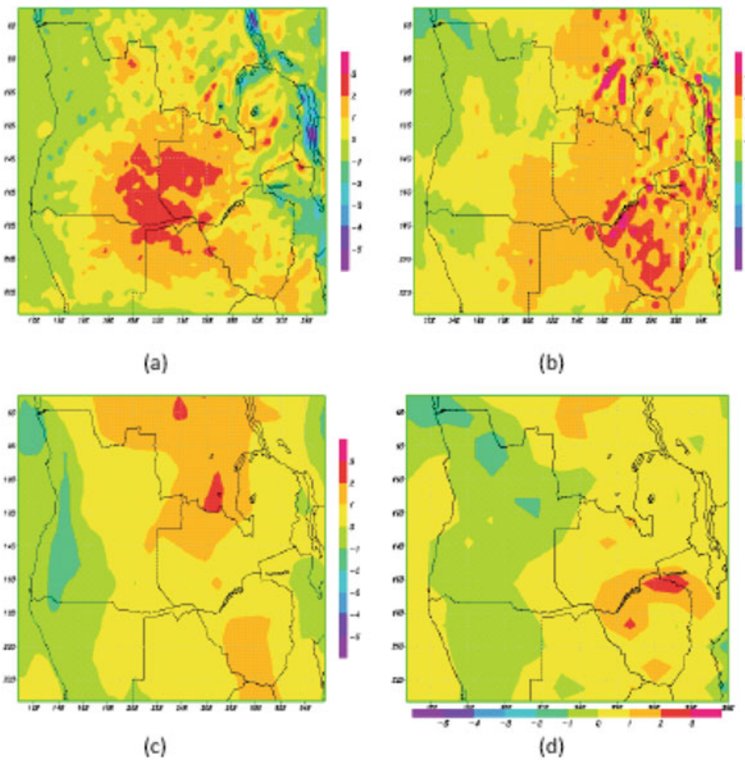



**Fig. 9** Comparison of projected change in precipitation over southwestern Africa simulated by selected GCMs and nested RCMs. Figures show percentage change for 2070–2080 relative to 1990–2000

(Fig. 9) adding further uncertainty to estimates of future climate change. As such, further hydrological model simulations driven by climate changes from the full suite of IPCC AR4 GCMs and downscaled by RCMs are likely to expand the envelope of non-discountable climate change impacts beyond that presented above.

Given the context of water resource policy it is useful to consider the projected climate change impacts within the context of potential development scenarios. To this end the WERRD project developed a range of possible development scenarios through stakeholder dialogue and expert analysis. Three scenarios of development were defined in which varying degrees of water use, river abstractions and flow regulation through hydro-electric power generation were quantified (see Andersson et al. 2006) for full details. The low-impact development scenario considers only a change in water demand due to increased consumptive use from population, livestock and informal irrigation, based on standard population projections for 2015 and 2025. The ‘‘business-as-usual’’ scenario also includes formal irrigation schemes described by Crerar (1997) and Mendelsohn and el Obeid (2003), deforestation in a 1 km buffer around major water courses, and construction of one hydropower dam at Malobas in Angola (Crerar 1997). The high impact development scenario includes all the other developments plus irrigation of all areas estimated as suitable for irrigation by Diniz and Aguiar (1973) (1,040 km$^2$ or 0.2% of the total upstream basin area), irrigation around the two urban areas of Menongue and Cuito-Cuanavale, deforestation of a 2 km buffer around major watercourses, all six potential dams in headwater rivers in Angola (Crerar 1997), and the operational use of the Eastern National Carrier pipeline planned to transfer water from the Okavango to the central area of Namibia near Windhoek.

The effect of the development scenarios is included in Figs. 5 and 7 and indicates that only the high impact development scenario will have a substantial impact on river flow and delta flooding, largely associated with changes to the flow regime associated with dam operations in Angola. However, it is clear that the potential climate change impacts are far greater than even the most extreme development scenarios. This suggests that evaluation of hydrological impacts of the future development considered in these scenarios should be conducted within the context of projected climate changes and associated uncertainty. This has important implications for environmental impact assessment of proposed developments.

### *3.5 Summary of Results from Okavango River Case Study*

This work has quantified climate change impacts on the Okavango river system in Southwestern Africa, and in particular on the extent and frequency of flooding in the Okavango delta, a unique wetland system of global importance whose ecological status is primarily driven by hydrology. The study is particularly challenging given the location of the basin in a region of pronounced gradients in mean climate and projected changes. The work shows that: (i) climate changes even by the middle of the twenty-first century are potentially very large and could exceed the very substantial natural variability experienced in recent decades; (ii) uncertainty in the sign and magnitude of the climate change signal is large; (iii) in the first half of twenty-first centrury this uncertainty in largely associated with uncertainty in the GCM precipitation signal; (iv) toward the latter decades of the twenty-first century there is greater convergence in the projected response towards a drying of the system, as the effects of increased temperature on evapotranspiration losses come to dominate; and (v) the climate change signal even in forthcoming decades, irrespective of the chosen GHG emission scenario, may be bigger than any development scenarios.

It is not unreasonable to infer that future development decisions in the basin (e.g. the development of headwater river dams and the proposed extension of the Eastern National Carrier pipeline to the Okavango) should incorporate projected climate changes and crucially the full range of non-discountable climate change into account. The tri-nation Permanent Okavango River Basin Water Commission (OKACOM) has been established to provide a coherent approach to managing the basin's resources, based upon equitable allocation, sound environmental management, and sustainable utilization. Recognition of potential climate change should be a central component of OKACOM's efforts to develop integrated basin water management. To better inform agencies such as OKACOM, further research should focus on a number of themes. Firstly, to extend the uncertainty analysis to include grand-ensembles of GCM experiments and hydrological model experiments, such that a more comprehensive estimate of non-discountable climate change impacts can be determined. This is being addressed partly through the UK NERC funded project QUEST-Global Scale Impacts (GSI) project. Secondly, to determine the effects of projected climate changes on river basin, delta ecology and biodiversity. The aim must be to determine appropriate 'environmental flows' to maintain aquatic and terrestrial biodiversity and ecological status of the Okavango system. This is being explored through the BIOKAVANGO (http://www.orc.ub.bw/biokavango/) and Aquatic biodiversity and Climate Change in the Okavango River Delta (ACCORD) projects, amongst others.

## 4 Case Study II: The Mitano River Basin, Uganda

### *4.1 The Hydro-Climate and Development Context*

This study differs from the previous example in a number of ways, not least of which is the explicit emphasis on groundwater resources rather than river flow and wetland flooding. Groundwater is the primary source of freshwater for drinking and irrigation around the world. In sub-Saharan Africa, groundwater supplies 75% of all improved (safe) sources of drinking water (Foster et al. 2006). The impacts of climate change on groundwater resources remain, however, very poorly understood (Bates et al. 2008). At present, estimates of freshwater resources (e.g. Shiklomanov 2000) and predictions of freshwater resources as a result of climate change (e.g. Arnell 2004) are commonly defined in terms of mean annual river discharge (runoff). Such estimates and predictions disregard soil water (i.e., water transpired by plants), despite the fact that this sustains almost all agricultural production in equatorial Africa, and fail to represent the proportion of riverflow derived from groundwater despite its importance to water supply. A quantitative understanding of the impacts of climate variability and change on both basin stores (i.e. soil water, groundwater) and flows (i.e. river discharge) is of critical importance to the development of climate change adaptation strategies. These issues are particularly important in Uganda where there is substantial dependence on precipitation-fed agriculture and heavy reliance upon localised (untreated) groundwater as a source of potable water. Here, we present results of a study that focuses on groundwater recharge in the Mitano basin in Uganda. The East African sector, including Uganda, is one of the few regions of the world where a consistent projection of future precipitation change is suggested, with most models showing increased precipitation in the future (Christensen et al. 2007, Meehl et al. 2007). However, concern over future water resources in Uganda is heightened by projections of a near doubling by 2025 of the current (2005) population of 25.8 million (UNDESA 2006).

The River Mitano basin is a relatively small basin (2,098 km$^2$), in southwestern Uganda (Fig. 10). The River Mitano drains areas of relatively high elevation (2,500 m) to the south and flows in a north-westerly direction towards the depression containing Lake Edward (975 mamsl). The basin is underlain by Precambrian crystalline rock that have are deeply weathered. Groundwater from the weathered

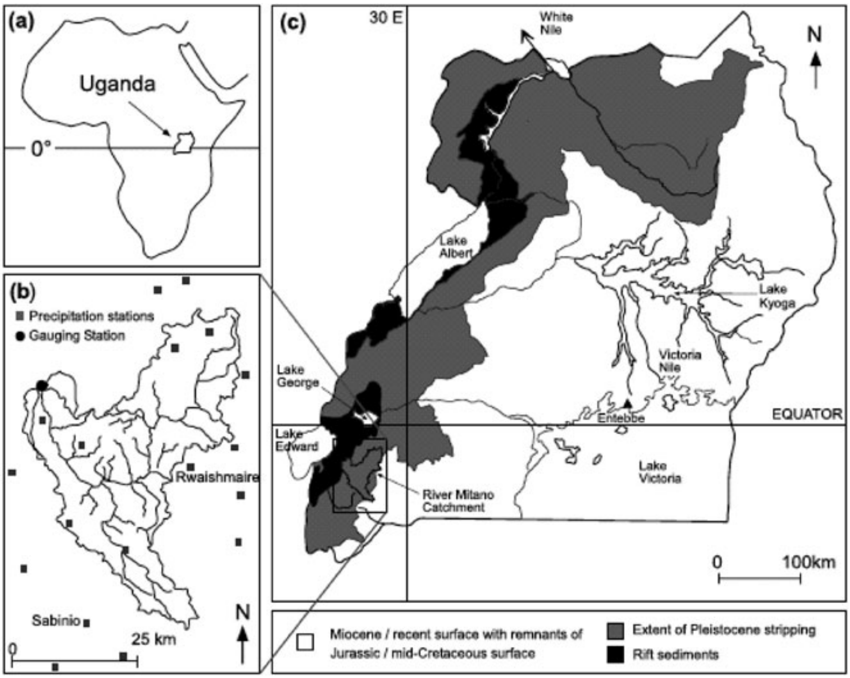



**Fig. 10** The Mitano river study region in Uganda

overburden and fractured bedrock discharges into the River Mitano drainage network. Land use is primarily agrarian (79%). Mean annual basin precipitation for the period 1965–1979 is 1,190 mm and exhibits a bi-modal regime with dominant modes (wet seasons) in March–May (MAM) and September–November (SON). Mean annual pan evaporation for the period 1967–1977 is 1,535 mm measured at Mbarara (approximately 50 km to the east of the basin) and exceeds precipitation in all months except SON. Discharge records (1965–1979) for the River Mitano reflect the bi-modal precipitation but lag peak precipitation by approximately 2–6 weeks.

## *4.2 Hydrological Modeling*

A daily soil moisture balance model (SMBM) for the basin was developed (see Mileham et al. 2008 for full details) to simulate groundwater recharge (R) from the infiltration of precipitation (P) based on changes in soil-moisture. According to Equations (1) and (2), R occurs when effective precipitation, P minus runoff (RO) at the soil surface exceeds evapotranspiration (ET) and when soil-moisture content exceeds field capacity. The additional P inputs are considered to pass through the soil into underlying strata. When the water content of the soil is less than field capacity, a soil-moisture deficit (SMD) exists and direct recharge is prevented.

$$R = (P - RO) - ET, \text{when } \mathrm{SMD}_t = 0 \tag{1}$$

,

$$R = 0, \text{when SMD} > 0 \tag{2}$$

A daily precipitation threshold (10 mm) is applied, above which it is assumed interception and evaporation are overcome and runoff occurs. Runoff is calculated as a percentage of daily precipitation above this threshold (i.e. runoff co-efficient). According to the SMBM, ET equals potential evapotranspiration ($E_p$) until the SMD reaches the root constant (the maximum rooting depth) that is a function of rooting depth and soil porosity. Beyond this, ET continues at a reduced rate (10% of PET). A SMD of a further 51 mm can develop before the wilting point (maximum SMD) is reached, beyond which transpiration ceases. $E_p$ is estimated using a modified Thornthwaite temperature-based equation, weighted (2:1) toward maximum air temperature, which produces estimates of PET that replicate (<5% bias) estimates of pan-derived evaporation observed at Mbarara (0°36'S, 30°39'E).

Daily precipitation data for twenty precipitation stations (1965–1980, within and surrounding the River Mitano basin) were obtained and gridded to the 0.25° resolution SMBM grid. Recharge and runoff estimated by the SMBM were calibrated over the period 1965–1979 using estimates of basin baseflow and stormflow derived from a hydrographic separation of river discharge.

### 4.3 Methodology for Climate Impacts Simulation

Given the small basin size and relatively high resolution of the SMBM, estimates of future climate were derived from downscaled GCM output using the PRECIS regional climate model (Jones et al. 2004) at 0.25° spatial resolution. PRECIS was nested in output from the HadCM3 GCM for historical baseline period 1960–1990 and for the future 2070–2099 period under forcing from the IPCC SRES A2 scenario. PRECIS precipitation and temperature-derived $E_p$ (using the modified Thornthwaite method) were used to derive the changes in future climatic conditions. Two methods were used to derive future estimates of P and $E_p$ as outlined below. (i) Monthly mean change factors derived from the future and historical PRECIS data were applied to the historical daily precipitation and $E_p$ data (as in the Okavango river study in Section 3) for each of the six grid cells. These Mean monthly change factors are a favoured approach for impact studies as a convenient way to circumvent the problem of GCM bias. (ii) A daily precipitation frequency distribution transformation was also developed in which the lognormal frequency distribution of historical daily precipitation is transformed to match the change in the mean and variance of the PRECIS daily precipitation frequency distribution. This will account for changes to the precipitation distribution not just the precipitation mean as in method (i). Given the non linear relationship between daily precipitation and groundwater recharge rate changes to the frequency distribution of precipitation is likely to be important.

### 4.4 Simulated Future Climate Change

Under the IPCC SRES A2 scenario the PRECIS model suggests an increase in annual precipitation of 17% with increases in all months except January (Fig. 11) and a 4.2°C increase in mean annual temperature, which gives rise to a 53% increase in annual $E_p$. These values are broadly similar to that of the driving GCM HadCM3. The projected increase in precipitation is in line with many other IPCC AR4 models (Meehl et al. 2007). Using the standard change factor approach (method (i) in Section 4.3) the SMBM indicates this will lead to a 49% reduction in recharge and a 72% increase in runoff (Table 3). In terms if the seasonal cycle (Fig. 12), under future climatic conditions little recharge occurs between January and July representing the first rains and most of the first dry season. Increases in precipitation in this period are more than offset by increases in $E_p$. During the second wet season recharge is reduced but not as dramatically as during the rest of the year.

However, PRECIS simulations also suggest important changes to the daily precipitation frequency distribution with reduction in the occurrence of small precipitation events (<10 mm) and an increase in the occurrence of large precipitation events (>10 mm) (Fig. 13). Applying a transformation in this daily precipitation frequency distribution (method (ii) in Section 4.3), the SMBM suggests an increase in both recharge and runoff under future climatic conditions relative to that observed by 62 and 137%, respectively (Table 3). The increase in intensity of precipitation

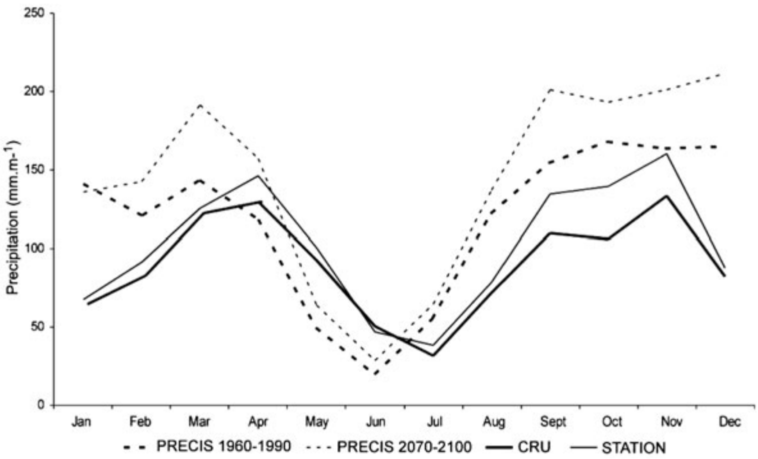



**Fig. 11** Simulated change in monthly mean precipitation over the Mitano river basin from PRECIS RCM under IPCC A2 GHG scenario. Plot also shows historical observations from interpolated gauge data and CRUTEM3 gridded dataset

events under future climate substantially increases recharge (and runoff) by overcoming the increase in $E_p$ on individual days so that infiltration and recharge occur more frequently. In terms of the seasonal cycle increases in recharge are most pronounced to the second rainy season (Fig. 14), most notably the early wet season (September) driven by the earlier precipitation onset and lower SMD.

The daily precipitation transformation approach results in substantially different climate change projections for groundwater recharge compared to the projections using monthly ‘change’ factors, namely a projected increase rather than decrease. This difference results solely from a more comprehensive representation of precipitation intensity under future climates, to which recharge and runoff are sensitive. The results indicate that the sign of the climate change signal for groundwater

**Table 3** Simulated groundwater recharge and runoff for the river Mitano basin in Uganda

| | For 1965–1980 | For 2070–2099 using mean ‘change’ factors (method (i) Section 4.3) | 2070–2099 using transformed daily precipitation frequency distribution (method (ii) Section 4.3) |
|---|---|---|---|
| Mean annual groundwater recharge (mm) | 104 | 53 | 169 |
| Mean annual river runoff (mm) | 144 | 247 | 341 |

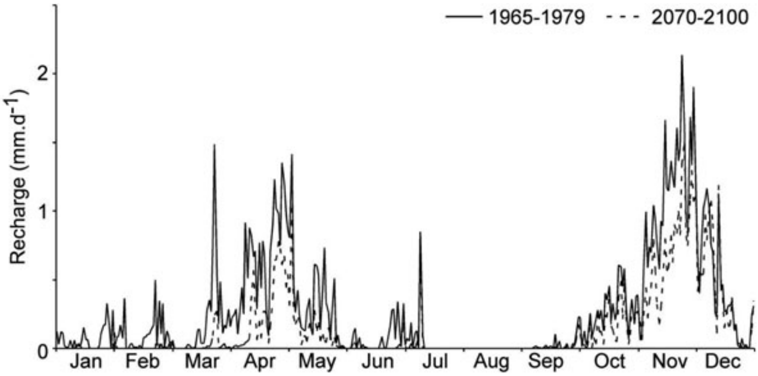



**Fig. 12** Simulated effect of climate change on groundwater recharge in the Mitano river basin for hydrological models driven by historical and future climate (PRECIS RCM under A2 GHG scenario). Climate change signal is simulated by perturbation of historical daily rainfall using monthly mean 'change' factors (method (i) in Section 4.3)

recharge is highly sensitive to the method by which the projected change in precipitation is applied. Simply scaling the daily historical precipitation data using the monthly change factor results in a projected decrease in groundwater recharge as the large projected increase in $E_p$ dominates the groundwater budget. However, when we account for projected changes in the daily precipitation frequency distribution in which there is a shift toward a greater contribution from intense precipitation events, a substantial increase in recharge is suggested. In this case we might assume that the latter, more sophisticated approach is preferable. However, the results highlight how a comprehensive end-to-end quantification of uncertainty in climate change impacts

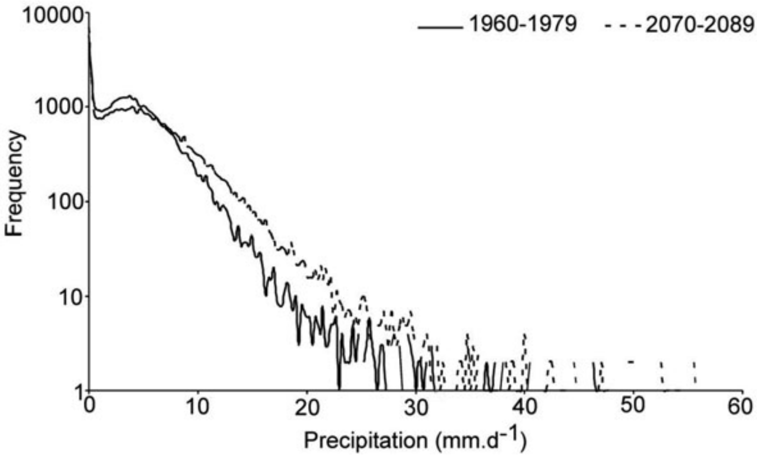



**Fig. 13** Simulated change in frequency distribution of daily precipitation over the Mitano river basin from PRECIS RCM under IPCC A2 GHG scenario

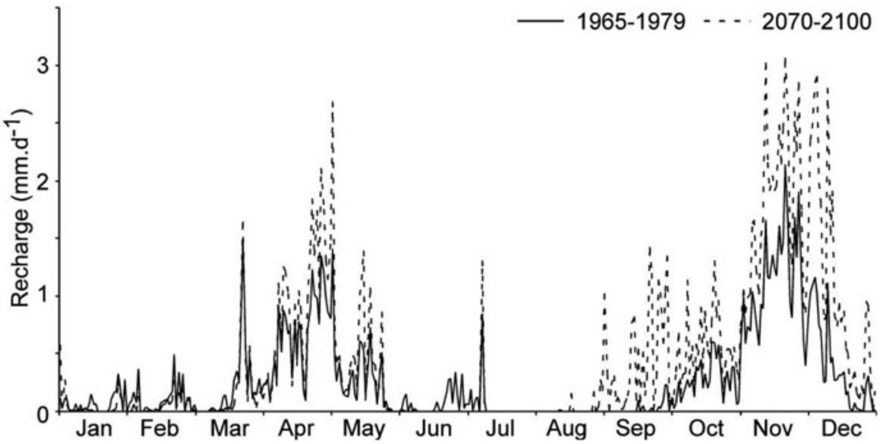



**Fig. 14** As Fig. 12, except climate change signal is simulated by perturbation of historical daily rainfall using transformation of the daily precipitation frequency distribution (method (ii) in Section 4.3)

studies should systematically address the propagation of uncertainty in complex, non-linear systems like surface hydrology (New et al. 2007).

### *4.5 Summary of Results from Mitano River Case Study and Implications for Water*

This study illustrates the potential for determining the response of groundwater resources to changing climate in a small basin in equatorial east Africa. High-resolution estimates of climate change are generated using a RCM. The hydrological response simulated by the SMBM is sensitive to the method by which the future climate change signal is determined. When the change in the frequency distribution of daily precipitation is considered rather than just the change in daily mean precipitation, groundwater recharge is projected to increase, rather than decrease. However, unlike the Okavango study only a single combination of GCM/RCM and emission scenario was examined. Although, the IPCC AR4 models indicate a relatively consistent mean precipitation change signal over East Africa (Christensen et al. 2007) the degree of consistency in projected changes to frequency and intensity of daily precipitation is as yet unclear. Therefore, further model simulations are required including grand-ensembles of GCM experiments and hydrological model experiments to determine the fuller extent of non-discountable climate change impacts. In addition, given the highly non-linear relationship between precipitation and recharge further work is required to improve our understanding of groundwater recharge processes.

Projected increases in recharge under future climatic conditions provide a promising outlook for future populations, yet increases in demand due to very rapid population increase in coming decades are likely to exert considerable pressure on finite water resources. Initial studies indicate that increased demand is already driving increases in motorised groundwater development, which has expanded dramatically since 2003 (MWLE 2006). Furthermore, the water supply system in Rukungiri town, the main urban area in the River Mitano basin has already been singled out as being inadequate for meeting current town water demand, making future expansions of intensive groundwater abstraction inevitable. Increases in intensive groundwater development are further expected as the Ugandan government intensifies its efforts to provide safe drinking water to urban populations (MWLE 2006). For example, 782 small towns were identified for the provision of piped water by June 2006 (Tindimugaya, C., pers. com.). Around 70% of water supplied to these towns is provided by groundwater, mainly through deep boreholes. Uncertainties in the future development of intensive irrigation under a changing climatic regime with increased dry-day frequency also pose a problem for future water resources demand. Socio-economic change rather than direct climate change impacts may therefore have a substantial influence on basin water resources. Nevertheless, plans for future development initiatives to develop groundwater resources, notably intensive groundwater abstraction for town water supplies or irrigation, need to account for the full range of possible hydrological responses to future climate.

## 5 Discussion and Conclusions

There is a clear consensus that anthropogenic climate change is real and that it presents a major challenge to many levels of society. Given that we are committed to increasing GHG levels for the foreseeable future, adaptation to climate change will be necessary. Therefore, various agencies need to incorporate climate related risk into their decision making. Vulnerability to climate change is likely to be most acute in the less developed parts of the world, including much of Africa. Within much of the tropics, the water resources sector will be particularly susceptible to climate change (Bates et al. 2008). Changes to the terrestrial hydrological cycle will further impact on the quality and availability of the ecosystem services on which many livelihoods depend. The development of strategies for climate risk management requires information on how climate may change in coming decades and the impact on water resources and ecosystem services. Such frameworks are the subject of ongoing research.

This chapter has provided a summary of two contrasting case studies of climate change impacts on basin scale hydrology in Africa. The large-scale Okavango river study addresses model uncertainty in a region where uncertainty in GCM projections of precipitation is high. Results show wide range of projected hydrological impacts with associated likely ecological impacts. At least in the first half of twentieth century uncertainty is dominated by GCM uncertainty rather than GHG emissions. The Mitano river study does not address GCM uncertainty explicitly but highlights how the projected impact on groundwater resources is critically sensitive to the method by which the projected precipitation change signal is transferred to the hydrological impact model. The project illustrates how hydrological processes are sensitive to projected changes in the frequency distribution of daily rainfall, at least in relatively small river basins.

These studies raise the issue of how such climate change impact projections might be incorporated into long-term decision making. Given the magnitude of projected climate change impacts in these cases there is a clear need to 'mainstream' climate information in development policies. To date, there are very few examples of this in practice (Washington et al. 2006). Stainforth et al. (2007b) have suggested an 'analysis pathway' which can guide the use of climate information and associated uncertainty in decision making. We draw on this to explore the policy implications of the two case studies presented in this chapter. Stainforth et al. (2007b) suggest that climate change adaptation is most relevant for decisions which exist irrespective of climate change but which have decadal time scale implications. There is often pressure to stabilise river flow regimes (through dams and interbasin transfers) in regions, such as the Okavango basin, where variability in flow is high and where the river corridor flow resource is especially valuable in a relatively dry environment. In the case of the Okavango, therefore, we might consider how decisions regarding large scale water abstractions (e.g. extending the Namibian Eastern National Water Carrier pipeline to the Okavango river) or construction and operation of dams for hydro-power generation in headwater streams (see Sections 3.3 and 3.4) might be influenced by projected climate change. The envelope of projected climate change impacts described in Section 3.4 can prove useful here, and there can be little doubt that the non-discountable climate change is highly relevant, even on the basis of this relatively limited exploration of uncertainty. In both these examples of infrastructural investment, determining the economic viability and environmental impact of the projects should be undertaken with respect to the full range of future hydro-climatic condition simulated in the model experiments, not solely on the basis of historical conditions. Still, there is a clear need for further uncertainty analysis using perturbed physics GCM experiments and assessment of uncertainty in hydrological models. For the Mitano River in Uganda, there can be little doubt that developing policy for investment to provide sustainable groundwater abstraction in the context of increasing demand will benefit from the kind of hydro-climate projection described here. A much more comprehensive uncertainty analysis is required, however, to determine the envelope of non-discountable climate change impacts. The study highlights how it is not just the changes in mean precipitation that are important to water resources but also the higher moments of the daily precipitation frequency distribution. It will be interesting to determine how the range of IPCC AR4 GCMs represent these features, and whether this leads to significantly less consistent hydrological response than that suggested by the relatively consistent response in the GCM mean precipitation climate change signal.

The development of climate change adaptation policy is in its infancy. Success in this requires a two-way communication between climate scientists and users of climate info. Further work should explore the link between climate change and real-world decision-making. Overall, in the context of large uncertainty in climate change impact projections, adaptation strategies should stress flexibility and resilience to future changes, including the adoption of water-efficient technologies and practices. This is particularly relevant in Africa where population growth is high and existing infrastructural capacity to cope with future climate change and variability is relatively low. There is no doubt that the process of 'mainstreaming' climate into development policy in Africa will be challenging. Nevertheless the existence already in Africa of regional centres disseminating climate information and the Regional Climate Outlook Fora (RCOF), which provide a unique dialogue between climate scientists and the wider user community, albeit for shorter seasonal timescales, provides a valuable platform for the development of adaptive strategies with relevance to climate change timescales.

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# Adaptation to Climate Change and Variability: Farmer Responses to Intra-seasonal Precipitation Trends in South Africa

**David S.G. Thomas, Chasca Twyman, Henny Osbahr, and Bruce Hewitson**

**Abstract** We describe the nature of recent (50 year) rainfall variability in the summer rainfall zone, South Africa, and how variability is recognised and responded to on the ground by farmers. Using daily rainfall data and self organising mapping (SOM) we identify 12 internally homogeneous rainfall regions displaying differing parameters of precipitation change. Three regions, characterised by changing onset and timing of rains, rainfall frequencies and intensities, in Limpopo, North West and KwaZulu Natal provinces, were selected to investigate farmer perceptions of, and responses to, rainfall parameter changes. Village and household level analyses demonstrate that the trends and variabilities in precipitation parameters differentiated by the SOM analysis were clearly recognised by people living in the areas in which they occurred. A range of specific coping and adaptation strategies are employed by farmers to respond to climate shifts, some generic across regions and some facilitated by specific local factors. The study has begun to understand the complexity of coping and adaptation, and the factors that influence the decisions that are taken.

**Keywords** South Africa · Climate change · Adaptation strategies · Coping mechanisms · Farmer responses · Perception · Self-organising mapping

## 1 Introduction

Individuals, communities, and nations have to varying degrees had to cope with and adapt to climate variability and change for centuries (e.g. Tyson et al. 2002, O'Connor and Kiker 2004). For societies that directly utilise natural resources within livelihoods, for example through farming, changes in climate during the twenty-first century may represent significant disturbances and threats, especially where changes may be significant and pervasive and incorporate elements of

D.S.G. Thomas (✉)
Oxford University Centre for the Environment, School of Geography, Oxford OX1 3QY, UK
e-mail: david.thomas@ouce.ox.ac.uk

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surprise through the occurrence of extreme events. Many climate models and predictions suggest that this will be the widespread case in significant areas of Africa (e.g. Desanker et al. 2001), where many societies still rely on rural livelihoods and the use of natural resources.

Being able to adapt to climate change and variability may be linked closely to vulnerability (Few 2003), with the ability to withstand shocks and stresses to livelihoods considered especially important (Moser 1998, Adger 2000, Sokona and Denton 2001, Beg et al. 2002, Metz et al. 2002). High levels of vulnerability and low adaptive capacity in the developing world have been linked to factors including reliance on natural resources (World Bank 2000), a limited ability to adapt financially and institutionally (Beg et al. 2002), low per capita GDP and a lack of safety nets (Desanker et al. 2001). The 'flip side' of vulnerability is resilience, (Klein et al. 2003), with growing evidence that people may act positively to enhance their resilience (Salinger et al. 2005, Tompkins 2005) if wider dimensions of livelihood change permit this (Robledo et al. 2004).

In subtropical areas of Africa climate variability, uncertainty and events such as drought are phenomena that some societies have coped with for many generations and even centuries (e.g. Nicholson 2001, Vogel 2005, Washington et al. 2005). There is a view however that many groups in the developing world are amongst the most vulnerable and helpless in the face of climate change (Sokona and Denton 2001), in part due to their vulnerability to changes in the natural resource base. Given the paradox between views of present day helplessness and historical adaptability, it is vital to investigate how exposure to climatically driven changes in the environment can affect both its use and people's livelihoods. An understanding so gained could make a contribution to facilitating and informing reactions to developing changes and uncertainties within climate systems more widely.

Progressing our understanding of both the science of climate change and societal responses is fraught with theoretical, conceptual and empirical challenges. One of the most pertinent is how to deal with uncertainty and variability. That climate is changing is a certainty (IPCC 2001). However knowing what this change will comprise in different places is uncertain, with different models and scenarios generating different and sometimes contradictory outcomes (IPCC 2001). Arguably it is becoming increasingly important to recognise the limits of our scientific knowledge (Brown 2004) and interrogate our understanding of what uncertainty and variability mean to how people live their everyday lives.

In this paper we investigate the nature of recent rainfall variability in part of southern Africa, and how, if at all, this variability is recognised and responded to on the ground by natural resource users. We have conducted research within part of the summer rainfall zone of South Africa, as part of a larger project investigating the adaptive capacity of natural-resource dependent societies to future climate changes. We take a research approach informed by political ecology and embedded in the discipline of geography, combining deep statistical analysis of climate data and the application of the livelihoods framework (e.g. Chambers 1995) for social data collection and analysis. Research in the overall project falls into four components, investigating (1) dimensions of recent historical climate variability, change and extreme events in the region; (2) recent and contemporary responses and coping strategies to these parameters by farmers, including whether or not these climate parameters were expressly recognised (cf Meze-Hausken 2004 in Ethiopia); (3) the processes that facilitate societal responses to changes in climate parameters, and (4) the transferability of any generic characteristics of learning and response, with a view to investigating whether the capacity to adapt to future changes can be identified or even facilitated in areas that may be 'at risk' in the future. In this paper we focus on the first two components.

We first identify and characterise spatial dimensions of climate phenomena that may have changed or varied within the recent historical past (defined as the last 50 years). Second we investigate, through qualitative and quantitative household level research within three regions that have experienced particular dimensions of climate variability, the ways in which climate dynamics are recognised and have been responded to in terms of adaptations in natural resource use and agricultural practices. The information gained may then be useful in beginning to understand why and how natural resource users make particular decisions, which is relatively poorly understood, particularly in Africa (Thomas and Sumberg 1995).

## 2 Climate Variability, Uncertainty and Change

A number of scales, approaches and organising frameworks have been employed to structure investigations of the relationships between environmental change and social behaviour (see Olson et al. 2004 for a review). Household-level studies have proved valuable for understanding the nuances of responses to environmental change, with for example several. studies of drought in Africa taking this approach (e.g. Bratton 1987, Corbett 1988, Campbell 1999). Household analyses need however to be situated in an understanding of the larger scale frameworks that impact on choice and behaviour, as illustrated in Campbell and Olsson's (1991) 'kite framework' of spiralling multiscalar interactions, an approach closely related to the political ecology framework (e.g. Zimmerer 1994, Rocheleau et al. 1996).

Our investigation is framed to enhance understanding of how societies may adapt to future climate change, and is strongly informed by political ecology, especially in the ideal of integrating environmental and societal processes in a balanced manner (Walker 2005). The research is also strongly framed by the traditions of geography (e.g. Turner 2002), whereby we sequence our analyses to first investigate climate trends and then secondly people's recognition of and reactions to these trends.

### *2.1 Climate Variables: Informing Adaptation Research*

It would not be sufficient to consider changes over time in mean annual climate parameters alone. Variations about the mean are neither sufficient to capture the attributes of climate than impact on natural resource users (Usman and Reason 2004), nor do they indicate the day-to-day conditions faced by farmers (Mortimore and Adams 2001). Actual climate phenomena, and their temporal and spatial dynamics, are more critical to understanding the triggers to behavioural responses

(Smit et al. 2001). The magnitude of variability, frequency of event occurrence and rate of change within climate systems are examples of important attributes as they can affect people's ability to respond, cope and to adapt (Dessai and Hulme 2003, Hulme 2003).

Rainfall has been regarded as the most significant climate parameter affecting human activities (Vogel 2000). The southern African summer rainfall zone has a relatively dry climate with a spatial patterning of mean annual rainfall, predominantly in the October-March summer months, that reflects factors including the penetration of moisture from sources in the southwest Indian Ocean associated with movements of the ITCZ, moisture penetration from the southeast tropical Atlantic (Reason 2001, Cook et al. 2004) and topographic effects. The consistency of rainfall within the wet season also varies, with dry spells being associated with shifts in the tropical temperate trough over the region (Washington and Todd 1999, Usman and Reason 2004). There is also a high degree of interannual variability reflecting ENSO events and regional SST effects (e.g. Mason and Jury 1997, Todd and Washington 1998). Droughts, linked to the failure of rains within the expected October-March period, and extreme rainfall events (Mason et al. 1999), such as that associated with cyclone Eline that brought flooding to parts of Limpopo Province (South Africa) and Gaza District (Mozambique) in February 2000, are not unexpected either. There are distinctions between these two extreme event phenomena because meteorological droughts are not unexpected, and which forecasting strategies are attempting to allow better prediction of, while extreme rainfall represents the type of 'surprise' event that is even less predictable than drought.

For farmers and other land users, the concepts of drought and extreme rainfall are not necessarily sufficient to fully capture the dynamics and characteristics of climate variability that are critical to decision making. Within the general phenomena of rainfall variability, intra-seasonal factors (Tennant and Hewitson 2002) including the timing of the onset of first rains, which affects crop planting regimes, the distribution and periodicity of rain events within the growing season (Mortimore and Adams 2001), and the effectiveness of the rains in each precipitation event (e.g. Usman and Reason 2004), represent real criteria that impinge of the effectiveness and success of farming (Levey and Jury 1996). These parameters can embody elements of uncertainty and unpredictability (or surprise), but also may experience trends in occurrence that could lead to changes in natural resource use and behaviour over and above those that might be facilitated by better drought forecasting.

## 3 Investigating Climate Variability Through Self Organising Mapping

Crane and Hewitson (2003) used self-organising maps (SOMs) to examine spatial and temporal dimensions of larger scale climate data sets. The SOM approach classifies and groups data into meaningful homogeneous regional representations of the variability within the total data. For precipitation data SOMs proportionally integrate rainfall records from station data into a regional data set. This is achieved by taking the shared regional variability from the locally derived variability in each station record. Nodal data points are identified statistically within the total area covered by the spatial data set, with the nodes representing the observed data distribution (Hewitson and Crane 2002). The number of nodes can be chosen manually, depending on the level of regionalisation that is required for a particular study. This formulates a method by which the total data set is then trained to produce a number of regions, each with distinctive criteria identified from within the data. This regionalisation is therefore based on the occurrence of rainfall events, so that stations within the data set that receive rainfall under related synoptic conditions fall within the same region (Tennant and Hewitson 2002).

Using a 276-record northeastern summer rainfall zone daily rainfall data set, part of the country-wide data of Tennant and Hewitson (2002), we focused on 1950–1999, the period of historical memory in the population, to produce a 12 region SOM analysis for the area 24°–35°E to 20°–30°S (Fig. 1). To understand the climatic underpinning of the regionalisation, it was necessary to calculate key rainfall parameters from the original station data from each region. Following Tennant and Hewitson (2002). we selected eight factors considered to capture components of rainfall relevant to farming activities and other forms of natural resource use:

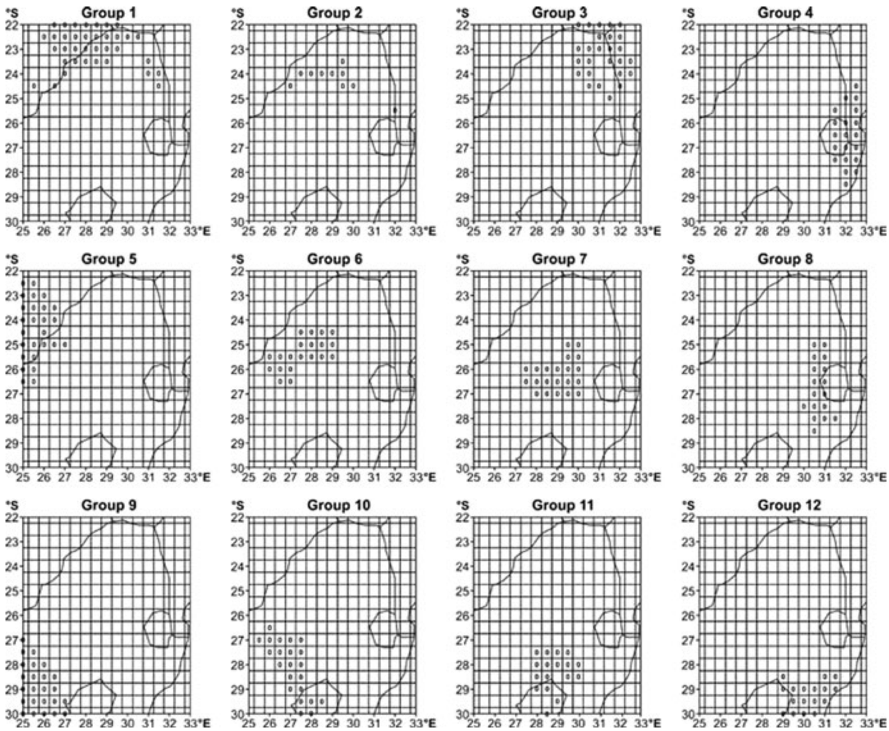


**Fig. 1** The twelve homogeneous rainfall regions produced by the SOM exercise for northeast South Africa rainfall data, 1950–1999. After analysis of the underlying data and trends in precipitation, regions 1, 6 and 11 were selected for further investigation

- mean rainfall per day (mean)
- maximum rainfall event per month (xmax)
- total number of rain days per month (rda)
- rain days exceeding 2 mm per month (rdb)
- rain days exceeding 20 mm per month (rdc)
- dry spell factor: the number of consecutive days without rainfall between station rain days with 2 mm or more rainfall (dfac)
- wet spell factor: the number of consecutive station rain days exceeding 2 and 20 mm (wfac)
- 80th percentile rainfall event (nth)

For each parameter, mean value and trend plots for the 50 year data set were produced. Figure 2 exemplifies this for the mean number of monthly rain days, showing 50 year mean values and the monthly trend plots. For each of the twelve regions, values for each parameter were calculated using a weighted mean of all station values from the region. Time-time plots, with the x axis representing years and the y axis months, were produced to allow trends in the parameters to be identified by region (Fig. 3). Taking the mean and trend plots for all eight parameters for the overall study area and the parameter plots for each of the twelve SOM regions, three regions, 1, 6 and 11, were selected for further investigations on the basis of the precipitation variability characteristics they possess.

### *3.1 Study Region Characteristics*

Region 1, in northern Limpopo Province, north of the Soutpansberg, has a long term mean annual rainfall of 400–500 mm. The climate data show evidence of a growing length to the dry season, resulting in a later start to the wet season, in late October-early November. Within the wet season there has been a trend towards fewer rain days in November and December and an increase in the overall occurrence of dry spells, in effect representing potentially damaging rainless spells within the growing season. Droughts have been frequent in the last two decades (1982–1983, 1987, 1990 and 1994 in particular).

Region 6 covers parts of North West Province, extending from Mafikeng in the west to the border area with Gauteng in the east. This is a dry region with 500–600 mm mean annual rainfall, and regular droughts. In the last 50 years early-season rain days have been increasing (September and October), but in the main wet season the principle characteristic has been interannual variability in rainfall amounts and distributions, without any specific trends in wetting or drying being identifiable.

Region 11 is in northwest KwaZulu Natal and has a recent historical mean rainfall in the 800–900 mm pa range. There has been increasing interannual variability in the rainfall record and a trend towards higher rainfall in the first half of the growing season, with an increase in early season rain days and a decline in late season (February and March) rains. This is further represented by an increase in heavier rainfall events in the early season and a predominance of low volume rain events

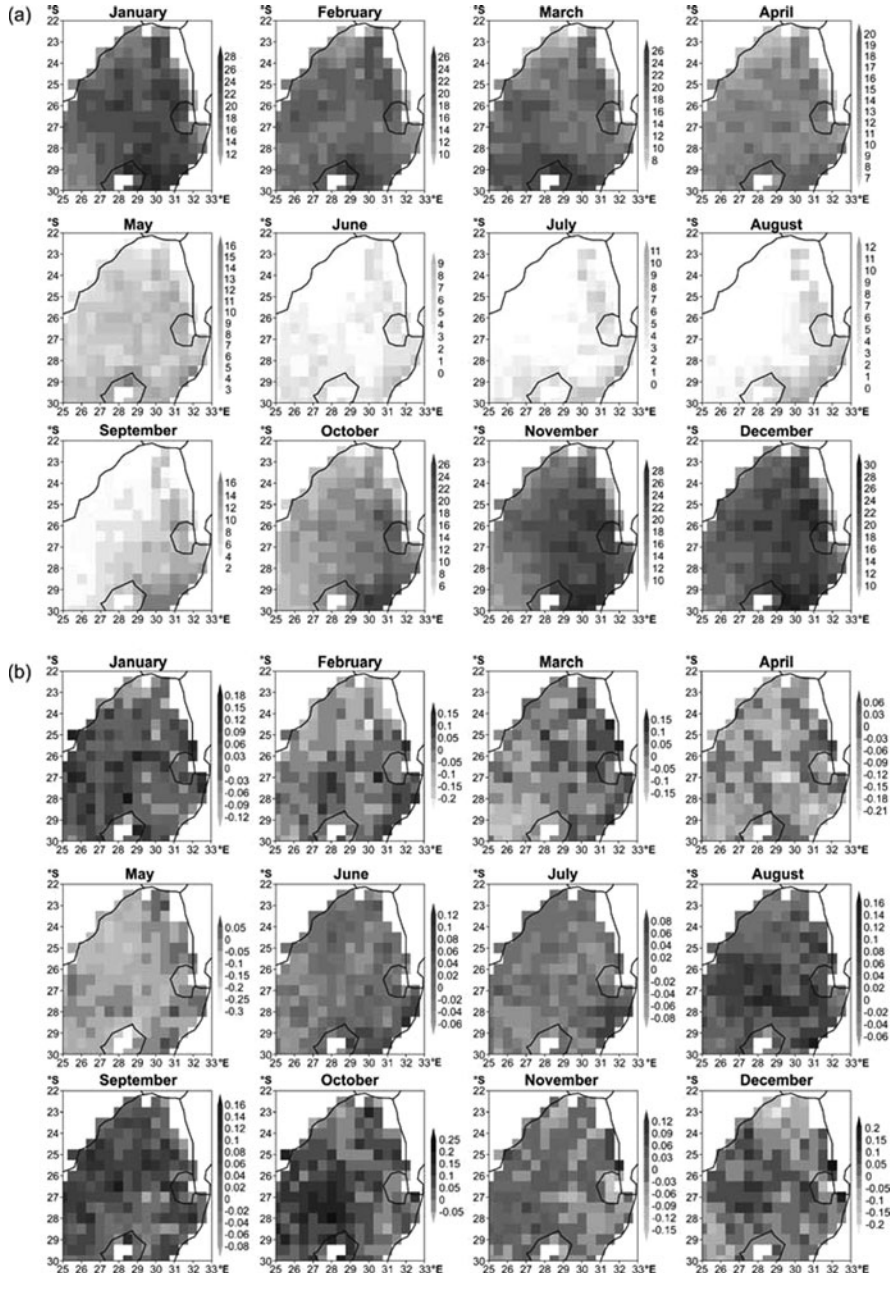


**Fig. 2** **a** Mean number of rain days per month by 0.5° grid cells, 1950–1999. **b** Trend plot for the total monthly number of rain days, 1950–1999. *Darker shades* indicate an increasing number of rain days per month over the 50 year period, *paler shades* a decreasing number. The data clearly show a declining number of rain days per month in all months in northern Limpopo Province, but a notable increase in early rain season (Sept–Oct) monthly rain days in western areas

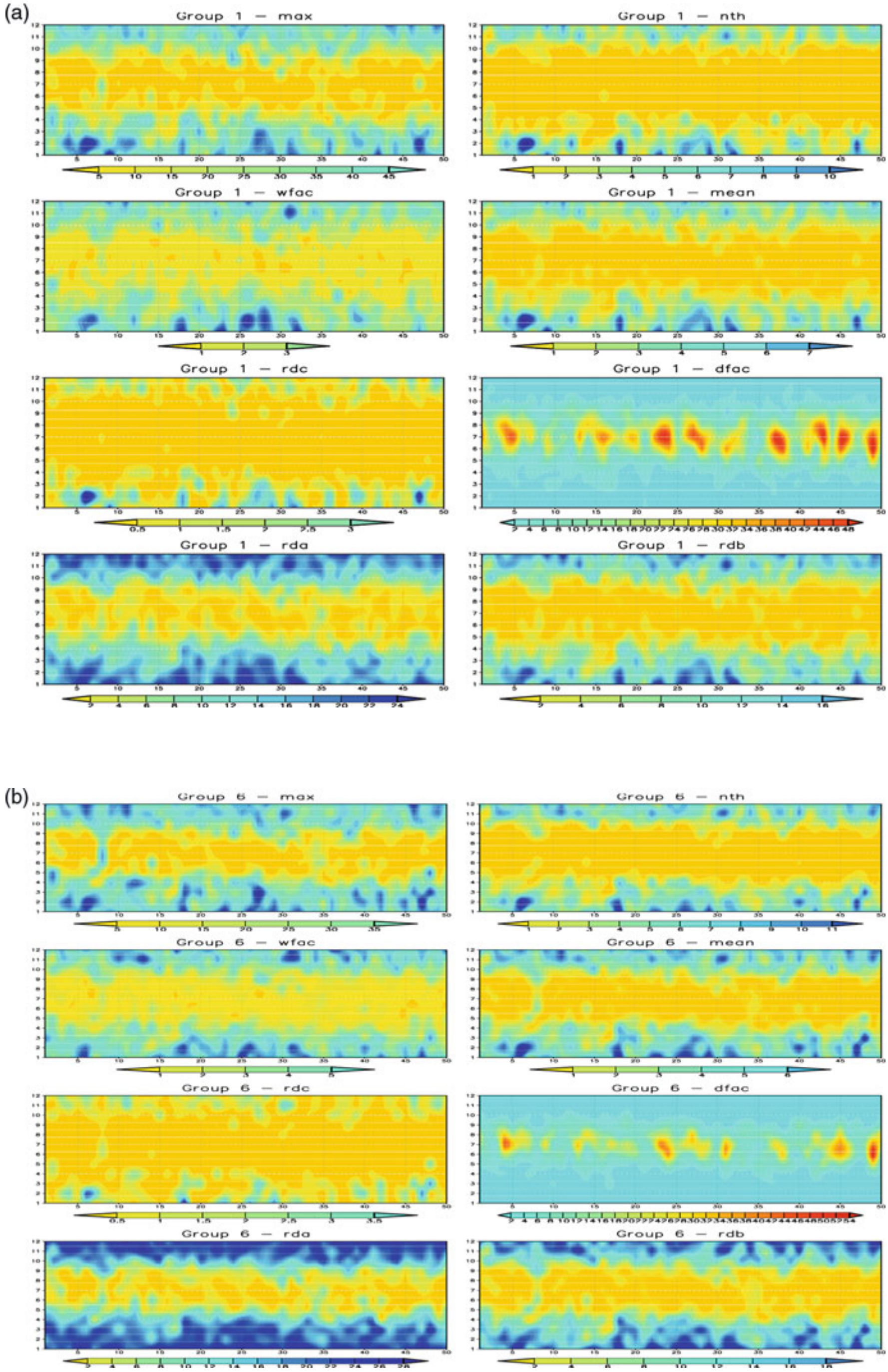


**Fig. 3** (continued)

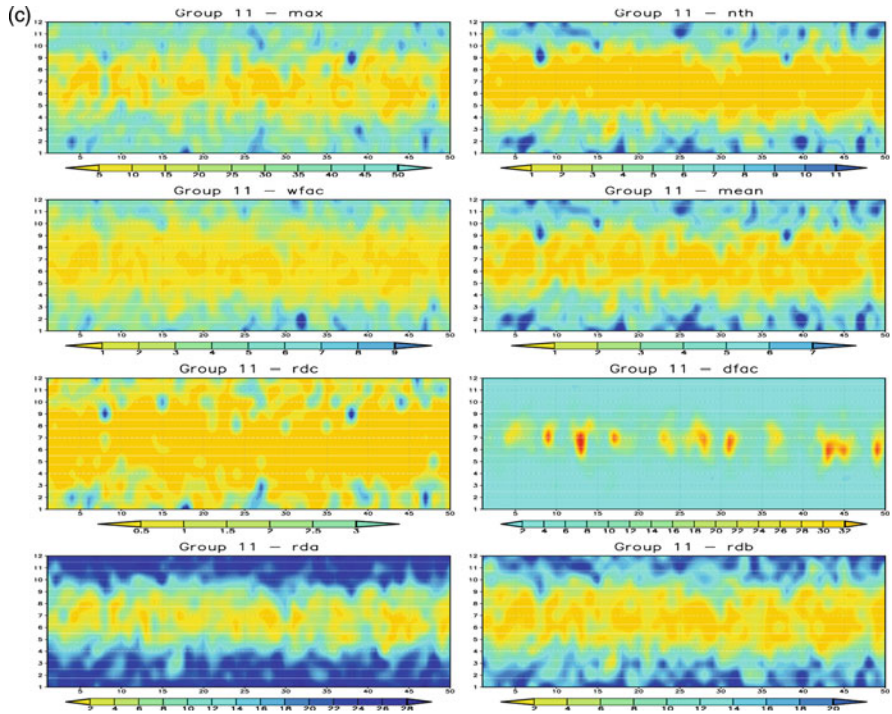


**Fig. 3** Time-time plots for the eight precipitation parameters (detailed in the text) for each region selected for the study: **a** Region 1, northern Limpopo Province, **b** Region 6, North West Province, **c** Region 11 Northwest KwaZulu Natal. On each graph the *x axis* represents years, starting from year 1, 1950. The *y axis* represents months of the year. The plots visualise complex data sets, such that for each parameter, *paler shades* represent lower numbers on the relevant scale and *darker shades* higher values. For example, on plot **a** Group 1-max, in year 1 (1950), the maximum rainfall event in months 6 (June) to 9 (September) was less than 10 mm; on plot **a** Group 1- rda, the total number of rain days in year 5 (1955) in month 12 (December) was over 22; on plot **c** Group 11 – rdb, the total number of days with more than 2 mm rainfall in month 1 of year 25 (January 1975) exceeded 20. The plots can be used to visualise year-to -year variability in each parameter in each of the study regions

later in the season. The growing variability in rains is illustrated by for example, rains starting late in 1990 and 1994, while in 1991 rains commenced in September but were subsequently limited until January 1992.

## 4 Living with Risk and Uncertainty

To investigate recognition of climate trends and to explore behaviour that may ultimately impact on resilience to climate changes, data were collected in March–July 2003 in the rural communities of Khomele (Dzanani District Limpopo Province: region 1), Mantsie (Lehurutshe District, North West Province, region 6) and eMcitsheni, (uThekula District, KwaZulu Natal, region 11).

In each village, community meetings were first held to give villagers the opportunity to raise questions about the research and to discuss perceptions of livelihood issues and the local environment. Fifty focus groups were used for repeated exercises, with people from all sectors of the communities, embracing both genders, different age groups, social statuses, and livelihood activities (Table 1), were held around specific topics. Meetings and exercises were conducted by an experienced researcher assisted by a trained translator, facilitating full group involvement and minimising dominance by individuals. Exercises were repeated between groups, some of which had overlapping membership that facilitated triangulation of findings. Participatory farm visits and the time spent in each village, plus repeat visits, enabled further triangulation and cross-checking of findings.

Structured questionnaires and semi-structured interviews were conducted with thirty key informants at each village, providing detailed livelihoods information and perceptions of risk and change, social capital, institutions and capacity (Table 1). A cross-section of each community was selected using wealth-proxy records and advice from NGO and agricultural extension officials and local leaders. Interviews were also conducted with different institutions and officials working in the area and province level authorities. Importantly for the goals of this research, early questions to communities were not expressly directed towards climate. Instead, questions addressed wider themes including environmental risk, uncertainty, and food security. Climate issues were only introduced into questioning when raised by respondents, or in the later stages of the process when different climate characteristics were considered, and when questions were asked relating to forecasting

**Table 1** Structure of the village-level research and data collection

| Research component | Content/activity |
|---|---|
| Introductory community meeting | Introductions, links with NGOs & ministries. Village mapping activity, history timeline for village, structure of village, associations & activities, Positives and negative of living in the village |
| Focus groups<br>Examples of groups:<br>• School, church, women and horticulture, tribal authorities, crop farmers, livestock farmer, irrigation groups, dryland farmers, youth, poultry and pig farmers, business, no participation | Specific exercises (timelines, ranking activities, network diagrams):<br>• History of the group<br>• Farming calendar (when relevant to group)<br>• Social and environmental changes<br>• Past, current, future responses to changes |
| Semi-structured questionnaires & follow-up interviews<br>30 key informants per village | • Baseline livelihood information, including household income & costs, livelihood components, farming activities<br>• Food security<br>• Trust, solidarity, reciprocity<br>• Understanding uncertainty<br>• Managing risks<br>• Forecasting |

(cf Eakin 2000, Ziervogel and Downing 2004). Questions relating to climate parameters were non-directional: for example, respondents were asked, in questions about uncertainty, what they considered normal rainfall to be in their community, and whether any changes appeared to have occurred over a range of different timescales. When respondents themselves introduced climate related issues into discussion, these were followed up in the same manner as other environmental and socio-economic factors relating to risk and uncertainty. Climate change and risk was therefore able to emerge within the analysis when included in the responses of those questioned, avoiding the possibility of researcher-directed responses, or the possibility that respondents would give answers 'preferred' by the researchers.

Data analysis comprised complementary qualitative and quantitative techniques, comparing statistical patterns in the data with patterns in coded thematic interview narratives, interpretation of participatory and ranking exercises. Such a mixed methods approach is seen as fundamental to challenging received wisdoms about the 'validity' and 'truth' associated with quantitative analyses and the 'soft' and 'subjective' accounts associated with qualitative analyses (Philip 1998, Valsiner 2000). By integrating data analyses rigorously, both across the quantitative and qualitative spectrum and across the social and natural sciences, these assumptions can be challenged (Demeritt and Dyer 2002). Articulating this process as we have done allows real progress to be made in addressing and understanding complex phenomenological issues such as adaptation to climate change.

## 5 Recognising Changes in Climate

Respondents showed an acute awareness of the changing climate trends around them, with for example, 80% of respondents across the three locations relating changes in long-term patterns to increased variability and unpredictability. Table 2 shows how climate characteristics are recognised in each area and illustrates the notable differences in the responses regarding the nature of these changes.

Analysis specifically aimed to distinguish between *variability* as an expected climate phenomenon and *increased variability* linked with unpredictability (Table 2). Importantly, people's knowledge of changes in climate in the recent past corresponds well, in terms of the phenomena recognised, with the outputs of the SOM analysis. In Khomele drought and dryness are seen as normal and expected events (70% of respondents). The main perceptions of change are in the increased variability and uncertainty of specific climate parameters (Table 2). Rains starting later, shorter wet seasons characterised by little but intense rainfall, and more intense heat in the summer were expressed as the key concerns about observed changes in, and unpredictability of, patterns of seasonality. It was reported that "*October used to be the start of the rains. The rain is not in a reliable pattern. . .not like before.*" *(respondent K22.061–64)*. Again, local views of changes in climate parameters correspond well with the regionalisation scenarios.

In Mantsie, dry conditions and drought were recognised as a normal climate characteristic by almost all respondents (Table 2). However, the periodicity of drought

**Table 2** Local recognition of changes in climate characteristics

| | Mantsie (region 6) | Khomele (region 1) | eMcitsheni (region 11) |
|---|---|---|---|
| **Characteristics from SOM analysis** | Dry, regular drought, no discernable wetting/drying trend, slight increase in inter-annual variation | Dry, regular drought, drying trend, shorter rainy seasons, increase in inter/intra-annual variability, hotter dry season | Increase in inter-annual variability and intensity of weather events, slight wetting trend |
| **Familiarity with:** | | | |
| Dry conditions | 93% | 70% | – |
| Sufficient rain/limited variability | – | – | 90% |
| **Surprise extremes:** | | | |
| Heavy rain/wind | 23% | 60% | 70% |
| More intense weather/unusual times | – | – | |
| **Recognised change during the last 20 years:** | 5–7 yr cycle of drought less predictable | 3 yr cyclic pattern drought extended | 5–10 yr cycle of drought unpredictable |
| Later onset rainy season | 67% | 86% | – |
| Increased variability | 73% | 83% | 77% |
| Total rainfall higher | – | – | 56% |
| Total rainfall less | 60% (in last 5 yrs) | 83% | – |
| Shorter rainy season | 30% (in last 5 yrs) | 40% | – |
| Hotter dry season | 13% (in last 10 yrs) | 23% | – |

was seen as becoming more uncertain by 73% of respondents, comparable with the increased interannual variability identified in the SOM analysis. One farmer commented "*I remember when there were heavy rains 7 years ago and the sorghum was badly damaged. It takes the 7 year cycle, this heavy rain. But now I think it takes longer between the cycles." (respondent M06.065–68)*. Within eMcitsheni increased variability and uncertainty was again raised as a key concern amongst local populations, with 40% commenting upon specific changes to climate patterns over a 5–10 year period. The following respondent details the changes in rainfall parameters that he has experienced: "*normally the rains start in September, they stop in December. In January there is a little and in February and March the main rains. Now the rains start later, often in November, or some years they are early with heavy rain." (respondent E14.065–67).*

## *5.1 Changing Climate Risk*

Risk is an understanding of *threat* (Kasperson and Kasperson 2001): that is, a product of both the probability or likelihood of a particular occurrence and the related consequences perceived to affect people's livelihoods (Stirling 2003). Awareness of climate risks is complicated when the nature of these risks evolves, for example as climate changes, which may result in differences developing from place to place in the significance attached to particular risks and the responses that develop to these risks (Bulkeley 2001).

Table 3 shows the most pertinent perceptions of risks today and the responses in the three study areas from the focus group discussions. The data in the lower part of Table 3 show differences in the recognition of distinctive risks between different groups in each village. Some of this differentiation can be explained by the relevance of different risks to particular farming activities: for example, in eMcitsheni heavy rain is not perceived as a major risk by livestock farmers but, because of its potential to damage plants, it is seen as a greater risk by crop growers, including those who run commercial gardens. The variation in the overall perception of risk between villages is also notable, with for example drought being most frequently cited as a risk in Mantsie, even though it was recognised to occur regularly and thus was a familiar event (Table 2). However, it is the enhanced unpredictability of climate, as identified by 77% of respondents (Table 3), that has turned it into a major risk, i.e. there is now an uncertainly associated drought that impacts upon farming activities. Over the last 20 years, inter- and intra-annual variability were viewed as increasing, illustrated by reports of a more erratic rainfall pattern which started late and only gave light showers and increased heat in summer months.

In Khomele and eMcitsheni, the most frequently cited climate characteristic causing a risk to livelihoods is uncertainty and unpredictability (90 and 73% respectively, Table 3). In eMcitsheni this is associated with extreme events (70% of respondents, Table 2) notably snow, frost, drought, and heavy rains while in Khomele changes in the pattern of the rainy season are seen as the most significant contributor (e.g. 86% cite a later onset of the rainy season: Table 2).

## 6 Strategies in Response to Disturbance and Change

While the focus of group discussions was explicitly on climate events, it was also clear that many of the impacts and responses transcend the climate dimension and actions are clearly played out within the context of other pressures and disturbances on livelihoods. For example, the perceived impact of animals dying may be co-related to disease issues and lack of access to veterinary care within the area, or a lack of financial capital to pay for medicines. The entwined nature of disturbances and change-inducing factors in livelihoods cannot be ignored and is widely recognised in the literature (e.g. Campbell 1999), including in attempts to disaggregate effects and show their linkages. In our analysis, we used coding that allowed climate dimensions to be identified in both the focus group discussions and questionnaire and interview responses. For adaptation to climate change to occur, it is not necessary for households and communities to ignore other livelihood disturbances. Indeed, to be successful, adaptation arguably needs to be embedded in the full milieu of life-affecting processes. However, it is important for climate to be recognised as a significant factor, and as noted earlier, for the subtle dimensions of

**Table 3** Local understandings/experience of risk and uncertainty in climate

| | Mantsie (region 6) | Khomele (region 1) | eMcitsheni (region 11) |
|---|---|---|---|
| Drought experienced as problematic/negative impact on livelihoods | Yes<br>1957, 1977, 1979, 1981–1985, 1992–1993, 2001–2003 | Yes<br>1974, 1982–1984, 1990–1993, 1997–1998, 2001–2003 | Yes<br>1983, 1999–1991, 1994, 2002–2003 |
| Heavy rain experienced as a problematic/negative impact on livelihoods | Sometimes<br>1994, 1999, 2000 | Occasionally<br>1958, 1977, 2000 | Yes<br>1996, 1998, 2001 |
| *Drought occurrence viewed as a distinctive risk* | 87 | 53 | 47 |
| (by % of household total) | | | |
| Women (as % of respondents recognising this characteristic) | 38 | 37 | 35 |
| Men (as % of respondents recognising this characteristic) | 62 | 63 | 65 |
| Livestock[a] (%) | 39 | 50 | 29 |
| Cropping[a] (%) | 56 | 69 | 64 |
| Off-farm[a] (%) | 35 | 19 | 21 |
| *Heavy rain occurrence viewed as a distinctive risk* | 23 | 63 | 53 |
| (by % of household total) | | | |
| Women (as % of respondents recognising this characteristic) | 71 | 47 | 69 |
| Men (as % of respondents recognising this characteristic) | 29 | 53 | 31 |
| Livestock [a] (%) | 0 | 31 | 13 |
| Cropping[a] (%) | 57 | 68 | 88 |
| Off-farm[a] (%) | 43 | 5 | 0 |
| *Increased variability and unpredictability of climate viewed as a risk to livelihoods* | 77 | 90 | 73 |
| (by % of household total) | | | |
| Women (as % of respondents recognising this characteristic) | 44 | 45 | 59 |
| Men (as % of respondents recognising this characteristic) | 56 | 55 | 41 |
| Livestock[a] (%) | 38 | 38 | 23 |
| Cropping[a] (%) | 42 | 63 | 86 |
| Off-farm[a] (%) | 20 | 0 | 9 |

[a]Livestock, cropping and off-farm categories represent dominant livelihood activities (by time) of respondent households who recognised each climate characteristic (i.e. for some locations this is more than 100% because some households devoted similar time to more than one type of livelihood activity).

**Table 4** The perception of livelihood-affecting risks: percentage of households identifying different risks

| Risk | Mantsie (region 6) | Khomele (region 1) | eMcitsheni (region 11) |
|---|---|---|---|
| Lack of capital | 57% | – | – |
| Political factors, inherited or current | 37% | – | 47% |
| Illness | 57% | – | 47% |
| Theft | 37% | – | – |
| Wildlife | 50% | 33% | – |
| Climate | 87% | 97% | 77% |
| Economy instability or legacies | 23% | – | 53% |
| Labour shortages | – | 23% | 30% |
| Crime | – | – | 67% |

climate parameter change, which are the experienced realities, to be understood and reacted to.

Table 4 shows the relative importance of different risks to livelihood decision making at the household level. Information from questionnaires and follow up discussions was coded into common themes. There are regional differences that reflect the situation of each study village, for example their rural isolation (regions 1 and 6), and in KwaZulu Natal (region 11) crime associated with proximity to an urban area. Amongst the milieu of risks recognised by people in each village, however, climate is presently identified as a highly significant factor. These data highlight that decisions are influenced by a range of factors, and while climate does not operate in isolation from other factors, it does play a significant role in how people attempt to shape their livelihoods for the future.

Table 5 shows the responses to risk that households employ, with activities falling into short-term coping mechanisms and longer-term adaptation measures. We have categorised them into four groups: changes to farming practices (coping); utilising the spatial and temporal diversity of the landscape (adapting); commercialising livelihoods (adapting); and, utilising networks (both coping and adapting). Of these, the first three can be linked most closely as specific responses to changes in climate parameters, and are therefore dealt with in this paper, with networks being addressed in a further project output.

### *6.1 Changes to Farming Practices: Short-Term Coping*

When short-term environmental variability occurs, rapid coping strategies (Berry 1989, Ellis 1998, Roncoli and Ingram 2001, Huq and Reid 2004) are employed, with similarities in actions across all three regions, During dry spells, the immediate farming response in Mantsie is to reduce investment or even to stop cropping and focus on livestock management. Half of the 80% of households with livestock in their farming portfolio chose to invest in animals during the last 5 years. An extract from a group interview illustrates this shift in focus: "*It has been some years since*

**Table 5** Impacts of, and responses to, locally identified climate parameters in the study villages

| MANTSIE<br>Parameters identified by focus group | Perceived impacts | Range of responses – rapid (coping) and longer-term (adaptation) |
|---|---|---|
| Little rain<br>Breaks in rainy season | • On welfare of household (e.g. hunger, family obligations, sickness/tiredness)<br>• On NR based livelihoods (e.g. crops/livestock die, loss of seeds/animal fodder, debt) | • Change a farming practice – coping (e.g. store fodder)<br>• Spatial/temp diversity-adapting (e.g. Take smallstock to river area or other villages, buy short-maturing crop varieties)<br>• Commercialising –adapting (e.g. sell animals, start business, get work)<br>• Networks- coping and adapting (e.g. community member to ask government for help, go to church, rely on relatives, collect welfare, steal) |
| KHOMELE<br>**Parameters** | **Impacts** | **Responses** |
| Less rain<br>Period of no rain<br>Unpredictable<br>Rain our of season<br>Late rain | • On welfare of household (eg. tiredness and hunger)<br>• On NR based livelihoods (e.g. loss of seeds/fodder, dryland crops/livestock die, more pests, soil unproductive, changes in vegetation species) | • Change a farming practice – coping (e.g. grind maize stalks as feed, use resistant maize, plant late-maturing fruit trees)<br>• Spatial/temp diversity-adapting (e.g. use irrigated land, cut fodder/wild plants)<br>• Commercialising –adapting (e.g. gardening projects, new business, sell livestock, get work, plant winter crops/late-maturing fruit trees, breed indigenous species)<br>• Networks- coping and adapting (e.g. rely on relatives/government, village meetings, go to church) |
| eMCITSHENI<br>**Parameters** | **Impacts** | **Responses** |
| Changing seasons<br>Hail<br>Drought<br>Frost<br>Heavy rain<br>snow | • On NR based livelihoods (e.g. loss of crops/animal feed, unproductive soils, no cash-crops, animals die, lack money for transport/seeds) | • Change a farming practice – coping (e.g. store fodder, build cattle shelter)<br>• Spatial/temp diversity-adapting (e.g. change vegetable or maize type – performance)<br>• Commercialising –adapting (change vegetable or maize type – sale opportunities, sell livestock/goods, start projects, find work)<br>• Networks- coping and adapting (e.g. rely on relatives, apply for government grant for vegetable project, village meetings, go to church, ask extension officer for information) |

Source: Focus group discussion in each village, 2003

*I farmed* [grew crops] *and I think the rains are too unpredictable to farm here. I think that livestock farming is more important and I will increase my goats if I can." (Respondent M04.011–13)... "It is very risky investing in ploughing only to lose your money. I think we should invest in livestock." (Respondent M08.035–36).* The average number of livestock per household was 19, with 30% of households exceeding this number up to a maximum of 57 head of cattle.

Some respondents noted the complex environmental pressures facing livestock farmers, particularly changes in grazing resources and plant communities. These changes are described in this detailed response from one farmer in Mantsie: *"There are twelve cattle which get kept in the kraal next to the house...we also have four sheep and fifteen goats which live in this kraal nearer the house...we spend money on feed for the livestock. I used to hire a shepherd to look after them...in the last five years [grazing has] got worse. Now the grasses are thinner and more easily destroyed with fewer cattle... we are always suffering from drought...my husband thinks we should increase the number of livestock that we have to cope with this risk...right now we have stopped ploughing because there is no rain...it is best to stop cropping and save your livestock" (Respondent M11.023–24/34–36/76–95).*

There are now fewer paid labouring opportunities available locally. This is partly because during a poor rain year people who can afford to hire labour stop cropping, and partly because more people are choosing to hire tractors from commercial farmers in the area during better rainfall years. Vegetables are sold to local markets and smallstock sold to commercial farmers with the profit used to buy replacement seeds for later planting of the fields.

In eMcitsheni, coping strategies include the storing of fodder prior to the end of the wet season, in preparation for drought events, the building of cattle shelters to protect animals from snow or cold, and in some cases, the selling of extra livestock and vegetables.

## *6.2 Exploiting the Spatial and Temporal Diversity of the Landscape*

Optimising livelihood outcomes by utilising spatial and temporal diversity in the landscape is one way in which people can spread the risks associated with climate variability and unpredictability (Eakin 2000). In eMcitsheni agricultural experimentation was viewed as a risk reduction strategy. Of the respondents, 53% noted that they had started to increase planting distances of some crops in response to perceived seasonal changes in moisture availability during the last 5 years. Others had introduced short-maturing varieties of maize in an attempt to respond to declining rainfall at the end of the growing season. Other new practices included building stone bunds to reduce soil erosion which was perceived to have increased in the last 5 years linked directly to changes in weather patterns (i.e. more intense and earlier rainfall events). The following respondent demonstrates how his farming practices have changed in direct response to the rainfall parameter changes he has experienced: *"I think it is a better strategy to start cropping earlier than September because the rains come earlier. We get more early rain. You can use this rain and* *then there is often a drought...I have also used some stone bunding to stop soil erosion when it rains." (Respondent E09.023–25/34–35).*

While these changing practices occur over relativity short temporal and spatial scales, they nevertheless demonstrate that people are making small adjustments to their farming practices in response to their understanding of changes in certain climate parameters. Changes in climate are very real to the people of eMcitsheni.

In Mantsie, 57% of respondents have also been experimenting. They have reacted to the shortening of the rainy season by the occasional use of winter maize and by trialling quick-maturing crop varieties, using seed bought in nearby towns during visits for piecework. With a growing time of three months, these reduce the risk of exposure to drought. The widely-held view in Mantsie is that drought-tolerant species offer greater flexibility in planting times. The following three cases show how attuned farmers are to the need to experiment: *"I think we need to have the correct varieties of seed to cope with this drier weather. You can get short varieties from the cooperative." (Respondent M09.037–39). "My son gets the seed to plant...he goes in September to buy them from Zeerust. I have a new mealie to plant...it grows in 3 months. This is better as it is less dependent on the rain." (Respondent M16.032–34/46–47). "We will be planting watermelons on the field because they survive in the dry...I bought some yellow maize...my friend said we should plant more crops in the winter." (Respondent M30.035/61).*

In Khomele the scale of response has been somewhat different. People have gained access to land beyond the village in attempts to tackle the problems associated with the drying trend through either exploiting the local spatial variability of rainfall or gaining access to alternative water resources. This has either been through utilising existing friendship networks and forming small groups for projects, or through drawing on extended family in nearby areas to gain access to land. The ability to access this land has also been made possible by the land redistribution policy of the post-apartheid government. Five young farmers from Khomele were successful in getting 10 ha plots in the Nwanedi farm area, which has given them regular access to river water that is used to irrigate large fields, a resource not available in Khomele.

By spreading risk in this way it is possible for households to take advantage of the often patchy nature of rainfall in the region. Whilst neighbouring villages are able to utilise land near water courses for small scale irrigated garden projects, few people in Mantsie have access to land with irrigation, and fewer still have business experience to exploit these commercial opportunities despite the close proximity to a market.

## 6.3 Commercialising Livelihoods Through Individual and Collective Action

Collective action has emerged as a key way to set up new opportunities to reduce vulnerability to the risks associated with climate uncertainty. This has emerged very strongly in Khomele and eMcitsheni, two communities with strong profiles of community cohesion and consensus around livelihood issues. Agricultural projects which utilised local knowledge and had a market base were the most successful. In Khomele the focus was principally on pig and cattle production to improve livelihood resilience and food security. Poultry and egg schemes were set up by government programmes as general poverty alleviation projects. Deliberate attempts to improve the resilience of these farming strategies by the government extension service has also led to a return to the incorporation of indigenous livestock breeds that are more drought resistant. Small-scale horticulture projects have also emerged to supplement the staple crops of sorghum and maize. Species of tomatoes were deliberately chosen for their drought resistant properties even though overall yields were lower than other varieties in good years, as illustrated by one entrepreneur: *"I use HTX14 tomatoes because I can sell them quickly, these tomatoes have a short growing time. This reduces the risk to me." (Respondent K18.N135–136).* Many of these projects built on existing groups of people who had built up trust over time so that experimentation and innovation were viewed as risk-averse rather than risk-prone strategies.

In eMcitsheni a maize cooperative has been established, to address marketing risks and reduce collective production and transport costs. The key to the success of the project has been cooperation and sharing of information and members all reported that it had significantly increased their resilience to adverse or unexpected weather conditions by smoothing costs and sharing risks. The following farmer demonstrates this by his emphasis on the group network: "*I only plant maize on the fields because I am part of a group of men who are my friends…we buy the maize together…we pool our resources to buy the right type…I discuss the forecast with my friends…I trust their advice. Experience has shown their advice to be reliable." (Respondent E05.010–13).*

However, by reducing individual risk, members of the group are also increasing their collective risk, for example by relying on one variety of maize rather than diversifying. Thus there is evidence that people weigh up the risks associated with different actions and make their decisions accordingly. Community horticulture projects for example were specifically set up to reduce food insecurity by reducing the vulnerability of people to the unpredictable weather. By irrigating and using collective labour supplies, these projects are seen as less sensitive to unpredictable weather patterns. These have proved exceedingly popular within the village, especially amongst women, with 87% of respondents reporting participation by household members. The women felt that these initiatives have endured because they reduce dependence on rainfed crops, which are vulnerable to damage by drought or heavy rain, and allow irrigated vegetables such as potatoes to be grown to compensate for lower maize production. The following two respondents highlight how this project has increased their food security as a direct response to unpredictable weather: "*The last three years have been successful in growing many types of vegetables…they can survive the droughts because people collect water from the taps and take it in donkey carts to the garden." (Respondent E14.096–98). "The best thing that we have done to make sure that we have food for most of the year is to become part of a vegetable project." (Respondent E20.055–56).*

In Mantsie many of the commercial activities that make overall livelihood portfolios more resilient revolve around individual rather than collective action. The village lacks effective leadership and has weak ties with external agencies such as government and non-governmental organisations. Exposure to successful projects is low and through sporadic family connections rather than more formalised networks as in other areas. Furthermore out migration of young men is still high and thus the stimulus for innovation here is low. Investments in livestock and poultry were seen as good ways for individuals to increase income during drought periods when crops were less reliable, thus acting as a buffer. Interestingly the closure of the government run cooperative forced small groups of friends to work together and two successful vegetable projects have emerged. Though mainly for home use to improve food security, surpluses have been successfully sold to local shops.

## 7 Discussion

The data we present illustrate that concerns about the effects of climate change on rural societies in the developing world, expressly Africa in this case, are justified: climate changes are occurring, and they are affecting activities that depend on the natural environment. Previous analyses of population responses to droughts have shown that coping strategies reflect opportunities framed by policy contexts and mediated by local circumstances (Campbell 1999), and involve trade-offs between immediate needs and future opportunities (Corbett 1988). In this study we have found adaptation to relate to expected or anticipated longer term climate changes, and to experienced changes.

Rather than being trapped in 'perennial cycles of destitution and impoverishment at the mercy of climate events' (Sokona and Denton 2001, p 120), our data illustrate that rural farmers in Africa recognise even subtle changes in climate parameters, and take steps to respond to these changes. The trends and variabilities in precipitation parameters that were identified in this study and spatially differentiated by the SOM analysis were recognised by people living in the areas in which they occurred. Furthermore, climate matters: amongst the plethora of disturbances that affect African societies today, including the impacts of HIV-AIDS and political changes, climate is recognised as significant, as demonstrated by the focus group discussions that we conducted and the data in Table 4.

The work within rural communities has allowed differing forms of responses to climate variability and change to be identified. These are outlined in Table 5, where we represent responses in terms of strategies that are simply means of 'getting by', or coping, and those that represent real forms of adaptation to the changes in precipitation parameters that have been occurring. Some of these adaptations, such as diversifying livelihoods, are not responses unique to climate disturbances, and all are embedded in the full range of livelihood-changing factors. However, as the data show, climate factors have been a significant trigger for changes that alter the nature of the risks associated with living in a variable and changing climate regime. It was also found that some forms of response are common across the range of risks and climatic changes in the three investigated regions. For example, commercialising small scale agricultural production is important in all areas, and is significant because it creates a source of cash that can then be used flexibly to meet household needs.

It is hard to argue a case for 'generic' adaptations solely being driven by climate factors, and we do not do so, because they are framed within the wider agendas of rural and economic change that form part of South Africa's development. Importantly however, these 'generic' changes are made at the local level with a clear knowledge of climate factors being present in the communities and households that are participating in them. Furthermore, along side these 'generic' adaptations we also found responses unique to each region. This can be explained by these responses being targeted to the specific regional characteristics of the changes in precipitation parameters, but also as a consequence of spatial differences in socio-political structures and the availability of information that facilitates adaptation opportunities. Therefore while the recognition of climate dynamics was prevalent in all our study areas, the ability to respond and the nature of adaptations has both generic and specific elements with some marked place-based differences occurring in what people were able or chose to do.

## 8 Conclusion

Research agendas that aim to improve understanding of people's potential to adapt to climate change require both appropriate frameworks for analysis and empirical data to interrogate questions about how adaptation occurs. These requirements can be met if research embodies (1) tools for climate data analysis, in order to identify the details of changes in climate parameters, and (2) methods for identifying and then exploring responses to the climate factors relevant to people's livelihoods. In this paper we have attempted to show how these requirements can be met, through an analysis of responses to scientifically identified climate dynamics.

The framework used to do this, involving initial climate data analysis and subsequent social enquiry and analysis, has embodied a balance of natural and social science analysis. By interrogating climate data with a methodology that unravels the subtle dimensions of precipitation variability and change, we have been able to identify the parameters of rainfall that impact on people's natural resource-based activities in South Africa. Combined with the application of qualitative and quantitative social science techniques at household and community levels, the complexity of coping and adaptation strategies have begun to be understood in ways that are potentially valuable for policy and decision makers throughout the developing world.

The initial climate data analysis and the subtleties of climate change that it revealed in terms of precipitation parameters, provided information that allowed aspects of the climate-led changes in livelihoods to be recognised. Livelihoods change and people adapt to the pressures and opportunities provided by many variables operating at a range of scales, of which climate is only one (e.g. Campbell and Olson 1991). Our findings suggest that with appropriate methodologies, climate contributions can be disaggregated and identified, facilitating understanding of the details and drivers of place-specific differences in adaptations. We have found that the farmers in our case studies recognise changes in climate that are subtle, and then respond to these changes. Even amongst the complex array of factors that bring disturbance to their livelihoods, including health and political changes, climate is recognised as significant, and is then responded to.

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# Climate Change and Migration: A Modelling Approach

**C. Smith, Dominic R. Kniveton, S. Wood, and R. Black**

**Abstract** Past estimates of the numbers of migrants caused to relocate as a result of climate change have ranged from millions to billions worldwide. Attempts to quantify the numbers of people affected have commonly been based around calculating the numbers of 'environmental refugees' by projecting physical climate changes, such as sea-level rise or rainfall decline, on an exposed population. These studies generally make simplistic assumptions about the ability of individuals to cope with variations in climate. However, empirical evidence of environmentally induced migration have not supported such an approach with the recognition that migration decisions are usually not mono-causal but influenced by multiple factors involving complex spatial interactions under heterogeneous conditions. In this context, agent based modelling offers a robust method to model autonomous decision making in relation to migration. In this chapter we discuss the theoretical development of an agent-based modelling approach to climate change-migration studies using the example of Burkina Faso. In doing so we cover questions of emergence, validation, and bounded rationality related to quantitative migration studies.

**Keywords** Burkina Faso · Climate change · Migration · Population changes · Adaptation · Agent-based modelling

## 1 Introduction

Despite widespread recognition that climate change is occurring, our capacity to accurately predict how it will affect the livelihoods of people is still limited. As a result, the impact of future climate change scenarios (already uncertain themselves) upon livelihood processes such as migration flows are highly speculative. The Intergovernmental Panel on Climate Change (Wilbanks et al. 2007) suggest that current estimates of what they term 'environmental migrants' are, at best, 'guesswork'. This is primarily due to current estimates failing to take into account the

C. Smith (✉)
School of Global Studies, University of Sussex, Brighton, UK
e-mail: C.D.Smith@sussex.ac.uk

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multiple and complex reasons behind migratory decisions. The issue of disaggregating the causes of migration has proven highly problematic and led to considerable debate around the legal definition and existence of 'environmental refugees' (Black 2001). The element of guesswork involved in migrant forecasts is reflected in the wide range of current estimates of global migration induced by climate change that place numbers of displaced persons between 150–200 million (Stern 2007) and 1 billion (Christian & Aid 2007).

Environmental and climatic changes are increasingly seen as having impacts upon the movement of people on local, regional and global scales as a result of both shock events and slow-onset degradation. Numbers of migrants generated by environmental and climatic changes have commonly been calculated by projecting physical climate changes on an exposed population and inherently assume that a person's ability to cope with variations in climate is proportional to such structural indicators as GDP growth. Such large-scale approaches however fail to adequately acknowledge the local and individual components of migration behaviour and have not successfully isolated environmental influences from the multitude of other factors that influence migration. On a more local scale, studies of the migration-climate nexus have sought to understand the process of migration by exploring the relationships of covariates to migratory and non-migratory outcomes by using such techniques as multi-level event-history analysis (Henry et al. 2004). Although such local-scale approaches can provide a more nuanced assessment of the triggers of migration than their global counterparts, they often fail to acknowledge the complex, non-linear and emergent processes inherently involved in the behavioural aspect of any social phenomena. Despite this fact, some value can be gained from the findings of such studies in their contribution to identifying the factors most likely to increase the risk of out-migration from a location. By neglecting to explicitly resolve the individual decision-making process much of the past research on quantifying climate change migration is limited as a basis for social simulation for conditions outside those experienced in the past. In a changing climate this may restrict the ability to predict new flows of people and to simulate the impact of different policy responses on these flows.

An alternative approach is to research and construct the rules of behaviour that govern how individuals respond to complex combinations of multi-level stimuli. These rules can then be applied to situations where they govern the behaviour of the individuals according to their specific context and circumstances. As a result, simulations may be produced that focus on the individual decision-making aspect of migration and can therefore be applied to modelling responses to conditions outside of those previously witnessed. A technique well-suited to this style of rule-based predictive simulation is agent-based modelling (ABM). Although there is no universal agreement on the precise definition of an agent, most suggestions insist that a component's behaviour must be adaptive for it to be considered to have agency. From a practical modelling perspective, Wooldridge and Jennings (2002) describe the key features common to most agents as autonomy, heterogeneity and activity (including reaction, perception, interaction, communication, mobility, adaptive capacity/learning and bounded rationality). Through the interactions and feedbacks determined by the constructed rules, an agent can learn from their environment and past experience and adapt their behaviour accordingly.

A major advantage of agent-based modelling is the fact that the result of a series of individual interactions may be more than the sum of the parts. As a result, unforeseen, or emergent (more than the sum of the parts), properties may arise from the simulation process that could not have been predicted through a simple linear analysis. The crux of a successful ABM lies in the formation of the rules of interaction that govern agent-agent and agent-environment interactions and feedbacks. In simulating a process such as the impact of climate change upon migration, the rules of interaction developed for the model must be evidence-based through extensive data analysis and fieldwork. Through the successful implementation of an agent-based modelling approach, the qualitative values used by individuals in the decision to migrate may be used as a predictive tool in quantifying the migration phenomenon resulting from environmental and climatic change. As a cognitive modelling technique that, in this context, deals with the bounded rationality of individuals, the first stage in developing an ABM is the construction of a conceptual framework. Such a framework sets out the basic structure of the individual cognition undertaken by agents and the manner in which external stimuli affect the decision-making process.

## 2 Climate Change Migration Modelling

Migration has always been a fundamental component of human history. Migratory events may be classified under a number of broad descriptive typologies including international/internal, permanent/temporary, voluntary/forced and legal/undocumented. Generally used to define and measure migration, such typologies are important to consider but do not explain anything of the motives behind migration. People move for a wide variety of reasons and a large body of literature exists that attempts to conceptualise the migration decision. There are at least two distinct approaches to the explanation of migration decisions in the existing literature. These are referred to as the 'structural' and 'individual' approaches and help identify the conceptual standpoint from which any study of migratory motives is based. Structural/macro theories of migration place social structures at the centre of analysis and deduce generalised functions from the influence of overarching components such as wage differentials upon the opportunities available to individuals. The approach therefore considers individuals to have virtually no control over the structural components that impose limitations on their actions. In contrast to structural theories, the individual agency/micro approach to migration research focuses upon notions of creativity/humanism and relates to the capacity of individuals to act independently on the basis of their own freedom of choice. A meso-level of analysis provided by institutional influences bridges the divide between structural and individual approaches to conceptualising migration by incorporating both.

In order to develop a conceptual framework of climate change migration it is useful to consider previous approaches used in research on the issue. Both climate and migration can be described as highly complex systems influenced by numerous

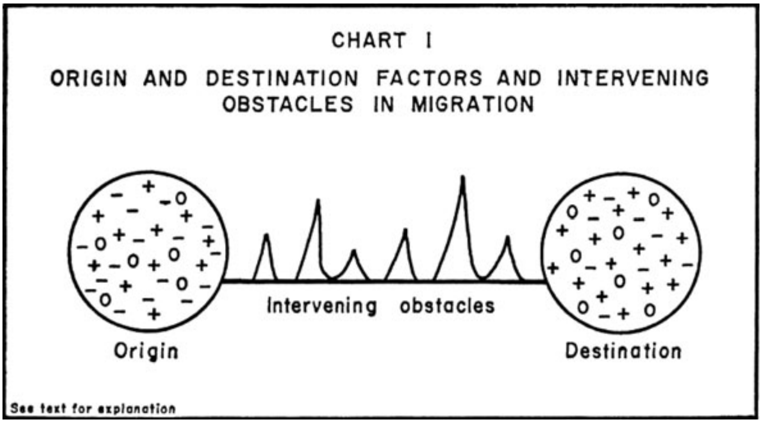


**Fig. 1** Simple conceptual model of intervening obstacles (Lee 1966)

feedbacks which require interdisciplinary understanding in order to fully comprehend them. Stehr (2001) suggests that most migration models can be thought of as focussing devices which reduce complexity by drawing attention towards certain aspects depending upon the theoretical approach employed by the model. By contrast, climate models (Burke et al. 2006) do not approach climate from a variety of competing theoretical viewpoints but are based on physical and chemical laws. While climate models are therefore generally mathematical, migration models, if mathematical at all, are described by Perch-Nielson (2004) as of empirical nature and independent of time and space. Migration analyses therefore often take the form of conceptual models such as that described by Lee (1966) (Fig. 1) of the simple concept of intervening obstacles that exist between a migrant's origin and destination. Lee's model accounts for the push and pull factors present in both origin and destination locations as well as identifying the presence of obstacles to undertaking migration. However, within its simplistic make-up, Lee's structural model does not consider either the specific perceptions of individuals or the institutional influences that may help them overcome the intervening obstacles.

McLeman and Smit (2006) present a more contemporary conceptual model (Fig. 2) in their investigation of migration as a possible adaptive response to the risks associated with climate. The conceptual model attempts to bridge the divide between theoretical advances in migration and climate change scholarship by focussing on factors influencing vulnerability. Following the assumption that climate change stimulates some form of change in the environmental and/or socio-economic conditions of a community, McLeman and Smit's model first considers the ability of community institutions to make the necessary adjustments to protect the well-being of community members. If the community's institutions are unable to cope with the changed environment, the obligation falls to individual households to implement their own adaptive strategies.

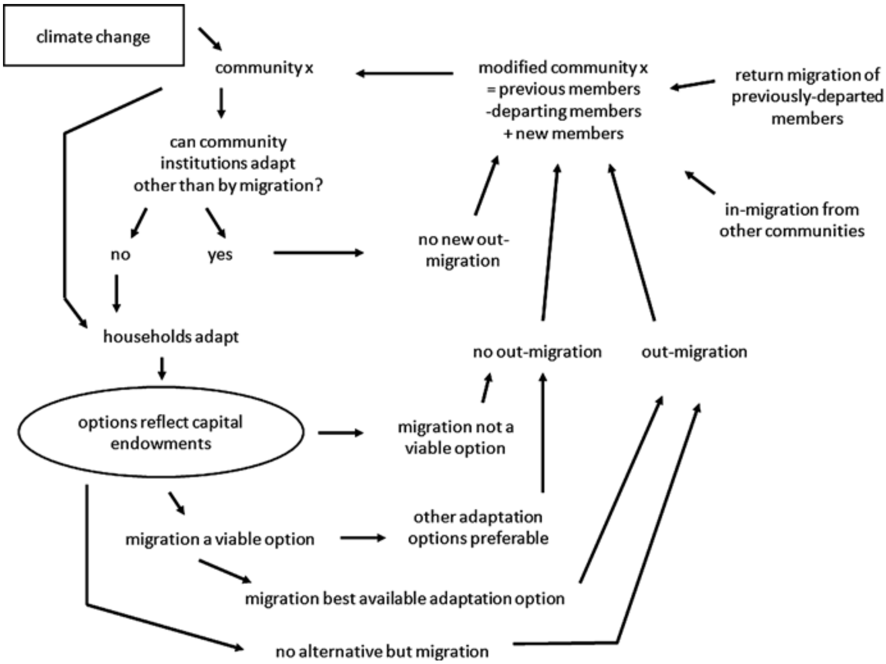


**Fig. 2** Model of migration in response to climate change (McLeman and Smit 2006)

As an investigative conceptual model McLeman and Smit's representation of the migration response to climate change presents a useful first step by developing the notions of vulnerability, risk and adaptive capacity in the context of migration. McLeman and Smit note that one of the inherent difficulties in constructing a conceptual model is the fact that the same climatic stimuli occurring in the same place but at a different point in time can lead to considerably different outcomes. As a result, they suggest that it is important to consider the adaptive capacity of the exposed populations in question and, with particular respect to the question of migration, consider the broader societal processes and contexts in which exposed populations are situated.

Within the household adaptation stage of McLeman and Smit's model the adaptation options available to households are reflected by their capital endowments. Although it is important that the model has identified such an issue, it goes no further in suggesting how the relationship between adaptive capacity and capital endowments affects the adaptation options available to individuals. In addition, although McLeman and Smit state that broader societal contexts will affect the adaptation options open to households, such factors are not explicitly incorporated into the model. Incorporating societal and psychological components into a conceptual model of climate change migration, although increasing the apparent complexity of the model, creates a more accurate representation of the process being modelled.

McLeman and Smit suggest that their model is modified on the basis of migration theory to portray migration not as a simple binary phenomenon but as a process where multiple possible outcomes exist. However, although this is true, the influence of capital endowments permitted by the model is only a small step-up from a binary analysis. With migration as the only adaptation option referred to and no inclusion of the psychological steps involved in taking action following exposure to risk, the value of the model for our purpose is limited by the causal nature of the model with no decision-making input. To incorporate the impact of decision-making into the conceptualisation of climate change migration, the impact of cognitive influences must be considered.

## 3 Proactive Conceptual Development

The context within which this paper addresses the concept of agent-based modelling of climate-induced migration comes from the country of Burkina Faso, in land-locked West Africa. One of the poorest countries in the world, more than 80% of the population of Burkina Faso relies on subsistence agriculture. Existing literature (Findley 1994) (Cordell et al. 1996) (Henry et al. 2004) suggests that the population of Burkina Faso has long been characterised by considerable mobility with long and short-term rainfall conditions thought to influence both temporary and permanent migrations. With a climate characterised by a south-north decreasing rainfall gradient and a population heavily reliant upon rain-fed subsistence agriculture, Burkina Faso presents an appropriate location for the consideration of climate change migration. For people living in a country such as Burkina Faso, migration presents one of the few adaptation strategies available to individuals and households in the face of the environmental impacts of climate change forecast for West Africa.

Adaptation strategies employed by individuals in response to climatic stimuli depend heavily upon variables such as the nature, duration and intensity of the stimulus, the present status of the individual, their previous experience and the networks to which they belong. In addition, the individual's perception of the event and their subsequent ability to manage, adapt to or escape from its impacts affects the adaptation strategy chosen. Perhaps as a result of the numerous contributing factors and their heterogeneous impact upon individuals, there is no explicit formula from which to accurately predict when migration is deemed to be the appropriate course of action. For an individual with the benefit of access to seasonal climate forecasts and information on predicted future climate change, the impact of such change will be assessed according to their perception of the risk posed to their livelihood. According to an individual's perception of that risk, and the potential for alleviating the risk by relocating to an alternative location, climate change may contribute to the decision of an individual to migrate. One component that may contribute to an individual's perception of the risk posed by climate change is the availability of accurate forecasts. However, using an agent-based model, Ziervogel et al. (2005) show that the impact of using forecasts depends upon the level of trust an individual places in the information. In West Africa, Roncoli et al. (2003) report

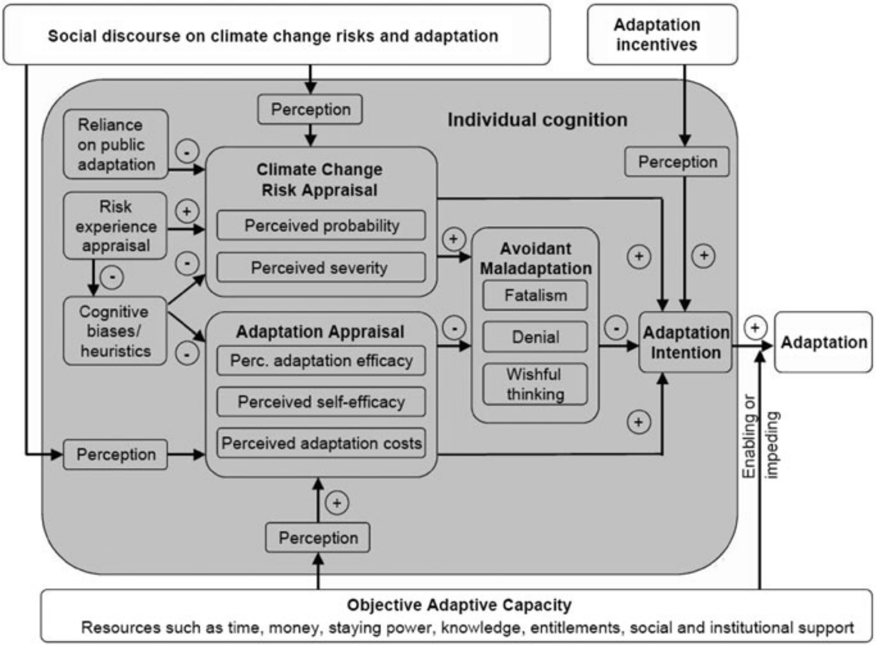


**Fig. 3** Process model of private proactive adaptation to climate change (MPPACC) (Grothmann and Patt 2005)

that seasonal forecasts are delivered in May that predict total rainfall during July, August and September, the 3 month period at the core of the rainy season. In locations across much of rural Burkina Faso, however, the problem exists of how to present probabilistic forecasts to potential users in a manner that enables them to be used in livelihood planning.

Conceptualising climate change migration as occurring on the basis of prior information, such as seasonal rainfall forecasts, involves the individual decision-maker adopting a proactive approach to adaptation. As a result, migration may be decided upon as an active option that can alleviate the impact of an expected occurrence on the basis of anticipated outcomes. In exploration of the human cognition behind adaptive capacity, Grothmann and Patt (2005) present a socio-cognitive model of private proactive adaptation to climate change (MPPACC) (Fig. 3). Based on Protection Motivation Theory (PMT) -which deals with the cognitive process mediating behavioural change- (Sivakumar and Gnoumou 1987), the model separates out the psychological steps to taking action in response to perceptions of climate.

By acknowledging the socio-physical context of the individual, the MPPACC attempts to explain why some people show adaptive behaviour while others do not. The model begins with a *climate change risk appraisal* within which there are two subcomponents; *perceived probability of exposure* and *perceived severity of harmful* *consequences*. The second major component, *adaptation appraisal*, comes after the risk perception process and only starts if a specific threshold of threat is exceeded. Within the adaptation appraisal, three subcomponents of *perceived adaptation efficacy*, *perceived self-efficacy* and *perceived adaptation costs* govern the response. Based on the outcomes of the risk and adaptation appraisal processes, an individual responds to the threat through either *adaptation* or *maladaptation* (which includes avoidant reactions and 'wrong' adaptations that inadvertently increase climate change damage). If an individual chooses to employ an adaptive response they first form a decision or intention to take these actions. Labelled as *adaptation intention*, this component of the model distinguishes between intention and actual behavioural adaptation. The MPPACC also incorporates an additional level of complexity by considering the *cognitive biases* that affect people's perceived adaptive capacity and their previous experience of risk affects subsequent appraisal.

Permitting deeper consideration of the cognitive process of individuals, the model also includes the socio-physical context of the individual by including *social discourse*. Based on Kasperson et al's (1988) framework of social amplification of risk, the inclusion of social discourse in the model permits the concept that people's perceptions of risk or adaptive capacity with regard to climate change may be amplified or attenuated by what they hear about the issue from the media, friends, colleagues, neighbours and public agencies. By highlighting the importance of people's perceptions of the stimuli affecting the appraisal processes, the MPPACC provides a good conceptual basis to consider the socio-cognitive process behind proactive adaptation to the risk posed by future climate change.

From the basic structure of risk and adaptation appraisals provided by the MPPACC, we present a conceptual agent-oriented model of the proactive adaptation to climate change (PACC) that, as a result of individual cognition, results in the selection of climate adaptation strategies, including migration (Fig. 4). The model incorporates the two major appraisals of *climate change risk* and *adaptation* used in the MPPACC, as well as the perceptions of *adaptation efficacy*, *self-efficacy* and *adaptation costs* contained within these appraisals. The main development presented by the conceptual agent-oriented model is the inclusion of a further level of detail within the adaptation appraisal and a subsequent comparison of adaptation options prior to the individual developing the actual intention to adapt.

In the PACC model, both *climate variability and change* and the *social discourse on climate risks and adaptation* undertaken by *community 'x'* contribute to the first stage in the cognitive process; *climate change risk appraisal*. Also contributing to this evaluation of risk is an appraisal of the individual's previous experience of risk and their *cognitive biases/heuristics*. If the assessment of risk returns an outcome greater than a specific threshold, the individual moves on to perform an appraisal of the process of adaptation and the options available to them. Contributing to this are both what the individual knows about the climate risk, their *objective adaptive capacity* in the face of such risk, and any adaptation incentives such as financial assistance that may be available. Within the *adaptation appraisal* individuals consider both in-situ *adaptation* and *migration*. If the adaptation appraisal returns a preference to adapt through migration, the individual weighs up the options for

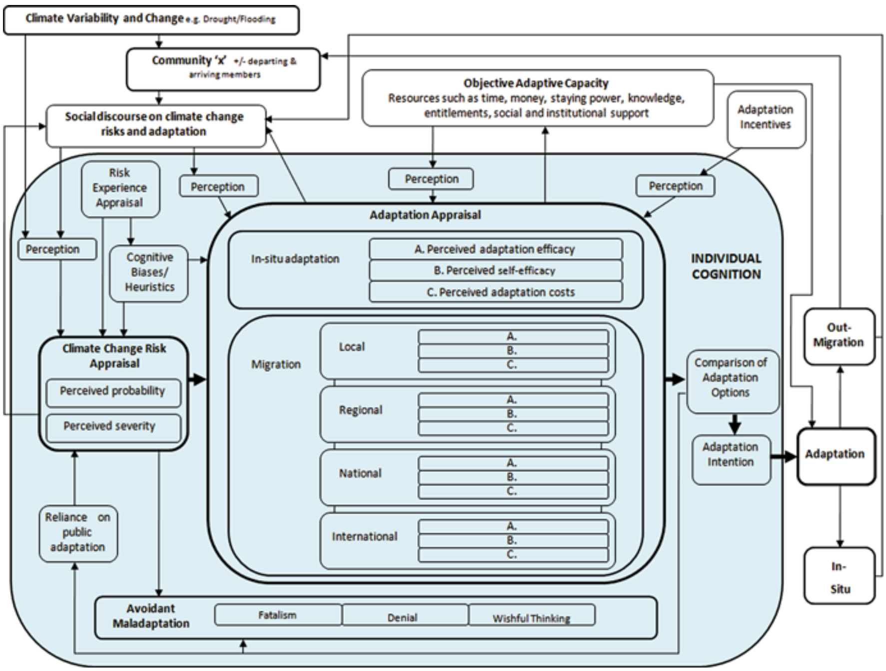


**Fig. 4** Conceptual agent-oriented model of proactive adaptation to climate change (PACC)

migration available to them (in terms of scale of movement) on the basis of the MPPACC's perceptions of *adaptation efficacy*, *self-efficacy* and *adaptation costs*. An individual's objective adaptive capacity is seen by this model to both affect the adaptation appraisal through a process of individual perception and be affected by that appraisal in a feedback mechanism where, for example, prior appraisals result in increased situational knowledge. *Adaptation incentives* also contribute to the adaptation appraisal from which the individual undertakes a comparison of their adaptation options and develops an intention to pursue in-situ or migratory adaptation strategies, rely on public adaptation, or pursue an avoidant maladaptation strategy. The chosen adaptation strategy then both impacts upon the social discourse on climate change risks and adaptation and affects the size of community 'x' which, in turn further impacts upon the social discourse. With this feedback mechanism in place, the conceptual model is structured to represent the cognition of an individual agent whose actions then impact upon the modelled environment and affect the actions of other agents in the system. The PACC model therefore presents a good first step in working towards and understanding of the climate-migration decision-making process.

Although the PACC model makes a valuable contribution to understanding the process of climate change migration it is limited in its capacity to suit this research as a result of two issues. The first of these is the lack of explicit consideration of other agents by the PACC. In developing an adaptation intention the PACC only considers the input of other agents in terms of their input to the social discourse. However, one of the inherent advantages of an ABM is the influence of agents upon others in their network as a result of social interactions. Within a dynamic decision-making process Schwenk and Reimer (2008) conclude that the interaction of agent cognition is central to the course of social processes. They find that the relatively high status of influential others within a network can lead to the otherwise unlikely persistence of a minority faction. Without incorporating the influence of the views/experience of specific others in the agent's network the PACC does not permit this level of influential interaction to occur and could therefore limit the emergent properties of the simulation.

The second limitation of the model is the proactive nature of the adaptive response being modelled. By including the climate change risk assessment component shown in the MPPACC, the PACC inherits the proactive nature of the model through the development of perceptions relating to the occurrence and severity of climate change. The structure of the model therefore follows proactive reasoning based on an individual's perception of the occurrence of climate change. In the behavioural response to structural components, Richmond (1993) argues for the existence of a continuum between the rational choice behaviour of proactive migrants and the reactive behaviour of those whose degrees of freedom are severely constrained. Richmond describes typical proactive migrants as professionals, entrepreneurs, retired people and temporary workers under contract. By contrast, he describes reactive migrants to include those who meet the UN Convention definition of refugees (people with a genuine fear of persecution and an inability of unwillingness to return) as well as others reacting to crisis situations caused by war, famine, economic collapse and other disasters. Although legally not meeting the UN Convention definition of a refugee (UNHCR 2006), individuals reacting to degradation or crisis caused by environmental change would, on this continuum, fall towards the reactive end of the scale. Indeed Richmond goes on to state that sudden changes in the economic, political or environmental situation may precipitate reactive migration. From a cognitive perspective, conceptualising the migration decision in question as reactive also presents advantages in terms of the ability of people to make rational decisions on the basis of the information available to them.

## 4 Bounded Rationality

Human beings are, to some extent, rational beings in the way that they attempt to understand things on the basis of logic and make sensible choices from this information. However, due to the size and complexity of our environment we do not have the capacity to understand everything. As a result of this, and the limits imposed by the mental structures we use to organise and simplify our knowledge of the world around us, our decisions cannot be described as completely rational. Simon (1982) therefore suggests that there are two major causes of bounded rationality: limitations of the human mind; and the structure within which the mind operates. Kant and Thiriot (2006) suggest that more traditional agents developed from Classical Decision Theories or Game Theory undertake 'too-rational behaviour' that is not compatible with the limitations of human cognitive capabilities and so are not compatible with Simon's concept of bounded rationality. In order to incorporate the limitations of human capabilities it is therefore important to start with a conceptual basis within which the bounded rationality of human decision-makers is considered. By failing to define what components make up the appraisal processes central to the PACC model it incorporates no limit on the rationality used by the modelled decision maker and is thus overly complicated as a conceptual process.

The reliance of a vast majority of the population of Burkina Faso on rain-fed subsistence agriculture and cattle-raising means that climate variability is a dominant control over individual livelihoods. Although Roncoli et al. (2003) show that both local-cultural and regional-scientific forecasts of seasonal rainfall affect the cognitive frameworks of farmers, they find that such forecasts can be often contradictory and result in only a limited livelihood response by farmers. When modelling the information that is available to an agent it is necessary to incorporate this concept of bounded rationality. Therefore, in the context of proactive model development, information available to the agent's network can be controlled to realistically limit their perception of, for example, a forecast. In order to both incorporate this notion of bounded rationality and move away from a proactive model of climate change we investigate theoretical developments that contribute to the development of a reactive model alternative. By developing a reactive model that includes consideration of bounded rationality it is intended that the decision-making process can be modelled in a more realistic cognitive manner.

## 5 Reactive Conceptual Development

In order to overcome the issues identified with the PACC model it is necessary to construct a conceptual model based on a reactive decision-making process that incorporates the notion of bounded rationality by ensuring that the cognitive process remains relatively simple. Seeking a basis for such a model we draw upon theoretical developments made in the field of social psychology. The Theory of Reasoned Action was developed by Fishbein and Ajzen (1975) as an expectancy-value model that recognises attitudes as just one determinant of behaviour within a network of predictor variables. The theory proposes that the proximal cause of behaviour is 'behavioural intention', a conscious decision to engage in certain behaviour. Making up this behavioural intention is the *attitude toward the behaviour* (defined as the sum of expectancy x value products) and the *subjective norm* (defined as the belief that a significant other thinks one should perform the behaviour and the motivation to please this person). By extending the theoretical model to incorporate the additional parameter of *perceived behavioural control*, Ajzen (1991) created the Theory of Planned Behaviour. Intended to aid prediction of behaviours over which a person does not have complete voluntary control, perceived behavioural control was conceptualised as the expected ease of actually performing the intended behaviour.

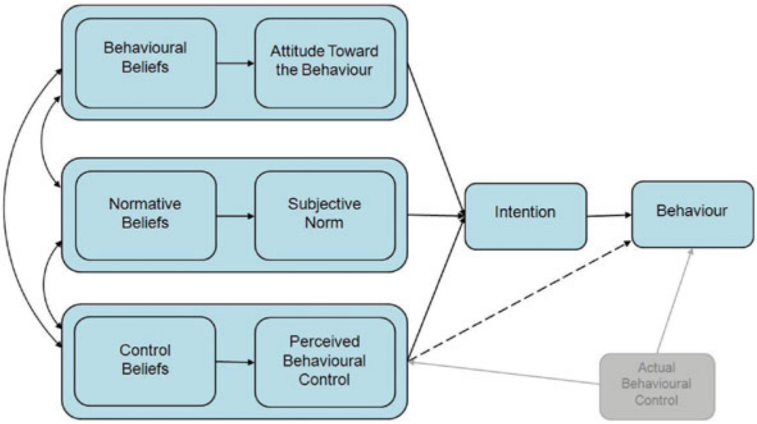


**Fig. 5** Theory of planned behaviour, adapted from (Ajzen 2006)

This concept of perceived behavioural control takes the place of the perceived self-efficacy incorporated into the adaptation appraisal stage of the MPPACC. Including attitudes toward behaviour, a subjective norm and perceived behavioural control (as well as the beliefs that make up these components), the Theory of Planned Behaviour (Fig. 5) can be used to effectively break down the cognitive process relating to the development of a behavioural intention.

Most previous applications of the theory of planned behaviour investigate health-related behaviours such as exercise (Nguyen et al. 1997), diet (Conner et al. 2003) and condom use (Albarracín et al. 2001). However, the theory has also been applied to numerous fields outside of health-related behaviour, including entrepreneurial intentions (Krueger and Carsrud 1993), conservation technology adoption (Lynne et al. 1995) and wastepaper recycling (Cheung et al. 1999). In the field of migration research, Lu (1999) suggests that the theory of planned behaviour can be used to investigate the reasons behind the inability of households to move when they express an intention to do so and the unexpected relocation of other households. De Jong (1999) backs this up by stating that the inclusion of expectations as a major component in the theory of planned behaviour is beneficial in capturing the dynamics of migration decision-making.

In adapting and applying the theory of planned behaviour to migration decision-making, De Jong (2000) suggests that intentions to move are the primary determinant of migration behaviour. Alongside this intention are the direct behavioural constraint and facilitator factors that make up the perceived behavioural control component of the model. The primary constraint/facilitator (contributing to the ability of the individual to undertake migration) is described by De Jong (2000) as prior migration behaviour in accordance with Ajzen's (1988) assertion that prior behaviour is a major facilitator to any application with the theory. By applying the theory of planned behaviour, De Jong (2000) suggests that expectations of achieving valued goals in a location other than the home community, along with perceived

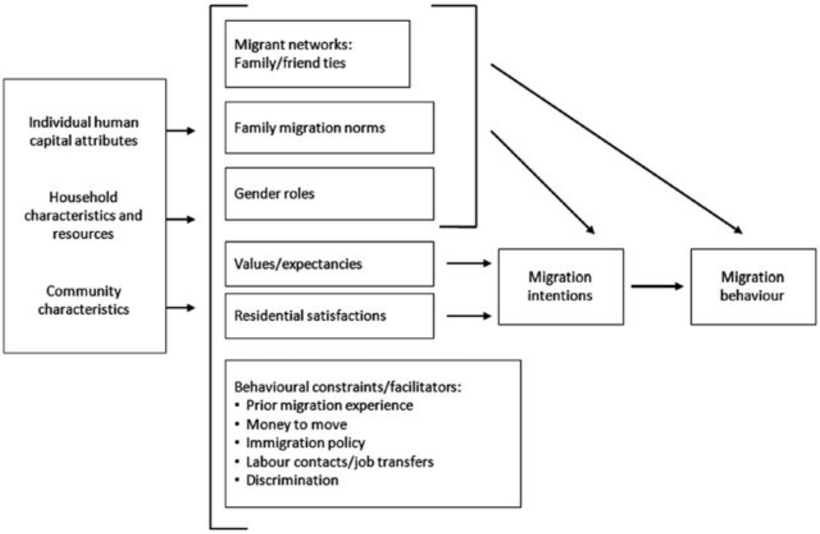


**Fig. 6** General model of migration decision-making (De Jong 2000)

family norms about migration behaviours (the 'behavioural beliefs' and 'normative beliefs' from Fig. 5) are the major determinants of migration decisions. Although identified by De Jong as not having a direct effect on migration behaviour (as a result of being mediated as constructs of the theory), traditional explanatory factors such as age, education, marital status, dependents and income have, in many cases been empirically shown to contribute to determining migration. As a result, in adapting and applying the theory of planned behaviour to migration decision-making (Fig. 6), De Jong has not discarded such factors as determinants.

In De Jong's model, individual, household and community characteristics contribute to six concepts that he has identified as uniquely relevant to migration decision-making: migrant networks; family migration norms; gender roles; values/expectancies; and behavioural constraints/facilitators. These components combine to produce a behavioural intention and ultimately, migration behaviour. De Jong concludes that the migration proposition posed by the theory of planned behaviour that 'intentions predict behaviour', is a statistically significant explanation for more permanent, but not for temporary, migration behaviour in a Thai context.

As a theoretical basis from which to investigate the conceptual foundations of the reactive migratory behaviour of human agents in Burkina Faso, the theory of planned behaviour presents a model that is both theoretically and empirically founded. With previous applications to the field of migration decision-making (De Jong 2000) and a more recent application to an agent-based model of the diffusion of organic farming practices (Kaufmann et al. 2008), the theory has some background in the topic. However, although De Jong adapted and applied the theory of planned behaviour to migration decision-making and incorporated components that form the attitude toward behaviour, subjective norm and perceived behavioural control, his model does not provide an explicit description of the agent decision-making process. As a result, although theoretically useful in conceptualising migration, the application of the model to the construction of an ABM is limited. In addition, De Jong's model does not show how the different adaptation options available to an individual are selected between to generate migration as an active outcome. By incorporating the value of Ajzen's (1991) theory of planned behaviour, and the conceptual advances on this made by De Jong's (2000) model of migration decision-making, we can work towards the development of a reactive model of climate change adaptation that is more suited to translation into an ABM.

## 6 Conceptual Model Development

As suggested by Richmond (1993), sudden changes in the economic, political or environmental situation of individuals may cause them to undertake reactive migration. On this basis, the migration response of subsistence agriculturalists in Burkina Faso is considered to fall close to purely reactive on the continuum ranging from purely proactive to reactive migration. In developing a conceptual model of adaptation to climate change from which an ABM will be constructed, a reactive approach to adaptation will be adopted. The first proactive conceptual model presented here, the PACC was constructed from the basis provided by Grothmann and Patt's (2005) MPPACC. As well as being a proactive model identified as inappropriate to the situation being modelled, the PACC was not directly based on any accepted theoretical model of proactive adaptation. In constructing a conceptual model of reactive adaptation to climate change therefore the development of a reactive conceptual model has been approached through the avenue of accepted social psychological theory.

With insight provided by the proactive conceptual model developed from the MPPACC and a theoretical basis offered by the theory of planned behaviour (Ajzen 1991, De Jong 2000), we present a conceptual agent-oriented model of reactive adaptation to climate change (RACC) (Fig. 7). As a result of the individual cognition presented in the RACC, it is considered that the reactive decision to migrate may be appropriately represented, at least from a theoretical standpoint. By translating this into a rule-based model such as an ABM it is proposed that a quantitative community output may be produced from a series of specified qualitative inputs. The RACC model incorporates much of the external structure used in the PACC with the most significant changes present in the process of individual cognition. However, as a result of the reactive nature of the model, the individual climate change risk appraisal process of the PACC has been removed with only a social discourse on events contributing to individual cognition. By basing the RACC model on the theory of planned behaviour the central appraisal components of the PACC are replaced with the core of the theory of planned behaviour: the *attitude toward adaptation behaviour*; the *subjective norm*; and the *perceived behavioural control*. The model is also divided into clear external, social, individual and household components to aid

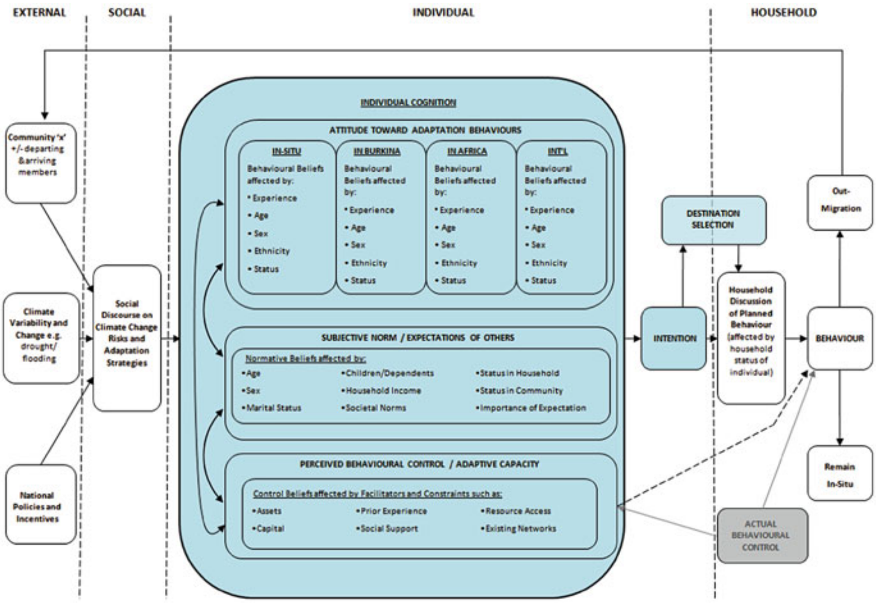


**Fig. 7** Conceptual agent-oriented model of reactive adaptation to climate change (RACC)

the process of translation into an ABM. As a result the RACC is intended to identify the external factors that contribute to a social discourse, the impact of this discourse upon the individual cognition behind adaptation, how the intention developed by an individual plays a part in household discussions on adaptation and, ultimately, results in an adaptation strategy which feeds back to affect the original community.

The RACC model presents several advantages over both the PACC model and De Jong's (2000) general model of decision-making when applied to the context of constructing an ABM of climate change migration. Although both the RACC and De Jong's model are developed from the theory of planned behaviour, the RACC model presents a more explicit representation of the cognitive process undertaken by an agent. As a result, there is greater potential for translating the model into an ABM. Through consideration of the bounded rationality of humans, the RACC model develops the internal structure of individual cognition upon those aspects of an agent's environment that they are likely to be able to understand and use. By breaking down the components involved in the cognitive process, the RACC model serves to both more explicitly represent cognition and simplify the process into just three core components.

Limiting the components involved in individual cognition within the RACC model both reduces the complexity of the cognitive process and removes the proactive component of the PACC model: the climate change risk appraisal. In this context, the rationality of the individual in perceiving climate change is bounded by the information available to them. Unless an individual is exceptionally well informed about the climate of their locality, it is unlikely that they would have the capacity to undertake an informed individual climate change risk assessment that led to proactive adaptation. Roncoli et al. (2002) suggest that a certain amount of forecast knowledge is shared amongst farmers in Burkina Faso. This knowledge is comprised of indicators that are used throughout the year to predict the coming rainy season and include: dry-season temperatures; flower and fruit production of local trees; the direction and intensity of winds; and the behaviour of birds and insects. In the RACC model this information contributes to the social discourse on climate change risks and adaptation strategies. When undertaking reactive adaptive behaviour, it is proposed that an individual is more likely to undertake a process of acceptance or denial of the social discourse on risks and adaptation that is available to them than an individual appraisal. As such, in the RACC model, the social discourse plays an explicit part in shaping the attitude of individuals toward adaptation behaviours, the expectations of others and the perceived behavioural control.

Incorporating an explicit input from the social discourse on climate change, the individual cognition occurring in the RACC model is broken down into: the simultaneous formation of attitudes toward different adaptation behaviours; the consideration of the expectations of others; and the perceived behavioural control/capacity to undertake adaptation. The *attitude toward adaptation behaviours* is formed on the basis of a series of beliefs about those behaviours. These beliefs are characterised by an individual's previous experience of the behaviour (De Jong 2000), their age, sex, ethnicity and status, and how these components are affected by the social discourse. The *subjective norm* component of the cognition represents the expectations of others and is developed from a series of normative beliefs. These beliefs are characterised by an individual's age, sex, marital status, and dependents, as well as their household income and status and the societal norms that exist for the community. As well as involving an individual's perception about the expectations of others regarding a particular behaviour, the subjective norm also incorporates their willingness to please the relevant others (Ajzen 1991) to which they are connected. The final component of *perceived behavioural control* relates to the adaptive capacity of the individual and is constructed on the basis of a series of control beliefs. These control beliefs are characterised by components such as an individual's assets, capital, social and institutional support, existing networks and access to resources. From these beliefs the individual constructs a perception of the ease/difficulty of performing a particular behaviour. As noted by Fishbein and Cappella (2006), perceived behavioural control is the same as Bandura's (1999) concept of self-efficacy which Grothmann and Patt use as one of the internal mechanisms of the adaptation appraisal component of the MPPACC.

The nature of the RACC model as incorporating both individual cognition and the external factors that contribute-to, and result-from, that cognition (in a feedback loop) allows it to form the basic structure that each agent in an agent-based model can be hypothesised to follow. Constructing a conceptual model of agent cognition prior to in-depth investigation of the actual circumstances occurring on the ground is however a top-down approach to the issue. Although useful to investigate theoretical influences, the actual process of constructing an agent-based model that represents a real-world phenomenon can also adopt a more bottom-up approach. In the case of modelling climate change migration in Burkina Faso, the RACC model provides a good conceptual basis from which to investigate further how climate change affects the cognitive process behind migration. It is useful to approach fieldwork intended for agent-based model data collection with some idea of the conceptual basis of what is being investigated. From such a vantage point data collection undertaken in the field can be guided by the principles presented through prior theoretical advances. However, although this basis can be used to inform the interview process, to ensure constructive and accurate model development, it is important not to approach field interviews with a preconceived bias as to the expected findings. When conducting interviews intended to inform the development of an agent-based model it is therefore possible to guide interviewees towards the issues you are investigating (which may be informed by theoretical developments such as RACC) but important to avoid leading their responses. In order to avoid purely top-down development of a model however, it is important not to reveal to respondents the cognitive outcomes that you anticipate from the top-down component of the research.

## 7 Translation into An Agent-Based Model

The process of developing an ABM from a cognitive structure such as the RACC model may therefore be informed by theory, data collection, or a combination of both. Whatever the situation, the cognitive representation constructed must be translated into an agent-based model through the development of rules that govern the important interactions of agents. The obvious advantage of constructing an ABM from evidence gained from a real-world scenario is the greater reliance that can be placed in the cognitive instruments included due to the manner in which the rules of interaction have been verified. Unlike the PACC model, the RACC breaks down complex components such as *perceived self-efficacy*, into the simpler underlying components – such as the assets, capital and prior experience which underlay *perceived behavioural control*. In constructing the rules of interaction that arise from a conceptual model, a major advantage of the RACC is therefore the relative ease with which the simple underlying features of complex components can be worked with. Keeping the basic rules of interaction as simple as possible in an agent-based model is important to ensure that the underlying interactions of emergent properties that arise from the model can be easily traced and understood. Computationally less intensive than more complex alternatives, even a simple agent-based model can exhibit complex behavioural patterns as a result of the interactions specified.

Constructing the rules of interaction that make up the basis of an agent-based model generally takes the form of a series of ‘if’ statements that combine to result in the calculation of a value which, if above or below a set threshold, determines behaviour. Kaufmann et al. (2008) present an agent-based model of organic farming adoption in two new EU Member States. Characterised by attributes adopted from the Theory of Planned Behaviour, their model calculates the behavioural intention $I$ of agent $i$ from their attitude $a_i$, subjective norm $s_i$, and perceived behavioural control $p_i$. Each of the three attributes ranges from –1 (extremely negative) to +1

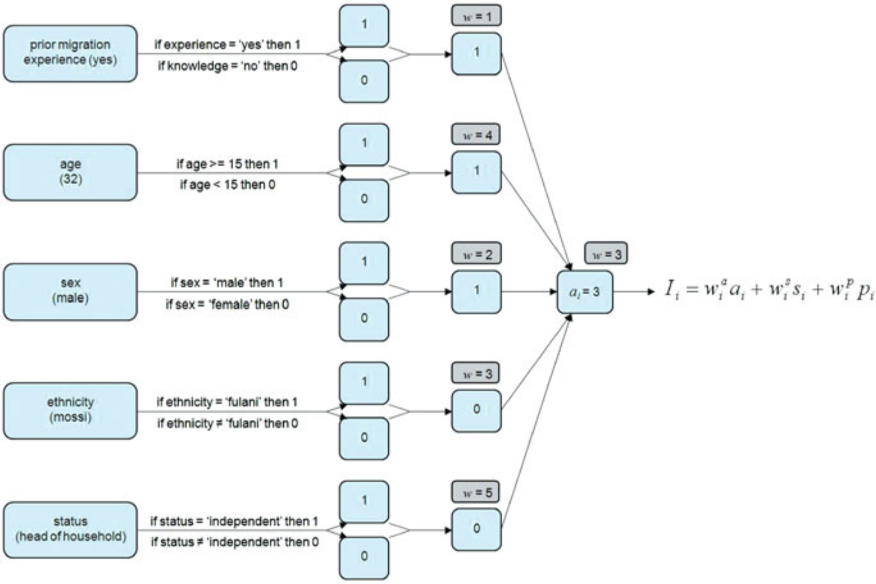


**Fig. 8** Diagram of rule structure behind adaptation attitude

(extremely positive) and is weighted by its relative contribution towards calculating the intention ($w_i{}^a$, $w_i{}^s$, $w_i{}^p$ accordingly). The weights defining the relative contributions of each predictor are derived empirically by means of regression analysis.

$$I_i = w_i^a a_i + w_i^s s_i + w_i^p p_i \tag{1}$$

If the resulting intention developed by an agent exceeds an empirically defined threshold then that agent is defined as having the intention to adopt organic farming practices. Basing an agent-based model of climate change migration behaviour upon the theory of planned behaviour, permits a similar calculation of intention to be used. It is however, the rule basis behind such a calculation that determines the outcomes and their value for further application. Figure 8 shows the 'if' statements that may be constructed to calculate the attitude toward adaptation behaviour in the RACC conceptual model and contribute an $a_i$ value for a calculation such as that in Equation 1.

The statements that contribute to a value of $a_i$ in Fig. 8 give an example of how individual agent components can be combined to deduce values that are of use in quantifying a process resulting from decisions that relate to known characteristics. In this case the output values from each 'if' statement relate to a binary output of 1 or 0 and are constructed on a purely theoretical basis. The weight of influence of each of these upon the final value of $a_i$ is specified above each binary output. When developing a final model the outcomes of such statements may be graduated (on a scale from –1 to 1 for example) to assign more detail to a particular phenomenon.

To aid in representing the real-world phenomenon under study these graded values can be developed on the basis of evidence gained through either data analysis or field observations. By calculating values for each of the components included in Equation 1 ($a_i$, $s_i$ and $p_i$), and assigning weights to these values, an agent-based model may be constructed that simulates the decision-making process of agents in response to climate change according to the theory of planned behaviour. From such a simulation that incorporates the climate variability and change impacting a location such as Burkina Faso, the phenomenon of climate change migration as a viable adaptation strategy may be hypothetically quantified.

## 8 Model Validation

Following the construction of an agent-based model a process of model validation can be undertaken to establish how adequately the model implements and reflects those aspects of the real world that it is designed to model. As a result, the representative value of the model can be ascertained. Carley (1996) suggests that general discussions of validity for computational models point to one or more of six types of validation: conceptual (adequacy of underlying concept in characterising the real world); internal (correct computer code); external (linkage between the simulated and the real); cross-model (degree to which two models match); data (accuracy of real and generated data); and security (safeguards to ensure model changes do not alter other parameters). However, Carley suggests that the most pertinent of these to the outcome of a social simulation is the external validity or the comparability between the simulated world of the model and the real world.

In a decision-making context such as climate change migration in Burkina Faso it is possible to assess model validity by comparing the quantitative migration output to migration data for the region. On this basis, if the model data relates well with the experimental data, it is generally assumed that the model fits the human data well and that the model is externally valid. A number of statistical approaches can be used to establish such a 'goodness of fit'. The most common of these is the use of linear correlations (r or r2 values) to capture relative trend magnitude and root mean square deviations (RMSD) to show deviations in data. Roberts and Pashler (2000) comment that many modelled theories are supported mainly by demonstrations that they can 'fit' data. This fit illustrates that the parameters can be adjusted so that the output of the theory resembles actual results. Although this fit is intended to show that the modelled theory is conceptually sound, Roberts and Pashler propose a number of serious problems with this validation argument. The most pertinent of these is the concept that, with a sufficient number of parameters, any model may fit any data almost perfectly. By tweaking modelled parameters to produce the desired output the evidence-base from which the model was developed is lost and the value of representing an observed process lost. If, for example, fieldwork reveals that married men do not often undertake migration in Burkina Faso but, in tweaking the model to 'fit' reality, the number of married men in the community must be decreased far below the observed figure, the value of the model is lost, even if it can be termed a good fit.

In constructing an agent-based model it is useful to place some limit on the number of parameters used (maintaining model simplicity) and avoid tweaking those parameters to produce the desired outcome. Although it is beneficial to conduct sensitivity analyses – where each parameter is varied over its entire range to test its impact upon the model – using this to over-fit the model should be avoided. As a result of the emergent nature of the outcomes of agent-based models, a number of model runs should be performed to test the variation in outcomes generated. Doing this reveals how the context and circumstances of agents has a considerable impact upon their behaviour according to the rules specified. As a model runs through its time-steps the context and circumstances of agents changes as a result of the different interactions undertaken. As a result, when externally validating a model, these multiple simulation runs should be considered along with their deviation away from each other and the real world. Finally, to ensure external validation of a model, providing sufficient implementation details in publications permits other researchers to reproduce the results generated.

## 9 Conclusion

The level of human migration resulting from climate change is a concept that is currently receiving widespread recognition within both humanitarian and policy discourses on an international scale. Forecasting the numbers of such migrants presents a significant challenge in terms of identifying the people displaced by climate change scenarios. As a rule-based simulation technique that has found recent success within the social sciences, agent-based modelling presents a potentially useful means of modelling climate change migration by focussing on the cognitive decision-making process behind migration. Indeed, one of the key advantages of an agent-based modelling architecture is the potential for models to generate unforeseen emergent properties that, through the interactions specified, are more than the sum of the parts. In developing a conceptual basis from which to model the migration decision we first investigate the proactive response to climate change. Incorporating a climate change risk appraisal, which involves perceptions of the probability and severity of climate change, the model of proactive adaptation to climate change (PACC) was developed from Grothmann and Patt's (2005) model of private proactive adaptation to climate change (MPPACC).

As a result of Richmond's (1993) assertions on the nature of reactive migration and the complexity involved in some of the internal components of the PACC we turn to social psychological theory in search of a theoretical basis for a reactive model. The resulting model of reactive adaptation to climate change (RACC) is developed from theoretical advances made by the theory of planned behaviour. By incorporating the three major components of individual cognition identified by the theory, the RACC provides a conceptual model that explicitly shows the cognitive process considered to occur. In doing so the RACC also maintains a level of simplicity appropriate to agent-based modelling and considers the limits of human rationality. From the conceptual basis provided by the RACC model, an agent-based model of climate change migration may be constructed using rules of interaction developed from field evidence.

The final component in constructing an agent-based model is the process of validation necessary to assess the value of the model outputs to society. In the context of climate change migration, the successful development of an agent-based model that can simulate the human displacement resulting from climatic change is of great value if the model can be reliably validated. If the outcomes of such agent-based models are to be of value to humanitarians and policy makers, their outcomes must be of representative value to stakeholders. To ensure such value the processes of model development and validation require careful control. However, by achieving reliable outputs, agent-based modelling may assist in developing appropriate adaptation strategies that can alleviate the pressures imposed on livelihoods by climate change.

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