AIACC Final Reports

The Development of Regional Climate Change Scenarios for Sub-Saharan Africa

A Final Report Submitted to Assessments of Impacts and Adaptations to Climate Change (AIACC), Project No. AF 07

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Table of Contents

About AIACC..vii

Summary Project Information..viii

Executive Summary..x

1. Introduction **1**

2. Characterization of current climate and scenarios of future climate change **2**

2.1. CHARACTERIZING AND MODELING CURRENT CLIMATE 2
2.1.1. Observed climate variability and trends over South Africa 2
2.1.2. Observed climate variability in Zambia 4
2.1.3. Observed climate variability in Zimbabwe 4
2.1.4. Trends in observations of the atmospheric circulation 6
2.1.5. GCM simulations of African climate 7
2.1.6. MM5 simulations of current climate over Zambia 7
2.1.7. Testing different physics options for MM5 simulations over southern Africa 8
2.1.8. RegCM3 and MM5 simulations of West African climate 10
2.1.9. Modeling land surface interactions and their effect on climate 12
2.1.9.1. Vegetation over Southern Africa 12
2.1.9.2. Soil moisture over Southern Africa 14
2.1.9.3. Land-surface fluxes over West Africa 16
2.2. SCENARIOS OF FUTURE CLIMATE 17
2.2.1. Guided perturbations and GCM output 17
2.2.1.1. ECHAM 4 17
2.2.1.2. Guided perturbations and DDC data 18
2.2.2. Statistical downscaling 20
2.2.3. Dynamical downscaling 25
2.2.3.1. PRECIS 25
2.2.3.2. MM5 26

3. Capacity building outcomes and remaining needs **27**

3.1. CAPACITY BUILDING IN ZAMBIA 27
3.2. CAPACITY BUILDING IN ZIMBABWE 28
3.3. CAPACITY BUILDING IN GHANA 28
3.4. CAPACITY BUILDING IN SENEGAL 29
3.5. LESSONS AND SUGGESTED SOLUTIONS 29

4. National communications, science-policy linkages and stakeholder engagement **31**

4.1. ZAMBIA 31
4.2. SENEGAL 31

5. Outputs of the project **32**

6. Policy implications and future directions **34**

7. References **35**

8. Figures and tables **38**

List of Tables

Table 1: Results of the selected indices calculated for the chosen stations. Selected indices are explained in the following figures 38

Table 2: Observed precipitation for 14 stations in Zambia for the four months November 1988 to February 1989 39

Table 3: MM5 modelled precipitation for 14 stations in Zambia for the four months November 1988 to February 1989 39

Table 4: Latitude-longitude ranges of major river basins for which climate change data has been provided to the ESKOM hydro-electric project. 40

List of Figures

Figure 1: Observational networks over Africa: a) Black + Green dots are the stations contributing to observations found on the GTS (General Telecommunications System), Green dots those stations reporting on any given day (approx 50%). b) Radiosonde count for January 1989 showing the locations of atmospheric observations entering the reanalyzes. 41

Figure 2: 200 hPa velocity potential of the ERA and NCEP reanalyzes. Two December – February (DJF) seasons are shown: 1988 (wet over southern Africa) and 1991 (dry over southern Africa). 42

Figure 3: Historical trend (1950-1999) of change per decade of mean monthly precipitation totals (mm) 43

Figure 4: Historical trend (1950-1999) of change per decade in mean monthly number of raindays (> 0mm) 44

Figure 5: Historical trend (1950-1999) of change per decade in mean monthly number of raindays (> 2mm). 45

Figure 6: Historical trend (1950-1999) of change per decade in mean monthly dry spell duration (days). 46

Figure 7: Historical trend (1950-1999) of change per decade in mean monthly 90th percentile magnitude precipitation event (mm). 47

Figure 8: Zambian rainfall anomaly by region for the years 1990-2004. 48

Figure 9: (a) Annual total precipitation in wet days with at least 1mm of rain, PRCPtot (mm). (b) Maximum number of consecutive dry days (dry spells), CDD. (c) Annual total precipitation exceeding 95th percentile of the rainfall, R95p and (d) Monthly maximum consecutive 5-day precipitation, RX5day. The red colours depict an increase whilst the blue is for a reduction. 49

Figure 10: (a) Annual count when daily minimum temperature is below 2°C, TNn. (b) Annual count when daily maximum temperature is above 25°C, TXx. (c) Percentage of days when daily minimum temperature is below 10th percentile, TN10P. (d) Percentage of days when daily maximum temperature is below 10th percentile, TX10P. (e) Percentage of days when daily minimum temperature exceeds 90th percentile, TN90P. (f) Percentage of days when daily maximum temperature exceeds 90th percentile, TX90P. 50

Figure 11: The Diurnal Temperature Range (DTR) (˚C) trends measured at an annual rate. The red colours depict an increase whilst the blue is for a reduction. There is some spatial coherence with most of Zimbabwe showing an increase in DTR 51

Figure 12: 3 × 2 SOM of ERA40 standardised 500 hPa daily eddy geopotentials for the 1979-2002 DJF seasons. 52

Figure 13: Frequency of each SOM node for the 1979-2002 DJF seasons. Lines demonstrate least squares trends in frequency and the probability of the null hypothesis, that no trend exists, is given at the top of each plot. 53

Figure 14: 4 x 3 Self Organising Map (SOM) of 30 years control & 30 years future December - January daily eddy (anomalies from the zonal mean) geopotential heights for the CSIRO, ECHAM4 and HadAM3 GCMs. Also included are ERA-15 and NCEP reanalysis data. All anomalies are standardised. Blue represents low pressures and red represents high pressures........ 54

Figure 15: Frequency of each pattern (node) in Figure 14 found in each of the five datasets: NCEP reanalysis, ERA-15 reanalysis, CSIRO control run, ECHAM 4 control run and HadAM3 control run. 55

Figure 16: Frequency change (future – control) of each pattern (node) in Figure 14 for both the CSIRO and HadAM3 simulations........ 56

Figure 17: Total seasonal rainfall (cm) for DJF 1988/89 as simulated by MM5 using the Grell convection scheme........ 57

Figure 18: December-February (DJF) 1988/89 seasonal rainfall (mm): a) CRU, b) CMAP. DJF interannual (1988/89 – 1991/92) rainfall anomaly (mm/season): c) CRU, d) CMAP. 57

Figure 19: MM5 simulated rain day anomaly (days/season) with respect to CRU observations (MM5-CRU) for the 1988/89 season. a) KF/MRF, b) BM/MRF, c) KF/ETA and d) BM/ETA. 58

Figure 20: The diurnal cycle (UTC) of rainfall (top panel, mm hr^{-1}), SW flux (middle panel, Wm^{-2}) and integrated CLW (mm)/cloud optical depth (bottom panel) for the 1988/89 season over southern Africa. Crosses indicate satellite-derived datasets, open triangles are BM/MRF simulation and closed circles KF/ETA simulation. Dashed curves are the DJF average, dotted curves the rain day average. 59

Figure 21: Vertical profile of zonal wind at different longitudes (10°W right and 0°W left) from MM5 simulations August 1988 (top) and 1990 (bottom). 60

Figure 22: Streamlines over West Africa from MM5 simulations, depicting an easterly wave with the trough from Nigeria to Niger. 60

Figure 23: Mean rain rate (mm/day) for july 1993, RegCM simulation........ 61

Figure 24: a) Potential natural vegetation as simulated by the Sheffield Dynamic Global Vegetation Model (SDGVM) and b) the United States Geological Survey (USGS) land-surface classification. Note agricultural land-use classes are not represented by SDGVM. Also evident in the SDGVM distribution is the greater extent dominated by forests and the lack of shrubland cover in the south-western regions........ 62

Figure 25: Anomalies of 2m air temperature (T2m) for December to February (DJF; SDGVM land-use minus USGS land-use). 63

Figure 26: As for Figure 25, but sensible heat flux........ 64

Figure 27: As for Figure 25, but latent heat flux. 65

Figure 28: As for Figure 25, but convective rainfall. 66

Figure 29: Total precipitation (mm/day) over Southern Africa (RegCM3). 67

Figure 30: Precipitation differences for fixed soil moisture values of (a) 75%, (b) 25% and the control run........ 67

Figure 31: Surface Temperature (°C) and Evapotranspiration differences (mm/day) for 25% fixed soil moisture values and the control simulation. 68

Figure 32: Projected change in mean monthly precipitation (mm) for 2046-2065, downscaled from three GCM simulations using the SRES A2 emissions scenario........ 69

Figure 33: Projected change in mean monthly number of raindays for 2046-2065, downscaled from three GCM simulations using the SRES A2 emissions scenario........ 70

Figure 34: Projected change in the magnitude of the 90th percentile precipitation event (mm) for 2046-2065, downscaled from three GCM simulations using the SRES A2 emissions scenario. 71

Figure 35: Projected change in the magnitude of the median monthly precipitation event (mm) for 2046-2065, downscaled from three GCM simulations using the SRES A2 emissions scenario. 72

Figure 36: PRECIS (nested within HadAM3P) predicted monthly change in number of rain days (2070's – 1970's). Months are January (top left) to December (bottom right) 73

Figure 37: PRECIS (nested within HadAM3P) predicted monthly change in average 2m surface temperature (2070's – 1970's). Months are January (top left) to December (bottom right) 74

Figure 38: MM5 (nested within HadAM3P) predicted monthly change in number of rain days (2070's– 1970's). Months are January (top left) to December (bottom right) 75

Figure 39: MM5 (nested within HadAM3P) predicted monthly change in average 2m surface temperature (2070's – 1970's). Months are January (top left) to December (bottom right) 76

About AIACC

Assessments of Impacts and Adaptations to Climate Change (AIACC) enhances capabilities in the developing world for responding to climate change by building scientific and technical capacity, advancing scientific knowledge, and linking scientific and policy communities. These activities are supporting the work of the United Nations Framework Convention on Climate Change (UNFCCC) by adding to the knowledge and expertise that are needed for national communications of parties to the Convention.

Twenty-four regional assessments have been conducted under AIACC in Africa, Asia, Latin America and small island states of the Caribbean, Indian and Pacific Oceans. The regional assessments include investigations of climate change risks and adaptation options for agriculture, grazing lands, water resources, ecological systems, biodiversity, coastal settlements, food security, livelihoods, and human health.

The regional assessments were executed over the period 2002-2005 by multidisciplinary, multi-institutional regional teams of investigators. The teams, selected through merit review of submitted proposals, were supported by the AIACC project with funding, technical assistance, mentoring and training. The network of AIACC regional teams also assisted each other through collaborations to share methods, data, climate change scenarios and expertise. More than 340 scientists, experts and students from 150 institutions in 50 developing and 12 developed countries participated in the project.

The findings, methods and recommendations of the regional assessments are documented in the *AIACC Final Reports* series, as well as in numerous peer-reviewed and other publications. This report is one report in the series.

AIACC, a project of the Global Environment Facility (GEF), is implemented by the United Nations Environment Programme (UNEP) and managed by the Global Change SysTem for Analysis, Research and Training (START) and the Third World Academy of Sciences (TWAS). The project concept and proposal was developed in collaboration with the Intergovernmental Panel on Climate Change (IPCC), which chairs the project steering committee. The primary funding for the project is provided by a grant from the GEF. In addition, AIACC receives funding from the Canadian International Development Agency, the U.S. Agency for International Development, the U.S. Environmental Protection Agency, and the Rockefeller Foundation. The developing country institutions that executed the regional assessments provided substantial in-kind support.

For more information about the AIACC project, and to obtain electronic copies of AIACC Final Reports and other AIACC publications, please visit our website at www.aiaccproject.org

Summary Project Information

Regional Assessment Project Title and AIACC Project No.

High Resolution Regional Climate Change Scenarios (AF 07)

Abstract

Africa is one of the regions most vulnerable to climate change, is likely the most under-resourced continent for climate change research, and is a region where some aspects of the regional climate dynamics are still poorly understood. This project addresses these needs, primarily through the development of downscaled regional scenarios of climate change from GCM simulations. Analyses of observations and historical data are also presented and provide the necessary context for these scenarios. Further, important aspects of uncertainty are addressed and ongoing work to understand how land-use change may contribute to this uncertainty is presented. A primary component of this project was to extend existing capacity among African scientists in methods and regional scenario construction. The scenarios focus on spatial and temporal scales appropriate to the primary vulnerability sectors in Africa, and incorporate both computationally efficient empirical downscaling and more computationally demanding regional climate models (RCMs) -- both of which have been identified in the IPCC 2001 TAR as having equal skill, with respective advantages in different impact sectors. Substantial capacity was developed at the host institution and through interactions with both partners and other stakeholders. Facilities for running RCMs (PC hardware and software) were installed at partner sites, enabling partners to investigate aspects of their local climate they considered important for realistic simulations. This capacity was supplemented by strong international links during all phases of scenario development. The project provides for the first time a comprehensive scenario base for IPCC and related impacts activities in Africa.

Besides increasing the capacity to conduct fundamental climate research within Africa, the project produced important scientific results, including: i) the development of a new empirical downscaling technique which demonstrated convergence between projections from a suite of GCMs; ii) the detection of trends in the regional climate dynamics which are also projected in the GCM future projections; iii) the dependence of an RCM's hydrological cycle on the choice of convection scheme and how this leads to RCM-dependent downscalings from one particular GCM, reinforcing the imperative that multiple RCMs be employed; iv) the impact of a changing land surface on the local climate and the importance of so far unquantified changes in land use. The resulting scenarios are continuing to be developed and analysed, however some consistent projected changes are apparent: i) a drying towards the west of southern Africa during summer, consistent with an increase in the frequency of extensive high pressure systems over the Atlantic; ii) an increase in rainfall over East Africa, iii) increases in rainfall over eastern southern Africa during late summer; iv) 1-5°C increases in temperature over much of southern Africa. It should be noted that these generalised projections are highly time- and space-dependent. Some of the projected changes are also more clearly apparent in the statistics of daily rainfall as opposed to changes in total rainfall e.g. changes in rainfall intensity and number of rain days may influence total rainfall in opposition to each other.

This project has laid the foundations for future research, which given a continued impetus can further improve scenario development. Such an impetus will involve multiple research thrusts, including efforts to reduce model uncertainty whilst incorporating aspects of environmental change, e.g. land-use change and biogenic aerosols, not accounted for in current scenario development.

Administering Institution:

University of Cape Town, South Africa.

Participating Stakeholder Institutions:

Water Research Commission, South Africa.

Regional Scope of Climate Change Scenarios:

Sub-Saharan Africa

Countries of primary focus for capacity building:

Ghana, Nigeria, Senegal, South Africa, Zambia, Zimbabwe.

Project Funding and In-kind Support:

Total from AIACC:	US $169,997 (original request $178,222)
Collateral funding:	~US $20,000 (year 1)
	~US $15,000 (year 2)
	~US $10,000 (year 3)
	~US $9,000 (Via DOE funded project)
	~US $20,000 (Via Hadley Center, see budget notes)

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Executive Summary

Research problem and objectives

Africa encompasses some of the worlds regions most vulnerable to climate change. Compounding this is the issue of a small under-resourced scientific community with minimal access to regionalized climate change scenarios. In addition, the limited methodological experience and skill in regional modeling and the under-researched regional climate system further aggravate the issue, increasing the potential severity of climate change impacts and limiting response options. As such, the impacts community has little to draw on beyond raw General Circulation Model (GCM) output produced by predominantly Northern Hemisphere, westernized nation modeling activities, with all the attendant problems of using GCM grid cell data. This situation in itself represents a significant vulnerability for the region. To address these needs the objectives of this project are thus fivefold:

1. Develop capacity within Africa to research aspects of the climate system pertinent to African needs;
2. Encourage a regional climate model-literate community within Africa;
3. Develop new statistical approaches to generating climate change scenarios at time and space scales appropriate for impacts research;
4. Develop regional climate model-based projections of climate change and assess their strengths and weaknesses;
5. Disseminate climate change information with appropriate guidance to impacts researchers.

Approach

The approach of this project has largely been dictated by the objectives stated above. The climate system is complex and climate models are both complex, computer intensive and require large volumes of data storage. In the past this has led to such research being confined to western developed nations with developing countries forced to rely on information generated elsewhere. Africa's needs are, however, often different. Additionally, the rapid development of computer technology has meant that advances in computer hardware have outstripped the increasing complexity of computer models and it is now possible to run climate models on desktop PCs. Together with the development of low-cost PC clusters and multiple hard disk storage arrays, these advances mean that it is now possible to run climate models, at low cost, within Africa. This project takes the view that an Africa-wide climate model-literate community, that can apply their knowledge to African problems, is essential to addressing Africa's needs. We also recognize that expertise in climate modeling often lies outside Africa and it is essential that African researchers be allowed to interact with their peers overseas.

Africa is also a difficult place for computer hardware, with a climate that is tough on computer components and the acquisition of spares often difficult. The project has thus promoted (by supplying both hardware and expertise) the use of climate models at five sites in Africa: Ghana, Nigeria, Senegal, Zambia and Zimbabwe. We have developed further capacity (both infrastructure and intellectual) at the project home base in Cape Town, building on existing capacity. This capacity has leant itself to the development of new techniques for scenario development, as well as the application of regional climate models to investigation of under-researched aspects of the local climate system and scenario development.

Scientific findings

The following summarizes some of the most pertinent findings of this project:

1. Global Climate Models (GCMs) vary widely in their representation of African climate, both in terms of parameterized variables (e.g. rainfall) and regional dynamics

2. Regional Climate Models (RCMs) also vary widely in their simulations of local climate. One particularly important aspect in this regard can be the choice of convective parameterization in the model.
3. The observational network for validating these models is sparse over most parts of Africa and non-existing in certain regions e.g. Democratic Republic of Congo and Angola.
4. Aspects of the land-surface are important to correctly simulate the climate of Africa e.g. soil moisture and vegetation. These may be important components of future change that are not currently addressed to a large degree.
5. There have been consistent trends in climate over southern Africa during the last three decades. Often these trends are easier to observe in statistics of daily climate e.g. rain days. However it is still unclear whether these trends are due to climate change or periodic changes in the circulation of the southern hemisphere.
6. Statistical downscaling of future climate can go some way to reducing the uncertainty found when using the direct output from multiple GCMs.
7. RCM projections of future climate will likely be influenced by the configuration and hydrological cycle of the RCM.

Capacity building outcomes and remaining needs

For the reasons listed below, efforts to install climate modeling facilities within Africa met with varying degrees of success. Of the five sites, three have contributed directly to this report and are continuing to research aspects of their local climate, despite hardware failures and often slow internet access. Results generated in Zambia and the experience of the local researcher led to investigations of the RCMs response over southern Africa, an important aspect of this project. The modeling undertaken in Senegal will also inform the generation of RCM scenarios in that region. Overall the capacity building aspects of this project have been successful with perhaps the most important aspect being the building of a model-literate community within Africa. It should also be noted that where the capacity building has been successful there have often been additional spinoffs, such as student teaching and projects.

The following is a list of some of the major factors that contribute to the success of installing climate-modeling facilities within Africa:

1. Internet access. When slow this restricts information flow both of data necessary to run a climate model and interactions with peers in other countries. Additionally it may preclude remote access and fixing of software problems by technicians at remote sites;
2. Access to spares, particularly hard disks, when faced with hardware failure and the required funds to buy such spares;
3. Availability of researchers with time. Many university teachers and researchers within Africa have high workloads and can only afford the luxury of research in their own spare time;
4. Local technical knowledge to fix problems either with hardware or software, in particular the operating system;
5. Data storage capacity and backups. This is very important given the large volumes of data generated by such activities and the propensity for hardware failure.

National communications, science-policy linkages and stakeholder engagement

This project has developed some of the highest resolution available climate change scenarios for the African continent. The statistical downscaling scenarios are now available and are in the process of being incorporated into a number of projects within South Africa. The RCM scenarios are starting to come online and will complement those from the statistical downscaling. These scenarios have been used to formulate adaptation strategies by the municipalities of Durban and Cape Town (South Africa). The scenarios will be made available via the internet, which will enable free access in the future. Data supplied via this project has been used to assess the impacts of climate change on river basins and hydro-electric power generation within Zambia and the southern African region.

It is anticipated that these interactions with stakeholders and policy makers will increase as the scenarios developed within this project become available and a wider group of potential users become aware of their existence. These data are already feeding into other projects in South Africa that seek to judge the impact of climate change on agriculture and the water resources of major river catchments such as the Tugela in KwaZulu-Natal. Other possibilities currently under discussion include the effect of climate change on the Okavango delta in Botswana.

Policy implications and future directions

All policy development for adaptation requires first, an understanding of the vulnerability and sensitivity of any given sector to the climate system, and second, credible and defensible projections of future change on spatial and temporal scales relevant to any given impact sector. Achieving these goals requires, in turn, a research community that has the appropriate skill base, infrastructure resource, and experiential knowledge in the scientific activities.

Aside from the actual adaptation policy and strategy development required to respond to climate change, it is imperative that the momentum achieved through the AIACC program and other complementary activities be maintained. In this regard it may be said that a priority policy need is for the sustainability of the distributed and collaborative scientific capacity, along with the related infrastructural resources. Of critical importance is the support of the junior, or emerging, scientists; such that they are not subsumed into the significant overheads of African institutionalised research structures. Following this need, perhaps of second importance is the need to foster communication; specifically between the science team engaged with scenario development and the impacts research community, thereby facilitating the dissemination of tailored scenario products and climate system understanding.

Overriding all the work to date, and the challenges of future research, is the critical need to access continued support to maintain momentum. If this cannot be attained, the developments of the AF07 project, while valuable for the immediate needs of the impacts community, will nonetheless be relegated to (merely) another finite lifetime project arising out of the intervention of foreign funding. However, the fact that the project has been African designed and African led is an important evolution in the application of foreign funding. Much has been achieved, and it is anticipated that this will catalyse appropriate development toward achieving the goal of a sustainable critical mass of climate change researchers within the continent.

1. Introduction

Africa encompasses some of the worlds regions most vulnerable to climate change. Compounding this is the issue of a small under-resourced scientific community with minimal access to regionalized climate change scenarios. In addition, the limited methodological experience and skill in regional modeling and the under-researched regional climate system further aggravate the issue, increasing the potential severity of climate change impacts and limiting response options. As such, the impacts community has little to draw on beyond raw General Circulation Model (GCM) output produced by predominantly Northern Hemisphere, westernized nation modeling activities, with all the attendant problems of using GCM grid cell data. This situation in itself represents a significant vulnerability for the region.

The activities of this project address the urgent need for climate change scenario information at spatial and temporal scales appropriate to the vulnerabilities of Africa, and the capacity of the African scientific community to generate such scenarios. To this end emphasis is placed on the development of multi-institutional capacity <u>within</u> Africa in the use and application of regional climate models (RCMs), partnered with focused activities on empirical downscaling, and the analysis of the relevant historical change and climate system processes. This effort expands an existing foundation for an African climate modeling community. Within this framework specific objectives achieved include:

a) Nurture of the embryonic Africa-wide climate modeling research team toward providing a sustainable in-continent resource base for further growth.

b) Implementing nested RCM studies of climate change scenarios.

c) Further the existing base of empirical downscaling to complement the regional modeling.

d) Undertaking perturbation studies with RCMs to investigate the sensitivity of regional climates to primary climate change processes (e.g: changing land surface cover).

e) Undertaking the development of regional climate change scenarios based on the application of RCMs and empirical downscaling to simulations from three different GCMs.

f) Evaluation of the uncertainty and viability of the scenarios.

Arising out of the project it is possible to say that there has been notable advancement of the collaborative model-literate research team within Africa, advances made in understanding of the sensitivity of Africa regional climates to environmental changes, and the generation of a suite of regionally focused climate change scenarios comparable to that which is available to developed nations.

These objectives were prioritised in the IPCC Third Assessment Report (TAR)[1], and of all continents Africa has been most disadvantaged in this respect. As a consequence of AIACC, significant progress toward sustainability of the research within Africa has been made, while large challenges remain to be addressed.

[1] IPCC Third Assessment Report, Chapter 10, and also reflected in the TAR Technical Summary and the TAR Summary for Policy Makers.

2. Characterization of Current Climate and Scenarios of Future Climate Change

This section details the work that has been completed either wholly or partly under the auspices of the AF07 project. The subject matter is broad and incorporates studies of both observed climate variability and trends in the historical record, as well as projections of future change. Analysis of the historical record is necessary to define current variability and provide the context for future change. The recent past is also the period when we expect to see the first signs of climate change should they exist.

2.1. Characterizing and Modeling Current Climate

The following studies all seek to characterize the current climate over a variety of countries in Africa. Much of the work has been completed within the southern Africa domain as this was the focus of the home institution in Cape Town. However, partner sites in West Africa (e.g. Ghana, Nigeria and Senegal) have completed assessments of their local climates prior to undertaking the model simulations detailed here.

Before moving on to discussions of observed climate variability in various regions it is important to note that all discussions and comparisons require densely populated and reliable observations. This is true whether the study focuses on observed variability or tries to identify the strengths and weaknesses of a model simulation. In this respect Africa is severely under resourced, as demonstrated in Figure 1, which shows the number of surface stations contributing to the Global Telecommunications System (GTS) global observations (Figure 1a) and the location of radiosonde observations of the atmosphere (Figure 1b) that are used to constrain the reanalyzes observations of the atmosphere. The surface observations are commonly used to constrain satellite-derived estimates of rainfall and the effect of the low concentration of these observations over the DRC and Angola can be seen in section 2.1.7. A dearth in radiosonde observations can be seen over the same areas (Figure 1b) and the resultant effect on the NCEP and ERA reanalyzes can be seen in Figure 2. This figure demonstrates that for both a dry (1991) and wet (1988) season over southern Africa the zero contour of the 200 hPa velocity potential lies further west, over the Atlantic, in the ERA reanalyzes. In the NCEP reanalyzes this contour is towards the east and generally lies over the landmass of southern Africa or the Indian Ocean. This demonstrates that in the upper atmosphere over southern Africa the ERA reanalyzes are more divergent than the NCEP reanalyzes. Similar figures (not shown) for the lower atmosphere demonstrate the opposite pattern, with more convergence in the ERA reanalyzes. Therefore the ERA reanalyzes indicate more convection and uplift over the southern African landmass than the NCEP reanalyzes and this is reflected in more moisture within the lower atmosphere of the ERA reanalyzes (not shown).

The sparcity of observations and inherent uncertainty this implies complicates the validation of climate models within Africa. It is difficult to find a definitive dataset that can be termed 'reality' or the 'truth'. In terms of RCM modeling over the region this leads to uncertainty in both the lateral boundary conditions with which to force the model and surface observations with which to validate the output

2.1.1. Observed climate variability and trends over South Africa

The South African climate system manifests a temporal and spatial variability that is conditioned by tropical, extra-tropical, and mid-latitude processes. While there are defined homogeneous climate regimes within the domain, they are nonetheless all influenced by the same set of large-scale circulation processes. It is appropriate to think of South Africa as an island continent, bordered on the west by the cool oceanic Benguela current with regionally strong upwelling, on the east by the energetic and warm Agulhas current, and to the south by the Agulhas retroflection and associated eddy transport of warm water westward into the Atlantic. As such, the regional ocean plays a significant role in modulating the larger scale synoptic circulation, and in governing local sources of moisture leading to significant aridity on the west of the sub-continent (Washington et al., 2003; Reason, 2002). A high altitude plateau with relatively narrow coastal margins characterizes the rest of the continent. In conjunction with the sub-tropical subsidence, the topographical features play an important role in governing moisture transport into the region from the surrounding oceans, while subsidence inhibits convection for much of the year through the presence of spatially extensive stable layers in the atmosphere (Freiman and Tyson, 2000).

Most of the continent experiences an austral summer wet season with a strong dependency on moisture transport from the Indian Ocean. For these regions, the passage of mid-latitude depressions south of the country plays a key role in triggering extensive tropical-temperate troughs that govern a significant proportion of the regions total rainfall (Todd et al., 2004; Todd and Washington, 1999; Washington and Todd, 1999). The southern coast is characterized by year round rainfall, and the extreme southwestern tip of the continent experiences a winter rainfall regime governed by the passage of mid-latitude depressions. Inter-annual variability for the region is high (Mason and Jury, 1997) with periodic drought/flood events, governed in part by the southward extension of the ITCZ, a semi-stable teleconnection to El Niño / Southern Oscillation (ENSO) and weaker linkages to regional oceanic temperatures (Rautenbach and Smith, 2001). On the east the coastal regions are vulnerable to topical cyclones which, given the subsistence nature of society in this region, has proved catastrophic in the past (Reason and Keible, 2004).

The recent historical record (20th century) shows strong trends in the regional climate. Notable is a spatially extensive trend showing an increase in dry spell duration with commensurate, but weaker, positive trends in rainfall intensity (New et al., 2005; Hewitson, 2005). Coupled with this are strong temperature trends, especially a reduction in the number of days where minimum temperature falls below the 10th percentile and an increase in days exceeding the 90th percentile (New et al., 2005). On the hemispheric scale there are also suggestions that the ENSO teleconnection to southern Africa may be becoming less robust (Landman and Mason, 1999; Sewell and Landman, 2001), with associated implications on predictability for the region.

Detailed spatial analysis of the historical trends of precipitation exceeds the scope of the report. However, broad statements of the trends with spatial homogeneity can be drawn from the analysis by Hewitson (2005). This study used robust regression with an interpolated 0.1° gridded precipitation data set (Hewitson and Crane, 2005a) that draws on over 3000 station records across South Africa. While interpolation can possibly introduce artefacts, comparison of the calculated trends show good agreement with trends calculated on the few stations with long-term records. The trends are assessed over the last 50 years, from 1950-1999.

While trends in the annual totals are not strong, when one considers trends on sub-annual and seasonal scales, some notable changes in the last 50 years may be identified. Figure 3 shows the seasonal changes in mean monthly totals, as change per decade. Figure 4 to Figure 7 show the trends in derivative statistics from the daily data, and include changes in raindays per month, dry spell duration, and the 90th percentile event magnitude.

The trends show a clear, spatially cohesive picture of historical change. While the spatial nature of the change has significant local detail, some of the broad regional characteristics include:

- Increases in regions where orography plays a strong role
- Increases in dry spell duration for much of the summer rainfall region
- Arid zones, in general, receiving more raindays
- Contrasting changes in the winter rainfall region, with mountainous regions receiving more raindays per month and increased totals, while the neighbouring coastal plain has the reverse.

The changes are, in places, strong, and of notable consequence for climate related impacts. Attribution of the change to anthropogenic forcing is not possible at this stage. The role of local land use change in forcing regional climate response is still unclear, as is the degree to which low frequency large-scale variability of the atmospheric circulation may be contributing to the change. Nonetheless, the changes are in line with what would be anticipated from global warming, given an atmosphere with increased humidity, and an expected increase in the Hadley circulation.

2.1.2. Observed climate variability in Zambia

Mrs. Suman Jain at the University of Zambia (UNZA) used the following observations of Zambian climate to test regional simulations of MM5 (see section 2.1.6 below). It was through these simulations that a negative bias in rainfall over the region became apparent, which prompted the testing of different convection and planetary boundary layer schemes detailed in section 2.1.7.

It has been felt and believed that the most raining seasons in Zambia in the past twenty years have shown a tendency of drought. A brief statistical analysis of Meteorological Station Data is done to trace the incidence of drought in Zambia during the period 1990 to 2003 (Figure 8). Zambia is divided into three main Agro Ecological Regions, which are defined on the basis of Climatic characteristics of which Rainfall is the dominant factor.

Region 1

The region (Zambezi and Luangwa Valley) covering Southern part of the country, receives less than 800 mm of rain annually and temperature in this region varies from 20^0 to 25^0 centigrade. It is the driest region in the country and is most prone to drought.

Region 2

The region covers central part of Zambia extending from the east through to the west. It receives rainfall of between 800 mm to 1000 mm. Temperatures during the raining season range from 23^0 to 25^0 centigrade.

Region 3

This region receives more than 1000 mm of rainfall in a season and covers the northern part of the country. Annual rainfall data for 29 meteorological stations was obtained from the Zambia Meteorological Services and analyzed for each of the three regions. The 30 year period 1970/1971 to 1999/2000 was adopted as a baseline climate. The panels in Figure 8 describe the seasonal normalized rainfall anomalies for the period 1990/1991 to 2003/2004 with respect to the baseline period. Although rainfall indices for 1970/71 to 1989/90 are not included in the figures below, there is a strong signal from the station data that most drought episodes during 1970/71 to 2003/2004 occurred in the recent 15 years.

It may be noted from the above figures that:

1. 1994/95 season experienced severe drought across all three regions.
2. Regions I and II are showing higher rainfall variability as compared to Region III.

2.1.3. Observed climate variability in Zimbabwe

The following work was completed by Marshall Mdoka as part of his masters thesis at the University of Cape Town. It involves the analysis of trends in climate at different stations in Zimbabwe.

Zimbabwe's rainfall is highly variable making it prone to future climate changes, which may either increase the current variability or change the mean climate around which this variability manifests. For a country that has more than 70% of its population relying on agriculture directly or indirectly, the impact of extreme weather events is critical. The study of the historical and current changes of extreme events is essential to place any future changes in context. Results attained from statistical analysis for trends in time series of daily data using RClimdex statistical package are presented. A selection of suitable indices over Zimbabwe are calculated and examined based on percentiles for rainfall, maximum and minimum temperatures.

The following overview is on the spatial variation in the direction of trends. The statistical significance is not shown in the maps but trend values noted as significant at 95% confidence level are highlighted in bold in Table 1. The indices are explained in the following figures.

Rainfall

Annual total precipitation has generally decreased across most of the country for the period between 1961 and 1990. Except for the extreme south-eastern areas and some parts of the central watershed where there has been a slight increase. The precipitation has decreased in the majority of stations with some marked decrease over the northern areas (Figure 9(a)). In Figure 9(b) the maximum number of dry days has increased over the northern areas of the country with a significant decrease over the southern areas and one exceptional station, Kadoma in the north showing a weak decline (not statistically significant).

As for the annual total, precipitation exceeding the 95th percentile indicated a positive trend over the southeastern areas and in some parts within central Zimbabwe such as at Gweru. The remainder of the country exhibited a negative trend (Figure 9(c)). The last map (Figure 9(d)) for monthly maximum consecutive 5-day precipitation shows a negative trend over the northern and southern areas with a positive trend over the central parts of the country.

Trends in the total precipitation, dry spells and maximum consecutive 5-day are spatially more coherent than trends for the annual total precipitation exceeding the 95th percentile. The southeastern areas around Chipinge show an increase in all four variables. Although not statistically significant (95% level) it shows that an increase in total rainfall is accompanied by more dry spells (CDD), which implies a rise in extreme events with higher rainfall intensity.

Temperature

The annual count when daily minimum temperature is below 2°C, TNn (the value of 2°C was chosen so that the index could be useful over Zimbabwe) is exhibiting a mixed trend although the majority of areas to the north are showing a decrease whereas the southern are showing an increase. Beitbridge and Bulawayo Goetz stations are exhibiting a significant increase with Kwekwe and Harare Kutsaga showing a significant decrease, Figure 10(a). Annual count when daily maximum temperature is above 25°C, TXx has increased at most stations except for the northernmost areas and Kadoma where there is a decrease, Beitbridge and West Nicholson showing a significant increase (Figure 10 (b)).

The number of cold nights has decreased at most stations (significantly at several stations) as depicted by the reduction in percentage of days when daily minimum temperature is below 10th percentile, Figure 10 (c). Cool days have also significantly declined at most stations as shown by percentage of days when daily maximum temperature is below 10th percentile, Figure 10 (d). The exception to these spatially consistent trends is Karoi in the north which indicates a statistically significant and large increase in the percentage of days below the 10th percentile for both minimum and maximum temperature. Warm nights increased across most of the country country, as depicted by the percentage of days when daily minimum temperatures exceeded the 90th percentile, Figure 10 (e) and most of these stations are statistically significant. Figure 10 (f) shows that the number of hot days has increased at all stations (significantly at several stations) as is being exhibited by percentage of days when daily maximum temperature exceeds the 90th percentile. Interestingly, Karoi station does not exhibit as significant a change in days crossing both the minimum and maximum 90th percentile, as was seen with the 10th percentiles of minimum and maximum temperature. The diurnal temperature range (Figure 11) has increased over most of the stations, with Chipinge, Karoi and Kwekwe exhibiting a significant increase, but reduced over the eastern Highlands (not statistically significant). Generally, there is more spatial coherence to the temperature trends of the 10th and 90th percentiles of the minimum and maximum temperatures than can be seen in the minimum and maximum mean values.

The trends displayed above reveal some intriguing perspectives on the local climate and climate change during the 1960-1990 period. Patterns of the temperature trends clearly show spatial cohesion of warming trends across Zimbabwe. Nearly all the stations (with the exception of Karoi in the north) are accompanied by a decrease of the number of days below the 10th percentile (implying a decrease in cold extremes), an increase in the number of days exceeding the 90th percentile (implying an increase in hot extremes) and an increase in the diurnal temperature range, DTR. It should be noted that most of these trends were statistically significant with the exception of the DTR. Similar positive trends in temperature have been identified in earlier studies. Hulme et al. (2001) obtained positive mean linear trends from the New et al. (2000) data set and found temperatures over the southern Africa region to be between 0.2 and 0.3˚C warmer than the 1961-90 average.

Precipitation has decreased over much of the country, with the spatial patterns less consistent than those for temperature. However there does appear to be some intriguing and spatially cohesive patterns in the trends for consecutive dry days, CDD. Although not statistically significant, the CDD shows an increase over the northern parts of the country where there is a decrease in precipitation. Also trends for increasing CDD are generally associated with higher altitudes over the central watershed. To a first approximation, an increase in intense rainfall (R95p) generally accompanies an increase in total rainfall (PRCPtot). Besides Beitbridge, stations where the total rainfall has increased are accompanied by an increase in the number of consecutive dry days and rainfall above the 95th percentile. In some areas, heavy rainfall increases in spite of a decrease in total precipitation. The implication is that although total rainfall may have increased, it comes in shorter bursts and with longer dry periods. This allows more time for evaporation and runoff is generally higher, leaving less moisture in the ground for plants and agriculture.

2.1.4. Trends in observations of the atmospheric circulation

To investigate whether there have been any changes in atmospheric circulation that may explain some of the observed changes in rainfall and temperature mentioned in the previous sections, a SOM was used to characterise daily patterns of mid-tropospheric geopotential heights. The daily 500 hPa heights were taken from the ERA40 reanalysis, which exhibits reasonable model climatology over data-sparse regions of the southern hemisphere (Bromwich and Fogt 2004). The SOM patterns associated with the normalised anomaly from the zonal mean for the 24 (1979-2002) DJF seasons are displayed in Figure 12. The patterns indicate that southern Africa is a region whose large-scale mid-tropospheric circulation is dominated by pressure gradients, often between competing highs and lows over the Indian and Atlantic Oceans. For example, the pattern in the top-right node (3,2) indicates a low-pressure system over the Atlantic, extending to the south east over the continent. Its opposing node (1,1) indicates a similarly extending high-pressure system. The two other corner nodes (1,2 and 3,1) are characterised by the weaker influence of the Atlantic and the increased influence of opposing pressures over the Indian Ocean. Figure 13 indicates the trends in frequency of each node for the 1979-2002 DJF seasons. Positive trends are demonstrated for nodes to the left of the SOM though only the trends for node 1,1 are significant at a high (98%) confidence level. This node indicates a broad band of high pressure extending over the continent from the Atlantic towards the south-east. The only other node with a significant trend (92% confidence level) is the node 2,2 which indicates a decreasing trend for low pressures over much of the continent. Together, these two nodes suggest a tendency towards days with higher relative pressures over the continent, which is consistent with the many of the observed trends in rainfall and surface temperatures noted in the previous sections.

The physical cause of these changes in atmospheric circulation is beyond the scope of this study, though the next section demonstrates that the trends are consistent with those expected as part of global climate change. It is noteworthy that the strong El-Niño events of the 1990's (1991 and 1997) are not clearly anomalous from the general trend in Figure 13. However, the Southern Annular Mode (SAM; Van Loon, 1967) is likely a major source of variability and disaggregating changes due to the SAM and those due to climate change remains a challenge.

2.1.5. GCM simulations of African climate

An in-depth analysis of GCMs and their relative performance over southern Africa alone (even neglecting a similar analysis over West Africa) is a long process. All the GCM's analysed as part of this project simulated climates that exhibited biases that depended on both location and time. Consistent biases in GCM-simulated precipitation and temperature were hard to identify. Also, for the purposes of downscaling presented in sections 2.2.2 and 2.2.3 it is more important to evaluate biases in the circulation or dynamics simulated by each GCM. Further, if we are interested in daily statistics of rainfall and temperature it is important that we evaluate the GCM dynamics at similar timescales.

Figure 14 demonstrates one such attempt at this for southern Africa. The figure shows a Self Organising Map (SOM) of daily eddy geopotential heights during the December to February period of each control and future run of each GCM. The SOM essentially picks common patterns found in the data which are the 12 patterns displayed in the figure. Also included in the training were 20 years of NCEP and 15 years of ERA reanalyzes daily data for the same season. These reanalyzes essentially represent the observed climate over the region. The SOM is essentially the same as that in Figure 12 except that other GCM data and the NCEP reanalyzes have been included and the patterns range over a wider area. Figure 15 demonstrates the frequency of each node as they are typically found in each of the 5 datsets (NCEP and ERA reanalyzes + 3 GCM control runs). The figure clearly shows that both the ERA and NCEP reanalyzes (observations) have a higher frequency of patterns found on the top row of the SOM. These patterns are for a high pressure over the tropical Atlantic extending to the south east over the continent, similar to the pattern with significant positive trends in Figure 12. Of the 3 GCMs, HadAM3 and CSIRO indicate a similar preference for this pattern. ECHAM indicates a preference for simulating a pattern of low pressure over the continent. It should be noted however that the HadAM3 data were forced with observed SSTs whereas the other GCMs were fully coupled model runs i.e. the ocean component of the model was left to simulate the SST. Therefore the relatively good performance of HadAM3 in this respect may be due to its more realistic surface forcing.

Although we are concentrating on simulation of the current or control climate it is interesting to see the predicted change in the future climate for these GCMs. Figure 16 presents the change in frequency (future – control) for the HadAM3 and CSIRO GCMs. The two predicted changes are different though they both agree on an increase in the frequency of patterns found towards the top right of the SOM (nodes 4,3 and 4,2). These are patterns with high pressures over the western tropical region, which extend towards the south east. Similar patterns to these were demonstrated in the previous section to have increased in frequency in the recent historical record. The effect of an increase in these patterns becomes apparent in section 2.2.3; over these same regions RCMs nested within the GCM data simulate a reduction in the number of rain days in a future climate.

2.1.6. MM5 simulations of current climate over Zambia

Several experiments of RCM MM5 have been done for past climate to assess model performance against observations on a Southern African domain spanning over Zambia. Mrs. Suman Jain at the University of Zambia (UNZA), using a desktop PC and skills developed through AIACC funded activities, performed these experiments. Figure 17 is an output from one of the several runs of MM5 model carried out by an undergraduate student at the UNZA as part of his project course .The figure represents total precipitation for the period 1 November 1988 to 28 February 1989.

Table 2 & Table 3 show the observed and MM5 simulated monthly total precipitation and four months total precipitation for November 1988 to February 1989. This summer season experienced above normal rainfall over most of Zambia. It may be noted from the above tables that there is no systematic bias (consistent across all stations) in the observations and simulated data for precipitation for the period 1 November 1988 to 28 February 1989. Simulations are indicating less rain than observed in the northern part of the country and the picture is the other way round for some stations in the east of the country for example Chipata.

These results are significant and provided evidence that this configuration of MM5 (using the Grell convection scheme) simulated an Inter-Tropical Convergence Zone that was too dry. The results indicate the need to test the model with other physics options and different parameterisations to improve its performance over Zambia. This work, undertaken at the UNZA, therefore led directly to the experiments presently described. This experience epitomises the philosophy behind project AF07. It highlights the synergy between developing regional capacity to undertake experiments at locations where the experiential knowledge of the local climate system is greatest, and the expertise to use that information and undertake more detailed investigations at remote sites where appropriate infrastructure is greatest.

2.1.7. Testing different physics options for MM5 simulations over southern Africa

As the above discussion demonstrates regional climate models often have many options for representing the physics of the atmosphere-land-ocean system. Changing these options can lead to very different simulations of precipitation and surface temperature; the two most important variables to the impacts community. Given the results over Zambia presented above, an experiment was designed to test the different options for representing the planetary boundary layer (PBL) and cumulus convection in MM5. The work has been accepted for publication (Tadross et al. 2005a) and below we present a summary, examples of some of the main findings and a discussion of the implications.

Summary:

Two cumulus convection and two planetary boundary layer schemes are used to investigate the climate of southern Africa using the MM5 regional climate model. Both a wet (1988/89) and a dry (1991/92) summer (December – February, DJF) rainfall season are simulated and the results compared with three different observational sources: Climate Research Unit seasonal data (precipitation, 2m surface temperature, number of rain days), satellite-derived diurnal precipitation and the Surface Radiation Budget diurnal short-wave fluxes and optical depth.

Using the ETA model boundary layer in MM5 simulates too much incident short-wave radiation at the surface at 12 UTC, whereas the medium range forecast model (MRF) boundary layer yields a diurnal cycle of short-wave radiation closer to the observed. Using the Betts-Miller (BM) convection scheme in MM5 simulates peak rainfall later in the day and less rain days than observed, whereas when using the Kain-Fritsch (KF) convection scheme a peak rainfall earlier in the day and more rain days than observed are simulated. The intensity of the hydrological cycle is therefore dependent on the choice of convection scheme, which in turn is further modified by the boundary layer scheme. Precipitation during the wet 1988/89 season is reasonably captured by most simulations, though using the Betts-Miller scheme more accurately simulates rainfall during the dry 1991/92 season. Mean DJF biases in the surface temperature and diurnal temperature range are consistent with biases in the number of rain days and the diurnal cycles of surface moisture and energy.

Key findings:

Figure 18 shows the 1988/89 DJF rainfall given by two observational datasets: a) the Climate Research Unit (CRU) station-only dataset (New et al., 2000) and b) the Climate Prediction Center Merged Analysis of Precipitation (CMAP) combined station and satellite dataset (Xie and Arkin, 1997). The station data contributing to the CMAP data is partly that communicated over the Global Telecommunications System (GTS) and comprises fewer stations than those used by the CRU. CMAP rainfall estimates are generally higher than those of CRU, especially over south-eastern Zambia, the Democratic Republic of Congo and Angola. These differences are due to the small number of station data available in these regions; where the station density is low, CMAP relies heavily on the satellite estimates whereas CRU data tends to climatology (New et al., 2000). Which analysis is a better representation of reality is therefore unclear. These discrepancies in observation-based datasets further complicate the validation of climate models over southern Africa. As noted previously, differences exist between the atmospheric fields of the ERA and NCEP reanalyzes and this is partly due to the lack of atmospheric observations over the same regions.

Figure 18c & d show the interannual anomaly (DJF 1988/9 – DJF 1991/2) in the CRU and CMAP datasets respectively. As expected, the wet-dry season anomaly is positive over most of the subcontinent. It is encouraging that south of 12S, away from the regions of sparse station data, the two datasets agree well on the pattern of the precipitation difference. Over northern Zimbabwe, southern Zambia and central Mozambique, the CMAP data has larger and more widespread anomalies than the CRU data. In part this may be because of the different spatial resolutions of the two datasets (CRU has a resolution of 0.5° × 0.5°, CMAP is 2.5° × 2.5°). In the following analysis we compare the CRU data to the MM5 simulations as it has a similar spatial resolution (approx 50 km) and the CRU dataset includes a suite of consistently derived surface parameters related to rainfall and temperature. However, CRU-CMAP differences in Figure 18 help indicate the uncertainty in climatological precipitation for southern Africa.

To investigate whether changes in the frequency of rainfall (and by implication average intensity) might be responsible for some of the differences noted in DJF rainfall, the number of simulated rain days was compared with CRU observations. Figure 19 demonstrate the bias in the number of MM5 simulated rain days (> 0.1 mm day^{-1}) with respect to the CRU observations for the 1988/89 season (depending on the region CRU indicated 30-50 raindays during the wet 1988/89). From Figure 19 it can be seen that using the KF scheme on average simulates too many rain days whereas using the BM scheme simulates too few rain days Over East Africa MM5 simulates the lowest biases, which are often negative, except using the KF scheme. The KF scheme simulates 20 to 40 more rain days than observed over the western regions of southern Africa with regions of lower bias (0 to 20 rain days) towards the east. Similar tendencies are indicated using the BM scheme but with generally negative biases (-20 to 0 rain days) over much of southern Africa and larger negative biases (-40 to –20 rain days) in particular over the Zambezi valley. As can be seen from Figure 19 this valley, which forms the border between Zambia and Zimbabwe, is generally at a lower altitude than much of southern Africa. This suggests that topography may play a role in determining the number of rain days simulated using the BM scheme in MM5.

As seen for total rainfall the choice of PBL scheme affects the simulated number of rain days less than the choice of convection scheme. However, during both seasons the BM/ETA combination produces less rain days than the BM/MRF combination, especially near the Zambezi valley where the negative bias is increased. On average, MM5 using the KF scheme simulates 20 to 30 more rain days than observed whilst using the BM scheme simulates 10 to 15 too few rain days. From an agricultural perspective it is important that MM5 simulates close to the correct number of rain days. Rain-fed agriculture in this water-scarce region is dependent on the quality of rain, and it is therefore important that both seasonal forecasts and climate change scenarios are able to correctly diagnose changes in rain day frequency and rainfall intensity.

Figure 20 shows the diurnal cycles of rainfall, SW flux at the surface and integrated CLW between 875 hPa and 450 hPa for two simulations over southern African. MM5 diurnal cycles are also calculated for days when it rained to see how the amplitude and phase of the diurnal cycles of SW and integrated CLW change due to precipitation. The observed (RGPI) rainfall has its minimum at 9 UTC (10-11 Local Standard Time[LST]) and maximum at 18 UTC (19-20 LST).

The rainfall panel in Figure 20 shows the DJF average diurnal cycle of rainfall for the two MM5 configurations, as well as the average diurnal cycle for the days when it rained (> 0.1 mm of rain in 24 hours, upper dotted curve). As expected, the exclusion of non-rain days has a greater impact on the diurnal cycle of the BM/MRF configuration (the number of rain days is fewer) and serves to highlight the intense nature of rainfall using this configuration. The exclusion of non-rain days in the KF/ETA configuration has a comparatively smaller effect, as there are more rain days. Using this same configuration simulates a diurnal cycle of rainfall symmetrical about a peak at 12 UTC (13-14 LST), with rainfall dropping to around 0.15 mm/hr towards the early morning and late afternoon. However, using the BM/MRF configuration simulates a minimum at 09-10 UTC, increasing to a maximum in the late evening around 20 UTC. This resembles the diurnal cycle indicated by the RGPI but with a later maximum. It is also noticeable that the RGPI cycle falls between the two BM/MRF curves (except during 03-06 UTC), indicating that when it rains the BM/MRF configuration simulates rainfall that is more intense than the RGPI rainfall.

The SRB (observed) SW (incident at the surface shortwave) flux in the middle panel of Figure 20 displays a maximum at 09 UTC with a similarly high value at 12 UTC. The DJF average SW flux for all days and for rain days only appears in the same panel for the two MM5 simulations. Of the two simulations it is the BM/MRF configuration that better represents the timing of the SRB diurnal cycle. At 12 UTC the BM/MRF simulation is a closer match to the SRB data, whereas at 09 UTC both MM5 simulations produce similar positive biases. Figure 20 also indicates that though using BM/MRF simulates the lowest SW fluxes of all the MM5 simulations at 12 UTC, according to the SRB data it is still positively biased. Taking the SW flux only during days with rain (dotted curves) reduces the positive SW bias, as might be expected given an increase in cloud cover. However, Figure 20 suggests that MM5 is simulating an optically thin atmosphere, which may be due to insufficient cloud cover and/or neglecting the effects of aerosols in the cloud-interactive radiation scheme (Chen and Dudhia, 2001).

The bottom panel in Figure 20 shows the integrated CLW (875-450 hPa) from the MM5 simulations and the SW optical thickness estimates used with the SRB SW data (valid 06-15 UTC). We found these optical thickness data to be regionally dependent with the highest values over the subtropical regions (south of 17°S) at 15 UTC. A similar peak value at 15 UTC occurred over the eastern region further north (25°-33° E, 17°-12° S), whereas the western region (17°-25° E, 17°-12° S) had peak values at 06 UTC. Therefore the early morning maximum in optical thickness is found primarily over the northeastern reaches of our southern African region. The diurnal cycle of total specific humidity was similar to that of CLW in the two MM5 simulations, therefore only integrated CLW is shown.

Using the KF/ETA configuration simulates a CLW maximum at approximately 06 UTC which is 07-08 LST, whereas using the BM/MRF combination simulates a CLW maximum at around 14 UTC, which is 15-16 LST. The SRB optical thickness estimates indicate peaks at both these times, suggesting that the two MM5 configurations are simulating different aspects in the observed diurnal cycle of clouds. Assuming CLW as a proxy for optical thickness in MM5, the SW fluxes in the middle panel suggest that the simulation of clouds (as represented by CLW) is partly responsible for the deficiencies in the simulation of the SW flux; the positive bias in SW simulated by BM/MRF during the morning coincides with its optically thin atmosphere during this time, and the same argument applies to the KF/ETA simulation during the afternoon. The difference between the integrated CLW for rain days (dotted curves) and the DJF average demonstrates that the phase of the diurnal cycle of CLW does not change between raining and non-raining days in each of the MM5 simulations.

The above findings indicate that the hydrological cycle of MM5 over southern Africa is dependent on the choice of convection scheme. This is essential to understand if regional climate change scenarios derived using MM5 (and other RCMs) are to be placed in context. The uncertainty in the correct representation of atmospheric processes (in this case atmospheric convection) needs to be incorporated in any assessment of climate change using these models. Therefore the recommendation is that many different RCMs, spanning a range of simulated hydrological cycles, should be used to make climate change assessments.

2.1.8. RegCM3 and MM5 simulations of West African climate

Dr. Abdoulaye Sarr who currently works for the Senegelese Meteorological service undertook the following work. Some of the work was accomplished whilst studying for his PhD and AIACC, through project AF07, provided the desktop PC on which some of the simulations were performed.

Modeling Activities

Because of the poor performance of GCMs in general and their coarse resolution, it is necessary in the framework of regional impact and adaptation to have high-resolution outputs for the study of adaptation and vulnerability. In that context, we are trying to adapt an existing model, mainly developed for use in high latitude regions, to work in our tropical region. Therefore, a lot of preliminary work has to be done in order to understand and have a good representation of the local climate system in the model. These preliminary steps, before undertaking long simulations, are critical and take much time and effort to avoid running the model without any validation. Within this framework many simulations, using different regional models with different dynamical parameterizations, were tested to see how well they simulated the climate of West Africa. Both a non-hydrostatic (MM5) and a hydrostatic (RegCM3) model were used in preliminary testing. To carry out this study various sensitiviy tests were made in order to optimize the quality of the simulation in the region. Non-resolved physics such as convection, boundary layer vertical diffusion and radiative interaction with clouds are parameterized using different methods, which are not applicable in all regions.

Various combinations of parameterization schemes were used with the aim of having the best model set up to simulate the climate of West Africa. For climate studies (variability and change) precipitation and temperature are the parameters most focused upon. They are the end product of dynamic and thermodynamic interactions in the climate system. This implies that a good simulation of precipitation and temperature requires a good representation of meteorological synoptic features. Most of the simulations focused on the monsoon system over West Africa. The investigations were mainly conducted on the most important dynamical features modulating rain-producing systems. Because of the long dry period that affected the Sahel from the late 60's to the 90's, the dynamics associated with dry and wet years is also important. The ability of regional climate models to simulate this variability and change is important for developing regional climate change projections.

Different domains were used in the study as the model results are also sensitive to domain configuration and size. Knowledge of the dominant features in a region is critical in setting the domain. Over West afica, the dominant dynamical features are the tropospheric jets at 700 and 200 hPa, which play an important role in the dynamic of the monsoon system. Another important feature is the monsoon associated with the ITCZ (Inter Tropical Convergence Zone). The rain activity over West Africa has two dominant modes; a unimodal behavior north of 08°N and a bimodal structure south of this latitude. This behavior is associated with the interseasonal movement of the ITCZ. Other major features of interest are African Easterly waves, which are the smallest dynamical features modulating rain producing systems over the Sahel. Aspects of these waves are also the generators of tropical depressions, storms and hurricanes over the Atlantic Ocean. A realistic simulation of these waves by regional models is necessary if they are to accurately simulate rainfall over the region.

Simulations using MM5

Versions 3.4, 3.5 and 3.6 of MM5 were used to simulate the climate over West Africa. The widest domain covered the area between 25°W and 45E and 0 to 30°N. Other smaller domains were also tested. Sensitivity tests to cumulus, boundary layer and radiation schemes were carried out. The periods of study were June – August 1988 and 1990, which are respectively wet and dry years. The results show that the model is able to realistically simulate the behavior of the major dynamical systems like the TEJ (Tropical Easterly Jet) located in the upper troposphere, the AEJ (African Easterly Jet) located between 700 and 600 hPa (see Figure 21)

A close look at Figure 21 shows that the model is able to simulate the position and strength of the different jets compared to NCEP reanalysis (not shown). The difference between the two contrasting years is also well simulated. During the dry year 1990 the AEJ is stronger and located further south compared to the position and strength in 1988. This is consistent with the findings by many authors. The model is also able to simulate African easterly waves as shown in Figure 22

Rainfall patterns over West Africa are also realistically simulated, but we noticed that the rainfall amounts were over estimated in general within the region. The Grell convective parameterization scheme tended to underestimate the rainfall in MM5. Also the northward displacement of the ITCZ and associated precipitation were not well simulated. Maxima of rainfall located around high altitudes are well simulated by the model when compared to the Global Precipitation Climatology Project dataset. However, rainfall simulations still remain problematic over West Africa and the recent investigations and configurations will be used for longer runs lasting many years to better understand the quality of the simulated precipitation over the region.

Simulations using RegCM

The regional climate model RegCM3 is also used to simulate the West African climate. After many sensitivity tests, multi-year simulations were carried out to investigated the ability of the model to simulate the climate of the region at different time scales. Preliminary results show that for precipitation, the model realistically simulates rainfall patterns and the magnitude in many areas is close to the observed value (given by data from the Climatic Research Unit, UK). There are also indications that the model well simulates both intraseasonal and interannnual rainfall variability. Figure 23 shows the rainfall distribution for august 1993 as simulated by RegCM3.

The maximum rainfall areas near the regions of high topography are well captured by the model. The northward extension of rainfall north of 15°N over Mali and Niger is in agreement with observations. To the west, over north Senegal the model tends to underestimate rainfall. However, investigation of all months is required to judge if this is a systematic bias or not. This work is in progress and the final results are currently being prepared for journal submission.

2.1.9. Modeling land surface interactions and their effect on climate

The following sections seek to understand the role of the land surface in determining the climate of Africa. There is now a significant body of literature, which suggests that land-surface-climate feedbacks impact local climates in Africa (e.g. Hoffman & Jackson 2000, Zeng & Neelin 2000, Wang & Eltahir 2000, Nicholson 2001). It is therefore important that these impacts be included in assessments of potential change affecting agriculture, especially in regions where land-use practices are changing. Hoffman & Jackson (2000) demonstrated that the conversion of tropical savanna to grassland resulted in a coincident decline in precipitation. They note that the main impact on precipitation is through an increase in the frequency of dry spells, which would be particularly damaging to shallow-rooted crops. Zeng & Neelin (2000) highlighted the interactive nature of this relationship by demonstrating that the savanna ecosystem is the result of a variable climate, which keeps the vegetation between extreme desert-like and forest-like states. Though not included in this report, an experiment to understand the uncertainty in climate modeling resulting from uncertain knowledge of a model's (MM5) land surface characteristics was accomplished as part of this project. The results were written up after this report was mostly compiled and have been submitted to the Journal of climate for publication (Tadross et al. 2005c). The main results of this work were that an alternative set of land surface characteristics produced changes in the regional dynamics, altering the east-west geopotential gradient which resulted in significant change in rainfall and surface temperature. These dynamical changes were of a greater magnitude when the model was forced by upper level high pressures, suggesting the resulting climate uncertainty associated with land surface characteristics may increase in a future climate given the projected increases in high pressure systems (section 2.1.5).

2.1.9.1. Vegetation over Southern Africa

Since the early work of Charney (1975) on land-atmosphere feedback in the Sahel region there has been an increasing awareness of the complex interaction between the land surface and the atmosphere (see Pielke 2001 for a review). Two important land-surface parameters that influence the climate are albedo (surface reflectance to incoming solar radiation) and soil moisture. Soil moisture affects evaporation and hence latent heat fluxes at the surface, while albedo influences surface temperature and hence specific heat fluxes. Since fluxes of water, energy, momentum and carbon dioxide at the land-surface are regulated by plant physiology and structure, vegetation distribution is an important consideration when evaluating land-surface climatology. Recent developments in coupling land surface models (LSMs) and regional climate models (RCMs) have helped to improve model simulations, but there is still scope for further improvements. Two potential avenues of development exist: 1) improving the numerical simulation of land surface processes and their interaction with the atmosphere, and 2) more accurately describing the regional land surface in terms of vegetation, soil and hydrological parameters. While much work has been done on developing accurate and comprehensive land surface datasets for the Northern Hemisphere, data for Africa are typically lacking.

Vegetation modeling

The complex nature of the biosphere makes it a challenging system to understand. Simple mathematical models have shed light on ecological processes and principles, and provide a convenient, but limited, representation of reality. More complex models have evolved in the form of process-based biogeographical and biogeochemical models, which incorporate detailed representations of plant growth and competition, chemical cycling and hydrology.

The two principle types of these complex models are static or equilibrium models and dynamic models (see Peng 2000 for a review). Equilibrium models are designed to compute a vegetation state that would exist given a particular climatic state. Dynamic models have the advantage of being able to simulate transient changes in vegetation in response to external forcing (eg. climate change). Relative changes in the distribution of plant life forms or plant functional types (PFT's) can be predicted based on environmental constraints (Peng 2000).

This study uses the Sheffield Dynamic Global Vegetation Model (SDGVM) to provide land-surface boundary conditions for the MM5 regional climate model. SDGVM supplies an alternative to the default vegetation map as used by MM5 and offers attractive possibilities for interactive coupling between the RCM and the vegetation model.

Model description: SDGVM

Developed by Woodward et al. (1995), SDGVM predicts potential natural vegetation according to the input variables of precipitation, temperature, relative humidity, CO_2 and soil texture. The model includes subroutines for biomass, phenology (the seasonal emergence and shedding of leaves), hydrology, carbon and nitrogen cycling, and dynamics (ie. transition between vegetation states). Disturbance by fire is an important controlling process in vegetation distribution (Bond and van Wilgen 1996; Bond et al. 2003). For this reason, an approximation of the occurrence of fire, and its impacts on vegetation, has been incorporated into the model. Vegetation type is given in terms of plant functional types (PFTs). SDGVM defines 6 such types, namely C_3 and C_4 grasses, evergreen broad- and needleleaf trees, and deciduous broad- and needleleaf trees. There is a 7^{th} category assigned to bare ground. It is important to note that the model predicts potential natural vegetation, so the influence of agriculture and other human land-use activities is removed.

Sensitivity experiment

Using SDGVM, a control vegetation state for southern Africa was computed. The climate input variables were provided by the University of East Anglia Climate Research Unit 0.5^{O}-resolution land-surface climate data for 1901-2000 (New et al. 2000). Average vegetation state for the years 1971-2000 was used as the land-surface climatology. For ease of comparison with other data and so that the information could be incorporated into MM5, the distribution of PFTs as given by SDGVM was reclassified in order to approximate commonly identified vegetation biomes in the USGS dataset (Figure 24). As with all models, SDGVM is imperfect, so discrepancies in its output when compared to observations of vegetation distribution are evident, but for the most part the model captures the general distribution of southern Africa's vegetation particularly well. If it can be assumed that the above vegetation distribution represents a plausible undisturbed natural vegetation state, then it follows that the difference between this distribution and present-day observations of land-surface conditions is largely attributable to the impact of human activities.

Figure 24 shows the SDGVM output in comparison to the United States Geological Survey (USGS) land-surface map as used by MM5. To assess the sensitivity of regional atmospheric circulation to these different vegetation distributions, two MM5 integrations were run. One used the default USGS map, whereas in the other this map was replaced by the SDGVM distribution. To investigate how this land-surface change has impacted on the climate of the region, a number of MM5 simulations were done. Two sets of runs were performed for the three summer seasons of 1984/85 (NEUT), 1988/89 (WET) and 1991/92 (DRY), which were neutral, wet and dry respectively. For each season, one simulation was run with the SDGVM land-surface map and another with the default USGS configuration. The horizontal grid resolution was approximately 50km, and 23 vertical levels were used.

Results

Comparison of the computed climate variables for the SDGVM and USGS land-surfaces reveals some significant anomalies. Surface air temperature at 2m above the surface (T2m) shows similar responses for the WET and DRY seasons, with positive anomalies over much of the region, reaching over $2^{O}C$ in the vicinity of central Mozambique (Figure 25). There is a marked difference in the NEUT season, which shows negative anomalies over eastern Zimbabwe, south-eastern Angola and most of Botswana. Changes in specific heat flux are spatially consistent with temperature (Figure 26), with positive anomalies of over 30 W m^{-2} corresponding to the areas of maximum temperature increase. This response is mirrored by widespread negative anomalies of up to 40 W m^{-2} in the latent heat flux (Figure 27). This suggests that a general reduction in evaporation is causing the increased surface temperatures. The reduced evaporation must in turn be associated with decreased moisture availability at the surface. Patterns of change for convective precipitation (Figure 28) are more noisy than for the variables discussed above, but it does appear that the areas of strongest temperature increase and latent heat decrease coincide with areas of reduced rainfall.

Relationships between these anomalies and the differences in vegetation characteristics are not readily apparent, but some deductions can be made. The areas of warming and reduced evaporation seem to correspond to a greater dominance of trees in the SDGVM distribution as opposed to the extensive agricultural regions shown in the USGS data. An initial interpretation of this result may be that more widespread forests would result in a darker land surface and thus reduced albedo, hence higher temperatures. However, one would also expect denser vegetation to intercept more precipitation in its canopy and transport more moisture from the soil to the atmosphere through transpiration, thus increasing the potential for evaporative cooling. In addition, it is seen in the results that the areas of cooling do not correspond with large differences in the land surface characteristics. This suggests a connection with regional horizontal circulation features, the transport of moisture and formation of clouds.

Conclusion

This experiment has demonstrated that different representations of vegetation in the MM5 RCM can result in significant anomalies in climate parameters. In this case surface temperature, for example, varies by up to $2^{O}C$. This demonstrates the importance of land-surface representation in regional climate modeling and confirms the need for ongoing improvements.

2.1.9.2. Soil moisture over Southern Africa

Marshall Mdoka, an MSc student at the University of Cape Town, conducted the simulations presented in this section. Coming from the Zimbabwe Meteorological Service Mr. Mdoka was able to perform the simulations that had originally been envisaged as being run at the DMC in Harare. He has now installed and supervised the running of RegCM3 at the University of Cape Town and has embarked on his PhD studies there.

Climate studies were performed using a regional climate model RegCM3 at the International Centre for Theoretical Physics (ITCP), Trieste, Italy. The main objectives were to determine the capabilities of RegCM3 in simulating precipitation over Southern Africa especially for extreme conditions; to determine if the model can simulate variability between the driest and wettest periods and to assess the sensitivity of the climate model to initial soil moisture and the associated feedbacks. 1991/92 or 1982/83 (driest seasons), 1999/00 or 1995/96 (wettest seasons) and 1983/84 and 1990/91 (normal seasons) were the seasons chosen for the simulation experiments. However, the simulations and initials results presented here are based on the 1995/96 wet season.

The dynamical core of RegCM is based on the hydrostatic version of the Mesoscale Model version 5 (MM5). The atmospheric radiative-transfer computations are performed using the Community Climate Model version 3 (CCM3) and the planetary boundary layer computations being of non-local formulation. Large-scale precipitation are computed using a sub-grid explicit moisture scheme (SUBEX) developed by Jeremy Pal of ICTP. The unresolvable precipitation process (Cumulus Convection) is represented by the

Grell scheme with the Fritsch and Chappell Closure assumption. The surface calculations are from Biosphere-Atmosphere Transfer Scheme (BATS), which is a soil vegetation hydrological model.

The RegCM3 was forced with National Centers for Environmental Prediction (NCEP) initial lateral boundary conditions data at 60km resolution in a grid of 102 by 109. The model run simulations were carried out at a time step of 150s. The default model settings resulted in too much precipitation over the region as compared to the available daily rainfall data and the CRU and CMAP data. Several experiments were then carried out to try and fine-tune the model physics. Some of the parameters altered include the threshold values at which rain form in the cloud, reduction of the Convective Available Potential Energy (CAPE) within the Fritsch Chappell closure system, increasing the raindrop re-evaporation rate, changing the cooling rate of convection, reducing the rate at which precipitation forms from the clouds.

Soil moisture plays an important role in land-atmosphere interactions. A better understanding of the nature and characteristics of the feedbacks associated with wet and dry seasons is very important and would be a very positive contribution to intraseasonal variability predictions in the Seasonal forecasts. Simulations to exhibit the effects/feedbacks of modifications on the soil moisture conditions (wet, normal, dry) were carried out. The experiments were designed such that the model was initialised with 75% and 25% soil moisture for wet and dry conditions respectively. The values were chosen as the logging and wilting threshold values within the model. The simulations were done for the soil moisture being fixed at the two values throughout and then for those initial conditions but being allowed to be interactive with the model climate.

Results:

The results from modifying the model physics had different effects to precipitation's spatial distribution with some areas being dried up and at times increasing the wetness elsewhere. The selected option was for an increase in re-evaporation rate of the raindrops with everything else being under the default settings within the Grell scheme.

Some point storms were observed in the simulations for mid-tropics areas especially near lakes and high terrain (Figure 29). This can possibly be associated with some local effects or the lake model scheme. Although, this simulation still overestimated precipitation over much of the region as compared to the observed daily station data and CRU/CMAP, the spatial distribution over mid-latitudes and areas of study was almost similar. There was an underestimation in some zones especially over northeastern South Africa and Swaziland (Figure 29).

Preliminary results (Figure 30) show that most of Zimbabwe, Zambia and DRC are sensitive to soil moisture changes whilst the western parts of the region are less responsive. However, these feedbacks as shown by the anomalies might be occurring at a different place from the original perturbation due to circulation patterns, advecting moisture into these zones.

The model depicts that when fixed at 25% soil moisture surface temperatures are increased for most of the region except for the western parts (Figure 31). The evapotransiration is thus reduced in response to the drier and warmer conditions. The northeastern portion of the region where the surface temperatures are higher has a significant drop in the evapotranspiration rate. As for the western areas, increase in surface temperature seems to be reasonable as the model shows those areas to be mostly dry in the January 1996 precipitation simulation. Fixing the moisture at 25% implies that there is more moisture for that region as shown in Figure 31.

The RegCM3 precipitates too much rainfall over Southern Africa although it is able to capture the inter-annual variability and associated wet and dry conditions. There are some boundary problems and this also requires a good choice of domain for better representation of the simulations. As for the sensitivity of the model to soil moisture conditions more simulations are required and look at other parameters such as latent and sensible heats. A suggested approach of analyzing the diurnal cycles will also be adopted to try and improve on model's precipitation simulations. Temperature simulations for the region depicted a very good representation.

Future activities:

- Run simulations for dry and normal seasons.
- Look at circulation patterns and moisture trajectories to aid in the feedbacks analysis.
- Assess the sensitivity within a window of interest whilst maintaining conditions elsewhere.

- Examine MM5 output from similar experiments.
- Use of the RegCM3 model in forecasting.
- Derive a PhD thesis from this preliminary work.

Acknowledgements:

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2.1.9.3. Land-surface fluxes over West Africa

The following work on land-surface fluxes over West Africa was conducted by Dr. Joseph Intsiful (Ghana) whilst undertaking PhD studies in Germany. He attended the original MM5 training workshop and most AF07 project meetings in Cape Town. The following summarises some of the research he accomplished whilst investigating the land-surface schemes within the regional climate models MM5 and RegCM3.

RegCM3:

RegCM3 was applied to the West African sub region for model validation.

Model inadequacies for predicting key climatic variables (e.g., temperature and precipitation) were observed. In particular, peak precipitation was simulated at locations not identified in the observations. Although the temperature pattern was captured quite well the model had noteable biases in the magnitude.

Possible causes of errors may be due to the landuse map, which is not representative of the region. Therefore one recommendation is for a more realistic landuse map. Additionally, the values for the land surface parameters were not accurate enough in the current landuse table.

A recommendation was also made to improve the convective rainfall schemes to enhance the simulation of rainfall.

MM5:

MM5 was applied to the West African subregion. The key climatic features (e.g., temperature and precipitation) were captured quite well. However, there is the need to improve on the magnitude of the simulated state variables.

In particular, the land surface parameters in the model were not representative of the observed (real) land surface parameters. There is, therefore, the need to improve on the land surface parameterisation.

Ongoing work aims at improving the accuracies of land surface parameters for the region.

BATS land surface model

The BATS scheme (used in RegCM3) was used to study the impact of bushfire-induced landuse change on the energy dynamics of the northern region of Ghana. The experiment was carried out during the hamattan season when bushfire commonly occur. The model was initialised with observed data; the simulations were carried out over a week. An Analysis was undertaken of the surface energy fluxes and moisture indicators. The results are consistent with observations. Measured soil physical properties were used to derive soil hydraulic parameters using empirical relationships. The default values in the BATS scheme were replaced with the derived values. More importantly, the results show that bushfire causes threshold changes in the energy and hydrological dynamics of the area. The BATS scheme looks very promising, as it accounts for seasonal variations in most critical land surface parameters. Extensive tuning of the land surface parameters would be a significant step towards improving climate predictions.

NOAH land surface model (LSM)

The NOAH LSM (used in MM5) was applied to investigate transpiration over a landuse transition zone (Ejura) in the middle part of Ghana. The NOAH LSM was coupled to a highly efficient nonlinear parameter estimation tool where some key vegetation parameters (roughness length and minimum stomatal resistance) were tuned. Good agreement was realised between the modeled and observed values. Additionally, the soil and vegetation components of the NOAH LSM, were reprogrammed in a Mathematica environment to study the sensitivity of evapotranspiration and the energy budget to the soil and vegetation parameters. This offered much flexibility to study the effect of perturbed land-surface parameters on the energy and hydrological budget. The main limitation of the NOAH model is that it does not account for seasonal variations in land surface parameters. This is particularly important for areas of bushfire prevalence and semi-deciduous vegetation. This exercise constitutes a significant step towards improving estimates of land surface parameters for the region.

Thesis work

Research into subgrid scale effects was undertaken for the thesis work. The motivation for this research came about as a result of the inability of existing climate models to properly capture subgrid scale effects associated with the savanna-mosaic and other forms of landuse types in Africa. The GLOWA-Volta project (ZEF), which was developing a decision support system for the sustainable use of water resources in the Volta Basin, West Africa, proposed research into the derivation of effective land surface parameters that produce scale-invariant representation of surface energy fluxes and moisture indicators. A model-independent method was developed for upscaling land surface parameters through inverse-SVAT modeling. Functional relationships that map the mean and standard deviation of distributed land surface parameters at the subgrid scale to their corresponding effective parameter at the grid scale were developed. Comparison of the proposed method to selected well-established methods shows better performance. Simpler, less CPU-intensive relationships were derived from the experimentation that yield comparable results and hence are very attractive. More importantly, the methodology is applicable to other fields where parameter refinement or model calibration is required.

2.2. Scenarios of Future Climate

This section covers the different methods utilized for predicting future climate change within the AF07 project. Broadly speaking this covers three major thrusts: direct use of GCM predictions/outputs, statistical downscaling of GCM dynamical fields and dynamical downscaling of GCM dynamical fields. The first of these methods is described in section 2.2.1, which also presents a method for smoothing the noisy rainfall predictions typical of GCM output. A novel method for statistical downscaling of GCM fields and predictions for the late 21st century are presented in section 2.2.2. Preliminary results from some of the ongoing dynamical downscaling predictions being generated at the University of Cape Town are presented in section 2.2.3.

2.2.1. Guided Perturbations And GCM Output

This section lists two sources of GCM output. The first describes the output from the ECHAM 4 model that was obtained from the Danish Meteorological Institute. This data was 6-hourly output for the model prognostic variables. This large amount of data was required to force the regional models and provided boundary forcings for dynamical (and statistical) downscaling. The second source of data was monthly mean GCM fields obtained from the IPCC DDC and this data was subjected to the guided perturbation methodology and distributed on CD to other AIACC projects.

2.2.1.1. ECHAM 4

The Danish Meteorological Institute was involved in AIACC project AF07 through Dr. Martin Stendel. Their contribution to the project was fourfold:

- Liaison to the ECHAM modeling and user group in Europe.
- Contribution of results from a coupled simulation with the ECHAM4/OPYC model to the AIACC partners.
- Expertise in global modeling with ECHAM, including strengths and weaknesses of the model in different regions of the Earth and under different forcing scenarios.

- Investigation of multicentury temperature and precipitation variability and change under realistic forcing assumptions.

The regional simulations run by the individual AIACC partners all require GCM input. One of these global models is the coupled Hamburg climate model, ECHAM4/OPYC. In the framework of this project, the results of two climate change simulations performed at the Danish Meteorological Institute were distributed to the AIACC partners.

ECHAM4 is the fourth version of the Hamburg climate model, which is based on the *EC*MWF weather forecast model. Prognostic variables are vorticity, divergence, surface pressure, temperature, water vapour and cloud water. ECHAM4 is a spectral model with a triangular truncation at wave number 42, which is equivalent to a horizontal resolution of about 2.8 degrees. Water vapour and cloud water are advected using a semi-Lagrangian scheme. The tropospheric sulfur cycle is calculated from past observations and future projections of sulfur emissions according to these scenarios. Both the direct and the indirect (cloud albedo) radiative effect of the aerosols are considered.

An increase of precipitation over land and a concomitant decrease over the oceans is found in the future climate change scnarios. Sea ice decreases dramatically in the shelf seas of the Arctic, whereas there are only minor changes for Antarctic sea ice. A poleward displacement and intensification of the storm tracks is found in both hemispheres.

The ocean and sea ice component is based on the OPYC model. OPYC is an isopycnal model consisting of three submodels for the interior ocean, the surface mixed layer and for sea ice, respectively. The horizontal resolution of the ocean model is the same as for the atmosphere except for an equatorial refinement to about 50 km, required to realistically resolve El Nino. The model components are coupled through an exchange of fluxes of momentum, heat and water vapour. For the latter two, an annual flux adjustment is required.

Two climate change simulations covering the period 1990 to 2100 have been run at the Danish Meteorological Institute (IPCC (2001), see Stendel et al. (2000) for a detailed description of the experiments). In these simulations, ECHAM4-OPYC3 is used to assess the time-dependent climate response to changing concentrations of greenhouse gases and sulfate aerosol. For the period 1860 to 1990, the concentrations have been prescribed according to observations, whereas for the period 1990 to 2100, projections according to the IPCC scenarios A2 and B2 have been used. These simulations have been made available to the AIACC partners.

In addition, a 500 year simulation covering the period 1500 to present has been performed. In this simulation, all relevant natural and anthropogenic forcings have been taken into account: solar irradiation changes, greenhouse gas and CFC concentrations, sulfur emissions as described above, anthropogenic vegetation changes and optical depth changes due to volcanic activity. As a novel approach, the volcanic dataset has a latitude dependency. The optical thicknesses are expressed as anomalous forcings. Since the actual position of the Sun is taken into account for the shortwave forcing, marked differences with respect to globally averaged volcanic datasets can be found in high latitudes.

The investigation of the dataset resulting from this simulation has not yet been finished. The results will be made available to AIACC partners after this has been achieved, e.g. for a long-term assessment of climate variability and change over sub-Saharan Africa.

2.2.1.2. Guided perturbations and DDC data

Project AF07 has produced two data CDs for distribution. These CDs contain climate information and climate change scenarios specifically for the African continent. These scenarios have been disseminated so that they can be used by research scientists in other AIACC projects.

The first of these CDs contained GCM model data downloaded from the IPCC Data Distribution Centre (DDC). Availability of this data to researchers on the continent is limited due to the difficulty of obtaining this data via the internet, as a result of limited bandwidth at most research facilities.

Project AF07 therefore obtained this data from the DDC and provided it on a CD. The original data was downloaded in GRIB format. The data was then converted into a GrADS compliant format to facilitate the visualization and analysis of the data. The data was also made available in ASCII format for those users who did not utilise GrADS (this program was made available to the users on the same CD). The data CD contained the output data from six GCM models available through the DDC. These are the HADCM3, ECHAM4/OPYC3, CSIRO-Mk2, CCCMA, NCAR-CSM and NCAR-PCM models. The model output data is available globally as monthly mean values for the variables; maximum surface temperature (tmax), minimum surface temperature (tmin), total precipitation (prec) and sea surface temperature (ts). From this the output for the A2 and B2 SRES scenarios for the African continent was extracted. The time period simulated differ amongst the models as well as between the scenarios, and the CD contains the time-range available at the time of downloading the data. From this data, sample of images were generated to allow a quick look at the model results, and to facilitate those individuals who may not have access to the necessary software to view the binary data. GIF images of the long-term monthly means for the model, (i.e from the start of the simulation to the end) as well as images of the 'control' and 'future' monthly means were constructed. In addition, monthly average anomaly (future-control) images were also produced. Inter-model comparison was also carried out with these data sets, and inter-model range images were constructed and provided on this CD. The CD also provided a brief description of the GCM models whose data is provided with access to the corresponding research institute's websites.

The second CD produced by project AF07 contained station data for the African continent. The station data are from the Climate Prediction Centre Global Summary of Day/Month Observations, beginning in 1979. The home page of this data set is found at http://dss.ucar.edu/datasets/ds512.0/. The data was obtained from the NCAR archives with the help of Mr. Francis Otieno, of the Iowa State University. The data in ASCII format contains a list of days with the recorded maximum, minimum temperatures as well as precipitation. The data was also made available in GrADS station data format. This CD also provided the users with a set of "guided perturbation" scenario data. The method used for this purpose is explained in greater detail in the AIACC Newsletter and EOS publication written by Prof Bruce Hewitson (Hewitson 2003). This procedure was developed to help researchers to examine the system sensitivity to larger scale climate perturbations before trying to attempt to downscale GCM data. This method was then applied to the station data set obtained from CPC to produce monthly precipitation anomaly values as well as maximum and minimum values. The procedure followed is outlined below;

Monthly Precipitation anomaly values:

The DDC data for each GCM was first smoothed and regridded using GrADS. The monthly percentage anomaly for the domain was then calculated as follows;

- Percentage anomaly=(Future value-Control value)/Control value
- where Control value is the monthly average between 1979-1999 and future value is the monthly average between 2079-2099. From this the monthly percentage anomaly for each station was obtained from each GCM perturbation calculations using the station coordinates. The monthly percentage anomaly was then **multiplied** with the corresponding monthly climatological average calculated using the station data. This gives a result of the expected change/anomaly for the future condition under a given climate change scenario using a particular GCM output.

Monthly Maximum and Minimum Temperature values:

The DDC data for each GCM was first smoothed and regridded using GrADS. The monthly anomalies were calculated simply as;

- Temperature anomaly=Future value-Control value
- where Control value is the monthly average between 1979-1999 and future value is the monthly average between 2079-2099. The temperature anomaly for each station was obtained from each of the GCM calculations and was **added** to the station climatological mean to obtain an absolute value for the future under a given climate change scenario and GCM. All the 'guided

perturbation' data was made available as a single EXCEL spreadsheet. This same method was applied to a set of station data for the Seychelles archipelago upon specific request from the research group based there. The research group provided the station data and a 'guided perturbation' data set using the same DDC data set was produced and provided to them. An ISO image for the two CDs produced by project AF07 was provided to the AIACC secretariat (via Neil Leary) for wider distribution amongst the research groups in the continent.

2.2.2. Statistical downscaling

The statistical downscaling procedure is developed, in part, from previous work and in partnership with the SA water Research Commission (WRC) project on developing regional climate change projections. The WRC project focused on specific elements of the problem, while within this project the procedures were further developed and extended to encompass the full African continent.

Methodology

This methodological description is largely drawn from the paper currently in submission by Hewitson and Crane (2005b). Empirical downscaling is a widely used technique for exploring the regional and local-scale response to global climate change as simulated by comparatively low resolution Global Climate Models (GCMs). As noted in the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC, 2001), empirical approaches have similar skill levels as current implementations of numerical Regional Climate Models (RCMs).

Empirical downscaling is conceptually very simple and is based on the premise that the local scale climate is in some measure a response to the larger, synoptic-scale, forcing. Observational data are used to derive a relationship between the synoptic scale and local climates, and that relationship can then be used with comparable resolution fields of a GCM to generate information on the local climate consistent with the GCM forcing. The assumption that the local climate is conditioned by the larger-scale forcing is reasonable, even where the local climate is governed by mesoscale events such as convective systems, as these are, in turn, conditional on the synoptic state.

Synoptic-Scale versus Local Forcing

While it is true that the synoptic-scale forcing will have some influence on local climate, there is also a degree of local forcing that will vary by region and by season. This local forcing can be both fixed and variable. Topography and land-water boundaries represent a fixed forcing for the local climate. The degree to which that forcing impacts the local climate is, however, also a function of the larger-scale flow. Consequently, the effects of this local forcing can be readily incorporated in the downscaling transfer function if appropriate measures of flow direction, stability, etc. are included in the predictor variables.

Variable local forcing would include, for example, land use and land cover change. For some regions, this could have a major impact on local climates, which can't be captured by empirical downscaling techniques. While impacts analyses can examine possible land cover/land use changes as one of a set of multiple stressors, the degree to which land cover changes can feedback to impact local climate represents a element of uncertainty in the climate projections analogous to, for example, uncertainty due to future levels of greenhouse gas emissions.

In addition, for any synoptic-state, there may be variation around a generalized response conditional on, for example, antecedent soil moisture. This small-scale variability is not captured by the GCM and the effects, therefore, are not included in the transfer function. These variations become a stochastic permutation of the response to a given synoptic state and can be modeled as such. Some downscaling methodologies are more appropriate for extracting the direct synoptic-scale forcing, while others are more effective at generating the stochastic element. At the same time, some techniques capture only the linear forcing, while others may capture any non-linear forcing that may be present.

Stationarity

Given that there is a relationship between the larger-scale and the local climate, and assuming an appropriate downscaling transfer function can be generated, an empirical downscaling of present climate is eminently feasible. However, an additional factor becomes important when considering future climates – that of stationarity of the downscaling function. It is not immediately obvious that a relationship derived for the present climate can be applied to a future climate state. Empirical downscaling implicitly assumes that the observational data from which the relationship is developed encompasses the required information for future cross-scale relationships. Essentially, this assumes that, for a given region, dominantly the same synoptic-scale states are present in the future and that climate change will for the most part manifest itself as a change in the timing, persistence, and frequency of these larger-scale events. While we can't verify stationarity until after the fact, we can at least make some assessment of the likelihood based on the changes in the large-scale climate of the GCM.

More difficult to assess is the possibility that the nature of the transfer function itself will change in the future. It is possible that the same synoptic situation will result in a different temperature, precipitation amount, etc. in the future -- i.e. the future pattern could be wetter or drier than its present day counterpart. Some element of this problem also exists for numerical models where sub-grid-scale parameterizations are based on empirical relationships derived from present day observations. The potential problem, however, is probably greater for empirical downscaling. The degree to which this is likely to be an issue will depend on the time scales considered (the further we project into the future the more likely this is to be an issue) and also on the choice of predictor variables used.

Predictor Variables

Past work (e.g. Hewitson and Crane, 1996; Cavazos and Hewitson, 2005) has shown that the choice of predictor variables is critical in capturing the anthropogenic climate change signal in the GCM. By using fields that reflect the primary circulation dynamics of the atmosphere one captures part of the synoptic-scale forcing. Neglecting the inclusion of some measure of atmospheric humidity as a predictor, however, could have a notable effect on a downscaled climate change precipitation signal (see Hewitson and Crane, 1996; Crane and Hewitson, 1998). For a precipitation downscaling, including humidity not only improves the transfer function predictions for the present climate, it also reduces the stationarity issue noted above as the dynamics and the humidity fields become separate predictors in the downscaling function. From this perspective, it is essential to have multiple predictor variables that have an understandable physical relationship to the downscaled parameter. Relationships that are purely correlative and for which there is no clear physical process linkage should be avoided.

Temporal Resolution

Downscaling from time-mean fields is clearly feasible. However, it is important to recognize that in some regions, climate change may be manifest as changes in the histogram of daily synoptic-scale events, with or without a change in the mean itself. Downscaling from time-averaged fields thus runs some risk of missing an important climate change signal.

In summary, the major issues to be addressed in any downscaling application should include:

- An assessment of the strength of the synoptic scale forcing on any given variable for a given location. In other words, an assessment of the relative importance of synoptic-scale, local, and stochastic forcing, and of the degree to which the synoptic-scale forcing is linear versus non-linear. In practice, this is most effectively accomplished through validation of downscaling product. The degree to which the local climate of a test data set is reproduced by the downscaling function is an indication of the relative strengths of the large-scale versus local forcing.
- An assessment of the degree to which the future climate regime is reflected in the observational data used to generate the relationship (i.e. the stationarity issue).
- The use of predictors that reflect the physical processes controlling the local climate response.
- Downscaling at the time scale of daily weather events, even if these are to be subsequently aggregated in some fashion for impacts analysis.

The utility of the final product will also depend on the GCM(s) used for the analysis, the quality and duration of the observational network, and issues related to specific techniques (for example, assumptions about data distributions that may be inherent in a particular statistical model). How all of these are addressed will affect the quality and the reliability of the downscaled climate projections. In some cases, this assessment process may indicate that empirical downscaling is not a viable approach for a particular region, application, or data set.

Downscaling with Self Organizing Maps

A Self Organizing Map (SOM) is a data description and visualization tool that extracts and displays the major characteristics of the multidimensional data distribution function. SOMs are typically depicted as a two dimensional array of nodes where each node is described by a vector representing the mean of the surrounding points in the multidimensional data space. SOMs were introduced by Kohonen (1989; 1990; 1991;1995) and examples in the literature include their potential applications to synoptic climatology (Hewitson and Crane, 2002), precipitation regimes (Crane and Hewitson, 2003), and interpolation schemes (Hewitson and Crane, 2005). SOMs were used by Malmgren (1999) and Cavazos (1999; 2000) for climate classification, by Hudson (1998) to examine synoptic circulation changes in GCM perturbation experiments, and by Ambroise et al. (2000) for cloud classification. Other related applications of SOMs are discussed in Cavazos et al. (2002), Huang et al. (2003) and Tennant (2003).

The SOMs are developed in an iterative training procedure. The SOM is a user specified 2-dimensional array of nodes, each defined by a reference vector of length n. For a (n x m) data set where n is the number of variables and m is the number of observations:

- We take the m'th observation vector and compare to each of the node reference vectors in the SOM (typically using Euclidean Distance as the measure of similarity). The reference vector that is closest to the observational vector is the "winning node."
- The reference vector of the winning node is then updated, adjusting it slightly in the direction of the observational vector by a user determined factor that represents the "learning rate" □, which is incrementally reduced through the iterative learning.
- All surrounding nodes are also updated, again being adjusted slightly (to a lesser degree than the winning node) in the direction of the observational vector. The radius of nodes around the winning node that are updated is determined by the "update kernel" that decreases that decreases in radius during the iterative learning.
- Each observational vector is then presented to the SOM in turn and the procedure repeated for all of the observations.
- The process is then repeated for multiple iterations until there is no change in the node assignment of each observation between iterations.

SOMs have some particularly advantageous characteristics from the point of view of climate downscaling:

- As noted above, each node reference vector is the n-dimensional mean of the nearby cloud of data points. The distribution of the SOM nodes in the data space is a function of data density and data similarity. The SOM mapping, therefore, provides a simple and effective visualization of the n-dimensional data structure.
- More nodes are, after training, located in areas with greater data densities, and fewer nodes where there are fewer data points. Because the update kernel adjusts surrounding nodes during the training process, it is possible that, if sufficient nodes are available (i.e. a large enough SOM), the SOM may also locate nodes in regions of the data space where there are no observations – in effect interpolating.
- SOMs, unlike statistical models, make no assumptions about the underlying data, and the iterative training allows the SOM to describe any arbitrary linear or non-linear data distribution function.
- The SOM is very effective at handling missing data in the observational vector.

In this application we use daily mean fields constructed from 6-hourly NCEP reanalysis data for 1979 to 2002, restricting the range to post 1979 when the advent of satellite data for the reanalysis significantly improved the quality of the reanalysis for the southern hemisphere. In this implementation the NCEP and GCM data are regridded to a common compromise grid of 3° by 3°. The data used to characterize the atmosphere are comparable to the boundary conditions used to force an RCM; and include the u and v wind vectors (surface and at 700hPa), temperature (surface), specific humidity (surface and at 700hPa), and relative humidity (surface and 700hPa). Both relative and specific humidity are included, as the former reflects how close to saturation the atmosphere is, while the latter reflects the total water content.

Two precipitation data sets are used; the high resolution gridded data set for South Africa described by Hewitson and Crane (2005a), and a station data for Africa, which although sparse, allows a perspective of the continental scale changes. The location of the precipitation data define the locations of the downscaling targets – the locations for which the atmospheric data are to be used to predict the local precipitation response.

The SOM Procedure:

A separate SOM is produced for each N x M window of the atmospheric data that overlays the downscaling targets, where a N x M window (currently 3 x 3 grid cells; ~1000km by 1000km over the domain of downscaling target) has the central grid cell most closely co-located with the target location. The trained SOM, using the selected atmospheric variables (above), characterizes the generalized daily atmospheric states. In this implementation, 9 selected variables for each of the 9 grid cells in the 3 x 3 window) create an 81-element vector describing the atmospheric state. The time series consists of 24 years of daily data. The individual height, specific humidity, and temperature fields are first standardized using the means and standard deviations of the N x M cell time series, thus preserving the local gradients in each field. These fields are then used to train a SOM of 9 by 11 nodes (allowing for 99 possible generalized atmospheric states, which if the observations were equally distributed across the nodes would lead to ~90 observations defining the generalized state represented by any given node).

The training uses the two-step process described above, with 500,000 iterations for each training step. Each day in the time series then maps to one of the trained 99 (of the 9 by 11 node array) different atmospheric states described by the SOM node vectors. This procedure is repeated for each downscaling target, so that, for each target, there is a unique set of possible synoptic states described by the spatially coincident 3x3 atmospheric window. As some targets in this application are close together, some targets will share a SOM of a common spatially coincident atmospheric window.

Determining a synoptically controlled precipitation PDF for each precipitation grid point:

For each target location in the precipitation data set, we take the most closely co-located GCM 3x3 window and related SOM. For each SOM node, we take all of the days that map to that node and subset the related daily precipitation. We then:

1. Rank order the precipitation observations for the node.
2. Fit a spline to the ranked data.
3. Interpolate off the spline to M ranks (typically 100). This forms the PDF of the rainfall for the node. This approach accounts for the fact that the nodes may have differing numbers of observations.
4. Repeat for all nodes in the SOM.
5. Repeat for all target grid cells.

Every target location is thus described by 99 different PDFs related to the 99 generalized atmospheric states.

Downscaling:

Using the same atmospheric window and the atmospheric variables that we used to train the SOM, the relevant data are extracted from the GCM data. We then standardize the GCM data using the same procedure as we used with the NCEP data. For the GCM simulation data of future climate, we standardize using means and standard deviations of the simulation data for the present day climate, hence preserving any changes in the future from the present day means and standard deviations. We then map these data to the already trained SOM, and find the node to which each atmospheric state of the GCM maps. In other words, for every atmospheric domain coincident to a given target location, we have a SOM that describes the synoptic states associated with that domain as derived from observational data, and we have mapped the daily atmospheric states of the GCM control and future climate simulation data onto that same set of observed synoptic states.

To downscale the precipitation data we take each target location and associated SOM of atmospheric states. For the SOM node to which a particular day maps we can then determine a precipitation value from the associated PDF generated in the earlier step by randomly selecting from the PDF. A random number generator is used to select a value (r) between zero and one, which is then multiplied by M (number of ranks extracted from the spline of the PDF) to determine where on the PDF to read the precipitation amount. This approach works reasonably well; it generates rainfall events of the correct magnitude but slightly underestimates the number of raindays in regions of higher rainfall amounts. For these regions, there is some degree of temporal autocorrelation that is not completely captured by this approach. Some persistence is included through the dependence on the synoptic state. However, a given state does not always produce rainfall – a factor that is accounted for by the PDF – but if a given state produces rainfall on day 1, it is likely that a similar state will produce rainfall the next day as well. The degree of persistence varies for each grid cell and for each synoptic state. It probably varies by season and may not be the same for a future climate state. For this reason, we account for persistence by simply modifying r (the random number generator). If rainfall occurs on day 1, then for day 2 we use the $\sqrt{r}$ generated for day 2. Using $\sqrt{r}$ nudges the selection slightly toward the wetter end when the antecedent day was wet, but as rainfall only occurs in approximately the top 30% of the PDF, this does not have a large impact. However, it does increase persistence slightly in the wet areas without the need to explicitly calculate persistence for every individual data point and time period.

Once the rainfall values have been extracted, we continue to generate the full time series (daily data for the length of record being used) and repeat this 100 times. That is, we produce 100 time series with slight variations due to the random selections from the PDFs, but where each record is still constrained by the same larger scale atmospheric controls. For each of these 100 records we calculate monthly precipitation statistics including:

1. Number of rain days
2. Number of rain days with greater than 2mm rainfall
3. Number of rain days with greater than 20 mm rainfall
4. Total rainfall in the month
5. The 90th percentile rainfall event
6. The mean and median dry spell duration.

For each month we determine the mean, median, and standard deviation of the above statistics across the 100 time series of monthly statistics, thus generating a monthly time series that reflects the median and mean responses within the stochastic envelope. The standard deviations present a measure of variability that is due to the stochastic contribution to precipitation at any target location, where the stochastic contribution has been conditioned by the larger-scale forcing. Finally, we take the monthly time series with the closest match to the median monthly time series of the iterations, and save the daily form of this as a representative time series of daily values.

<u>Projected climate change</u>

In this report we focus on the Africa projections; further details of the methodology and related tests are in Hewitson and Crane (2005b) along with the South Africa gridded projections. In addition, the raw data products are being distributed to relevant interested impacts researchers, and a web site for more accessible distribution is in development.

Shown in Figure 32 through Figure 35 are the downscaled precipitation projections for Africa. In each case the mean anomaly is shown for the austral summer (December-January-February) and the austral winter (June-July-August).

Figure 32 shows the climate change anomaly of mean monthly total derived by differencing the downscaled control and future daily atmospheric data of the three GCMs. Two facts are of immediate note; the downscaling provides regional detail that is consistent with the actual spatial gradients over the region, and the pattern agreement of positive and negative changes are remarkably consistent across the three GCMs. The most reasonable explanation for the cross-GCM agreement is that the GCM's atmospheric circulation dynamics are responding in like manner to global forcing. This suggests that the spread of projected change that is found when considering the GCM native parameterized precipitation is possibly due in part to the parameterization itself, whereas the models are far more consistent in their circulation. As the circulation conditions the downscaling, this allows the downscaling procedure to focus on the coherent circulation changes, and in turn, generate a downscaled change signal that shows a strong pattern agreement between GCMs.

As noted earlier, since the downscaling generates daily data, it is possible to calculate a number of relevant statistics about the attributes of the daily precipitation. Figure 33 through Figure 35 show the climate change anomaly in terms of, respectively, the number of raindays, the 90th percentile event, and the magnitude of the median precipitation event. These are parameters of particular significance to hydrology and water resources, as well agriculture. At the same time, these are difficult parameters to estimate from GCMs, as the GCM grid cells tend to precipitate on most days, being a large area average parameter. The downscaled derivative statistics of Figure 33 through Figure 35 track the spatial changes in rainfall totals to a fair degree, but not completely, in some cases showing an decrease in raindays where totals increase, or vice versa, and indicating that there are changes in intensity as well.

In general some notable coherent changes emerge from the analysis. The strongest changes are related to the Sahel region and the east Africa rift valley. Over the Sahel there is an indicated strong drying in the main precipitation belt, with complementary increase in precipitation in some coastal regions, and also on the arid boundary to the north. Over the east Africa rift valley region there is a strong increase in precipitation. Less strong, but nonetheless spatially cohesive, are drying over the north Africa coast and in the south west of sub-equatorial Africa. The changes in the derivative statistics of rainfall in general mirror these patterns, and where rainfall is increasing there is a coincident increase in intensity and in the number of raindays, and vice versa in regions where reduced rainfall is indicated.

The downscaling is being extended to additional GCMs (9 in total). The results, both in terms of time series of daily data, and as mean changes, are available to impacts researchers. A web site is in development for facilitating distribution.

2.2.3. Dynamical downscaling

The dynamical downscaling of multiple GCMs using even a single RCM is CPU intensive and generates a large amount of data requiring large storage volumes. Nevertheless within this project we have embarked upon using 2 RCMs (PRECIS & MM5) and 3 GCMs (CSIRO, ECHAM4 & HadAM3P) for dynamical downscaling. Using multiple GCMs and RCMs is believed necessary to fully capture the range of uncertainty inherent in model representations of the climate system. In particular multiple GCMs represent a range of possible changes in the lateral or synoptic forcings whereas multiple RCMs represent a range of local responses to those forcings. The former is exemplified in section 2.1.5 where it was shown that the three GCMs had different biases in their representation of the mid-latitude westerly flow that will result in different forcings at the southern boundary of an RCM. This will affect the representation of tropical temperate troughs, which are an important rainfall producing mechanism over southern Africa. The latter issue, namely that of how an RCM represents the local response, is highlighted by the findings in section 2.1.7. There it was demonstrated that an RCMs hydrological cycle is dependent on the choice of convective parameterisation. This tendency for a model to convect/rain affects the formation of clouds and evapotranspiration at the surface, thereby altering predicted temperature changes in a future climate. It also affects how responsive the model is to the GCM large scale forcing.

The following two sections present preliminary results from the two RCMs nested within the same GCM field (that of HadAM3P). They are extracted from short periods within the ongoing data generation exercise and are presented here to illustrate how at the broad scale the RCMs produce similar projections of change, yet at the local scale the choice of RCM clearly affects the downscaling results. An in-depth comparison and discussion of these results can be found in Tadross et al. (2005b)

2.2.3.1. <u>PRECIS</u>

The PRECIS RCM is a regional version of the UKMO unified model. A domain at 0.44 degrees resolution was configured over southern Africa and the model forced with lateral boundary conditions from HadAM3P, the Hadley Centre global atmospheric model. The lower boundary forcing is provided by observed SSTs for the control and future SSTs are calculated as the HadCM3 (coupled model) predicted change in SST added to the observed SST. An interactive land surface is allowed to freely evolve in the model. Altogether 30 years of control (1960-1990) and 30 years of future (2070-2100, A2 scenario) will be extracted. However the results presented here are for only the first 20 years of each simulation as this is an ongoing activity.

Figure 36 demonstrates the predicted change in the number of rain days (rain day is greater than 0.1 mm) per month over the southern African domain. There is a tendency for less rain days to be found over the western tropical regions during most months and this corresponds with an increase in high pressures simulated by all three GCMs over this region (see section 2.1.5). Over the eastern oceanic regions there is also a tendency for less rain days whereas over the landmass there is a mixed response. During October there is a notable reduction whereas for the peak summer months (January – February) there is an increase in rain days over the eastern portion of subtropical southern Africa.

The results for 2m surface temperature change are presented in Figure 37 and not surprisingly show an increase in temperature, the magnitude of which is dependent on location and time of year. Again it is the western tropical region that most consistently presents the largest increases in temperature, especially during late winter and early summer. Concomitant with the reduced rainfall in October in Figure 36 there are large increases in surface temperature, highlighting the association between rainfall, cloud cover, evaporation and surface temperature. It is also important to note that projected changes in both precipitation and temperature vary significantly depending on the location and time of year which is of interest.

2.2.3.2. *MM5*

For the results presented here MM5 was configured to use the Kain-Fritsch convection scheme and MRF planetary boundary layer. This choice reflected the results presented in section 2.1.7 and a desire to use a model configuration that together with the PRECIS data presented earlier would span a range of RCM hydrological cycles. Tests not shown here suggested that PRECIS simulated too many rain days and a diurnal cycle of rainfall that peaked too early in the day. Although the MM5 configuration used here also simulated too many rain days it is less than PRECIS and the intensity of rainfall is greater (Tadross et al. 2005b). To fully explore the range of uncertainty due to the RCMs hydrological cycle future work will produce the same scenarios using the Betts-Miller scheme in MM5 as that scheme was earlier shown to simulate too few rain days and a late peak in the diurnal cycle of rainfall. A domain at 50 km resolution was configured over southern Africa and the model forced with both lower and lateral boundary conditions from HadAM3P (for the results presented here – similar data forced by ECHAM4.5 and CSIRO are currently being produced). An interactive land surface is allowed to freely evolve in the model. Altogether 15 years of control (1975-1990) and 15 years of future (2070-2085, A2 scenario) will be extracted. However the results presented here are for only the first 10 years of each simulation as this is an ongoing activity. These results can be directly compared with the results presented for the PRECIS model earlier.

Figure 38 & Figure 39 present the predicted changes in monthly rain days and surface temperature respectively. They are the MM5 equivalent of Figure 36 & Figure 37. Contrasting the four figures it is apparent that the tendency for less rain days over the western regions is simulated by both model configurations. Both models also indicate an increase in rain days over the south-eastern continental regions during peak summer. However, there are indications that each model is predicting changes in line with their known bias in the simulation of rain days e.g the control climate of each model simulates a rain day minimum towards the south-east, allowing the largest increases in this region, presumably due to increases in thermal heating in the future climate. Similarly, as PRECIS simulates on average more rain days than MM5, it is able to simulate a larger decrease than MM5 during October. This cautions against using RCM-projected absolute changes for impacts research and suggests that rather the RCM data be used to perturb observed rainfall (and other) data. Again the changes in surface temperature are projected to be 1-5°C and clearly reflect the changes in rain days (which are associated with changes in cloud cover and evaporative cooling due to rainfall). For a more rigorous comparison of these two datasets the reader is referred to Tadross et al. (2005b).

It remains to be seen whether these indications will be consistent with the final results once all simulations are complete. However, in the light of known biases in the models they are enough to urge caution when trying to interpret the results of a single RCM.

3. Capacity Building Outcomes and Remaining Needs

Much of the capacity building through project AF07 followed on from earlier efforts at developing local capacity to undertake regional climate modeling. A significant part of this effort had been the workshop, held at the University of Cape Town during June 2001, which brought together climate modelers from around Africa to learn how to use the MM5 RCM. After this workshop a number of individuals who were able to continue these efforts in a range of African countries (Ghana, Senegal, Nigeria, Zambia and Zimbabwe) were identified and asked to participate in AF07. Through AF07 these participants (listed below) were given desktop computers and software with which they could run the MM5 RCM.

3.1. Capacity Building in Zambia

Contact: Mrs. Suman Jain, Department of Mathematics, University of Zambia (UNZA).

In particular Mrs. Jain undertook the following research activities, which were made possible through having access to the computer and data provided as part of the AF07 project:

1. Supervised an undergraduate project course P495 as a part of Physics major programme to Fred Nambala in numerical climate modeling using MM5.
2. Supervised a post graduate student Gilbert Phiri in constructing precipitation scenarios from HADCM3 simulations for the ESKOM project.

Problems:

1. Very little help is available locally for LINUX related problems.
2. The hard disc of the computer used for modeling crashed in March 2004.
3. In the absence of proper hardware to back up data, all programs and simulated data were lost.
4. Poor e-mail facilities and internet connectivity at the University of Zambia make climate modeling work more difficult.

Problem 4 exacerbated problem 1 above. Whereas in Senegal (see below) it was possible for colleagues at the University of Cape Town to remotely access the PC and fix problems related to software and/or the PC operating system, this was not feasible for Zambia. An examination of IP routing (the physical route taken by data packets on the internet) revealed that a communication from Cape Town, South Africa to Lusaka, Zambia went first to the UK, then to France, across the Atlantic to America and via satellite to Zambia. Once in Zambia all internet traffic to the university went through a 96 kb link which serviced all computers at the university.

Notably the AF07 work at UNZA has helped develop capacity at an African campus where students lack access to appropriate computing facilities. The interaction between the University of Cape Town and the physics and maths departments at the UNZA has led to these departments acquiring cheap second-hand computers from the UK and installing a network on which students can practice their programming. This is also a benefit to the University of Cape Town where there are several Zambian masters students undertaking courses in climatology. If these students can acquire programming skills and experience with regional climate models before they arrive in Cape Town this will greatly benefit their further studies.

3.2. Capacity Building in Zimbabwe

Contact: Mr. Brad Garanganga, Drought Monitoring Centre, Harare, Zimbabwe.

A preliminary run of the MM5 was made at the Southern Africa Development Community (SADC) Drought Monitoring Centre (DMC) in Harare, Zimbabwe. The successful running of an MM5 simulation generated a good deal of interest from the personnel of the 14 National Meteorological Services (NMS's) attending the DMC and representing the countries which comprise SADC. The run was carried out on a PC loaned by the Meteorological Services of Zimbabwe to the SADC DMC and unfortunately this PC was later withdrawn and the person responsible for running the model left the DMC. No further runs using MM5 have been completed at the DMC and there is currently no technical person who can run the model. However, as the interest from NMS personnel demonstrates there is scope for carrying out regional climate modeling exercises and further training. The appropriate format and location is not clear, though if a technical person with the relevant computing and modeling experience could be identified at the DMC it could provide an appropriate base for interacting with regional NMS's.

The following problems and benefits are from the experience of Marshall Mdoka, an MSc student at the University of Cape Town who is on leave from Zimbabwe Meteorological Services. He has completed simulations whilst on sabbatical at ICTP in Trieste, Italy.

Problems:

The work was carried out at ICTP in Italy and remote access to University of Cape Town. (UCT) was difficult or slow at times. Most of the guidance there was from Experts who had not done any work over Southern Africa. Not so much work has been done using the RegCM3 model over this region thus there is still a lot of model refinement work to be done. Although, the hardware and software is available in abundance at ICTP the remote access and continuation of the model simulations from here is not easy. I have to wait for times when the machines are free to access and do some processing. There are other issues like compliers since I found out simulations with different compliers tended to give different output. For continuation of my work, I will have to set up the model and rerun it. My main challenge for future work or continuation will be hardware/software resources when I complete my studies at UCT or when I intend to do my work outside campus such as at Zimbabwe Meteorological Services. This will also include having a good internet connection.

Advances and Benefits:

Mr. Mdoka has been introduced and trained in modeling work. From a capacity building perspective he is now able impart or train people back in Zimbabwe on aspects of regional climate modeling. He has acquired the skills to set up and run a model like RegCM3.

3.3. Capacity building in Ghana

Contact: Dr. Joseph Intsiful, Kofi Annan Center of Excellence in ICT (KACE), Accra, Ghana.

AIACC support:

The AIACC program provided training on MM5 and related applications. It also provided a Portland compiler license to help run MM5 and related programs on a linux platform. Additionally, critical technical support in terms of IT related issues and climate modeling in general were essential to continued research. The project also afforded the opportunity for Dr. Intsiful to interact with other climate scientists within the African continent and worldwide.

Problems:

The most significant hurdle was the lack of a PC and accessories to undertake detailed investigations. Hence much of the work was restricted to 1D SVAT modeling. The lack of internet access and literature also constitute formidable problems to effective research.

3.4. Capacity Building in Senegal

Contact: Dr, Abdoulaye Sarr, Meteorological department, Senegal.

Close contact was maintained between Dr. Sarr and the University of Cape Town throughout the lifetime of project AF07. Dr. Sarr was equipped with a PC after the first MM5 modeling workshop in June 2001 and technical assistance was provided several times. The provision of such assistance greatly benefited from access to high-speed internet access enjoyed by much of Senegal. This allowed colleagues at the University of Cape Town to remotely access the PC in Senegal when there was a problem and either diagnose or solve the problem online e.g. in one instance a display problem on the PC in Senegal was solved from Cape Town. This situation was in stark contrast to that in Zambia where remote access was unfeasible due to the speed and bandwidth of the telecommunications in Zambia.

Problems:

The first major problem was a disk crash due to frequent power cuts. More than 50 Gb of simulations were lost and as post processing and data analysis was ongoing, some results were not analysed. The replacement of this disk drive on a visit to Cape Town during the 2002 workshop enabled the possibility to redo some of the simulations, which can be found in this report (section 2.1.2.3). The intention is to publish these results as journal papers.

Another problem is the time available for research. Largely this is because of other work commitments within the meteorological service. This means that at busy times of the year and especially during the rainy season there is little time to conduct research and write research papers.

The close collaboration with LPA (Laboratoire Physiques des Atmosphere, Universite Cheik Anta Diop, Dakar, Senegal) helped in many aspects of this work. The internet connection for downloading data (e.g. reanalysis boundary conditions) is very important. The huge amount of data to be download and output from the simulation showed that to carry out a very long simulation for the control run and for future projections, more computing capacity and disk storage is required. For the computing power required to derive future climate change projections such resources should be coupled to a stable power supply (Uninterruptible Power Supply, UPS) and reliable backup system (e.g. large capacity tape storage).

3.5. Lessons and Suggested Solutions

An important problem that was often encountered and is mentioned in several of the country reports above is that of computer equipment failure. In particular this was often tied to hard disk failure. Africa is generally tough on electronic equipment for several reasons: high temperatures can lead to overheating, dust interferes with cooling devices as well as mechanically moving parts and there are often power outages/spikes. Hard disks in particular are vulnerable to all three of these influences and at least two sites (Zambia and Senegal) suffered from hard disks failing and loss of data. However, the cost of hard disks has sharply declined (in relation to their storage capacity) in the last few years and it is now feasible to have a second disk acting as a backup should the primary disk fail. It is also feasible to have a third external disk (connected through the computers USB port) which can serve as an external backup and means of transporting data between sites, replacing transfers over the internet when connections are slow. To combat abrupt power outages and surges (or spikes) in the supply, small UPS's can be bought which provide power for 10 minutes or so after a failure in the regular power supply. These also provide protection against power surges by modulating the supply entering the computer.

Based on the above observations a system was designed that was simple to set up (and maintain) and provides as much redundancy as possible at a low cost. The system incorporated the following features:

- 2 x 250 Gb mirrored internal disks for storage and redundancy.
- 1 x 250 Gb USB external drive for backup and transporting large volumes of data.
- UPS Power surge protector and power supply to minimise the disruption of power outages.
- 1 Gb internal memory to increase computation efficiency.
- CD-Writer for backup of key files e.g. MM5 deck/config files.

Funds were sourced through AIACC supplemental grants to provide 5 of these systems, one for each remote partner site. Much of the computer hardware that was being used at the partner sites in Africa was old and utilised slow CPU units and little memory. Therefore these funds provided the opportunity to also fully upgrade existing hardware. So far the system has been installed in Senegal and Zambia and is being used successfully to produce the results reported earlier in this report.

A second problem often encountered was that of time available for research. Most researchers within Africa are employed to do work other than research. Teaching loads on university lecturers are high and employees of meteorological services often have to provide services to government or the private sector first, before being able to make time for research. It was clear during the course of this project that Dr. Sarr had produced excellent results that reuired reporting in the appropriate literature. However his time to do this was limited in Senegal. Extra funds through AIACC were therefore sourced so that he could travel to Cape Town and spend a month writing during March 2005. Professor Gutowski from Iowa State university in the US also traveled to Cape Town to work with Dr. Sarr. This interaction and time for writing research results is important for developing the capacity of African researchers to fully analyse their results. Funding for projects in the future should allow for researchers to travel to common bases and interact with experts in their field.

4. National Communications, Science-Policy Linkages and Stakeholder Engagement

The project has developed some of the highest resolution available climate change scenarios for the African continent. The statistical downscaling scenarios are now available and are in the process of being incorporated into a number of projects in South Africa. The RCM developed scenarios are still in the production stage though there is already a keen interest in using their projections of future climate. Both scenarios have been used by South African municipalities (Durban and Cape Town) to formulate adaptation strategies. Additionally, the scenarios will be made available via the internet. The following sections detail some of the other engagements that have been made with those seeking to formulate policies of adaptation and assess vulnerability.

4.1. Zambia

A Hydro-electric project titled 'Impacts of Local, Regional and Global Climate Change with particular reference to Hydro electric Generation on the Zambezi River Basin' started in 2003. Run by the South African electricity producer ESKOM the project seeks to understand the possible impact of climate change on the electricity generating potential of the Zambezi river. AF07, through Mrs. Suman Jain at the University of Zambia contributed by providing climate change information and expertise. The following details some of this work.

The Zambezi river basin, located between 8º to 20º South and 16.5º to 36º East drains an area of about 1.385 million km^2. The basin's rivers provide water to a population of about 38 million people, water for irrigation and industrial use including mining activities and electric power generation. The sub basins of Zambezi which have been selected for assessing impacts of Climate Change on hydro power generation are the Zambezi River main around Livingstone, Kariba sub basin around Kariba, Kafue sub basin around Kasaka and Zambezi river main sub basin around Cahora Bassa. Data for monthly precipitation scenario for periods 2010-2040, 2040-2070 and 2070-2100 was constructed from the HADCM3 simulated data provided by the Climate Systems Analysis Group, EGS Department, University of CapeTown. In the first year of the study, the Pitman 's water balance model was run for Kafue Gorge and Livingstone sites. During 2004, climate scenarios for the sites detailed in Table 4 were assembled.

<u>Publications/Communications</u>

The following are publications and communications that directly result from AIACC funded activities:

1. Impacts of Climate Change on Hydro Power Potential of Southern Africa , ESKOM Research Report, December 2004
2. Presented Seminar titled ' Climate Models', University of Zambia Mathematical Association (UNZAMA), 14 April 2005

4.2. Senegal

The Senegalese Meteorological office is highly interested in climate change and many efforts are currently being taken to assess the potential impact over West Africa. The IPCC focal point at the national level is the Meteorological Service and at the regional level it is AGRHYMET (located in Niamey, Niger). AGRHYMET is now conducting a climate change project involving all Sahelian countries in which Dr. Sarr is a valuable participant. At the national level the Meteorological service is interacting with other sectors such as agriculture and water management to design vulnerability and adaptation strategies.

Outputs of the project

Project AF07 has provided support for the following papers that have been prepared or are published. This is not a complete list and does not include those papers published by partners in Zimbabwe, Zambia, Nigeria, Senegal and Ghana.

Crane, R.G. and Hewitson, B.C. (2003) Upscaling of station precipitation records to regional patterns using Self-Organizing Maps (SOMs), *Climate Research*, 25, 95-107

Karanja, F.K., Hewitson B.C., and Tadross M., 2004: *Contribution to UNEP commissioned paper* 'Climate change scenarios and vulnerability assessments for selected countries in Eastern and Southern Africa.'

Hewitson, B.C., Crane R.G., and Tadross M.A., 2005: Regional climate scenarios for impact assessment. Chapter in START book 'Africa Global Change Synthesis'.

Hewitson, B.C., and R.G. Crane (2005) Gridded Area-Averaged Daily Precipitation via Conditional Interpolation, *Journal of Climate*, 18, 41-57.

Hewitson, B.C. (2003) Developing perturbations for climate change impact assessments, *EOS*, Vol 84(35), p337-348.

Hewitson, B.C., and R.G. Crane (2005) Consensus between GCM climate change projections with empirical downscaling, *International J. Climatology*, accepted.

Tadross, M., B.C. Hewitson, and M. Usman, 2003: Calculating the onset of the maize growing season over southern Africa using GTS and CMAP data, *CLIVAR-exchanges,* 27. 48-50.

Tadross, M.A., Hewitson B.C. and Usman M.T., 2005: The interannual variability of the onset of the maize growing season over South Africa and Zimbabwe. *Journal of Climate*, 18(16), 3356-3372.

Tadross, M.A., Gutowski W.J. Jr., Hewitson B.C., Jack C.J., New M., 2005: Southern African interannual and diurnal climate variability in the MM5 regional climate model. *Theoretical and Applied Climatology*, accepted.

Tadross, M.A., Mdoka M., Hewitson B.C. (2005b) On RCM-based projections of change in southern African summer climate. *Geophysical Research Letters*, Vol. 32, L23713, doi 10.1029/2005GL024460.

The following is a list of outputs, including papers currently submitted for peer-review, that have been produced as part of project AF07:

1. Tadross, M.A. and Hewitson B.C., 2005: Climate modeling uncertainty over southern Africa attributable to land-surface characteristics. submitted Journal of Climate.
2. Midgley, G.F., Chapman, R.A., Hewitson, B., Johnston, P., de Wit, M., Ziervogel, G., Mukheibir, P., van Niekerk, L., Tadross, M., van Wilgen, B.W., Kgope, B., Morant, P.D., Theron, A., Scholes, R.J., Forsyth, G.G. (2005). A status quo, vulnerability and adaptation assessment of the physical and socio-economic effects of climate change in the western Cape. Report to the Western Cape Government, Cape Town, South Africa. CSIR Report No. ENV-S-C 2005-073, Stellenbosch.
3. Hewitson BC (2003) GCM guided perturbations for regional climate change assessment, AIACC notes, vol 2, issue 1.
4. Hewitson BC (2004) Spatially cohesive changes in precipitation over South Africa, 9th International Conference on Statistical Climatology, Cape Town, South Africa.
5. Hewitson, B.C. (2005a) Historical trends in South African precipitation, draft.
6. PRECIS training workshop, 3-7 March 2003, Cape Town, South Africa. Eight African researchers wishing to use the PRECIS regional climate modeling system of the UK Meteorological Office attended this workshop. Trainers from the UK attended and lectured on the use of RCMs for climate change assessments.
7. LAS server distribution of DDC GCM climate change predictions for Africa (http://www.csag.uct.ac.za/las). A similar server will distribute the predictions for the statistical and dynamical downscaling in the coming months.

8. CDROM. African station data. Obtainable from the AIACC secretariat this CD contains the 1979-2001 Africa-wide station data transmitted via the General Telecommunications System (GTS).

9. CDROM. DDC GCM monthly mean climate change data. Obtainable from the AIACC secretariat this CD contains the data for control and future climate of nine GCMs. It also includes the results of applying the guided perturbation methodology to the station data.

5. Policy Implications and Future Directions

An appropriately scaled, and timeous response by Africa nations to the issue of climate change and related impacts is predicated on the understanding of the regional character of climate change. All policy development for adaptation requires first, an understanding of the vulnerability and sensitivity of any given sector to the climate system, and second, credible and defensible projections of future change on spatial and temporal scales relevant to any given impact sector. Achieving these goals requires, in turn, and research community that has the appropriate skill base, infrastructure resource, and experiential knowledge in the science activities.

The situation in Africa is far from reaching these goals. Nonetheless, through the AIACC project significant advances have been made in key areas; capacity to undertake regional modeling and empirical downscaling, understanding of the core climate system processes of relevance, and the development of a collaborative and distributed team across the continent.

Aside from the actual adaptation policy and strategy development required to respond to climate change, it is imperative that the momentum achieved through the AIACC program and other complementary activities be maintained. In this regard it may be said that a priority policy need is for the sustainability of the distributed and collaborative scientific capacity, along with the related infrastructural resources. Of critical importance is the support of the junior, or emerging, scientists; such that they do not be subsumed into the significant overhead structures of African institutionalised research. Following this need, perhaps of second importance is the need to foster communication; specifically between the science team engaged with scenario development and the impacts research community, and facilitate the dissemination of tailored scenario products, and climate system understanding.

In a more specific sense, members of project AF07 are currently engaged in:

- Extending the scenario products initiated within the AIACC project
- Developing dissemination channels for scenario information to reach the relevant parties in government and the broader research community
- Negotiation with major funding agencies about the establishment of a distributed centre of excellence for climate change research within Africa.

Within these activities, two key, broad scientific questions of priority for future activity may be identified:

- Understanding the role of land surface feedbacks on regional climate change, and the relative importance of changing land use practice
- Assessing uncertainty, and seeking convergence in the climate change scenarios developed across multiple GCM simulations of future climate

Overriding all the work to date, and the challenges of the future research, is the critical need to access continued support to maintain momentum. If this cannot be attained, the developments of the AF07 project, while valuable for the immediate needs of the impacts community, will nonetheless be relegated to (merely) another finite lifetime project arising out of foreign intervention of funding. However, the fact that the project has been African designed and African led is an important evolution in the application of foreign funding. Much has been achieved, and it is anticipated that this will catalyse appropriate development toward achieving the goal of a sustainable critical mass of climate change researchers within the continent.

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7. Figures and Tables

Index/Station	Beitbridge	Belvedere	Chipinge	Goetz	Kadoma	Karoi	Kwekwe
TXx (degC)	**0.02**	0.006	0.002	0.009	-0.007	-0.015	0.014
TNn (degC)	**0.026**	0.02	-0.03	**0.027**	0.032	-0.027	**-0.036**
TN10p (days/year)	**-0.141**	**-0.166**	0.06	**-0.159**	**-0.109**	**0.619**	**-0.083**
TX10p (days/year)	**-0.072**	**-0.15**	**-0.071**	**-0.087**	-0.092	**0.495**	**-0.098**
TN90p (days/year)	**0.111**	**0.199**	0.06	**0.248**	**0.136**	-0.065	0.042
TX90p (days/year)	**0.2**	**0.208**	**0.162**	**0.24**	**0.188**	0.169	**0.102**
DTR (degC)	0.007	0.005	**0.025**	0.004	0.009	**0.022**	**0.013**
RX5day (mm)	-0.045	**-0.861**	0.597	0.176	0.103	0.224	-0.488
CDD (days)	-0.422	0.951	0.081	0.243	-0.36	0.186	0.424
R95p (mm)	1.028	**-2.747**	2.501	-0.125	-1.005	-1.162	-0.339
PRCPtot (mm)	0.781	-3.732	0.772	-0.942	-2.414	-3.816	-3.117

Index/Station	Nyanga	Rusape	Kutsaga	Gweru	West Nicholson	Makoholi	Masvingo
TXx (degC)	-0.003	0.019	-0.011	-0.003	**0.045**		
TNn (degC)	0.02	-0.009	**-0.054**	0.003			
TN10p (days/year)	**-0.324**	-0.112	0.108	**-0.219**	**-0.238**		
TX10p (days/year)	-0.028	0.019	-0.04	-0.131	-0.101		
TN90p (days/year)	**0.277**	0.039	**0.102**	**0.222**	**0.278**		
TX90p (days/year)	**0.274**	0.052	0.052	0.368	**0.423**		
DTR (degC)	-0.008	-0.008	0.008	0.006	0.008	0.017	
RX5day (mm)	-0.368	-0.252	-0.066	0.227	-1.289	0.084	
CDD (days)	0.51	0.356	0.259	0.184	-0.863	-0.826	-0.75
R95p (mm)	-0.396	1.022	2.410	2.594	-2.299	1.721	-1.374
PRCPtot (mm)	-5.198	-0.246	3.401	0.6	-2.467	-0.739	-0.362

Table 1: *Results of the selected indices calculated for the chosen stations. Selected indices are explained in the following figures*

Station	Nov-88	Dec-88	Jan-89	Feb-89	Four month Total
Kabwe	55	114.7	233.8	279	682.5
Ndola	70.4	220.9	372.2	384.2	1047.7
Chipata	26	218.7	582.7	223.5	1050.9
Kawambwa	221	189.2	171.3	183.5	765
Kafue	42.6	125.9	268.4	516	952.9
Lusaka	10	97	412.1	419.9	939
Kasama	159.1	204	269.9	228.2	861.2
Mpika	179.4	184.1	267.5	222.6	853.6
Mwinilunga	145.1	216.7	160.7	161.8	684.3
Solwezi	103.2	179.3	205.6	101.2	589.3
Choma	40.3	116	320.9	429.2	906.4
Livingstone	75.2	139.1	157.9	298.9	671.1
Mongu	40.3	194.6	253.7	318.4	807
Sesheke	50	163.1	198.9	241.9	653.9

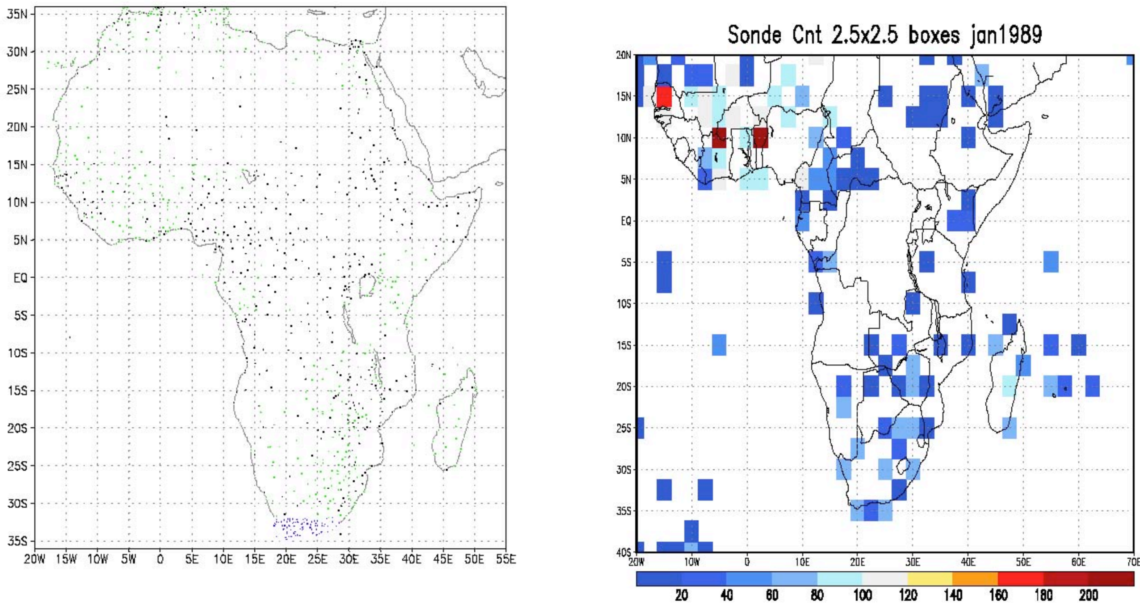
Table 2: *Observed precipitation for 14 stations in Zambia for the four months November 1988 to February 1989*

Station	Nov-88	Dec-88	Jan-89	Feb-89	Four month Total
Kabwe	0-100	0-200	0-200	200-400	300-600
Ndola	0-100	0-200	200-400	200-400	600-900
Chipata	0-100	0-200	200-400	200-400	300-600
Kawambwa	0-100	0-200	200-400	200-400	300-600
Kafue	0-100	0-200	0-200	200-400	600-900
Lusaka	0-100	0-200	0-200	200-400	600-900
Kasama	0-100	0-200	0-200	200-400	300-600
Mpika	0-100	0-200	200-400	400-600	600-900
Mwinilunga	200-300	400-600	600-800	400-600	600-900
Solwezi	0-100	0-200	200-400	200-400	600-900
Choma	0-100	0-200	200-400	200-400	600-900
Livingstone	0-100	0-200	0-200	200-400	300-600
Mongu	0-100	0-200	200-400	200-400	300-600
Sesheke	0-100	0-200	0-200	200-400	300-600

Table 3: *MM5 modelled precipitation for 14 stations in Zambia for the four months November 1988 to February 1989*

COUNTRY	NAME OF BASIN	LATITUDE	LONGITUDE
Zambia	**Luangwa**	28.0° E to 32.8° E	10.0° S to 14.7° S
	Barotse	21.5° E to 26.3° E	14.2° E to 17.1° S
	Luanginga	19.6° E to 23.0° E	13.0° E to 15.0° S
	Kabompo	23.2° E to 26.2° E	11.4° E to 14.6° S
	Lungue Bungo	18.4° E to 23.0° E	12.2° E to 14.3° S
	Chongwe	26.0° E to 30.2° E	14.3° E to 15.8° S
	Upper Zambezi	19.4° E to 24.2° E	11.3° E to 14.2° S
Zimbabwe	**Gwayi**	26.8° E to 28.8° E	18.0° S to 20.5° S
	Sanyati	28.6° E to 29.9° E	16.6° S to 17.8° S
	Manyame	30.2° E to 31.5° E	16.0° S to 18.5° S
	Mazowe	30.8° E to 33.0° E	16.5° S to 17.7° S
	Shangani	27.3° E to 29.7° E	18.4° S to 20.0° S
	Angwa	29.6° E to 30.3° E	15.5° S to 18.3° S
	Deka	26.0° E to 27.0° E	18.0° S to 18.5° S
	Zambezi	Discontinuous west to east, through Binga and Kariba.	
Mozambique	**Zambeze**	30.3° E to 36.9° E	14.6° S to 19.0° S
	Cahora Bassa		
Malawi	**Shire**	32.5° E to 34.9° E	09.2° S to 17.4° S

Table 4: Latitude-longitude ranges of major river basins for which climate change data has been provided to the ESKOM hydro-electric project.



(a) **(b)**

Figure 1: *Observational networks over Africa: a) Black + Green dots are the stations contributing to observations found on the GTS (General Telecommunications System), Green dots those stations reporting on any given day (approx 50%). b) Radiosonde count for January 1989 showing the locations of atmospheric observations entering the reanalyzes.*

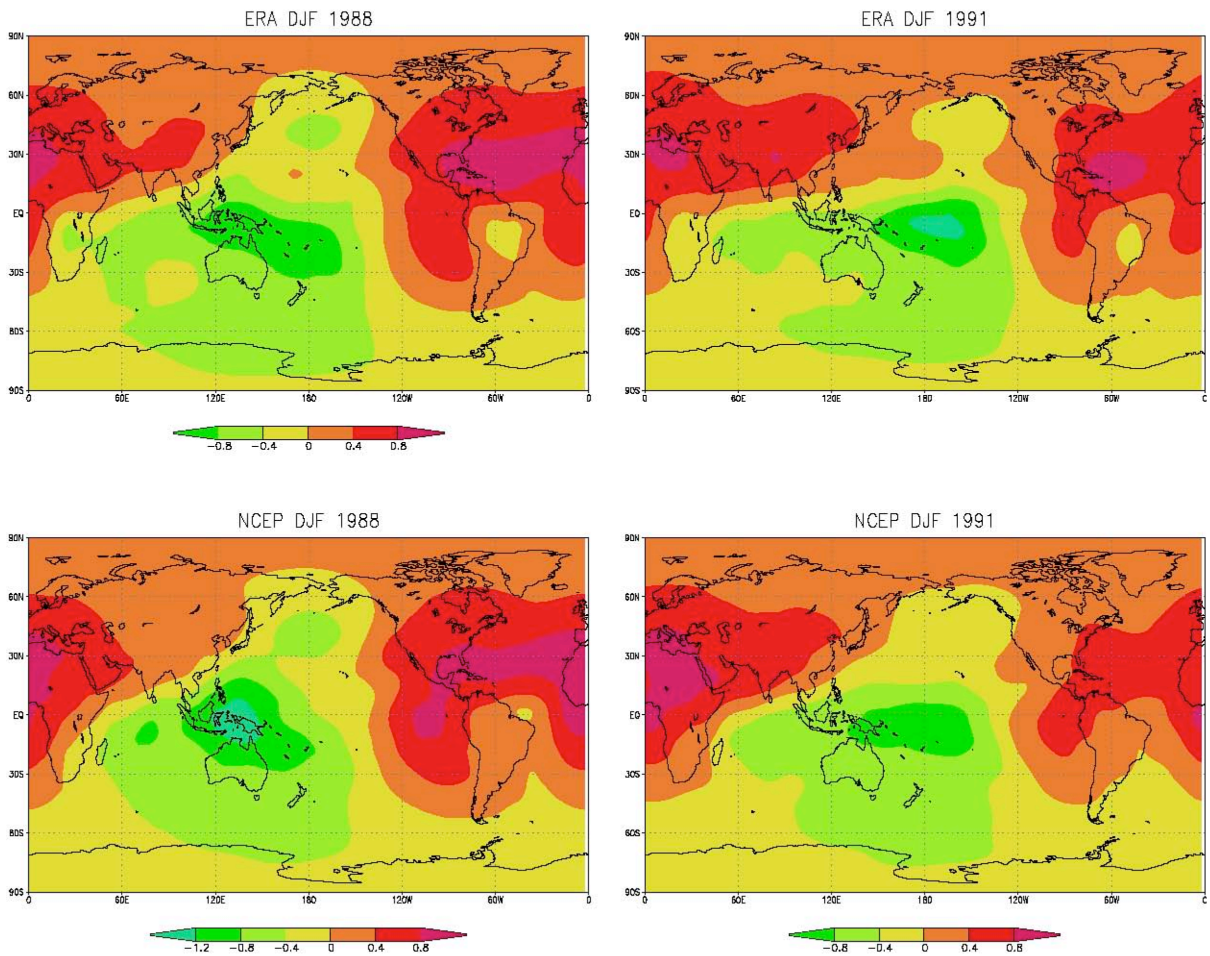


Figure 2: *200 hPa velocity potential of the ERA and NCEP reanalyzes. Two December – February (DJF) seasons are shown: 1988 (wet over southern Africa) and 1991 (dry over southern Africa).*

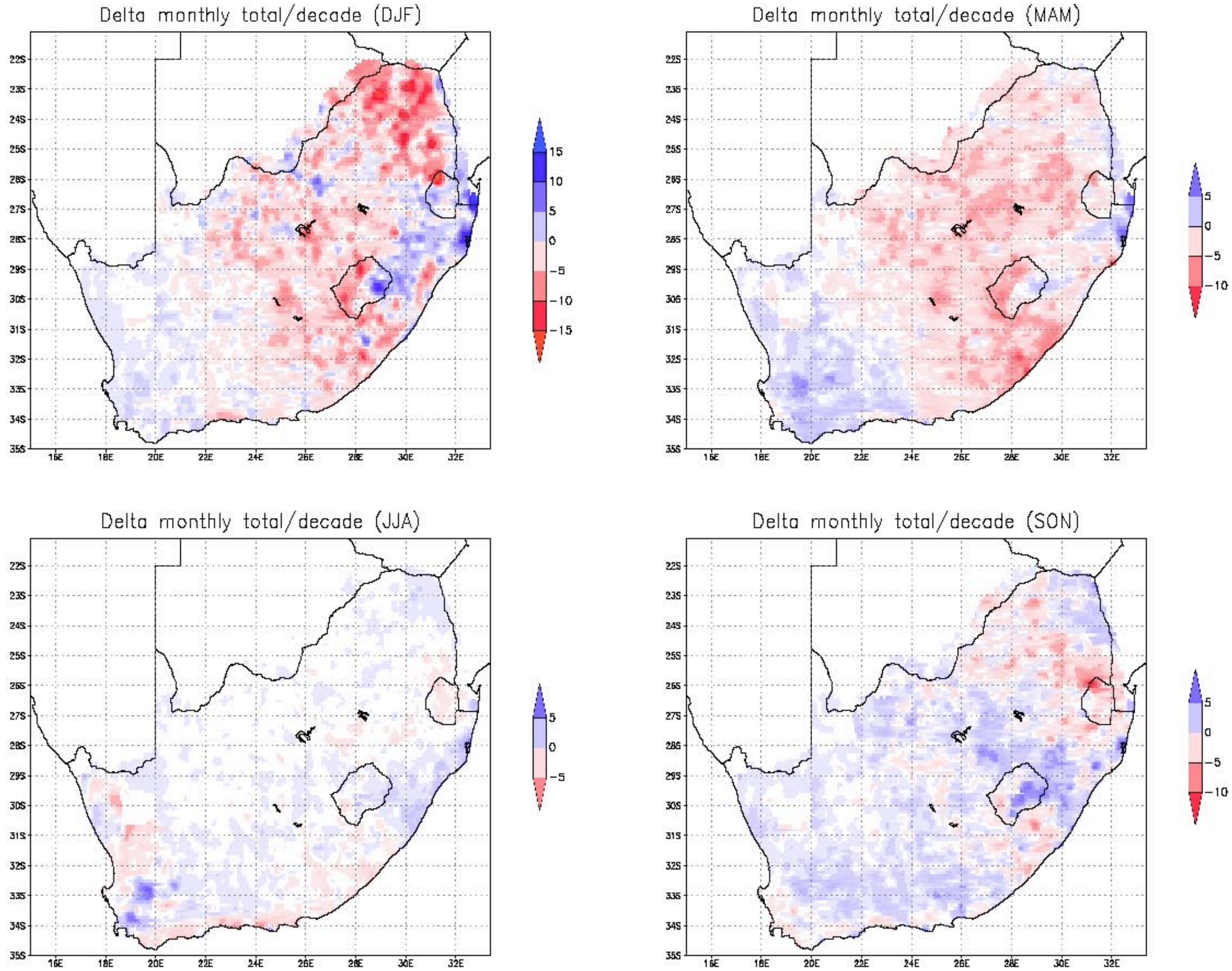


Figure 3: *Historical trend (1950-1999) of change per decade of mean monthly precipitation totals (mm).*

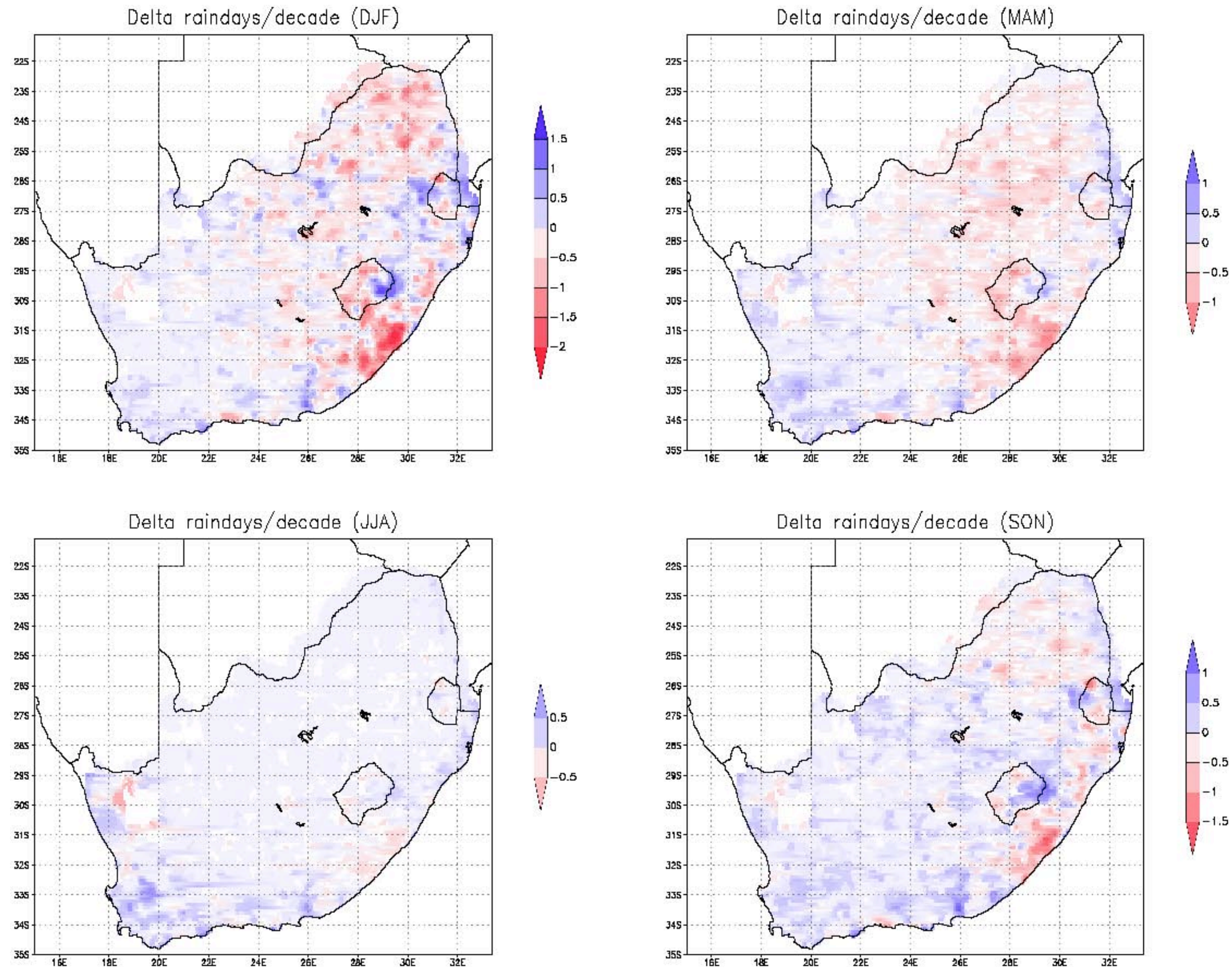


Figure 4: *Historical trend (1950-1999) of change per decade in mean monthly number of raindays (>0mm)*

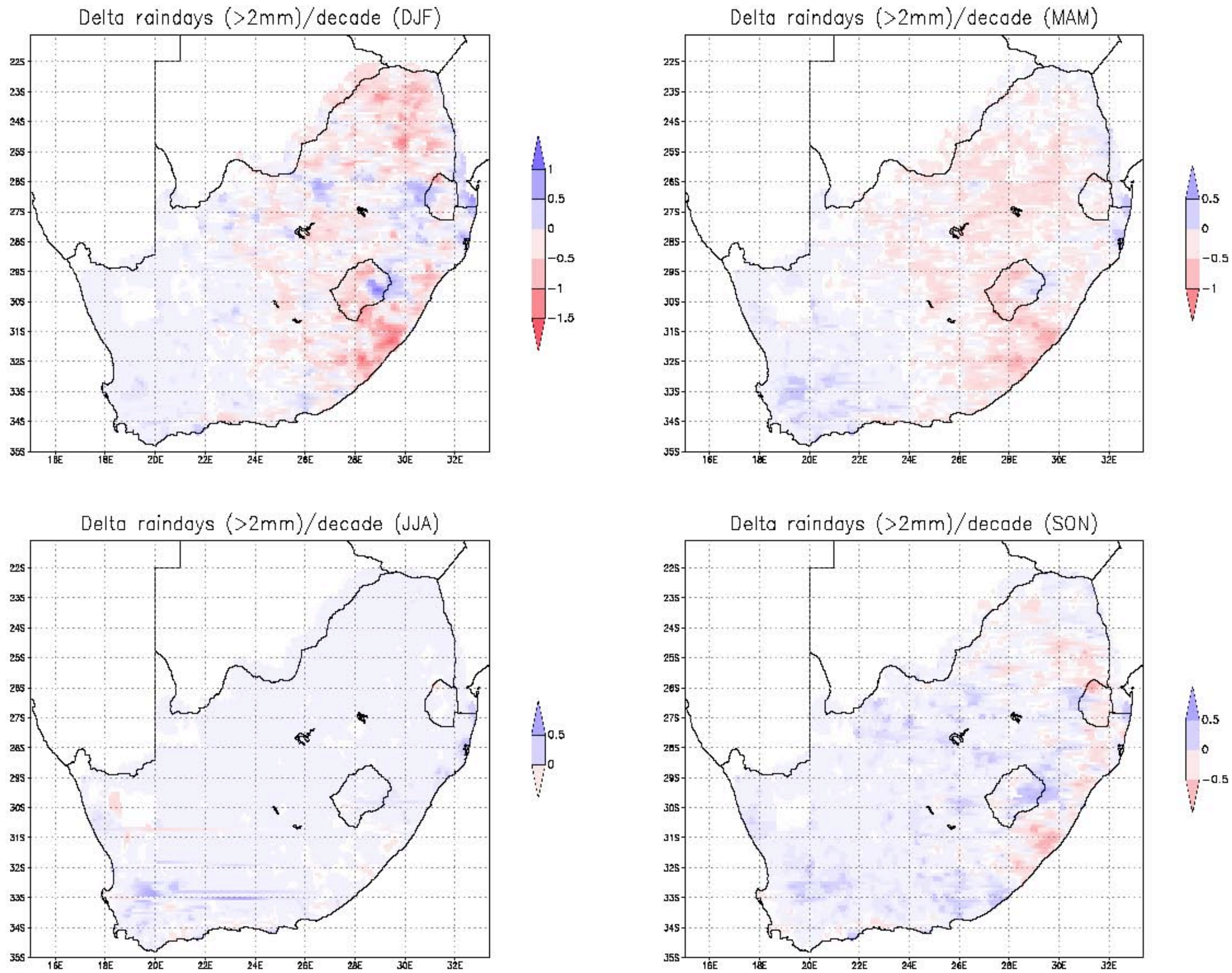


__Figure 5:__ Historical trend (1950-1999) of change per decade in mean monthly number of raindays (>2mm).

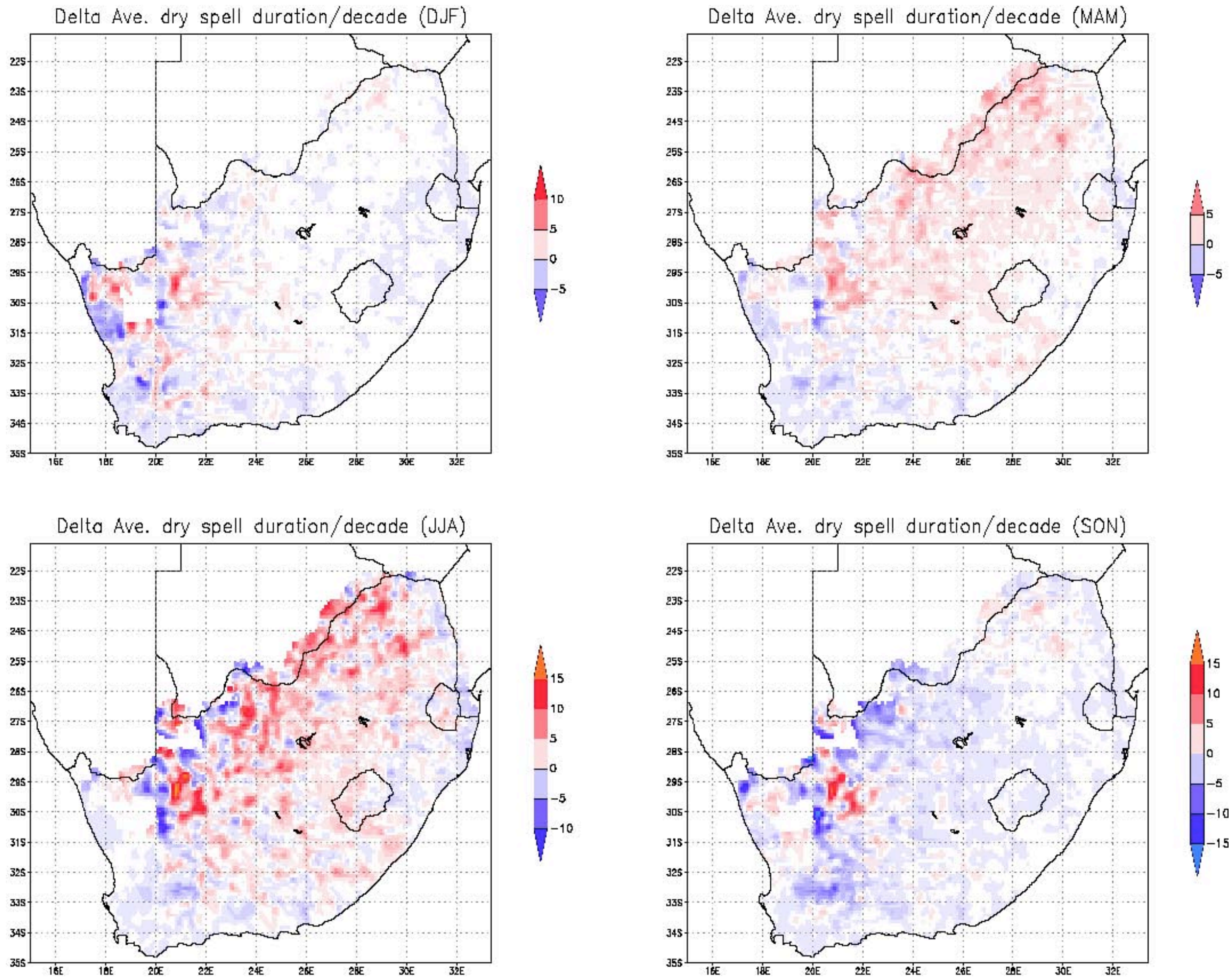


Figure 6: *Historical trend (1950-1999) of change per decade in mean monthly dry spell duration (days).*

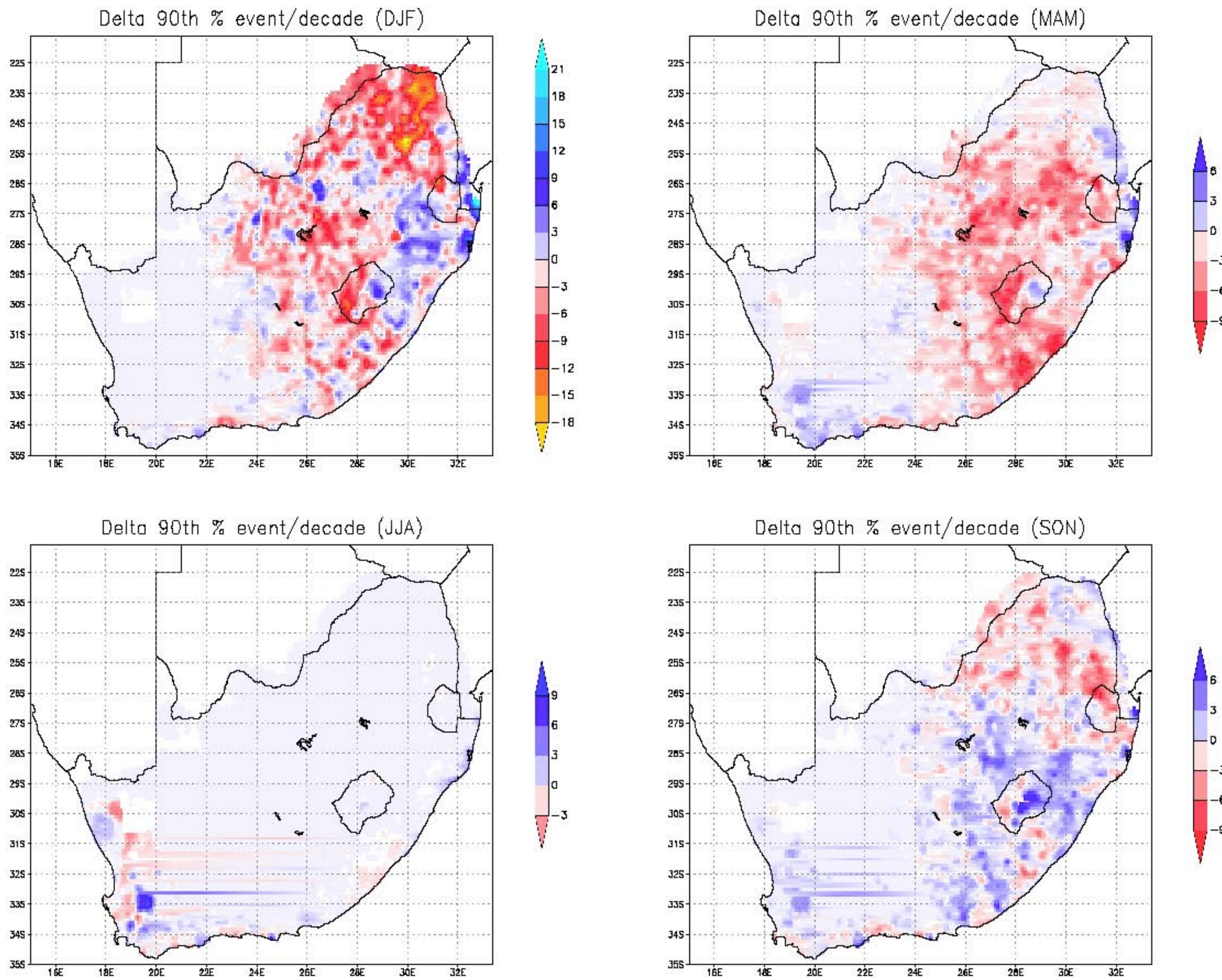


Figure 7: *Historical trend (1950-1999) of change per decade in mean monthly 90th percentile magnitude precipitation event (mm).*

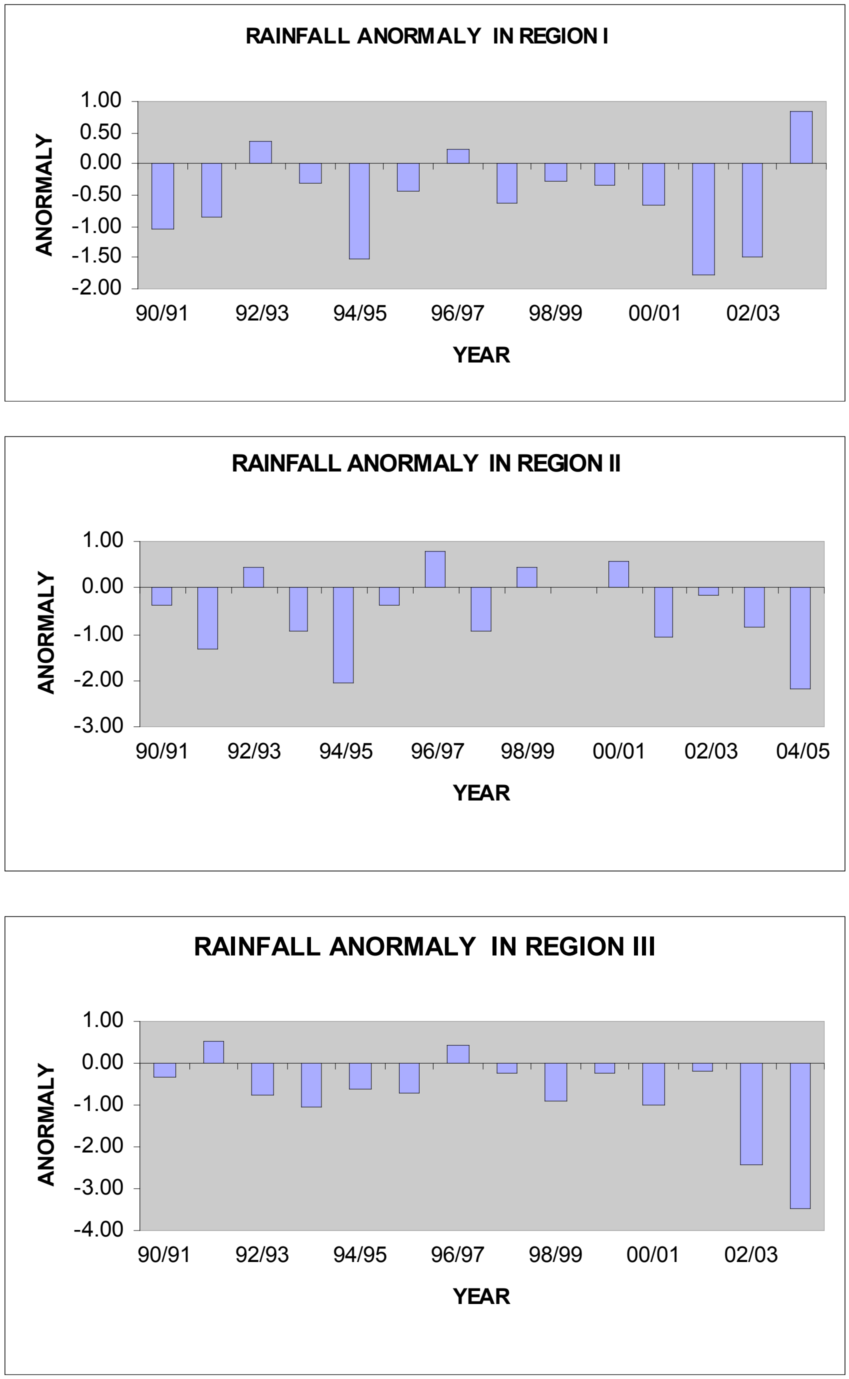


Figure 8: *Zambian rainfall anomaly by region for the years 1990-2004.*

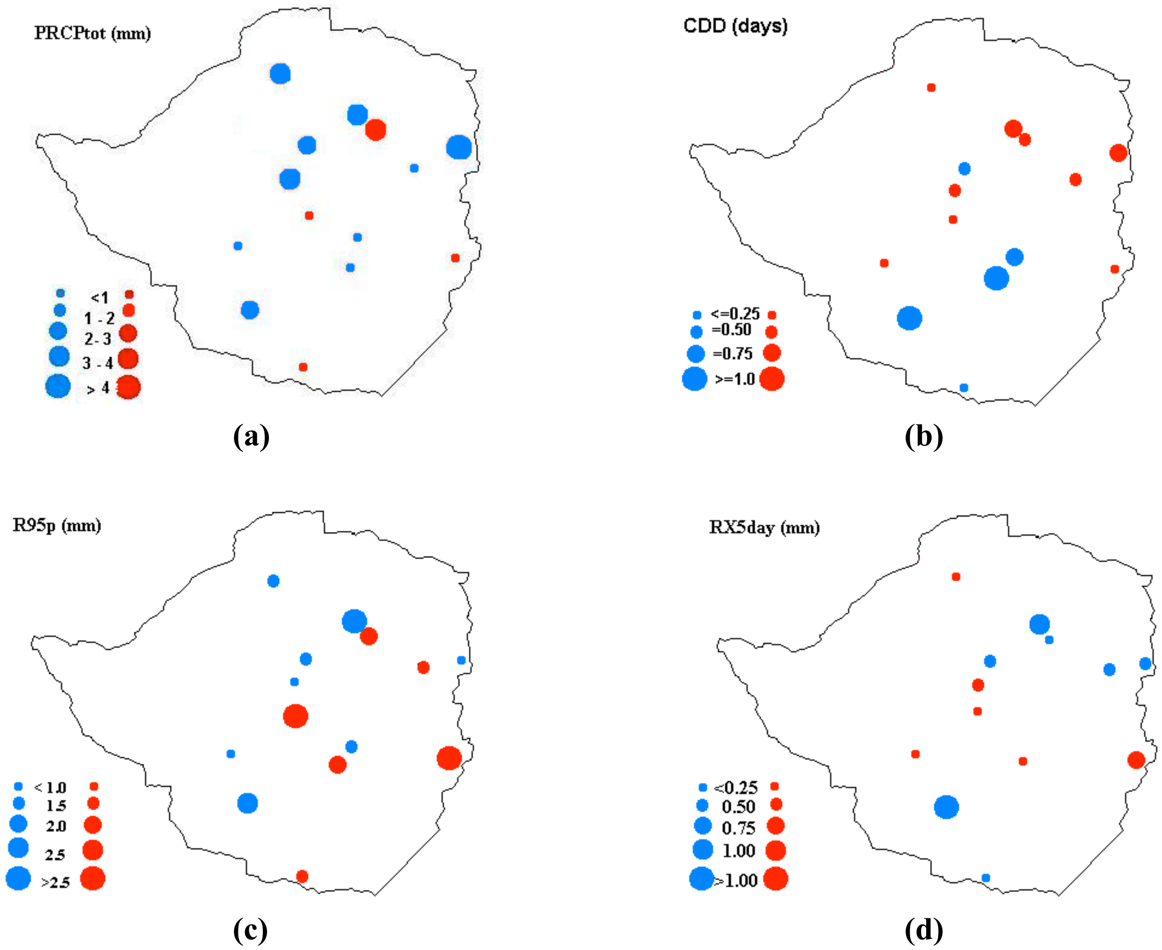


Figure 9: *(a) Annual total precipitation in wet days with at least 1mm of rain, PRCPtot (mm). (b) Maximum number of consecutive dry days (dry spells), CDD. (c) Annual total precipitation exceeding 95th percentile of the rainfall, R95p and (d) Monthly maximum consecutive 5-day precipitation, RX5day. The red colours depict an increase whilst the blue is for a reduction.*

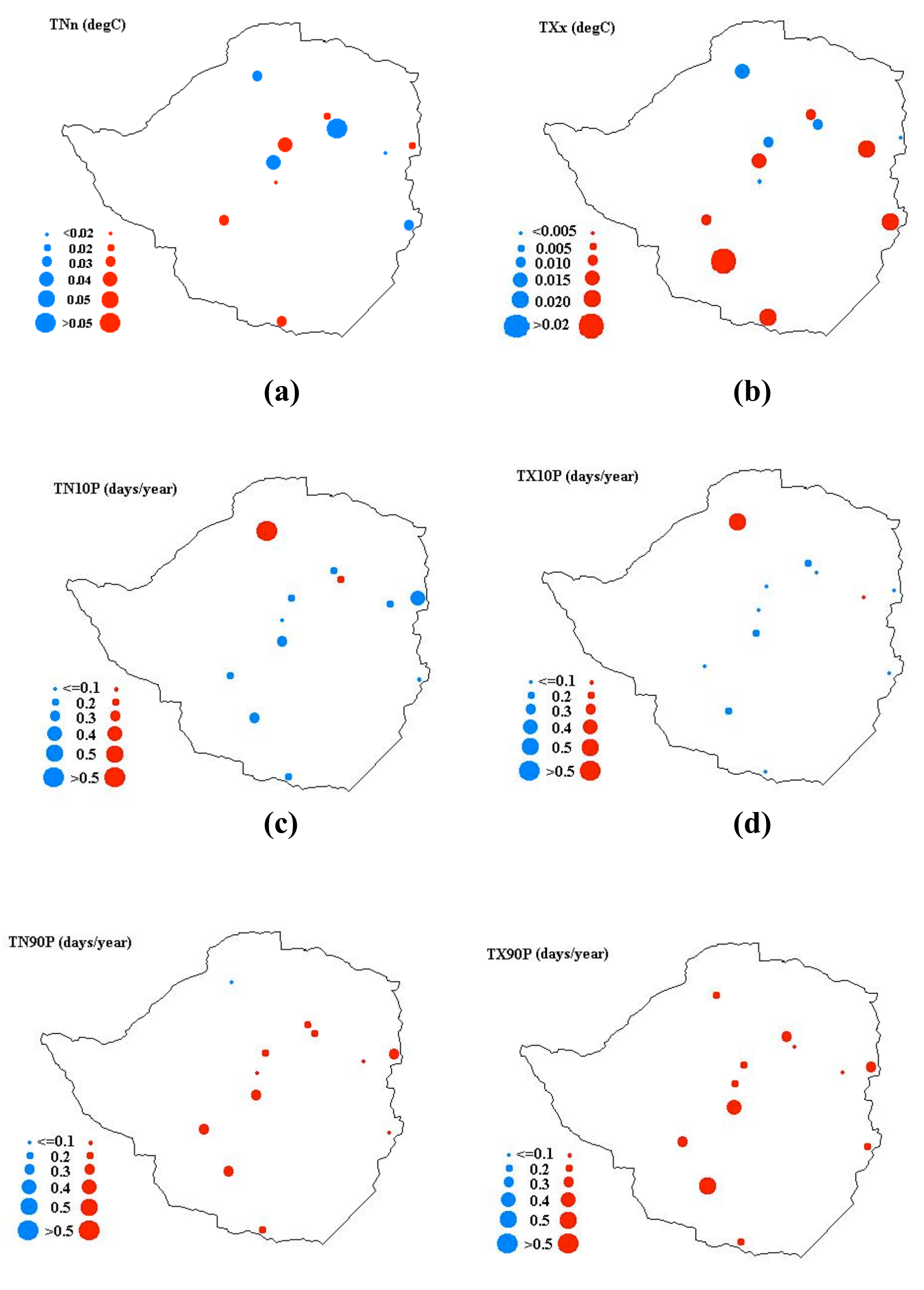


Figure 10: *(a) Annual count when daily minimum temperature is below 2°C, TNn. (b) Annual count when daily maximum temperature is above 25°C, TXx. (c) Percentage of days when daily minimum temperature is below 10th percentile, TN10P. (d) Percentage of days when daily maximum temperature is below 10th percentile, TX10P. (e) Percentage of days when daily minimum temperature exceeds 90th percentile, TN90P. (f) Percentage of days when daily maximum temperature exceeds 90th percentile, TX90P.*

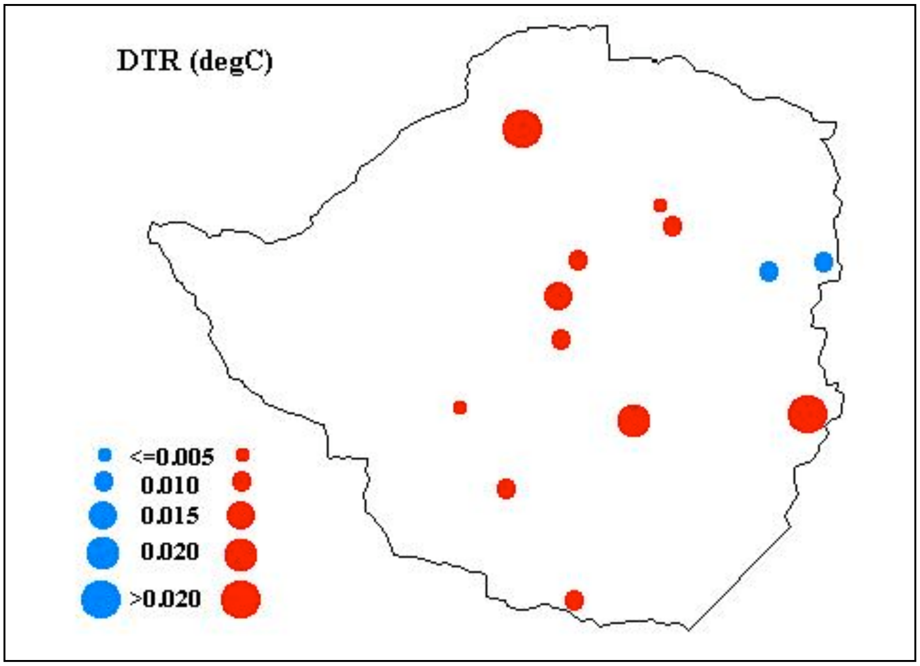


Figure 11: *The Diurnal Temperature Range (DTR) (˚C) trends measured at an annual rate. The red colours depict an increase whilst the blue is for a reduction. There is some spatial coherence with most of Zimbabwe showing an increase in DTR*

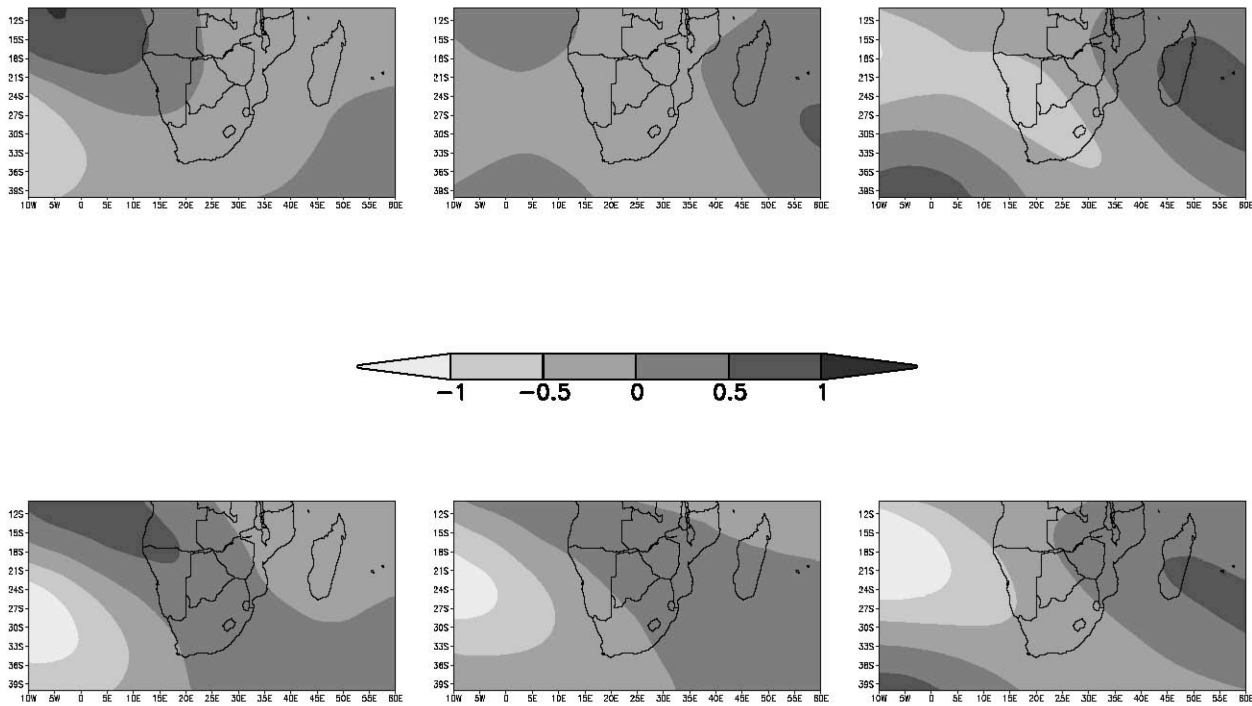


Figure 12: *3 × 2 SOM of ERA40 standardised 500 hPa daily eddy geopotentials for the 1979-2002 DJF seasons.*

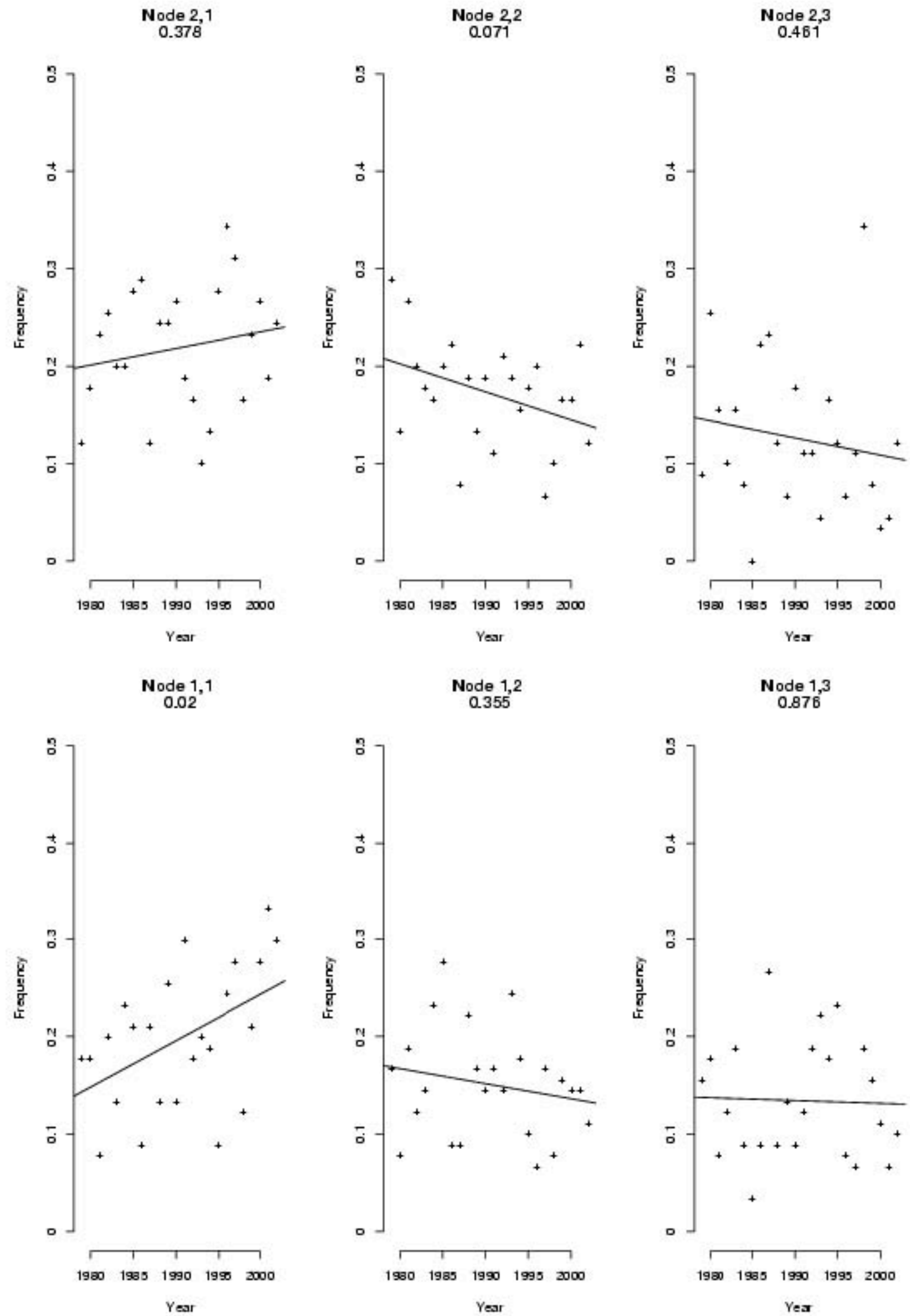


Figure 13: *Frequency of each SOM node for the 1979-2002 DJF seasons. Lines demonstrate least squares trends in frequency and the probability of the null hypothesis, that no trend exists, is given at the top of each plot.*

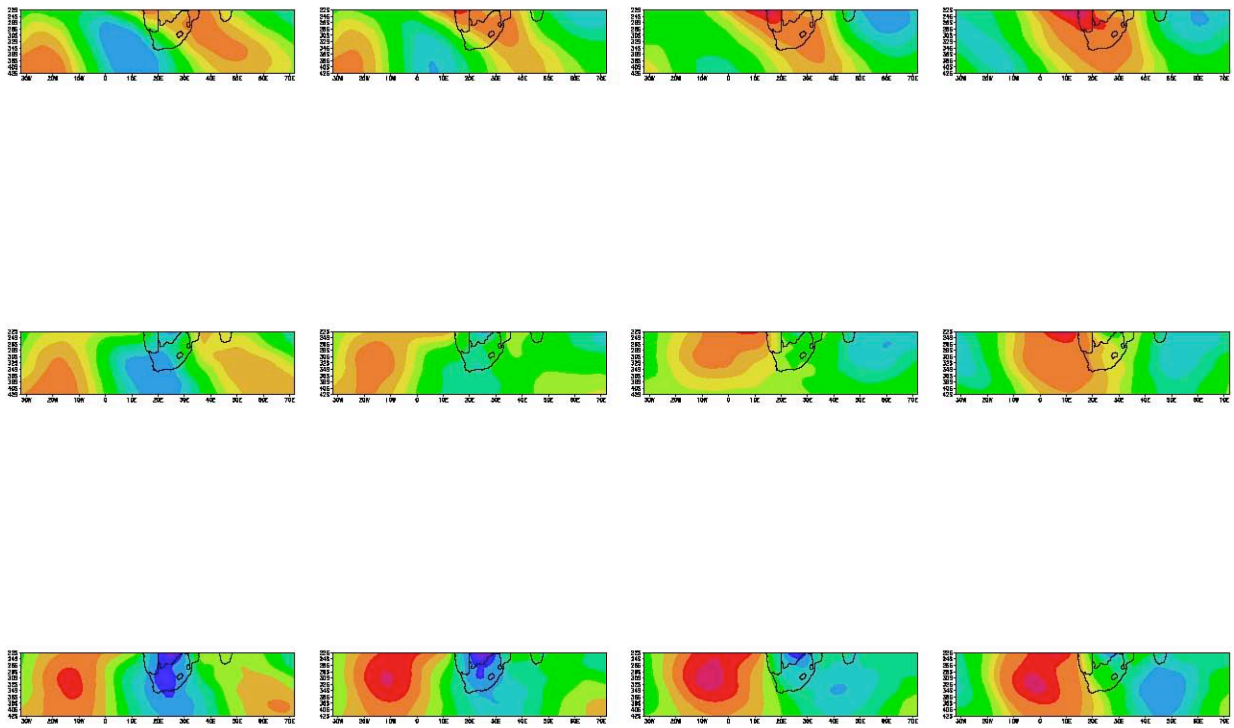


Figure 14: *4 x 3 Self Organising Map (SOM) of 30 years control & 30 years future December - January daily eddy (anomalies from the zonal mean) geopotential heights for the CSIRO, ECHAM4 and HadAM3 GCMs. Also included are ERA-15 and NCEP reanalysis data. All anomalies are standardised. Blue represents low pressures and red represents high pressures*

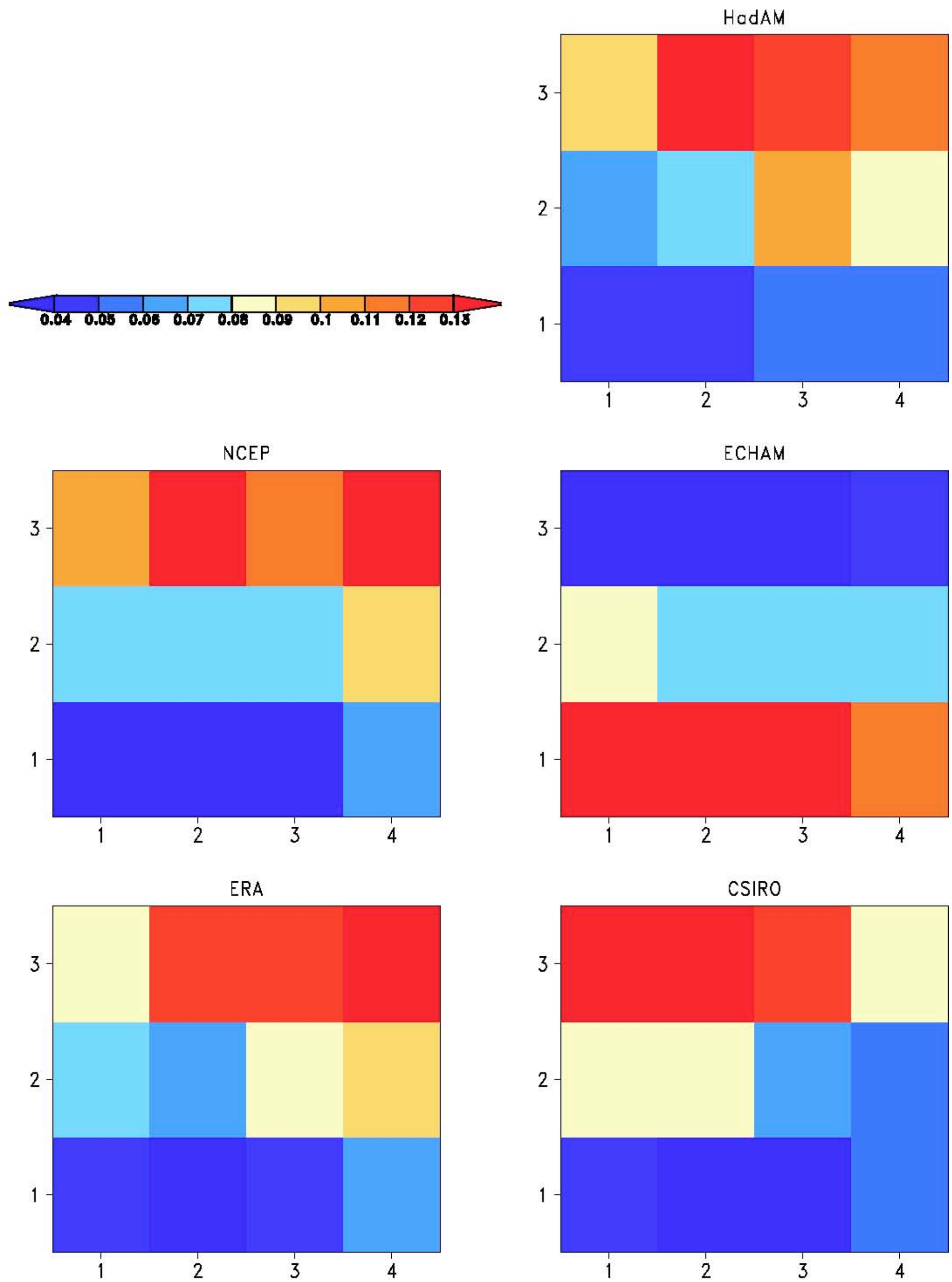


Figure 15: *Frequency of each pattern (node) in Figure 14 found in each of the five datasets: NCEP reanalysis, ERA-15 reanalysis, CSIRO control run, ECHAM 4 control run and HadAM3 control run.*

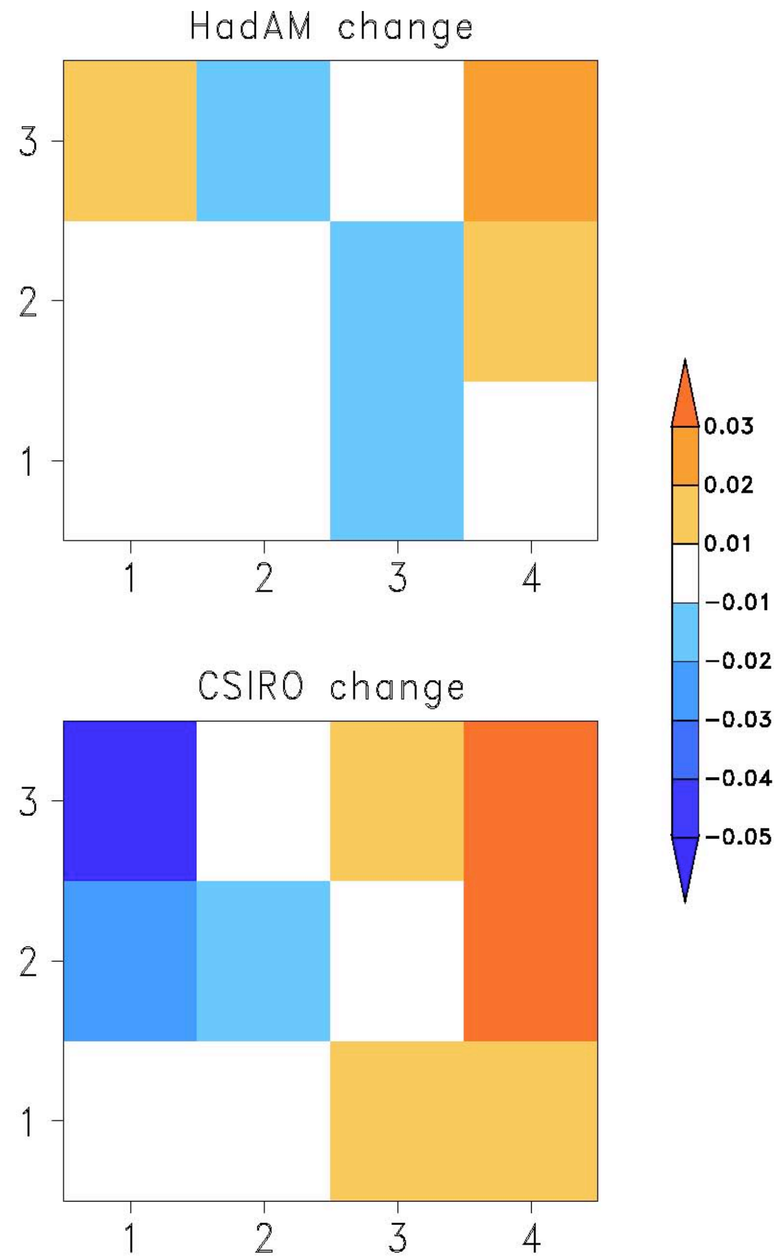


Figure 16: *Frequency change (future – control) of each pattern (node) in Figure 14 for both the CSIRO and HadAM3 simulations.*

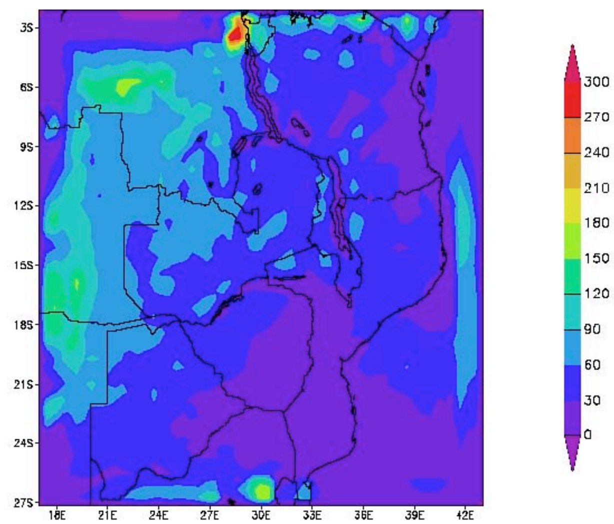


Figure 17: *Total seasonal rainfall (cm) for DJF 1988/89 as simulated by MM5 using the Grell convection scheme.*

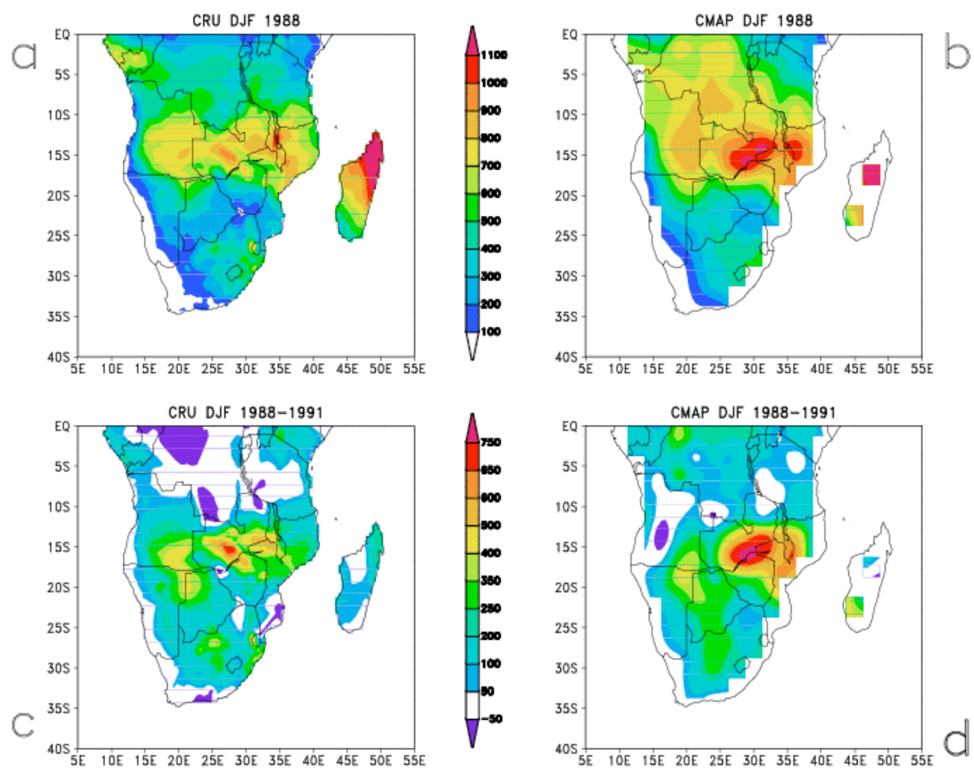


Figure 18: *December-February (DJF) 1988/89 seasonal rainfall (mm): a) CRU, b) CMAP. DJF interannual (1988/89 – 1991/92) rainfall anomaly (mm/season): c) CRU, d) CMAP.*

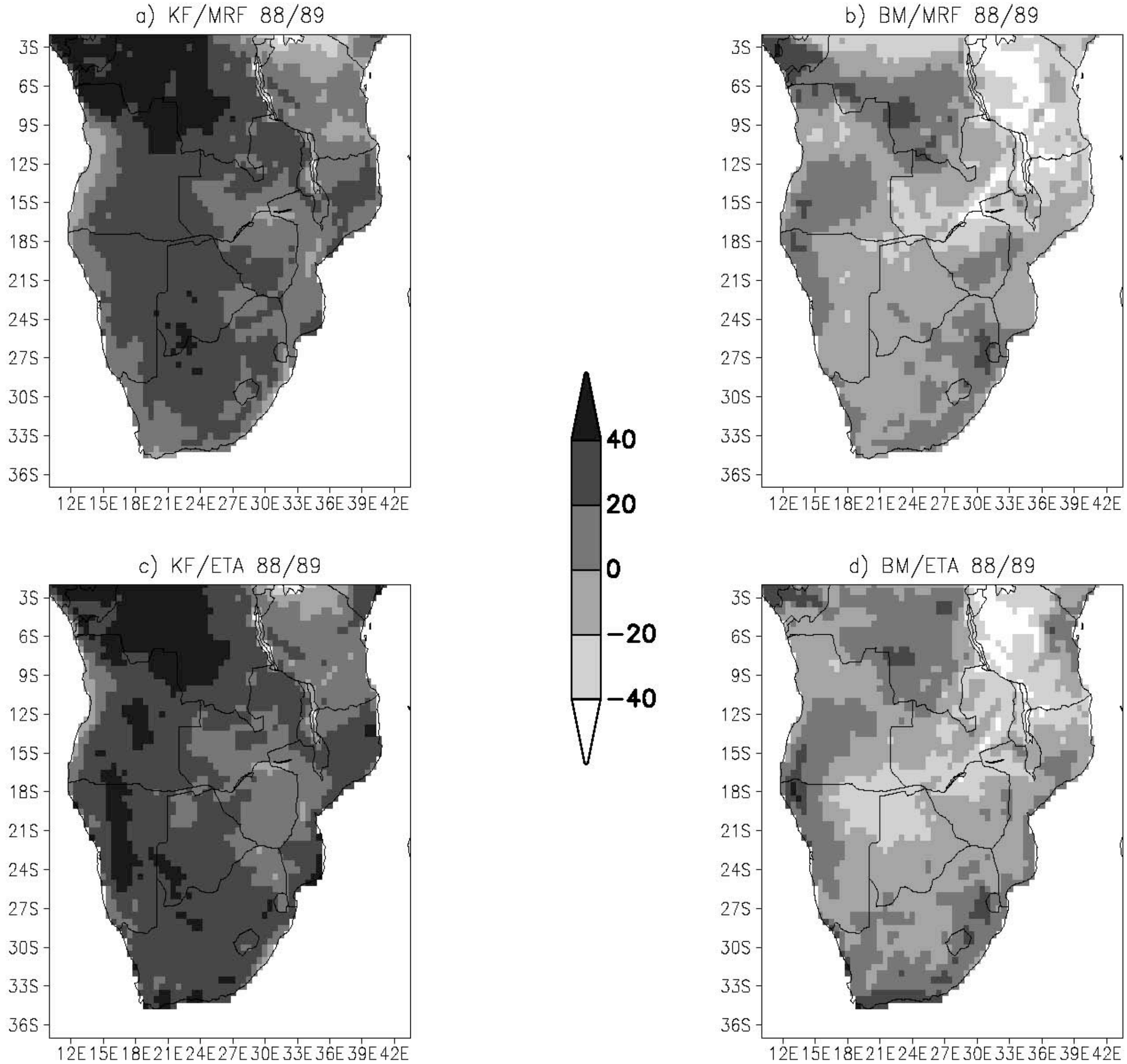


Figure 19: *MM5 simulated rain day anomaly (days/season) with respect to CRU observations (MM5-CRU) for the 1988/89 season. a) KF/MRF, b) BM/MRF, c) KF/ETA and d) BM/ETA.*

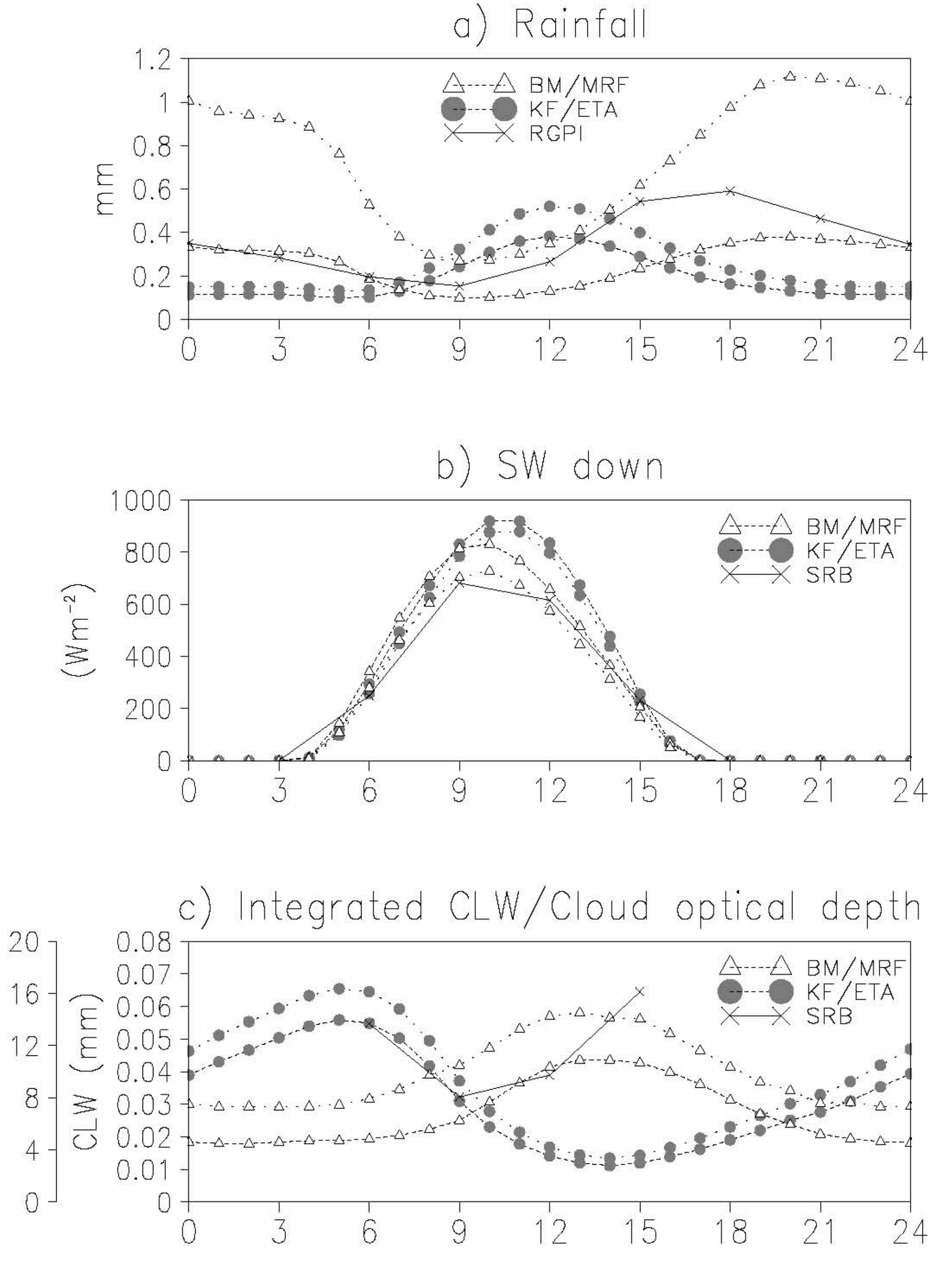


Figure 20: *The diurnal cycle (UTC) of rainfall (top panel, mm hr^{-1}), SW flux (middle panel, Wm^{-2}) and integrated CLW (mm)/cloud optical depth (bottom panel) for the 1988/89 season over southern Africa. Crosses indicate satellite-derived datasets, open triangles are BM/MRF simulation and closed circles KF/ETA simulation. Dashed curves are the DJF average, dotted curves the rain day average.*

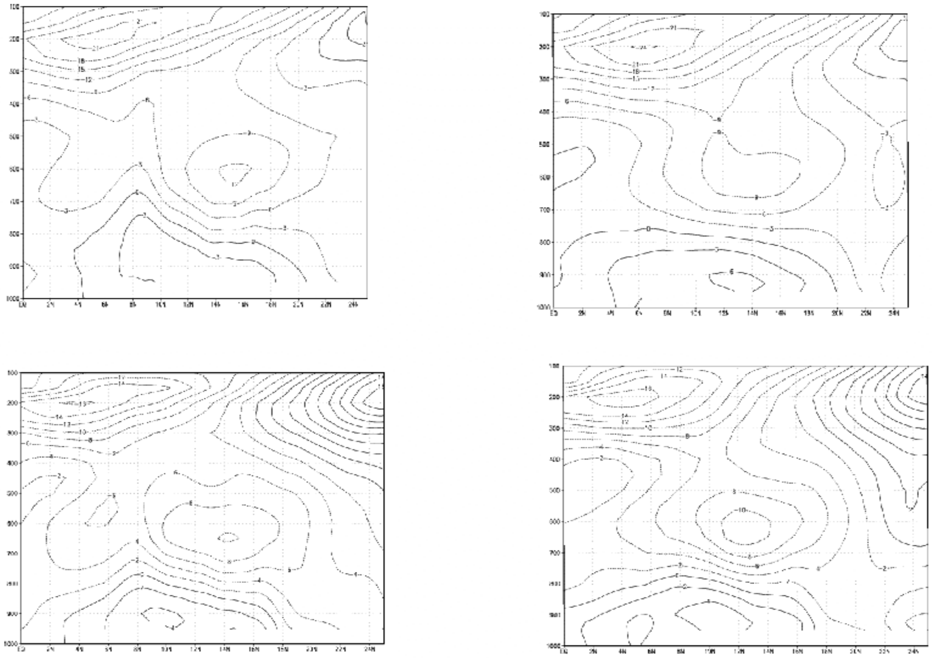


Figure 21: *Vertical profile of zonal wind at different longitudes (10°W right and 0°W left) from MM5 simulations August 1988 (top) and 1990 (bottom).*

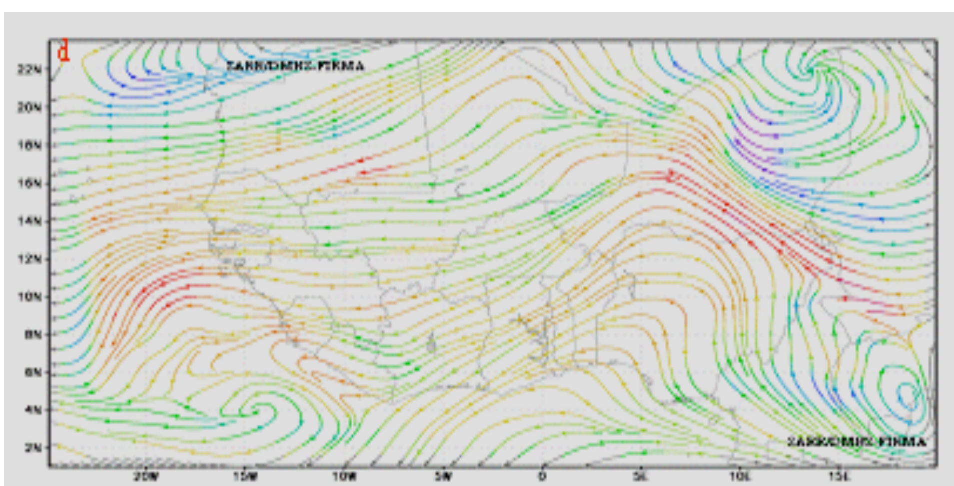


Figure 22: *Streamlines over West Africa from MM5 simulations, depicting an easterly wave with the trough from Nigeria to Niger.*

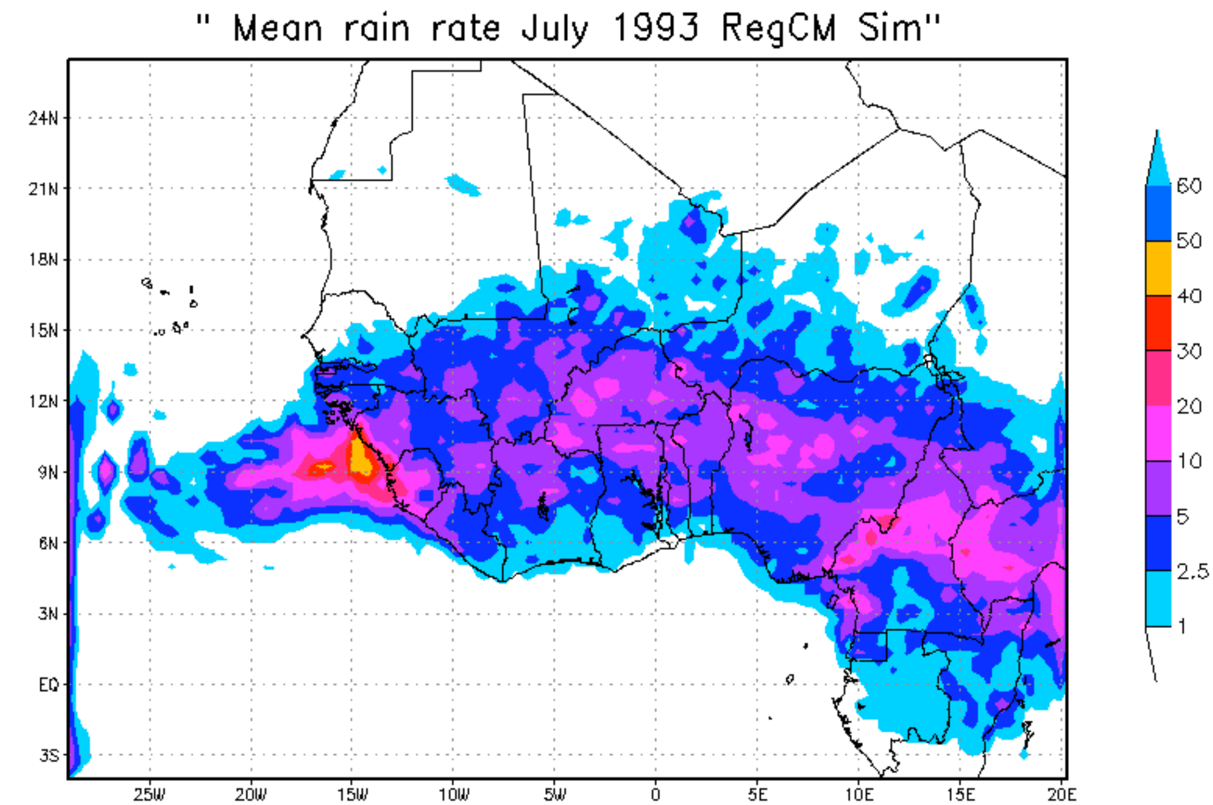


Figure 23: *Mean rain rate (mm/day) for july 1993, RegCM simulation.*

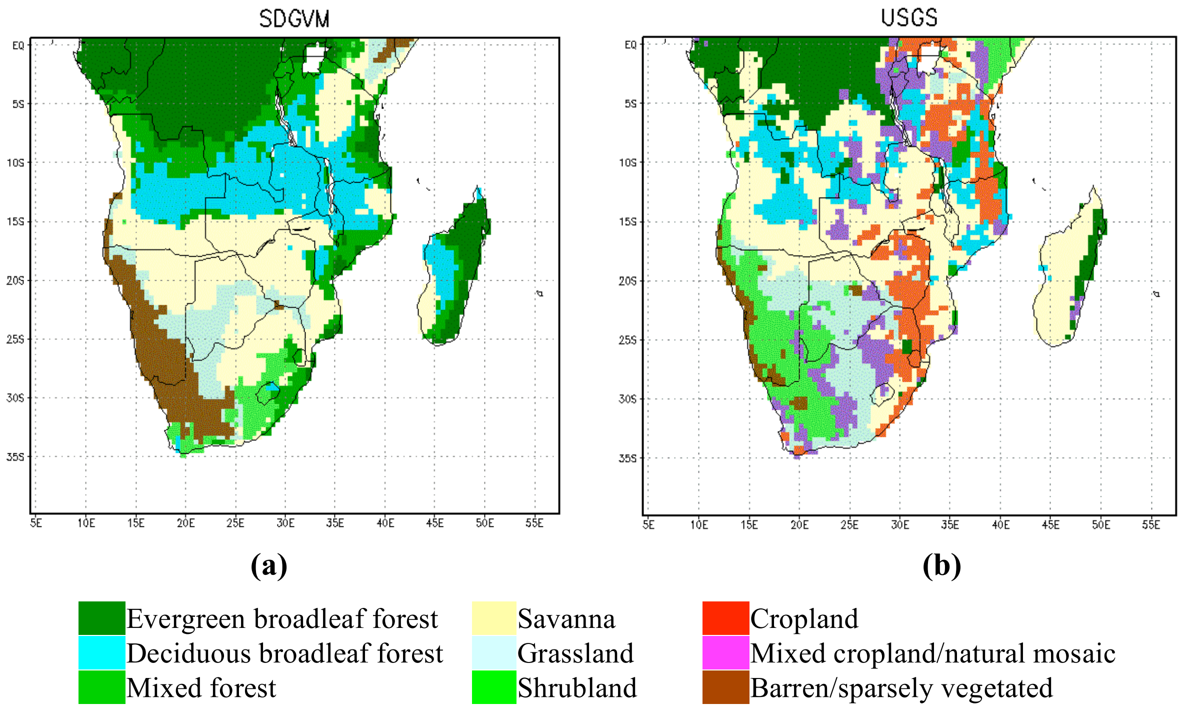


Figure 24: *a) Potential natural vegetation as simulated by the Sheffield Dynamic Global Vegetation Model (SDGVM) and b) the United States Geological Survey (USGS) land-surface classification. Note agricultural land-use classes are not represented by SDGVM. Also evident in the SDGVM distribution is the greater extent dominated by forests and the lack of shrubland cover in the south-western regions.*

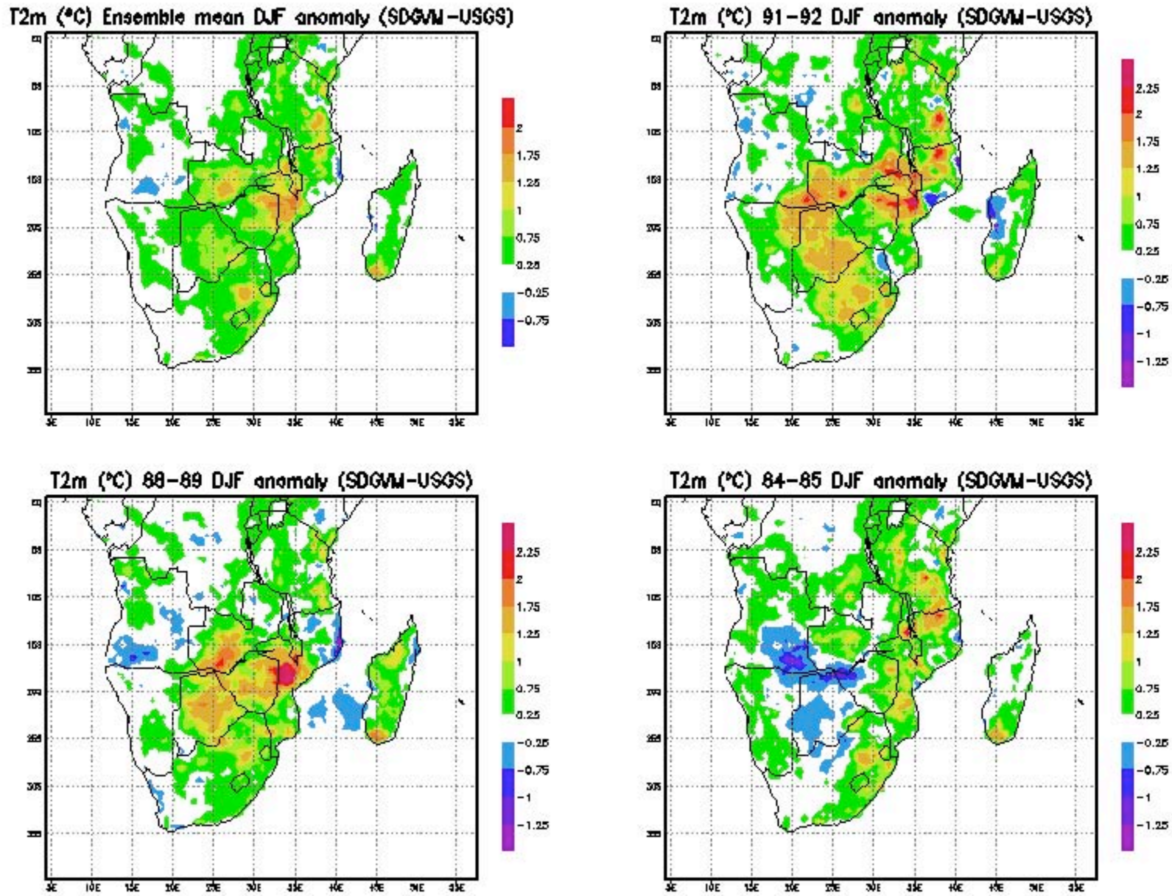


Figure 25: *Anomalies of 2m air temperature (T2m) for December to February (DJF; SDGVM land-use minus USGS land-use).*

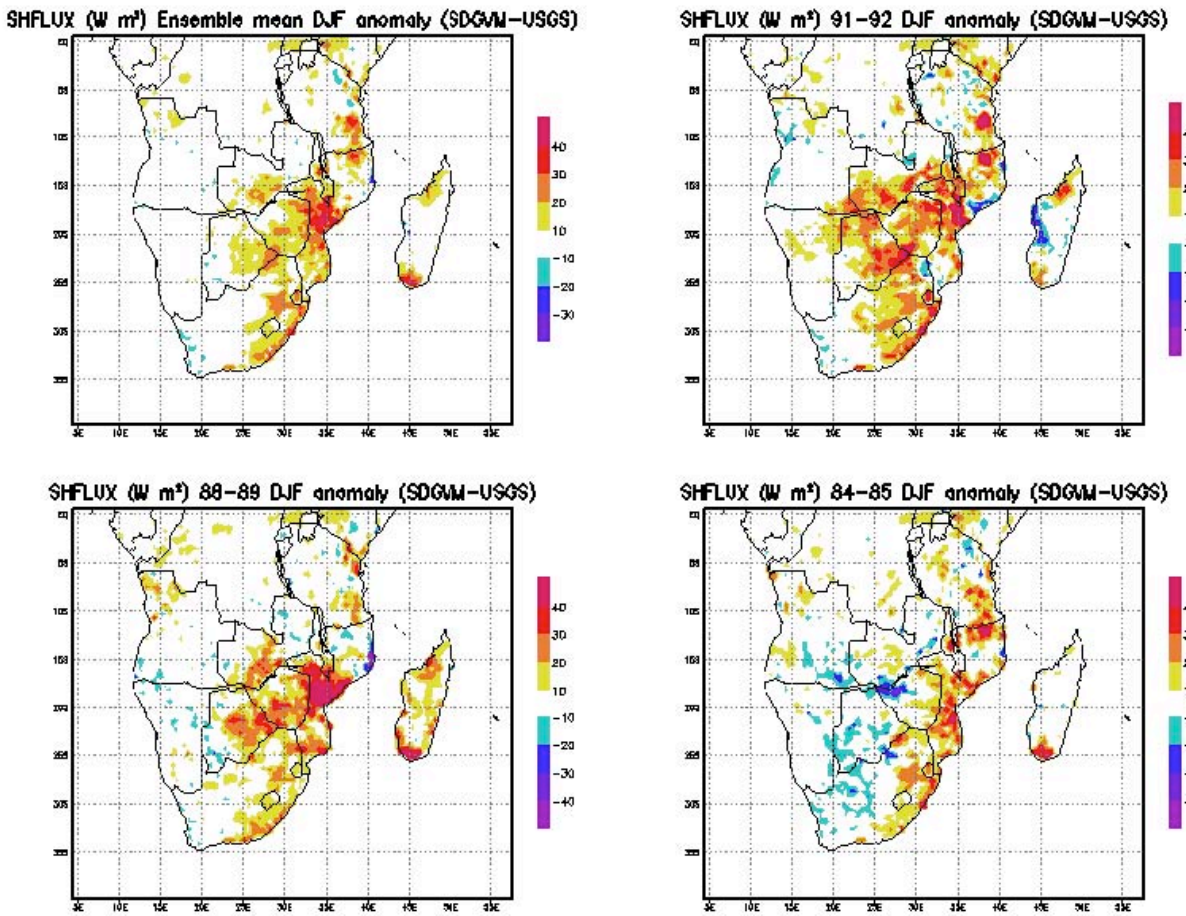


Figure 26: *As for Figure 25, but sensible heat flux.*

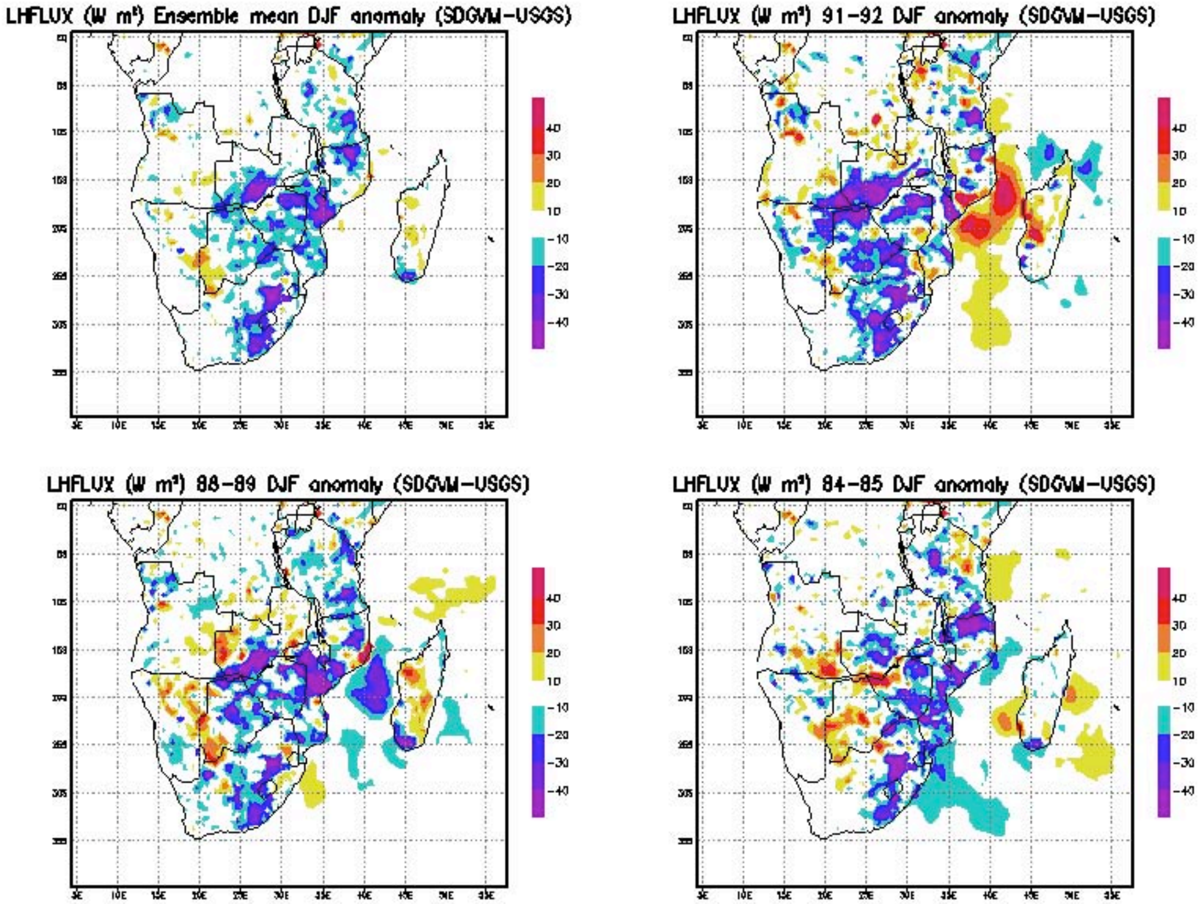


Figure 27: *As for Figure 25, but latent heat flux.*

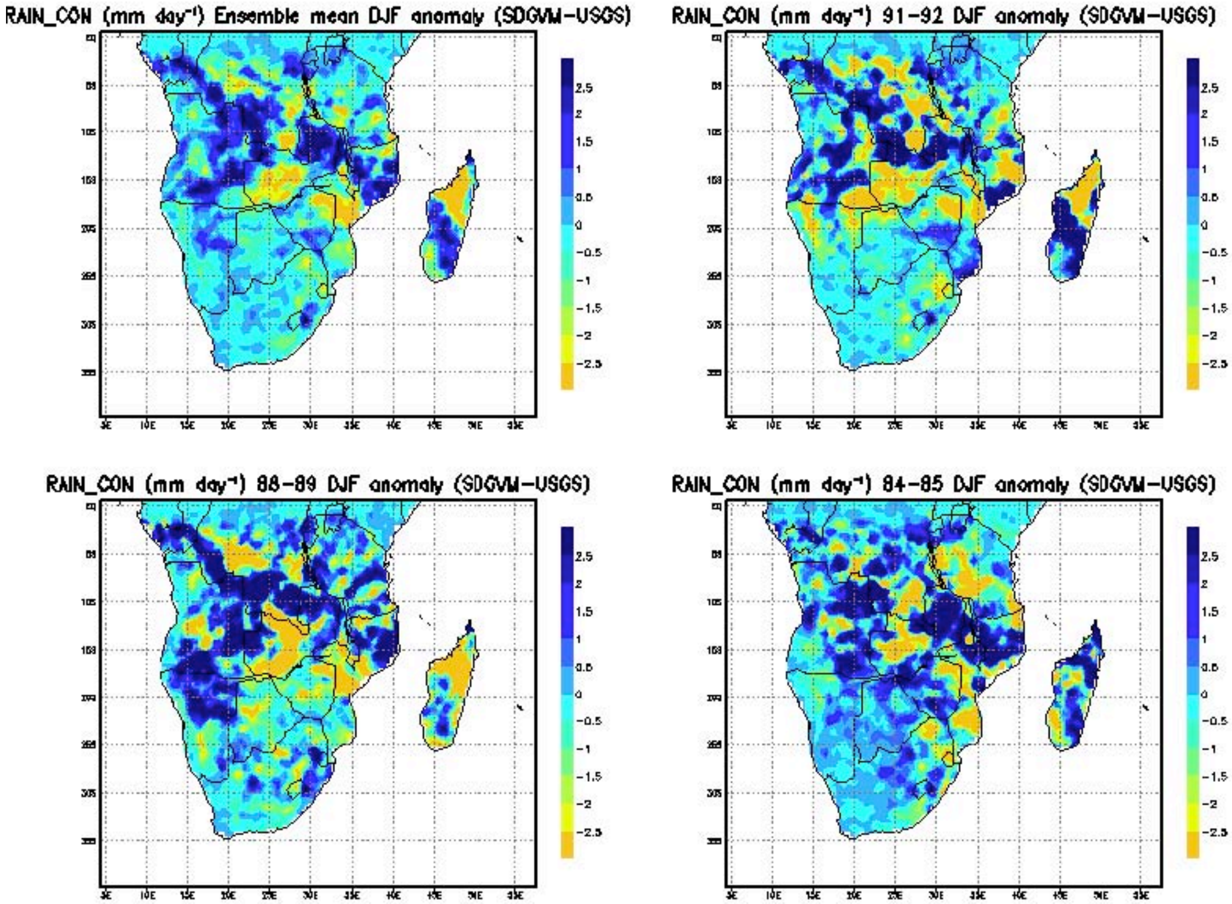


Figure 28: *As for Figure 25, but convective rainfall.*

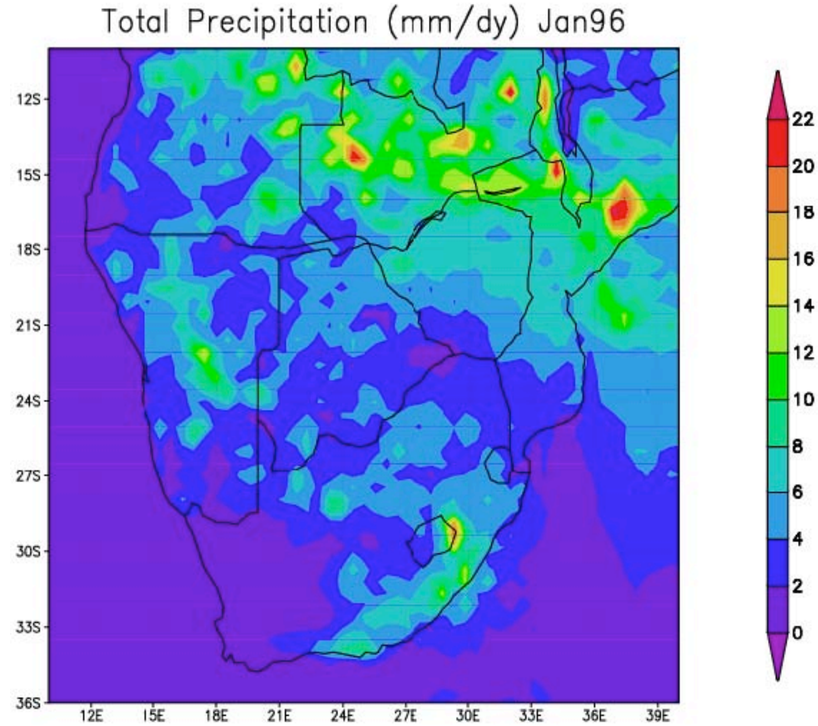
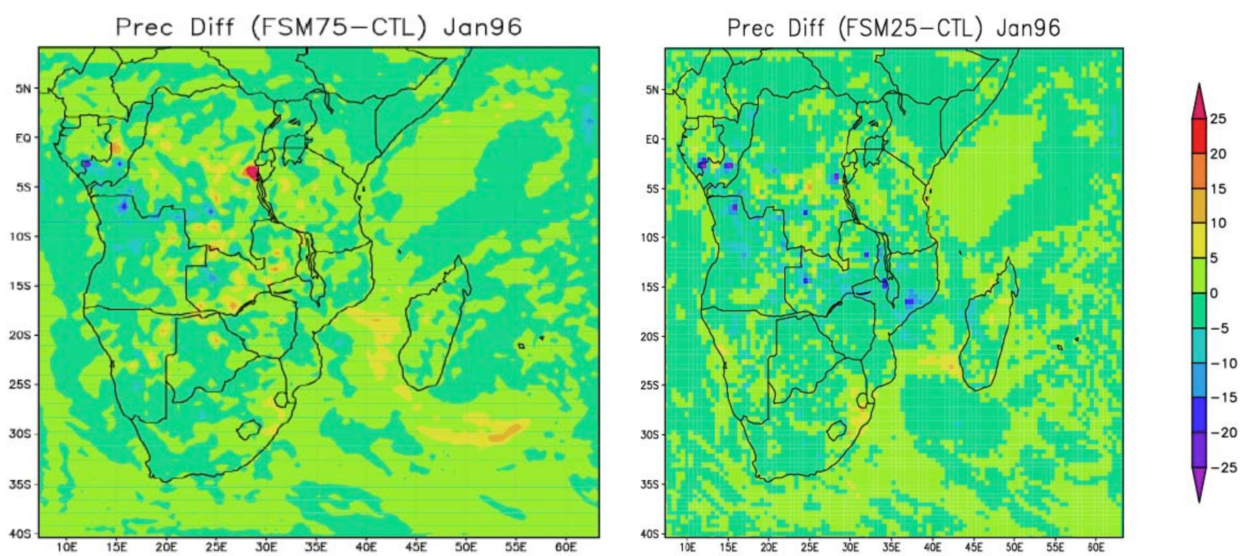


Figure 29: Total precipitation (mm/day) over Southern Africa (RegCM3).



(a) **(b)**

***Figure 30:** Precipitation differences for fixed soil moisture values of (a) 75%, (b) 25% and the control run.*

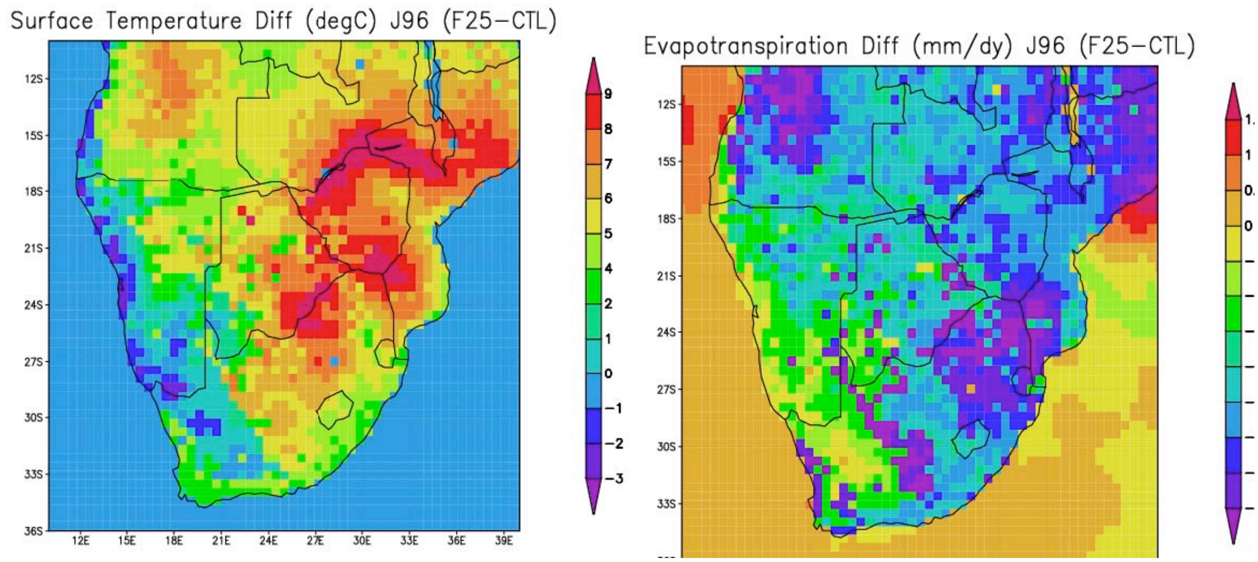


Figure 31: *Surface Temperature (°C) and Evapotranspiration differences (mm/day) for 25% fixed soil moisture values and the control simulation.*

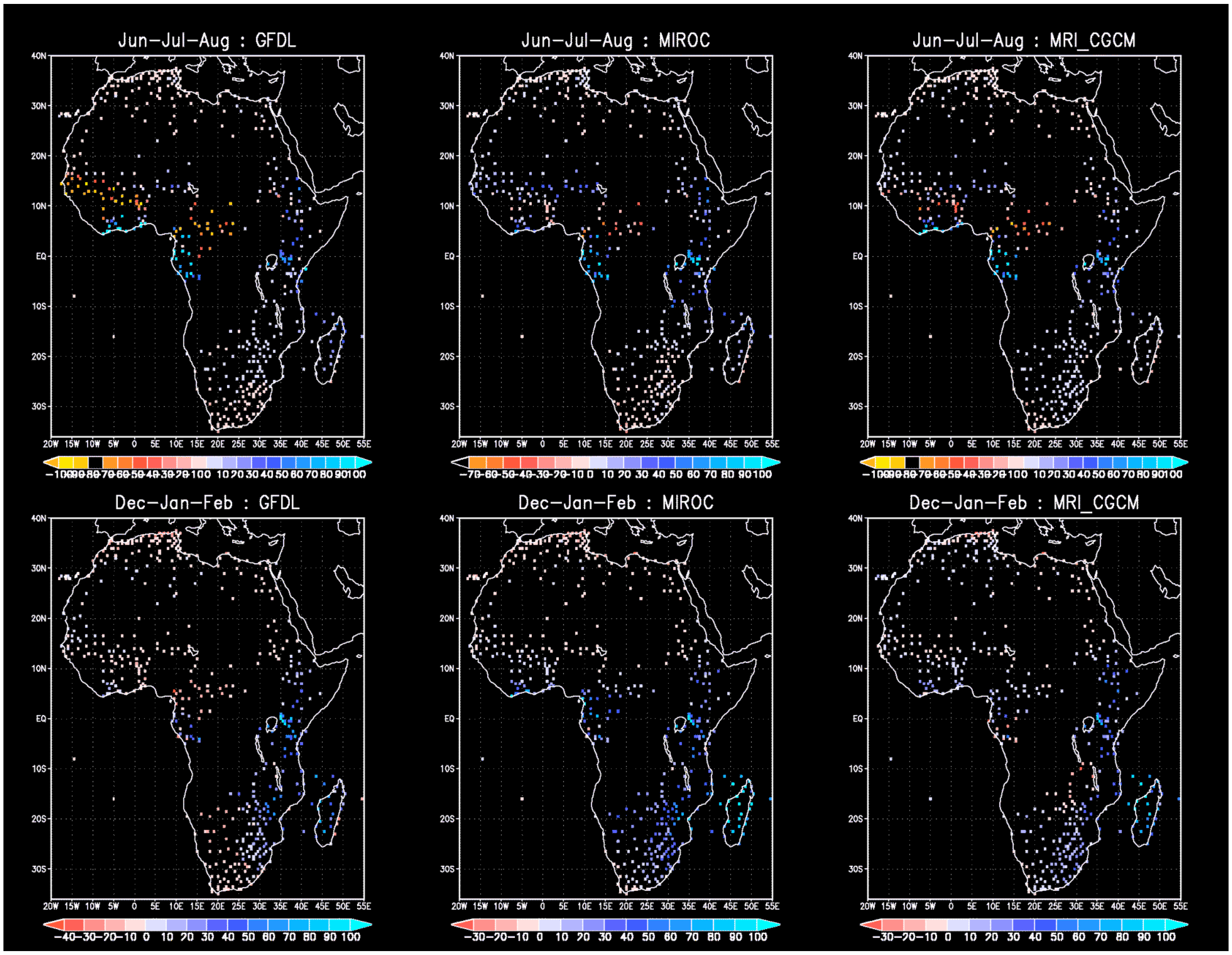


Figure 32: *Projected change in mean monthly precipitation (mm) for 2046-2065, downscaled from three GCM simulations using the SRES A2 emissions scenario.*

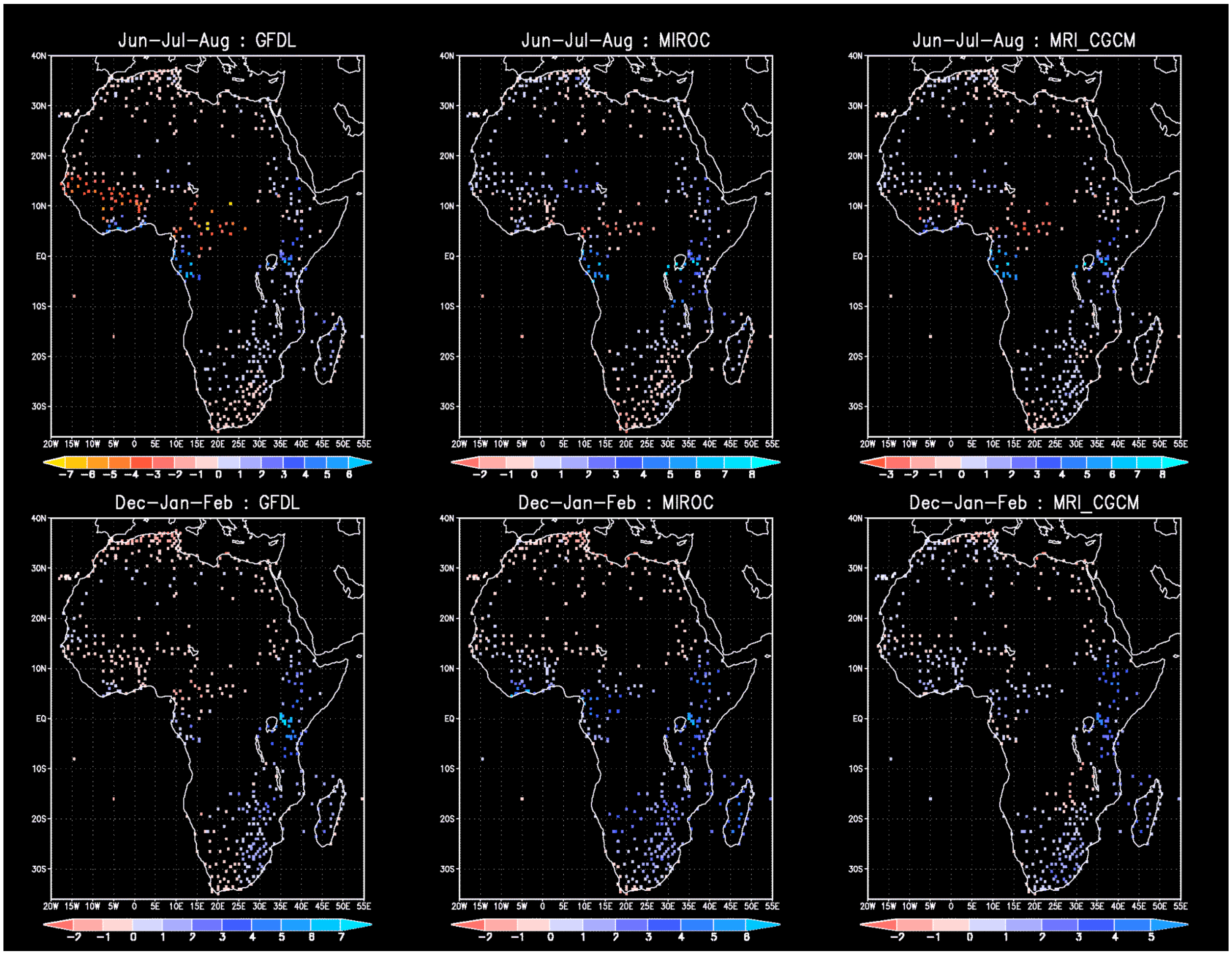


Figure 33: *Projected change in mean monthly number of raindays for 2046-2065, downscaled from three GCM simulations using the SRES A2 emissions scenario.*

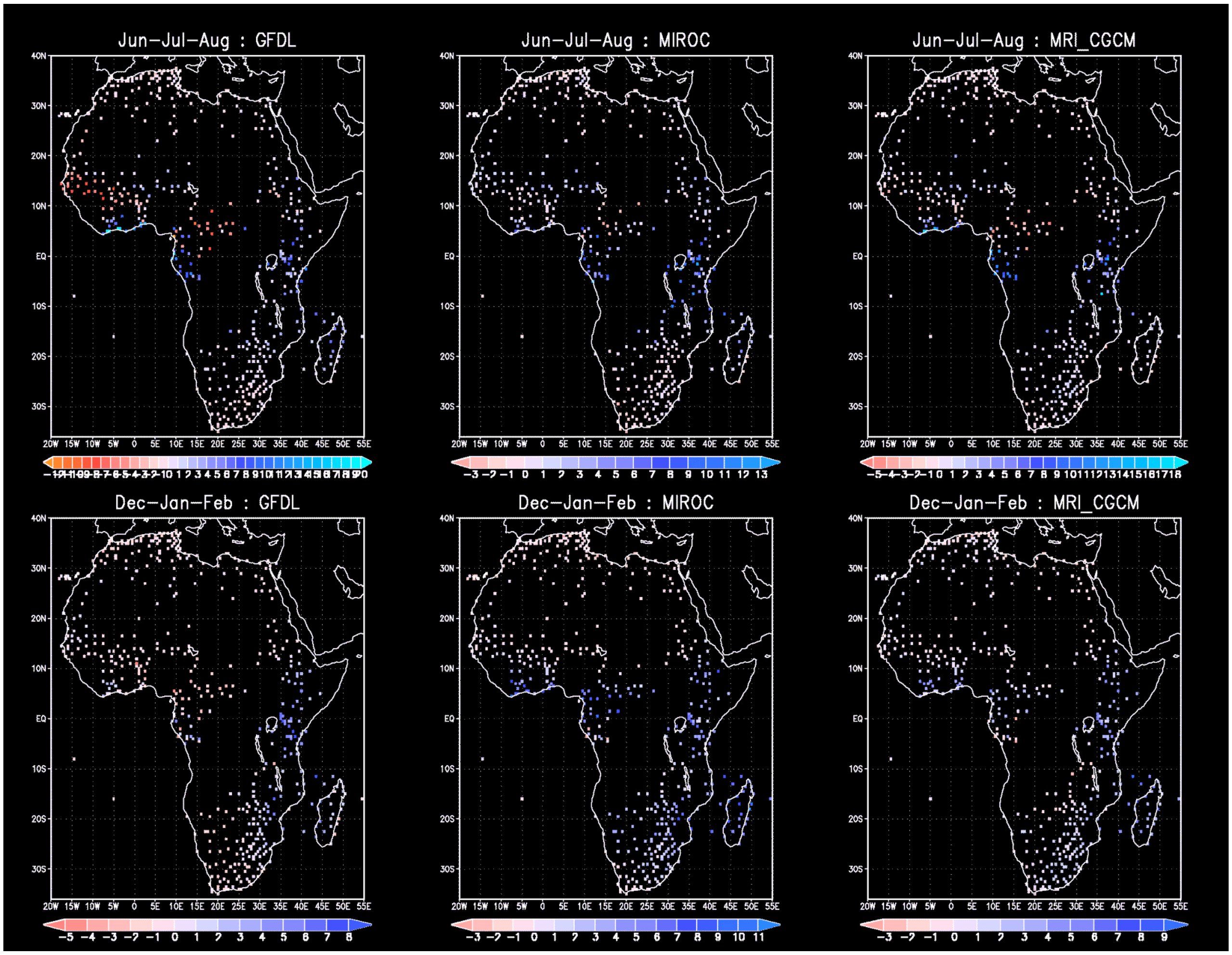


Figure 34: *Projected change in the magnitude of the 90th percentile precipitation event (mm) for 2046-2065, downscaled from three GCM simulations using the SRES A2 emissions scenario.*

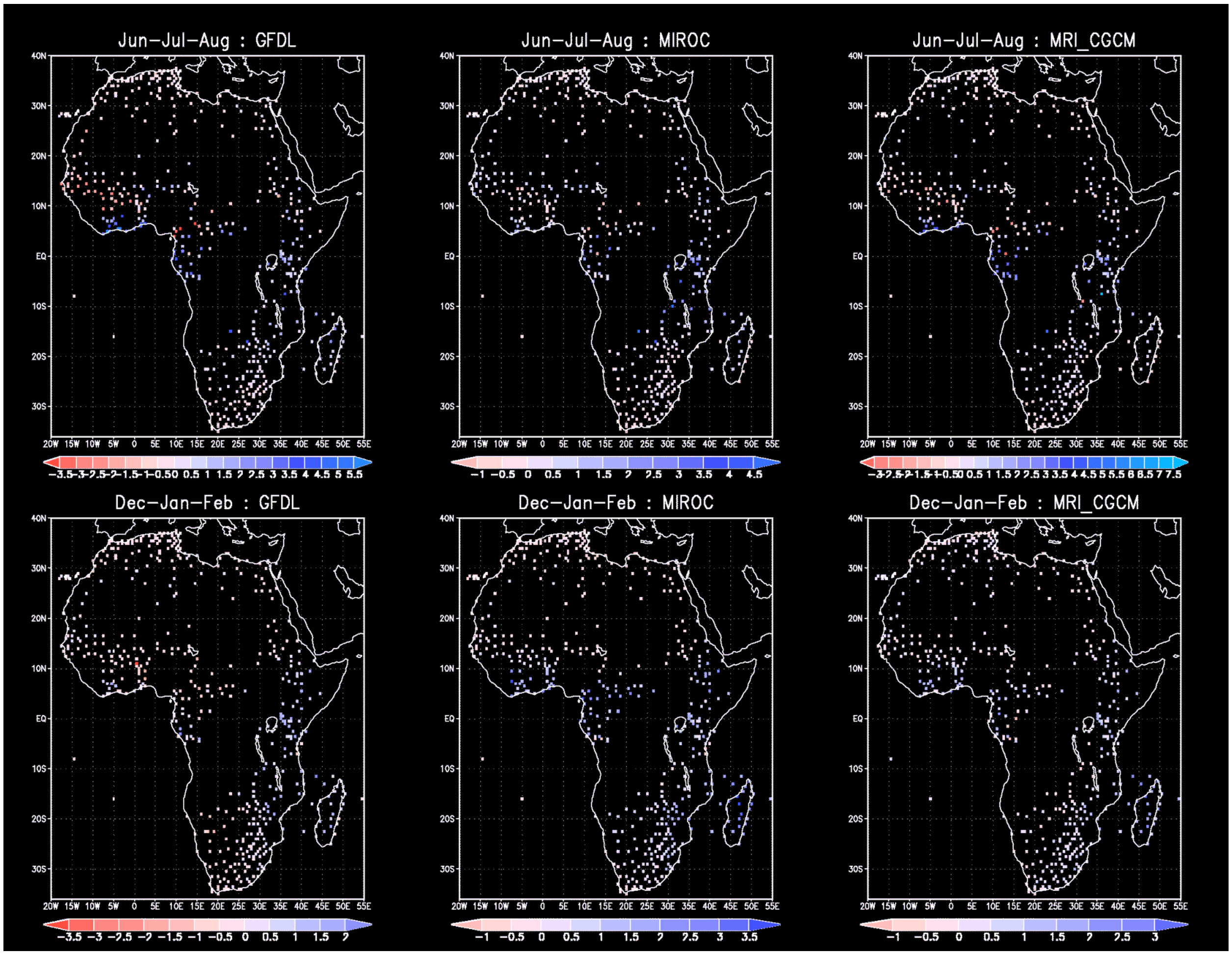


Figure 35: *Projected change in the magnitude of the median monthly precipitation event (mm) for 2046-2065, downscaled from three GCM simulations using the SRES A2 emissions scenario.*

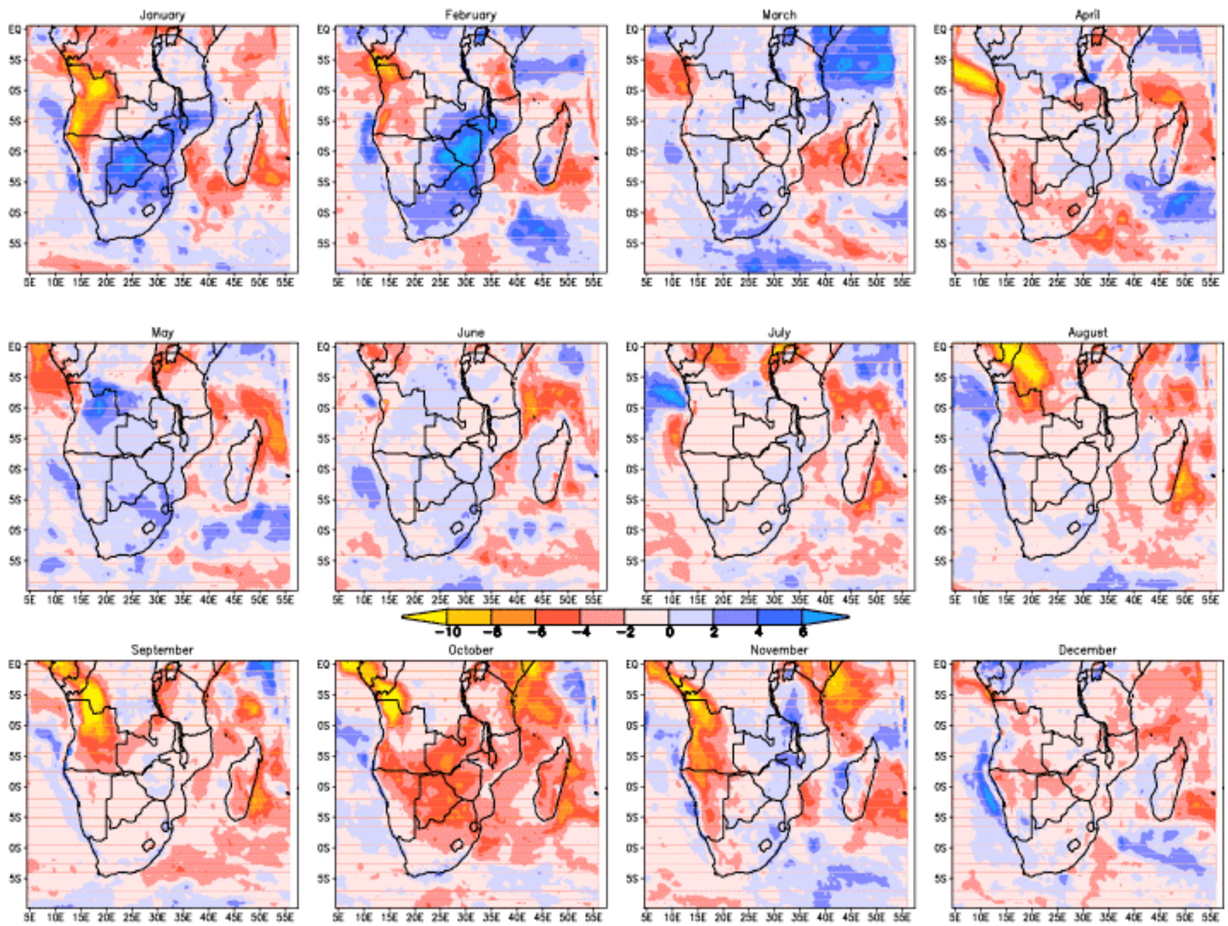


Figure 36: *PRECIS (nested within HadAM3P) predicted monthly change in number of rain days (2070's – 1970's). Months are January (top left) to December (bottom right)*

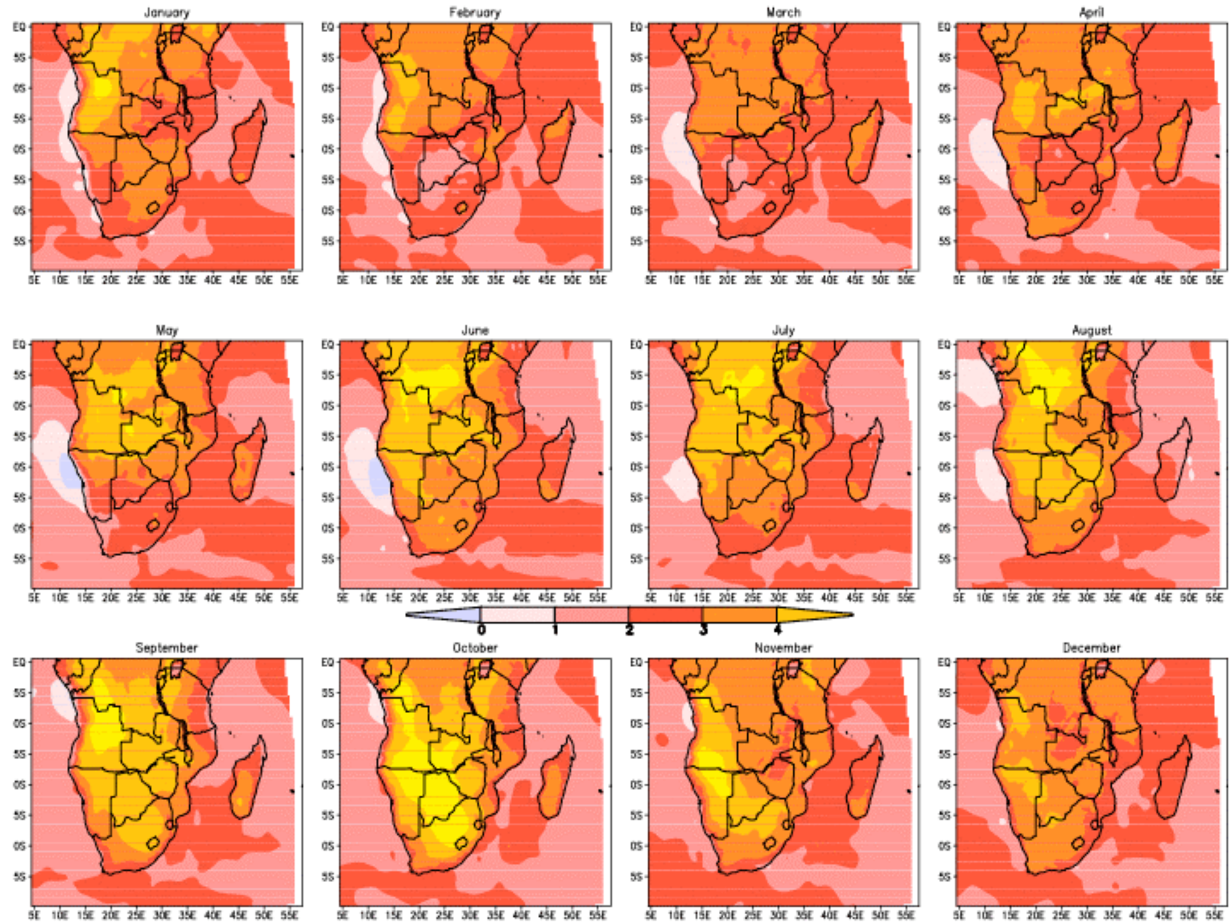


Figure 37: *PRECIS (nested within HadAM3P) predicted monthly change in average 2m surface temperature (2070's – 1970's). Months are January (top left) to December (bottom right)*

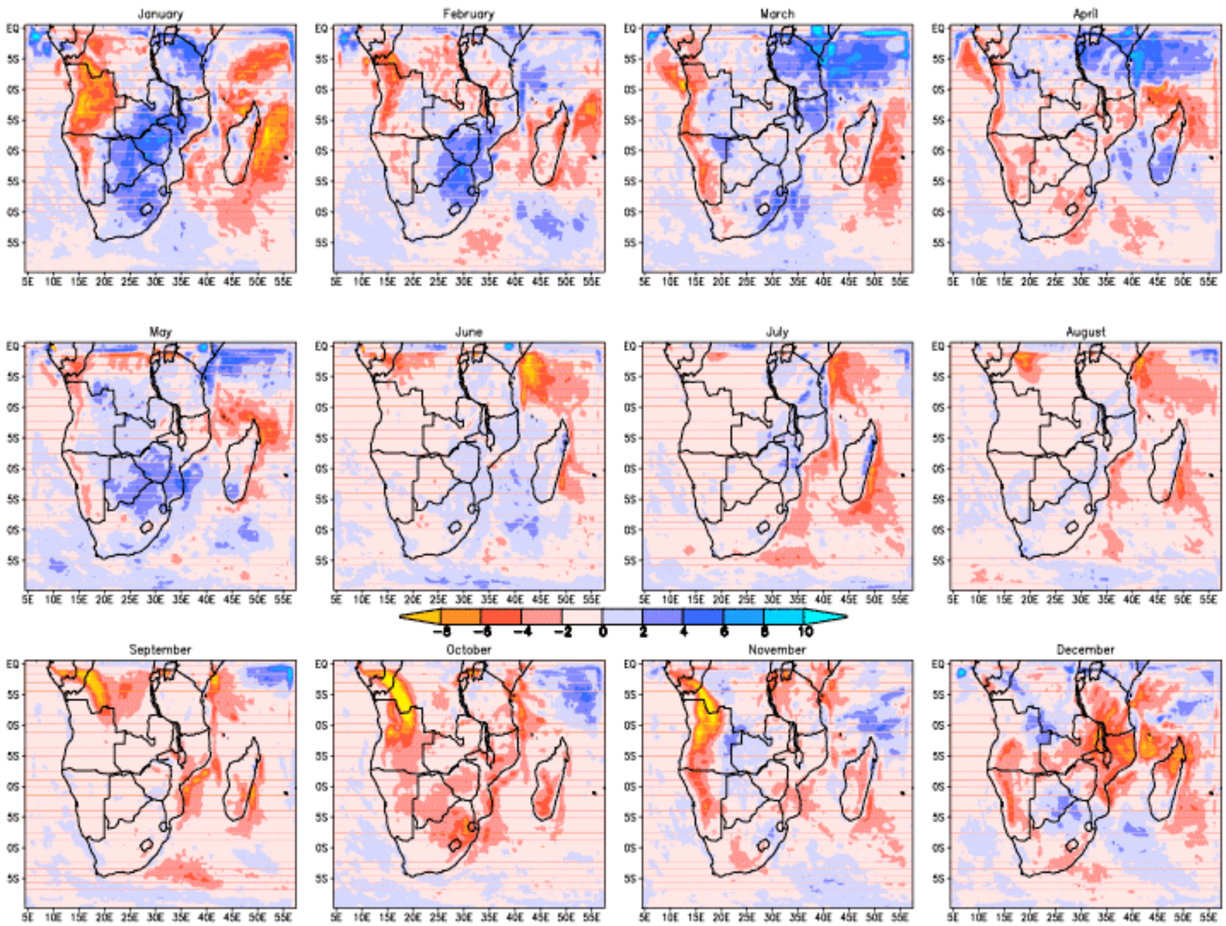


Figure 38: *MM5 (nested within HadAM3P) predicted monthly change in number of rain days (2070's– 1970's). Months are January (top left) to December (bottom right)*

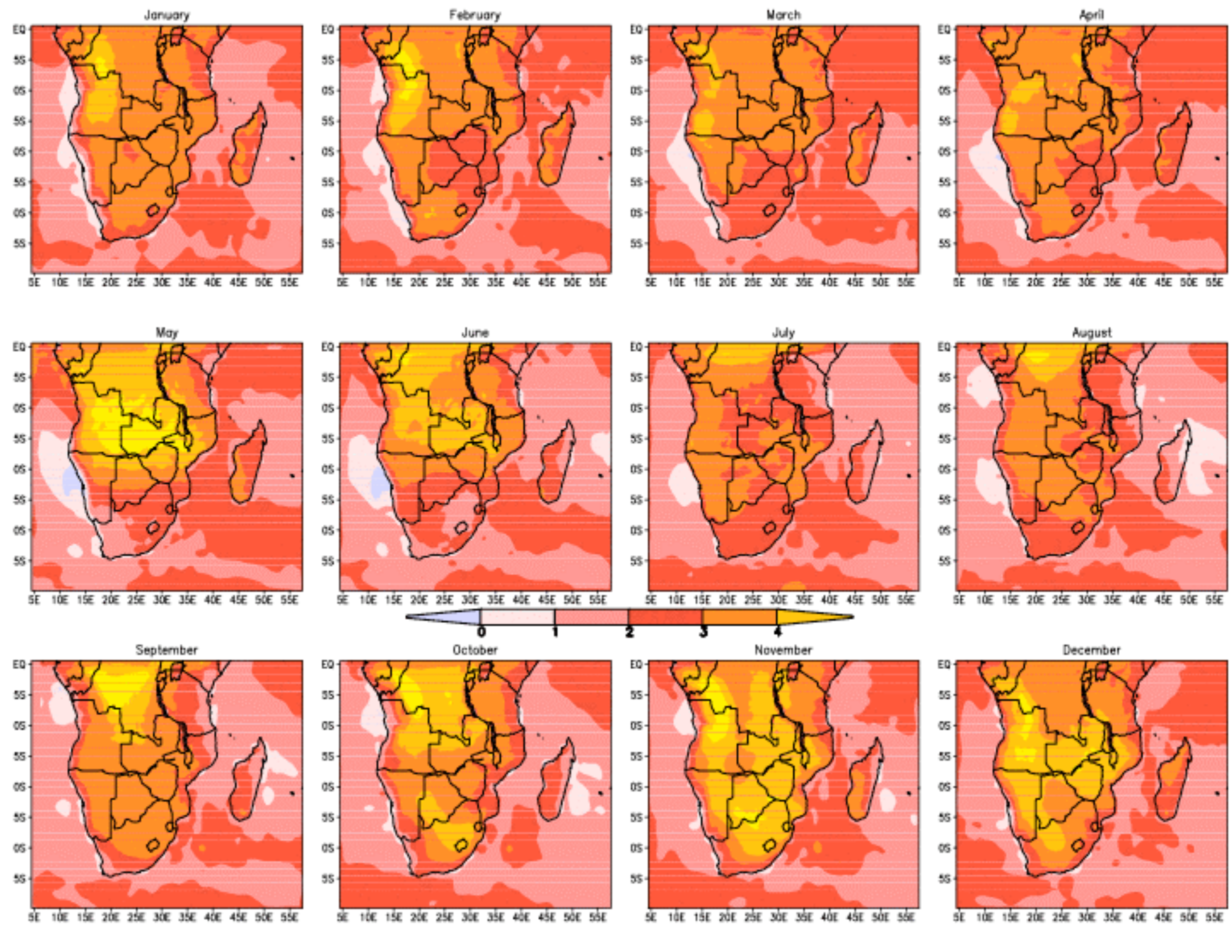


Figure 39: *MM5 (nested within HadAM3P) predicted monthly change in average 2m surface temperature (2070's – 1970's). Months are January (top left) to December (bottom right)*

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