IMPROVED DROUGHT EARLY WARNING AND FORECASTING TO STRENGTHEN PREPAREDNESS AND ADAPTATION TO DROUGHTS IN AFRICA

DEWFORA

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Review of dynamic and statistical downscaling of climate projections to the regional and local scale, and guidelines for application in the African context

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SUMMARY

Coupled global climate models (CGCMs) have become the primary tools for the projection of future climate change. Their projections of changes in the future large-scale circulation patterns, such as the poleward displacement of the westerly wind regime and the strengthening and poleward expansion of the subtropical highs, are thought to be reliable. However, CGCM simulations do contain some systematic errors that increase the uncertainty associated with the projections of future climate change. For example, many CGCMs display systematic errors in simulating the attributes of El Niño Southern Oscillation (ENSO) events, and consequently their simulations of the response of African climate to the ENSO signal may be compromised. CGCM simulations are also of too course horizontal resolution to be of direct value in application modelling, or in climate-change impact studies. The methods of dynamic and statistical downscaling may be used to obtain more detailed projections of future climate change over an area of interest. However, only a small number of such high-resolution studies are currently available over the African continent. This report provides an overview of the relative strengths and weaknesses of CGCM projections, as well as their dynamic and statistical downscaling, within the context of African climate. The projections of future climate change currently available over Africa, from both CGCM and downscaling studies, are subsequently reviewed. For some regions of the subcontinent, robust signals of the direction of future change for both temperature and rainfall can be identified. However, for other regions (most importantly West Africa and the Sahel) there is more uncertainty regarding the range of possible climate futures.

The report concludes with a section that reviews the available insights into future changes in extreme weather events over Africa, as obtained from currently available CGCM projections and downscaled results. The particular focus of FP7 project DEWFORA within the context of future climate change over Africa, namely the potential effects of enhanced anthropogenic forcing on the attributes of African droughts, is emphasised. The research activities that are underway to address specifically this topic are discussed. Firstly, the very high-resolution projections under construction over the Niger and Blue Nile river basins, for application within the project, are introduced, and their potential for the analysis of the changing attributes of hydrological and meteorological drought over Africa is indicated. Secondly, an outline is provided of experiments under construction that are designed to gain more insight into the pronounced effects of the El Niño Southern Oscillation (ENSO) on African drought. Of particular interest in these experiments are the effects of El Niño and La Niña events on the occurrence of anomalous rainfall over the upper catchment of the Blue Nile in the Ethiopian Highlands.

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1. INTRODUCTION

The African continent is thought to be highly vulnerable to anthropogenically induced climate change (e.g. Meadows, 2006). The rate of warming over the continent is robustly projected to be in the order of 1.5 times the global mean rate of temperature increase (Christensen et al., 2007), according to the coupled global climate model (CGCM) projections described in Assessment Report Four (AR4) of the Intergovernmental Panel on Climate Change (IPCC). It seems plausible for large parts of subtropical Africa, including southern Africa and the northern Sahara, to become drier within this warming climate, whilst East Africa is robustly projected to become wetter (e.g. Christensen et al., 2007; Engelbrecht et al., 2009). These changes in African climate may be expected to have wide-ranging implications, including largely negative impacts on agriculture (e.g. Thornton et al., 2011), water security and the abundance and distribution of pests and diseases (e.g. Olwoch et al., 2008).

The CGCM projections described in AR4 and elsewhere are of course horizontal resolution, and therefore to some extent inadequate to describe the regional details of climate change over Africa. Only a few detailed projections of climate change have been obtained to date for parts of the continent, using dynamic regional climate models (e.g. Tadross et al., 2005; Engelbrecht et al., 2009; Engelbrecht et al., 2012). These experiments have mostly focused on the southern African region, and have suggested the plausibility of the eastern parts of southern Africa becoming wetter during summer, with an associated increase in the frequency of occurrence of convective rainfall events (Tadross et al., 2005; Hewitson and Crane, 2006; Engelbrecht et al., 2009). Annual rainfall totals have, consistent with the CGCM projections, been projected to decrease over most of the southern African subcontinent in response to a general strengthening of the subtropical high-pressure belt (e.g. Seidel, 2008; Engelbrecht et al., 2009). This drying is projected to occur despite the projected increase in summer rainfall totals over the eastern parts of the subcontinent.

There is a need for larger ensembles of high-resolution regional projections of climate change to be obtained for the African continent, in order to describe more comprehensively the uncertainty range associated with these projections. Now that super-computing facilities are becoming more generally available on the African continent (for example in South Africa, through the computer clusters of the Centre for High Performance Computing (CHPC) of the Meraka Institute of the Council for Scientific and Industrial Research (CSIR)), there is the potential to perform more of these computationally expensive regional climate modelling experiments. FP7 project DEWFORA has the aim of generating very high-resolution projections of regional climate change over key river basins of the continent – in particular the Niger and Eastern Nile river basins. Where CGCM projections typically have horizontal resolutions that vary between 100 km and 300 km, the DEWFORA projections have been designed to have horizontal resolutions in the order of 8 km. Such simulations would be ideally suitable to provide forcing to the hydrological models that are to be integrated over these two river basins as part of the project research, and will additionally be analysed to study the changing attributes of meteorological drought over these regions.

This document serves to review the current insights into future climate change over the African continent – as is described in AR4 of the IPCC and a number of regional modelling studies that are available over the continent. In particular, existing insights into the projected climate-change signal of changes in the frequency of occurrence of average rainfall, temperature and extreme rainfall and temperature events, are reviewed.

2. COUPLED GLOBAL CLIMATE MODELS, REGIONAL MODELS AND DOWNSCALING

2.1 COUPLED GLOBAL CLIMATE MODELS

CGCMs are the primary tools used for the projection of future climate change. These models simulate the intricate interactions between the ocean, atmosphere and land-surface, and how this coupled system may be expected to respond to enhanced anthropogenic forcing. CGCMs are based on the laws of physics, which when expressed in mathematical form constitute a complex set of partial differential equations. The discretized form of these equations is solved numerically within CGCMs, at a given grid resolution. On present-day supercomputers, CGCMs may be integrated to perform climate simulations of several hundreds of years in length, at spatial resolutions that vary between 100 km and 300 km in the horizontal. Smaller scale processes such as cumulus convection and gravity wave drag, which can't be resolved at these grid resolutions, are treated statistically by means of parameterization schemes. CGCMs are thought to provide reliable projections of future changes in the large scale circulation patterns, such as the poleward shift of the westerly wind regime and the expansion of the tropical belt. CGCM projections, such as those described in AR4 of the IPCC, are currently the main source of information regarding plausible scenarios of future climate change over southern Africa. The projections of large-scale changes in the African climate, such as subtropical Africa (southern Africa and the Sahara) and the extra-tropical margins of the continent (Mediterranean coast of North Africa and the winter rainfall region of the Cape south coast of South Africa) becoming generally drier, are thought to be robust (e.g. Christensen et al., 2007).

However, CGCM simulations over Africa do display some systematic errors, which contribute to the uncertainty in their projections of future climate change. Of key importance are the systematic errors associated with the simulation of El Niño Southern Oscillation (ENSO) events, and the resulting signal of these events over southern and East Africa (e.g. Hulme et al., 2001). Of particular importance is a problem common to almost all CGCMs, namely the “cold tongue” bias along the equatorial Pacific. This bias leads to significant distortions of atmospheric flow patterns over the equatorial Pacific in the host CGCMs (e.g. Katzfey et al., 2009; McGregor et al., 2011). Other key problems identified in the CGCM simulations of AR4 of the IPCC (see Christensen et al., 2007) include the overestimation of rainfall over southern Africa, the equatorward displacement of the Atlantic Inter-Tropical Convergence Zone (ITCZ) and insufficient upwelling along the African west coast. Most CGCMs of AR4 do not produce realistic climate variability over the Sahel, in fact, several models fail in adequately simulating the West African monsoon (e.g. Christensen et al., 2007). Most models also simulate an equatorward displacement of the mid-latitude jet, compared to observations. Of lesser importance is probably that most CGCM simulations rely on static descriptions of the land-surface, that is, they do not simulate aspects such as dynamic changes in the land-surface (e.g. vegetation change in response to climate change) and the effects of dust aerosol feedbacks to the continental climate system.

CGCM projections of future climate change over Africa are described in more detail in the sections that follow.

2.2 DYNAMIC REGIONAL MODELS

Despite the systematic errors in current CGCM simulations, their projections are thought to provide reliable estimates of the large-scale future changes in African climate (e.g. drying of the northern Sahara and southern Africa). However, the simulations are of inadequate spatial resolution to be of direct value for application modelling and studies focusing on the regional impacts of future climate change. Of particular importance in FP7 project DEWFORA, is the application of hydrological models over the Niger and Eastern Nile river basins. Climate model simulations at resolutions as high as 8 km are required over these regions, to provide adequate descriptions of the intensity and spatial resolution of rainfall events for the forcing of hydrological models.

Such detailed simulations may be obtained through the use of dynamic regional climate models (RCMs). These models are typically atmosphere-only models, and are applied at high spatial resolution over selected areas of interest. There are two main types of RCMs: limited-area models, which have fixed lateral boundaries, and variable-resolution global models. The latter models are applied globally, but with finer resolution over an area of interest, from where the resolution decreases towards the far-field (see Engelbrecht et al., 2009). In order for limited-area models to be able to produce simulations of present-day climate or future climate change, they need to be provided with information of the atmospheric state, as simulated by a CGCM, at their lateral boundaries. To this approach is referred to as “nested climate modelling” (e.g. McGregor, 1997). Variable-resolution global models may similarly be nudged within the output of CGCMs, either in the form of grid-point nudging, or by means of spectral nudging at a given length scale (Thatcher and McGregor, 2009, 2010). Variable-resolution models avoid the problems that limited-area models experience with the reflection of atmospheric waves at their lateral boundaries, and provide a more flexible framework for the downscaling of CGCM simulations to high spatial resolution. Alternatively, variable-resolution models may be applied at quasi-uniform resolution to function as conventional global models. At their lower boundaries, all RCMs need to be provided with the state of the ocean and its evolution in time, that is, RCMs are forced with the sea-surface temperature (SST) and possibly sea-ice simulations of the host CGCMs. Present-day computational power allow RCMs to be applied at horizontal resolutions of about 50 km at the continental scale, and at even higher resolution at the sub-continental or smaller scales (e.g. Lal et al., 2008; Roux, 2009).

It may be expected, at least from theoretical arguments, that the detailed simulations of RCMs should improve on and be more accurate than those of the forcing CGCMs. Errors resulting from numerical approximations of the forcing equations are smaller in RCMs, compared to the errors in the coarser resolution CGCMs. Also, regional models can resolve meso-scale flow features, such as those resulting from steep topography, which can't be resolved at typical CGCM resolutions. However, RCMs are prone to systematic errors, similar to those occurring in the forcing CGCMs. Firstly, systematic errors in the CGCM simulations of synoptic-scale circulation patterns may be expected to carry over to to RCMs nested or nudged within the circulation fields of the forcing CGCM. Similarly, biases in the CGCM simulations of SST and sea-ice patterns are likely to impact negatively on the forced RCM simulations, especially if climate over the area of interest is strongly forced by the relevant SST and sea-ice patterns. Within the context of African climate, CGCMs are known to have systematic errors in simulating SST patterns in the Pacific Ocean associated with ENSO (see the previous subsection), as well as significant biases in simulating key SST patterns along the Guinean coast and in the Indian Ocean (e.g. Christensen et al., 2007, also see the previous subsection). Recently, attempts have been made to at least partially eliminate some of these problems, by forcing variable-resolution models with the bias-corrected SSTs and sea-ice of the host CGCM. In such simulations, the RCM runs in “stand-alone mode”, that is, it is not nudged within the simulated atmospheric circulation patterns of the CGCMs. There is evidence that this approach leads to improved simulations of regional pressure gradients and precipitation fields, compared to simulations where the raw CGCM fields are used to drive the RCM (Katzfey et al., 2009). Finally, RCMs are vulnerable to systematic errors introduced by imperfect parameterizations of physical processes. The parameteization of cumulus convection is known to be a particular course of uncertainty in RCM simulations over Africa (see Tadross et al., 2005). It may be noted in this regard that present-day computational power limits the application of RCMs over Africa to horizontal resolutions of about 50 km. Thus, even within current RCMs cumulus convection can't be resolved, and needs to be treated statistically for simulations performed at the continental scale.

Compared to continents such as Europe, Asia, North America and Australia, as pointed out in AR4, relatively few detailed regional climate simulations have been obtained to date over

Africa. This stems from the lack of supercomputing facilities on the continent, and a relatively small number of climate modellers (compared to countries in the developed world). Also, only a small number of international modelling groups have, at the time of AR4, devoted their computational resources to high-resolution climate modelling over Africa. Currently, the Coordinated Regional Downscaling Experiment (CORDEX) is in the process of generating a large ensemble of high-resolution projections of future climate change over Africa, using a variety of different regional climate models from different institutions, downscaling the output of the CGCM projections contributing to the Coupled Model Inter-comparison Project (CMIP5) and AR5. These simulations are performed at a resolution of about 50 km over Africa, and are expected to become available towards the end of 2012. In the next section of this report, the regional projections of climate change currently available over Africa are reviewed, including some recently obtained projections obtained at the Council for Scientific and Industrial Research (CSIR) in South Africa. It may be noted that even climate simulations obtained at 50 km resolution may not be sufficient for some climate change impact studies and to drive application models, such as hydrological and biodiversity models. This is especially true if simulations are needed over regions of steep topography, or at the sub-regional scale over small catchments. Such very high resolutions are being constructed as part of FP7 project DEWFORA, over the Niger and Eastern Nile river basins.

2.3 STATISTICAL DOWNSCALING

The methodology of statistical downscaling provides a computationally inexpensive alternative to dynamic regional climate modelling, in order to obtain high-resolution projections of future climate change over an area of interest. Statistical downscaling relies on finding empirical relationships between large-scale observed flow patterns and the the high-resolution observations of near-surface variables such as rainfall and temperature. Under the assumptions that CGCMs can skilfully simulate the large-scale circulation patterns and that the relationships between the large-scale patterns and the relevant surface variables remain constant in time, statistical downscaling can be used to obtain detailed projections of change in the near-surface variables from the CGCM projections of change in large-scale circulation fields.

The main advantage of statistical downscaling is that it is computationally efficient. It can be used to obtain large ensembles of high-resolution projections of future climate change from the forcing CGCM projections, without requiring super-computing facilities. However, statistical downscaling suffers from two major drawbacks. Firstly, the assumption that present-day relationships between large-scale circulation patterns and near-surface variables such as rainfall will remain stationary in time, under conditions of enhanced anthropogenic forcing, may not be valid. This assumption is particularly questionable given the projected changes in the thermodynamic profile of the atmosphere (e.g. a warmer troposphere, different atmospheric stability profile and higher moisture content) compared to present-day conditions. Statistical downscaling also depends on the existence of time-series of observational records of sufficient quality and length, for the empirical relationships to be established. Statistical downscaling can therefore only be performed over for those near-surface variables with sufficiently long observational records over the area of interest. For many parts of the world, such observations are only available for the variables of rainfall and temperature. In fact, over the African continent, the restricted observational record for the case of weather station data places rather severe limitations on the application of statistical downscaling.

Hewitson and Crane (2005) provided high-resolution downscalings of rainfall over South Africa, and illustrated that the methodology can accurately represent observed rainfall totals over the region. In particular, over the eastern escarpment of South Africa, an area where dynamic regional models and CGCMs are known to overestimate rainfall totals, statistical downscaling was shown to yield more realistic results. For other parts of the African continent, the statistical downscaling methodology was limited to providing estimations of precipitation at the point-scale, at specific sites where quality observations were available for sufficiently long periods. Statistically downscaled projections of future rainfall patterns over

South Africa are provided by Hewitson and Crane (2006). An interesting feature of this study is that the downscaling the different CGCMs produced a consistent precipitation signal, whilst the raw CGCM rainfall fields provided a more diverse rainfall response.

2.4 VERIFICATION OF CLIMATE MODEL SIMULATIONS OVER AFRICA: UNIQUE OPPORTUNITIES OFFERED BY FP7 PROJECT DEWFORA

Although the projections of dynamic climate models (CGCMs and RCMs) are being used increasingly to inform climate-change adaptation studies, they are sometimes being criticised as not being verifiable. That is, it will only be possible to verify the reliability of the projections several decades from now. However, confidence in the projections of climate change may be enhanced through the application and verification of climate models at verifiable time scales. That is, within the context of FP7 project DEWFORA, simulations and forecasts at the seasonal time-scale provide the opportunity to verify a climate model's ability to replicate the inter-annual variability in present-day African climate. Of key importance here is the model's ability to realistically simulate the attributes of ENSO and the Madden-Julian Oscillation (MJO), the main sources of climate variability at the global scale, as well as their impacts on climate variability over Africa. It is also important to test whether a climate model can replicate the trends observed in African climate over the last few decades.

Not all currently existing climate models are versatile enough to be applied across a range of time (and spatial) scales. In fact, most of the traditionally formulated limited-area RCMs do not have the capability to be used as global models, whilst the majority of global models cannot be applied as regional climate models (except for the computationally expensive case of high-resolution global runs). Variable-resolution global models provide perhaps the best framework for performing simulations across a range of spatial and time scales. These models may be applied in stretched-grid mode over selected areas of interest, thereby functioning as regional climate models. In FP7 project DEWFORA such a variable-resolution global atmospheric model, the conformal-cubic atmospheric model (CCAM), is applied for both seasonal forecasting and the projection of future climate change. If it can be shown that the model can realistically simulate and forecast inter-annual variability in African climate, for example the rainfall response over southern and East Africa during ENSO events, as well as the key observed trends in African climate, it would significantly strengthen the confidence in the model projections of future climate change.

3. PROJECTIONS OF FUTURE CLIMATE CHANGE OVER AFRICA

3.1 PROJECTED CHANGES IN TEMPERATURE PATTERNS

Most land areas, including the African continent, are projected to warm faster than the global average rate of temperature increase - largely due to the heat capacity of the landmasses being significantly lower than that of the oceans. The median of the ensemble of CGCM projections described in Assessment Report Four (AR4) of the IPCC, indicates a temperature increase of about 3 °C to 4 °C across the African continent for the period 2080 to 2099 relative to 1980 to 1999, under the A1B scenario of the Special Report on Emission Scenarios (SRES) (Christensen et al., 2007). This implies warming at about 1.5 times the global rate of temperature increase. This signal is robust across the ensemble of projections, with half of the models projecting warming within 0.5 °C of these median values (Christensen et al., 2007). Somewhat smaller warming, in the order of 3 °C, is projected for tropical Africa by the model mean, as well as over the coastal areas in general. The subtropical parts of the continent (southern Africa and the northern Sahara) are projected to warm faster than the tropics. There is some seasonal variation in the temperature signal over Africa, although this is relatively small compared to that in extra-tropical regions (see Christensen et al., 2007). Over southern Africa, the largest temperature increases are projected to occur during the austral spring (September to November), whilst over North Africa the largest temperature increases are projected for the boreal summer (July to August) (Christensen et al., 2007).

At the time of AR4, few regional projections of future temperature changes were available over the African continent. In regional model simulations over southern Africa under the A2 scenario, the regional model produced warming at a slower rate compared to that of the forcing CGCM (e.g. Tadross et al., 2005). Figure 1 shows the projected change in annual average temperatures over Africa for the period 2071-2100 relative to 1961-1990, as obtained from a high-resolution regional climate modelling experiment recently completed at the Council for Scientific and Industrial Research (CSIR) in South Africa. The 25th percentile (lower panel), median (middle panel) and 75th percentile (upper panel) of the ensemble of projected changes are shown. In these simulations, the variable-resolution global model CCAM (conformal-cubic atmospheric model) (McGregor, 2005) was used to downscale the output of six CGCMs of AR4 of the IPCC to a resolution of about 60 km over Africa. All the simulations were for 1961-2100, with future greenhouse gas forcing specified according to the A2 scenario. Consistent with the CGCM projections of AR4, the subtropical parts of the continent (southern Africa and the northern Sahara) are projected to warm more than the tropics. In general, warming is also more moderate along the coastal areas compared to inland areas. These patterns of warming are robust across the different ensemble members.

The drastic temperature increases that are projected for large parts of southern Africa and the northern Sahara under the A2 scenario – more than 4°C for the period 2071-2100 relative to 1961-1990, are highly significant. This signifies regional warming at about twice the global rate of temperature increase. This strong amplitude in the warming over southern Africa and the northern Sahara is robust across the different ensemble members. The rapid rise in temperature over southern Africa, compared to the rise in average global temperature, seems to related to the strengthening of the subtropical high-pressure belt over the region in the future climate, between spring to autumn (e.g. Engelbrecht et al., 2009; Engelbrecht and Bopape, 2011b). For the summer months, the somewhat smaller increases in near-surface temperatures are projected to occur in association with increased cloud cover and rainfall (see the next subsection).

Keeping the rise in the global average near-surface temperature below 2 °C (compared to the global temperature at pre-industrial times) during the 21st century, through a binding international treaty on greenhouse gas emissions, has become a primary objective of the IPCC and the United Nations Framework Climate Change Convention (UNFCC). It is thought that keeping the global temperature increase below this threshold may prevent "dangerous climate change". However, the results presented here indicate that even if this target is reached, it would still imply strong warming over large parts of southern Africa – in the order of 4 °C. The projected rapidly rising temperatures over the southern African subcontinent may be expected to have numerous impacts, for example on agriculture (e.g. Thornton et al., 2011), water resources (through increased evaporation), biodiversity and energy consumption (for example, the household energy demand for cooling in summer may be expected to increase, whilst the demand for warming in winter may be expected to decrease).

3.2 PROJECTED CHANGES IN RAINFALL PATTERNS

Figure 2 shows the projected change in annual rainfall totals (expressed as a percentage change) over Africa for the period 2071-2100 relative to 1961-1990, as obtained from the ensemble of high-resolution regional projections performed at the CSIR in South Africa. The 25th percentile (lower panel), median (middle panel) and 75th percentile (upper panel) of the ensemble of projected changes are shown. A number of studies have demonstrated the ability of CCAM to realistically simulate the attributes of the present-day rainfall climatology over southern Africa, including annual rainfall totals and the seasonal cycle in rainfall (Engelbrecht et al., 2009), inter-annual rainfall variability (Landman et al., 2009) and the frequency of occurrence of extreme rainfall events (Engelbrecht et al., 2012). The satisfactory simulation of these present-day attributes provides some confidence in the model projections of the future attributes of rainfall over the continent. Consistent with the ensemble of CGCM projections of AR4 of the IPCC, the projected rainfall signal shows great variation across the continent. It seems plausible that the subtropical parts of the continent (including southern Africa and the northern Sahara) will become drier in response to enhanced anthropogenic forcing (Christensen et al., 2007; also see Figure 2). Similarly, regions poleward of the subtropics are likely to dry – Mediterranean Africa, north of the Sahara, as well as the winter rainfall region in the southwest and south of South Africa. Conversely, there is evidence that East Africa and tropical Africa may be expected to become wetter. Projections of future changes in rainfall over West Africa (including the Sahel and Guinean coast) and the southern Sahara are more uncertain (Christensen et al., 2007). The projected changes are discussed in more detail on a regional basis in the following subsections.

3.2.1 Southern Africa

A robust pattern of change, of the subtropical high-pressure belt strengthening and expanding towards the south, is projected to occur over the southern African continent (e.g. Engelbrecht et al., 2009). Decreases in summer precipitation and annual rainfall totals over southern Africa are projected as a consequence (Christensen et al., 2007; also see Figure 2). Strengthening of the high-pressure belt in winter is associated with the southward displacement of the westerly wind regime and the cold fronts that bring rainfall to the winter rainfall region of South Africa (the southwestern Cape and the Cape south coast). This is one of the most robust rainfall signals in the CGCM projections described in AR4 for the African continent (Christensen et al., 2007).

3.2.2 East Africa

The ensemble of CGCMs described in AR4 projects a robust pattern of rainfall increases over East Africa, east of Great Lakes area, and extending into the Horn of Africa (Christensen et al., 2007). This signal is robust for annual rainfall as well as for December to February (DJF) rainfall totals. However, for the period June to August (JJF), there is greater uncertainty among the CGCM ensemble members about the sign of the rainfall changes. Similar patterns of increases in annual rainfall totals over East Africa are projected by the higher resolution CCAM ensemble (Figure 2). This signal is also evident in the projections described by Hulme et al. (2001), Ruosteenoja et al. (2003) and in the regional model projection of Engelbrecht et al. (2009). There is evidence that the East African monsoon may be expected to increase in intensity in response to the enhanced anthropogenic forcing and warming of the African continent (e.g. Engelbrecht et al., 2009). This is associated with the increased transport of moisture into East Africa (e.g. northern Mozambique, Tanzania and Kenya) with associated increases in precipitation.

3.2.3 Tropical Africa

Warming is projected to be associated with an increase or little change in precipitation in the African tropics (Christensen et al., 2007). The CCAM ensemble provides a robust message of rainfall increases across the African tropics (Figure 2). Consistent with the AR4 projections, these increases are projected to be rather small (less than 10 %).

3.2.4 West Africa and the Sahel

A robust pattern of drying is projected over the North African west coast by the ensemble of AR4 CGCMs, as far south as 15° N. This occurs in response to the systematic poleward shift of storm tracks (e.g. Christensen et al., 2007). This pattern of change is also reflected in the median of the ensemble of CCAM projections, with the exception of the wetter conditions that are projected for the coastal areas around 20° N. This wetting is to occur as part of a zonal band of precipitation increase over the southern Sahara. Off the Guinean coast to the south, and over the Sahel, the projected rainfall changes across the different CGCM projections of AR4 display a great deal of variation. The CCAM ensemble indicates rainfall decreases over this region.

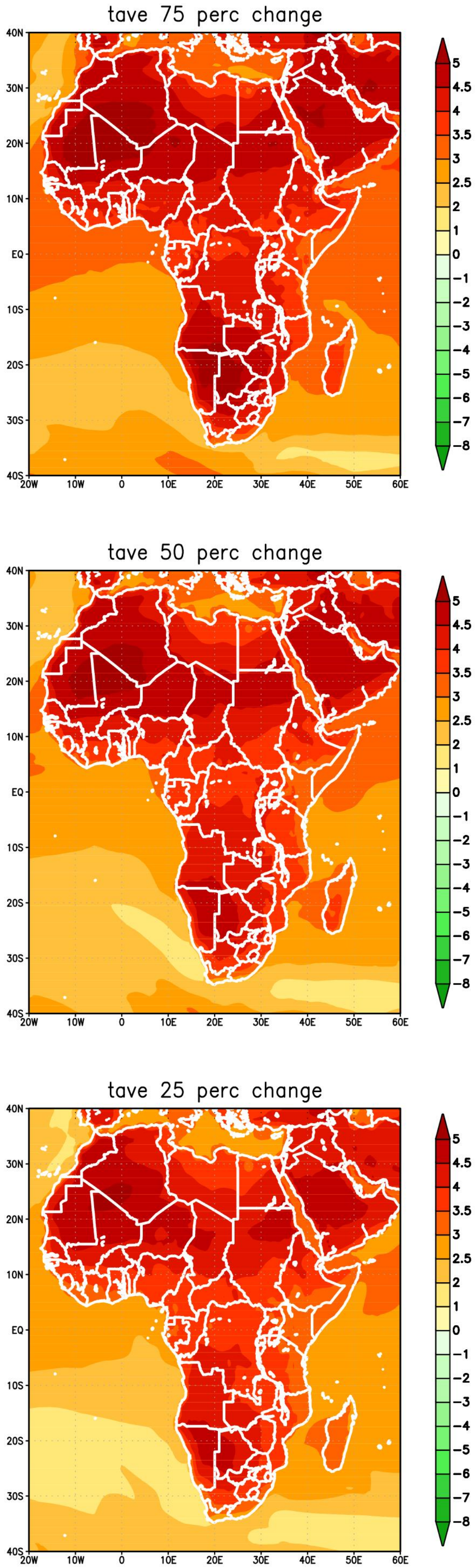

Figure 1. Projected change in the annual average maximum temperature over Africa, for the period 2071-2100 relative to 1961-1990. The 75th percentile (upper panel), median (middle panel) and 25th percentile (lower panel) are shown for an ensemble of six downscalings of CGCM projections, generated using the regional model CCAM. All the CGCM projections contributed to AR4 of the IPCC and are for the A2 SRES scenario.

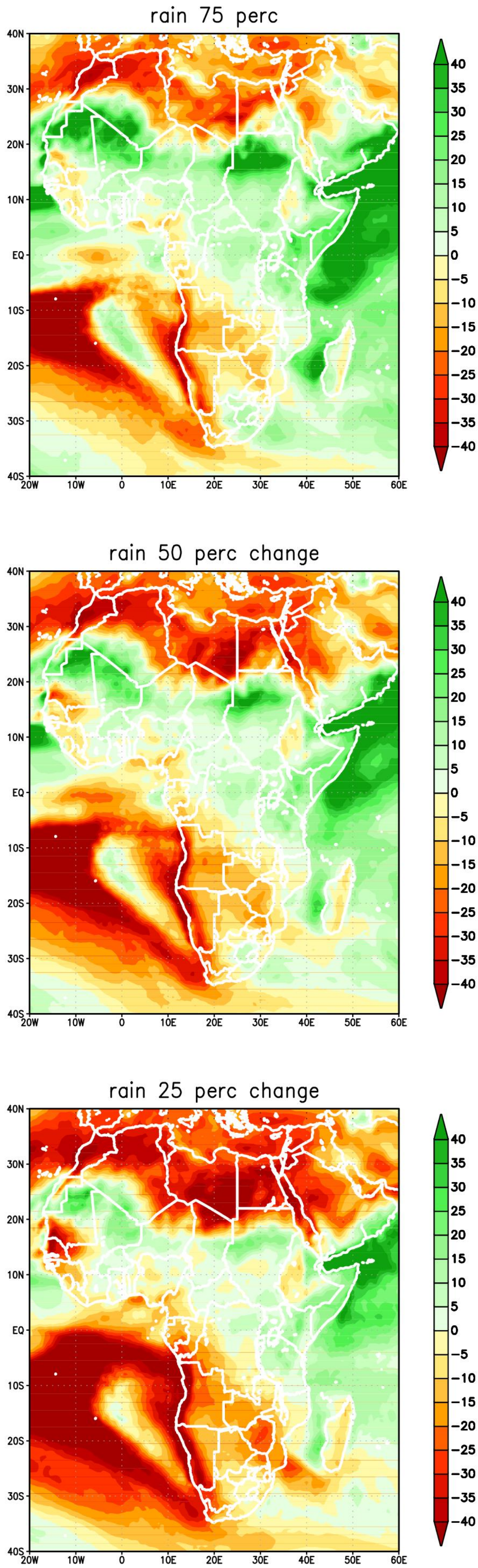

Figure 2. Projected change in the annual total rainfall (expressed as a percentage change) over Africa, for the period 2071-2100 relative to 1961-1990. The 75th percentile (upper panel), median (middle panel) and 25th percentile (lower panel) are shown for an ensemble of six downscalings of CGCM projections, generated using the regional model CCAM. All the CGCM projections contributed to AR4 of the IPCC and are for the A2 SRES scenario.

3.2.5 Sahara

A robust pattern of drying is projected across the northern Sahara by the high-resolution CCAM ensemble (Figure 2), consistent with the ensemble of AR4 CGCMs (Christensen et al., 2007). This occurs in association with drying projected over the Mediterranean coast, and the strengthening and northward expansion of the subtropical high-pressure belt. The CCAM ensemble is indicative of quite substantial rainfall increases over the southern Sahara, whilst AR4 of the IPCC concluded that indications of the likely sign of the rainfall signal over this region are inconclusive.

3.2.6 The African Mediterranean coast

The African Mediterranean coast is expected to dry, in response to the large-scale poleward shift of the westerly wind regime and storm tracks, in conjunction with the strengthening and northward expansion of the subtropical high-pressure belt. This signal is robust across the ensemble of CGCM simulations described in AR4, with the rainfall decreases projected to be in the order of 20%. The CCAM ensemble consistently indicates a robust message of drastic decreases in precipitation over the Mediterranean coast, as large as 40% over some regions.

4. PROJECTED CHANGES IN EXTREME EVENTS

The African continent exhibits a high degree of natural climate variability, and is prone to the sporadic occurrence of droughts and floods. Flooding may result from a number of different weather systems. Tropical cyclones are perhaps the most devastating; however, these systems make landfall over Africa rather infrequently, and only over the eastern coastal areas of Mozambique and South Africa (Malherbe et al., 2011). Other types of tropical systems, such as mesoscale convective complexes, typically cause flooding over tropical and subtropical Africa. Weather systems from the westerly wind regime, mostly cut-off lows, frequently bring damaging floods to the southern parts of South Africa. At the other end of the scale, dry spells, heat waves and prolonged periods of agricultural drought also occur sporadically as part of the natural climate of the continent, often in association with ENSO events. Climate change over Africa may manifest itself not only in a change in the long-term mean seasonal rainfall, temperature and circulation patterns (as described in the previous sections), but also through an increase in the frequency of occurrence of extreme events. However, the IPCC pointed out in AR4 that research on potential changes in extreme weather events over Africa is limited.

The projected change in the frequency of occurrence of extreme rainfall events (here defined as 20 mm of rain falling within 24 hours over an area of 0.5° x 0.5°) is shown in Figure 4 (25^{th} percentile, median and 75^{th} percentile of the ensemble of projections performed at the CSIR). The figure indicates a robust signal of an increase in extreme rainfall events over tropical Africa – consistent with a general (global) increase in such events that is projected to occur in association with an increase in atmospheric water vapor in a warmer atmosphere. The ensemble of CGCM projections described in AR4 of the IPCC indeed indicate that extremely wet seasons are projected to increase over both East Africa and West Africa (Christensen et al., 2007). Extreme rainfall events are projected to decrease in frequency over parts of southern Africa (Namibia, Zambia, Botswana and Zimbabwe) and the Sahara – consistent with the general patterns of drying projected for these regions (Figure 2). This signal is robust for the southern African region in the ensemble of projections, but is not well-established in the 75^{th} percentile of the ensemble over the Sahara. Over South Africa a projected increase in the frequency of extreme rainfall events is found consistent with earlier studies (e.g. Tadross et al., 2005; Engelbrecht et al., 2011; Engelbrecht et al., 2012) – despite the general decrease in precipitation that is projected for this region. The increase in extreme events may be at least partially be ascribed to the significant increase in surface temperatures over the region (Figure 3). Such an increase in surface temperature would be conducive to a deepening of the continental heat low, and a subsequent increase in the occurrence of heat convection and convective rainfall. In fact, a general decrease in the frequency of cut-off lows over southern Africa has been projected in previously performed simulations (see

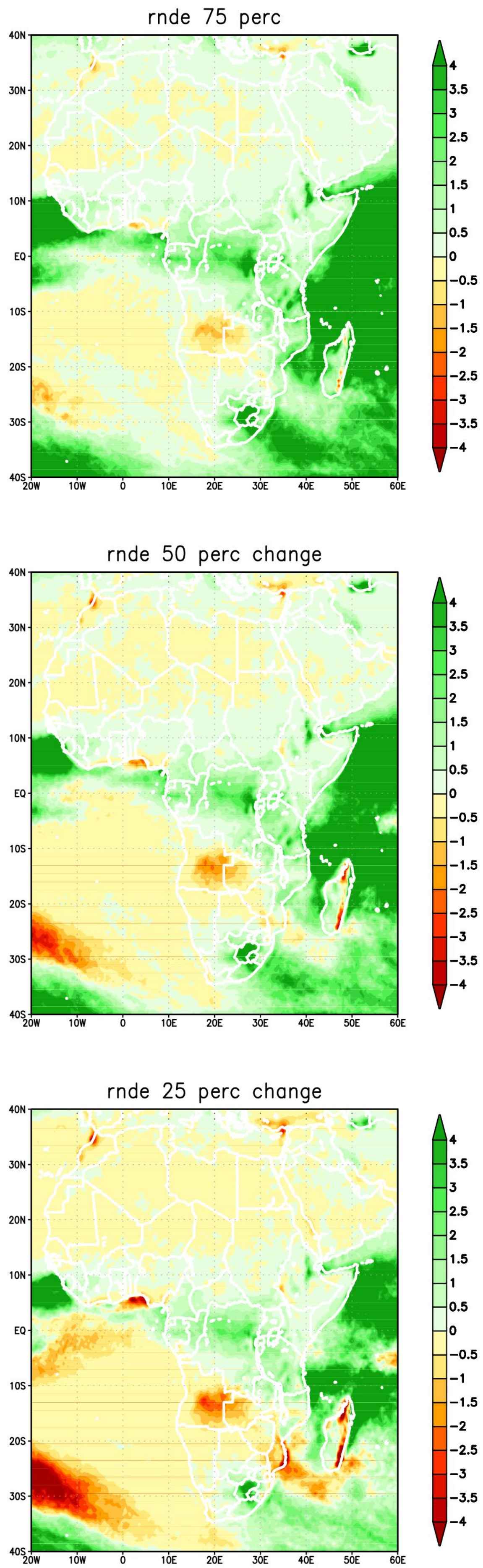

Figure 3. Projected change in the annual frequency of occurrence of extreme rainfall events over Africa, for the period 2071-2100 vs 1961-1990. The 75th percentile (upper panel), median (middle panel) and 25th percentile (lower panel) are shown for an ensemble of six downscalings of CGCM projections, generated using the regional model CCAM. All the CGCM projections contributed to AR4 of the IPCC and are for the A2 SRES scenario. Units are the number of events per grid point per year.

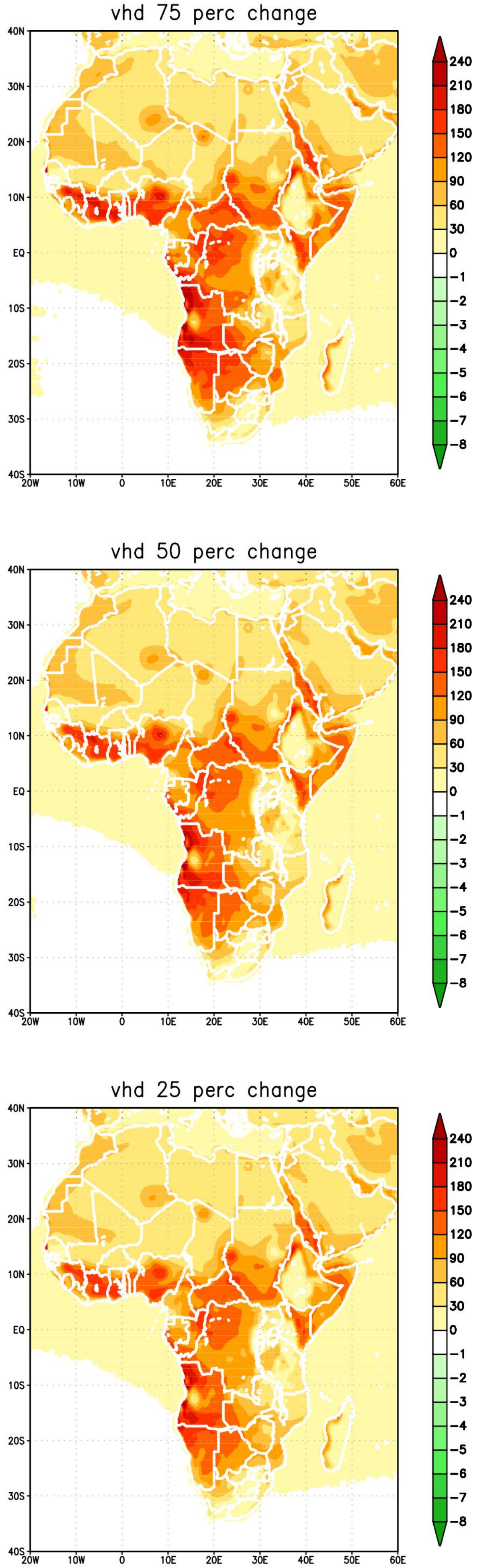

Figure 4. Projected change in the annual frequency of occurrence of very hot days over Africa, for the period 2071-2100 vs 1961-1990. The 75th percentile (upper panel), median (middle panel) and 25th percentile (lower panel) are shown for an ensemble of six downscalings of CGCM projections, generated using the regional model CCAM. All the CGCM projections contributed to AR4 of the IPCC and are for the A2 SRES scenario. Units are the number of events per grid point per year.

Engelbrecht et al., 2012). This provides confirmation that the projected increase in extreme precipitation events over South Africa is the result of an increase in convective rainfall events, rather than in the widespread occurrence of heavy rainfall, as induced by cut-off lows.

The IPCC pointed out in AR4 that potential changes in the frequency of occurrence tropical cyclones over the southwestern Indian Ocean have not been investigated rigorously through modelling studies. Only a single study addressing this topic was available for inclusion in AR4. This found a significant reduction in the frequency of tropical storms in the Indian Ocean under future forcing, using a high-resolution AGCM for its simulations (Oouchi et al., 2006). The ensemble of projections performed at the CSIR has been analysed in detail by Malherbe et al. (2012) to determine whether enhanced anthropogenic forcing may be expected to lead to changes in the frequency of occurrence and tracks of landfalling tropical lows and cyclones over the southern Africa. Most of the downscaled CGCM projections exhibit a pattern of higher rainfall totals and an increase in extreme rainfall events over the Indian Ocean to the north of Madagascar and over northern Mozambique (Figures 2 and 3). This is indicative of a northward shift in the preferred location of tropical low and cyclone tracks, as induced by a strengthening of the Indian Ocean High over the southwest Indian Ocean during the late summer – see Malherbe et al. (2012) for a detailed discussion of the underlying circulation dynamics. The general drying that is projected over north-eastern South Africa and the Limpopo River Basin during summer and autumn (Figure 2), is partially the result of the northward displacement of tropical low and cyclone tracks over the southwestern Indian Ocean (Malherbe et al., 2012).

Drastic increases in the annual frequency of occurrence of very hot days (here defined as days when the maximum temperature exceeds 35° C) are projected (Figure 4) across the African continent. This figure shows the 25th percentile, median and 75th percentile of the projected change in very hot days across the ensemble. The projected pattern of change is robust. The largest increases in very hot days (increases of more than 100 very hot days per year) are projected to occur over southern Africa. The relatively small increases over the Sahara may be attributed to the relatively high occurrence of such days in the present-day climate. Relatively small increases in the number of very hot days are also projected over the eastern escarpment areas of South Africa and the highlands of East Africa.

5. CLIMATE SIMULATIONS AND PROJECTIONS OF CLIMATE CHANGE IN DEWFORA

Of particular interest in FP7 project DEWFORA, is the impact of enhanced anthropogenic forcing on the occurrence of meteorological and hydrological drought over the Niger and Blue Nile river basins. Very high-resolution simulations (8 km in the horizontal) for the period 1961-2100, under the A2 scenario, are under construction at the CSIR. It is expected that analysis of these simulations would provide new insight into how the attributes of meteorological drought over these regions may change in response to enhanced anthropogenic forcing. The simulations are also to be applied by project partners to force hydrological models over these catchments. An aspect of particular interest is the impact of ENSO on rainfall over the Eastern Nile basin, under both present-day and future forcing. This aspect is to be investigated through analysis of the 8 km simulations, as well as through specially designed sea-surface temperature (SST) sensitivity tests under construction at the Dinder Center for Environmental Research (DCER).

The SST sensitivity tests under construction at DCER are to be designed to gain comprehensive insight into the effects of ENSO on the Blue Nile, one of the two major tributaries of the Nile. The Blue Nile originates from Lake Tana in Ethiopian Highland and contributes about 70 % of the flow in the main Nile. The rainfall regime depends on the seasonal fluctuation of the ITCZ, and the rainy season extends from approximately June to September. The Blue Nile and its tributaries rise on the Ethiopian plateau, at elevations of

2000-3000 m or more. The two main tributaries are Rahad and Dinder. The Blue Nile sustains the life of millions of people in Ethiopia, Sudan and Egypt. About 25% of the natural variability in the annual flow of the Nile is associated with ENSO. In this component of the DEWFORA research, more insight is sought into the connections between ENSO and Nile droughts, using a regional climate model. Both the forecasting of Nile droughts at the seasonal time scale, and the impacts of enhanced anthropogenic forcing on ENSO and Nile droughts, are of interest.

The Niño 3.4 region in the Pacific Ocean (120 W to 170 W and 5 N to 5 S) displayed a trend towards more frequent or stronger El Niño episodes over the past 50 to 100 years (Vecchi and Wittenberg, 2010). The tendency for recent El Niño episodes to be centred more in the central equatorial Pacific than in the east Pacific (Yeh et al., 2009), and increasing in intensity for these central Pacific events (Lee and McPhaden, 2010) are also of interest. Some authors (Yeh et al., 2009) attribute these changes to the enhanced greenhouse effect and rising global temperatures, whilst others argue that the changes still fall within the range of natural variability. Although the CGCM projections analysed in AR4 of the IPCC provide an incoherent picture of the future attributes of ENSO, all models exhibit continued ENSO inter-annual variability in their projections through the 21st century (Seneviratne et al., 2012). This confirms the importance of continued research into the skilful prediction of the effects of ENSO events over the African continent. The hypothesis that changes in the spatial attributes of El Niño episodes (e.g. central vs eastern Pacific events) may explain the severe drought in remote areas like Horn of Africa in recent years, will be rigorously investigated in the DEWFORA research.

Figure 5 serves to illustrate the significant rainfall variability that can occur over tropical and East Africa in response to different ENSO signals. In the upper panel the JJA rainfall difference between 1988 (La Niña) and 1984 (El Niño) is shown, using GPCC (Global Precipitation Climate Center) data (Adler et al. 2003). The Sahel region experienced more rainfall during the La Niña year, and less rainfall during the El Niño year. The upper catchment of the Blue Nine in Ethiopian Highland similarly experienced rainfall more rainfall during the La Niña year and less rainfall during the El Niño year. Data from the Climatic Research Unit (CRU) in the lower panel shows almost the same results as the GPCP data.

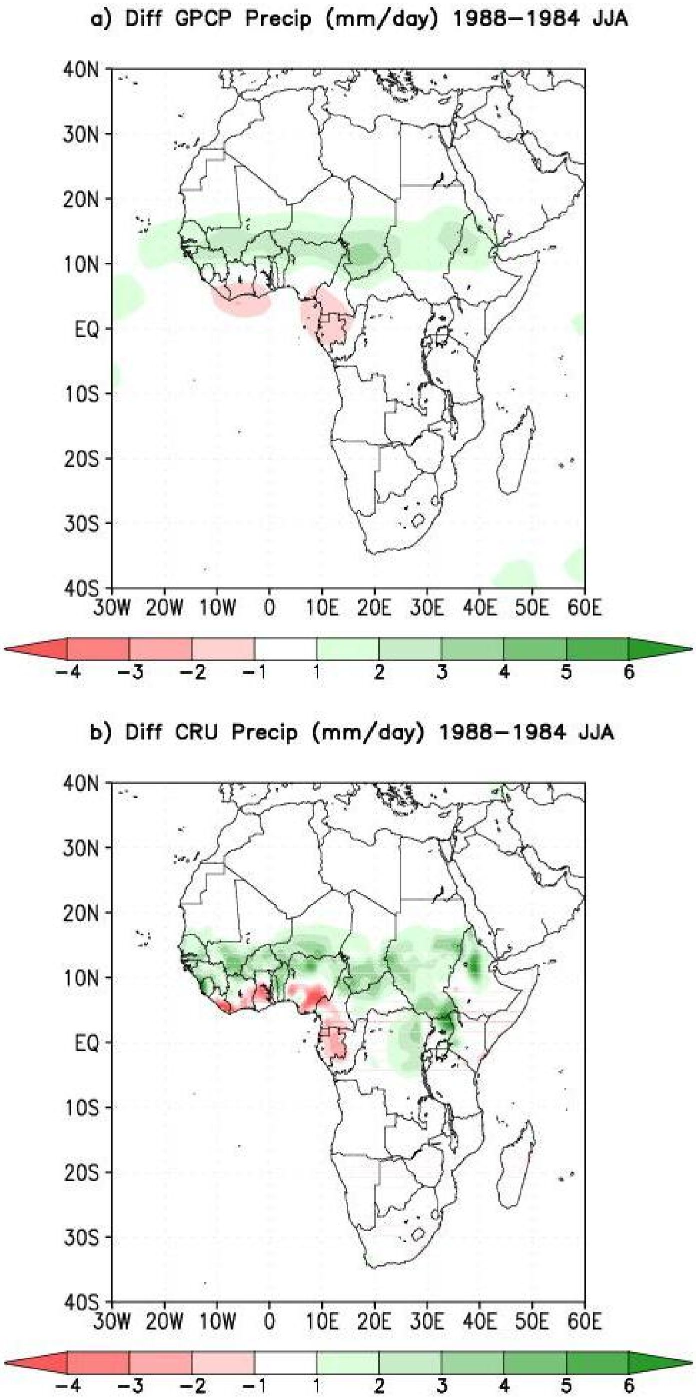

Figure 5: The difference between JJA rainfall (mm/day) for a La Niña year (1988) relative to an El Niño year (1984), as estimated from GPCP data (top panel) and CRU data (lower panel).

6. CONCLUSIONS

The ensemble of CGCM projections described in AR4 of the IPCC has over the last few years been the primary source of information regarding the projected future climates of the African continent. Although the spatial resolution of CGCM projections is often too course for the simulations to be of direct value in application modelling and climate-change impact studies, only a small number of high-resolution, regional projections of future climate change have been obtained to date over the continent (e.g. Tadross et al., 2005; Hewitson and Crane, 2006; Engelbrecht et al., 2009). Currently, the international collaborative effort CORDEX is in the process of generating a much larger ensemble of regionally downscaled scenarios of future climate change over Africa, downscaling the output of CGCMs of CMIP5 (and AR5) to high spatial resolution.

The available CGCM and regionally downscaled projections of future climate change over Africa provide a number of robust messages of future change. The African continent is projected to experience strong warming, of about 1.5 times the global average rate of temperature increase, for the period 2080 to 2099 relative to 1980 to 1999, under the A1B scenario. The median temperature increase for 2080 to 2099, compared to 1980-1999, varies between 3 and 4 °C across the continent, for this particular scenario (Christensen et al., 2007). The subtropical regions of the continent (southern Africa and the northern Sahara) are projected to warm most, at a rate of about twice the global rate of temperature increase. That is, drastic increases in surface temperature are likely over the subtropical parts of the continent, even if the UNFCCC would be successful in restraining the global increase in temperature to 2° C.

Although the projections of future rainfall changes over the continent show considerable variation across the continent, there are robust signals of some large-scale changes. The subtropical parts of the continent (southern Africa and the northern Sahara) are projected to become drier, with even more drastic decreases in rainfall projected for the extra-tropical margins of the continent – the Mediterranean coast of North Africa, and the southwestern Cape and Cape south coast of South Africa. These changes seem to be driven by the strengthening of the subtropical highs in each of the hemispheres, with an associated poleward displacement of the westerly wind regime. There is also a robust signal of East Africa becoming wetter in response to the strengthening of the East African monsoon. More uncertainty surrounds projections of future climate change over West Africa and the Sahel, where many CGCMs fail to simulate realistically key aspects of African climate – such as the West African monsoon. Another key aspect contributing to the uncertainty of CGCM projections over Africa, is the current unsatisfactory simulation of the attributes of ENSO in most CGCMs, with consequences for the simulation of the ENSO rainfall signal over Africa.

Research into the projected future changes in extreme weather events over the African continent is currently limited. The ensemble of RCM projection results presented in this report provide evidence that the frequency of occurrence of very hot days is likely to increase across the continent, and in particular over subtropical southern Africa. This is to occur in association with the strengthening of the subtropical highs and the poleward displacement of the westerly wind regime, with associated decreases in rainfall over large parts of the continent. It is likely that extreme rainfall events will increase in frequency across the tropics, in response to the general increase in moisture in the warmer atmosphere. Over East Africa, where the monsoon is projected to strengthen, robust increases in precipitation are projected. Similarly, rainfall increases are projected over the northern parts of Mozambique, due to a northward displacement of tropical cyclone tracks. FP7 project DEWFORA is focused on analysing projections of future changes in extreme weather events over Africa in more detail, with a focus on the occurrence of heat waves, meteorological and hydrological drought. For this purpose, an extensive set of 8 km resolution projections over the Niger and Eastern Nile river basins is under construction.

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