

African Climate Change: 1900-2100

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Abstract

This paper reviews observed (1900-2000) and possible future (2000-2100) continent-wide changes in temperature and rainfall for Africa. For the historic period we draw upon a new observed global climate data set which allows us to explore aspects of regional climate change related to diurnal temperature range and rainfall variability. The latter includes an investigation of regions where seasonal rainfall is sensitive to El Niño climate variability. This review of past climate change provides the context for our scenarios of future greenhouse gas-induced climate change in Africa. These scenarios draw upon the new preliminary emissions scenarios prepared for the Intergovernmental Panel on Climate Change's Third Assessment Report, a suite of recent global climate model experiments, and a simple climate model to link these two sets of analyses. We present a range of four climate futures for Africa, focusing on changes in both continental and regional seasonal-mean temperature and rainfall. Estimates of associated changes in global CO₂ concentration and global-mean sea-level change are also supplied. These scenarios draw upon some of the most recent climate modelling work. We also identify some fundamental limitations to knowledge with regard to future African climate. These include the often poor representation of El Niño climate variability in global climate models, and the absence in these models of any representation of regional changes in land cover and dust and biomass aerosol loadings. These omitted processes may well have important consequences for future African climates, especially at regional scales. We conclude by discussing the value of the sort of climate change scenarios presented here and how best they should be used in national and regional vulnerability and adaptation assessments.

Key Words: African climate, climate scenarios, rainfall variability,
climate modelling, seasonal forecasting, land cover changes

1 Introduction

The climates of Africa are both varied and varying; *varied*, because they range from humid equatorial regimes, through seasonally-arid tropical regimes, to sub-tropical Mediterranean-type climates, and *varying* because all these climates exhibit differing degrees of temporal variability, particularly with regard to rainfall. Understanding and predicting these inter-annual, inter-decadal and multi-decadal variations in climate has become the major challenge facing African and African-specialist climate scientists in recent years. Whilst seasonal climate forecasting has taken great strides forward, both its development and application (Folland *et al.*, 1991; Stockdale *et al.*, 1998; Washington and Downing, 1999; SARCOF, 1999), the ultimate causes of the lower frequency decadal and multi-decadal rainfall variability that affects some African climate regimes, especially in the Sahel region, remain uncertain (see Rowell *et al.*, 1995 vs. Sud and Lau, 1996; also Xue and Shukla, 1998). This work examining the variability of African climate, especially rainfall, is set in the wider context of our emerging understanding of human influences on the larger, global-scale climate. Increasing greenhouse gas accumulation in the global atmosphere and increasing regional concentrations of aerosol particulates are now understood to have detectable effects on the global climate system (Santer *et al.*, 1996). These effects will be manifest at regional scales although perhaps in more uncertain terms (Mitchell and Hulme, 1999; Giorgi and Francisco, 2000).

Africa will be no exception to experiencing these human-induced changes in climate. Much work remains to be done, however, in trying to isolate those aspects of African climate variability that are ‘natural’ from those that are related to human influences. African climate scientists face a further challenge in that in this continent the role of land cover changes - some natural and some human-related - in modifying regional climates is perhaps most marked (Xue, 1997). This role of land cover change in altering regional climate in Africa has been suggested for several decades now. As far back as the 1920s and 1930s theories about the encroachment of the Sahara and the desiccation of the climate of West Africa were put forward (Stebbing, 1935; Aubreville, 1949). These ideas have been explored over the last 25 years through modelling studies of tropical north African climate (e.g. Charney, 1975; Cunnington and Rowntree, 1986; Zheng and Eltahir, 1997). It is for these two reasons - large internal climate variability as driven by the oceans and the confounding role of human-induced land cover change - that climate change ‘predictions’ (or the preferable term scenarios) for Africa based on greenhouse gas warming remain highly uncertain. While global climate models (GCMs) simulate changes to African climate as a result of increased greenhouse gas concentrations, these two potentially important drivers of African climate variability – for example El Niño/Southern Oscillation (poorly) and land cover change (not at all) - are not well represented in the models.

Nevertheless, it is of considerable interest to try and explore the magnitude of the problem that the enhanced greenhouse effect may pose for African climate and for African resource managers. Are the changes that are simulated by GCMs for the next century large or small in relation to our best estimates of 'natural' climate variability in Africa? How well do GCM simulations agree for the African continent? And what are the limitations/uncertainties of these model predictions? Answering these questions has a very practical relevance in the context of national vulnerability and adaptation assessments of climate change currently being undertaken by many African nations as part of the reporting process to the UN Framework Convention on Climate Change. This paper makes a contribution to these assessments by providing an overview of future climate change in Africa, particularly with regard to simulations of greenhouse gas warming over the next 100 years. We start the paper (Section 2) by reviewing some previous climate change scenarios and analyses for regions within Africa. Such studies have been far from comprehensive. Section 3 explains the data, models and approaches that we have taken in generating our analyses and constructing our climate change scenarios for Africa. In Section 4 we consider the salient features of African climate change and variability over the last 100 years, based on the observational record of Africa climate. Such a historical perspective is essential if the simulated climates of the next century are to be put into their proper context. Section 5 then presents our future climate change scenarios for Africa, based on the preliminary Special Report on Emissions Scenarios range of future greenhouse gas emissions (SRES, 2000) and the GCM results deposited with the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre (DDC, 2000). Changes in mean seasonal climate are shown as well as some measures of changed interannual variability. Section 6 then discusses these future climate simulations in the light of modelling uncertainties and in the context of other causes of African climate variability and change. We consider how much useful and reliable information these types of studies yield and how they can be incorporated into climate change impacts assessments. Our key conclusions are presented in Section 7.

2 Review of Previous African Climate Change Scenario Work

There has been relatively little work published on future climate change scenarios for Africa. The various IPCC assessments have of course included global maps of climate change within which Africa has featured and in Mitchell *et al.* (1990) the African Sahel was identified as one of five regions for which a more detailed analysis was conducted. Kittel *et al.* (1998) and Giorgi and Francisco (2000) also identify African regions within their global analysis of inter-model differences in climate predictions, but no detailed African scenarios are presented.

Tyson (1991) published one of the first scenario analyses specifically focused on an African region. In this case some climate change scenarios for southern Africa were constructed using results from the first generation GCM equilibrium $2\times\text{CO}_2$ experiments. In a further development, Hulme (1994a) presented a method for creating regional climate change scenarios combining GCM results with the newly published IPCC IS92 emissions scenarios and demonstrated the application of the method for Africa. In this study mean annual temperature and precipitation changes from 1990 to 2050 under the IS92a emission scenario were presented.

Some more recent examples of climate scenarios for Africa use results from transient GCM climate change experiments. Hernes *et al.* (1995) and Ringius *et al.* (1996) constructed climate change scenarios for the African continent that showed land areas over the Sahara and semi-arid parts of southern Africa warming by the 2050s by as much as 1.6°C and the equatorial African countries warming at a slightly slower rate of about 1.4°C . These studies, together with Joubert *et al.* (1996), also suggested a rise in mean sea-level around the African coastline of about 25cm by 2050. A more selective approach to the use of GCM experiments was taken by Hulme *et al.* (1996a). They describe three future climate change scenarios for the Southern African Development Community (SADC) region of southern Africa for the 2050s on the basis of three different GCM experiments. These experiments were selected to deliberately span the range of precipitation changes for the SADC region as simulated by GCMs. Using these scenarios, the study then describes some potential impacts and implications of climate change for agriculture, hydrology, health, biodiversity, wildlife and rangelands. A similar approach was adopted by Conway *et al.* (1996) for a study of the impacts of climate change on the Nile Basin. More recently, the Africa chapter (Zinyowera *et al.*, 1998) in the IPCC Assessment of Regional Impacts of Climate Change (IPCC, 1998) also reported on some GCM studies that related to the African continent.

Considerable uncertainty exists in relation to large-scale precipitation changes simulated by GCMs for Africa (Hudson and Hewitson, 1997; Hudson, 1997; Joubert and Hewitson, 1997; Feddema, 1999). Joubert and Hewitson (1997) nevertheless conclude that, in general, precipitation is simulated to increase over much of the African continent by the year 2050. These GCM studies show, for example, that parts of the Sahel could experience precipitation increases of as much as 15 per cent over the 1961-90 average by 2050. A note of caution is needed, however, concerning such a conclusion. Hulme (1998) studied the present-day and future simulated inter-decadal precipitation variability in the Sahel using the HadCM2 GCM. These model results were compared with observations during the twentieth century. Two problems emerge. First, the GCM does not generate the same magnitude of inter-decadal precipitation variability that has been observed over the last 100 years, casting doubt on the extent to which the most

important controlling mechanisms are being simulated in the GCM. Second, the magnitude of the future simulated precipitation changes for the Sahel is not large in relation to 'natural' precipitation variability for this region. This low signal:noise ratio suggests that the greenhouse gas-induced climate change signals are not well defined in the model, at least for this region. We develop this line of reasoning in this paper and illustrate it in Section 5 with further examples from Africa.

Although there have been studies of GCM-simulated climate change for several regions in Africa, the downscaling of GCM outputs to finer spatial and temporal scales has received relatively little attention in Africa. Hewitson and Crane (1998) and Hewitson and Joubert (1998) have applied empirical downscaling methods to generate climate change scenarios for South Africa using Artificial Neural Networks and predictors relating to upper air circulation and tropospheric humidity. The usual caveats, however, apply to these downscaled scenarios (Hulme and Carter, 1999a) - they are still dependent on the large-scale forcing from the GCMs and they still only sample one realisation of the possible range of future possible climates, albeit with higher resolution. The application of Regional Climate Models is still in its infancy, although some initiatives are now under way for East Africa (Sun *et al.*, 1999), West Africa (Wang and Eltahir, 2000) and southern Africa (Bruce Hewitson, pers.comm.). These initiatives have not yet generated experimental results from regional climate change simulations for use in scenario construction.

3 Data and Methods

For our analyses of observed climate variability in Africa we use the global gridded data sets of Jones (1994, updated; mean temperature), Hulme (1994b, updated; precipitation), and New *et al.* (1999, 2000; ten surface climate variables). These data sets are all public domain and are available, along with some documentation on their construction, from the web sites listed in the acknowledgements to this paper. The former two data sets exist on a relatively coarse grid (5° latitude/longitude and 2.5° latitude by 3.75° longitude respectively), while the data set of New *et al.* exists on a 0.5° latitude/longitude resolution. These observed data are resolved only to monthly time-steps and we therefore undertake no original analyses of observed daily climate variability. For Ethiopia and Zimbabwe we analyse unpublished monthly mean maximum and minimum temperature data for a number of stations in each country. These data originate from the respective National Meteorological Agencies. For the index of the Southern Oscillation we use the updated index of Ropelewski and Jones (1987), calculated as the normalised mean sea-level pressure difference between Tahiti and Darwin and available from CRU (2000).

Other climate-related and continent-wide data sets also have value for some climate analyses, whether these data are derived from satellite observations (e.g. Normalised Difference Vegetation Index or

satellite-derived precipitation estimates), or from numerical weather prediction model re-analyses (e.g. the NCEP re-analysis from 1948 to present). Although these alternative data sets have some real advantages in particular environmental or modelling applications (e.g. modelling malaria; Lindsay *et al.*, 1998; evaluating dust forcing; Brooks, 1999), we prefer to limit our analysis here to the use of conventional observed climate data sets derived from surface observations.

The GCM results used in this study are mainly extracted from the IPCC Data Distribution Centre (DDC, 2000). This archive contains results from climate change experiments performed with seven coupled ocean-atmosphere global climate models (Table 1). All these experiments have been conducted using similar greenhouse gas or greenhouse gas plus aerosol forcing. In this study only the results from the greenhouse gas forced simulations for reasons outlined below. We also use results from the 1400-year control simulation of the HadCM2 climate model (Tett *et al.*, 1997) to derive model-based estimates of natural multi-decadal climate variability. The data were re-gridded using a Gaussian space-filter onto a common grid, namely the HadCM2 grid. Later results are presented on this common grid.

	Country of origin	Approximate resolution (lat. x long.)	Climate sensitivity (degC)	Integration length	Reference
CCSR-NIES	Japan	5.62° by 5.62°	3.5	1890-2099	Emori <i>et al.</i> (1999)
CGCM1	Canada	3.75° by 3.75°	3.5	1900-2100	Boer <i>et al.</i> (2000)
CSIRO-Mk2	Australia	3.21° by 5.62°	4.3	1881-2100	Hirst <i>et al.</i> (2000)
ECHAM4	Germany	2.81° by 2.81°	2.6	1860-2099	Roeckner <i>et al.</i> (1996)
GFDL-R15	USA	4.50° by 7.50°	3.7	1958-2057	Haywood <i>et al.</i> (1997)
HadCM2**	UK	2.50° by 3.75°	2.5	1860-2099	Mitchell and Johns (1997)
NCAR-DOE	USA	4.50° by 7.50°	4.6	1901-2036	Meehl <i>et al.</i> (2000)

** An ensemble of four climate change simulations were available from the HadCM2 model.

Table 1: Characteristics of the seven global climate models available at the IPCC Data Distribution Centre from which experimental results were used in this study. Only the greenhouse gas forced integrations were used here. The climate sensitivity describes the estimated equilibrium global-mean surface air temperature change of each model following a doubling of atmospheric carbon dioxide concentration.

Climate can be affected by a number of other agents in addition to greenhouse gases; important amongst these are small particles (aerosols). These aerosols are suspended in the atmosphere and some types (e.g. sulphate aerosols derived from sulphur dioxide) reflect back solar radiation, hence they have a cooling effect on climate. Although there are no measurements to show how these aerosol concentrations have changed over the past 150 years, there *are* estimates of how sulphur dioxide emissions have risen (one of the main precursors for aerosol particles) and scenarios of such emissions into the future. A number of such scenarios have been used in a sulphur cycle model to calculate the future rise in sulphate aerosol

concentrations (Penner *et al.*, 1998). When one of these scenarios was used, along with greenhouse gas increases, as input to the DDC GCMs, the global-mean temperature rise to 2100 was reduced by between a quarter and a third. The reductions over Africa were less than this.

These are very uncertain calculations, however, due to a number of factors. First, the old 1992 IPCC emissions scenario on which it was based (IS92a; Leggett *et al.*, 1992) contains large rises in sulphur dioxide emissions over the next century. Newer emissions scenarios, including the preliminary SRES scenarios, estimate only a small rise in sulphur dioxide emissions over the next couple of decades followed by reductions to levels lower than today's by 2100 (SRES, 2000). Over Africa, sulphur emissions remain quite low for the whole of next century. The inclusion of such modest sulphur dioxide emissions scenarios into GCM experiments would actually produce a small temperature *rise* relative to model experiments that excluded the aerosol effect (Schlesinger *et al.*, 2000). Results from GCM experiments using these revised sulphur scenarios are not available yet. Second, more recent sulphur cycle models generate a lower sulphate burden per tonne of sulphur dioxide emissions and the radiative effect of the sulphate particles in more sophisticated radiation models is smaller than previously calculated. Third, in addition to their direct effect, sulphate aerosols can also indirectly cool climate by changing the reflectivity and longevity of clouds (Schimel *et al.*, 1996). These indirect effects are now realised as being as at least as important as the direct effect, but were not included in the present DDC GCM climate change simulations. Fourth, there are other types of aerosols (e.g. carbon or soot) which may also have increased due to human activity, but which act to warm the atmosphere. Finally and above all, the short lifetime of sulphate particles in the atmosphere means that they should be seen as a temporary masking effect on the underlying warming trend due to greenhouse gases. For all these reasons, model simulations of future climate change using *both* greenhouse gases and sulphate aerosols have *not* been used to develop the climate change scenarios illustrated in this paper.

The future greenhouse gas forcing scenario used in the DDC experiments approximated a 1% per annum growth in greenhouse gas concentrations over the period from 1990 to 2100. Since the future growth in anthropogenic greenhouse gas forcing is highly uncertain, it is important that our climate scenarios for Africa reflect this uncertainty; it would be misleading to construct climate change scenarios that reflected just one future emissions growth curve. We therefore adopt the four preliminary marker emissions scenarios of the IPCC Special Report on Emissions Scenarios (SRES, 2000): B1, B2, A1 and A2. None of these emissions scenarios assumes any climate policy implementation, the differences resulting from alternative developments in global population, the economy and technology. Our method of climate change scenario construction follows that adopted by Hulme and Carter (1999b) in their generation of

climate change scenarios for Europe as part of the ACACIA assessment of climate impact in Europe. Full details may be found there, but we provide a short summary of the method in Section 5 below.

4 Twentieth Century Climate Change

Temperature

The continent of Africa is warmer than it was 100 years ago. Warming through the twentieth century has been at the rate of about 0.5°C/century (Figure 1), with slightly larger warming in the June-August and September-November seasons than in December-February and March-May. The six warmest years in Africa have all occurred since 1987, with 1998 being the warmest year. This rate of warming is not dissimilar to that experienced globally and the periods of most rapid warming - the 1910s to 1930s and the post-1970s - occur simultaneously in Africa and the world.

Few studies have examined long-term changes in the diurnal cycle of temperature in Africa. Here, we show results for four countries for which studies have been published or data were available for analysis - for Sudan and South Africa as published by Jones and Lindesay (1993) and for Ethiopia and Zimbabwe (unpublished). While a majority of the Earth's surface has experienced a decline in the mean annual diurnal temperature range (DTR) as climate has warmed (Nicholls *et al.*, 1996), our examples here show contrasting trends for these four African countries. Mean annual DTR decreased by between 0.5° and 1°C since the 1950s in Sudan and Ethiopia, but increased by a similar amount in Zimbabwe (Figure 2). In South Africa, DTR decreased during the 1950s and 1960s, but has remained quite stable since then. Examination of the seasonal variation in these trends (not shown) suggests that different factors contribute to DTR trends in different seasons and in different countries. For example, in Sudan DTR shows an increasing trend during the July-September wet season, probably caused by trends towards reduced cloudiness, while DTR decreased during the rest of the year, probably due to trends for increased dustiness (Brooks, 1999). Both of these two factors are related to the multi-decadal drought experienced in Sudan since the 1950s (Hulme, 2000). The long-term increase in annual DTR in Zimbabwe is due almost entirely to increases during the November-February wet season; trends during the rest of the year have been close to zero. We are not aware of published analyses of diurnal temperature trends in other African countries.

Rainfall

Interannual rainfall variability is large over most of Africa and for some regions, most notably the Sahel, multi-decadal variability in rainfall has also been substantial. Reviews of twentieth century African rainfall variability have been provided by, among others, Janowiak (1988), Hulme (1992) and Nicholson

(1994). To illustrate something of this variability we present an analysis for the three regions of Africa used by Hulme (1996b) - the Sahel, East Africa and southeast Africa (domains shown in Figure 4). These three regions exhibit contrasting rainfall variability characteristics (Figure 3): the Sahel displays large multi-decadal variability with recent drying, East Africa a relatively stable regime with some evidence of long-term wetting, and southeast Africa also a basically stable regime, but with marked inter-decadal variability. In recent years Sahel rainfall has been quite stable around the 1961-90 annual average of 371mm, although this 30-year period is substantial drier (about 25 per cent) than earlier decades this century. In East Africa, 1997 was a very wet year and, like in 1961 and 1963, led to a surge in the level of Lake Victoria (Birkett *et al.*, 1999). Recent analyses (Webster *et al.*, 1999; Saji *et al.*, 1999) have suggested these extreme wet years in East Africa are related to a dipole mode of variability in the Indian Ocean. In southeast Africa, the dry years of the early 1990s were followed by two very wet years in 1995/96 and 1996/97. Mason *et al.* (1999) report an increase in recent decades in the frequency of the most intense daily precipitation over South Africa, even though there is little long-term trend in total annual rainfall amount.

Figure 3 also displays the trends in annual temperature for these same three regions. Temperatures for all three regions during the 1990s are higher than they have been this century (except for a period at the end of the 1930s in the Sahel) and are currently between 0.2° and 0.3°C warmer than the 1961-90 average. There is no simple correlation between temperature and rainfall in these three regions, although Hulme (1996b) noted that drying in the Sahel was associated with a moderate warming trend.

Spatial Patterns

Our analysis is summarised further in Figure 4 where we show mean linear trends in annual temperature and precipitation during the twentieth century. This analysis first filters the data using a 10-point gaussian filter to subdue the effects on the regression analysis of outlier values at either end of the time period. While warming is seen to dominate the continent (*cf.* Figure 1 above), some coherent areas of cooling are noted, around Nigeria/Cameroon in West Africa and along the coastal margins of Senegal/Mauritania and South Africa. In contrast, warming is at a maximum of nearly 2°C/century over the interior of southern Africa and in the Mediterranean countries of northwest Africa.

The pattern of rainfall trends (Figure 4) reflects the regional analysis shown in Figure 3 with drying of up to 25 per cent/century or more over some western and eastern parts of the Sahel. More moderate drying - 5 to 15 per cent/century - is also noted along the Mediterranean coast and over large parts of Botswana and Zimbabwe and the Transvaal in southeast Africa. The modest wetting trend noted over East Africa is

seen to be part of a more coherent zone of wetting across most of equatorial Africa, in some areas of up to 10 per cent or more per century. Regions along the Red Sea coast have also seen an increase in rainfall, although trends in this arid/semi-arid region are unlikely to be very robust.

ENSO Influence on Rainfall

With regard to interannual rainfall variability in Africa, the El Niño/Southern Oscillation (ENSO) is one of the more important controlling factors, at least for some regions (Janowiak, 1988; Ropelewski and Halpert, 1987; 1989; 1996; Dai and Wigley, 2000). These studies have established that the two regions in Africa with the most dominant ENSO influences are in eastern equatorial Africa during the short October-November rainy season and in southeastern Africa during the main November-February wet season. Ropelewski and Halpert (1989) also examined Southern Oscillation and rainfall relationships during La Niña or high index years. We have conducted our own more general analysis of Southern Oscillation-rainfall variability for the African region over the period 1901-1998 using an updated and more comprehensive data set (Hulme, 1994b) than was used by these earlier studies. We also use the Southern Oscillation Index (SOI) as a continuous index of Southern Oscillation behaviour rather than designating discrete 'warm' (El Niño; low index) and 'cold' (La Niña; high index) Southern Oscillation events as was done by Ropelewski and Halpert (1996).

We defined an annual average SOI using the June-May year, a definition that maximises the coherence of individual Southern Oscillation events, and correlated this index against seasonal rainfall in Africa. We performed this analysis for the four conventional seasons (not shown) and also for the two extended seasons of June to October (Year 0) and November (Year 0) to April (Year 1; Figure 5a). This analysis confirms the strength of the previously identified relationships for equatorial east Africa (high rainfall during a warm ENSO event) and southern Africa (low rainfall during a warm ENSO event). The former relationship is strongest during the September-November rainy season (the 'short' rains; not shown), with an almost complete absence of ENSO sensitivity in this region during the February-April season ('long' rains) as found by Ropelewski and Halpert (1996). The southern African sensitivity is strongest over South Africa during December-February before migrating northwards over Zimbabwe and Mozambique during the March-May season (not shown). There is little rainfall sensitivity to ENSO behaviour elsewhere in Africa, although weak tendencies for Sahelian June-August drying (Janicot *et al.*, 1996) and northwest African March-May drying (El Hamly *et al.*, 1998) can also be found.

5 Twenty-first Century Climate Change

For a comprehensive assessment of the impact and implications of climate change it is necessary to apply a number of climate change scenarios that span a reasonable range of the likely climate change distribution. The fact that there *is* a distribution of future climate changes arises not only because of incomplete understanding of the climate system (e.g. the unknown value of the climate sensitivity, different climate model responses, etc.), but also because of the inherent unpredictability of climate (e.g. unknowable future climate forcings and regional differences in the climate system response to a given forcing because of chaos). The 'true' climate change distribution is of course unknown, but we can make some sensible guesses as to its magnitude and shape and then make some choices so as to sample a reasonable part of its range.

We have done this at a global scale by making choices about future greenhouse gas forcings and about the climate sensitivity (see Table 1 for definition). We follow Hulme and Carter (1999b) and Carter *et al.* (1999) in this procedure, yielding the four global climate scenarios shown in Table 2. We have chosen the SRES A2 emissions scenario combined with a high climate sensitivity (4.5°C), SRES A1 and SRES B2 combined with medium climate sensitivities (2.5°C) and SRES B1 combined with a low climate sensitivity (1.5°C). These four scenarios are subsequently termed A2-high, A1-mid, B2-mid and B1-low, respectively, and yield a range of global warming by the 2050s of 0.9° to 2.6°C. We chose the two middle cases deliberately because, even though the global warming is similar, the worlds which underlie the B2 and A1 emissions scenarios are quite different (SRES, 2000). The impacts on Africa of what may be rather similar global and regional climate changes could be quite different in these two cases. For example, global (and African) population is lower in the A1 world than in the B2 world, but carbon and sulphur emissions and CO₂ concentrations are higher (Table 2).

Scenario/ Climate sensitivity	Population (billions)	C emissions from energy (GtC)	Total S emissions (TgS)	Global ΔT (°C)	Global ΔSL (cm)	pCO ₂ (ppmv)
B1-low / 1.5°C	8.76	9.7	51	0.9	13	479
B2-mid / 2.5°C	9.53	11.3	55	1.5	36	492
A1-mid / 2.5°C	8.54	16.1	58	1.8	39	555
A2-high / 4.5°C	11.67	17.3	96	2.6	68	559

Table 2: The four climate scenarios. Estimates shown here are for the 2050s (i.e., 2055), but the values for the 2020s and 2080s were also calculated. Temperature and sea-level changes assume no aerosol effects and are calculated from a 1961-90 baseline using the MAGICC climate model (Wigley and Raper, 1992; Raper *et al.*, 1996; Wigley *et al.*, 2000). C is annual carbon emissions from fossil energy sources, S is annual sulphur emissions, ΔT is change in mean annual temperature, ΔSL is change in mean sea-level and pCO₂ is the atmospheric carbon dioxide concentration.

Having defined these four global climate scenarios, we next consider the range of climate changes for Africa that may result from each of these four possible futures. Again, we have a distribution of possible regional outcomes for a given global warming. We use results from the seven GCM experiments (*cf.* Table 1) to define this range (note: for HadCM2 there are four simulations for the same scenario thus the total GCM sample available to use is 10. This gives more weight in our final scenarios to the HadCM2 responses than the other six GCMs). We present the scenario results for seasonal mean temperature and precipitation for the 2020s, 2050s and 2080s in two different ways: Africa-wide maps and national-scale summary results for four representative countries within Africa.

African Scenario Maps

The construction of the scenario maps follows the approach of Hulme and Carter (1999b) and Carter *et al.* (1999). We first standardise the 2071-2100 climate response patterns - defined relative to the 1961-90 model average - in the DDC GCMs using the global warming values in each respective GCM. These standardised climate response patterns are then scaled by the global warming values for our four scenarios and three time periods calculated by the MAGICC climate model (see Table 2). Scaling of GCM response patterns in this way assumes that local greenhouse gas-induced climate change is a linear function of global-mean temperature. This may be a poor assumption to make, especially for rainfall. Only a selection of the full set of maps is shown here. For each scenario, season, variable and time-slice we present two maps representing the change in mean seasonal climate for the respective 30-year period (Figures 6 to 11). One map shows the Median change from our sample of ten standardised and scaled GCM responses (left panels) and the other map shows the absolute Range of these ten model responses (right panels).

We also introduce the idea of signal:noise ratios by comparing the Median scaled GCM change against an estimate of natural multi-decadal climate variability. In the maps showing the Median change we only plot these values where they *exceed* the one standard deviation estimate of natural 30-year time-scale climate variability. These estimates were extracted from the 1400-year unforced simulation of the HadCM2 model (Tett *et al.*, 1997). We use a climate model simulation to quantify the range of natural climate variability rather than observations because the model gives us longer and more comprehensive estimates of natural climate variability. This has the disadvantage that the climate model may not accurately simulate natural climate variability, although at least for some regions and on some time-scales, HadCM2 yields estimates of natural variability quite similar both to observations (Tett *et al.*, 1997) and to

climatic fluctuations reconstructed from proxy records over the past millenium (Jones *et al.*, 1998). We discuss this problem further in Section 6.

The resulting African scenario maps therefore inform at a number of levels:

- Africa-wide estimates are presented of mean seasonal climate change (mean temperature and precipitation) for the four adopted climate change scenarios;
- These estimates are derived from a sample (a pseudo-ensemble) of ten different GCM simulations, rather than being dependent on any single GCM or GCM experiment;
- Only Median changes that exceed what may reasonably be expected to occur due to natural 30-year time-scale climate variability are plotted;
- The extent of inter-model agreement is depicted through the Range maps.

For our scenarios, future annual warming across Africa ranges from below 0.2°C per decade (B1-low scenario; Figure 6) to over 0.5°C per decade (A2-high; Figure 7). This warming is greatest over the interior semi-arid tropical margins of the Sahara and central southern Africa, and least in equatorial latitudes and coastal environments. The B2 and A1 scenarios (not shown) fall roughly in between these two extremes. All of the estimated temperature changes exceed the one sigma level of natural temperature variability (as defined by unforced HadCM2 simulation), even under the B1-low scenario. The inter-model range (an indicator of the extent of agreement between different GCMs) is smallest over northern Africa and the Equator, and greatest over the interior of central southern Africa. For example, the inter-model range falls to less than 25 per cent of the model median response in the former regions, but rises to over 60 per cent of the model median response in the latter areas.

Future changes in mean seasonal rainfall in Africa are less well defined. Under the B1-low scenario, relatively few regions in Africa experience a change in either DJF or JJA rainfall that exceeds the one sigma level of natural rainfall variability simulated by the HadCM2 model (Figures 8 and 9). The exceptions are parts of equatorial East Africa where rainfall increases by 5 to 30 per cent in DJF and decreases by 5 to 10 per cent in JJA. Some areas of Sahelian West Africa and the Mahgreb also experience 'significant' rainfall decreases in JJA season under the B1-low scenario. The inter-model range for these rainfall changes is large and in the cases cited above always exceeds the magnitude of the Median model response. Over the seasonally-arid regions of Africa, the inter-model range becomes very large (>100 per cent) because of relatively large per cent changes in modelled rainfall induced by very small baseline seasonal rainfall quantities.

With more rapid global warming (e.g. the B2, A1 and A2-high scenarios), increasing areas of Africa experience changes in DJF or JJA rainfall that *do* exceed the one sigma level of natural rainfall variability. Thus for the A2-high scenario, large areas of equatorial Africa experience ‘significant’ increases in DJF rainfall of up to 50 or 100 per cent over parts of East Africa (Figure 10), while rainfall decreases ‘significantly’ in JJA over parts of the Horn of Africa and northwest Africa (Figure 11). Some ‘significant’ JJA rainfall increases occur over the central Sahel region of Niger and Chad, while ‘significant’ decreases in DJF rainfall (15 to 25 per cent) occur over much of South Africa and Namibia and along the Mediterranean coast. The inter-model range for these rainfall changes remains large, however, and with very few exceptions exceeds the magnitude of the Median model response. Even for the seasonally wet JJA rainfall regime of the Sahel, inter-model ranges can exceed 100 per cent, suggesting that different GCM simulations yield (sometimes) very different regional rainfall responses to a given greenhouse gas forcing. This large inter-model range in seasonal mean rainfall response is not unique to Africa and is also found over much of south and southwest Asia and parts of Central America (Carter *et al.*, 1999).

National Scenario Graphs

To condense this scenario information further, we also constructed ‘national’-scale summary graphs for four smaller regions – centred on the countries of Senegal, Tunisia, Ethiopia and Zimbabwe. These chosen domains are shown in Figure 6 (top left panel) and reflect the diversity of existing climate regimes across the continent from north to south and from west to east. Each country graph shows, for the 2050s, the distribution of the mean annual changes in mean temperature and precipitation for each GCM simulation and for each of our four scenarios. As with the continental maps, these changes are compared with the natural multi-decadal variability of annual-mean temperature and precipitation extracted from the HadCM2 1400-year unforced simulation. These graphs provide a quick assessment at a ‘national’-scale of the likely range and significance of future climate change and again shows the extent to which different GCMs agree in their regional response to a given magnitude of global warming.

For each country there is a spread of results relating to inter-model differences in climate response. For example, in Tunisia the change in annual rainfall is predominantly towards drying (only ECHAM4 displays wetting), although the magnitude of the drying under the A2-high scenario is between 1 per cent and 30 per cent. Natural climate variability is estimated to lead to differences of up to ± 10 per cent between different 30-year mean climates, therefore the more extreme of these scenario outcomes would appear to be ‘significant’ for Tunisia. The picture would appear at first sight to be less clear for Zimbabwe

where four of the GCMs suggest wetting and three - including the HadCM2 ensemble of four simulations - suggest drying. However, the range of natural variability in annual rainfall when averaged over 30-years is shown to be about ± 6 per cent and most of the wetting scenarios fall within this limit. It is the drying responses under the more extreme A2-high, B2 and A1 scenarios that would appear to yield a more 'significant' result.

It is also important to point out that inter-ensemble differences in response at these national scales can also be large. The four-member HadCM2 ensemble for Tunisia yields differences in rainfall change of 15 per cent or more, while for Ethiopia inter-ensemble differences can lead to a sign change in the rainfall scenario. In this latter case, however, few of these HadCM2 rainfall changes are larger than the estimate of natural rainfall variability for Ethiopia. It is also worth noting that the relative regional response of different GCMs is not always the same. Thus for Ethiopia, the CCSR-NIES GCM generates the most extreme wetting scenario, whereas for Tunisia the same model yields the most extreme drying scenario. We discuss the significance of some of these differences and similarities between different GCMs in our discussion of uncertainties in Section 6.

Changes in ENSO-related Rainfall Variability

Given the important role that ENSO events exert on interannual African rainfall variability, at least in some regions, determining future changes in interannual rainfall variability in Africa can only be properly considered in the context of changes in ENSO behaviour. There is still ambiguity, however, about how ENSO events may respond to global warming. This is partly because global climate models only imperfectly simulate present ENSO behaviour. Tett *et al.* (1997) demonstrate that HadCM2 simulates ENSO-type features in the Pacific Ocean, but the model generates too large a warming across the Tropics in response to El Niño events. Timmermann *et al.* (1999), however, have recently argued that their ECHAM4 model (cf. Table 1) has sufficient resolution to simulate 'realistic' ENSO behaviour. They analyse their greenhouse gas forced simulations to suggest that in the future there are more frequent and more intense 'warm' and 'cold' ENSO events, a result also found in the HadCM2 model (Collins, 2000).

What effects would such changes have on interannual African rainfall variability? This not only depends on how ENSO behaviour changes in the future, but also upon how realistically the models simulate the observed ENSO-rainfall relationships in Africa. Smith and Ropelewski (1997) looked at Southern Oscillation-rainfall relationships in the NCEP atmospheric GCM, where the model is used to re-create observed climate variability after being forced with observed sea surface temperatures (SSTs). Even in this most favourable of model experiments the model relationships do not always reproduce those

observed. Over southeastern Africa, the simulated rainfall percentiles are consistent with the observations reported by Ropelewski and Halpert (1996), but over eastern equatorial Africa the model simulates an opposite relationship to that observed. The recently elucidated role of the Indian Ocean dipole (Webster *et al.*, 1999; Saji *et al.*, 1999) in modulating eastern African rainfall variability may be one reason simple ENSO-precipitation relationships are not well replicated by the GCMs in this region.

We analysed 240 years of unforced simulated climate made using the HadCM2 GCM (cf. Table 1) to see to what extent this model can reproduce observed relationships. We performed the identical analysis to that performed on the observed data in Section 4 and the results are plotted in Figure 5b. The two strongest ENSO signals in African rainfall variability are only imperfectly reproduced by the model. The East African negative correlation in November to April is rather too weak in the model and also too extensive, extending westwards across the whole African equatorial domain. The positive correlation over southern Africa is too weak in HadCM2 and displaced northwards by some 10° latitude. The absence of any strong and coherent relationship during the June to October season *is* reproduced by the model (Figure 5b).

On the basis of this analysis, and our assessment of the literature, we are not convinced that quantifying future changes to interannual rainfall variability in Africa due to greenhouse gas forcing is warranted. At the very least, this issue deserves a more thorough investigation of ENSO-rainfall relationships in the GCMs used here, and how these relationships change in the future. Such an analysis might also be useful in determining the extent to which seasonal rainfall forecasts in Africa that rely upon ENSO signatures may remain valid under scenarios of future greenhouse gas forcing.

6 Uncertainties and Limitations to Knowledge

In the introduction to this paper we alluded to some of the limitations of climate change scenarios for Africa and those shown in this paper are no exception. These limitations arise because of, *inter alia*, (1) the problem of small signal-to-noise ratios in some scenarios for precipitation and other variables, (2) the inability of climate model predictions to account for the influence of land cover changes on future climate, and (3) the relatively poor representation in many models of some aspects of climate variability that are important for Africa (e.g. ENSO). Some of these limitations have been revealed by analyses presented earlier.

Even though we have presented a set of four climate futures for Africa, where the range reflects unknown future global greenhouse gas emissions and three different values for the global climate sensitivity, we

cannot place probability estimates on these four outcomes with much confidence. While this conclusion may well apply for most, or all, world regions, it is particularly true for Africa where the roles of land cover change and dust and biomass aerosols in inducing regional climate change are excluded from the climate change model experiments reported here.

This concern is most evident in the Sahel region of Africa. None of the model-simulated present or future climates for this region displays behaviour in rainfall regimes that is similar to that observed over recent decades. This is shown in Figure 13 where we plot the observed regional rainfall series for 1900-1998, as used in Figure 3, and then append the ten model-simulated evolutions of future rainfall for the period 2000-2100. These future curves are extracted directly from the ten GCM experiments reported in Table 1 and have not been scaled to our four scenario values (this scaling *was* performed in the construction of Figures 8 to 11 as discussed in Section 5). One can see that none of the model rainfall curves for the Sahel displays multi-decadal desiccation similar to what has been observed in recent decades. This conclusion also applies to the multi-century unforced integrations performed with the same GCMs (Brooks, 1999).

There are a number of possible reasons for this. It could be that the climate models are poorly replicating 'natural' rainfall variability for this region. In particular the possible role of ocean circulation changes in causing this desiccation (Street-Perrott and Perrott, 1990) may not be well simulated in the models. It could also be that the cause of the observed desiccation is some process that the models are not including. Two candidates for such processes would be the absence of a dynamic land cover/atmosphere feedback process and the absence of any representation of changing atmospheric dust aerosol concentration. The former of these feedback processes has been suggested as being very important in determining African climate change during the Holocene by amplifying orbitally-induced African monsoon enhancement (Kutzbach *et al.*, 1996; Claussen *et al.*, 1999; Doherty *et al.*, 2000). This feedback may also have contributed to the more recently observed desiccation of the Sahel (Xue, 1997). The latter process of elevated Saharan dust concentrations may also be implicated in the recent Sahelian desiccation (Brooks, 1999).

Without such a realistic simulation of observed rainfall variability, it is difficult to define with confidence the true magnitude of natural rainfall variability in these model simulations and also difficult to argue that these greenhouse gas-induced attributed rainfall changes for regions in Africa will actually be those that dominate the rainfall regimes of the twentyfirst century. Notwithstanding these model limitations due to omitted or poorly represented processes, Figure 13 also illustrates the problem of small signal-to-noise ratios in precipitation scenarios. The ten individual model simulations yield different signs of

precipitation change for these three regions as well as different magnitudes. How much of these differences are due to model-generated natural variability is difficult to say. In our scenario maps (Figures 8 to 11) we presented the *median* precipitation change from these ten (scaled) model simulations, implying that we can treat these climate change simulations as individual members of an ensemble. The ensemble-mean or median therefore yields our 'best' estimate of the true response to greenhouse gas forcing, much as in numerical weather prediction the ensemble-mean forecast is often taken as the 'best' short-range weather forecast. In our example, for the Sahel and southern African the median response was for annual drying, whereas for East Africa the median response was for wetting (Figure 13).

One other concern about the applicability in Africa of climate change scenarios such as those presented here is the relationship between future climate change predictions and seasonal rainfall forecasts. There is increasing recognition (e.g. Downing *et al.*, 1997; Ringius, 1999; Washington and Downing, 1999) that for many areas in the tropics one of the most pragmatic responses to the prospect of long-term climate change is to strengthen the scientific basis of seasonal rainfall forecasts. Where forecasts *are* feasible, this should be accompanied by improvements in the management infrastructure to facilitate timely responses. Such a research and adaptation strategy focuses on the short-term realisable goals of seasonal climate prediction and the near-term and quantifiable benefits that improved forecast applications will yield. At the same time, the strengthening of these institutional structures offers the possibility that the more slowly emerging signal of climate change in these regions can be better managed in the decades to come. It is therefore an appropriate form of climate change adaptation. This means that two of the objectives of climate change prediction should be to determine the effect global warming may have on seasonal predictability - will forecast skill levels increase or decrease or will different predictors be needed? - and to determine the extent to which predicted future climate change will impose additional strains of natural and managed systems over and above those that are caused by existing seasonal climate variability. For both of these reasons we need to improve our predictions of future climate change and in particular to improve our quantification of the uncertainties.

7 Conclusions

The climate of Africa is warmer than it was 100 years ago. Although there is no evidence for widespread desiccation of the continent during this century, in some regions substantial interannual and multi-decadal rainfall variations have been observed and near continent-wide droughts in 1983 and 1984 had some dramatic impacts on both environment and some economies (Benson and Clay, 1998). The extent to which these rainfall variations are related to greenhouse gas-induced global warming, however, remains

undetermined. A warming climate will nevertheless place additional stresses on water resources, whether or not future rainfall is significantly altered.

Model-based predictions of future greenhouse gas-induced climate change for the continent clearly suggest that this warming will continue and, in most scenarios, accelerate so that the continent on average could be between 2° and 6°C warmer in 100 years time. While these predictions of future *warming* may be relatively robust, there remain fundamental reasons why we are much less confident about the magnitude, and even direction, of regional *rainfall* changes in Africa. Two of these reasons relate to the rather ambiguous representation in most global climate models of ENSO-type climate variability in the tropics (a key determinant of African rainfall variability) and the omission in all current global climate models of any representation of dynamic land cover-atmosphere interactions and dust and biomass aerosols. Such interactions have been suggested to be important in determining African climate variability during the Holocene and may well have contributed to the more recently observed desiccation of the Sahel.

We suggest that climate change scenarios, such as those presented here, should nevertheless be used to explore the sensitivity of a range of African environmental and social systems, and economically valuable assets, to a range of future climate changes. Some examples of such exploration were presented by Dixon *et al.* (1996), although in these studies there was little co-ordinated and quantified use of a coherent set of climate futures. Further work can be done to elaborate on some of the higher order climate statistics associated with the changes in mean seasonal climate shown here - particularly daily temperature and precipitation extremes. It may also be worthwhile to explore the sensitivity of these model predictions to the spatial resolution of the models - i.e., explore the extent to which downscaled scenarios differ from GCM-scale scenarios - although such downscaling techniques do not remove the fundamental reasons why we are uncertain about future African rainfall changes.

The exploration of African sensitivity to climate change must also be undertaken, however, in conjunction with the more concrete examples we have of sensitivity to short-term (seasonal time-scale) climate variability. These estimates may be based on observed reconstruction of climate variability over the last century, or on the newly emerging regional seasonal rainfall forecasts now routinely being generated for southern, eastern and western Africa (e.g. NOAA, 1999; SARCOF, 2000; IRI, 2000). Because of the uncertainties mentioned above about future regional climate predictions for Africa, initial steps to reduce vulnerability should focus on improved adaptation to existing climate variability (Downing *et al.*, 1997; Adger and Kelly, 1999; Ringius, 1999). Thus, emphasis would be placed on reducing vulnerability to

adverse climate-events and increasing capacity to adapt to short-term and seasonal weather conditions and climatic variability. The likelihood of significant economic and social benefits from adaptation to short-term climate variability in Africa justifies this activity. Additionally, and importantly, lessons from adaptation to short-term climate variability would build capacity to respond incrementally to longer-term changes in local and regional climates.

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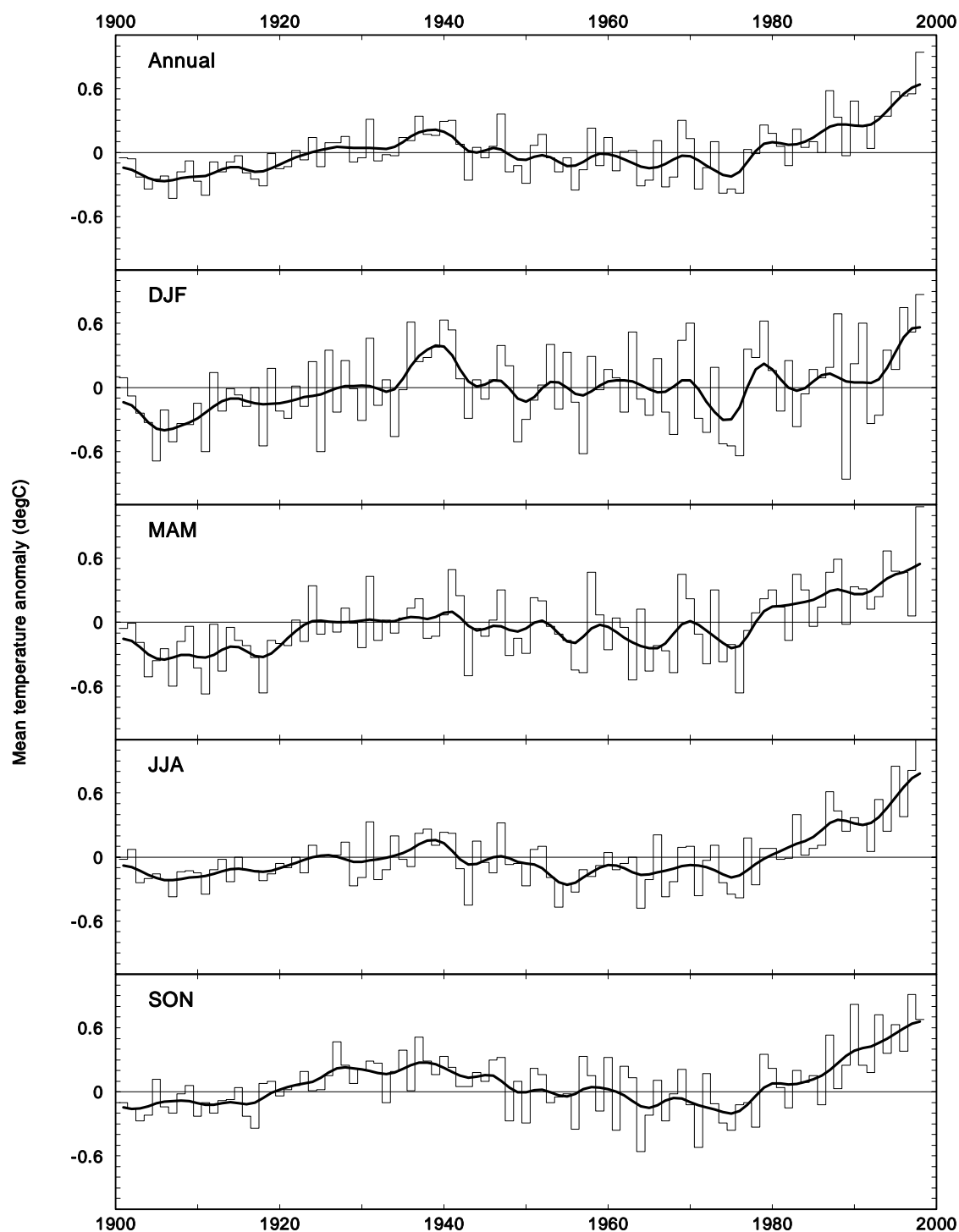
Figures

Figure 1: Mean surface air temperature anomalies for the African continent, 1901-1998, expressed with respect to the 1961-90 average; annual and four seasons - DJF, MAM, JJA, SON. The smooth curves result from applying a 10-year Gaussian filter.

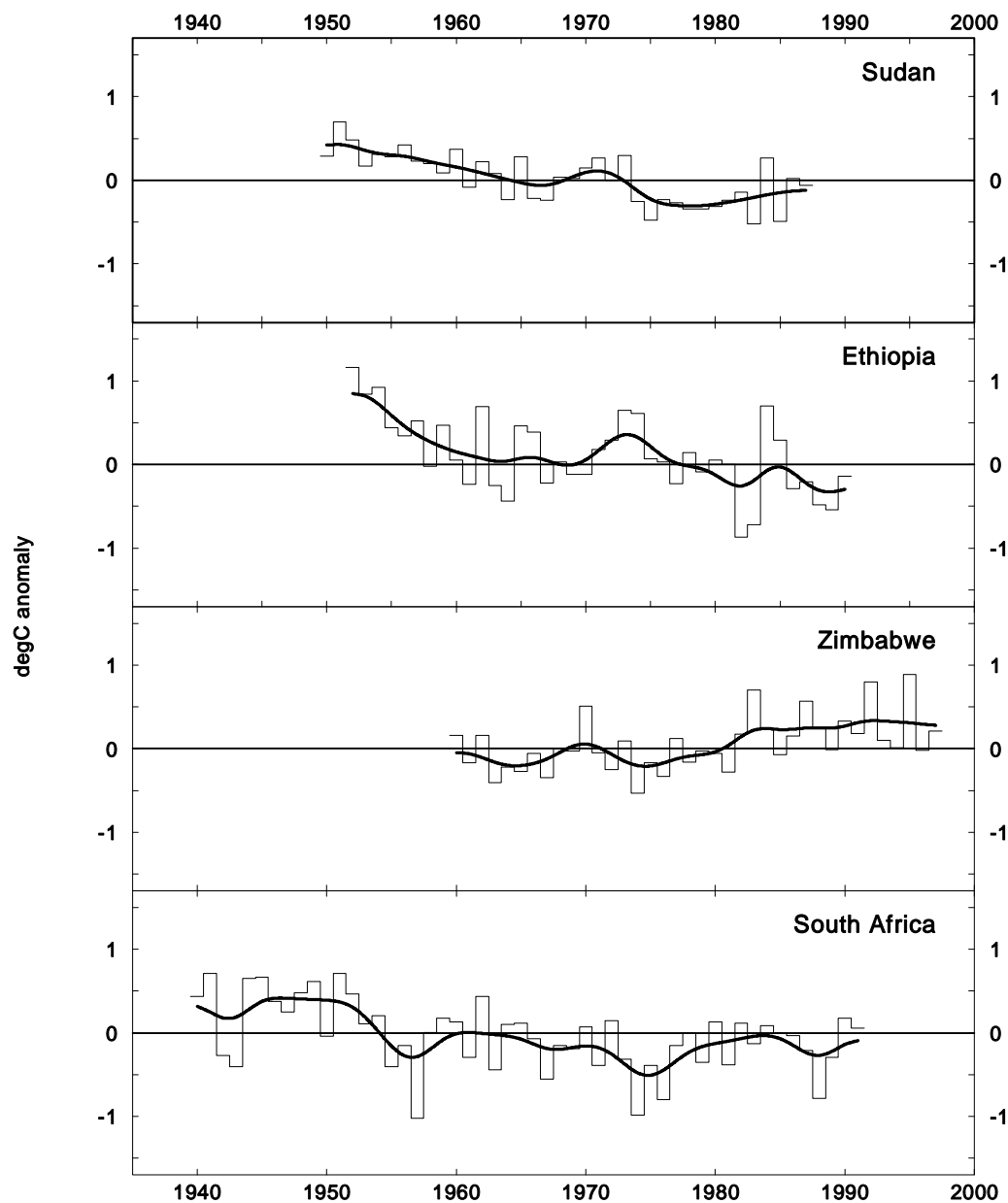


Figure 2: Mean annual diurnal temperature range ($T_{max} - T_{min}$) for a number of African countries: Sudan (data end 1987), Ethiopia (1990), Zimbabwe (1997) and South Africa (1991). The smooth curves result from applying a 10-year Gaussian filter. Sudan and South Africa are from Jones and Lindesay (1993), while data for Ethiopia and Zimbabwe are unpublished.

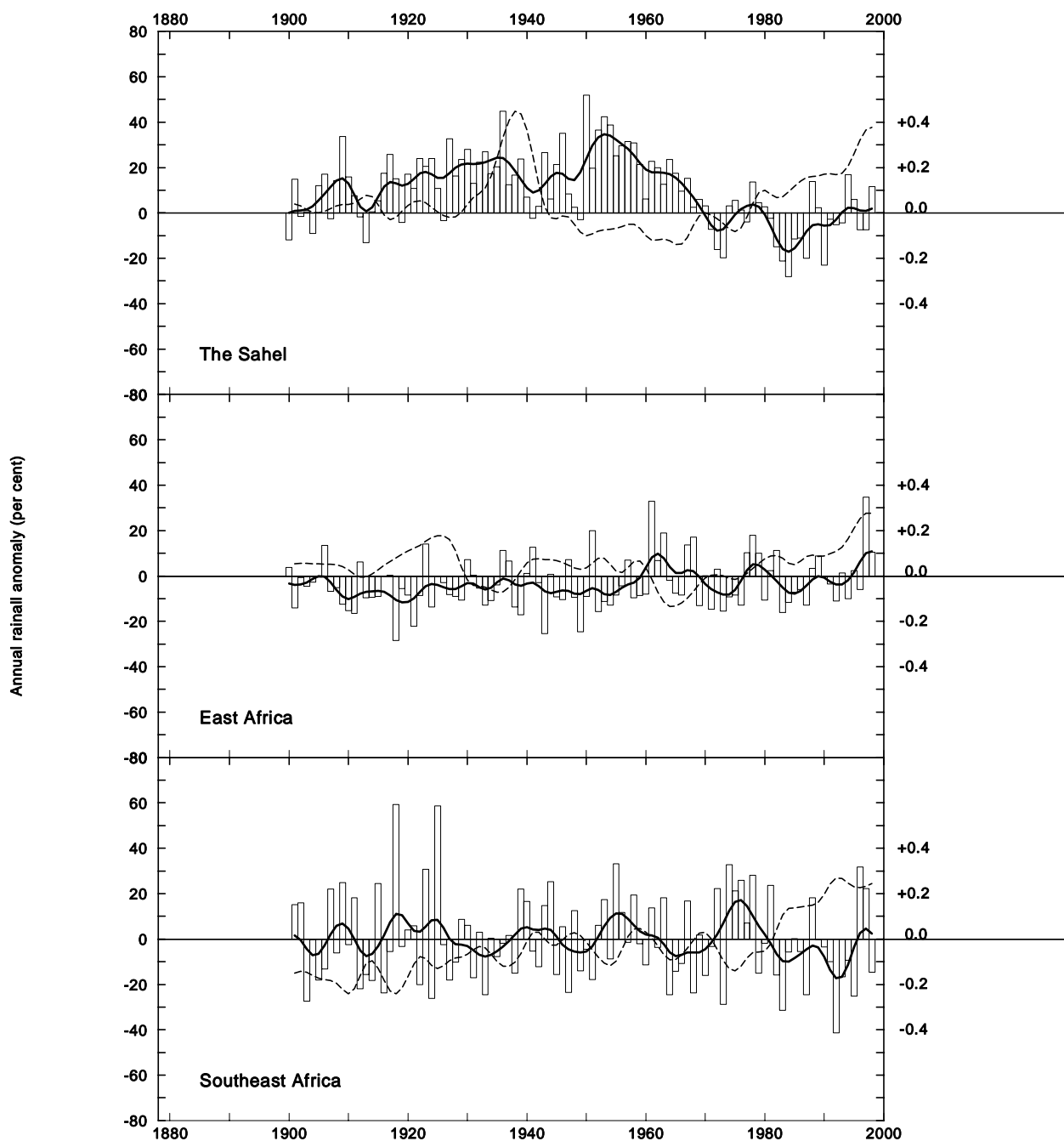


Figure 3: Annual rainfall (1900-98; histograms and bold line; per cent anomaly) and mean temperature anomalies (1901-98; dashed line; degC anomaly) for three African regions, expressed with respect to the 1961-90 average: Sahel, East Africa and southeastern Africa (regional domains marked on Figure 4). Note: for southeast Africa year is July to June. The smooth curves for rainfall and temperature result from applying a 10-year Gaussian filter.

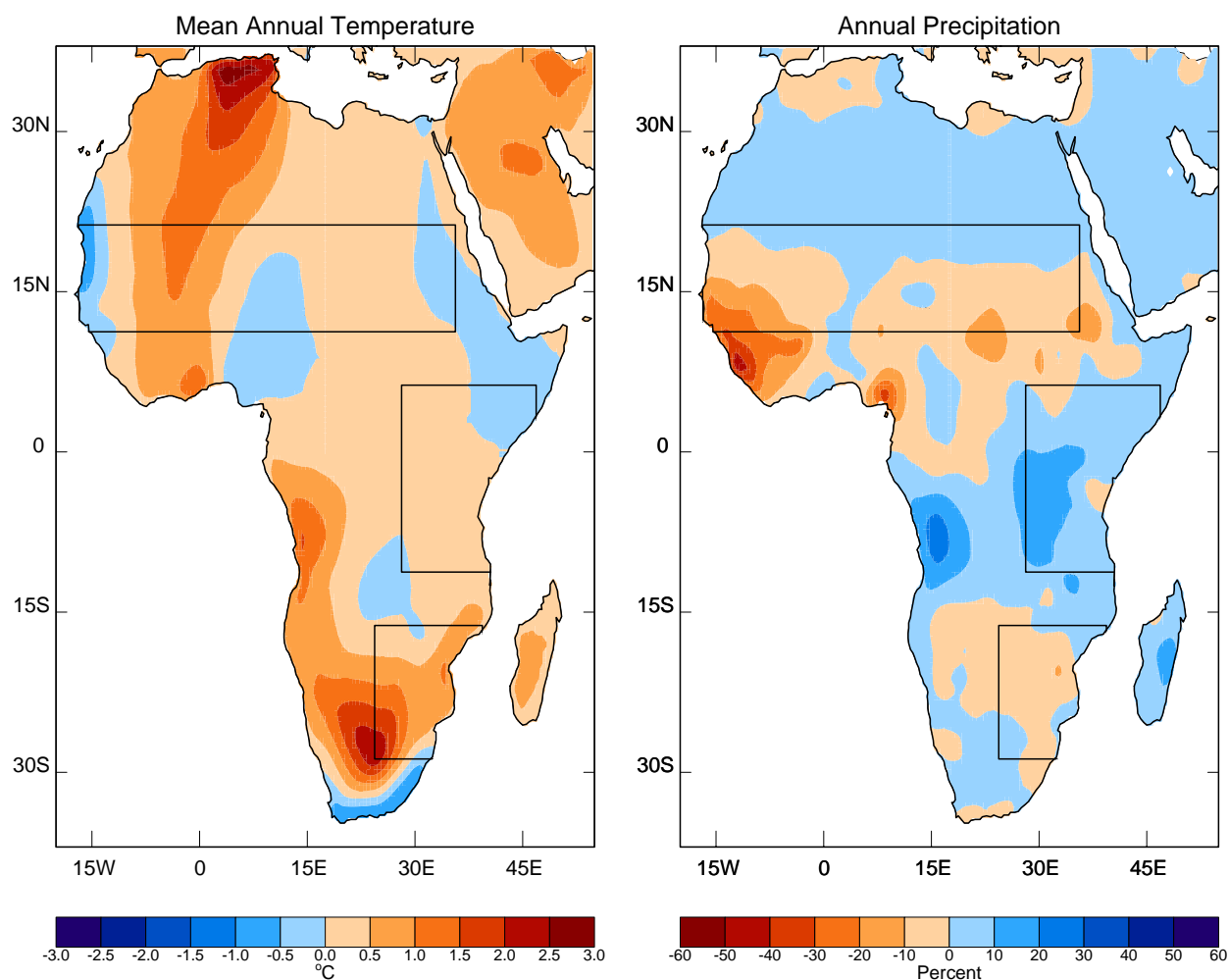


Figure 4: Mean linear trends in annual temperature (left; °C/century) and annual rainfall (right; per cent/century), calculated over the period 1901-1995 from the New *et al.* (1999, 2000) data set. Data were filtered with a 10-point Gaussian filter before being subject to regression analysis. The three regions shown are those depicted in Figures 3 and 13.

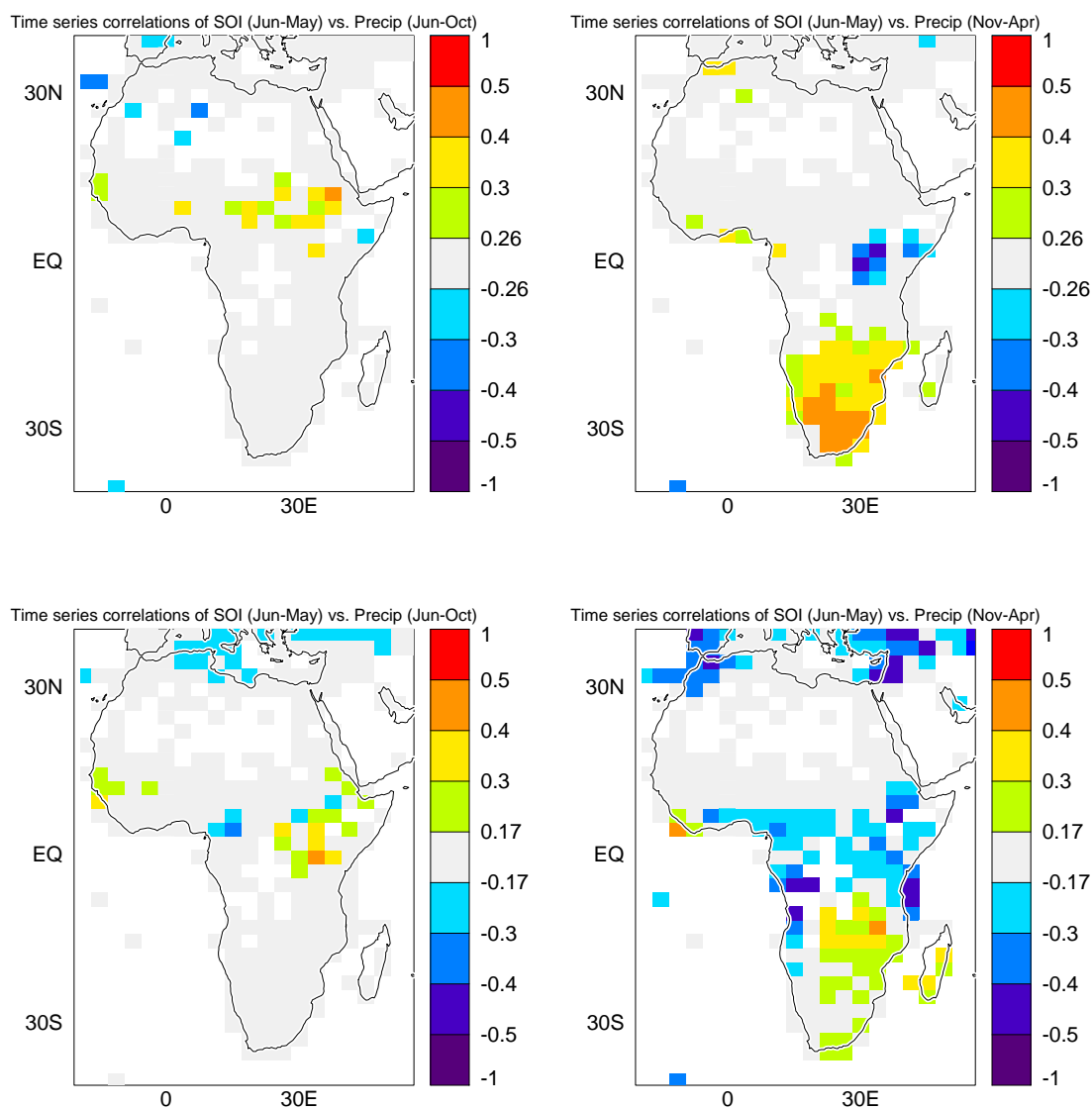


Figure 5: Correlation between annual (June-May) SOI and seasonal rainfall; left: June-October (Year 0) rainfall; right: November-April (Year 0 to +1) rainfall. Top panel (5a): observed relationship over the period 1901-1998. Bottom panel (5b): HadCM2 model-simulated relationship over a 240-year unforced simulation. Correlations are only plotted where they are significant at 95% and in regions where the respective seasonal rainfall is greater than 20mm and greater than 20 per cent of annual total.

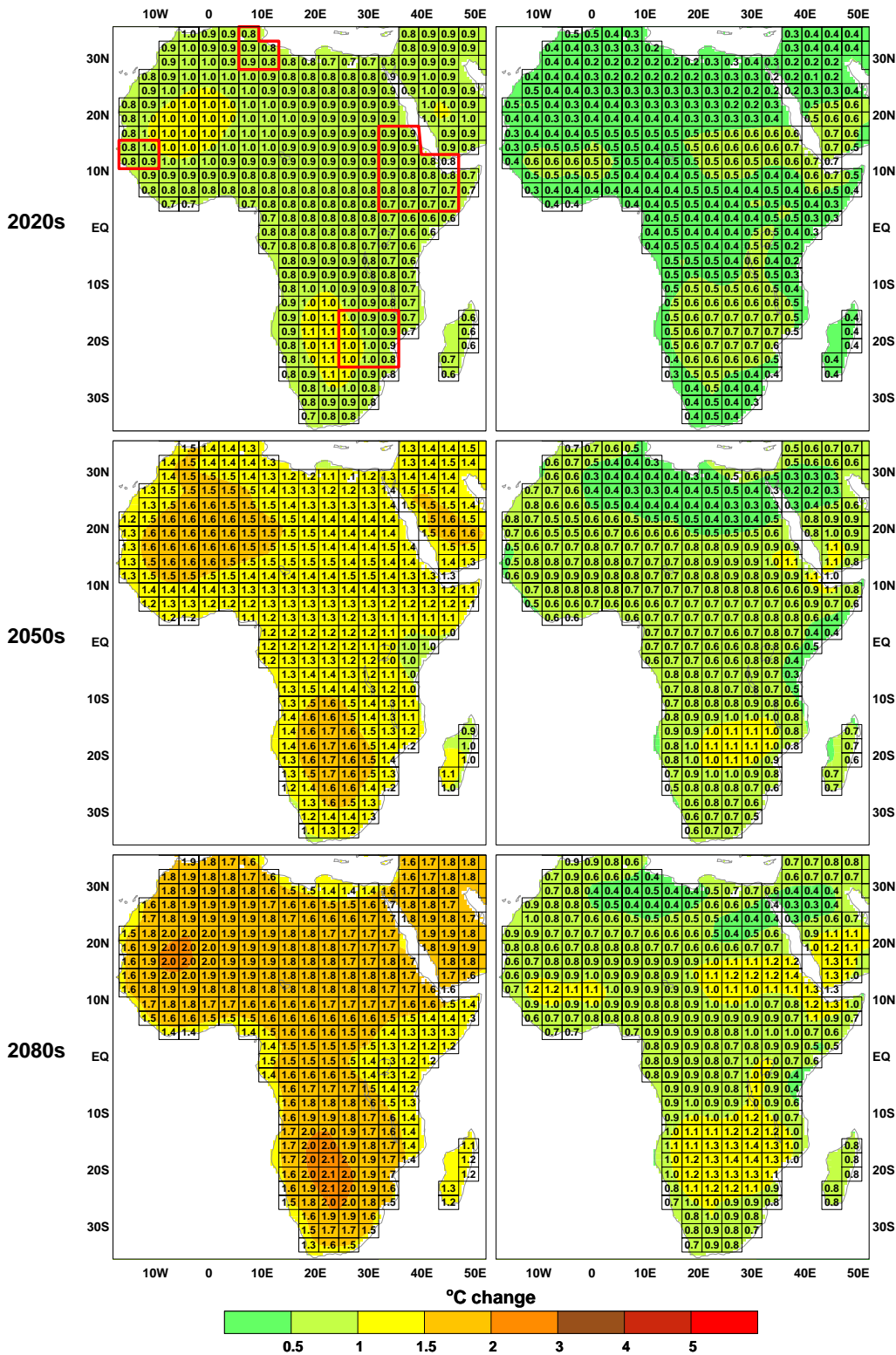


Figure 6: (Left panels) Change in mean annual temperature for the 2020s, 2050s and 2080s (with respect to 1961-90) for the B1-low scenario; median of seven GCM experiments. (Right panels) Inter-model range in mean annual temperature change. See text for further explanation. Selected domains in the top left panel are the four 'national' regions used in Figure 12.

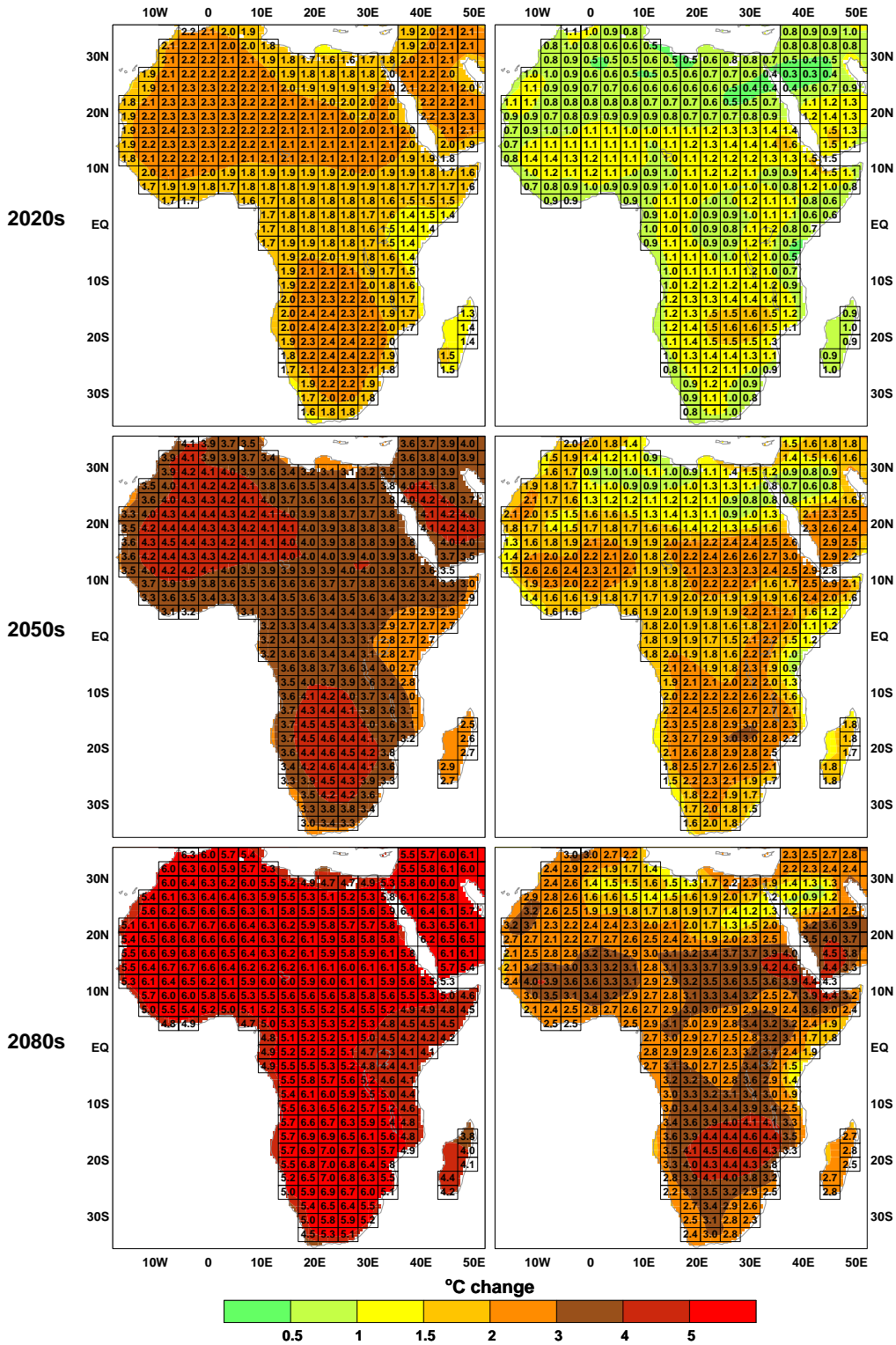


Figure 7: (Left panels) Change in mean annual temperature for the 2020s, 2050s and 2080s (with respect to 1961-90) for the A2-high scenario; median of seven GCM experiments. (Right panels) Inter-model range in mean annual temperature change. See text for further explanation.

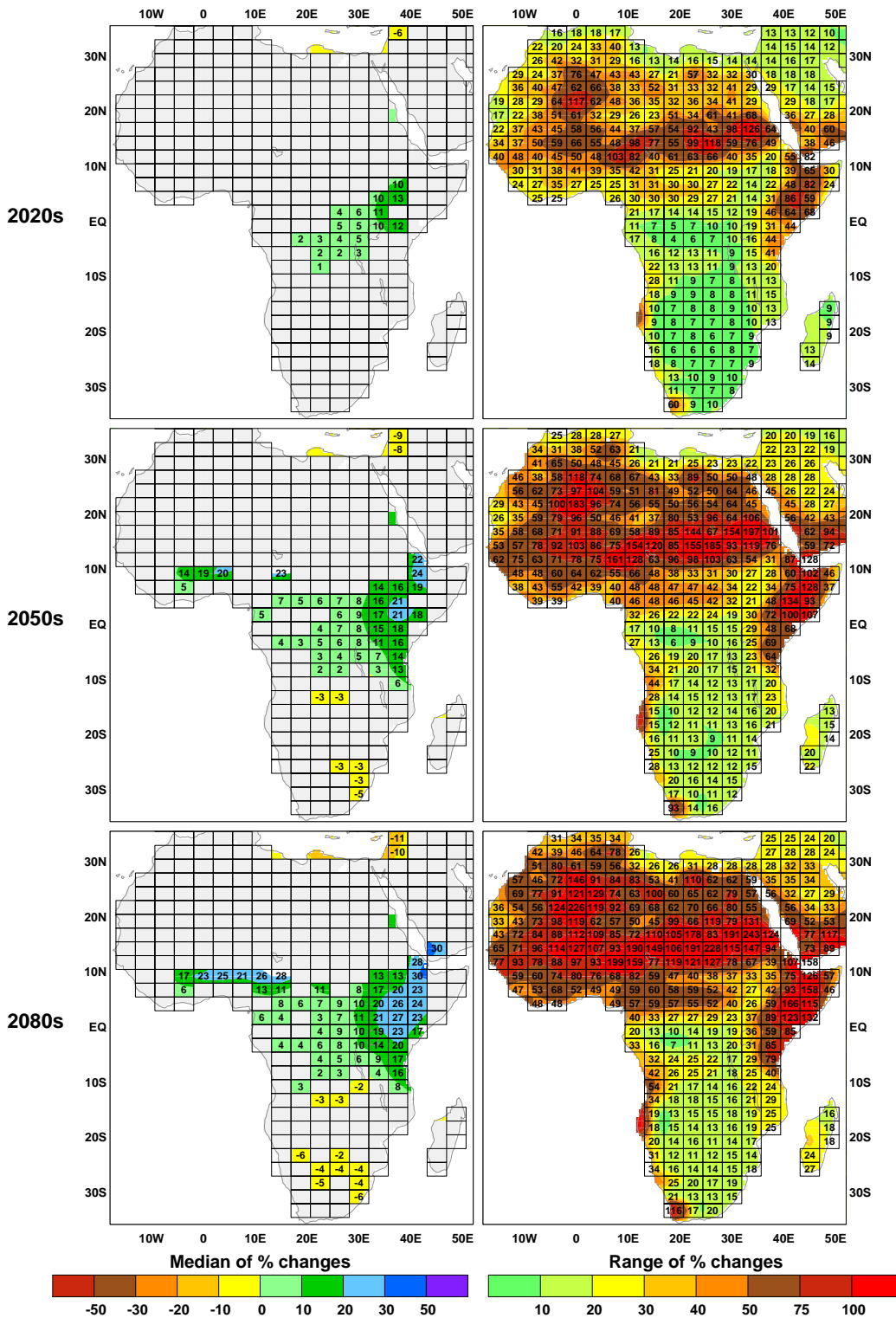


Figure 8: (Left panels) Change in mean DJF rainfall for the 2020s, 2050s and 2080s (with respect to 1961-90) for the B1-low scenario; median of seven GCM experiments. For areas with no change shown the model median response fails to exceed the one sigma level of natural rainfall variability as defined by HadCM2. (Right panels) Inter-model range in mean annual temperature change. See text for further explanation.

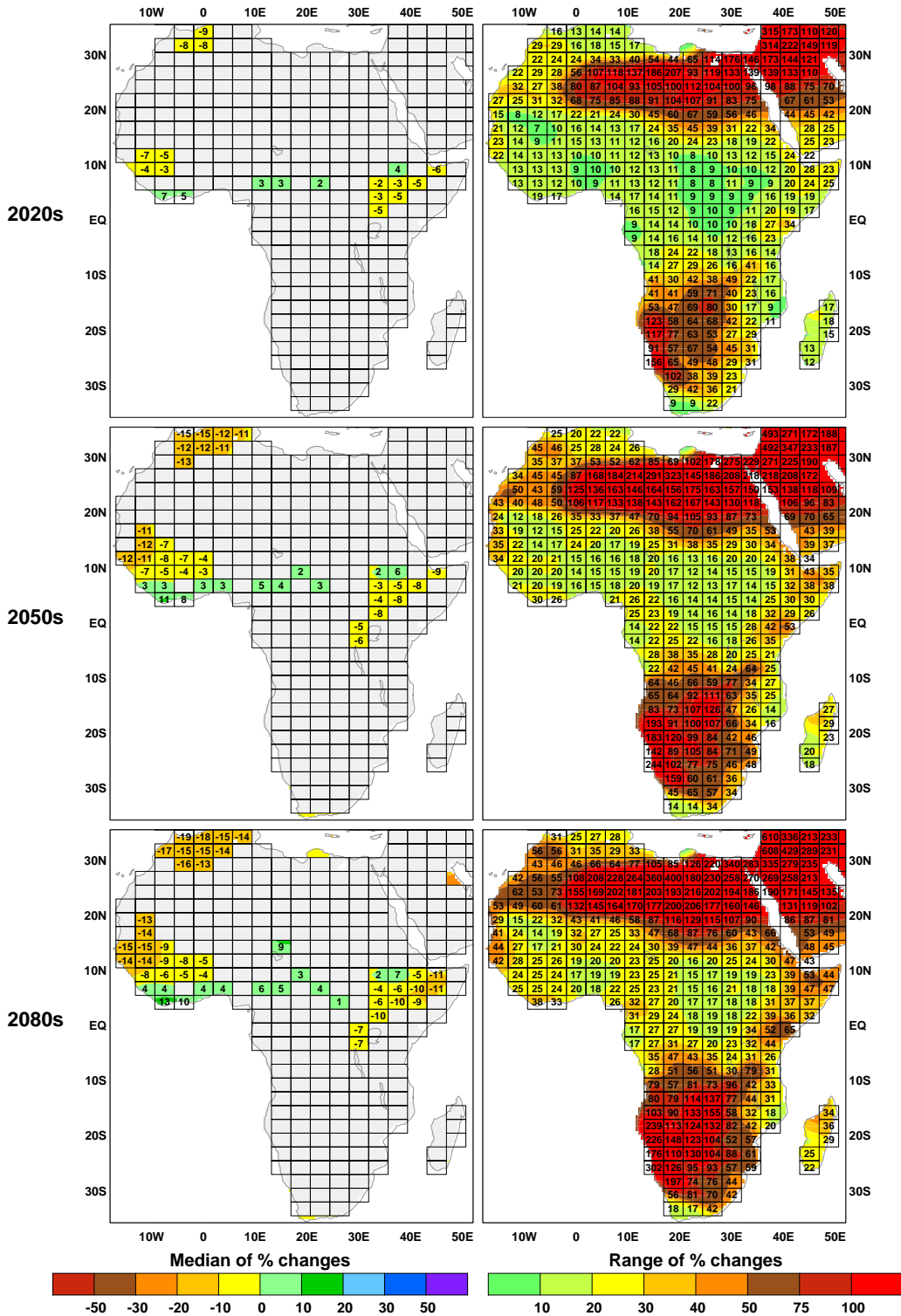


Figure 9: (Left panels) Change in mean JJA rainfall for the 2020s, 2050s and 2080s (with respect to 1961-90) for the B1-low scenario; median of seven GCM experiments. For areas with no change shown the model median response fails to exceed the one sigma level of natural rainfall variability as defined by HadCM2. (Right panels) Inter-model range in mean annual temperature change. See text for further explanation.

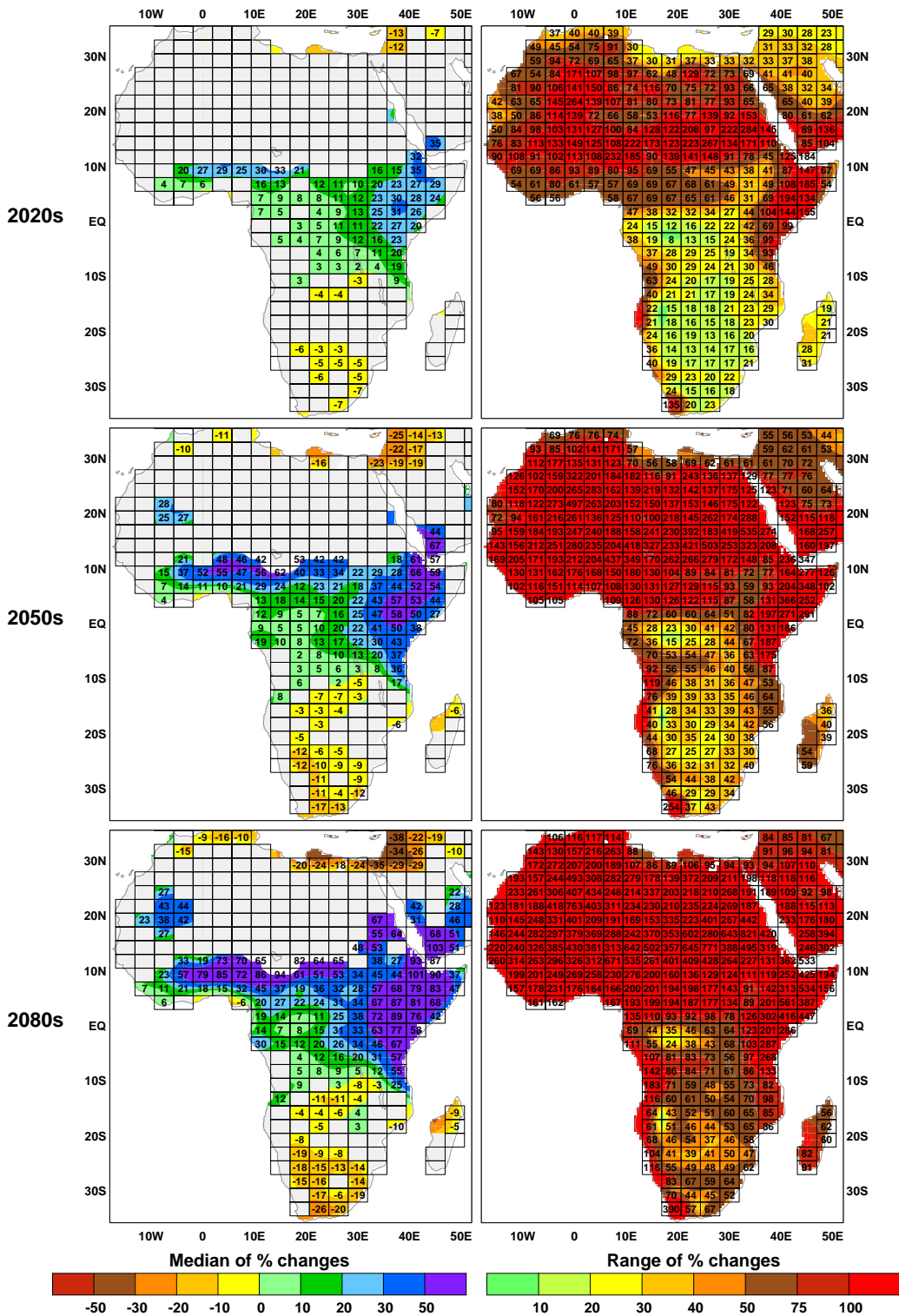


Figure 10: (Left panels) Change in mean DJF rainfall for the 2020s, 2050s and 2080s (with respect to 1961-90) for the A2-high scenario; median of seven GCM experiments. For areas with no change shown the model median response fails to exceed the one sigma level of natural rainfall variability as defined by HadCM2. (Right panels) Inter-model range in mean annual temperature change. See text for further explanation.

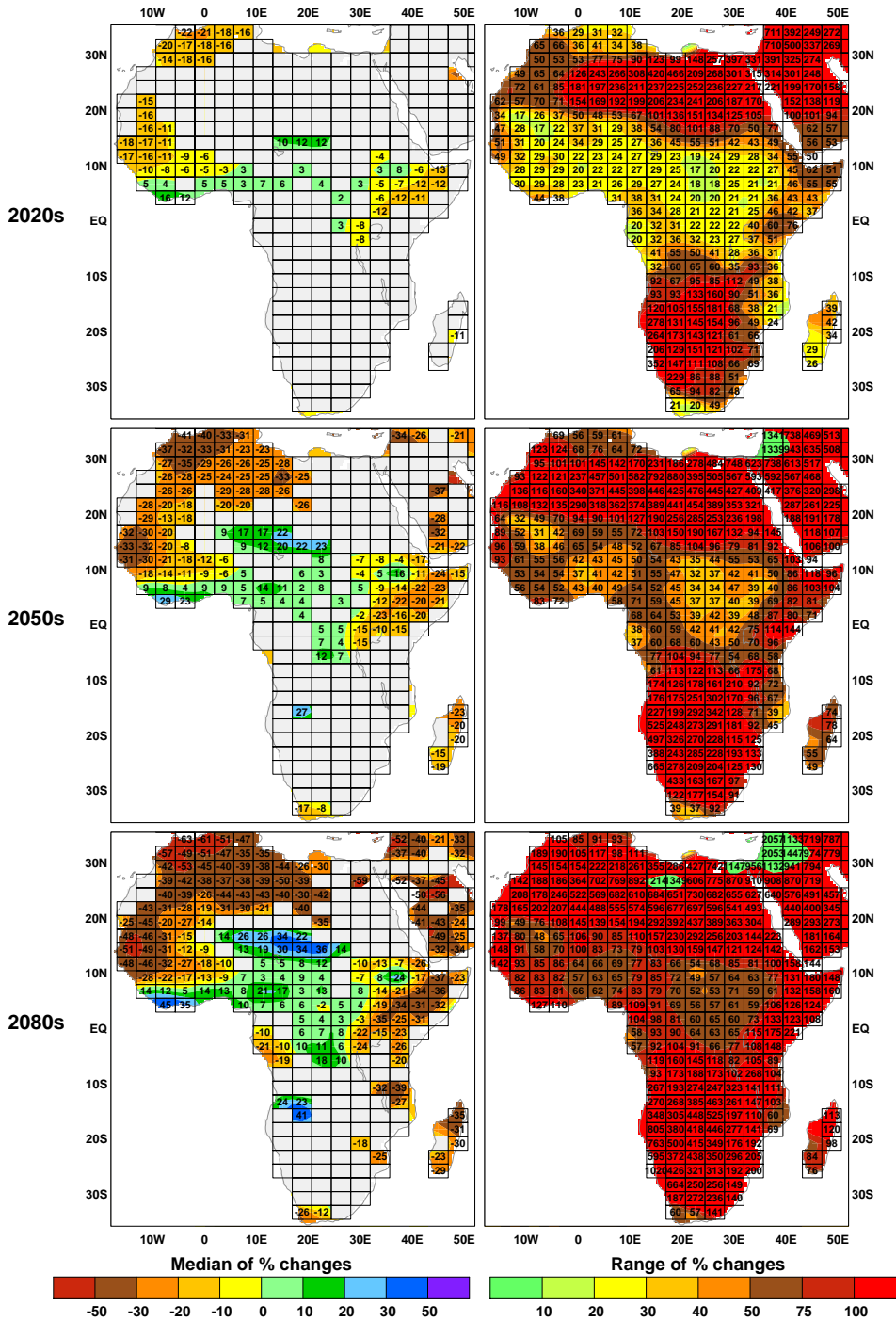


Figure 11: (Left panels) Change in mean JJA rainfall for the 2020s, 2050s and 2080s (with respect to 1961-90) for the A2-high scenario; median of seven GCM experiments. For areas with no change shown the model median response fails to exceed the one sigma level of natural rainfall variability as defined by HadCM2. (Right panels) Inter-model range in mean annual temperature change. See text for further explanation.

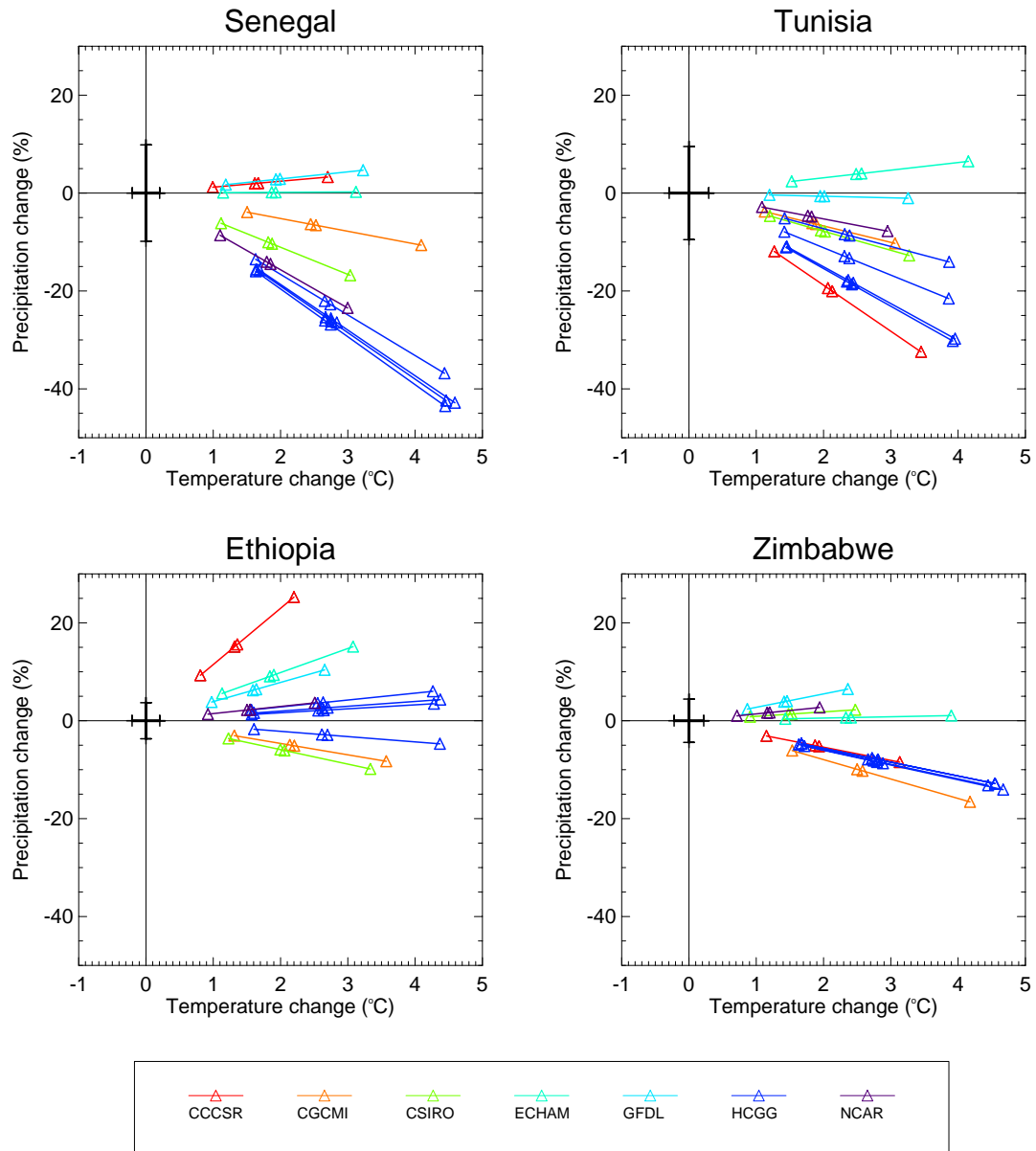


Figure 12: Change in mean annual temperature and precipitation for the 2050s (with respect to 1961-90) for regions centred on Senegal, Tunisia, Ethiopia and Zimbabwe (see Figure 6, top left panel, for selected domains). Results from the seven DDC GCMs are shown, scaled to reflect the four climate change scenarios adopted in this study: A2-high, A1-mid, B2-mid and B1-low. Note: the HadCM2 GCM has four results reflecting the four-member ensemble simulations completed with this GCM. The bold lines centred on the origin indicate the two standard deviation limits of natural 30-year time-scale natural climate variability defined by the 1400-year HadCM2 control simulation.

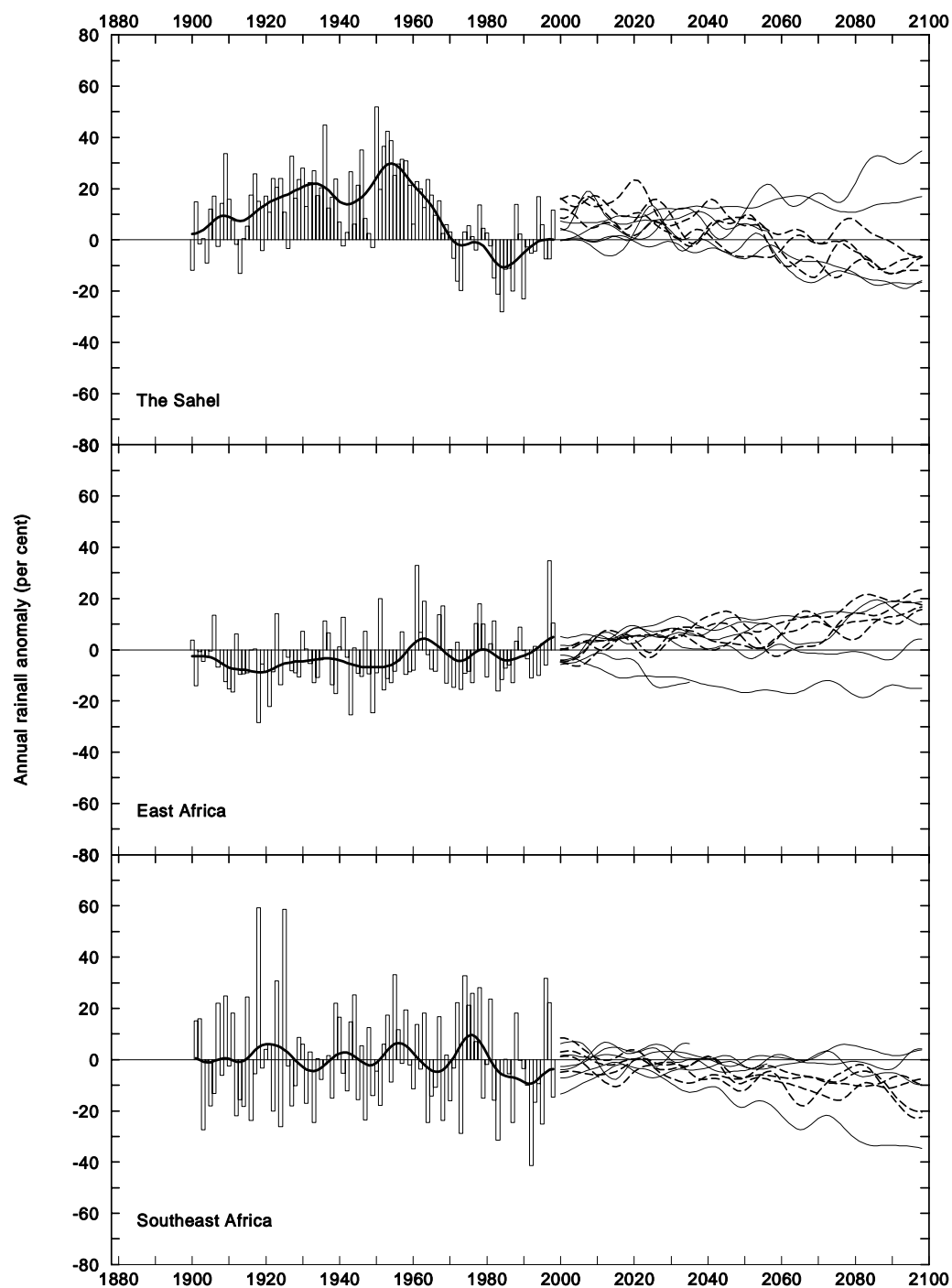


Figure 13: Observed annual rainfall anomalies for three African regions, 1900-1998 (*cf.* Figure 3), and model-simulated anomalies for 2000-2099. Model anomalies are for the 10 model simulations derived from the seven DDC GCM experiments - the four HadCM2 simulations are the dashed curves (*cf.* Table 1). All anomalies are expressed with respect to either observed or model-simulated 1961-90 average rainfall. The model curves are extracted directly from the GCM experiments and the results are *not* scaled to the four scenarios used in this paper. The smooth curves result from applying a 20-year Gaussian filter.