Climatic Change (2013) 117:859–872
DOI 10.1007/s10584-012-0581-7

Changes in African temperature and precipitation associated with degrees of global warming

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Received: 30 April 2012 / Accepted: 27 August 2012 / Published online: 15 September 2012

Abstract For almost two decades, politicians have been negotiating temperature limits to which anthropogenic global warming should be restricted, and 2 °C has emerged as benchmark for danger. However, there has been a lack of scientific research into the implications of such a change for African climate. This study aims to provide information for mitigation debates; through an examination of temperature and precipitation changes in Africa associated with 1 °C, 2 °C, 3 °C, and 4 °C of global warming. Data from Global Climate Models show little significant precipitation change at 1 °C, then larger anomalies at 2 °C which are strengthened and extended at 3 °C and 4 °C, including a wet signal in East Africa, and dry signals in Southern Africa, the Guinea Coast, and the west of the Sahel. Some of the models project changes with potential for severe societal implications. Despite the uncertainty attached to these projections, they highlight risks associated with 2 °C and beyond. Using these findings as a framework for impact assessment and evaluation, further research has the potential to uncover the implications of global warming for African regions.

1 Introduction

Political debates on whether to limit global mean temperature change (ΔT_g) to 1.5 °C or 2 °C have limited scientific backing in the context of African climate. The majority of climate projection research has presented the impacts of anthropogenic interference in time-slices, for instance 2075–2100 (e.g. Giannini et al. 2008). Using these studies, policy-makers can develop adaptation strategies for specific decades, but cannot determine what level of global warming might be dangerous from a regional perspective. Important questions remain unanswered. Will

Electronic supplementary material The online version of this article (doi:10.1007/s10584-012-0581-7) contains supplementary material, which is available to authorized users.

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changes be amplified as ΔT_g increases? Will the rate of change allow for incremental adaptation, or involve non-linear transformations which require early mitigation to avoid? By examining projections at specific levels of ΔT_g, this study will begin to confront these questions.

There is an additional, scientific, justification for taking this approach. In a time-slice, models have consistent greenhouse gas (GHG) concentrations but inconsistent ΔT_g, due to variation in climate sensitivity and feedbacks. GHGs have been shown to influence precipitation directly (Allen and Ingram 2002), but this effect is smaller than their indirect influence via global temperature (Andrews et al. 2010). Comparing models with consistent ΔT_g might develop understanding of the important radiative impact of temperature on precipitation.

Research into climate changes associated with ΔT_g has begun, showing that some changes projected at 2 °C would have serious implications (e.g. Kaplan and New 2006), and there are larger shifts at 4 °C (e.g. Zelazowski et al. 2011). However, these studies have rarely allowed for thorough assessments of difference between ΔT_g intervals: either focusing on one level of warming (e.g. May 2008), or assuming change will be linear (e.g. Zelazowski et al. 2011). Furthermore, whilst the importance of vulnerable regions has been highlighted, the implications of ΔT_g have not been investigated for African climate.

Many African regions are prone to large interannual precipitation variability, which has substantial human impacts, in part due to high dependence on rain-fed agriculture, which in many cases is already limited by a lack of precipitation. There have been efforts to investigate how African climate will change in future, including several continent-wide studies (Christensen et al. 2007; Giannini et al. 2008; Hulme et al. 2001). The models project a decrease (increase) in precipitation in much of the subtropics (tropics). Research into specific regions has revealed trends for which there is substantial inter-model agreement, including a wet signal in East Africa (Shongwe et al. 2011), and a dry signal in southern Africa (Shongwe et al. 2009). The Sahel has a more uncertain future (Biasutti and Giannini 2006), and other regions have received little research attention (Todd and Washington 2004). For all of Africa, there is relative uncertainty in future climate, due to under-researched and complex systems which are poorly understood and inadequately modelled in comparison to the mid-latitudes (Cook and Vizy 2006).

The present study proposes to re-evaluate the implications of climate change for precipitation across the African continent, by isolating changes at specific levels of ΔT_g. The paper will first outline the Global Climate Model (GCM) data employed and the tools for analysis. The results section will present the temperature and precipitation projections at 1 °C, 2 °C, 3 °C and 4 °C of ΔT_g. Then the implications of these results will be discussed, including the lessons for mitigation debates. In the fifth section, potential effects of global warming on precipitation mechanisms will be explored, and conclusions will follow.

2 Data and methods

2.1 GCM data

Monthly data were selected from the World Climate Research Programme (WCRP)'s Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, documented by Meehl et al. (2007b) (Table 1). Data were interpolated to 1x1° spatial resolution. The models were run with the 20C3M scenario, which incorporates historical forcings; and two SRES scenarios: A2 and A1B, in which GHGs are increased to 2100. In A1B, some models

Table 1 GCMs used in this study

Model Name[a]	Country	Resolution[b]	A2	A1B
BCCR-BCM2.0	Norway	1.9°×1.9° L16	2001–2099	2001–2099
CCSM3.0	USA	1.4°×1.4° L26	2001–2099	2000–2349
CGCM3.1 (T47)	Canada	2.8°×2.8° L31	2001–2099	2001–2300
CGCM3.1 (T63)	Canada	1.9°×1.9° L31	–	2001–2300
CNRM-CM3	France	1.9°×1.9° L45	2001–2099	2000–2299
CSIRO-Mk3.0	Australia	1.9°×1.9° L18	2001–2099	2001–2200
CSIRO-Mk3.5	Australia	1.9°×1.9° L18	2001–2099	2001–2300
ECHAM5/MPI-OM	Germany	1.9°×1.9° L31	2001–2099	2001–2300
ECHO-G	Germany/Korea	3.9°×3.9° L19	2001–2099	2001–2300
FGOALS-g1.0	China	2.8°×2.8° L26	–	2000–2199
GFDL-CM2.0	USA	2.0°×2.5° L24	2001–2099	2001–2300
GFDL-CM2.1	USA	2.0°×2.5° L24	2001–2099	2001–2300
GISS-AOM	USA	3.0°×4.0° L12	–	2001–2100
GISS-EH	USA	4.0°×5.0° L20	–	2001–2099
GISS-ER	USA	4.0°×5.0° L20	2004–2099	2004–2199
INGV-SXG	Italy	1.1°×1.1° L19	2001–2099	2001–2099
INM-CM3.0	Russia	4.0°×5.0° L21	2001–2099	2001–2200
IPSL-CM4	France	2.5°×3.75° L19	2001–2099	2000–2230
MIROC3.2(hires)	Japan	1.1°×1.1° L56	–	2001–2099
MIROC3.2(medres)	Japan	2.8°×2.8° L20	2001–2099	2001–2300
MRI-CGCM2.3.2a	Japan	2.8°×2.8° L30	2001–2099	2001–2300
PCM	USA	2.8°×2.8° L26	2001–2099	2000–2299
UKMO-HadCM3	UK	2.5°×3.75° L19	2001–2099	2000–2199
UKMO-HadGEM1	UK	1.3°×1.9° L38	2001–2099	2000–2199

[a] Naming conventions are taken from the IPCC www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php

[b] Horizontal resolution is expressed as approximate degrees latitude by longitude. Vertical resolution (L) is the number of vertical levels

were run in longer integrations in which GHGs are held at the same concentration from 2100 to 2200 and beyond. One realisation was used for each model in each scenario. The longest integrations available were selected.

Model projections of tropical precipitation are highly uncertain, owing to difficulties in representing convective systems and a lack of detailed observations (Randall et al. 2007). Previous studies have used assessments of model similarity and agreement with observations in model selection and weighting schemes, leading to contrasting conclusions for some regions, including the Sahel (Cook and Vizy 2006; Lau et al. 2006). In this study, data from all available models were employed, and the models were weighted equally in the calculation of the ensemble mean.

2.2 Deriving global mean temperature change

Annual ΔT_g time-series were constructed for each model in each scenario. Temperature data were weighted to correct grid-boxes to equal area; and spatially averaged annual global means were calculated. 20C3M data for 1985–99 were then averaged to create a reference climatology, and each year in A2 and A1B was differenced from this baseline (as described in Online Resource 1). The analysis was also repeated with a 1955–69 start point (see Online Resource 2, 3).

The ΔT_g time-series were smoothed using 15 year running means. For each model, the date at which the resulting time-series crossed 1 °C, 2 °C, 3 °C, 4 °C, and 5 °C of ΔT_g was extracted (Online Resource 4) and defined as the median of a 15 year period, to be used to analyse local temperature and precipitation change. The 15 year sample length was designed to eliminate interannual variability. Ensemble mean climatologies were computed for A2 and A1B using the maximum number of models available in both scenarios: 19 at 1 °C and 2 °C, and 12 at 3 °C; as well as the 6 models available at 4 °C in A1B (see Online Resource 4). None of the models reached 4 °C in time to take a 15 year sample when run in A2. One model reached 5 °C in A1B, and projections from this model are provided online (Online Resource 5, 6), alongside ensemble means using all available models run in A1B.

2.3 Measuring local changes associated with ΔT_g

Having acquired samples corresponding to 1 °C, 2 °C, 3 °C, 4 °C, and 5 °C ΔT_g, the temperature and precipitation anomalies and proportional changes relative to the climatology were calculated for each available model and the ensemble mean, on a grid-point by grid-point basis (as described in Online Resource 1). These statistics were computed for the annual mean and 8 seasons, DJF, MAM, JJA, SON, JFM, AMJ, JAS, and OND (denoted by the initial letter of each month); since precipitation seasonality in Africa is regionally specific.

The percentage of models with positive anomalies was calculated on a grid-point by grid-point basis to illustrate model agreement on the direction of change. Statistical significance tests of difference between the baseline and each of the 15 year sample climatologies (at 1 °C, 2 °C, 3 °C, 4 °C, and 5 °C) were undertaken for each model and the ensemble mean, at a confidence level of 0.95, also on a grid-point by grid-point basis. The Mann-Whitney U test was used, as precipitation has a skewed distribution in many arid regions and the test makes no assumptions about distribution. Due to the small sample size (15 years), the direct method was applied. The percentage of models with significant change was computed to identify grid-points where there is agreement on a lack of signal.

2.4 Regional area-averaging

Sub-regions were chosen for further analysis (Online Resource 7), and area weighted area averages of temperature and precipitation climatologies were calculated for each model and the ensemble mean. These were used to compute anomalies and proportional changes, which were tested for significance in the same manner as above except on a regional basis.

3 Results

3.1 Time of global warming

All of the models project increasing global temperatures in both A2 and A1B (Fig. 1). For the same GHG scenario, different models show different rates of warming, leading to variation in year at which the models exceed specific ΔT_g thresholds (Online Resource 4).

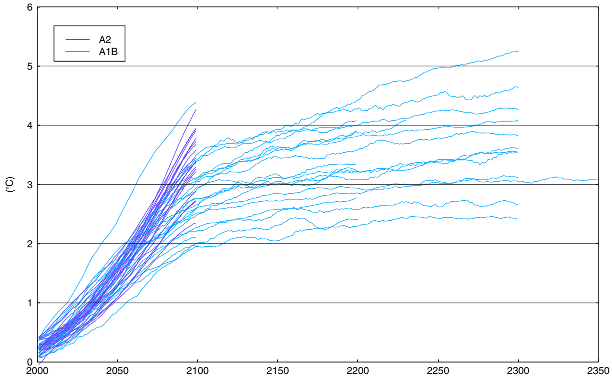

Fig. 1 Global annual mean temperature anomalies (°C) relative to 1985–99 in 19 models run in A2, and 24 models run in A1B

For example, the timing of a 2 °C warming has a range of 2056–2083 in A2 and 2040–2116 in A1B.

3.2 African temperature change

African temperatures are projected to rise with ΔT_g. Most of the continent warms more than the global average. The ensemble mean annual mean temperature change for Africa is 1.1 °C at 1 °C, 2.3 °C at 2 °C, 3.4 °C at 3 °C, and 4.3 °C and 4 °C in A1B, an approximately linear increase which is similar for A2. The highest anomalies are found in arid subtropical regions, particularly surrounding the Angolan and Saharan heat lows. Figure 2 shows how this varies seasonally. Other seasons, JFM, AMJ, JAS, and OND (not shown) are similar to DJF, MAM, JJA, and SON, respectively. The most pronounced warming occurs in JJA, when the ensemble mean for Africa in A2 (A1B) is 3.6 °C (3.5 °C) at 3 °C ΔT_g, compared to 3.2 °C (3.1 °C) in DJF. This is particularly anomalous in the northern hemisphere subtropics: in JJA there is an increase of 5.3 °C averaged 20–30°N at 4 °C ΔT_g in A1B. These spatial and seasonal patterns are qualitatively consistent between A2 and A1B, and from model to model.

3.3 African precipitation change

The precipitation projections exhibit more spatial, seasonal, and inter-model variability than projections for temperature, and there are some distinctions between A2 and A1B. The differences between 1 °C, 2 °C, 3 °C, and 4 °C are also more complex (Figs. 3 and 4). At 1 °C there is model agreement for a lack of significance across much of the continent (shown in grey). At 2 °C many more regions exhibit statistically significant anomalies, in some cases with model agreement on the direction of change. The progression from 2 °C to 3 °C is matched mainly in the magnitude of these regional changes. The models which reach 4 °C in A1B show a further strengthening and extension of precipitation changes, with some new anomalies; although this is in part due to a different number of models being averaged (Online Resources 8 and 9 show the mean of these models at 1 °C–3 °C).

Some regions experience consistent precipitation change in all seasons, for example the Mediterranean where there is strong drying from 2 °C. In most other regions there is marked seasonal variation. In DJF the most prominent signal is moistening in East Africa. This

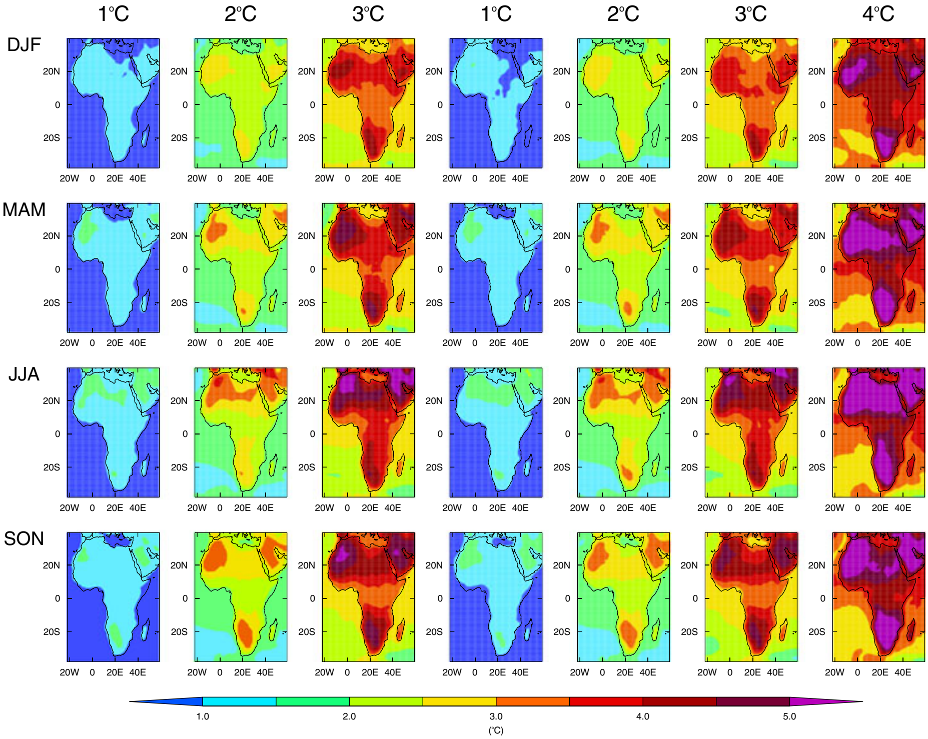

Fig. 2 Ensemble mean seasonal temperature anomalies associated with global warming, in A2 (first 3 columns), and A1B (last 4 columns)

constitutes a large proportional change in South Sudan, Ethiopia, and Somalia, where DJF is mostly a dry season, and a smaller ratio further south where the anomalies extend towards the climatological maximum (Online Resource 10). In MAM, there is also an increase in precipitation in East Africa. This is orientated further south than during DJF in most models, and at 3 °C extends into Central Africa to the south of the equator. The opposite trend is shown at the Guinea Coast during this season: on average a 10 % (5 %) decrease at 3 °C in the A2 (A1B) ensemble mean.

In JAS projections for much of tropical and North Africa are characterised by a lack of agreement between models, particularly at 2 °C (as shown by the large areas in white in Figs. 3 and 4). Some individual models produce contrasting futures, for example GFDL-CM2.0 experiences large amplitude drying throughout West Africa from 2 °C, and ECHO-G projects extensive moistening from 3 °C (not shown). Many other models and the ensemble means share a dry signal in west Sahel and a wet signal further east, although this has more model agreement in A2 than A1B. The sensitivity of this trend to the choice of baseline was tested, due to the prevalence of interdecadal variability in this region. Changes relative to 1955–69 also show a dry west and wet central Sahel, in both scenarios (Online Resource 2, 3).

In southern Africa, over 80 % of models show a dry signal for South Africa, Botswana, Zimbabwe, and Madagascar by 2 °C during JAS. Relative to the low climatological precipitation this is a large proportional change (25 % (24 %) in the regionally averaged ensemble mean by 3 °C in A2 (A1B)), but anomalies are relatively small (−0.2 mm day^{-1} in A2 and A1B). Projections for JJA are similar to JAS (not shown), and the dry signal in southern Africa continues into SON, when anomalies are largest over Angola. In some

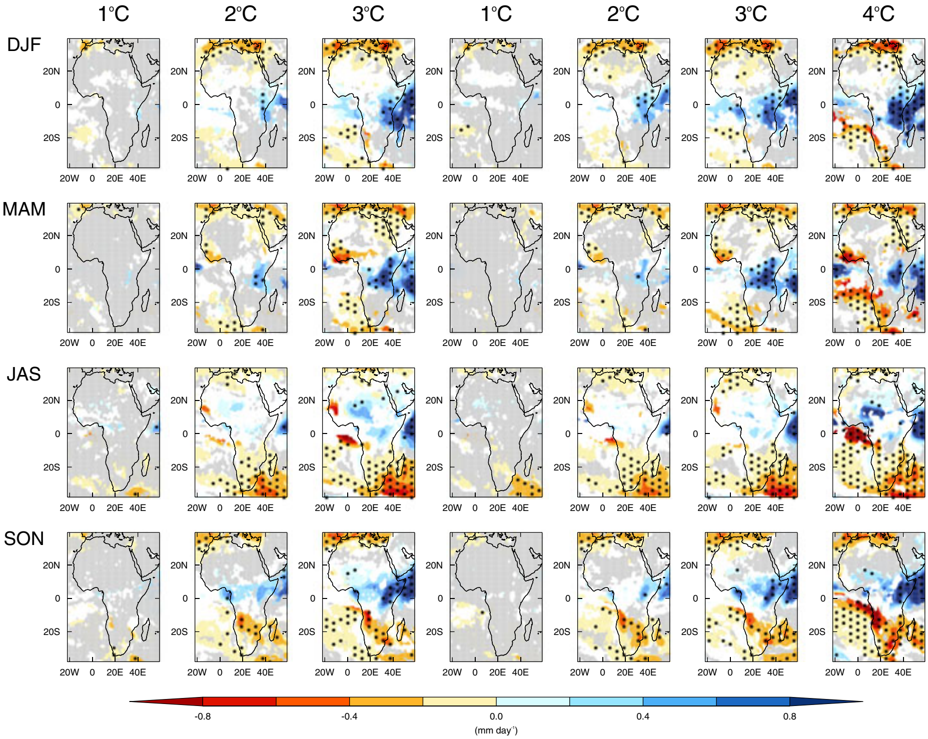

Fig. 3 Ensemble mean seasonal precipitation anomalies (mm day^{-1}) associated with global warming, in A2 (first 3 columns) and A1B (last 4 columns). Grid-points where <66 % of models agree on the direction of change are masked in white, and grid-points where >80 % of models show no significant change are shown in grey. Stippling shows grid-points where >80 % of models agree on the direction of change

models the negative changes extend towards the equator, into the south of the Congo basin. The north of the convective zone mainly shows the opposite trend in this season: an increase in precipitation, which forms an approximately zonal band around 0–5°N at 2 °C in A2 and 3 °C in A1B. As in DJF and MAM, the wet signal is more pronounced over East Africa than Central Africa, particularly at 3 °C and 4 °C.

4 Implications of projected changes

Climate change is widely recognised as one of the prime challenges facing Africa, and the continent is often cited as the hardest hit by potential transformations (Boko et al. 2007). Scientific rigour underpinning climate assessments does not match the strength of such claims, most notably in connection with what might be considered dangerous levels of warming. Whereas almost all projection work focuses on time-slices in the 21st century, mitigation debates are geared around degrees of global change for which there is a dearth of corresponding information in the case of African climate.

The projected changes in global temperature over time (Fig. 1) illustrate that approaches based on time-slices conflate and therefore conceal differences between temperature intervals. As has been previously illustrated by Joshi et al (2011), there is a range of years at

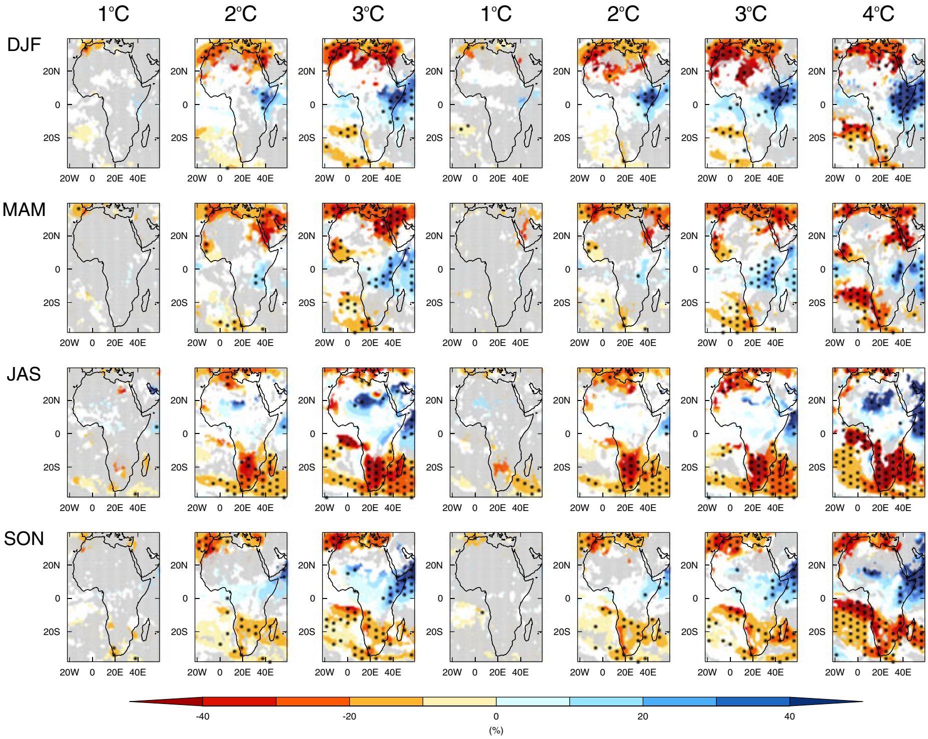

Fig. 4 As Fig. 3 but for proportional change relative to 1985–99 (%)

which the models reach 2 °C and other ΔT_g intervals. Equally, for the same level of GHG forcing, models project different ΔT_g, due to variation in feedbacks (Bony et al. 2006), and forcings (Kiehl 2007). The time-averaged ΔT_g for 2085–99 ranges from 2.3–3.9 °C in A2 and 1.8–4.2 °C in A1B, so precipitation changes averaged across this time-slice give little information about the impact of 2 °C or 3 °C or 4 °C. As a result, a time-slice approach is at odds with and inappropriate for mitigation debates as they are currently posed.

The analysis employed here, of climate change in Africa as a function of degrees of warming, can deliver more evidence about the implications of ΔT_g. Note that the changes identified are relative to 1985–99, whereas policy documents refer to temperature increase above preindustrial levels. Projections using an alternative baseline chosen to represent a period prior to the detection of anthropogenic influence (1955–69) have similar patterns but a slightly larger magnitude at 1 °C (Online Resource 2, 3). The results presented here (for 1985–99) can therefore be considered a conservative estimate of changes associated with anthropogenic warming. These results reveal a heterogeneous spatial structure of associated climate responses. Moreover, where the same magnitude of precipitation response occurs in different regions, it is likely to have quite different consequences. The implications thus need to be assessed separately for each region.

In East Africa, OND precipitation is projected to increase by 3 % (3 %) at 1 °C, 7 % (8 %) at 2 °C, and 14 % (13 %) at 3 °C in the A2 (A1B) ensemble mean (Table 2). In the 20th century, anomalously wet seasons have been associated with higher agricultural yields, but also flooding. For example, high precipitation October 1997 to January 1998 caused floods which led to loss of life, damage to infrastructure, and an outbreak of Rift Valley Fever (Conway et al. 2005). This was associated with a 40 % precipitation increase in OND relative to 1985–99 (in NCEP-NCAR reanalysis, not shown). Ensemble mean changes projected are much smaller, even at 4 °C (16 %), but these are for 15 year climatologies, which preclude interannual variability. In a study of future East African precipitation, Shongwe et al. (2011) found an 8–21 % shift in the mean was associated with an increase in the intensity of 10 year wettest seasons, suggesting that the mean change at 2 °C, 3 °C or 4 °C might be accompanied by wetter extremes. Furthermore, high rainfall events are expected to intensify in general in response to global warming (Christensen et al. 2007). Some individual models show substantial changes in the 15 year mean. The model with the largest wet signal, MIROC3.2(medres) shows a 43 % (62 %) increase at 3 °C in A2 (A1B) and a 68 % increase at 4 °C (Fig. 5). If this model's 3 °C or 4 °C scenario were realised the region would have more precipitation in an average short rains season than in the extreme 1997 season.

In southern Africa, the largest proportional changes are in JAS, when there is a decrease in the ensemble mean of 19 % at 2 °C, and 31 % at 4 °C (Table 2). However, this is a very dry season for this region, and most models overestimate precipitation in the Southern Hemisphere mid-latitude storm tracks during JJA (Neelin et al. 2006), meaning this trend should be interpreted cautiously without further work into the associated dynamics and impacts. A dry signal is also projected for southern Africa during SON, when the ensemble mean shows a 17 mm (21 mm) or 10 % (12 %) reduction by 2 °C in A2 (A1B). In individual models this change is as high as 24 % for 2 °C and 33 % for 3 °C (GFDL-CM2.0 in A2). This suggests a delay in onset of the precipitation season (Shongwe et al. 2009) with possible implications for agriculture, such as a decrease in the growing season for maize. Little significant change is projected for the summer precipitation season itself in most models. However, Kay and Washington (2008) find more extreme wet and dry summers in HadCM3, a model which shows no significant change in the JFM mean at 2 °C or 3 °C (not shown). It is therefore difficult to decipher the implications from mean precipitation alone, particularly for JFM.

The multi-decadal Sahel drought in the 1970s–80s had particularly large social implications. Projections for the Sahel show little model agreement when zonally averaged, but there is some consensus for a drying at the west coast in JAS. Several previous studies have revealed this signal (e.g. Christensen et al. 2007), but it has only recently been highlighted (Fontaine et al. 2011). In the ensemble mean, the change is much smaller than the 40 % reduction in rainfall associated with the 20th century drought (Held et al. 2005): at 12 % (8 %) for a 3 °C warming in A2 (A1B). However, three models show more than 20 % drying at 3 °C (in A2 and A1B). Such changes might have serious ramifications for food security, especially given the reliance of local economic systems on rainfed agriculture (Biasutti et al. 2009).

The projections generally indicate that there will be greater consequences at higher degrees of warming. Some models project very large changes at 2 °C, 3 °C, and 4 °C. These outliers cannot be rejected by default, as previous studies have shown that some reproduce observations well, for example GFDL-CM2.0 shows a large dry signal for the Sahel and also has one of the best 20th century hindcasts (Held et al. 2005).

Mapping regional climate change as a function of ΔT_g is a necessary but not sufficient step if dangerous climate change is to be assessed. An obvious next step is to consider the impacts of the associated climate on health, agriculture and water. This requires attention to measures of precipitation change which are most relevant to each sector. For example rainfed agriculture in southern Africa is dependent on the onset, length, and dry spells within the growing season (Mupangwa et al. 2011). Research on the mechanisms behind precipitation

Table 2 Area-averaged precipitation change for A2 and A1B, for selected regions and seasons. The values given for the anomaly (mm season^{-1}) and proportional change relative to 1985–99 (%) refer to the ensemble mean. Significant changes are highlighted in grey. Model agreement refers to the number of models which show the same direction of change as the ensemble mean, with the number of significant models to show the same direction of change in brackets

		Anomaly (mm season^{-1})							Proportional Change (%)							Model Agreement						
		A2			A1B				A2			A1B				A2			A1B			
Region	**Season**	**1°C**	**2°C**	**3°C**	**1°C**	**2°C**	**3°C**	**4°C**	**1°C**	**2°C**	**3°C**	**1°C**	**2°C**	**3°C**	**4°C**	**1°C**	**2°C**	**3°C**	**1°C**	**2°C**	**3°C**	**4°C**
Angola	SON	-14	-25	-33	-11	-28	-32	-59	-6	-10	-15	-5	-12	-14	-24	12(4)	14(6)	10(7)	11(3)	17(7)	10(7)	6(5)
Central African Republic	MAM	8	10	30	-1	16	39	15	2	2	6	0	3	8	3	15(1)	14(3)	9(4)	8(0)	15(2)	11(7)	5(2)
Central African Republic	SON	1	6	9	2	-2	11	2	0	1	2	0	0	2	0	9(2)	12(3)	5(5)	11(0)	8(3)	6(5)	2(1)
Congo Basin	MAM	1	2	-3	-1	7	8	-3	0	0	-1	0	2	2	-1	10(0)	10(3)	6(2)	9(0)	12(2)	7(3)	3(1)
Congo Basin	SON	6	20	27	6	8	29	28	1	4	6	1	2	6	5	13(1)	15(7)	9(8)	13(3)	13(5)	9(6)	4(3)
East Africa	DJF	14	27	50	15	37	55	82	4	7	13	4	10	15	24	13(3)	15(7)	11(9)	13(2)	15(10)	11(10)	6(4)
East Africa	MAM	15	34	56	14	28	56	52	4	10	17	4	8	17	17	13(3)	16(9)	10(9)	14(4)	14(9)	11(9)	5(4)
East Africa	OND	13	28	56	12	31	50	63	3	7	14	3	8	13	16	12(2)	18(8)	11(9)	13(3)	17(10)	11(7)	5(3)
Guinea Coast	MAM	-11	-15	-36	-8	-17	-20	-43	-3	-4	-10	-2	-4	-5	-11	12(2)	16(4)	10(7)	14(0)	13(5)	9(5)	6(4)
Mediterranean	Annual	-5	-9	-12	-5	-10	-13	-14	-12	-21	-28	-12	-23	-31	-26	18(7)	18(15)	11(9)	18(6)	18(15)	12(10)	6(5)
Mozambique	SON	-10	-18	-21	-9	-18	-23	-30	-7	-12	-15	-6	-12	-17	-24	14(4)	17(8)	10(5)	13(3)	17(9)	12(4)	6(5)
Sahel	JAS	2	2	4	9	-2	3	21	1	1	1	3	-1	1	7	13(1)	14(4)	7(4)	14(2)	11(4)	7(3)	3(2)
West Sahel	JAS	-4	-16	-36	2	-12	-26	-23	-1	-5	-12	1	-4	-8	-7	9(4)	13(3)	8(5)	9(1)	13(5)	8(6)	4(3)
Central Sahel	JAS	6	16	35	13	7	25	54	3	6	14	5	3	10	19	13(3)	14(6)	9(5)	15(4)	12(3)	8(4)	4(3)
Southern Africa	JAS	-6	-12	-15	-7	-12	-14	-18	-9	-19	-25	-11	-19	-24	-31	15(6)	19(9)	12(8)	16(6)	18(13)	12(10)	6(4)
Southern Africa	SON	-11	-17	-21	-9	-21	-21	-34	-6	-10	-13	-5	-12	-13	-21	16(1)	16(8)	10(8)	14(1)	19(9)	11(6)	6(6)

responses would also be useful in diagnosing the effect on the climate system: does African climate shift into a new state at 2 °C or 4 °C? A thorough investigation of atmospheric processes is left for later work, but changes in mechanisms inferred from precipitation trends will be explored in the next section.

5 Potential changes in precipitation mechanisms

On a large scale, the model projections suggest an evolution towards wetter tropical regions and dryer subtropical regions, in agreement with previous research for Africa (e.g. Giannini et al. 2008) and the global tropics (e.g. Allan et al. 2010). Robust trends in keeping with this include dry signals in many parts of the Mediterranean from 1 °C ΔT_g. This is consistent with the "rich-get-richer mechanism", whereby moisture increases associated with higher tropospheric temperatures reduce gross moist stability, enhancing convection and precipitation in convective regions, whilst stability increases in subsidence regions (e.g. Chou and Neelin 2004). This tendency is helpful in explaining why temperature projections, in this study as in previous research (Fig. 2; and Christensen et al. 2007), show greater change in the subtropics, as positive tropical rainfall anomalies might dampen surface temperature increases through cloud cover and/or soil moisture feedbacks. This has the potential to decouple local temperature from ΔT_g.

If this "rich get richer" response were the only impact of global warming, the pattern of precipitation anomalies could be expected to match the observed 20th century climatology (Online Resource 10), with the amplitude of anomalies gradually increasing from 1 °C to 4 °C, but with those anomalies spatially anchored in the regions of current rainfall receipt. Figures 3 and 4 illustrate that this is not the case. This might be partly due to biases in the modeled climatologies, which could produce "wet-get-wetter" (and "dry-get-drier") responses in regions which are not wet (or dry) in observations. In the west of the Sahel, many models show a dry bias and also a dry signal associated with global warming. However, the other robust changes identified do not fit with this explanation. For example during MAM East Africa has a dry bias but a wet signal in response to warming. Furthermore, we should not expect all changes to be governed by the "rich-get-richer" mechanism,

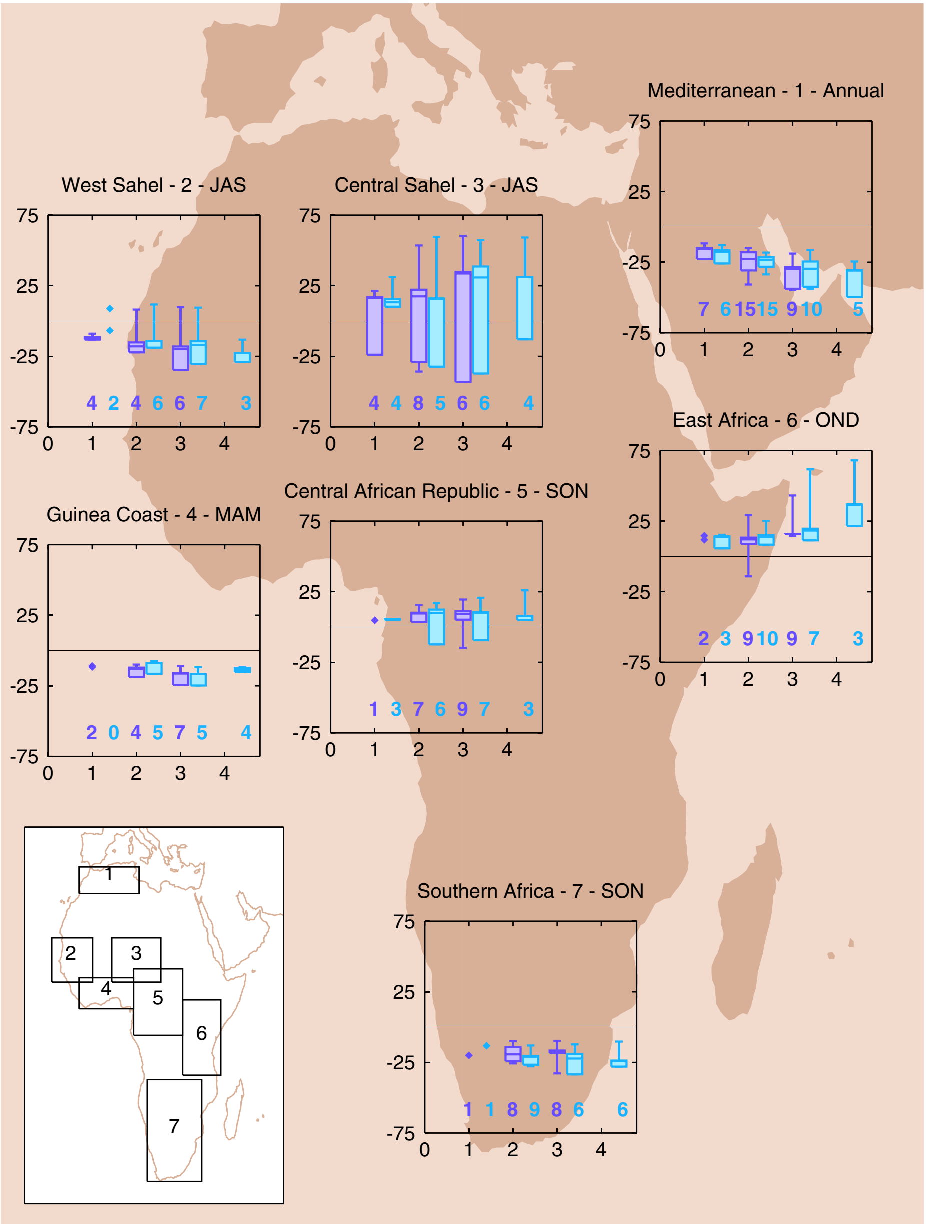

Fig. 5 Proportional precipitation change relative to 1985–1999 (%) associated with global warming, for selected regions and seasons, in A2 (*purple*) and A1B (*blue*). Only models with significant change are included, the number of which is indicated below each boxplot. Where fewer than 3 models show significant change, boxplots are replaced with points to represent each individual model

as previous literature has demonstrated many other thermodynamic and dynamic influences on precipitation which can result from anthropogenic forcing (e.g. Chou et al. 2009; Held and Soden 2006). The interaction and relative importance of such mechanisms must be diagnosed on a case by case basis.

Central Africa, the core convective region, might be expected to see the greatest precipitation enhancement due to the “rich get richer” mechanism; however, projected changes here are small, particularly in comparison to East Africa. Shongwe et al. (2011) suggest that the strong wetting of East Africa in OND is associated with changes in the Indian Ocean Dipole, which alter the Walker circulation, weakening subsidence over the western Indian Ocean. At the same time, most models experience a decrease in ascent over Central Africa. Vecchi and Soden (2007) show annual mean upward (downward) anomalies in vertical velocity over East (Central and West) Africa, associated with a widespread weakening of tropical circulation.

The potential delay in the rainfall season in southern Africa during austral spring also deserves further attention, particularly as other studies have found evidence for delayed precipitation seasons in observations for many parts of Africa (Kniveton et al. 2009), and in projections for West Africa (e.g. Biasutti and Sobel 2009). This delay is not visible in the projections for the Sahel presented in Fig. 3 due to the seasonal timescale, but monthly projections for many CMIP3 models reveal that the enhancement of precipitation in central Sahel witnessed here occurs at the end of the rainfall season (Monerie et al. 2012).

There are various potential mechanisms to explain why delayed tropical precipitation seasons might be a general phenomenon induced by global warming. Chou et al. (2007) suggest that longer dry seasons might be expected as part of the “rich get richer” mechanism. Seth et al. (2011) find a decrease in spring convection in many monsoon regions, including West and southern Africa, due to increased stability and reduced surface moisture resulting from a more intense dry season. In contrast, Biasutti and Sobel (2009) ascribe the projected late onset of the West African Monsoon (WAM) to a delay in the seasonal cycle of SSTs. Under normal conditions, the maximum northern hemisphere SSTs occur in August, but with global warming models show a later peak in temperature, likely due to Northern Hemisphere sea ice loss. As well as influencing the WAM, this could be responsible for a large scale shift in the annual cycle of precipitation globally. This would not only explain drying in southern Africa during SON, but also negative anomalies at the Guinea Coast in MAM from 2 °C. Both of these changes occur at the leading edge of tropical convection, suggesting a delay in its migration. This hypothesis is further supported by the fact that the projected tropical precipitation enhancement in SON is further north than in MAM despite the symmetry of these transition seasons in the modelled climatology (Online Resource 10) and in observations (Waliser and Gautier 1993).

A delay in the annual cycle of tropical convection would constitute a major modification of the atmospheric circulation, and the apparent link to sea ice opens up the possibility of nonlinearity, as accelerated sea ice loss is projected for the Arctic (Meehl et al. 2007a). It is unclear whether the models have the ability to adequately represent such teleconnections. GCMs simulate 20th century precipitation well when forced with observed SSTs, but do not always capture interannual SST variability (e.g. Hoerling et al. 2006). Biasutti and Sobel (2009) show that there is little variation between models in the projected change in the global annual cycle of SSTs, but more research is needed to assess the plausibility of this mechanism, particularly given the potential implications of such a change at 2 °C of global warming.

6 Summary and conclusions

GCM data have been employed to investigate temperature and precipitation changes associated with 1 °C, 2 °C, 3°, and 4 °C of global warming in Africa. Temperatures are projected to rise more than the global average, particularly in arid regions. Precipitation projections show more variation between models in the amplitude and direction of change, but in all models precipitation changes are enhanced as global temperature increases, and the degree of response is regionally specific. At 1 °C no significant change is projected for most parts of Africa, except for a dry signal in the Mediterranean, and a wet signal in East Africa in many models. At 2 °C these trends are strengthened, and many other regions experience robust changes, including southern Africa and the Guinea Coast which show dry signals in SON and MAM respectively. In the Sahel there is a drying at the west coast. At 3 °C and 4 °C these anomalies are strengthened and extended. The projected changes imply a delay in precipitation seasons at 2 °C and beyond, possibly associated with changing SSTs and sea ice loss. This would constitute a major shift in teleconnections, which warrants further investigation.

The magnitude of change projected by some models at 2 °C, 3 °C, and 4 °C would likely have large societal implications, including for East Africa and the Sahel. Despite the uncertainty attached to the projections, they suggest that there are risks associated with these levels of global warming. More research is needed to investigate extremes, variability, and impacts associated with the mean precipitation projections presented here as well as the different climate sensitivities of the models. This study provides a framework for such analysis.

Acknowledgements The authors would like to thank Gil Lizcano for technical support, and acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison, and the WCRP's Working Group on Coupled Modelling for their roles in making available the CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

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